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ISO 10303-104

Product data representation and exchange: Integrated application resource: Finite element analysis

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ABSTRACT:
This part of ISO 10303 specifies the integrated resources to represent a finite element model and the associated analysis control and output.

KEYWORDS: finite elements, finite element model, finite element analysis

COMMENTS TO READER:
This document has been reviewed using the internal review checklist, the project leader approval checklist and the convener approval checklist, and has been determined to be ready for publication. It contains revisions to take account of all DIS ballot issues.

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this part of ISO 10303 may be subject of patent rights. ISO shall not be held responsible for any or all such patent rights.

International Standard ISO 10303–104 was prepared by Technical Committee ISO/TC 184, *Industrial automation systems and integration*, Subcommittee SC4, *Industrial data*.

This part of ISO 10303 is a member of the integrated resources series. The integrated resources specify a single conceptual product data model.

This International Standard is organized as a series of parts, each published separately. The structure of this International Standard is described in ISO 10303–1. The numbering of the parts of this Interational Standard reflects its structure:

— Parts 11 to 14 specify the description methods;

— Parts 21 to 29 specify the implementation methods;

— Parts 31 to 35 specify the conformance testing methodology and framework;

— Parts 41 to 50 specify the integrated generic resources;

— Parts 101 to 107 specify the integrated application resources;

— Parts 201 to 237 specify the application protocols;

— Parts 301 to 337 specify the abstract test suites;

— Parts 501 to 520 specify the application interpreted constructs.

A complete list of parts of ISO 10303 is available from the internet:

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<http://www.nist.gov/sc4/editing/step/titles/>

Should further parts of ISO 10303 be published, they will follow the same numbering pattern.

Annexes A and B form a normative part of this part of ISO 10303. Annexes C, D, and E are for information only.

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Introduction

ISO 10303 is an International Standard for the computer-interpretable representation and exchange of product data. The objective is to provide a neutral mechanism capable of describing product data throughout the life cycle of a product independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving.

This International Standard is organized as a series of parts, each published separately. The parts of ISO 10303 fall into one of the following series: description methods, integrated resources, application interpreted constructs, application protocols, abstract test suites, implementation methods, and conformance testing. The series are described in ISO 10303–1. This part of ISO 10303 is a member of the integrated resources series.

This part of ISO 10303 is concerned with information exchange needs of finite element analysis. Many types of analyses can be conducted to ensure the performance and integrity of a product. Different aspects of a product may be idealized and then analyzed as a continuum. Exact mathematical models for any but the simplest continuum shapes are intractable. Therefore analytical methods that represent the continuum as discrete tractable shapes are used. There are many discrete analytical methodologies, some of which are finite element, finite difference, and boundary element. This part of ISO 10303 addresses only finite element analysis.

In performing an analysis with finite element analysis methods the continuum of a product is discretized into a finite element model that consists of a mesh of points (nodes) which are connected with elements. The elements represent finite portions of the product that when connected with shared nodes collectively respond as would the entire product. The elements have associated physical and material properties. There are also coordinate systems, groups, and administrative information associated with the finite element model. Load, constraint, and analysis output control information, along with analysis selection information, are combined with the finite element model to form a complete input to an analysis. Once an analysis is performed, analysis results information may be output at the nodes and at one or more positions within an element. There may be other output information not associated with a position within the finite element model such as total strain energy.

This part of ISO 10303 specifies the resources for the exchange of the information associated with the discretized (finite element) model, and the analysis controls, boundary conditions, and analysis results information that are associated with it. It is expected that the reader of this part of ISO 10303 is familiar with finite element analysis techniques.

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Industrial automation systems and integration — Product data representation and exchange — Part 104: Integrated application resource: Finite element analysis

1 Scope

This part of ISO 10303 specifies the resources for finite element analysis input and output information. This includes finite element models, the analysis control information, and the analysis results. The finite element analysis information model is partitioned into four schemas: the **structural_response_-definition_schema**, the **structural_response_representation_schema**, the **finite_element_analysis_-control_and_result_schema** and the **fea_scalar_vector_tensor_schema**.

NOTE 1 The EXPRESS-G schema level model in Figure 1 shows the relationships of the four schemas and their relationships to other parts of ISO 10303.

NOTE 2 The following rules apply to the entire FEA information model:

— a model shall be combined with a control to produce a complete FEA input;

— a result shall be combined with a model and a control to be valid.

NOTE 3 The FEA information model includes the consideration of a multi-disciplinary analysis environment, which is presented in detail in annex E.

1.1 Analysis type scope

The following types of analyses are within the scope of this part of ISO 10303:

— linear static analysis and linear dynamic modes and frequencies analysis of general 3D stress, plane stress, axisymmetric strain, and simple plane strain, based upon h-version finite element formulation using 2D and 3D continua and embedded elements which include thick shells, thin shells, beams, and bars.

The following types of analyses are outside the scope of this part of ISO 10303:

— linear static analysis of generalized plane strain.

1.2 Structural response definition schema scope

The following are within the scope of the **structural_response_definition_schema** of this part of ISO 10303:

— the definitional aspects of a finite element analysis model;

— the definitional aspects of a finite element;

— the definitional aspects of a node.

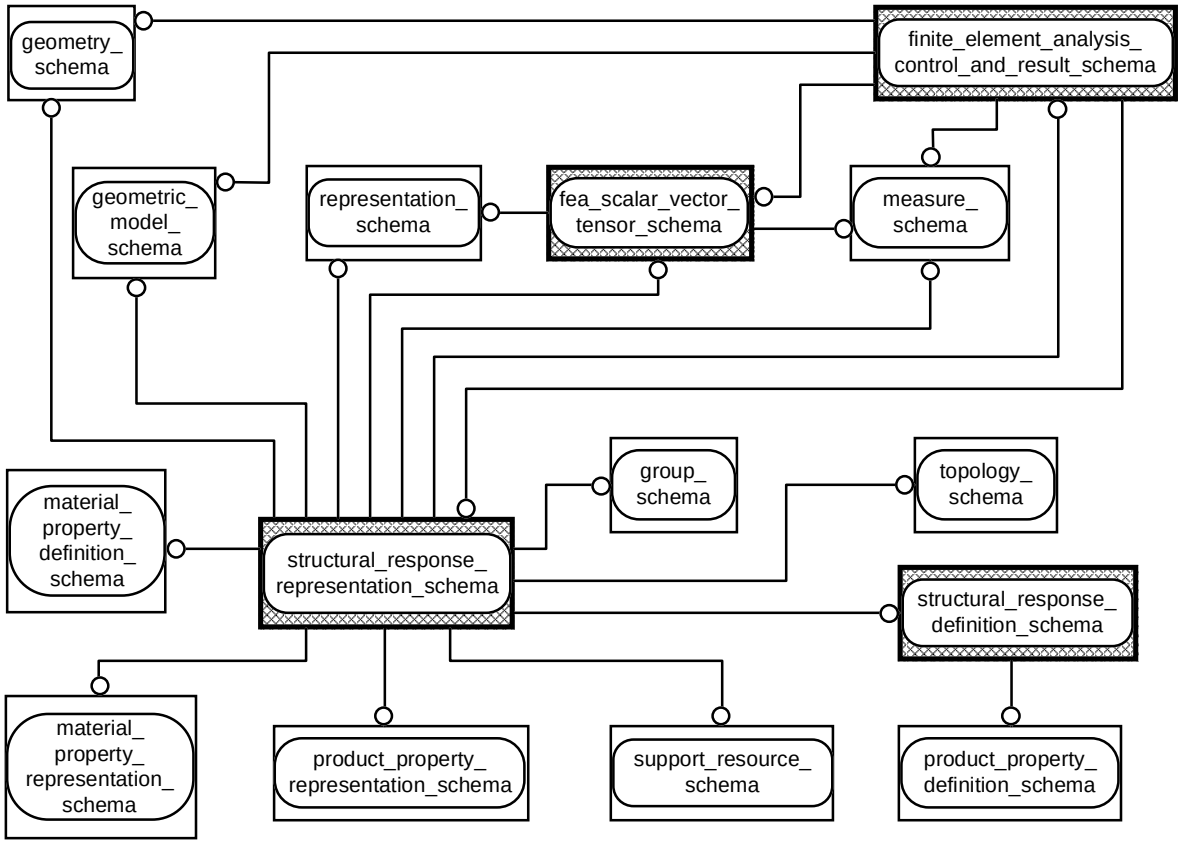

Figure 1 – FEA schema level model in EXPRESS-G

1.3 Structural response representation schema scope

The following are within the scope of the **structural_response_representation_schema** of this part of ISO 10303:

— nodes, h-version finite elements, and the associated element material and geometric property representations that combine to form a discretised mesh;

— material representations;

— coordinate space representations;

— administrative information.

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The following are outside the scope of the **structural_response_representation_schema** of this part of ISO 10303:

— p-version finite elements.

1.4 Finite element analysis control and result schema scope

The following are within the scope of the **finite_element_analysis_control_and_result_schema** of this part of ISO 10303:

— analysis selection and related information;

— environment information;

— output control information;

— nodal and element output information;

— output information applying to a whole model;

— administrative information.

1.5 Scalars, vectors, and tensors schema scope

The following scalars, vectors and tensors which are necessary to represent the input and output of finite element analyses are within the scope of the **fea_scalar_vector_tensor_schema** of this part of ISO 10303:

— scalars;

— 2D and 3D first order tensors;

— 2D and 3D second order tensors;

— 2D and 3D symmetric fourth order tensors.

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2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 10303. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 10303 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO/IEC 8824-1:1995, *Information technology — Open Systems Interconnection — Abstract Syntax Notation One (ASN.1) — Part 1: Specification of Basic Notation.*

ISO 10303-1:1994, *Industrial automation systems and integration — Product data representation and exchange — Part 1: Overview and fundamental principles.*

ISO 10303-11:1994, *Industrial automation systems and integration — Product data representation and exchange — Part 11: Description methods: The EXPRESS language reference manual.*

ISO 10303-41:1994, *Industrial automation systems and integration — Product data representation and exchange — Part 41: Integrated generic resources: Fundamentals of product description and support.*

ISO 10303-42:1994, *Industrial automation systems and integration — Product data representation and exchange — Part 42: Integrated generic resources: Geometric and topological representation.*

NOTE This part of ISO 10303 utilizes the corrections published in ISO 10303-42:1994/Cor.1:1998, ISO 10303-42:1994/Cor.2:1999 and ISO 10303-42:1994/Cor.3:—[1].

ISO 10303-43:1994, *Industrial automation systems and integration — Product data representation and exchange — Part 43: Integrated generic resources: Representation structures.*

ISO 10303-45:1998, *Industrial automation systems and integration — Product data representation and exchange — Part 45: Integrated generic resource: Materials.*

[1] To be published.

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3 Terms, definitions, abbreviations, and symbols

For the purposes of this part of ISO 10303, the following terms, definitions, abbreviations, and symbols apply.

3.1 Terms defined in ISO 10303-1

For the purposes of this part of ISO 10303, the following terms defined in ISO 10303-1 apply.

— application;

— application context;

— application protocol;

— application resource;

— data;

— data exchange;

— generic resource;

— information;

— information model;

— integrated resource;

— model;

— product;

— product data;

— structure.

3.2 Other terms and definitions

For the purposes of this part of ISO 10303, the following terms and definitions apply.

3.2.1
2d_model
a finite element model that has geometry restricted to a plane that is either swept around an axis of symmetry (axisymmetric model) or projected perpendicular to a plane (planar model) to create the third dimension of the volume.

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3.2.2
3d_model
a finite element model that has one or more 3D finite elements.

3.2.3
analysis step
the act of proceding from an initial state to a new state in the analysis as required by a control process.

3.2.4
control
the operations that are carried out upon a model as a set of analysis steps. A model may have one or more sets of control information.

3.2.5
control process
the way in which a model is caused to depart from its initial state. For linear analysis a control process specifies a final state of the model.

3.2.6
h-version
the method of hierarchically reducing elements in size to provide a finer analysis resolution, producing a larger number of smaller elements

3.2.7
p-version
the method of parametrically increasing the order of the elements while the size and shape remains constant, to provide a finer analysis resolution

3.2.8
result
the response of a model to a control as calculated by a finite element analysis application.

3.2.9
state
an aggregation of information about the analysis variables of a model that describes the model at an instant.

3.2.10
state definition
values of the analysis variables of a model that are calculated by or requested from a finite element analysis application.

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3.3 Symbols

For the purposes of this part of ISO 10303, the following symbols apply. The notation in Table 1 is used in the definition of element coordinate systems:

Table 1 – Element coordinate system definition symbols

Symbol	Definition
$\mathbf{X}$	Vector quantity
$\langle\rangle$	Vector normalisation
$\times$	Vector (cross) product
$\cdot$	Scalar product
$\lvert\lvert$	Vector magnitude

The notation in Table 2 is used to denote the axes of a coordinate system:

Table 2 – Element coordinate axis symbols

Normalized axes	Definition of the coordinate system
(ξ,η,ζ)	an element parametric system
$(\mathbf{x},\mathbf{y},\mathbf{z})$	an element orthogonal system
$(\mathbf{x}',\mathbf{y}',\mathbf{z}')$	an intermediate element orthogonal system (used in the derivation of an element orthogonal system)
$(\mathbf{X},\mathbf{Y},\mathbf{Z})$	a specified arbitrary system
$(\mathbf{i},\mathbf{j},\mathbf{k})$	the 2D analysis plane definition system

3.4 Abbreviations

For the purposes of this part of ISO 10303, the following abbreviations apply.

DOF degree of freedom

FEA finite element analysis

ref reference

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4 Structural response definition schema

The following EXPRESS declaration begins the **structural_response_definition_schema** and identifies the necessary external references.

EXPRESS specification:

```
*)
SCHEMA structural_response_definition_schema;

  REFERENCE FROM product_property_definition_schema
      (property_definition,
       shape_aspect);
(*
```

NOTE The schema referenced above can be found in the following part of ISO 10303:

product_property_definition_schema	ISO 10303-41

4.1 Introduction

The subject of the **structural_response_definition_schema** is the definitional aspects of a finite element analysis model that describe the structural response of a product.

4.2 Fundamental concepts and assumptions

The definitional aspects of a finite element model are related to the representational aspects that they describe by a **property_definition_representation** association to a **structural_response_property**. This relationship is enforced by the rules in the **structural_response_property_definition_representation** entity in the **structural_response_representation_schema**.

NOTE The relationships of the definitional and representational aspects of the FEA information model, which are established by the **property_definition_representation** and **structural_response_property** entities, are shown in Figure 2.

4.3 Structural response definition schema entity definitions

4.3.1 structural_response_property

A **structural_response_property** relates the response of a finite element model representation of a product to the properties characterizing the product.

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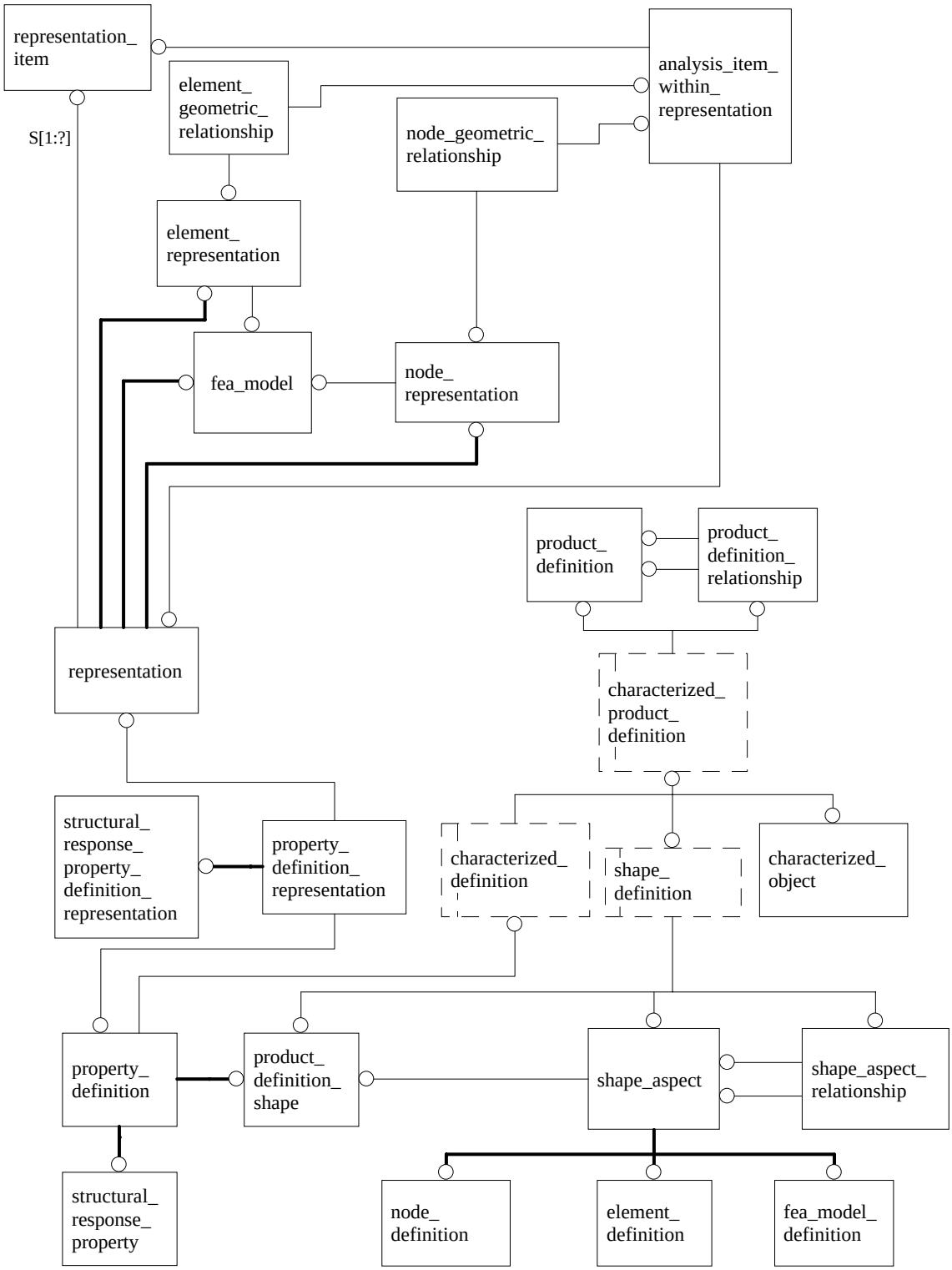

Figure 2 – FEA information model high level relationships EXPRESS-G partial model

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EXPRESS specification:

```
*)
ENTITY structural_response_property
  SUBTYPE OF (property_definition);
END_ENTITY;
(*
```

4.3.2 fea_model_definition

An **fea_model_definition** describes a specific finite element analysis model. A finite element analysis model is a collection of information associated with the definition of a finite element analysis of a product.

EXPRESS specification:

```
*)
ENTITY fea_model_definition
  SUBTYPE OF (shape_aspect);
END_ENTITY;
(*
```

4.3.3 node_definition

A **node_definition** is a description of the shape aspect of a product that a node represents. Nodes are the discretized points in the continuum being modelled that are connected with elements.

EXPRESS specification:

```
*)
ENTITY node_definition
  SUBTYPE OF (shape_aspect);
END_ENTITY;
(*
```

4.3.4 element_definition

An **element_definition** is a description of the shape aspect of a product that a finite element represents. A finite element is an analytical subdivision of a continuum connected to nodes to model the continuum being analyzed.

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EXPRESS specification:

```
*)
ENTITY element_definition
  SUBTYPE OF (shape_aspect);
END_ENTITY;
(*
```

EXPRESS specification:

```
*)
END_SCHEMA; -- structural_response_definition_schema
(*
```

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5 Structural response representation schema

The following EXPRESS declaration begins the **structural_response_representation_schema** and identifies the necessary external references.

EXPRESS specification:

```
*)
SCHEMA structural_response_representation_schema;

  REFERENCE FROM fea_scalar_vector_tensor_schema
      (scalar,
       symmetric_tensor2_2d,
       symmetric_tensor2_3d,
       symmetric_tensor4_2d,
       symmetric_tensor4_3d);

  REFERENCE FROM finite_element_analysis_control_and_result_schema
      (curve_element_variable,
       measure_or_unspecified_value,
       surface_2d_edge,
       surface_2d_face,
       surface_3d_edge,
       surface_3d_face,
       surface_element_variable,
       volume_2d_edge,
       volume_2d_face,
       volume_3d_edge,
       volume_3d_face,
       volume_variable);

  REFERENCE FROM geometric_model_schema
      (solid_model);

  REFERENCE FROM geometry_schema
      (axis2_placement_2d,
       axis2_placement_3d,
       cartesian_point,
       cross_product,
       curve,
       cylindrical_point,
       degenerate_pcurve,
       direction,
       geometric_representation_context,
       geometric_representation_item,
       normalise,
       point,
       point_on_curve,
       point_on_surface,
       point_replica,
```

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```
        spherical_point,
        surface);

  REFERENCE FROM group_schema
      (group,
       group_relationship);

  REFERENCE FROM material_property_definition_schema
      (material_property);

  REFERENCE FROM material_property_representation_schema
      (material_property_representation);

  REFERENCE FROM measure_schema
      (context_dependent_measure,
       length_measure,
       parameter_value,
       plane_angle_measure,
       thermodynamic_temperature_measure);

  REFERENCE FROM product_property_representation_schema
      (property_definition_representation);

  REFERENCE FROM representation_schema
      (representation,
       representation_item,
       representation_relationship,
       using_representations);

  REFERENCE FROM structural_response_definition_schema
      (element_definition,
       fea_model_definition,
       node_definition,
       structural_response_property);

  REFERENCE FROM support_resource_schema
      (identifier,
       label,
       text);
(*
```

NOTE The schemas referenced above can be found in the following parts of ISO 10303:

fea_scalar_vector_tensor_schema	Clause 7 of this part of ISO 10303
finite_element_analysis_control_and_result_schema	Clause 6 of this part of ISO 10303
geometric_model_schema	ISO 10303-42
geometry_schema	ISO 10303-42
product_property_definition_schema	ISO 10303-41
product_property_representation_schema	ISO 10303-41
representation_schema	ISO 10303-43
material_property_definition_schema	ISO 10303-45
material_property_representation_schema	ISO 10303-45

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measure_schema	ISO 10303-41
structural_response_definition_schema	Clause 4 of this part of ISO 10303
support_resource_schema	ISO 10303-41

5.1 Introduction

The subjects of the **structural_response_representation_schema** are the generalized nodes, elements, materials, and element properties which are combined to create an FEA model of a product.

NOTE 1 The overall structure of the FEA information model and the external relationships with the Integrated Resources are shown in Figure 1.

NOTE 2 Many model generation and representation features contained in input files for some FEA applications are not reproduced exactly as an application would represent them within this information model, but the requisite information can be derived from the more generic form in this part of ISO 10303. Hence information may be expanded during conversion from the input file for an FEA application into the structures in this part of ISO 10303. If the information is then converted back, an equivalent but expanded input file may be obtained.

5.2 Fundamental concepts and assumptions

The fundamental concepts and assumptions include the uniqueness of a finite element analysis model, the relationships of a finite element model to a product, the geometric founding and the definition of 2D and 3D finite element models, identifiers, coordinate systems, element integration, units and measures, the interface with the Materials schema, the relationships between the model definition and representation, control, and result portions of a finite element analysis.

NOTE 1 The concept of subtyping to allow extensibility with a minimum of impact on the existing information model was a key design philosophy. Several single subtypes occur in the Finite Element Analysis information model for reasons of upward compatibility and extensibility.

NOTE 2 The element entities are subtyped for extensibility with a minimum of disturbance to the existing information model (See Figures 7, 8, and 9). Extensibility to other analysis disciplines is discussed in annex E.

5.2.1 Product relationship

The relationship between a finite element analysis model and the product it represents is specified using a **structural_response_property** entity.

5.2.2 Finite element analysis model relationships

Nodes, elements, surface element properties, curve element properties, FEA materials, groups, and controls are associated with a unique finite element model.

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5.2.3 Geometric founding and analysis space

The **fea_model** is a **representation** and is therefore geometrically founded in a coordinate space. This reference defines the basic coordinate system of the **fea_model**. See ISO 10303-43 for a definition of geometric founding. The number of dimensions (two or three) of the basic coordinate system establishes the dimensionality of the analysis. In turn 2D elements must reside in 2D spaces, and 3D elements must reside in 3D spaces.

5.2.4 Identifiers

An identifier within the FEA information model commonly is an integer. In this part of ISO 10303 integer identifiers are represented by string identifiers that may contain only digits. An identifier can be any string of characters, both letters and digits, in any combination.

5.2.5 Coordinate systems

The placement coordinate systems and geometric founding specified in ISO 10303-42 are generalized in this part of ISO 10303 to include spherical and cylindrical coordinate systems. All coordinate systems shall be right handed. These coordinate systems apply to models, controls, and results information.

5.2.6 Element matrix integration

Many finite elements require numerical integration of the matrices that are generated from the element specification. Element matrix information is included in this part of ISO 10303 to provide flexibility in defining element matrix integration options. This information is optional. A textual description may be associated with an element to provide a simple integration specification option.

NOTE It is intended that the element integration and basis information provide the translator or interface writer with information for a best guess match for the more unusual types of elements.

5.2.7 Units and measures

Units are assigned in a context, and the value of the measure is assigned directly. Thus the units for each of the aspects of a measure such as mass or length are obtained from the **representation_context** entity associated with the **fea_model** entity.

5.2.8 Interface with the materials schema

The FEA idealisation of material response behavior matrices is included in this part of ISO 10303. Information associated with a material such as supplier and information generation environment is given in ISO 10303-45.

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NOTE FEA element integration points and composite materials in material layers are correlated to plies by geometric position. The plies are defined by an Application Protocol using this part of ISO 10303 as a resource. This makes possible the use of a completely general integration and output point location definition capability within all elements.

5.2.9 Finite element analysis model, control, and result relationships

Result information may exist only with respect to an analysis control, which in turn may only exist with respect to a finite element model. This is enforced by the **result** entity referrring to a **control** entity which in turn refers to a **fea_model**.

5.2.10 Use of element

When element is used alone it is a general term refering to all element types. If a specific element type is being referenced, the specific element type will be used.

5.3 Structural response representation schema type definitions

The following TYPES are a resource for the entities in the **structural_response_representation_-schema**.

NOTE The types in this clause are organized in groups of similar subject matter.

5.3.1 axi_or_plane

An **axi_or_plane** specifies whether an **fea_model_2d** is axisymmetric or planar.

EXPRESS specification:

```
*)
TYPE axi_or_plane = ENUMERATION OF
  (axisymmetric,
   planar);
END_TYPE;
(*
```

Enumerated item definitions:

axisymmetric: the **fea_model** is an axisymmetric analysis model where 2D element geometry is assumed to be swept about the j axis of the founding coordinate system to create a volume.

planar: the **fea_model** is a 2D analysis model where 2D elements are assumed to be extruded perpendicular to the analysis plane to create a volume.

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5.3.2 coordinate_system_type

A **coordinate_system_type** specifies the allowable types of coordinate systems.

Figures 3, 4, and 5 define conventions for cartesian, cylindrical, and spherical coordinate systems, respectively.

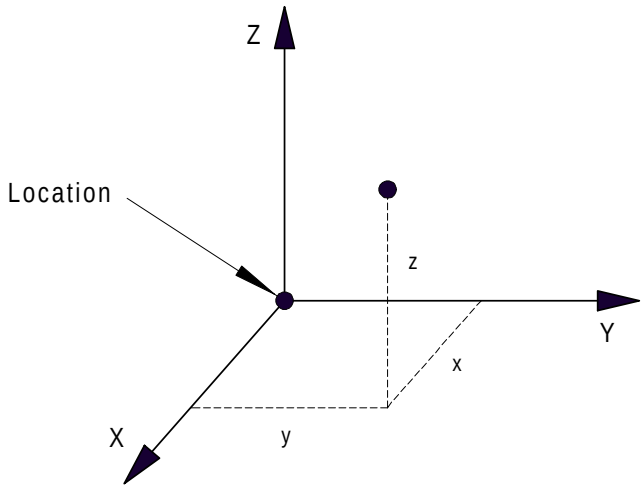

Figure 3 – Cartesian coordinate system definition

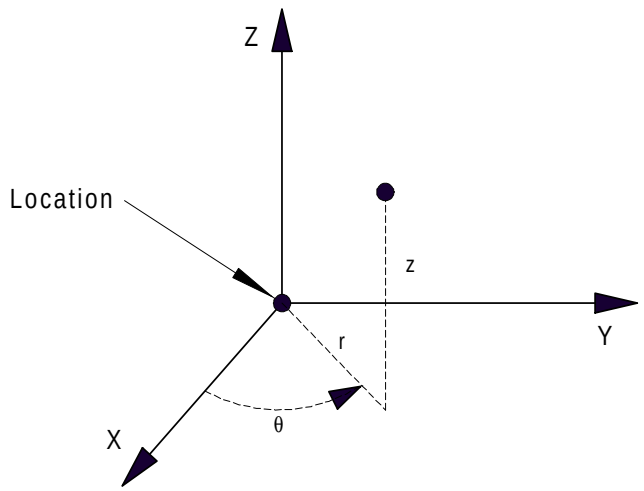

Figure 4 – Cylindrical coordinate system definition

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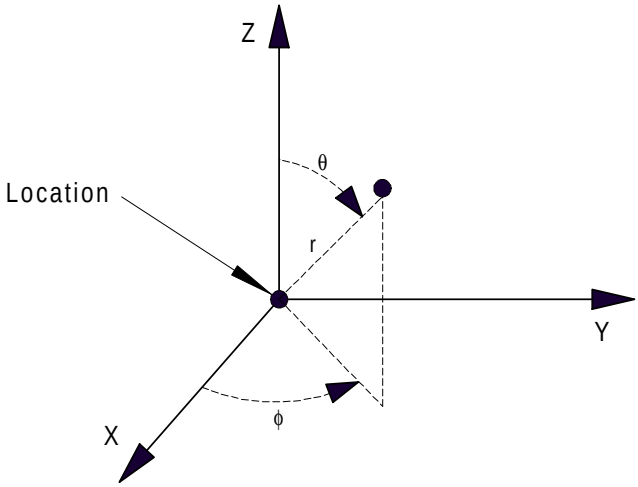

Figure 5 – Spherical coordinate system definition

EXPRESS specification:

```
*)
TYPE coordinate_system_type = ENUMERATION OF
     (cartesian,
      cylindrical,
      spherical);
END_TYPE;
(*
```

Enumerated item definitions:

cartesian: the coordinate system is of type cartesian.

cylindrical: the coordinate system is of type cylindrical.

spherical: the coordinate system is of type spherical.

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5.3.3 element_order

An **element_order** specifies the allowable geometric order of the element interpolation functions of a finite element.

EXPRESS specification:

```
*)
TYPE element_order = ENUMERATION OF
     (linear,
      quadratic,
      cubic);
END_TYPE;
(*
```

Enumerated item definitions:

linear: the element basic interpolation order is linear.

quadratic: the element basic interpolation order is quadratic.

cubic: the element basic interpolation order is cubic.

5.3.4 plane_2d_element_purpose

A **plane_2d_element_purpose** specifies the allowable assumptions of response through the thickness of a finite element.

EXPRESS specification:

```
*)
TYPE plane_2d_element_purpose = SELECT
     (enumerated_plane_2d_element_purpose,
      application_defined_element_purpose);
END_TYPE;
(*
```

5.3.5 enumerated_plane_2d_element_purpose

An **enumerated_plane_2d_element_purpose** specifies the allowable assumptions of response through the thickness of a finite element.

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EXPRESS specification:

```
*)
TYPE enumerated_plane_2d_element_purpose = ENUMERATION OF
     (plane_stress,
      plane_strain);
END_TYPE;
(*
```

Enumerated item definitions:

plane_stress: a specialised case of 2D plane elements where the stress normal to the element is zero.

plane_strain: a specialised case of 2D plane elements where the strain normal to the element is zero, but the stress is not.

5.3.6 application_defined_element_purpose

An application_defined_element_purpose is the specification of an allowable response purpose to be considered for an element.

EXPRESS specification:

```
*)
TYPE application_defined_element_purpose = STRING;
END_TYPE;
(*
```

5.3.7 volume_element_purpose

A **volume_element_purpose** specifies the allowable types of strain-displacement relationship assumed for a volume element.

EXPRESS specification:

```
*)
TYPE volume_element_purpose = SELECT
     (enumerated_volume_element_purpose,
      application_defined_element_purpose);
END_TYPE;
(*
```

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5.3.8 enumerated_volume_element_purpose

An **enumerated_volume_element_purpose** specifies the allowable types of strain-displacement relationship assumed for a volume element.

EXPRESS specification:

```
*)
TYPE enumerated_volume_element_purpose = ENUMERATION OF
     (stress_displacement);
END_TYPE;
(*
```

Enumerated item definitions:

stress_displacement: the element considers only stress-displacement behaviour.

5.3.9 surface_element_purpose

A **surface_element_purpose** specifies the allowable types of strain-displacement relationship assumed for a surface element.

EXPRESS specification:

```
*)
TYPE surface_element_purpose = SELECT
     (enumerated_surface_element_purpose,
      application_defined_element_purpose);
END_TYPE;
(*
```

5.3.10 enumerated_surface_element_purpose

An **enumerated_surface_element_purpose** specifies the allowable types of strain-displacement relationship assumed for a surface element.

NOTE The **surface_element_purpose** is referenced as a SET of SETs to allow the appropriate combinations of coupled and uncoupled responses, such as ((.MEMBRANE_DIRECT.)(.MEMBRANE_-DIRECT.,.BENDING_DIRECT.)) to specify that an element has membrane direct and coupled membrane - bending direct responses.

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EXPRESS specification:

```
*)
TYPE enumerated_surface_element_purpose = ENUMERATION OF
     (membrane_direct,
      membrane_shear,
      bending_direct,
      bending_torsion,
      normal_to_plane_shear);
END_TYPE;
(*
```

Enumerated item definitions:

membrane_direct: in-plane deformations of the surface element contribute to the element's strain energy.

membrane_shear: in-plane shear deformations contribute to the element's strain energy.

bending_direct: changes in curvature of the surface element contribute to the element's strain energy.

bending_torsion: torsional deformations of the surface element contributes to the element's strain energy.

normal_to_plane_shear: normal-to-plane shear deformations contribute to the element's strain energy.

5.3.11 curve_element_purpose

A **curve_element_purpose** specifies the allowable types of strain-displacement relationship assumed for a curve element.

EXPRESS specification:

```
*)
TYPE curve_element_purpose = SELECT
     (enumerated_curve_element_purpose,
      application_defined_element_purpose);
END_TYPE;
(*
```

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5.3.12 enumerated_curve_element_purpose

An **enumerated_curve_element_purpose** specifies the allowable types of strain-displacement relationship assumed for a curve element.

NOTE The **curve_element_purpose** is referenced as a SET of SETs to allow the appropriate combinations of coupled and uncoupled responses, such as ((.AXIAL.)(.TORSION.,.WARPING.)) to specify that an element has axial and coupled torsion - warping responses.

EXPRESS specification:

```
*)
TYPE enumerated_curve_element_purpose = ENUMERATION OF
     (axial,
      y_y_bending,
      z_z_bending,
      torsion,
      x_y_shear,
      x_z_shear,
      warping);
END_TYPE;
(*
```

Enumerated item definitions:

axial: axial deformation along the curve of the element contributes to the element's strain energy.

y_y_bending: changes in curvature about the curve element's local y axis contribute to the strain energy.

z_z_bending: changes in curvature about the curve element's local z axis contribute to the strain energy.

torsion: torsion about the curve of the element contribute to the element's strain energy.

x_y_shear: shear deformation in the xy plane of the curve contributes to the element's strain energy.

x_z_shear: shear deformation in the xz plane of the curve contributes to the element's strain energy.

warping: warping deformation of the cross-section of the curve contributes to the element's strain energy.

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5.3.13 volume_3d_element_shape

A **volume_3d_element_shape** specifies the allowable geometric shapes of a 3D finite element.

EXPRESS specification:

```
*)
TYPE volume_3d_element_shape = ENUMERATION OF
     (hexahedron,
      wedge,
      tetrahedron,
      pyramid);
END_TYPE;
(*
```

Enumerated item definitions:

hexahedron: a six-sided polyhedron where all sides are quadrilaterals.

wedge: a five-sided polyhedron where three sides are quadrilaterals, and two are triangles.

tetrahedron: a four-sided polyhedron where all sides are triangles.

pyramid: a five-sided polyhedron where four sides are triangles and one a quadrilateral.

5.3.14 element_2d_shape

An **element_2d_shape** specifies the allowable geometric shapes of a 2D finite element.

EXPRESS specification:

```
*)
TYPE element_2d_shape = ENUMERATION OF
     (quadrilateral,
      triangle);
END_TYPE;
(*
```

Enumerated item definitions:

quadrilateral: a four-edged polygon.

triangle: a three-edged polygon.

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5.3.15 matrix_property_type

A **matrix_property_type** specifies an allowable matrix property type to be considered for an expicit or volume element.

EXPRESS specification:

```
*)
TYPE matrix_property_type = SELECT
  (enumerated_matrix_property_type,
   application_defined_matrix_property_type);
END_TYPE;
(*
```

5.3.16 enumerated_matrix_property_type

An **enumerated_matrix_property_type** specifies the allowable property types of an explicit or volume element matrix. The type is used to define the matrix integrated within an explicit or volume element thus allowing different interpolation rules and integration methods to be used for different types of response relationships.

EXPRESS specification:

```
*)
TYPE enumerated_matrix_property_type = ENUMERATION OF
     (stiffness,
      mass,
      damping);
END_TYPE;
(*
```

Enumerated item definitions:

stiffness: the matrix contributes to the explicit or volume element small displacement linear elastic stiffness matrix.

mass: the matrix contributes to the explicit or volume element mass matrix.

damping: the matrix contributes to the explicit or volume element damping matrix.

5.3.17 application_defined_matrix_property_type

An application_defined_matrix_property_type is the specification of an allowable matrix property type to be considered for an element.

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EXPRESS specification:

```
*)
TYPE application_defined_matrix_property_type = STRING;
END_TYPE;
(*
```

5.3.18 surface_matrix_property_type

A **surface_matrix_property_type** specifies an allowable matrix property type to be considered for a surface element.

EXPRESS specification:

```
*)
TYPE surface_matrix_property_type = SELECT
  (enumerated_surface_matrix_property_type,
   application_defined_matrix_property_type);
END_TYPE;
(*
```

5.3.19 enumerated_surface_matrix_property_type

An **enumerated_surface_matrix_property_type** specifies the allowable property types of a surface element matrix. The type is used to define the matrix integrated within a surface element thus allowing different interpolation rules and integration methods to be used for different types of response relationships.

EXPRESS specification:

```
*)
TYPE enumerated_surface_matrix_property_type = ENUMERATION OF
     (membrane_direct,
      membrane_shear,
      bending_direct,
      bending_torsion,
      normal_to_plane_shear,
      membrane_direct_mass,
      membrane_shear_mass,
      bending_direct_mass,
      bending_torsion_mass,
      normal_to_plane_shear_mass,
      mass);
END_TYPE;
(*
```

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Enumerated item definitions:

membrane_direct: the matrix contributes direct membrane stiffness to the surface element small displacement linear elastic stiffness matrix.

membrane_shear: the matrix contributes shear membrane stiffness to the surface element small displacement linear elastic stiffness matrix.

bending_direct: the matrix contributes direct bending stiffness to the surface element small displacement linear elastic stiffness matrix.

bending_torsion: the matrix contributes bending torsional stiffness to the surface element small displacement linear elastic stiffness matrix.

normal_to_plane_shear: the matrix contributes normal to plane shear stiffness to the surface element small displacement linear elastic stiffness matrix.

membrane_direct_mass: the matrix contributes direct membrane mass to the surface element mass matrix.

membrane_shear_mass: the matrix contributes shear membrane mass to the surface element mass matrix.

bending_direct_mass: the matrix contributes direct bending mass to the surface element mass matrix.

bending_torsion_mass: the matrix contributes bending torsional mass to the surface element mass matrix.

normal_to_plane_shear_mass: the matrix contributes normal to plane shear mass to the surface element mass matrix.

mass: the matrix contributes mass to the surface element mass matrix.

5.3.20 curve_matrix_property_type

A **curve_matrix_property_type** specifies an allowable matrix property type to be considered for a curve element.

EXPRESS specification:

```
*)
TYPE curve_matrix_property_type = SELECT
  (enumerated_curve_matrix_property_type,
   application_defined_matrix_property_type);
END_TYPE;
(*
```

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5.3.21 enumerated_curve_matrix_property_type

An **enumerated_curve_matrix_property_type** specifies the allowable property types of curve element matrix. The type is used to define the matrix integrated within a curve element thus allowing different interpolation rules and integration methods to be used for different types of response relationships.

EXPRESS specification:

```
*)
TYPE enumerated_curve_matrix_property_type = ENUMERATION OF
     (axial,
      y_y_bending,
      z_z_bending,
      torsion,
      x_y_shear,
      x_z_shear,
      warping,
      axial_mass,
      y_y_bending_mass,
      z_z_bending_mass,
      torsion_mass,
      x_y_shear_mass,
      x_z_shear_mass,
      warping_mass,
      mass);
END_TYPE;
(*
```

Enumerated item definitions:

axial: the matrix contributes axial stiffness to the curve element small displacement linear elastic stiffness matrix.

y_y_bending: the matrix contributes y bending stiffness to the curve element small displacement linear elastic stiffness matrix.

z_z_bending: the matrix contributes z bending stiffness to the curve element small displacement linear elastic stiffness matrix.

torsion: the matrix contributes torsional stiffness to the curve element small displacement linear elastic stiffness matrix.

x_y_shear: the matrix contributes y shear stiffness to the curve element small displacement linear elastic stiffness matrix.

x_z_shear: the matrix contributes z shear stiffness to the curve element small displacement linear elastic stiffness matrix.

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warping: the matrix contributes warping stiffness to the curve element small displacement linear elastic stiffness matrix.

axial_mass: the matrix contributes axial mass to the curve element mass matrix.

y_y_bending_mass: the matrix contributes y bending mass to the curve element mass matrix.

z_z_bending_mass: the matrix contributes z bending mass to the curve element mass matrix.

torsion_mass: the matrix contributes torsional mass to the curve element mass matrix.

x_y_shear_mass: the matrix contributes y shear mass to the curve element mass matrix.

x_z_shear_mass: the matrix contributes z shear mass to the curve element mass matrix.

warping_mass: the matrix contributes warping mass to the curve element mass matrix.

mass: the matrix contributes mass to the curve element mass matrix.

5.3.22 matrix_symmetry

A **matrix_symmetry** specifies the allowable types of symmetry of a square matrix. The type of symmetry determines the position in an ARRAY attribute for each term of a matrix. Except for asymmetric matrices, only the lower half of the matrix is populated.

For a **symmetric** matrix of size n (where n denotes the number of freedoms defined by the degree_of_-freedom_list) the position of the terms shall be:

$$\begin{pmatrix} 1 & & & & & \text{(symmetric)} \\ 2 & n+1 & & & & \\ 3 & n+2 & 2n & & & \\ \cdot & \cdot & \cdot & 3n-2 & & \\ \cdot & \cdot & \cdot & \cdot & \cdot & \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ n & 2n-1 & 3n-3 & \cdot & \cdot & \cdot \quad n(n+1)/2 \end{pmatrix}$$

For a **diagonal** matrix of size n (where n denotes the number of freedoms defined by the degree_of_-freedom_list) the position of the terms shall be:

$$\begin{pmatrix} 1 & & & & \\ & 2 & & 0 & \\ & & 3 & & \\ & 0 & & \ddots & \\ & & & & n \end{pmatrix}$$

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EXPRESS specification:

```
*)
TYPE matrix_symmetry = ENUMERATION OF
     (symmetric,
      diagonal);
END_TYPE;
(*
```

Enumerated item definitions:

symmetric: the matrix and its transpose are identical.

diagonal: the matrix has non-zero terms on the main diagonal only.

5.3.23 degree_of_freedom

A **degree_of_freedom** is the allowable degrees of freedom to be considered for the intended analysis.

EXPRESS specification:

```
*)
TYPE degree_of_freedom = SELECT
  (enumerated_degree_of_freedom,
   application_defined_degree_of_freedom);
END_TYPE;
(*
```

5.3.24 enumerated_degree_of_freedom

An **enumerated_degree_of_freedom** specifies the allowable degrees of freedom to be considered for the intended analysis.

EXPRESS specification:

```
*)
TYPE enumerated_degree_of_freedom = ENUMERATION OF
     (x_translation, y_translation, z_translation,
      x_rotation, y_rotation, z_rotation,
      warp);
END_TYPE;
(*
```

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Enumerated item definitions:

x_translation: a translation degree of freedom along the x-axis.

y_translation: a translation degree of freedom along the y-axis.

z_translation: a translation degree of freedom along the z-axis.

x_rotation: a rotation degree of freedom about the x-axis.

y_rotation: a rotation degree of freedom about the y-axis.

z_rotation: a rotation degree of freedom about the z-axis.

warp: a warping degree of freedom of a curve element cross-section.

5.3.25 application_defined_degree_of_freedom

An **application_defined_degree_of_freedom** is the specification of an allowable degree of freedom to be considered for the intended analysis.

EXPRESS specification:

```
*)
TYPE application_defined_degree_of_freedom = STRING;
END_TYPE;
(*
```

5.3.26 curve_element_freedom

A **curve_element_freedom** specifies the allowable degrees of freedom to be considered for a curve element.

EXPRESS specification:

```
*)
TYPE curve_element_freedom = SELECT
     (enumerated_curve_element_freedom,
      application_defined_degree_of_freedom);
END_TYPE;
(*
```

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5.3.27 enumerated_curve_element_freedom

An **enumerated_curve_element_freedom** specifies the allowable degrees of freedom to be considered for a curve element.

EXPRESS specification:

```
*)
TYPE enumerated_curve_element_freedom = ENUMERATION OF
     (x_translation, y_translation, z_translation,
      x_rotation, y_rotation, z_rotation,
      warp,
      none);
END_TYPE;
(*
```

Enumerated item definitions:

x_translation: a translation degree of freedom along the x-axis.

y_translation: a translation degree of freedom along the y-axis.

z_translation: a translation degree of freedom along the z-axis.

x_rotation: a rotation degree of freedom about the x-axis.

y_rotation: a rotation degree of freedom about the y-axis.

z_rotation: a rotation degree of freedom about the z-axis.

warp: a warping degree of freedom of a curve element cross-section.

none: no degree of freedom of a curve element is specified.

5.3.28 integration_rule

An **integration_rule** specifies the allowable types of numerical integration rules to be considered by subtypes of the volume, surface and curve integration entities.

EXPRESS specification:

```
*)
TYPE integration_rule = ENUMERATION OF
     (gaussian,
      simpson);
END_TYPE;
(*
```

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Enumerated item definitions:

gaussian: gaussian integration.

simpson: bart simpson's rule integration.

5.3.29 shape_function

A **shape_function** specifies the allowable types of interpolation function.

EXPRESS specification:

```
*)
TYPE shape_function = ENUMERATION OF
     (lagrangian,
      serendipity,
      hermitian,
      unspecified);
END_TYPE;
(*
```

Enumerated item definitions:

lagrangian: the shape function is based upon lagrangian polynomials.

serendipity: the shape function is based upon the serendipity modification of the lagrangian polynomials.

hermitian: the shape function is based upon hermitian polynomials.

unspecified: the shape function is not specified.

5.3.30 volume_2d_element_representation

A **volume_2d_element_representation** is either an axisymmetric or plane volume 2D element.

EXPRESS specification:

```
*)
TYPE volume_2d_element_representation = SELECT
  (axisymmetric_volume_2d_element_representation,
   plane_volume_2d_element_representation);
END_TYPE;
(*
```

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5.3.31 surface_2d_element_representation

A **surface_2d_element_representation** is either an axisymmetric or plane surface 2D element.

EXPRESS specification:

```
*)
TYPE surface_2d_element_representation = SELECT
  (axisymmetric_surface_2d_element_representation,
   plane_surface_2d_element_representation);
END_TYPE;
(*
```

5.3.32 curve_2d_element_representation

A **curve_2d_element_representation** is either an axisymmetric or plane curve 2D element.

EXPRESS specification:

```
*)
TYPE curve_2d_element_representation = SELECT
  (axisymmetric_curve_2d_element_representation,
   plane_curve_2d_element_representation);
END_TYPE;
(*
```

5.3.33 volume_2d_element_descriptor

A **volume_2d_element_descriptor** is a collection of information that specifies either an axisymmetric or plane volume element.

EXPRESS specification:

```
*)
TYPE volume_2d_element_descriptor = SELECT
     (axisymmetric_volume_2d_element_descriptor,
      plane_volume_2d_element_descriptor);
END_TYPE;
(*
```

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5.3.34 surface_2d_element_descriptor

A **surface_2d_element_descriptor** is a collection of information that specifies either an axisymmetric or plane surface element.

EXPRESS specification:

```
*)
TYPE surface_2d_element_descriptor = SELECT
     (axisymmetric_surface_2d_element_descriptor,
      plane_surface_2d_element_descriptor);
END_TYPE;
(*
```

5.3.35 curve_2d_element_descriptor

A **curve_2d_element_descriptor** is a collection of information that specifies either an axisymmetric or plane curve element.

EXPRESS specification:

```
*)
TYPE curve_2d_element_descriptor = SELECT
     (axisymmetric_curve_2d_element_descriptor,
      plane_curve_2d_element_descriptor);
END_TYPE;
(*
```

5.3.36 volume_3d_element_coordinate_system

A **volume_3d_element_coordinate_system** is the orthogonal coordinate system for a volume 3D element that shall be either an arbitrary or a parametric coordinate system.

EXPRESS specification:

```
*)
TYPE volume_3d_element_coordinate_system = SELECT
  (arbitrary_volume_3d_element_coordinate_system,
   parametric_volume_3d_element_coordinate_system);
END_TYPE;
(*
```

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5.3.37 volume_2d_element_coordinate_system

A **volume_2d_element_coordinate_system** is the orthogonal coordinate system for a volume 2D element that shall be either an arbitrary or a parametric coordinate system.

EXPRESS specification:

```
*)
TYPE volume_2d_element_coordinate_system = SELECT
  (arbitrary_volume_2d_element_coordinate_system,
   parametric_volume_2d_element_coordinate_system);
END_TYPE;
(*
```

5.3.38 surface_3d_element_coordinate_system

A **surface_3d_element_coordinate_system** is an orthogonal coordinate system for a surface 3D element that shall be either an aligned, constant, or a parametric coordinate system.

EXPRESS specification:

```
*)
TYPE surface_3d_element_coordinate_system = SELECT
  (aligned_surface_3d_element_coordinate_system,
   parametric_surface_3d_element_coordinate_system,
   constant_surface_3d_element_coordinate_system);
END_TYPE;
(*
```

5.3.39 surface_2d_element_coordinate_system

A **surface_2d_element_coordinate_system** is a coordinate system for a surface 2D element that shall be either an aligned or a parametric coordinate system.

EXPRESS specification:

```
*)
TYPE surface_2d_element_coordinate_system = SELECT
  (aligned_surface_2d_element_coordinate_system,
   parametric_surface_2d_element_coordinate_system);
END_TYPE;
(*
```

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5.3.40 curve_3d_element_coordinate_system

A **curve_3d_element_coordinate_system** is an orthogonal coordinate system for a curve 3D element that shall be either aligned or parametric.

EXPRESS specification:

```
*)
TYPE curve_3d_element_coordinate_system = SELECT
  (aligned_curve_3d_element_coordinate_system,
   parametric_curve_3d_element_coordinate_system);
END_TYPE;
(*
```

5.3.41 curve_element_end_coordinate_system

A **curve_element_end_coordinate_system** is a coordinate system for the end offset and end release of curve elements.

EXPRESS specification:

```
*)
TYPE curve_element_end_coordinate_system = SELECT
     (fea_axis2_placement_3d,
      curve_3d_element_coordinate_system);
END_TYPE;
(*
```

5.3.42 directionally_explicit_element_coordinate_system

A **directionally_explicit_element_coordinate_system** is a directionally explicit element coordinate system that shall be either an aligned or arbitrary coordinate system that is used for orienting property information associated with a directionally explicit element.

EXPRESS specification:

```
*)
TYPE directionally_explicit_element_coordinate_system = SELECT
  (directionally_explicit_element_coordinate_system_arbitrary,
   directionally_explicit_element_coordinate_system_aligned);
END_TYPE;
(*
```

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5.3.43 element_aspect

An **element_aspect** is the aspect of an element(volume, face, or edge) to be associated with a geometric shape representation.

EXPRESS specification:

```
*)
TYPE element_aspect = SELECT
     (element_volume,
      volume_3d_face,
      volume_2d_face,
      volume_3d_edge,
      volume_2d_edge,
      surface_3d_face,
      surface_2d_face,
      surface_3d_edge,
      surface_2d_edge,
      curve_edge);
END_TYPE;
(*
```

5.3.44 element_volume

An **element_volume** is the entire volume of an **element_representation**.

EXPRESS specification:

```
*)
TYPE element_volume = ENUMERATION OF
     (volume);
END_TYPE;
(*
```

Enumerated item definitions:

volume: the volume of an element.

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5.3.45 curve_edge

A **curve_edge** is the edge of a curve element.

EXPRESS specification:

```
*)
TYPE curve_edge = ENUMERATION OF
     (element_edge);
END_TYPE;
(*
```

Enumerated item definitions:

element_edge: the edge of a curve element.

5.3.46 node_or_node_group

A **node_or_node_group** is a node or set of nodes.

EXPRESS specification:

```
*)
TYPE node_or_node_group = SELECT
     (node_representation,
      node_group);
END_TYPE;
(*
```

5.3.47 element_or_element_group

An **element_or_element_group** is an element or set of elements.

EXPRESS specification:

```
*)
TYPE element_or_element_group = SELECT
     (element_representation,
      element_group);
END_TYPE;
(*
```

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5.4 Structural response representation schema entity definitions: Finite element analysis model

A finite element analysis model is a collection of information that represents the finite element analysis of a product. This information includes generalised nodes, elements, materials, properties, and groups which are combined to form a discrete mesh model of the product.

NOTE The entities in this clause are organized in groups of similar subject matter.

5.4.1 fea_model

An **fea_model** represents a specific finite element analysis model.

EXPRESS specification:

```
*)
ENTITY fea_model
  SUPERTYPE OF (ONEOF(fea_model_2d,
                      fea_model_3d))
  SUBTYPE OF (representation);
  creating_software         : text;
  intended_analysis_code    : SET [1:?] OF text;
  description               : text;
  analysis_type             : text;
UNIQUE
  UR1:  SELF\representation.name;
END_ENTITY;
(*
```

Attribute definitions:

creating_software: the name of the software used to create an **fea_model**. The version of the software shall be specified.

intended_analysis_code: the set of one or many names of the intended analysis code that an **fea_model** was created for. Each intended analysis code shall have the vendor, version, computer system, operating system and descriptions specified.

description: a description of the **fea_model** providing supporting information supplied by the author(s) of the model.

analysis_type: a description of what type of analysis is to be performed with this **fea_model**.

NOTE The model id, a unique application defined identifier of an **fea_model**, is specified by the **name** attribute of the **representation** supertype.

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Formal propositions:

UR1: the model id shall be unique to each finite element analysis model.

5.4.2 fea_model_3d

An **fea_model_3d** is an **fea_model** that has geometry in three dimensions for 3D analyses.

EXPRESS specification:

```
*)
ENTITY fea_model_3d
  SUBTYPE OF (fea_model);
WHERE
  WR1: SELF\representation.context_of_items\
       geometric_representation_context.coordinate_space_dimension = 3;
END_ENTITY;
(*
```

Formal propositions:

WR1: the dimension count of the founding coordinate system shall be 3.

5.4.3 fea_model_2d

An **fea_model_2d** is an **fea_model** whose geometry is restricted to a plane for planar or axisymmetric analyses.

EXPRESS specification:

```
*)
ENTITY fea_model_2d
  SUBTYPE OF (fea_model);
  type_of_2d_analysis       : axi_or_plane;
WHERE
  WR1: SELF\representation.context_of_items\
       geometric_representation_context.coordinate_space_dimension = 2;
END_ENTITY;
(*
```

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Attribute definitions:

type_of_2d_analysis: indicates whether the **fea_model** is axisymmetric or planar.

Formal propositions:

WR1: the dimension count of the founding coordinate system shall be 2.

5.4.4 structural_response_property_definition_representation

A **structural_response_property_definition_representation** is an association between the property of a finite element model, node or element and its representation.

EXPRESS specification:

```
*)
ENTITY structural_response_property_definition_representation
  SUBTYPE OF (property_definition_representation);
WHERE
  WR1: (('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
         'STRUCTURAL_RESPONSE_PROPERTY') IN TYPEOF
         (SELF\property_definition_representation.definition));
  WR2: ((('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.FEA_MODEL'
        IN TYPEOF
        (SELF\property_definition_representation.used_representation))
        AND
        ('STRUCTURAL_RESPONSE_DEFINITION_SCHEMA.FEA_MODEL_DEFINITION'
        IN TYPEOF
        (SELF\property_definition_representation.definition.definition)))
       OR
      (('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.ELEMENT_REPRESENTATION'
        IN TYPEOF
        (SELF\property_definition_representation.used_representation))
        AND
        ('STRUCTURAL_RESPONSE_DEFINITION_SCHEMA.ELEMENT_DEFINITION'
        IN TYPEOF
        (SELF\property_definition_representation.definition.definition)))
       OR
      (('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.NODE_REPRESENTATION'
        IN TYPEOF
        (SELF\property_definition_representation.used_representation))
        AND
        ('STRUCTURAL_RESPONSE_DEFINITION_SCHEMA.NODE_DEFINITION'
        IN TYPEOF
        (SELF\property_definition_representation.definition.definition))));
END_ENTITY;
(*
```

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Formal propositions:

WR1: the property being represented shall be a **structural_response_property**.

WR2: the **fea_model** shall be associated with the shape definition of a model, or the **element_-representation** shall be associated with the shape definition of an element, or the **node_representation** shall be associated with the shape definition of a node.

5.4.5 fea_representation_item

An **fea_representation_item** is the different types of coordinate system for a finite element. The use of the appropriate type of coordinate system for a type of element is governed by rules within each of the **element_representation** subtypes.

EXPRESS specification:

```
*)
ENTITY fea_representation_item
  SUPERTYPE OF (ONEOF
               (arbitrary_volume_3d_element_coordinate_system,
                parametric_volume_3d_element_coordinate_system,
                arbitrary_volume_2d_element_coordinate_system,
                parametric_volume_2d_element_coordinate_system,
                aligned_surface_3d_element_coordinate_system,
                parametric_surface_3d_element_coordinate_system,
                constant_surface_3d_element_coordinate_system,
                aligned_surface_2d_element_coordinate_system,
                parametric_surface_2d_element_coordinate_system,
                aligned_curve_3d_element_coordinate_system,
                parametric_curve_3d_element_coordinate_system,
                parametric_curve_3d_element_coordinate_direction,
                curve_2d_element_coordinate_system,
                directionally_explicit_element_coordinate_system_arbitrary,
                directionally_explicit_element_coordinate_system_aligned))
  SUBTYPE OF (representation_item);
END_ENTITY;
(*
```

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5.5 Structural response representation schema entity definitions: Node and element geometry, geometric coordinate systems, and geometric associativity

Nodes are the discretized points in the continuum being modelled that are connected with elements. There are three types of nodes: **node**, **geometric_node**, and **dummy_node**.

In a finite element analysis model a **node** shall have the following purposes:

— a **node** shall be a discretisation point for the field variables of the finite element analysis model. A finite element analysis model field has independent variables only at the **node**s.

— a **node** shall be connected to an element.

A model may contain **geometric_node**s that are not discretisation points for field variables and not connected to an element. A **geometric_node** shall define the geometry of an element.

EXAMPLE 1 The point associated with a **geometric_node** may provide an off-axis position for a curve element to define the orientation of the section properties.

Alternatively, a model may contain some **dummy_node**s that are not discretisation points for field variables. These **dummy_node**s are used as place holders in element **node_list**s when the optional (called additional in this information model) mid-edge, mid-side, and mid-volume nodes are not present.

Geometric coordinate systems provide a frame of reference for finite element analysis model geometric constructs.

EXAMPLE 2 Nodal coordinates and material axis orientations are types of geometric information within a finite element analysis model.

All FEA coordinate systems shall be defined with respect to the master or basic coordinate system defined by the **representation** entity SUBTYPE reference in the **fea_model** entity. The master coordinate system shall be Cartesian. All coordinate systems shall be right handed. The FEA information model generalizes coordinate systems to include cylindrical and spherical types. To this end, subtypes have been added to the following ISO 10303-42 entities:

— **direction**: specialised with a subtype to allow the definition of direction ratios with nodes;

— **axis2_placement_3d**: specialised with a subtype to allow specification of the coordinate system type.

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Nodes are aggregated together in a **node_set** in order to facilitate geometric founding. An application protocol will define a **shape_representation** subtype that will in turn aggregate a **node_set** and optionally a **placement** entity, which also may be combined with other entities from ISO 10303-43 to complete relationships with other coordinate frames.

An element coordinate system is derived from element nodal geometry. All element nodal geometry is founded by first aggregating **node_representation** entities in a **node_set**, and then associating the **node_-set** with a **placement** by a combination of **mapped_item** and **representation_relationship** entities in a manner consistent with the shape representation specifications of a referencing application protocol.

NOTE Figure 6 shows the relationships of FEA with Geometry and Representation.

5.5.1 direction_node

A **direction_node** is the components of the direction vector defined by a line from **node_1** to **node_2**. The actual magnitudes of the components have no effect upon the direction being defined; only the ratios x:y:z or x:y are significant.

NOTE It is assumed that this vector will be normalised when used.

EXPRESS specification:

```
*)
ENTITY direction_node
  SUBTYPE OF (direction);
  node_1                    : node_representation;
  node_2                    : node_representation;
DERIVE
  SELF\direction.direction_ratios : LIST [2:3] OF REAL :=
                                    build_direction_node (node_1, node_2);
WHERE
  WR1: SIZEOF (QUERY(item <* node_1\representation.items |
             'GEOMETRY_SCHEMA.CARTESIAN_POINT' IN TYPEOF (item))) = 1;
  WR2: SIZEOF (QUERY(item <* node_2\representation.items |
             'GEOMETRY_SCHEMA.CARTESIAN_POINT' IN TYPEOF (item))) = 1;
  WR3: NOT ((direction_ratios[1] = 0.0) AND
           (direction_ratios[2] = 0.0) AND
           (direction_ratios[3] = 0.0));
END_ENTITY;
(*
```

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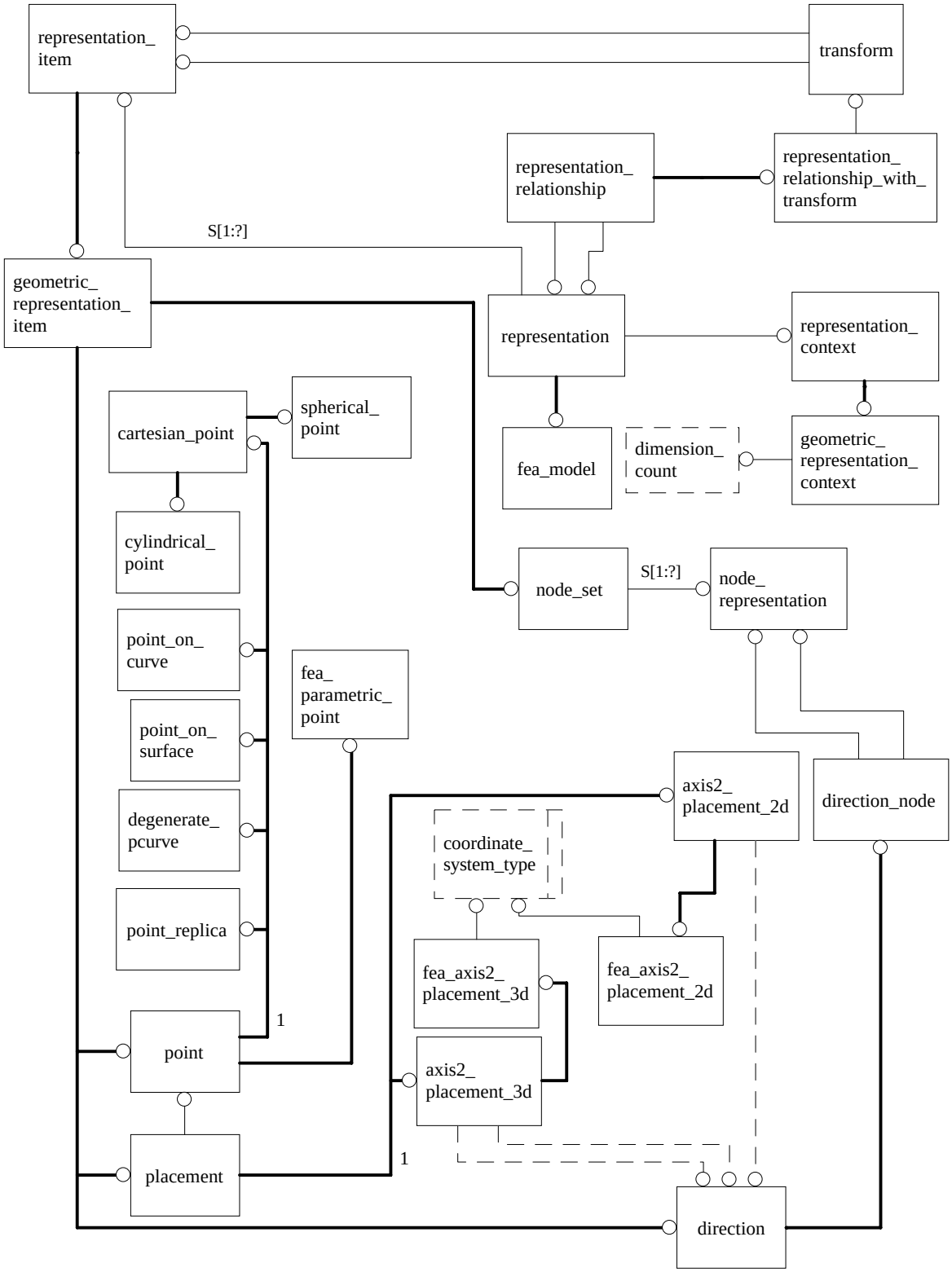

Figure 6 – EXPRESS-G partial model illustrating finite element analysis relationships with geometry and representation

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Attribute definitions:

node_1: the first node used to define the direction vector.

node_2: the second node used to define the direction vector.

direction_ratios [1]: the component of the direction in the X axis.

direction_ratios [2]: the component of the direction in the Y axis.

direction_ratios [3]: the component of the direction in the Z axis; this will not be present in the case of a 2D space.

Formal propositions:

WR1: **node_1** shall represent a cartesian point.

WR2: **node_2** shall represent a cartesian point.

WR3: the magnitude of the direction vector shall be greater than zero.

5.5.2 fea_axis2_placement_2d

An **fea_axis2_placement_2d** is a location and orientation in 2D space, and declares that the Placement Coordinate System may be either Cartesian, Cylindrical, or Spherical. All coordinate systems in a finite element analysis model shall be right handed.

EXPRESS specification:

```
*)
ENTITY fea_axis2_placement_2d
  SUBTYPE OF (axis2_placement_2d);
  system_type               : coordinate_system_type;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

system_type: the type of placement coordinate system, which may be a right handed Cartesian, Cylindrical, or Spherical coordinate system.

description: additional information about the formulation or purpose of the coordinate system.

NOTE The coordinate system id, a unique application defined identifier of an **fea_axis2_placement_2d**, is specified by the **name** attribute of the **representation_item** supertype.

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Informal propositions:

IP1: the combination of an **fea_model** and coordinate system id shall be unique within a finite element analysis model.

5.5.3 fea_axis2_placement_3d

An **fea_axis2_placement_3d** is a location and orientation in 3D space, and declares that the Placement Coordinate System may be either Cartesian, Cylindrical, or Spherical. All coordinate systems in a finite element analysis model shall be right handed.

EXPRESS specification:

```
*)
ENTITY fea_axis2_placement_3d
  SUBTYPE OF (axis2_placement_3d);
  system_type               : coordinate_system_type;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

system_type: the type of placement coordinate system, which may be a right handed Cartesian, Cylindrical, or Spherical coordinate system.

description: additional information about the formulation or purpose of the coordinate system.

NOTE The coordinate system id, a unique application defined identifier of an **fea_axis2_placement_3d**, is specified by the **name** attribute of the **representation_item** supertype.

Informal propositions:

IP1: the combination of an **fea_model** and coordinate system id shall be unique within a finite element analysis model.

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5.5.4 node_set

A **node_set** is the aggregation of **node_representation** entities for geometric founding in a common coordinate frame.

EXPRESS specification:

```
*)
ENTITY node_set
  SUBTYPE OF (geometric_representation_item);
  nodes                     : SET [1:?] OF node_representation;
WHERE
  WR1: SIZEOF (QUERY (tmp <* nodes |
              tmp\representation.context_of_items :<>:
              nodes[1]\representation.context_of_items)) = 0;
END_ENTITY;
(*
```

Attribute definitions:

nodes: the **node_representation**s to be founded in a common coordinate frame.

Formal propositions:

WR1: the geometric representation context of each of the nodes in the set shall be the same.

5.5.5 analysis_item_within_representation

An **analysis_item_within_representation** is a reference to an individual **representation_item** used in a specified **representation**.

EXPRESS specification:

```
*)
ENTITY analysis_item_within_representation;
  name                      : label;
  description               : text;
  item                      : representation_item;
  rep                       : representation;
WHERE
  WR1: SIZEOF (QUERY (tmp <* using_representations(item) |
                      tmp :=: rep)) = 1;
END_ENTITY;
(*
```

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Attribute definitions:

name: the word or group of words by which the **analysis_item_within_representation** is known.

description: the word or of group of words that characterize the **analysis_item_within_representation**.

item: a **representation_item** used in the **representation** referenced by rep.

rep: the **representation** that the item is used in.

Formal propositions:

WR1: the referenced **representation_item** shall be used in the referenced **representation**.

5.5.6 node_geometric_relationship

A **node_geometric_relationship** is the association of a node or set of nodes with a geometric shape representation item.

EXPRESS specification:

```
*)
ENTITY node_geometric_relationship;
  node_ref                  : node_or_node_group;
  item                      : analysis_item_within_representation;
WHERE
  WR1: 'GEOMETRY_SCHEMA.GEOMETRIC_REPRESENTATION_ITEM' IN TYPEOF(item.item);
END_ENTITY;
(*
```

Attribute definitions:

node_ref: the node or set of nodes being related to geometry.

item: the geometric representation item to which the node or set of nodes is being related.

Formal propositions:

WR1: the item associated with the node or set of nodes shall be a geometric representation item.

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5.5.7 element_geometric_relationship

An **element_geometric_relationship** is the association of an aspect (edge, face, or entire volume) of an element or set of elements with an appropriate type of geometric representation item.

EXPRESS specification:

```
*)
ENTITY element_geometric_relationship;
  element_ref                : element_or_element_group;
  item                       : analysis_item_within_representation;
  aspect                     : element_aspect;
WHERE
  WR1: 'GEOMETRY_SCHEMA.GEOMETRIC_REPRESENTATION_ITEM' IN TYPEOF(item.item);
  WR2: consistent_geometric_reference (aspect, item.item);
  WR3: consistent_element_or_group_reference (aspect, element_ref);
END_ENTITY;
(*
```

Attribute definitions:

element_ref: the element or set of elements being related to geometry.

item: the geometric representation item to which the element aspect is being related.

aspect: the edge, face, or volume for the element or set of elements.

Formal propositions:

WR1: the item associated with the element or set of elements shall be a geometric representation item.

WR2: the element aspect shall be related to the appropriate geometric shape representation item. Element edges shall be related to a curve, element faces to a surface, and the volume of an element to a solid model.

WR3: the element aspect shall be consistent with the element type for the element or set of elements.

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5.6 Structural response representation schema entity definitions: Node representation

Node representations are in the most general sense locations within a finite element model. These locations may be associated with geometric shape representations.

5.6.1 node_representation

A **node_representation** is location within a finite element model that may have associated degrees of freedom.

EXPRESS specification:

```
*)
ENTITY node_representation
  SUPERTYPE OF (ONEOF
                     (node,
                      dummy_node,
                      geometric_node))
  SUBTYPE OF (representation);
  model_ref                 : fea_model;
UNIQUE
  UR1: model_ref, SELF\representation.name;
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the node.

NOTE The node id, a unique application defined identifier of a **node_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and node id shall be unique within a model.

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5.6.2 node

A **node** is a discretisation point for the field variables of the finite element analysis model.

EXPRESS specification:

```
*)
ENTITY node
  SUPERTYPE OF (node_with_vector ANDOR
                node_with_solution_coordinate_system)
  SUBTYPE OF (node_representation);
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
              'GEOMETRY_SCHEMA.POINT'
              IN TYPEOF (item))) = 1;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be exactly one position associated with a **node**. The position (POINT) is the coordinates of the node with respect to the founding placement coordinate system in the using **node_set**.

5.6.3 node_with_vector

A **node_with_vector** is a discretisation point with a normal for the field variables of surface elements in a finite element analysis model.

EXPRESS specification:

```
*)
ENTITY node_with_vector
  SUBTYPE OF (node);
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
              'GEOMETRY_SCHEMA.DIRECTION'
              IN TYPEOF (item))) = 1;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be exactly one surface normal associated with a **node_with_vector**. The surface normal (DIRECTION) is defined at the node with respect to the founding placement coordinate system,

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which is needed only when a node is connected to surface elements that require this information. The **normal** may correspond to the $Z - axis$ of the **solution_coordinate_system**.

5.6.4 node_with_solution_coordinate_system

A **node_with_solution_coordinate_system** is a discretisation point with a solution coordinate system for the field variables of elements in a finite element analysis model.

EXPRESS specification:

```
*)
ENTITY node_with_solution_coordinate_system
  SUBTYPE OF (node);
WHERE
  WR1: ( (SIZEOF (QUERY(item <* SELF\representation.items |
             'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'FEA_AXIS2_PLACEMENT_3D'
             IN TYPEOF (item))) = 1)
          AND
          (SELF\representation.context_of_items\
       geometric_representation_context.coordinate_space_dimension = 3) )
     OR
       ( (SIZEOF (QUERY(item <* SELF\representation.items |
             'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'FEA_AXIS2_PLACEMENT_2D'
             IN TYPEOF (item))) = 1)
          AND
          (SELF\representation.context_of_items\
       geometric_representation_context.coordinate_space_dimension = 2) );
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be exactly one solution coordinate system associated with a **node**, and it shall be of the same coordinate space dimension as the corresponding geometric representation context. The solution coordinate system (FEA_AXIS2_PLACEMENT_3D or FEA_AXIS2_PLACEMENT_2D) is the coordinate system in which the degrees of freedom of the node are defined.

Informal propositions:

IP1: the coordinate system types shall correspond between **point**s and **placement**s if the points are cylindrical, spherical, or cartesian.

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5.6.5 dummy_node

A **dummy_node** is a placeholder in the node list for an element representation. It is used where an element representation does not have one or more of the mid-edge, mid-face, or mid-volume nodes that are shown in the node sequence diagrams in Figures 10 through 39.

EXAMPLE The ninth node for a quadratic-order quadrilateral element is a mid-face node as shown in the node sequence diagram in Figure 20. Thus for an eight-noded serendipity element, a **dummy_node** may be included in the ninth position in the node list. In addition, if any of the four mid-edge nodes are also missing, a **dummy_node** shall be used in its place in the node list.

NOTE An instantiation of an FEA model has only one instance of **dummy_node**.

EXPRESS specification:

```
*)
ENTITY dummy_node
  SUBTYPE OF (node_representation);
END_ENTITY;
(*
```

5.6.6 geometric_node

A **geometric_node** is a node that is for geometric reference only and therefore shall not be connected to an element.

EXPRESS specification:

```
*)
ENTITY geometric_node
  SUBTYPE OF (node_representation);
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
              'GEOMETRY_SCHEMA.POINT'
              IN TYPEOF (item))) = 1;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be exactly one position associated with a **geometric_node**. The position (POINT) is the coordinates of the node with respect to the founding placement coordinate system in the using **node_set**.

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5.6.7 substructure_node_relationship

A **substructure_node_relationship** is a association of two nodes where each node is in a separate substructure. During matrix assembly the two nodes will be merged to provide assembly between the two subsructures.

EXPRESS specification:

```
*)
ENTITY substructure_node_relationship
  SUBTYPE OF (representation_relationship);
WHERE
  WR1: 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.NODE_REPRESENTATION'
       IN TYPEOF (SELF\representation_relationship.rep_1);
  WR2: 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.NODE_REPRESENTATION'
       IN TYPEOF (SELF\representation_relationship.rep_2);
END_ENTITY;
(*
```

Formal propositions:

WR1: the rep_1 attribute shall be associated with a **node_representation**.

WR2: the rep_2 attribute shall be associated with a **node_representation**.

5.7 Structural response representation schema entity definitions: Element representations

Elements are analytical subdivision of a continuum connected to nodes to model the continuum being analyzed. Different types of elements have different characteristics due to different idealisations of the continuum being analyzed. The idealisations are represented in the subtypes of the **element_representation** entity.

EXAMPLE 1 Surface element and volume element are among the types of different idealisations: surface element has a thickness, but a volume element does not.

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The subtypes are defined as follows:

— **volume element**: A volume element includes all elements which describe a volume continuum, and have properties appropriate for a volume.

EXAMPLE 2 A 2D quadrilateral in an axisymmetric analysis is a volume element.

— **surface element**: A surface element includes all elements which describe a surface continuum, and have properties appropriate for a surface.

EXAMPLE 3 A curve 2D element in an axisymmetric analysis is a surface element.

— **curve element**: A curve element includes all elements which describe a curve of material (cable, truss, or beam), and have properties appropriate for a cable, truss, or beam.

EXAMPLE 4 A point in an axisymmetric analysis is a curve element.

— **point element**: A point element includes point masses, grounded springs, and grounded dampers.

— **directionally explicit element**: A directionally explicit element includes all elements which are defined by explicit matrices, and which have an orientation defined in part by the location of the nodes of an element.

EXAMPLE 5 Two noded springs, dampers, and coupled masses are all directionally explicit elements.

— **explicit element**: An explicit element includes elements which have an explicit matrix definition.

EXAMPLE 6 Explicit elements include externally defined elements and substructures.

The geometry of a volume, surface or curve element is defined by the element shape, variable order, coordinate (and optionally the surface normal) for each of the nodes of an element, and the details of the shape functions of an element for geometric interpolation. A computer readable definition of the mathematical form of element shape functions for geometric interpolation is not provided. However, the exact specifications of these shape functions are important for they determine the element parametric coordinate system and hence the element geometry, any location in the element (if specified with respect to the element parametric coordinate system), and any orientations within the element (if specified with respect to the element parametric coordinate system). The element basis entity for a volume, surface, or curve element has an attribute **variable_shape_function** that can be used to describe the geometric shape function.

Aspects of element geometry (edge, face, volume) may be related to an appropriate geometric shape representation. In particular, an edge may be related to a curve, a face to a surface, and the volume to a solid model.

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Volume, surface, and curve element representations are subtyped for 2D (plane stress, plane strain or axisymmetric analyses), and for 3D. This split of subtypes reflects the physical idealisation of the element rather than merely the topology. As a consequence, the physical properties appropriate for each element subtype are stated precisely by the appropriate entity.

NOTE 1 The **element_representation** entity has subtypes as shown in Figure 7.

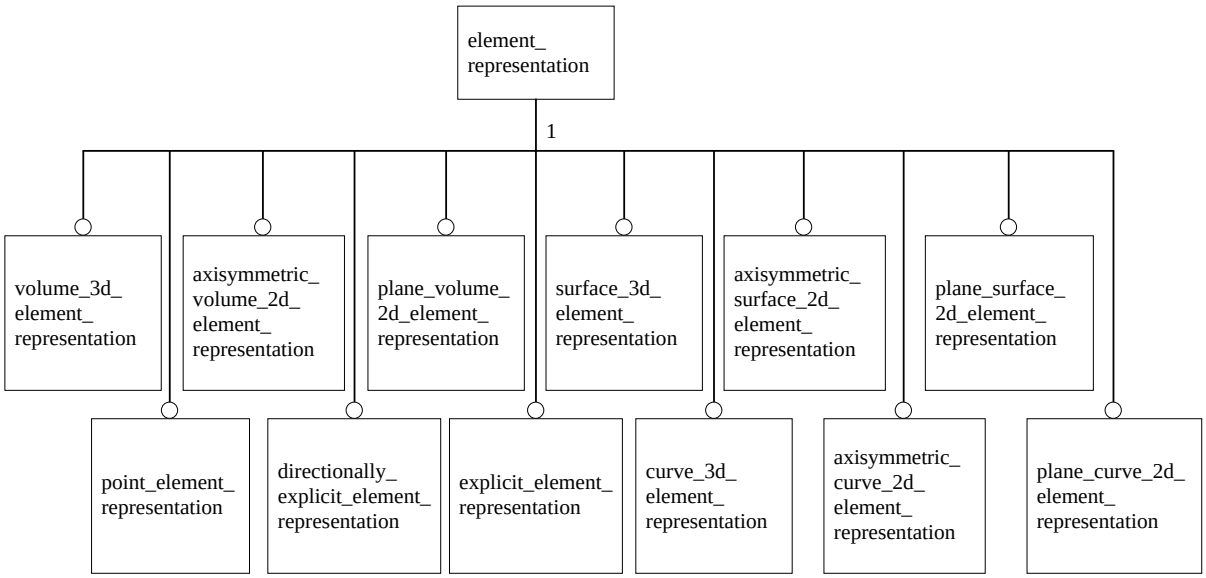

Figure 7 – Element subtyping

The element coordinate system attributes of volume, surface, and curve elements are specified with the **representation_item** subtype **fea_representation_item**. The association of the proper subtypes of volume, surface, and curve elements with the appropriate subtypes of **representation_item** is specified with EXPRESS rules.

NOTE 2 The EXPRESS-G Partial Model in Figure 8 shows the relationship of volume elements to FEA and FEA material property representations. Surface and curve elements have similar relationships, and also have a relationship to element property entities.

Point elements are different representations of nodal response matrices than the volume, surface, and curve elements. Rather than implicitly defining the element nodal response matrices as the volume, surface, and curve elements do, the point elements instead explicitly define the stiffness, mass, and damping nodal response matrices of an element. Thus a point element is a single node element that is a convenient way to define these matrices, rather than the more general matrix definition capability offered by the multi-noded explicit elements. The element coordinate system attributes of the matrices are associated with their **element_representation** by rules, as discussed above for volume, surface, and curve elements.

NOTE 3 The EXPRESS-G Partial Model in Figure 9 illustrates the relationships of the SUBTYPE trees of the point, directionally explicit and explicit elements.

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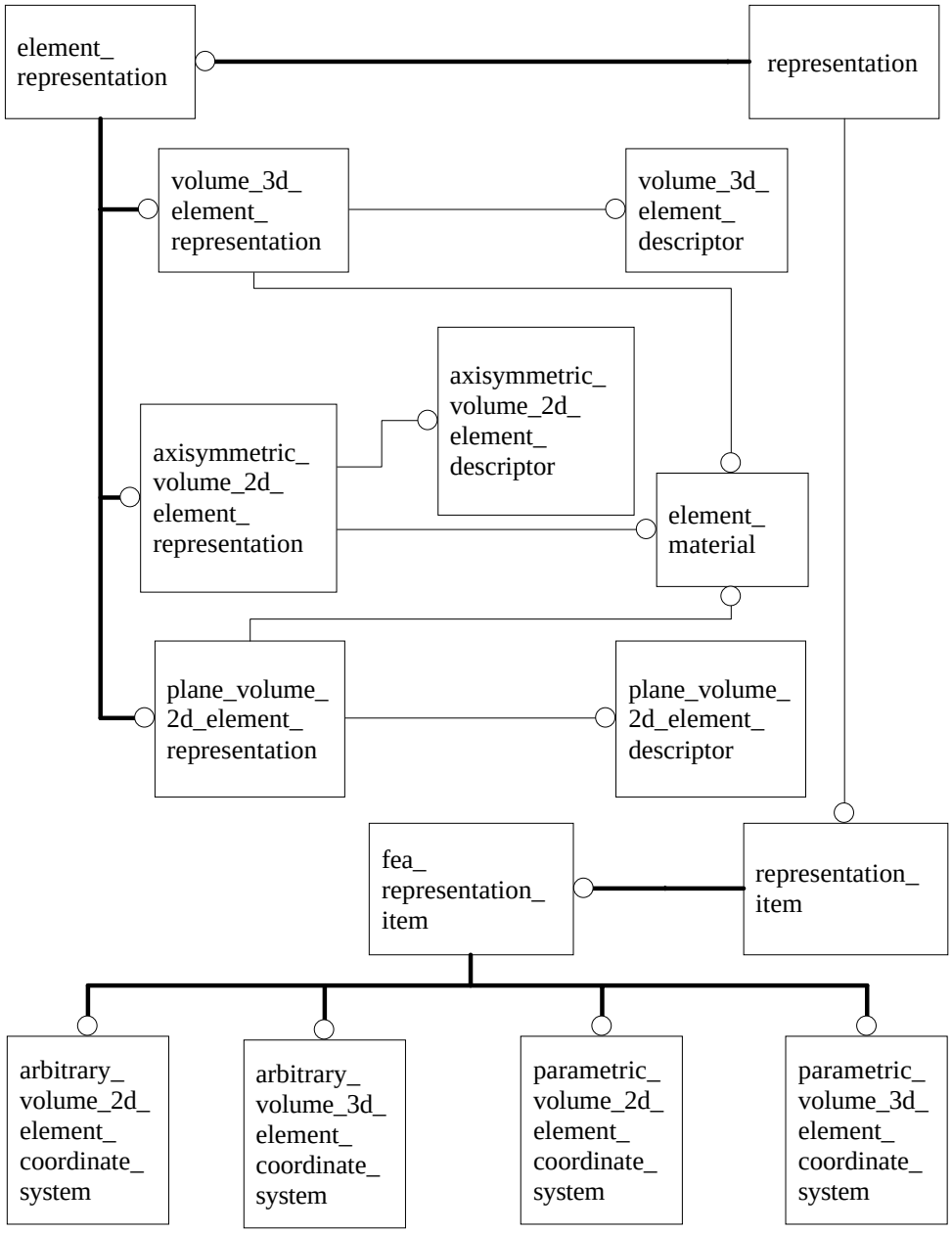

Figure 8 – Volume element properties EXPRESS-G partial model

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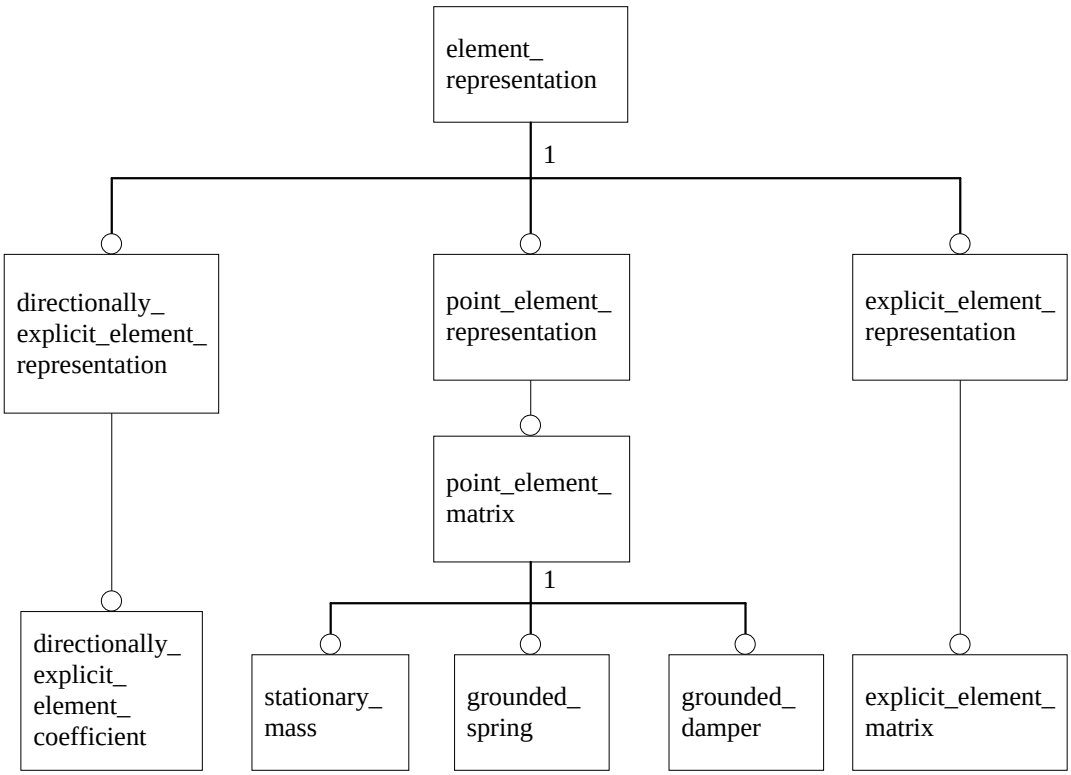

Figure 9 – Point, directionally explicit and explicit elements EXPRESS-G partial model

A nodal response matrix defined by a point, directionally explicit or explicit element, shall be one of:

stiffness: A stiffness between nodes for a directionally explicit or an explicit element, or a grounded spring for a point element, defined as follows:

$$\mathbf{f} = K\mathbf{d}$$

damping: A damping between nodes for a directionally explicit or an explicit element, or a grounded damper for a point element, defined as follows:

$$\mathbf{f} = D\mathbf{v}$$

mass: A mass for a directionally explicit, explicit or point element, defined as follows:

$$\mathbf{f} = M\mathbf{a}$$

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where:

K is the element stiffness matrix;

D is the element damping matrix;

M is the element mass matrix;

$\mathbf{f}$ is the vector of generalised forces applied to the element at nodal degrees of freedom;

$\mathbf{d}$ is the vector of generalised displacements imposed upon nodal degrees of freedom;

$\mathbf{v}$ is the vector of generalised velocities imposed upon nodal degrees of freedom;

$\mathbf{a}$ is the vector of generalised accelerations imposed upon nodal degrees of freedom.

5.7.1 element_representation

An **element_representation** is the aspect of a finite element that represents the mathematical relationships between the nodes of a finite element model.

EXPRESS specification:

```
*)
ENTITY element_representation
  SUPERTYPE OF (ONEOF(volume_3d_element_representation,
                      axisymmetric_volume_2d_element_representation,
                      plane_volume_2d_element_representation,
                      surface_3d_element_representation,
                      axisymmetric_surface_2d_element_representation,
                      plane_surface_2d_element_representation,
                      curve_3d_element_representation,
                      axisymmetric_curve_2d_element_representation,
                      plane_curve_2d_element_representation,
                      point_element_representation,
                      directionally_explicit_element_representation,
                      explicit_element_representation,
                      substructure_element_representation))
  SUBTYPE OF (representation);
  node_list                 : LIST [1:?] OF node_representation;
WHERE
  WR1: SIZEOF (QUERY(item <* node_list |
             'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'GEOMETRIC_NODE'
             IN TYPEOF (item))) = 0;
 END_ENTITY;
(*
```

Attribute definitions:

node_list: the list of nodes that make up the element.

NOTE 1 The node list defines the connection of an element to other elements within the model.

NOTE 2 For volume, surface, or curve elements the positions of the nodes together with the element shape functions define the shape and orientation of an element. The position of a node in the node list depends on the element shape and order as established graphically in the figures in 5.8.

Formal propositions:

WR1: there shall be no geometric nodes in the list of nodes for the element.

Informal propositions:

IP1: TYPE **dummy_nodes** shall be used as placeholders in the **node_list** if the element formulation does not include mid-edge, mid-face, and mid-volume nodes.

5.7.2 volume_3d_element_representation

A **volume_3d_element_representation** is a 3D shape.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_3d;
  element_descriptor        : volume_3d_element_descriptor;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_VOLUME_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ARBITRARY_VOLUME_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) = 1;
  WR2: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
```

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```
          SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_LINEAR_ELASTICITY',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_MASS_DENSITY',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_MOISTURE_ABSORPTION'] * TYPEOF (item2)
                   ) = 1
        )) = 1
       ))) >= 1;
  WR3: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_3d_nodes (
        SELF\element_representation.node_list,
        element_descriptor.shape,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the volume 3D element.

element_descriptor: a collection of information that specifies a **volume_3d_element_representation**.

material: the material properties associated with a **volume_3d_element_representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: there shall be either a parametric material coordinate system (PARAMETRIC_VOLUME_3D_-ELEMENT_COORDINATE_SYSTEM) or an arbitrary material coordinate system (ARBITRARY_-VOLUME_3D_ELEMENT_COORDINATE_SYSTEM) associated with a **volume_3d_element_-representation**.

The material coordinate system (parametric or arbitrary) is the orientation of the element coordinate system for the material of the **volume_3d_element_representation**. The x axis of the element coordinate system shall coincide with the x axis of the material coordinate system, the y axis of the element coordinate system shall coincide with the y axis of the material coordinate system, and the z axis of the element coordinate system shall coincide with the z axis of the material coordinate system.

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WR2: there shall be at least one of the following **fea_material_property_representation_item** subtypes referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_tangential_coefficient_-of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_expansion**, and **fea_-moisture_absorption**.

WR3: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of a **volume_3d_element_representation** shall be the proper number based on the shape and order of the **volume_3d_element_representation**.

5.7.3 axisymmetric_volume_2d_element_representation

An **axisymmetric_volume_2d_element_representation** is a 2D shape swept about the **j** axis of the (**i**,**j**) plane of the founding coordinate system (see 5.2.3). An **axisymmetric_volume_2d_element_-representation** shall lie in the (**i**,**j**) plane of the founding coordinate system.

EXPRESS specification:

```
*)
ENTITY axisymmetric_volume_2d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_2d;
  element_descriptor        : axisymmetric_volume_2d_element_descriptor;
  angle_property            : axisymmetric_2d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: model_ref.type_of_2d_analysis = axisymmetric;
  WR2: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_VOLUME_2D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ARBITRARY_VOLUME_2D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) = 1;
  WR3: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
```

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```
                    'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_MOISTURE_ABSORPTION'] * TYPEOF (item2)
                    ) = 1
        )) = 1
       ))) >= 1;
  WR4: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_2d_nodes (
        SELF\element_representation.node_list,
        element_descriptor.shape,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the axisymmetric volume 2D element.

element_descriptor: a collection of information that specifies an **axisymmetric_volume_2d_-element_representation**.

angle_property: the properties for an axisymmetric section. Analysis applications often assume that the value of the angle attribute of this property is 2π.

material: the material properties associated with an **axisymmetric_volume_2d_element_-representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: the **fea_model** shall be axisymmetric.

WR2: there shall be either a parametric material coordinate system (PARAMETRIC_VOLUME_2D_-ELEMENT_COORDINATE_SYSTEM) or an arbitrary material coordinate system (ARBITRARY_-VOLUME_2D_ELEMENT_COORDINATE_SYSTEM) associated with an **axisymmetric_volume_-2d_element_representation**.

The material coordinate system (parametric or arbitrary) is the orientation of the element coordinate system for the material of the **axisymmetric_volume_2d_element_representation**. The $\mathbf{x}$ axis of the element coordinate system shall coincide with the $\mathbf{x}$ axis of the material coordinate system, the $\mathbf{y}$ axis of the element coordinate system shall coincide with the $\mathbf{y}$ axis of the material coordinate system, and the $\mathbf{z}$ axis of the element coordinate system shall coincide with the $\mathbf{z}$ axis of the material coordinate system.

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WR3: there shall be at least one of the following **fea_material_property_representation_item** subtypes referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_expansion**, and **fea_moisture_absorption**.

WR4: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of an **axisymmetric_volume_2d_element_representation** shall be the proper number based on the shape and order of the **axisymmetric_volume_2d_element_representation**.

5.7.4 plane_volume_2d_element_representation

A **plane_volume_2d_element_representation** is a 2D shape in the (**i**,**j**) plane of the founding coordinate system (see 5.2.3) with a depth perpendicular to the (**i**,**j**) plane. A **plane_volume_2d_element_representation** shall lie in the (**i**,**j**) plane of the founding coordinate system.

EXPRESS specification:

```
*)
ENTITY plane_volume_2d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_2d;
  element_descriptor        : plane_volume_2d_element_descriptor;
  depth_property            : plane_2d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: model_ref.type_of_2d_analysis = planar;
  WR2: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_VOLUME_2D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ARBITRARY_VOLUME_2D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) = 1;
  WR3: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
```

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```
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_MOISTURE_ABSORPTION'] * TYPEOF (item2)
                    ) = 1
        )) = 1
       ))) >= 1;
  WR4: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_2d_nodes (
        SELF\element_representation.node_list,
        element_descriptor.shape,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the plane volume 2D element.

element_descriptor: a collection of information that specifies a **plane_volume_2d_element_-representation**.

depth_property: the properties for a plane section. Analysis applications often assume that the value of the depth attribute of this property is 1.0.

material: the material properties associated with a **plane_volume_2d_element_representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: the **fea_model** shall be planar.

WR2: there shall be either a parametric material coordinate system (PARAMETRIC_VOLUME_2D_-ELEMENT_COORDINATE_SYSTEM) or an arbitrary material coordinate system (ARBITRARY_-VOLUME_2D_ELEMENT_COORDINATE_SYSTEM) associated with a **plane_volume_2d_-element_representation**.

The material coordinate system (parametric or arbitrary) is the orientation of the element coordinate system for the material of the **plane_volume_2d_element_representation**. The x axis of the element coordinate system shall coincide with the x axis of the material coordinate system, the y axisof the element coordinate system shall coincide with the y axis of the material coordinate system, and the z axis of the element coordinate system shall coincide with the z axis of the material coordinate system.

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WR3: there shall be at least one of the following **fea_material_property_representation_item** subtypes referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_expansion**, and **fea_moisture_absorption**.

WR4: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of a **plane_volume_2d_element_representation** shall be the proper number based on the shape and order of the **plane_volume_2d_element_representation**.

5.7.5 surface_3d_element_representation

A **surface_3d_element_representation** is an element that is a surface with a specified section that is a 2D shape (a triangle or quadrilateral) in 3D space.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_3d;
  element_descriptor        : surface_3d_element_descriptor;
  property                  : surface_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'CONSTANT_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ALIGNED_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) = 1;
  WR2: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
```

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```
                    'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_MOISTURE_ABSORPTION',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_SHELL_MEMBRANE_STIFFNESS',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_SHELL_BENDING_STIFFNESS',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_SHELL_MEMBRANE_BENDING_COUPLING_STIFFNESS',
                    'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                    'FEA_SHELL_SHEAR_STIFFNESS'] * TYPEOF (item2)
                    ) = 1
        )) = 1
       ))) >= 1;
  WR3: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_2d_nodes (
        SELF\element_representation.node_list,
        element_descriptor.shape,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the surface 3D element.

element_descriptor: a collection of information that specifies a **surface_3d_element_representation**.

property: the section properties of the surface.

material: the material properties associated with a **surface_3d_element_representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: there shall be either a parametric property coordinate system (PARAMETRIC_SURFACE_-3D_ELEMENT_COORDINATE_SYSTEM), a constant property coordinate system (CONSTANT_-SURFACE_3D_ELEMENT_COORDINATE_SYSTEM), or an aligned property coordinate system (ALIGNED_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM) associated with a **surface_3d_-element_representation**.

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The property coordinate system (parametric, constant, or aligned) is the orientation of the coordinate system for the element material and section properties. For a **surface_3d_element_representation** the property coordinate system is defined such that its **z** axis is normal to the element surface at each point on the surface of the element.

WR2: there shall be at least one of the following **fea_material_property_representation_item** subtypes referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_-tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_-expansion**, **fea_moisture_absorption**, **fea_shell_membrane_stiffness**, **fea_shell_bending_stiffness**, **fea_shell_membrane_bending_coupling_stiffness**, and **fea_shell_shear_stiffness**.

WR3: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of a **surface_3d_element_representation** shall be the proper number based on the shape and order of the **surface_3d_element_representation**.

5.7.6 axisymmetric_surface_2d_element_representation

An **axisymmetric_surface_2d_element_representation** is an element that is a surface with a specified section that is a 1D shape (curve) that is swept about the **j** axis of the (**i**,**j**) plane of the founding coordinate system (see 5.2.3). An **axisymmetric_surface_2d_element_representation** shall lie in the (**i**,**j**) plane of the founding coordinate system. An illustration of a 2D founding coordinate system is shown in Figure 49.

EXPRESS specification:

```
*)
ENTITY axisymmetric_surface_2d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_2d;
  element_descriptor        : axisymmetric_surface_2d_element_descriptor;
  property                  : surface_element_property;
  angle_property            : axisymmetric_2d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: model_ref.type_of_2d_analysis = axisymmetric;
  WR2: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_SURFACE_2D_ELEMENT_COORDINATE_SYSTEM'
                IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ALIGNED_SURFACE_2D_ELEMENT_COORDINATE_SYSTEM'
                IN TYPEOF (item))) = 1;
  WR3: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
```

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```
          SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_LINEAR_ELASTICITY',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_MASS_DENSITY',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_AREA_DENSITY',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_MOISTURE_ABSORPTION',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_SHELL_MEMBRANE_STIFFNESS',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_SHELL_BENDING_STIFFNESS',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_SHELL_MEMBRANE_BENDING_COUPLING_STIFFNESS',
                   'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                   'FEA_SHELL_SHEAR_STIFFNESS'] * TYPEOF (item2)
                   ) = 1
        )) = 1
       ))) >= 1;
  WR4: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_1d_nodes (
        SELF\element_representation.node_list,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the axisymmetric surface 2D element.

element_descriptor: a collection of information that specifies an **axisymmetric_surface_2d_-element_representation**.

property: the section properties of the surface.

angle_property: the properties for an axisymmetric section. Analysis applications often assume that the value of the angle attribute of this property is 2π.

material: the material properties associated with an **axisymmetric_surface_2d_element_-representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

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Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: the **fea_model** shall be axisymmetric.

WR2: there shall be either a parametric property coordinate system (PARAMETRIC_SURFACE_-2D_ELEMENT_COORDINATE_SYSTEM) or an aligned property coordinate system (ALIGNED_-SURFACE_2D_ELEMENT_COORDINATE_SYSTEM) associated with an **axisymmetric_surface_-2d_element_representation**.

The property coordinate system (parametric or aligned) is the orientation of the coordinate system for the element material and section properties. For an **axisymmetric_surface_2d_element_representation** the property coordinate system is defined such that: the **x** axis is normal to the 2D analysis plane in the direction of the **k** axis of the analysis 2D definition coordinate system, and the **z** axis is normal to the element surface as shown in Figure 49.

WR3: there shall be at least one of the following **fea_material_property_representation_item** subtypes referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_-tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_-expansion**, **fea_moisture_absorption**, **fea_shell_membrane_stiffness**, **fea_shell_bending_stiffness**, **fea_shell_membrane_bending_coupling_stiffness**, and **fea_shell_shear_stiffness**.

WR4: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of an **axisymmetric_surface_2d_element_representation** shall be the proper number based on the order of the **axisymmetric_surface_2d_element_-representation**.

5.7.7 plane_surface_2d_element_representation

A **plane_surface_2d_element_representation** is an element that is a surface with a specified section that is a 1D shape (curve) in the (**i**,**j**) plane of the founding coordinate system (see 5.2.3) with a depth perpendicular to the (**i**,**j**) plane. A **plane_surface_2d_element_representation** shall lie in the (**i**,**j**) plane of the founding coordinate system.

EXPRESS specification:

```
*)
ENTITY plane_surface_2d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_2d;
  element_descriptor        : plane_surface_2d_element_descriptor;
  property                  : surface_element_property;
  depth_property            : plane_2d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
```

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```
WHERE
  WR1: model_ref.type_of_2d_analysis = planar;
  WR2: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_SURFACE_2D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ALIGNED_SURFACE_2D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) = 1;
  WR3: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MOISTURE_ABSORPTION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_MEMBRANE_STIFFNESS',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_BENDING_STIFFNESS',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_MEMBRANE_BENDING_COUPLING_STIFFNESS',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_SHEAR_STIFFNESS'] * TYPEOF (item2)
                  ) = 1
        )) = 1
       ))) >= 1;
  WR4: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_1d_nodes (
        SELF\element_representation.node_list,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

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Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the plane surface 2D element.

element_descriptor: a collection of information that specifies a **plane_surface_2d_element_-representation**.

property: the section properties of the surface.

depth_property: the properties for a plane section. Analysis applications often assume that the value of the depth attribute of this property is 1.0.

material: the material properties associated with a **plane_surface_2d_element_representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: the **fea_model** shall be planar.

WR2: there shall be either a parametric property coordinate system (PARAMETRIC_SURFACE_-2D_ELEMENT_COORDINATE_SYSTEM) or an aligned property coordinate system (ALIGNED_-SURFACE_2D_ELEMENT_COORDINATE_SYSTEM) associated with a **plane_surface_2d_-element_representation**.

The property coordinate system (parametric or aligned) is the orientation of the coordinate system for the element material and section properties. For a **plane_surface_2d_element_representation** the property coordinate system is defined such that: the x axis is normal to the 2D analysis plane in the direction of the k axis of the analysis 2D definition coordinate system, and the z axis is normal to the element surface.

WR3: there shall be at least one of the following **fea_material_property_representation_item** sub-types referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_-tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_-expansion**, **fea_moisture_absorption**, **fea_shell_membrane_stiffness**, **fea_shell_bending_stiffness**, **fea_shell_membrane_bending_coupling_stiffness**, and **fea_shell_shear_stiffness**.

WR4: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of a **plane_surface_2d_element_representation** shall be the proper number based on the order of the **plane_surface_2d_element_representation**.

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5.7.8 curve_3d_element_representation

A **curve_3d_element_representation** is an element that is a 1D shape (a curve) with a specified cross section.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_3d;
  element_descriptor        : curve_3d_element_descriptor;
  property                  : curve_3d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'PARAMETRIC_CURVE_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) +
       SIZEOF (QUERY(item <* SELF\representation.items |
               'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
               'ALIGNED_CURVE_3D_ELEMENT_COORDINATE_SYSTEM'
               IN TYPEOF (item))) = 1;
  WR2: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MOISTURE_ABSORPTION'] * TYPEOF (item2)
                  ) = 1
        )) = 1
       ))) >= 1;
  WR3: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_1d_nodes (
        SELF\element_representation.node_list,
        element_descriptor\element_descriptor.topology_order);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the curve 3D element.

element_descriptor: a collection of information that specifies a **curve_3d_element_representation**.

property: the cross section properties of a **curve_3d_element_representation**.

material: the material properties associated with a **curve_3d_element_representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: there shall be either a parametric property coordinate system (PARAMETRIC_CURVE_3D_-ELEMENT_COORDINATE_SYSTEM) or an aligned property coordinate system (ALIGNED_-CURVE_3D_ELEMENT_COORDINATE_SYSTEM) associated with a **curve_3d_element_-representation**.

The property coordinate system (parametric or aligned) is the orientation of the coordinate system for the element material and section properties.

WR2: there shall be at least one of the following **fea_material_property_representation_item** sub-types referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_-tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_-expansion**, and **fea_moisture_absorption**.

WR3: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of a **curve_3d_element_representation** shall be the proper number based on the order of the **curve_3d_element_representation**.

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5.7.9 axisymmetric_curve_2d_element_representation

An **axisymmetric_curve_2d_element_representation** is an element with a specified cross section that is a 0D shape (a point) that is swept about the **j** axis of the (**i**,**j**) plane of the founding coordinate system (see 5.2.3). An **axisymmetric_curve_2d_element_representation** shall lie in the (**i**,**j**) plane of the founding coordinate system.

EXPRESS specification:

```
*)
ENTITY axisymmetric_curve_2d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_2d;
  element_descriptor        : axisymmetric_curve_2d_element_descriptor;
  property                  : curve_2d_element_property;
  angle_property            : axisymmetric_2d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: model_ref.type_of_2d_analysis = axisymmetric;
  WR2: SIZEOF (QUERY(item <* SELF\representation.items |
             'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'CURVE_2D_ELEMENT_COORDINATE_SYSTEM'
             IN TYPEOF (item))) = 1;
  WR3: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MOISTURE_ABSORPTION'] * TYPEOF (item2)
                  ) = 1
        )) = 1
       ))) >= 1;
  WR4: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_0d_nodes (
        SELF\element_representation.node_list);
END_ENTITY;
(*
```

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Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the axisymmetric curve 2D element.

element_descriptor: a collection of information that specifies an **axisymmetric_curve_2d_element_-representation**.

property: the cross section properties of an **axisymmetric_curve_2d_element_representation**.

angle_property: the properties for an axisymmetric section. Analysis applications often assume that the value of the angle attribute of this property is 2π.

material: the material properties associated with an **axisymmetric_curve_2d_element_-representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: the **fea_model** shall be axisymmetric.

WR2: there shall be a property coordinate system (CURVE_2D_ELEMENT_COORDINATE_-SYSTEM) associated with an **axisymmetric_curve_2d_element_representation**.

The property coordinate system is the orientation of the coordinate system for the element material and section properties.

WR3: there shall be at least one of the following **fea_material_property_representation_item** sub-types referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_-tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_-expansion**, and **fea_moisture_absorption**.

WR4: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of an **axisymmetric_curve_2d_element_representation** shall be the proper number for a point element.

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5.7.10 plane_curve_2d_element_representation

A **plane_curve_2d_element_representation** is an element with a specified cross section that is a 0D shape (a point) in the (**i**,**j**) plane of the founding coordinate system (see 5.2.3) with a depth perpendicular to the (**i**,**j**) plane. A **plane_curve_2d_element_representation** shall lie in the (**i**,**j**) plane of the founding coordinate system.

EXPRESS specification:

```
*)
ENTITY plane_curve_2d_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model_2d;
  element_descriptor        : plane_curve_2d_element_descriptor;
  property                  : curve_2d_element_property;
  depth_property            : plane_2d_element_property;
  material                  : element_material;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: model_ref.type_of_2d_analysis = planar;
  WR2: SIZEOF (QUERY(item <* SELF\representation.items |
             'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'CURVE_2D_ELEMENT_COORDINATE_SYSTEM'
             IN TYPEOF (item))) = 1;
  WR3: SIZEOF (QUERY(item1 <* material.properties |
        (SIZEOF (QUERY (item2 <*
        item1\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MOISTURE_ABSORPTION'] * TYPEOF (item2)
                  ) = 1
        )) = 1
       ))) >= 1;
  WR4: 'REPRESENTATION_SCHEMA.PARAMETRIC_REPRESENTATION_CONTEXT'
        IN TYPEOF (SELF\representation.context_of_items);
  FU1:  required_0d_nodes (
        SELF\element_representation.node_list);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the plane curve 2D element.

element_descriptor: a collection of information that specifies **plane_curve_2d_element_representation**.

property: the cross section properties of a **plane_curve_2d_element_representation**.

depth_property: the properties for a planar section. Analysis applications often assume that the value of the depth attribute of this property is 1.0.

material: the material properties associated with a **plane_curve_2d_element_representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: the **fea_model** shall be planar.

WR2: there shall be a property coordinate system (CURVE_2D_ELEMENT_COORDINATE_SYSTEM) associated with a **plane_curve_2d_element_representation**.

The property coordinate system is the orientation of the coordinate system for the element material and section properties.

WR3: there shall be at least one of the following **fea_material_property_representation_item** subtypes referenced by a **material**: **fea_linear_elasticity**, **fea_mass_density**, **fea_area_density**, **fea_tangential_coefficient_of_linear_thermal_expansion**, **fea_secant_coefficient_of_linear_thermal_expansion**, and **fea_moisture_absorption**.

WR4: there shall be a parametric representation context associated with the element.

FU1: the number of nodes in the node list of a **plane_curve_2d_element_representation** shall be the proper number for a point element.

5.7.11 element_descriptor

An **element_descriptor** is a collection of information that specifies an element.

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EXPRESS specification:

```
*)
ENTITY element_descriptor
  SUPERTYPE OF (ONEOF (volume_3d_element_descriptor,
                       axisymmetric_volume_2d_element_descriptor,
                       plane_volume_2d_element_descriptor,
                       surface_3d_element_descriptor,
                       axisymmetric_surface_2d_element_descriptor,
                       plane_surface_2d_element_descriptor,
                       curve_3d_element_descriptor,
                       axisymmetric_curve_2d_element_descriptor,
                       plane_curve_2d_element_descriptor));
  topology_order            : element_order;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

topology_order: the highest degree polynomial interpolation function used to describe the geometric shape of any edge of an element, which in turn is used to relate the node list of the element to the appropriate topology diagram in 5.8.

description: additional information about the formulation or purpose of an element.

5.7.12 volume_3d_element_descriptor

A **volume_3d_element_descriptor** is a collection of information that specifies a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF volume_element_purpose;
  shape                     : volume_3d_element_shape;
END_ENTITY;
(*
```

Attribute definitions:

purpose: the enumerated value specifying the response of a volume 3D element.

shape: the geometric shape of a volume 3D element.

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5.7.13 axisymmetric_volume_2d_element_descriptor

An **axisymmetric_volume_2d_element_descriptor** is a collection of information that specifies an axisymmetric volume 2D element.

EXPRESS specification:

```
*)
ENTITY axisymmetric_volume_2d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              volume_element_purpose;
  shape                     : element_2d_shape;
END_ENTITY;
(*
```

Attribute definitions:

purpose: the enumerated value specifying the response of an **axisymmetric_volume_2d_element_representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

shape: the geometric shape of an **axisymmetric_volume_2d_element_representation**.

5.7.14 plane_volume_2d_element_descriptor

A **plane_volume_2d_element_descriptor** is a collection of information that specifies a plane volume 2D element.

EXPRESS specification:

```
*)
ENTITY plane_volume_2d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              volume_element_purpose;
  shape                     : element_2d_shape;
  assumption                : plane_2d_element_purpose;
END_ENTITY;
(*
```

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Attribute definitions:

purpose: the enumerated value specifying the response of **plane_volume_2d_element_-representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

shape: the geometric shape of a **plane_volume_2d_element_representation**.

assumption: the use of a **plane_volume_2d_element_representation** with 2D shape to model a volume.

5.7.15 volume_3d_element_basis

A **volume_3d_element_basis** is the information that forms the basis of a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_basis;
  descriptor                : volume_3d_element_descriptor;
  variable                  : volume_variable;
  variable_order            : element_order;
  variable_shape_function   : shape_function;
  evaluation_points         : LIST [1:?] OF volume_element_location;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **volume_3d_element_representation**.

variable: the variable to be associated with an order and shape function for a **volume_3d_element_-representation**.

variable_order: the mathematical order of polynomials used to define the shape function.

variable_shape_function: the type of polynomial shape function used to interpolate the variable within a **volume_3d_element_representation**.

evaluation_points: the locations within a **volume_3d_element_representation** where the **variable** is evaluated using the **variable_shape_function**.

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5.7.16 volume_2d_element_basis

A **volume_2d_element_basis** is the information that forms the basis of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_basis;
  descriptor                : volume_2d_element_descriptor;
  variable                  : volume_variable;
  variable_order            : element_order;
  variable_shape_function   : shape_function;
  evaluation_points         : LIST [1:?] OF volume_element_location;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **volume_2d_element_representation**.

variable: the variable to be associated with an order and shape function for a **volume_2d_element_-representation**.

variable_order: the mathematical order of polynomials used to define the shape function.

variable_shape_function: the type of polynomial shape function used to interpolate the variable within a **volume_2d_element_representation**.

evaluation_points: the locations within a **volume_2d_element_representation** where the **variable** is evaluated using the **variable_shape_function**.

5.7.17 surface_3d_element_descriptor

A **surface_3d_element_descriptor** is a collection of information that specifies a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              surface_element_purpose;
  shape                     : element_2d_shape;
END_ENTITY;
(*
```

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Attribute definitions:

purpose: the enumerated value specifying the response of a **surface_3d_element_representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

shape: the geometric shape of a **surface_3d_element_representation**.

5.7.18 axisymmetric_surface_2d_element_descriptor

An **axisymmetric_surface_2d_element_descriptor** is a collection of information that specifies an axisymmetric surface 2D element.

EXPRESS specification:

```
*)
ENTITY axisymmetric_surface_2d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              surface_element_purpose;
END_ENTITY;
(*
```

Attribute definitions:

purpose: the enumerated value specifying the response of an **axisymmetric_surface_2d_element_representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

5.7.19 plane_surface_2d_element_descriptor

A **plane_surface_2d_element_descriptor** is a collection of information that specifies a plane surface 2D element.

EXPRESS specification:

```
*)
ENTITY plane_surface_2d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              surface_element_purpose;
  assumption                : plane_2d_element_purpose;
END_ENTITY;
(*
```

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Attribute definitions:

purpose: the enumerated value specifying the response of a **plane_surface_2d_element_-representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

assumption: the use of a curve element to model a surface.

5.7.20 surface_3d_element_basis

A **surface_3d_element_basis** is the information that forms the basis of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_basis;
  descriptor                : surface_3d_element_descriptor;
  variable                  : surface_element_variable;
  variable_order            : element_order;
  variable_shape_function   : shape_function;
  evaluation_points         : LIST [1:?] OF surface_element_location;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **surface_3d_element_representation**.

variable: the variable to be associated with an order and shape function for a **surface_3d_element_-representation**.

variable_order: the mathematical order of polynomials used to define the shape function.

variable_shape_function: the type of polynomial shape function used to interpolate the variable within a **surface_3d_element_representation**.

evaluation_points: the locations within a **surface_3d_element_representation** where the **variable** is evaluated using the **variable_shape_function**.

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5.7.21 surface_2d_element_basis

A **surface_2d_element_basis** is the information that forms the basis of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_basis;
  descriptor                : surface_2d_element_descriptor;
  variable                  : surface_element_variable;
  variable_order            : element_order;
  variable_shape_function   : shape_function;
  evaluation_points         : LIST [1:?] OF surface_element_location;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **surface_2d_element_representation**.

variable: the variable to be associated with an order and shape function for a **surface_2d_element_-representation**.

variable_order: the mathematical order of polynomials used to define the shape function.

variable_shape_function: the type of polynomial shape function used to interpolate the variable within a **surface_2d_element_representation**.

evaluation_points: the locations within a **surface_2d_element_representation** where the **variable** is evaluated using the **variable_shape_function**.

5.7.22 curve_3d_element_descriptor

A **curve_3d_element_descriptor** is a collection of information that specifies a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              curve_element_purpose;
END_ENTITY;
(*
```

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Attribute definitions:

purpose: the enumerated value specifying the response of a **curve_3d_element_representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

5.7.23 axisymmetric_curve_2d_element_descriptor

An **axisymmetric_curve_2d_element_descriptor** is a collection of information that specifies an axisymmetric curve 2D element.

EXPRESS specification:

```
*)
ENTITY axisymmetric_curve_2d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              curve_element_purpose;
END_ENTITY;
(*
```

Attribute definitions:

purpose: the enumerated value specifying the response of an **axisymmetric_curve_2d_element_-representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

5.7.24 plane_curve_2d_element_descriptor

A **plane_curve_2d_element_descriptor** is a collection of information that specifies a plane curve 2D element.

EXPRESS specification:

```
*)
ENTITY plane_curve_2d_element_descriptor
  SUBTYPE OF (element_descriptor);
  purpose                   : SET [1:?] OF SET [1:?] OF
                              curve_element_purpose;
  assumption                : plane_2d_element_purpose;
END_ENTITY;
(*
```

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Attribute definitions:

purpose: the enumerated value specifying the response of a **plane_curve_2d_element_representation**. The purpose is a SET of SETs in order to allow the appropriate combinations of coupled and uncoupled responses.

assumption: the use of the element to model a curve.

5.7.25 curve_3d_element_basis

A **curve_3d_element_basis** is the information that forms the basis of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_basis;
  descriptor                : curve_3d_element_descriptor;
  variable                  : curve_element_variable;
  variable_order            : element_order;
  variable_shape_function   : shape_function;
  evaluation_points         : LIST [1:?] OF curve_element_location;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **curve_3d_element_representation**.

variable: the variable to be associated with an order and shape function for a **curve_3d_element_-representation**.

variable_order: the mathematical order of polynomials used to define the shape function.

variable_shape_function: the type of polynomial shape function used to interpolate the variable within a **curve_3d_element_representation**.

evaluation_points: the locations within a **curve_3d_element_representation** where the **variable** is evaluated using the **variable_shape_function**.

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5.7.26 curve_2d_element_basis

A **curve_2d_element_basis** is the information that forms the basis of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_basis;
  descriptor                : curve_2d_element_descriptor;
  variable                  : curve_element_variable;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **curve_2d_element_representation**.

variable: the variable to be associated with an order and shape function for a **curve_2d_element_-representation**.

5.7.27 point_element_representation

A **point_element_representation** is a single noded explicit element.

EXPRESS specification:

```
*)
ENTITY point_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model;
  description               : text;
  matrix_set                : SET [1:?] OF point_element_matrix;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
             'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'FEA_AXIS2_PLACEMENT_3D'
             IN TYPEOF (item))) = 1;
  FU1:  required_0d_nodes (
        SELF\element_representation.node_list);
END_ENTITY;
(*
```

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Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the point element.

description: information about the **point_element** purpose.

matrix_set: the explicit element matrices.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: there shall be exactly one coordinate system associated with a **point_element_representation**.

A matrix coordinate system (FEA_AXIS2_PLACEMENT_3D) is the coordinate system with respect to which all of the matrices of the point element are defined. The degrees of freedom at a node are defined with respect to the local orthogonal triad of the specified coordinate system at that node.

FU1: the number of nodes in the node list of a **point_element_representation** shall be the proper number for a point element.

5.7.28 point_element_matrix

A **point_element_matrix** is a matrix that represents a stationary mass, grounded spring, or grounded damper.

EXPRESS specification:

```
*)
ENTITY point_element_matrix
  SUPERTYPE OF (ONEOF(stationary_mass,
                      grounded_spring,
                      grounded_damper));
END_ENTITY;
(*
```

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5.7.29 stationary_mass

A **stationary_mass** is a point element nodal response matrix of type stationary mass. The **stationary_mass** matrix is populated as follows:

$$\begin{pmatrix} m_x & & & & & \\ & m_y & & & & \\ & & m_z & & & \\ & & & i_{xx} & i_{xy} & i_{xz} \\ & & & i_{xy} & i_{yy} & i_{yz} \\ & & & i_{xz} & i_{yz} & i_{zz} \end{pmatrix}$$

NOTE In all physical cases mass acts equally in all directions.

EXPRESS specification:

```
*)
ENTITY stationary_mass
  SUBTYPE OF (point_element_matrix);
  mass                      : ARRAY [1:3] OF context_dependent_measure;
  moments_of_inertia        : symmetric_tensor2_3d;
  coordinate_system         : fea_axis2_placement_3d;
  offset_vector             : ARRAY [1:3] OF context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

mass: the point masses in the different directions is populated as follows:

Array item 1 is the mass acting in the **x** direction, and is denoted m_x in the matrix shown above;
Array item 2 is the mass acting in the **y** direction, and is denoted m_y in the matrix shown above;
Array item 3 is the mass acting in the **z** direction, and is denoted m_z in the matrix shown above;

moments_of_inertia: the moments of inertia of a point (denoted by i_{xx} ... i_{zz} in the matrix shown above) in the different directions. The values of the inertias should be set to 0.0 if unwanted. The inertias are evaluated about the centre of mass.

coordinate_system: the coordinate system which is used to specify the offset.

offset_vector: the distance from the node to the position of the centre of mass with respect to the local orthogonal triad of the specified coordinate system at the node.

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5.7.30 grounded_spring

A **grounded_spring** is a point element nodal response matrix of type grounded spring. The **grounded_spring** matrix is populated as follows:

$$\begin{pmatrix} kt_x & & & & & \\ & kt_y & & & & \\ & & kt_z & & & \\ & & & kr_x & & \\ & & & & kr_y & \\ & & & & & kr_z \end{pmatrix}$$

EXPRESS specification:

```
*)
ENTITY grounded_spring
  SUBTYPE OF (point_element_matrix);
  stiffness_coefficients    : ARRAY [1:6] OF context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

stiffness_coefficients: the stiffnesses in the different directions is populated as follows:

Array item 1 is the translational stiffness in the **x** direction, denoted kt_x in the matrix shown above.
Array item 2 is the translational stiffness in the **y** direction, denoted kt_y in the matrix shown above.
Array item 3 is the translational stiffness in the **z** direction, denoted kt_z in the matrix shown above.
Array item 4 is the rotational stiffness about the **x** direction, denoted kr_x in the matrix shown above.
Array item 5 is the rotational stiffness about the **y** direction, denoted kr_y in the matrix shown above.
Array item 6 is the rotational stiffness about the **z** direction, denoted kr_z in the matrix shown above.

5.7.31 grounded_damper

A **grounded_damper** is a point element nodal response matrix of type grounded damper. The **grounded_damper** matrix is populated as follows:

$$\begin{pmatrix} dt_x & & & & & \\ & dt_y & & & & \\ & & dt_z & & & \\ & & & dr_x & & \\ & & & & dr_y & \\ & & & & & dr_z \end{pmatrix}$$

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EXPRESS specification:

```
*)
ENTITY grounded_damper
  SUBTYPE OF (point_element_matrix);
  damping_coefficients      : ARRAY [1:6] OF context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

damping_coefficients: the damping in the different directions is populated as follows:

Array item 1 is the translational damping in the x direction, denoted dt_x in the matrix shown above.
Array item 2 is the translational damping in the y direction, denoted dt_y in the matrix shown above.
Array item 3 is the translational damping in the z direction, denoted dt_z in the matrix shown above.
Array item 4 is the rotational damping about the x direction, denoted dr_x in the matrix shown above.
Array item 5 is the rotational damping about the y direction, denoted dr_y in the matrix shown above.
Array item 6 is the rotational damping about the z direction, denoted dr_z in the matrix shown above.

5.7.32 directionally_explicit_element_representation

A **directionally_explicit_element_representation** is a two noded element for which the matrices (stiffness, damping and mass) are characterized by a single coefficient k. The x direction of the matrix is defined with respect to a coordinate system.

All elements of the matrix are populated from the single coefficient k. The matrix is of the form:

$$\begin{array}{cc} \begin{pmatrix} +k & -k \\ \\ -k & +k \end{pmatrix} & \begin{array}{l} \cdots \text{ degree of freedom 1, node 1} \\ \\ \cdots \text{ degree of freedom 2, node 2} \end{array} \\ \begin{array}{cc} \vdots & \vdots \\ \text{degree of freedom 1, node 1} & \text{degree of freedom 2, node 2} \end{array} & \end{array}$$

Different degrees of freedom can be specified for the two nodes. For a simple axial spring or damper the x translation degree of freedom in the aligned system is specified for both nodes. A two node explicit element can be used instead of a directionally explicit element, but an explicit element is less convenient because it is necessary to define each of the four matrix terms separately. Also, an aligned coordinate system cannot be defined for an explicit element.

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EXPRESS specification:

```
*)
ENTITY directionally_explicit_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model;
  systems_and_freedoms      : LIST [2:2] OF system_and_freedom;
  description               : text;
  coefficient               : directionally_explicit_element_coefficient;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  FU1:  required_1d_nodes (
        SELF\element_representation.node_list,
        linear);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the directionally explicit element.

systems_and_freedoms: the coordinate systems and degrees of freedom with respect to which all of the matrices of the **directionally_explicit_element_representation** are defined. List item 1 specifies the coordinate system and degree of freedom at node 1 and list item 2 specifies the coordinate system and degree of freedom at node 2.

description: information about the purpose of a **directionally_explicit_element_representation**.

coefficient: the single coefficient that characterizes the matrices of a **directionally_explicit_element_-representation**.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

FU1: the number of nodes in the node list of a **directionally_explicit_element_representation** shall be the proper number based on the linear order of the **directionally_explicit_element_representation**.

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5.7.33 system_and_freedom

A **system_and_freedom** is the coordinate system and degree of freedom for a **directionally_explicit_-element_representation** node.

EXPRESS specification:

```
*)
ENTITY system_and_freedom;
  matrix_coordinate_system  :
                     directionally_explicit_element_coordinate_system;
  freedom                   : degree_of_freedom;
END_ENTITY;
(*
```

Attribute definitions:

matrix_coordinate_system: the coordinate system with respect to which all of the matrices of the **directionally_explicit_element_representation** are defined for a node. This system can be an aligned system derived form the positions of the element nodes, or it can be an arbitrary system. An aligned system shall not be specified if the two nodes of the element are coincident.

freedom: the degree of freedom at a node of a **directionally_explicit_element_representation**.

5.7.34 directionally_explicit_element_coefficient

A **directionally_explicit_element_coefficient** is the coefficient that characterizes the matrices of the directionally explicit element.

EXPRESS specification:

```
*)
ENTITY directionally_explicit_element_coefficient;
  property_type             : matrix_property_type;
  coefficient               : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

property_type: the enumerated value specifying the type of matrix (stiffness, mass, or damping).

coefficient: the coefficient that defines the matrix.

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5.7.35 explicit_element_representation

An **explicit_element_representation** is an element in which the associated matrices (stiffness, mass, and damping) are specified directly.

EXPRESS specification:

```
*)
ENTITY explicit_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model;
  description               : text;
  matrix                    : explicit_element_matrix;
UNIQUE
  UR1: model_ref, SELF\representation.name;
WHERE
  WR1: SIZEOF (QUERY(item <* SELF\representation.items |
             ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
             'FEA_AXIS2_PLACEMENT_3D')
             IN TYPEOF (item))) = 1;
  WR2:  SIZEOF (matrix.node_dof_list) =
        SIZEOF (SELF\element_representation.node_list);
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application defined identifier of the **fea_model** which possesses the explicit element.

description: information about an **explicit_element_representation** purpose.

matrix: the explicit element matrix.

NOTE The element id, a unique application defined identifier of an **element_representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

WR1: there shall be exactly one matrix coordinate system associated with an **explicit_element_representation**.

A matrix coordinate system (FEA_AXIS2_PLACEMENT_3D) is the coordinate system with respect to which all of the matrices of an **explicit_element_representation** are defined. The degrees of freedom

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at a node are defined with respect to the local orthogonal triad of the specified coordinate system at that node.

WR2: the lengths of the degree of freedom list and the required node list shall be the same.

5.7.36 explicit_element_matrix

An **explicit_element_matrix** is stiffness, mass, or damping matrix associated with an **explicit_-element_representation**.

EXPRESS specification:

```
*)
ENTITY explicit_element_matrix;
  property_type             : matrix_property_type;
  symmetry                  : matrix_symmetry;
  node_dof_list             : LIST [1:?] OF LIST [1:?] OF degree_of_freedom;
  matrix_values             : LIST [1:?] OF context_dependent_measure;
WHERE
  WR1: SIZEOF (matrix_values) = number_of_terms (node_dof_list, symmetry);
END_ENTITY;
(*
```

Attribute definitions:

property_type: the type of matrix (stiffness, mass, or damping).

symmetry: the symmetry of the matrix (symmetric or diagonal).

node_dof_list: the degree of freedom at the nodes. The first list shall have the dimension of the number of **explicit_element_representation** nodes, the second list shall have the dimension of the number of freedoms for that node.

matrix_values: the coefficients that define the matrices of the **explicit_element_representation**.

NOTE The matrix is square with freedoms in the sequence specified by the node_dof_list. The number of independent terms in the matrix and their position in the list depends on the attribute **matrix_symmetry**. Refer to the **matrix_symmetry** TYPE for the definitions of how these matrices are populated.

Formal propositions:

WR1: the length of the **matrix_values** list shall be appropriate for the size and symmetry of the matrix.

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5.7.37 substructure_element_representation

A **substructure_element_representation** is a model that may have reduced degrees of freedom and is assembled into another model.

NOTE 1 The connectivity between the substructure nodes and the model is established with the **substructure_node_relationship** entity.

EXPRESS specification:

```
*)
ENTITY substructure_element_representation
  SUBTYPE OF (element_representation);
  model_ref                 : fea_model;
  substructure_model_ref    : fea_model;
UNIQUE
  UR1: model_ref, SELF\representation.name;
END_ENTITY;
(*
```

Attribute definitions:

model_ref: the **fea_model** in which the substructure element is to be assembled.

substructure_model_ref: the **fea_model** that possesses the substructure element.

NOTE 2 The element id, a unique application defined identifier of an **substructure_element_-representation**, is specified by the **name** attribute of the **representation** supertype.

Formal propositions:

UR1: the combination of an **fea_model** and element id shall be unique within a finite element analysis model.

5.8 Structural response representation schema definitions: Element topologies

The relationship between a node and the element geometry is determined by its position in the element node list. This relationship depends on the element shape and order, and is shown below for each element shape and order.

The orientation of the parametric coordinate system has been defined for each type of element. This orientation has the relationship to the nodes referenced from the element node lists as shown in the element node sequence diagrams below. The sequence of vertex nodes has the same relationship to the

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orientation of the parametric coordinate system for each order of a particular element shape, hence for clarity of presentation the orientation of the parametric coordinate system of an element is only shown in the diagram for the linear element of a particular shape. The axes of the element parametric coordinate system are denoted by (ξ,η,ζ). The values of (ξ,η,ζ) shall range from -1.0 to 1.0.

Triangular, wedge, tetrahedron, and pyramid elements are defined with collapsed rectangular coordinate systems. The figures for these elements denote which node is the singularity by specifying the edge of the element to which an axis of the parametric coordinate system is parallel.

The sequence of the nodes in the element node list has been defined for each type of element. In each case the following classes of nodes are in the sequence:

— vertex nodes are required for the definition of the element geometry and shall be specified;

— edge nodes are additional nodes to be specified based on the shape and order of the element;

— face nodes are additional nodes to be specified based on the shape and order of the element;

— body nodes are additional nodes to be specified based on the shape and order of the element.

For each element SUBTYPE, the WHERE rule ensures that the proper number of nodes are supplied.

The element node list shall refer to the nodes in the following order:

— vertex nodes are referenced first in the **node_list** attribute of the **element_representation** entity where the position in the list is the number in the diagram;

— any additional nodes (edge, face or body) are then referenced by the **node_list** attribute where the position in the list is the number in the diagram;

— face and body nodes may be omitted from the node list.

NOTE A **dummy_node** is referenced as a placeholder if an element formulation does not have a mid-edge, mid-face, or mid-volume node shown in the node sequence diagrams in Figures 10 through 39.

The ordering of the element faces and edges is determined by the ordering of the vertex nodes. The element node sequence, face, and edge diagrams follow in Figures 10 through 39:

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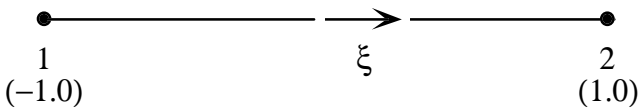

Figure 10 – Curve 3D or surface 2D elements - linear

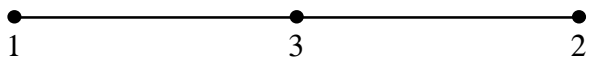

Figure 11 – Curve 3D or surface 2D elements - quadratic

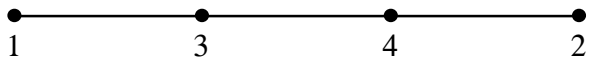

Figure 12 – Curve 3D or surface 2D elements - cubic

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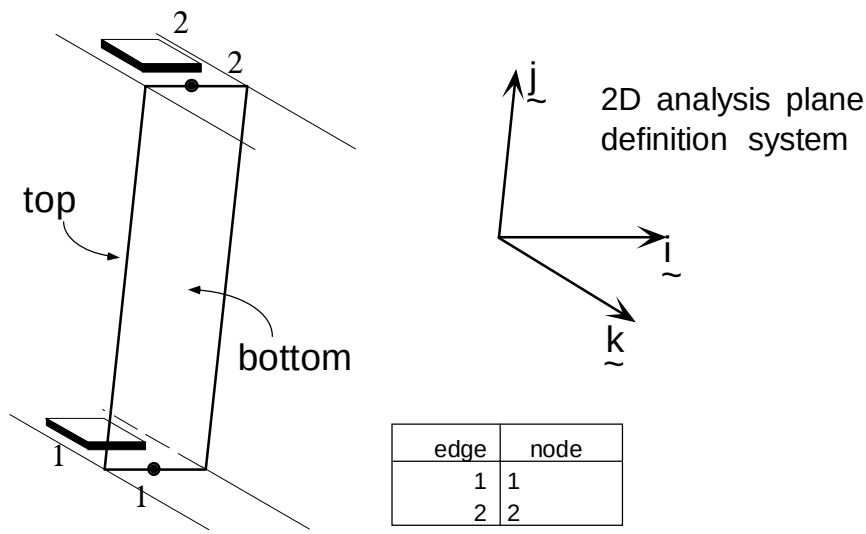

edge	node
1	1
2	2

face	outward normal
top	in the direction of the positive element orthogonal coordinate system z axis.
bottom	in the direction of the negative element orthogonal coordinate system z axis.

Figure 13 – Surface 2D elements - faces and edges

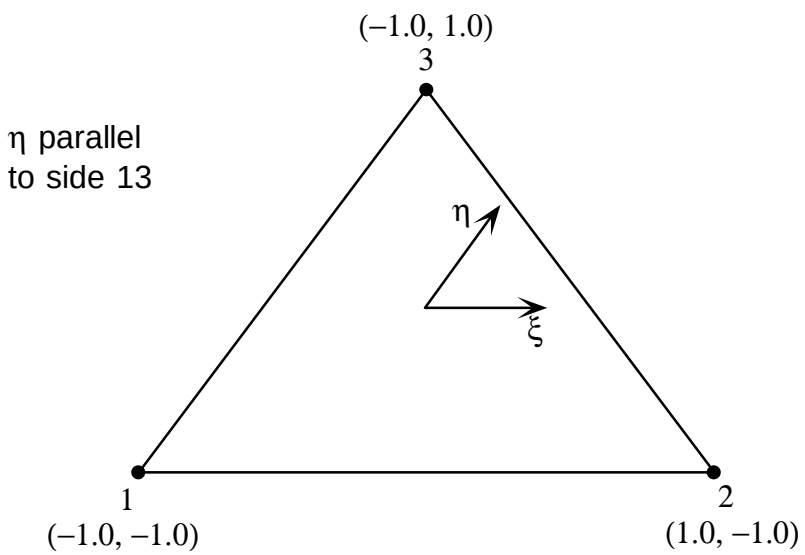

Figure 14 – Surface 3D or volume 2D elements - triangle - linear

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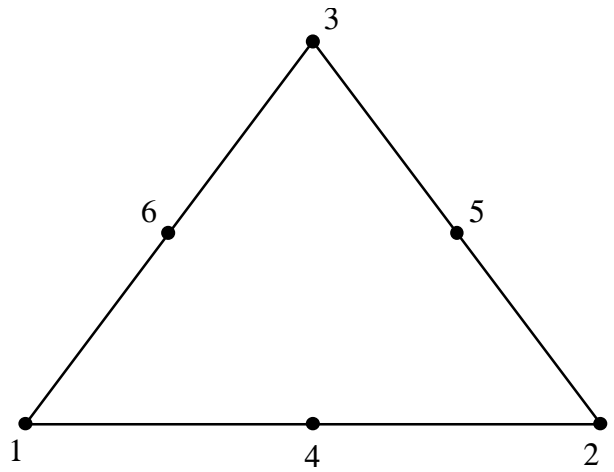

Figure 15 – Surface 3D or volume 2D elements - triangle - quadratic

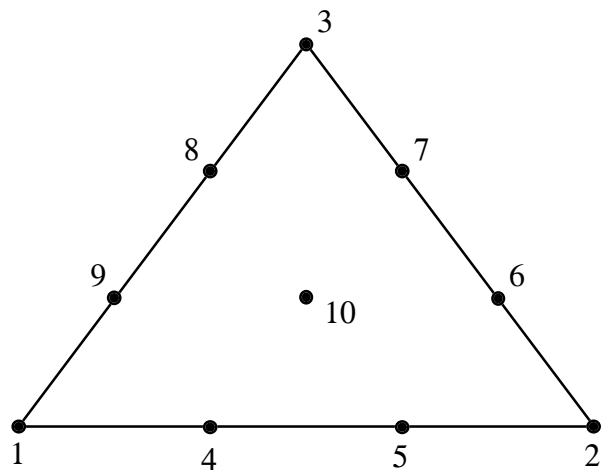

Figure 16 – Surface 3D or volume 2D elements - triangle - cubic

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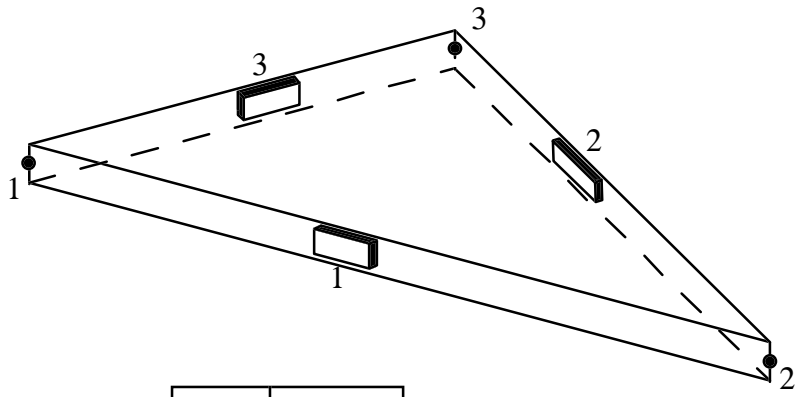
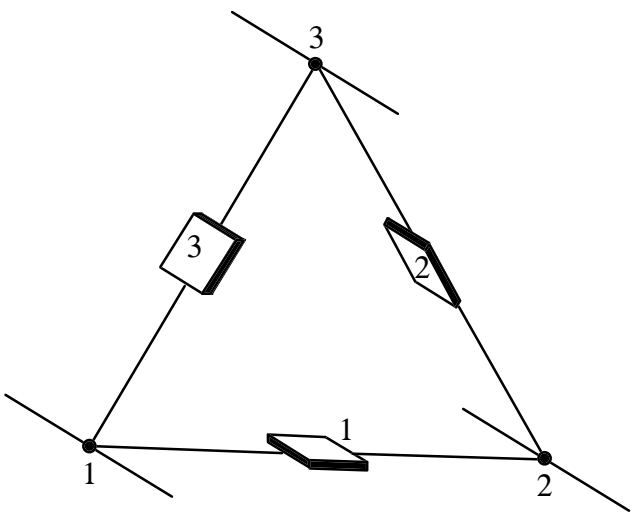


edge	nodes
1	1 2
2	2 3
3	3 1

face	outward normal
top	in the direction of the positive element orthogonal coordinate system z axis.
bottom	in the direction of the negative element orthogonal coordinate system z axis.

Figure 17 – Surface 3D elements - triangle faces and edges



edge	node
1	1
2	2
3	3

face	node
1	1 2
2	2 3
3	3 1

Figure 18 – Volume 2D elements - triangle faces and edges

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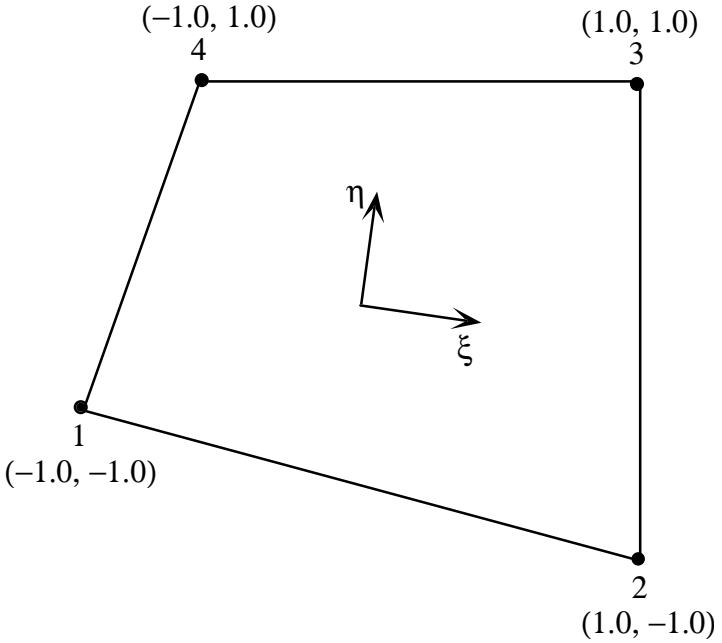

Figure 19 – Surface 3D or volume 2D elements - quadrilateral - linear

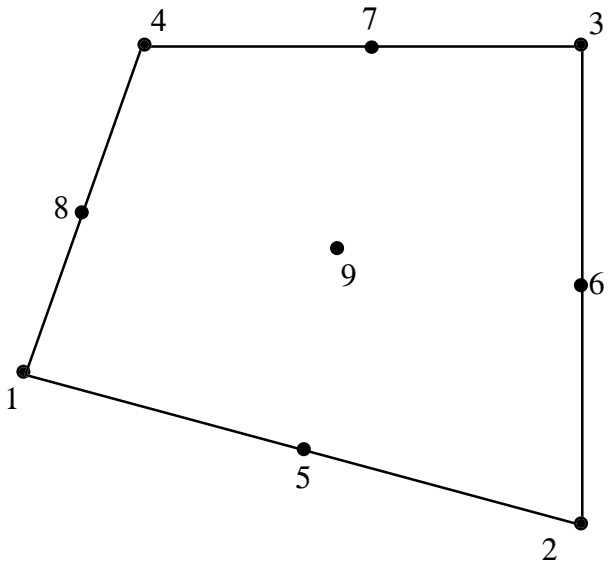

Figure 20 – Surface 3D or volume 2D elements - quadrilateral - quadratic

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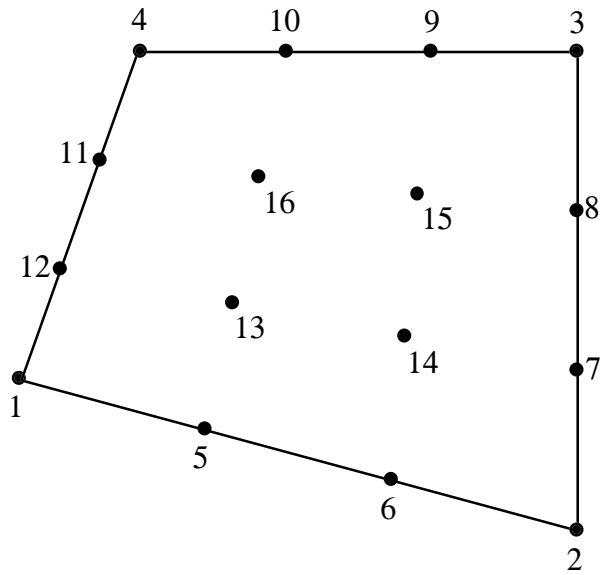
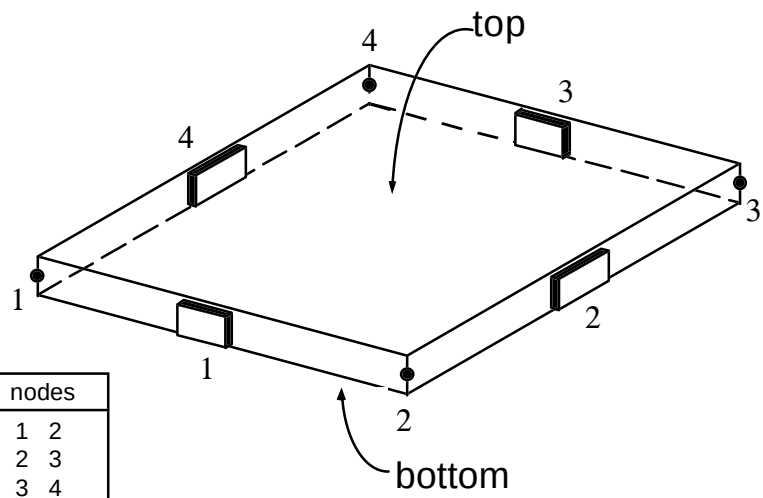


Figure 21 – Surface 3D or volume 2D elements - quadrilateral - cubic



edge	nodes
1	1 2
2	2 3
3	3 4
4	4 1

face	outward normal
top	in the direction of the positive element orthogonal coordinate system z axis.
bottom	in the direction of the negative element orthogonal coordinate system z axis.

Figure 22 – Surface 3D elements - quadrilateral faces and edges

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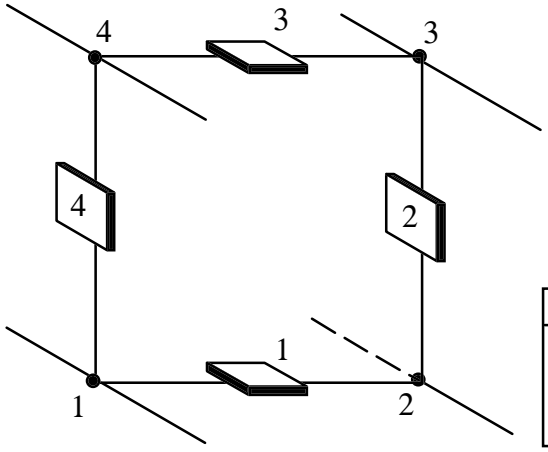

edge	node
1	1
2	2
3	3
4	4

face	nodes
1	1 2
2	2 3
3	3 4
4	4 1

Figure 23 – Volume 2D elements - quadrilateral faces and edges

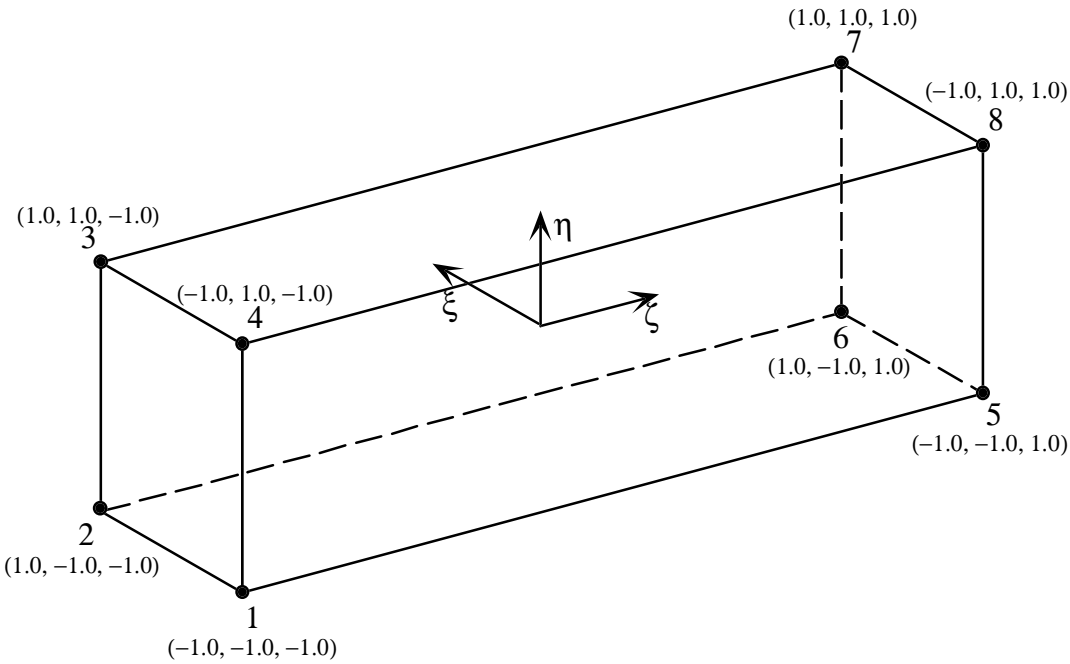

Figure 24 – Volume 3D elements - hexahedron - linear

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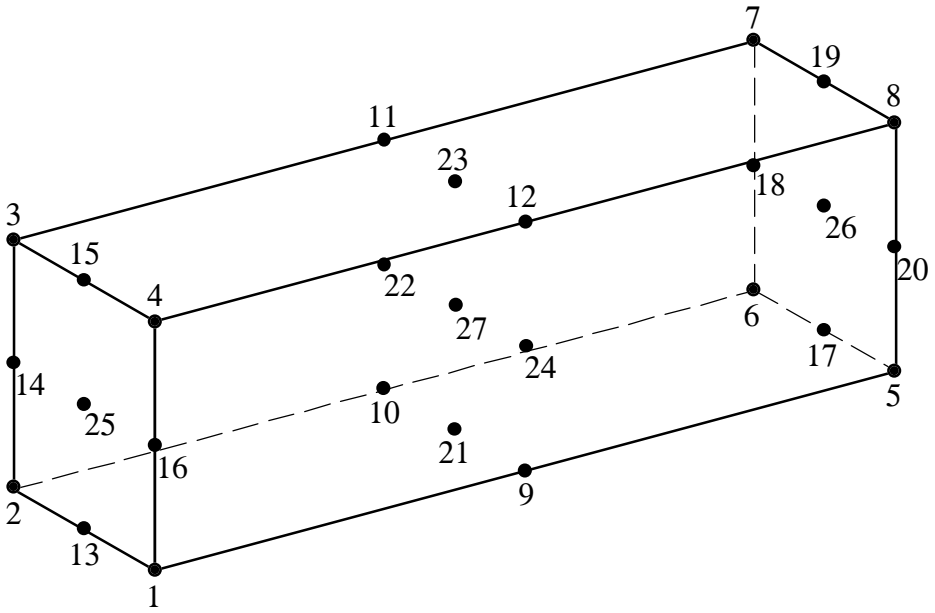

Figure 25 – Volume 3D elements - hexahedron - quadratic

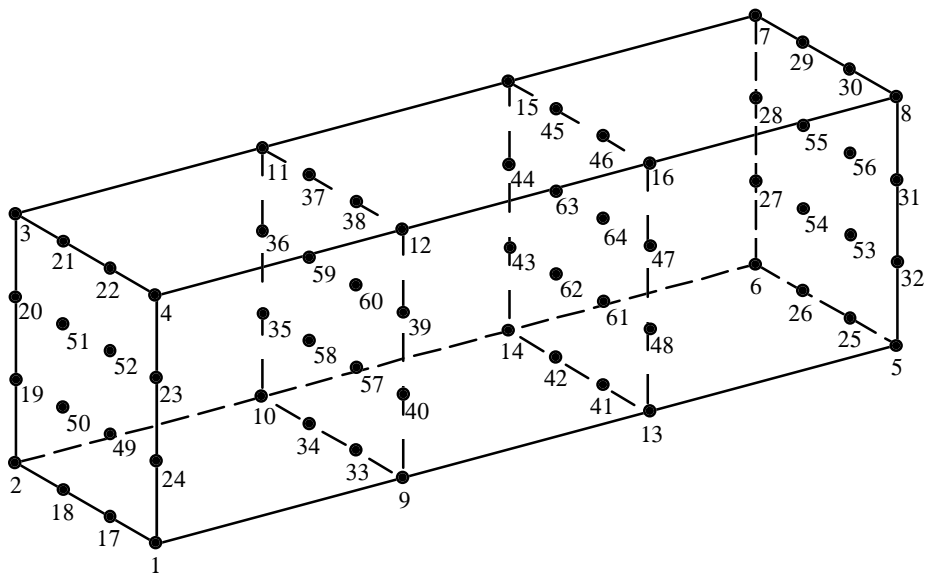

Figure 26 – Volume 3D elements - hexahedron - cubic

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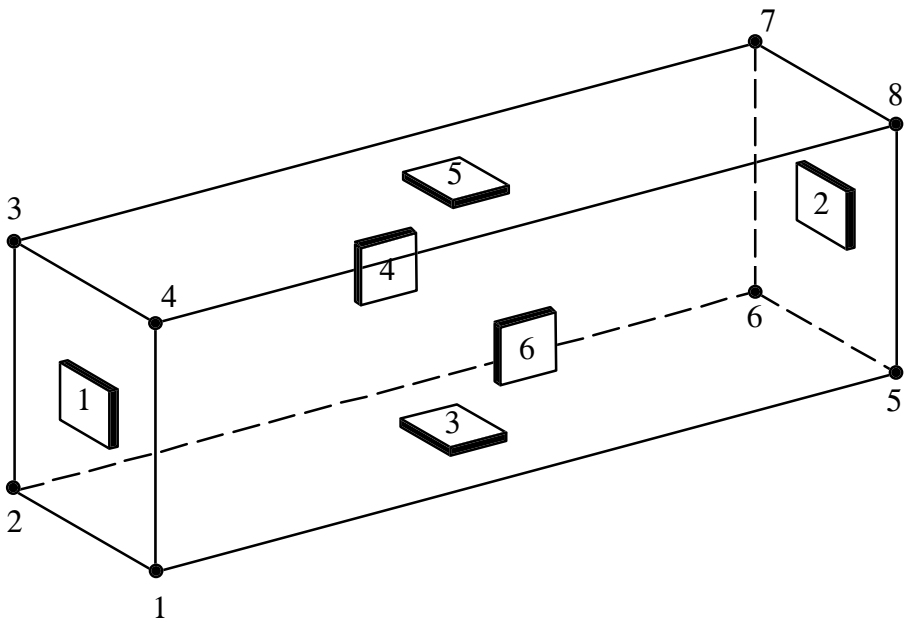

face	nodes
1	1 4 3 2
2	5 6 7 8
3	1 2 6 5
4	3 7 6 2
5	3 4 8 7
6	1 5 8 4

edge	nodes
1	1 2
2	2 3
3	3 4
4	4 1
5	5 6
6	6 7
7	7 8
8	8 5
9	1 5
10	2 6
11	3 7
12	4 8

Figure 27 – Volume 3D elements - hexahedron faces and edges

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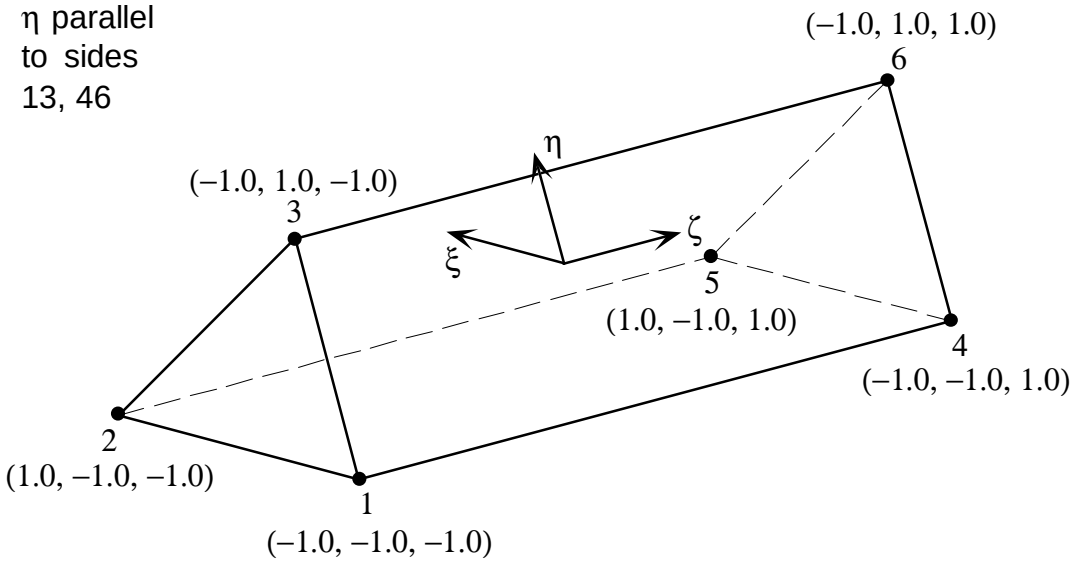

Figure 28 – Volume 3D elements - wedge - linear

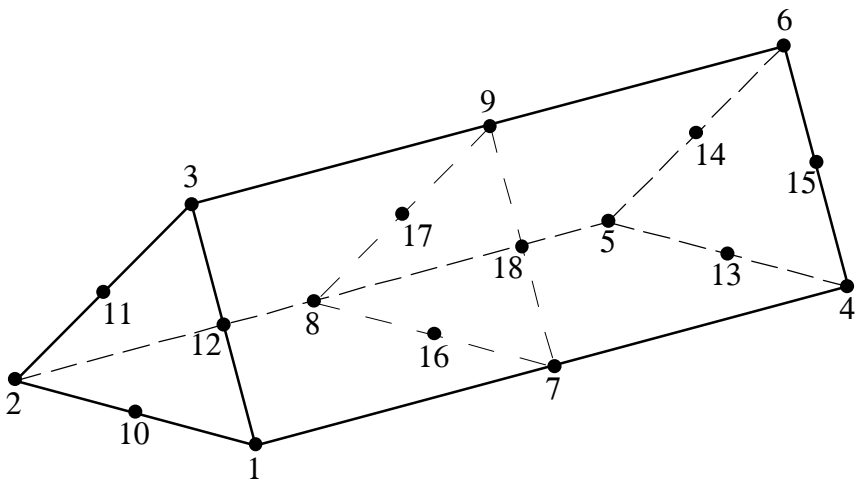

Figure 29 – Volume 3D elements - wedge - quadratic

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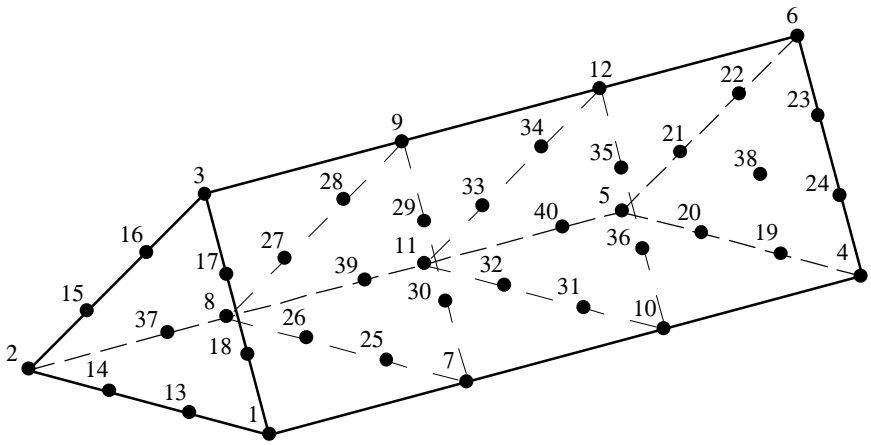
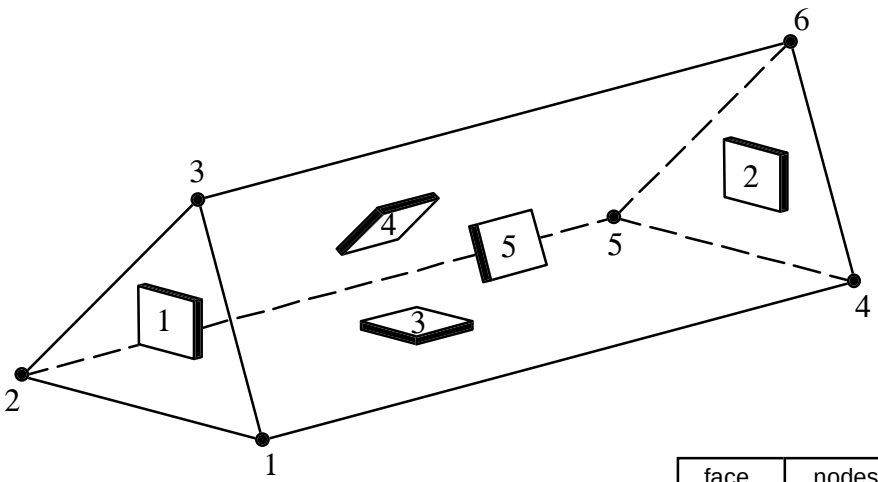


Figure 30 – Volume 3D elements - wedge - cubic



nodes	edge
1	1 2
2	2 3
3	3 1
4	4 5
5	5 6
6	6 4
7	1 4
8	2 5
9	3 6

face	nodes
1	1 3 2
2	4 5 6
3	1 2 5 4
4	2 3 6 5
5	1 4 6 3

Figure 31 – Volume 3D elements - wedge faces and edges

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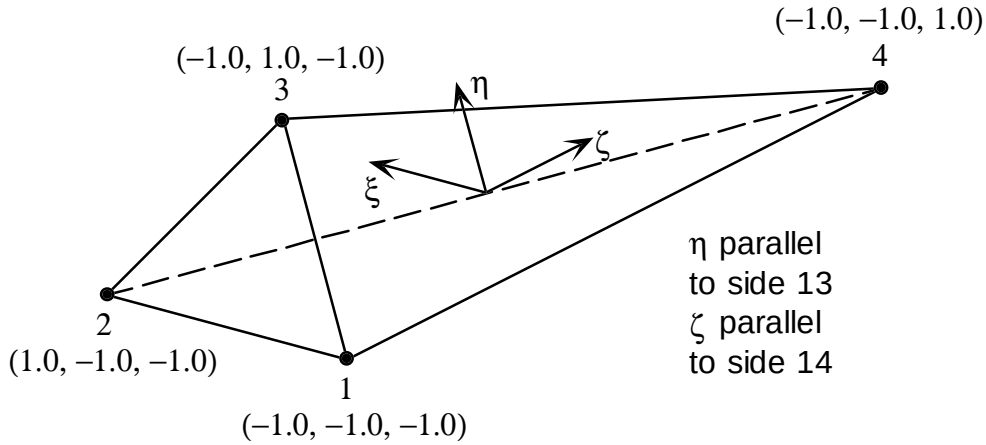

Figure 32 – Volume 3D elements - tetrahedron - linear

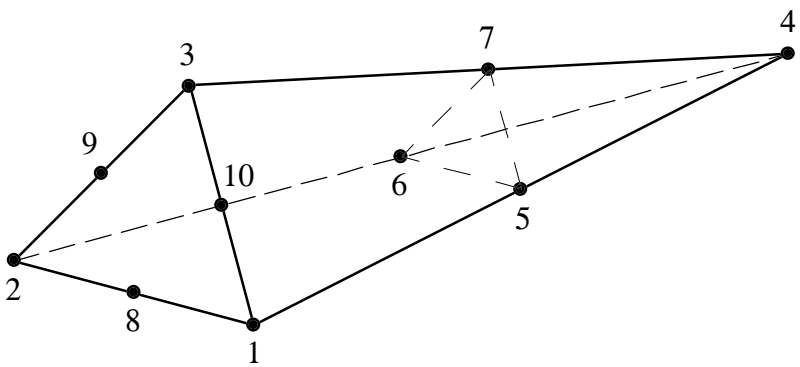

Figure 33 – Volume 3D elements - tetrahedron - quadratic

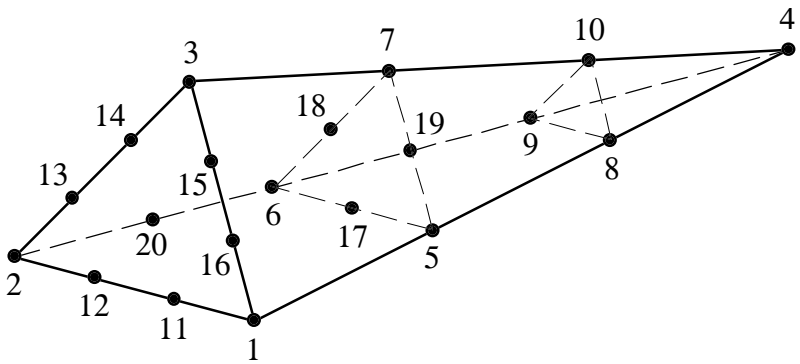

Figure 34 – Volume 3D elements - tetrahedron - cubic

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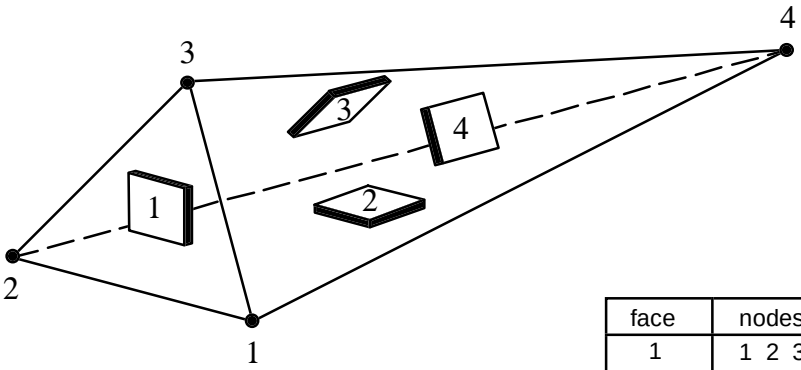

nodes	edge
1	1 2
2	2 3
3	3 1
4	1 4
5	2 4
6	3 4

face	nodes
1	1 2 3
2	1 4 2
3	2 4 3
4	3 4 1

Figure 35 – Volume 3D elements - tetrahedron faces

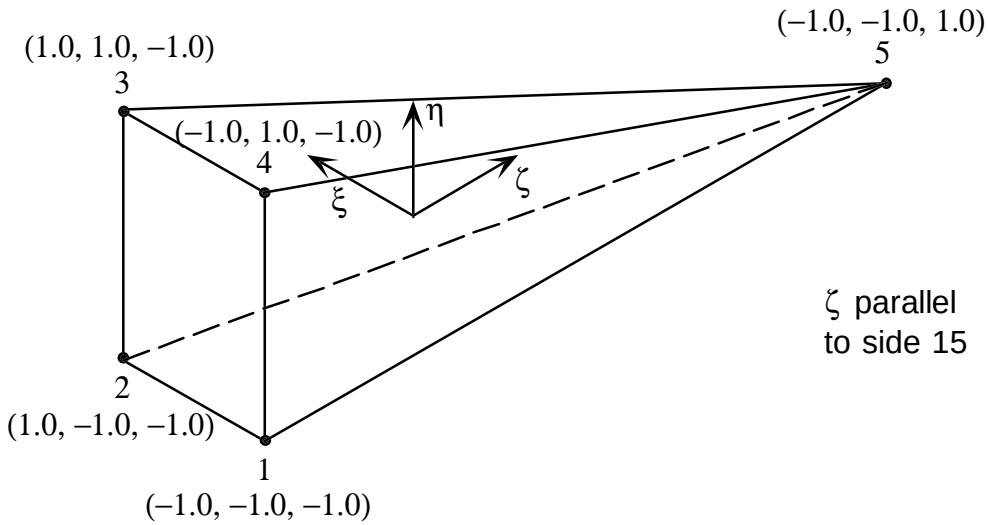

Figure 36 – Volume 3D elements - pyramid - linear

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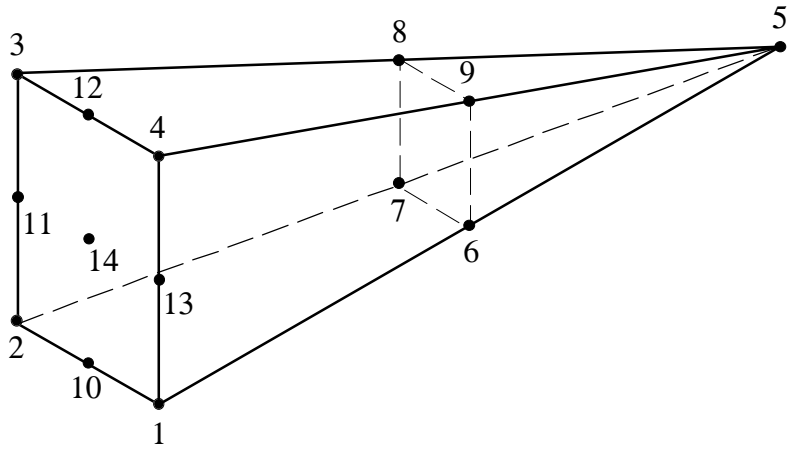

Figure 37 – Volume 3D elements - pyramid - quadratic

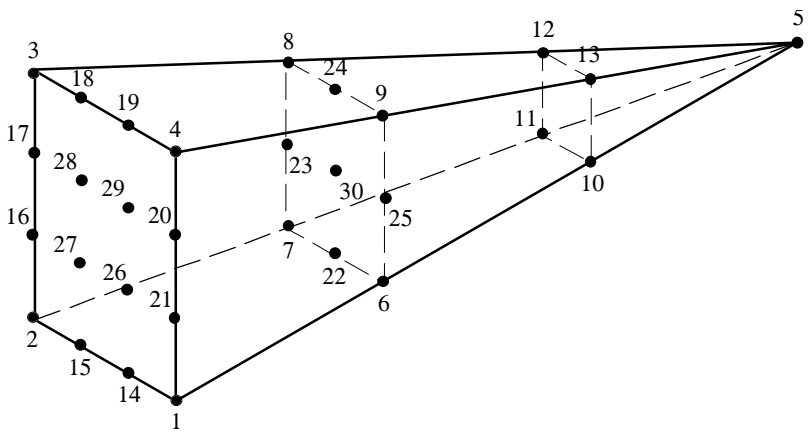

Figure 38 – Volume 3D elements - pyramid - cubic

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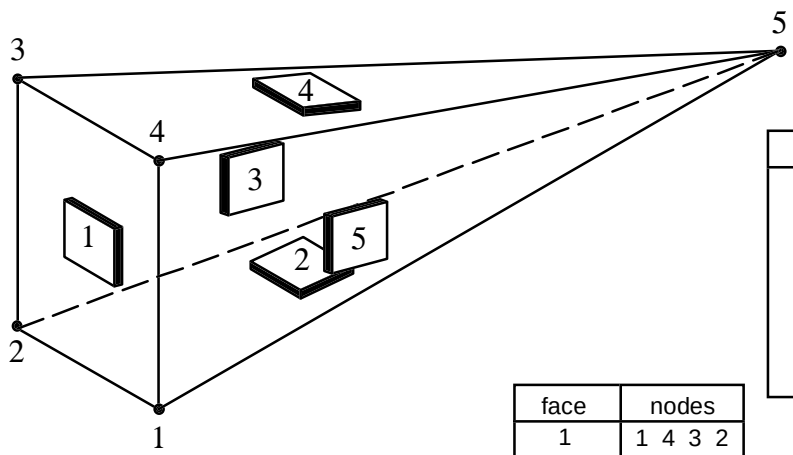

edge	nodes
1	1 2
2	2 3
3	3 4
4	4 1
5	1 5
6	2 5
7	3 5
8	4 5

face	nodes
1	1 4 3 2
2	1 2 5
3	2 3 5
4	3 4 5
5	4 1 5

Figure 39 – Volume 3D elements - pyramid faces and edges

5.9 Structural response representation schema entity definitions: Element coordinate systems

The coordinate systems that are used for element information fall into three different categories:

— an arbitrary placement coordinate system that is defined without reference to the geometry of the element. Such a system can be used to orient property information associated with a volume 3D element.

— an aligned orthogonal system in which the orientation of the axes for a surface or curve element coordinate system at each point in the element is partly defined by the element geometry;

— a parametric coordinate system whereby each point within an element is derived from the orientation of the parametric axes for the element at that point. The parametric axes are not necessarily orthogonal. Such a system can be used when a curved surface of orthotropic or anisotropic material is modelled by volume or surface 3D elements.

If a non-cartesian coordinate system is specified for an element then information at a point within an element is defined with respect to the local orthogonal cartesian coordinate system whose axes are coincident to the specified system at that point. An aligned system at a point is also derived from an orthogonal cartesian coordinate system whose axes are coincident to the specified coordinate system and the element geometry at that point.

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Element information may be defined with respect to an orthogonal system of coordinate axes derived from the parametric coordinate system of the element. A parametric coordinate system orientation is established graphically for each element type along with the element node sequence in the figures in 5.8. In this clause only two axes for each orthogonal coordinate system are specified. The third axis is then chosen according to right hand rule to complete the triad. The axes of an orthogonal element coordinate system are denoted (x,y,z). The orthogonal system may be an intermediate orthogonal system, with the element orthogonal system related to the intermediate orthogonal coordinate system by one angle (for surface elements) or three angles (for volume elements).

Finite element information is defined with respect to an orthogonal coordinate system that shall obey the following rules:

— for a surface element, the z axis of the coordinate system is defined to remain normal to the element surface. Hence for a non-planar (curved) element the orientation of the coordinate system varies over the element surface. The z axis of a surface element is normal to the surface in both 2D and 3D analyses.

— for a curve element, the x axis of the coordinate system is defined to be tangential to the curve. Hence for a curved element the orientation of the coordinate system varies along the curve.

5.9.1 aligned_axis_tolerance

An **aligned_axis_tolerance** is a value for the tolerance of the alignment of coordinate systems

EXPRESS specification:

```
*)
ENTITY aligned_axis_tolerance;
  model_ref                 : fea_model;
  tolerance                 : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

model_ref: the model to which the tolerance applies.

tolerance: the value of the alignment tolerance.

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5.9.2 arbitrary_volume_3d_element_coordinate_system

An **arbitrary_volume_3d_element_coordinate_system** is an arbitrary orthogonal coordinate system for a volume 3D element.

EXPRESS specification:

```
*)
ENTITY arbitrary_volume_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  coordinate_system         : fea_axis2_placement_3d;
END_ENTITY;
(*
```

Attribute definitions:

coordinate_system: the coordinate system for the volume 3D element. At a point within the element, information is defined with respect to the local orthogonal coordinate system triad of the specified coordinate system at that point.

5.9.3 parametric_volume_3d_element_coordinate_system

A **parametric_volume_3d_element_coordinate_system** is the orthogonal coordinate system for a volume 3D element. At each point in the element an intermediate orthogonal coordinate system is derived from the parametric coordinate system of an element. Let the triad (ξ,η,ζ) denote the axes of the parametric coordinate system, and ($\mathbf{x}'$,$\mathbf{y}'$,$\mathbf{z}'$) denote the axis of an intermediate orthogonal coordinate system. The orthogonal coordinate system used to define information for the element, denoted ($\mathbf{x}$,$\mathbf{y}$,$\mathbf{z}$), is related to this intermediate orthogonal coordinate system ($\mathbf{x}'$,$\mathbf{y}'$,$\mathbf{z}'$) by Euler angles.

For the purpose of reference by attributes **axis_1** and **axis_2**, let ξ = 1, η = 2 and, ζ = 3. The intermediate orthogonal coordinate system shall be derived from the parametric coordinate system by the various combinations of **axis_1** and **axis_2** as follows:

— **axis_1** = 1 and **axis_2** = 2:

$$\begin{aligned} \mathbf{x}' &= \xi \\ \mathbf{z}' &= \langle \xi \times \eta \rangle \end{aligned}$$

— **axis_1** = 2 and **axis_2** = 3:

$$\begin{aligned} \mathbf{y}' &= \eta \\ \mathbf{x}' &= \langle \eta \times \zeta \rangle \end{aligned}$$

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— **axis_1** = 3 and **axis_2** = 1:

$$\begin{aligned} \mathbf{z}' &= \zeta \\ \mathbf{y}' &= \langle \zeta \times \xi \rangle \end{aligned}$$

— **axis_1** = 1 and **axis_2** = 3:

$$\begin{aligned} \mathbf{x}' &= \xi \\ \mathbf{y}' &= \langle \zeta \times \xi \rangle \end{aligned}$$

— **axis_1** = 2 and **axis_2** = 1:

$$\begin{aligned} \mathbf{y}' &= \eta \\ \mathbf{z}' &= \langle \xi \times \eta \rangle \end{aligned}$$

— **axis_1** = 3 and **axis_2** = 2:

$$\begin{aligned} \mathbf{z}' &= \zeta \\ \mathbf{x}' &= \langle \eta \times \zeta \rangle \end{aligned}$$

The derivation of an orthogonal coordinate system for **axis_1** = 1 and **axis_2** = 2 is shown in Figure 40 for a linear hexahedron element. Here, the $(\mathbf{x},\mathbf{y},\mathbf{z})$ system is not rotated from the $(\mathbf{x}',\mathbf{y}',\mathbf{z}')$ system and is therefore coincident. The $\mathbf{z}$ and $\mathbf{z}'$ axes are perpendicular to the $\xi\eta$ plane. The $\mathbf{y}$ and $\mathbf{y}'$ axes are perpendicular to the $\mathbf{x}'\mathbf{z}'$ and $\mathbf{x}\mathbf{z}$ planes, positive right-hand rule.

EXPRESS specification:

```
*)
ENTITY parametric_volume_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  axis_1                    : INTEGER;
  axis_2                    : INTEGER;
  eu_angles                 : euler_angles;
WHERE
  WR1:  (axis_1 >= 1) AND (axis_1 <= 3) AND
        (axis_2 >= 1) AND (axis_2 <= 3) AND
        NOT (axis_1 = axis_2);
END_ENTITY;
(*
```

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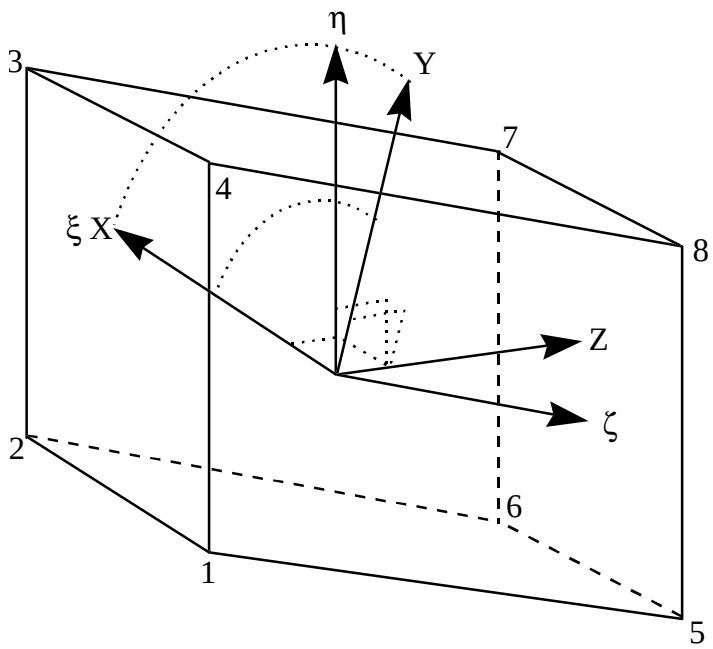

Figure 40 – Orthogonal volume 3D element coordinate system derivation for axis_1 = 1 and axis_2 = 2

Attribute definitions:

axis_1: the first parametric axis used to derive the orthogonal coordinate system.

axis_2: the second parametric axis used to derive the orthogonal coordinate system.

eu_angles: three Euler angles that define the orthogonal element coordinate system (x,y,z) with respect to (x′,y′,z′).

Formal propositions:

WR1: the two defining axes of the coordinate system shall be 1, 2, or 3, and they shall not be the same.

5.9.4 arbitrary_volume_2d_element_coordinate_system

An **arbitrary_volume_2d_element_coordinate_system** specifies an arbitrary orthogonal coordinate system for a volume 2D element, for which the x axis shall be normal to the 2D analysis plane and in the direction of the k axis of the 2D analysis plane definition coordinate system.

The orientation of the coordinate systems is shown in Figure 41. The j axis is the axis of symmetry, and the ij plane is the 2D analysis plane. The yz plane is coincident with the ij plane. The y axis is oriented by the vector **direction**.

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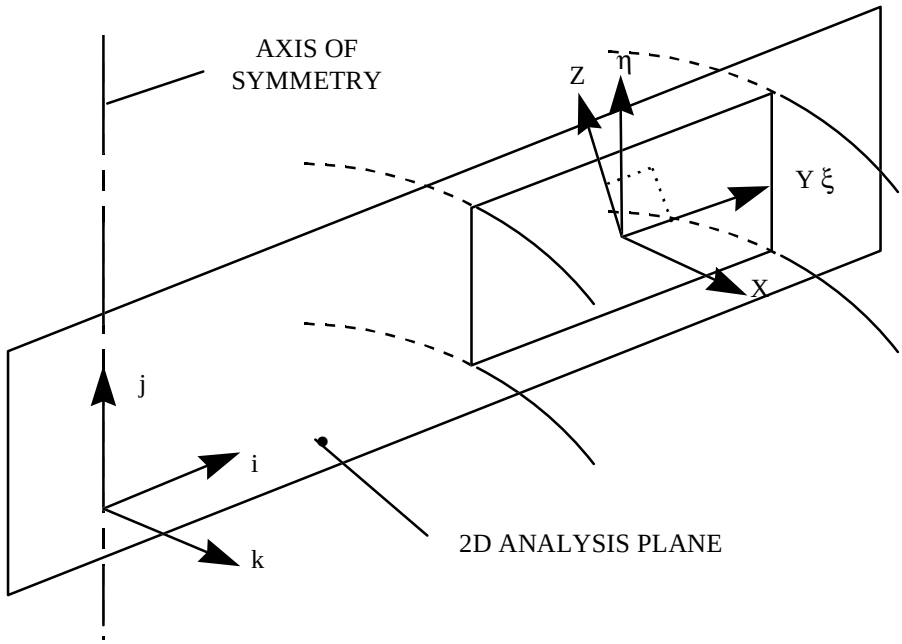

Figure 41 – Arbitrary volume 2D element coordinate system orientation

EXPRESS specification:

```
*)
ENTITY arbitrary_volume_2d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  orientation               : direction;
WHERE
  WR1: SELF\geometric_representation_item.dim=2;
END_ENTITY;
(*
```

Attribute definitions:

orientation: the direction used to orient the orthogonal coordinate system at each point within the element.

Formal propositions:

WR1: the space dimensionality of the direction shall be 2.

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5.9.5 parametric_volume_2d_element_coordinate_system

A **parametric_volume_2d_element_coordinate_system** is an orthogonal coordinate system for a volume 2D element. An intermediate orthogonal coordinate system $(\mathbf{x}',\mathbf{y}',\mathbf{z}')$ is derived from the parametric coordinate system (ξ,η) of an element. The $\mathbf{z}'$ axis of the intermediate orthogonal coordinate system is normal to the 2D analysis plane and in the direction of the $\mathbf{k}$ axis of the 2D analysis plane definition coordinate system. An axis of the intermediate orthogonal coordinate system in the 2D analysis plane shall be derived according to the **axis** attribute as follows:

— for **axis** = 1 the $\mathbf{y}'$ axis of the intermediate orthogonal system is on the same direction as the axis ξ of the parametric coordinate system;

— for **axis** = 2 the $\mathbf{z}'$ axis of the intermediate orthogonal system is in the same direction as the axis η of the parametric system.

The orthogonal coordinate system defined for the element, denoted $(\mathbf{x},\mathbf{y},\mathbf{z})$ is related to the intermediate orthogonal system $(\mathbf{x}',\mathbf{y}',\mathbf{z}')$ by an angle.

The derivation of an orthogonal coordinate system for axis = 1 is shown in Figure 42. Here, the $(\mathbf{x},\mathbf{y},\mathbf{z})$ system is not rotated from the $(\mathbf{x}',\mathbf{y}',\mathbf{z}')$ system and is therefore coincident. The $\mathbf{x}$ and $\mathbf{x}'$ axes are perpendicular to the $\xi\eta$ plane. The $\mathbf{z}$ and $\mathbf{z}'$ axes are perpendicular to the $\mathbf{x}'\mathbf{y}'$ and $\mathbf{xy}$ planes, positive right-hand rule.

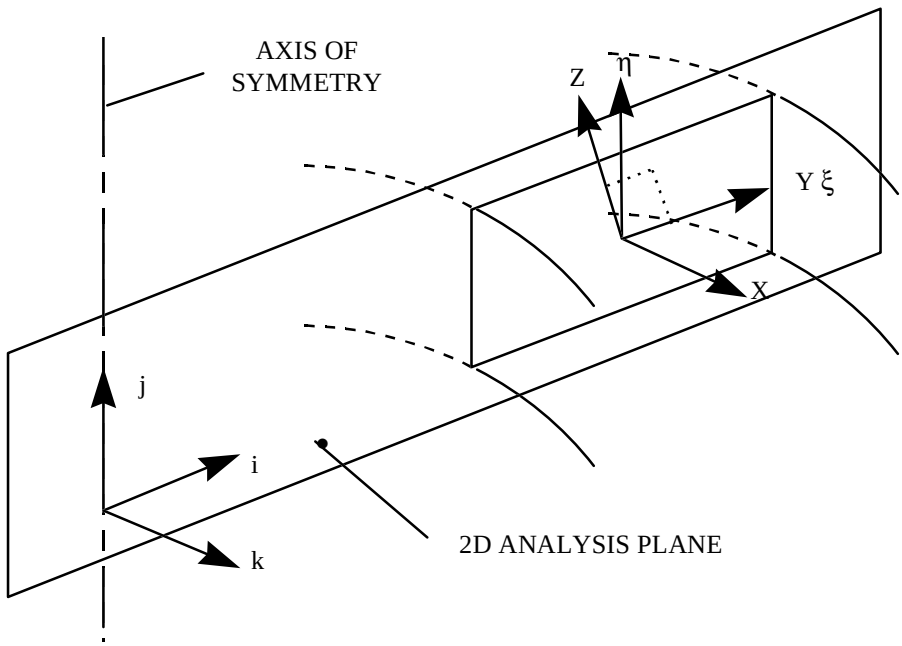

Figure 42 – Parametric volume 2D element coordinate system derivation for axis = 1

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EXPRESS specification:

```
*)
ENTITY parametric_volume_2d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  axis                      : INTEGER;
  angle                     : plane_angle_measure;
WHERE
  WR1:  (axis >= 1) AND (axis <= 2);
END_ENTITY;
(*
```

Attribute definitions:

axis: the axis of the parametric and intermediate coordinate systems that are aligned.

angle: the angle from the $\mathbf{x}'$ to the $\mathbf{x}$ axis measured in a positive sense about the $\mathbf{z}'$ axis.

Formal propositions:

WR1: the defining axis of the coordinate system shall be either 1 or 2.

5.9.6 aligned_surface_3d_element_coordinate_system

An **aligned_surface_3d_element_coordinate_system** is an aligned orthogonal coordinate system for a surface 3D element that is derived from the local orthogonal triad of the specified arbitrary coordinate system and the normal to the surface of an element. Let the triad ($\mathbf{x}$,$\mathbf{y}$,$\mathbf{z}$) denote the axes of the aligned orthogonal system, and let ($\mathbf{X}$,$\mathbf{Y}$,$\mathbf{Z}$) denote the local orthogonal triad of the specified arbitrary system. At each point in the element the $\mathbf{z}$ axis of the aligned orthogonal system shall be normal to the surface of an element such that:

$$\mathbf{z} \cdot \mathbf{Z} > \mathbf{0}$$

The $\mathbf{y}$ axis of the aligned orthogonal system is such that:

$$\mathbf{y} = \langle \mathbf{z} \times \mathbf{X} \rangle$$

Hence the $\mathbf{X}$ axis is projected on the surface of the element to form the $\mathbf{x}$ axis of the aligned orthogonal system. It is important that the aligned orthogonal coordinate system be well conditioned. To ensure this $\mathbf{Z}$ shall be specified such that:

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$$\mathbf{z} \cdot \mathbf{Z} > \mathbf{tolerance}\,|\mathbf{z}|\,|\mathbf{Z}|$$

where the tolerance is specified by an **aligned_axis_tolerance** entity for the model.

The derivation of a surface 3D element aligned orthogonal coordinate system from an arbitrary coordinate system is shown in Figure 43.

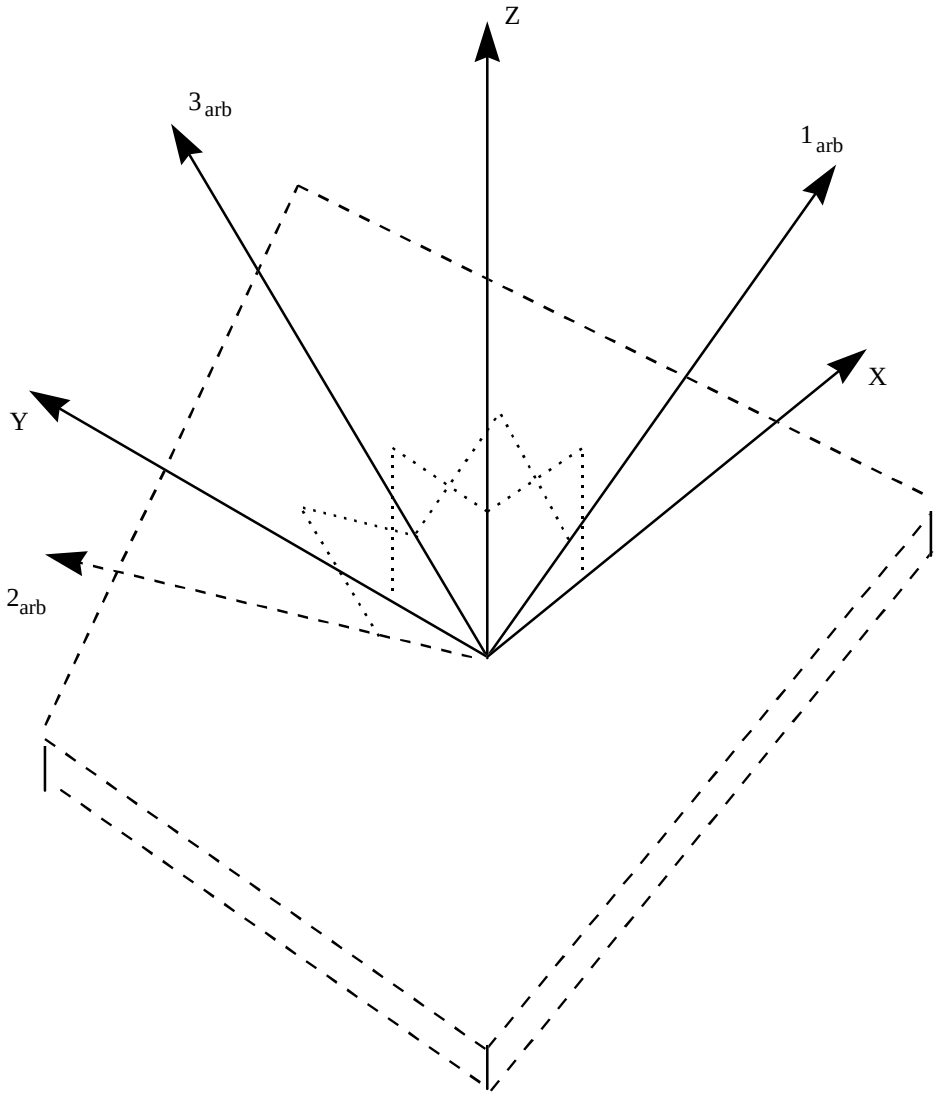

Figure 43 – Aligned surface 3D element coordinate system derivation

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EXPRESS specification:

```
*)
ENTITY aligned_surface_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  coordinate_system         : fea_axis2_placement_3d;
END_ENTITY;
(*
```

Attribute definitions:

coordinate_system: the coordinate system for the element.

5.9.7 parametric_surface_3d_element_coordinate_system

A **parametric_surface_3d_element_coordinate_system** is an orthogonal coordinate system for a surface 3D element. An intermediate orthogonal coordinate system (ξ,η,ζ) at any point on the element is derived from the parametric coordinate system. This intermediate orthogonal system shall be derived from the parametric system according to the value of **axis** attribute as follows:

— for **axis** = 1 the $\mathbf{x}'$ axis of the intermediate orthogonal system is in the same direction as the axis ξ of the parametric coordinate system;

— for **axis** = 2 the $\mathbf{y}'$ axis of the intermediate orthogonal system is in the same direction as the axis η of the parametric coordinate system.

The $\mathbf{z}'$ intermediate orthogonal axis shall be normal to the surface in the direction of the ζ parametric coordinate system axis. The orthogonal coordinate system defined for the element, denoted ($\mathbf{x}$,$\mathbf{y}$,$\mathbf{z}$) is related to the intermediate orthogonal coordinate system ($\mathbf{x}'$,$\mathbf{y}'$,$\mathbf{z}'$) by the **angle** attribute.

The derivation of an orthogonal coordinate system for axis = 1 is shown in Figure 44. Here, the ($\mathbf{x}$,$\mathbf{y}$,$\mathbf{z}$) system is not rotated from the ($\mathbf{x}'$,$\mathbf{y}'$,$\mathbf{z}'$) system and is therefore coincident. The $\mathbf{z}$ and $\mathbf{z}'$ axes are perpendicular to the $\xi\eta$ plane. The $\mathbf{y}$ and $\mathbf{y}'$ axes are perpendicular to the $\mathbf{x}'\mathbf{z}'$ and $\mathbf{xz}$ planes, positive right-hand rule.

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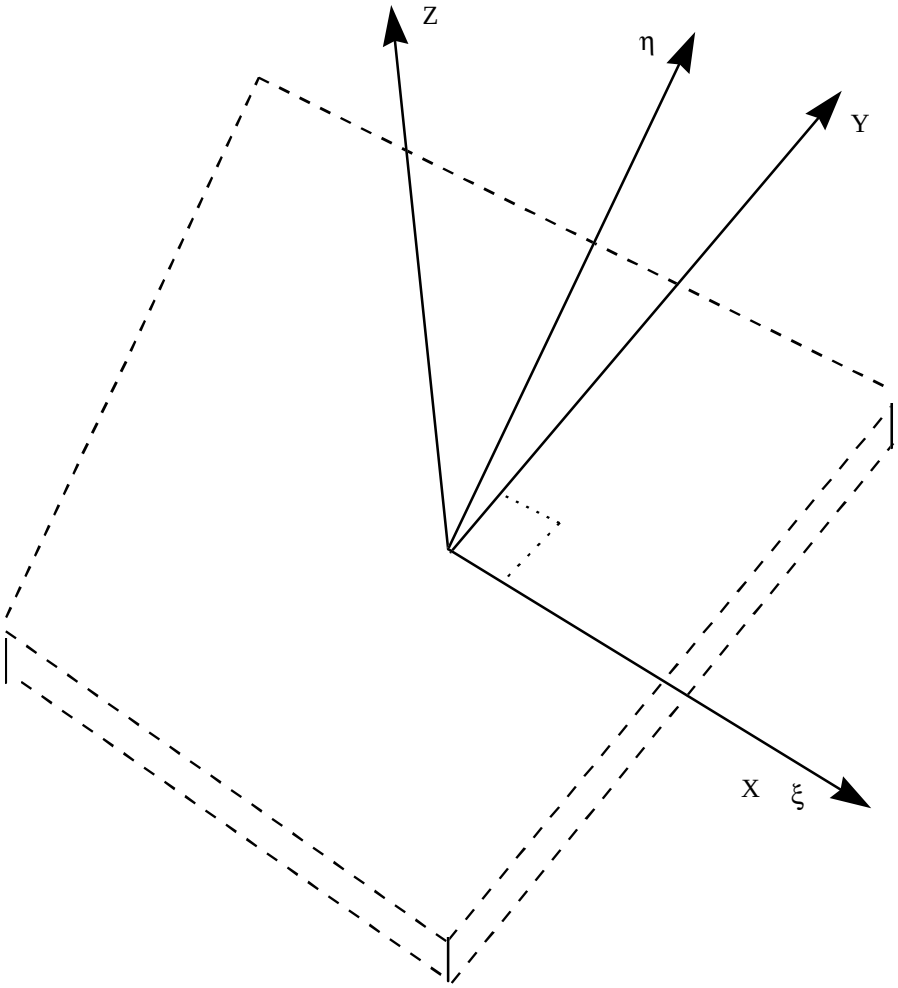

Figure 44 – Parametric surface 3D element coordinate system derivation for axis = 1

EXPRESS specification:

```
*)
ENTITY parametric_surface_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  axis                      : INTEGER;
  angle                     : plane_angle_measure;
WHERE
  WR1:  (axis >= 1) AND (axis <= 2);
END_ENTITY;
(*
```

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Attribute definitions:

axis: the axis of the parametric and intermediate orthogonal coordinate systems that are aligned.

angle: the angle from the x' to the x axis measured in a positive sense about the z' axis.

Formal propositions:

WR1: the defining axis of the coordinate system shall be either 1 or 2.

5.9.8 constant_surface_3d_element_coordinate_system

A **constant_surface_3d_element_coordinate_system** is an aligned orthogonal coordinate system for a surface 3D element, and is defined for each point on the surface as follows:

— an intermediate orthogonal coordinate system is derived from the parametric coordinate system at the centroid of the element in the way specified for the **parametric_surface_3d_element_-coordinate_system**;

— an aligned orthogonal coordinate system is derived from this intermediate orthogonal system in the way specified for entity **aligned_surface_3d_element_coordinate_system**.

EXPRESS specification:

```
*)
ENTITY constant_surface_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  axis                      : INTEGER;
  angle                     : plane_angle_measure;
WHERE
  WR1:  (axis >= 1) AND (axis <= 2);
END_ENTITY;
(*
```

Attribute definitions:

axis: the axis of the parametric and intermediate orthogonal coordinate systems that are aligned.

angle: the angle from the x' to the x axis measured in a positive sense about the z' axis.

Formal propositions:

WR1: the defining axis of the coordinate system shall be either 1 or 2.

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5.9.9 aligned_surface_2d_element_coordinate_system

An **aligned_surface_2d_element_coordinate_system** is an aligned orthogonal coordinate system for a surface 2D element.

For the **aligned_surface_2d_element_coordinate_system** the $\mathbf{x}$ axis shall be normal to the 2D analysis plane and in the direction of the $\mathbf{k}$ axis of the 2D analysis plane. At each point in the element the $\mathbf{z}$ axis of the aligned orthogonal coordinate system shall be normal to the surface of an element in the $\mathbf{z} > \mathbf{0}$ direction, and $\mathbf{y} = \mathbf{z} \times \mathbf{x}$ such that:

$$\mathbf{z} \cdot \mathbf{d} > \mathbf{0}$$

where $\mathbf{d}$ is the specified direction.

It is important that the aligned orthogonal coordinate system be well conditioned. To ensure this, $\mathbf{d}$ shall be specified such that:

$$\mathbf{d} \cdot \mathbf{x} > \mathbf{tolerance}\,|\mathbf{d}|\,|\mathbf{x}|$$

where the tolerance is specified by an **aligned_axis_tolerance** entity for the model.

The derivation of a surface 2D element aligned coordinate system is shown in Figure 45.

EXPRESS specification:

```
*)
ENTITY aligned_surface_2d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  orientation               : direction;
WHERE
  WR1: SELF\geometric_representation_item.dim=2;
END_ENTITY;
(*
```

Attribute definitions:

orientation: the direction used to orient the orthogonal coordinate system at each point within the element.

Formal propositions:

WR1: the space dimensionality of the direction shall be 2.

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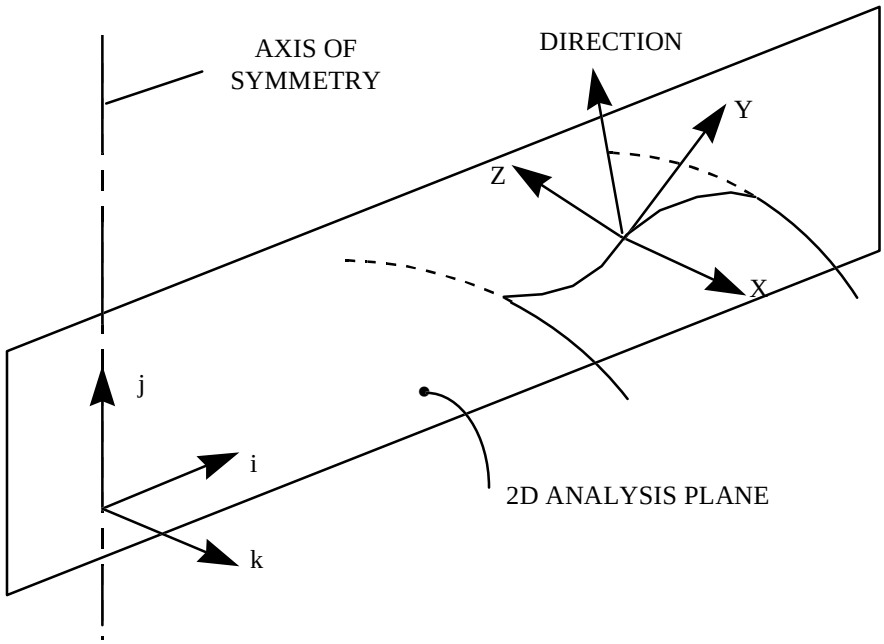

Figure 45 – Aligned surface 2D element coordinate system derivation

5.9.10 parametric_surface_2d_element_coordinate_system

A **parametric_surface_2d_element_coordinate_system** is an orthogonal coordinate system for a surface 2D element. The $\mathbf{y}$ orthogonal axis shall be in the direction of the parametric axis ξ. The $\mathbf{x}$ orthogonal axis is normal to the 2D analysis plane and in the direction of the $\mathbf{k}$ axis of the 2D analysis plane definition system. The derivation of an orthogonal coordinate system is shown in Figure 46.

EXPRESS specification:

```
*)
ENTITY parametric_surface_2d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
END_ENTITY;
(*
```

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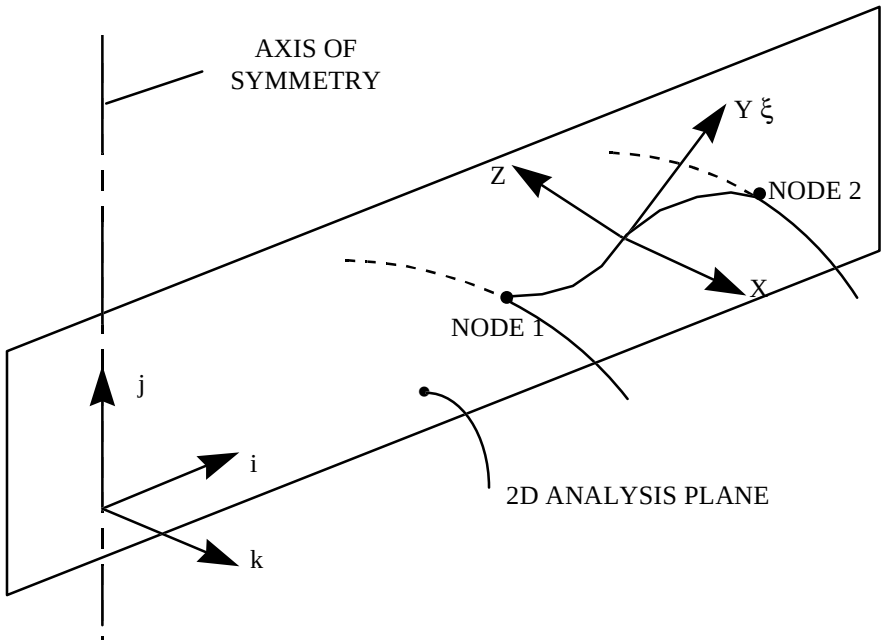

Figure 46 – Parametric surface 2D element coordinate system derivation

5.9.11 aligned_curve_3d_element_coordinate_system

An **aligned_curve_3d_element_coordinate_system** is an aligned orthogonal coordinate system for a curve 3D element. Let the triad $(\mathbf{x},\mathbf{y},\mathbf{z})$ denote the axes of the aligned orthogonal system and let $(\mathbf{X},\mathbf{Y},\mathbf{Z})$ denote the local orthogonal triad of the specified arbitrary system. At each point in the element the $\mathbf{x}$ axis is tangential to the curve such that:

$$\mathbf{x} \cdot \mathbf{X} > \mathbf{0}$$

The $\mathbf{z}$ axis of the aligned orthogonal system is such that:

$$\mathbf{z} = \langle \mathbf{x} \times \mathbf{Y} \rangle$$

The derivation of the aligned orthogonal system needs to be well conditioned. To ensure this $\mathbf{X}$ shall be specified such that:

$$\mathbf{x} \cdot \mathbf{X} > \mathbf{tolerance}\, |\mathbf{x}|\, |\mathbf{X}|$$

where the tolerance is specified by an **aligned_axis_tolerance** entity for the model.

The derivation of a curve 3D element aligned orthogonal coordinate system is shown in Figure 47.

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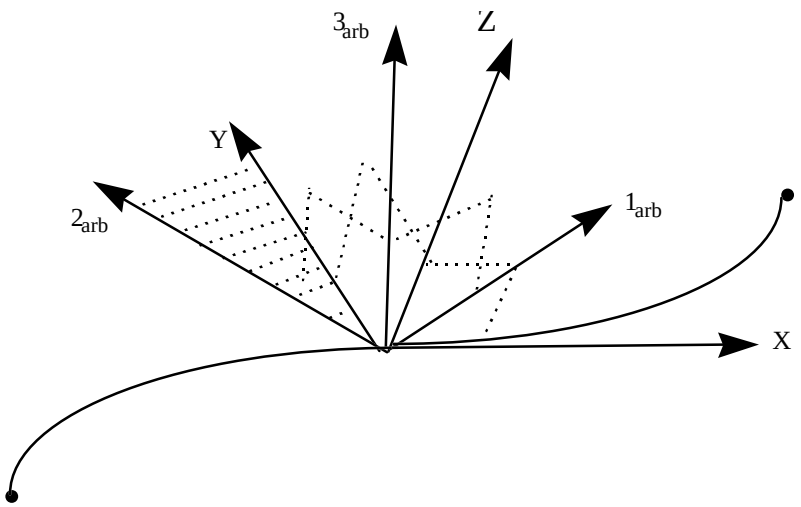

Figure 47 – Aligned curve 3D element coordinate system derivation

EXPRESS specification:

```
*)
ENTITY aligned_curve_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  coordinate_system         : fea_axis2_placement_3d;
END_ENTITY;
(*
```

Attribute definitions:

coordinate_system: the coordinate system for the element.

5.9.12 parametric_curve_3d_element_coordinate_system

A **parametric_curve_3d_element_coordinate_system** is an orthogonal coordinate system that is derived from the parametric coordinate system for a curve 3D element. Let the triad $(\mathbf{x},\mathbf{y},\mathbf{z})$ denote axes of the orthogonal system and let $\mathbf{d}$ denote the specified direction. The $\mathbf{x}$ orthogonal axis is tangential to the curve in the direction of the parametric axis ξ. The $\mathbf{z}$ orthogonal axis is defined such that:

$$\mathbf{z} = \langle \mathbf{x} \times \mathbf{d} \rangle$$

The derivation of the orthogonal system needs to be well conditioned. To ensure this $\mathbf{d}$ shall be specified such that:

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$$\mathbf{y} \cdot \mathbf{d} > \mathbf{tolerance}\,|\mathbf{y}|\,|\mathbf{d}|$$

where the tolerance is specified by an **aligned_axis_tolerance** entity for the model.

The derivation of an orthogonal coordinate system is shown in Figure 48.

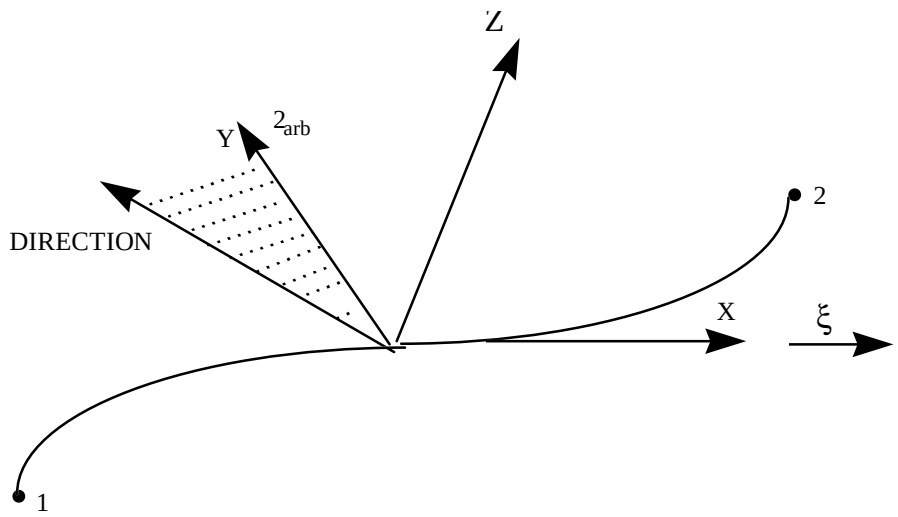

Figure 48 – Parametric curve 3D element coordinate system derivation

EXPRESS specification:

```
*)
ENTITY parametric_curve_3d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  direction            :  parametric_curve_3d_element_coordinate_direction;
END_ENTITY;
(*
```

Attribute definitions:

direction: a direction used to orient the orthogonal coordinate system at each point in the element.

5.9.13 parametric_curve_3d_element_coordinate_direction

A **parametric_curve_3d_element_coordinate_direction** is the parametric direction used to orient the orthogonal 3D coordinate system for a curve 3D element by the use of a direction.

EXPRESS specification:

```
*)
ENTITY parametric_curve_3d_element_coordinate_direction
  SUBTYPE OF (fea_representation_item);
  orientation               : direction;
WHERE
  WR1: SELF\geometric_representation_item.dim=3;
END_ENTITY;
(*
```

Attribute definitions:

orientation: a direction used to orient the orthogonal coordinate system at each point in the element.

Formal propositions:

WR1: the space dimensionality of the direction shall be 3.

5.9.14 curve_2d_element_coordinate_system

A **curve_2d_element_coordinate_system** is an orthogonal coordinate system for a curve 2D element. The x axis is tangential to the curve in the direction of the k axis of the 2D analysis plane. The y axis of the aligned orthogonal system shall be in the specified direction. The derivation of an orthogonal coordinate system is shown in Figure 49.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_coordinate_system
  SUBTYPE OF (fea_representation_item);
  orientation               : direction;
WHERE
  WR1: SELF\geometric_representation_item.dim=2;
END_ENTITY;
(*
```

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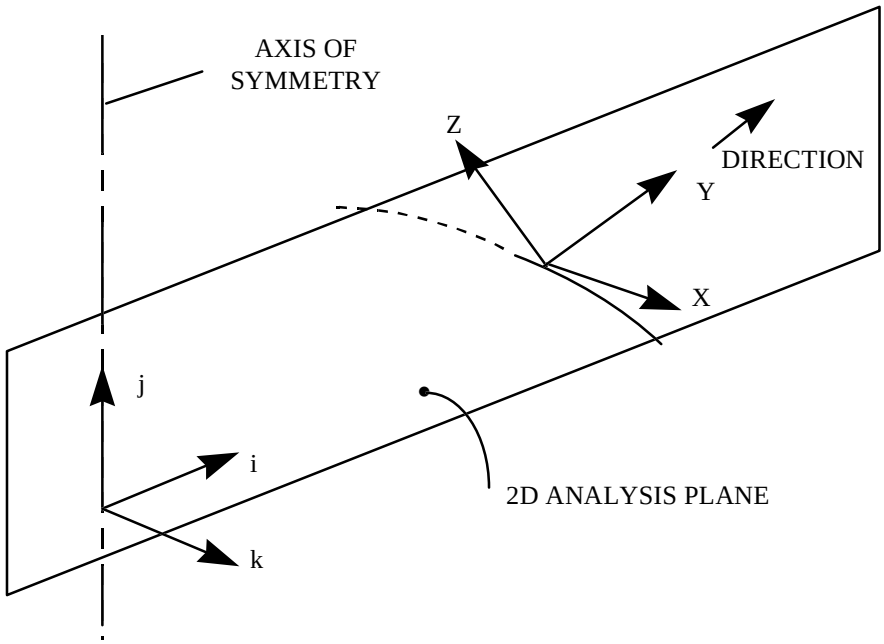

Figure 49 – Curve 2D element coordinate system derivation

Attribute definitions:

orientation: the direction of the **y** axis, which is defined in the 2D analysis plane, used to orient the orthogonal coordinate system at each point in the element.

Formal propositions:

WR1: the space dimensionality of the direction shall be 2.

5.9.15 directionally_explicit_element_coordinate_system_arbitrary

A **directionally_explicit_element_coordinate_system_arbitrary** is an arbitrary orthogonal coordinate system for a directionally explicit element.

EXPRESS specification:

```
*)
ENTITY directionally_explicit_element_coordinate_system_arbitrary
  SUBTYPE OF (fea_representation_item);
  arbitrary_system          : fea_axis2_placement_3d;
END_ENTITY;
(*
```

Attribute definitions:

arbitrary_system: an arbitrary coordinate system. Information is defined with respect to the local orthogonal triad of the specified system. The information is evaluated at the nodes of an element.

5.9.16 directionally_explicit_element_coordinate_system_aligned

A **directionally_explicit_element_coordinate_system_aligned** is an aligned orthogonal coordinate system for orienting a directionally explicit element.

EXPRESS specification:

```
*)
ENTITY directionally_explicit_element_coordinate_system_aligned
  SUBTYPE OF (fea_representation_item);
  aligned_system            : curve_3d_element_coordinate_system;
END_ENTITY;
(*
```

Attribute definitions:

aligned_system: a curve 3D element coordinate system. The information is evaluated at the nodes of an element. A coordinate system is defined for the directionally explicit element as if it were a linear curve element.

5.9.17 euler_angles

An **euler_angles** is used to define a coordinate system relative to a defining coordinate system. Typically the defining coordinate system will be an element coordinate system, and the relative coordinate system used to define anisotropic material directions.

EXPRESS specification:

```
*)
ENTITY euler_angles;
  angles                    : ARRAY [1:3] OF plane_angle_measure;
END_ENTITY;
(*
```

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Attribute definitions:

angles: the relative orientation of a new (rotated) coordinate system with respect to a defining coordinate system using a series of three consecutive rotations. This method is known as Euler angles. The original coordinate system $\mathbf{x1}$, $\mathbf{y1}$, $\mathbf{z1}$ is rotated about the $\mathbf{z1}$ axis over angle angles[1], with the angle positive right hand rule. This yields coordinate system $\mathbf{x2}$, $\mathbf{y2}$, $\mathbf{z2}$. Coordinate system $\mathbf{x2}$, $\mathbf{y2}$, $\mathbf{z2}$ is rotated about the $\mathbf{y2}$ axis over angle angles[2], with the angle positive right hand rule. This yields coordinate system $\mathbf{x3}$, $\mathbf{y3}$, $\mathbf{z3}$. Coordinate system $\mathbf{x3}$, $\mathbf{y3}$, $\mathbf{z3}$ is rotated about the $\mathbf{x3}$ axis over angle angles[3], positive right hand rule. This yields the final coordinate system.

5.10 Structural response representation schema entity definitions: Element matrix integration

A finite element formulation is typically composed of many different matrices, including stiffness, mass, and others. For some of the more complex elements, the stiffness matrix may be partitioned into several matrices. Each of these matrices typically needs to be integrated, mostly over the element area or volume. Many of these matrices are mathematically complex that explicit integration is not feasible, and, therefore, numerical integration techniques are used. For each matrix being integrated, the element integrated matrix definition can specify the interpolation rule for the quantity within the element, and the method of integration of the quantity. An element may have different interpolation rules for different matrices. Diagonal (lumped) matrices are often used for element mass and damping. Such matrices are not treated as a special case, but are specified by numerical integration points at the nodes of an element.

As described in 5.8, a volume, surface or curve element has shape functions for geometric interpolation. The definitions of these shape functions depend on the element type, and in some element formulations, the actual element node coordinates and normals. The element descriptor entity for the particular element type specifies the element shape (such as triangle or quadrilateral), the element order, and a text description that can be used to make the element geometric shape functions definitions precise. All locations within an element are specified using the parametric axes system derived from the element shape functions for geometric interpolation. However, the interpolation of other quantities within an element need not use the same shape functions. Each quantity may have a different interpolation rule that is defined by the shape functions and the element geometry. The element shape function specifies the interpolation order for the quantity and a text description that can be used to make the shape function definitions for the quantity precise.

NOTE 1 For volume, surface, and curve elements it is possible to define an explicit numerical integration by an arbitrary selection of integration points and weights within the volume of the element. This is shown in Figure 50 for volume elements.

However for surface and curve elements it is more common to define field and section integration methods separately where **field integration** is integration over the surface or along the length of an element, and **section integration** is the integration through the thickness of a surface element or over the cross section of a curve element. The separate field and section integration definitions are used even when each point of a numerical field uses the same integration method. For linear analyses, section integrations are usually carried out algebraically; thus only one integration point would be defined through the section.

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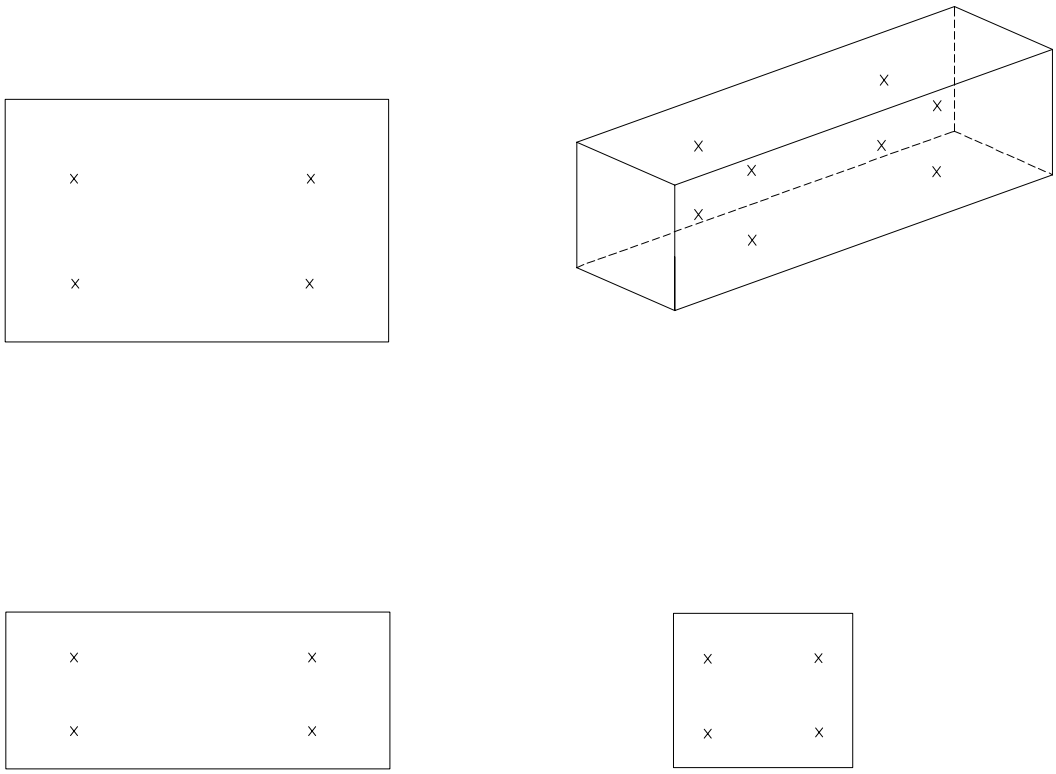

Figure 50 – Volume element integration points

NOTE 2 Figure 51 illustrates the location of integration points in the field of a surface element and through the section (thickness) of the element. The section positions are with respect to the entire section depth, which is the sum of all the plies in a layered material. A series of extent searches needs to be made to correlate integration points with a given ply. See the Fundamental Concepts and Assumptions subclause of this clause for discussion on why this modelling method was selected.

There are three choices of defining the location of an integration point within a volume element.

NOTE 3 The EXPRESS-G Partial Model shown in Figure 52 is presented as an aid in visualising the integration options for volume elements.

The algebraic integration option does not have integration points as this option defines that the integration is done exactly. The rule option defines that an integration rule and integration order is used to integrate the matrix. The explicit option is the most general numerical integration option where the integration positions and weights are explicitly defined. This option is included to avoid having to catalogue all the many types of integration rules. The explicit integration option will form the foundation for the description of analysis output points when that portion of this standard is complete.

EXAMPLE Integration rule includes Gaussian integration and Simpson's rule.

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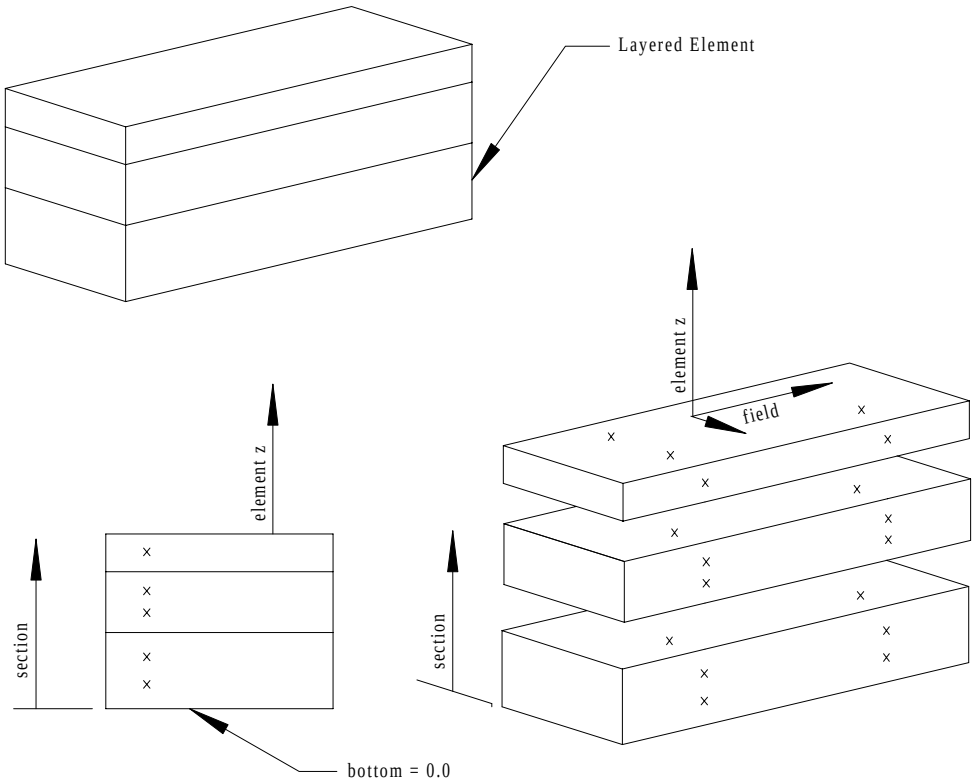

Figure 51 – Surface element integration points

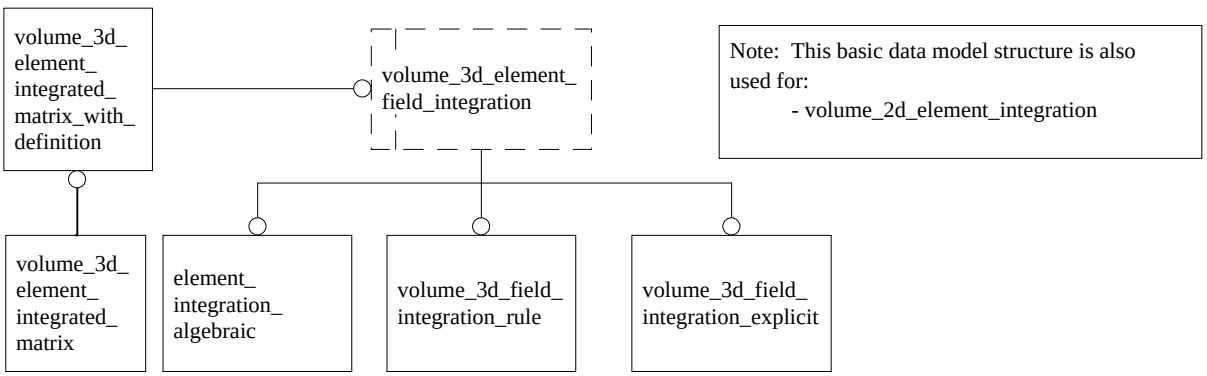

Figure 52 – Volume element integration EXPRESS-G partial model

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The way in which the location of an integration point is defined within a surface or curve element depends on whether surface-section or surface-field integration is being used.

NOTE 4 The curve and surface element integration EXPRESS-G Partial Model is shown in Figure 53 to aid in visualising the integration options available.

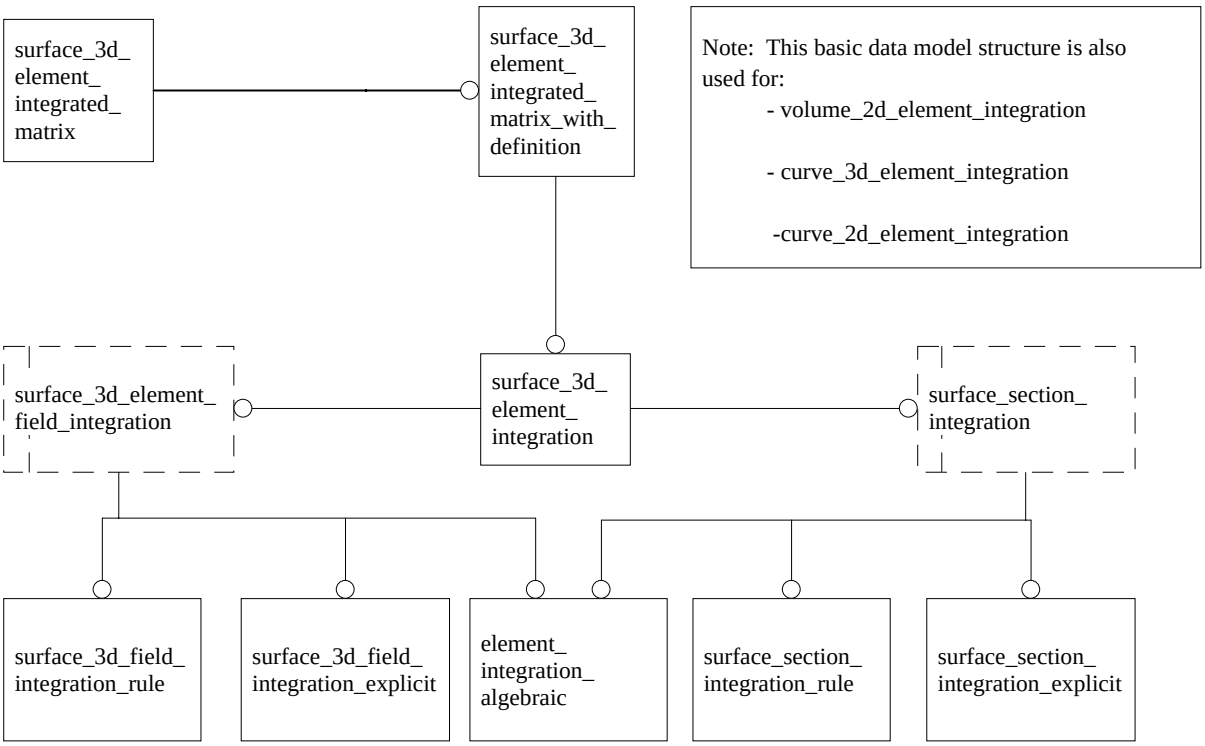

Figure 53 – Surface and curve element integration EXPRESS-G partial model

For surface-section integration there are no integration points within an element as the integration for both surface and section is carried out exactly.

For surface-field integration the location of an integration point within an element is defined by both a field location specified using the element parametric coordinate system and a section location with respect to the element coordinate system. In a surface 3D element a field location has two parametric coordinates, a surface 2D element or curve 3D element has a single parametric coordinate, and a field location is undefined for a 2D curve element. The field integration can be carried out by either algebraic (exact integration), rule or explicit integration options. The definition of these options is identical to that presented in the discussion on volume elements above.

In a surface element a section location is defined by the distance from the reference plane of the element in the direction of the z axis of the surface element property coordinate system. In a curve element a section location is defined by the distances from the reference axis of the element in the y and z directions of the curve element property coordinate system. A section location is defined using physical distances,

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not unit distances. The field and section axes when used in combination to define a location within a surface or curve element do not necessarily form a right hand triad.

The following paragraphs are included as a reference for the theoretical basis of the integration referenced in this standard.

The numerical integration of a quantity within the volume of an element requires the evaluation of that quantity at one or more points within the element. The integral is a weighted sum of these values. The location of the integration points and the weighting assigned to them are defined either by a numerical integration rule (Gaussian or Simpson's rule) or by an explicit list of locations and weights.

The integration rules specify points within a unit space, usually within the range of -1.0 to 1.0. If section integration by rule is specified then these unit distances are converted to physical distances separately for each field integration point. Hence section integration by rule can only be specified for a surface with a defined thickness.

The form of the summation and the weighting depend of the type of the element. The specific forms for volume, surface and curve elements follow:

5.10.1 Volume 3D Element

For a volume 3D element, the integral quantity can be obtained numerically by a summation of the form:

$$Q = \sum_{i=1}^{n} j_i \, w_i \, q_i$$

where:

n is the number of points within the volume;

q_i is the value of the quantity at point i;

w_i is the weighting for the evaluation at point i;

j_i is the determinant of the Jacobian matrix at point i.

This form of integration may also be used for a surface 3D element or curve 3D element, however it is more usual to use separate field and section integrations for these elements.

5.10.2 Volume 2D Element

For a volume 2D element, the integral quantity can be obtained numerically by a summation of the form:

$$Q = \sum_{i=1}^{n} s_i \, j_i \, w_i \, q_i$$

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where:

n is the number of points within the volume;

q_i is the value of the quantity at point i;

w_i is the weighting for the evaluation at point i;

j_i is the determinant of the Jacobian matrix at point i;

s_i is either the depth of section for a plane stress or strain element or the distance from the axis of symmetry for an axisymmetric element, of point i.

This form of integration may also be used for a surface 2D element, however it is more usual to use separate field and section integrations for these elements.

5.10.3 Curve 2D Element

For a curve 2D element, the integral quantity can be obtained numerically by a summation of the form:

$$Q = \sum_{i=1}^{n} s_i \, w_i \, q_i$$

where:

n is the number of points within the volume;

q_i is the value of the quantity at point i;

w_i is the weighting for the evaluation at point i;

s_i is either the depth of section for a plane stress or strain element or the distance from the axis of symmetry for an axisymmetric element, of point i.

5.10.4 Surface 3D or Curve Element

For a surface 3D or curve element with separate integration the integral quantity can be obtained numerically by a summation of the form:

$$Q = \sum_{i=1}^{n} j_i \, w_i^f \, Q_i^s$$

where Q_i^s is the integral of the quantity through the section at field point i, which can be obtained numerically by a summation of the form:

$$Q_i^s = \sum_{j=1}^{m} w_j^s \, q_{ji}$$

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where:

n is the number of points over the field;

m is the number of points through the section;

q_{ji} is the value of the quantity at section point j and field point i;

w_i^f is the weighting for the evaluation of the field integration at point i;

w_j^s is the weighting for the evaluation of the section integration at point j;

j_i is the determinant of the Jacobian matrix at field point i.

5.10.5 Surface 2D Element

For a surface 2D element with separate integration the integral quantity can be obtained numerically by a summation of the form:

$$Q = \sum_{i=1}^{n} j_i \, w_i^f \, Q_i^s$$

where Q_i^s is the integral of the quantity through the section at field point i, which can be obtained numerically by a summation of the form:

$$Q_i^s = \sum_{j=1}^{m} s_{ji} \, w_j^s \, q_{ji}$$

where:

n is the number of points over the field;

m is the number of points through the section;

q_{ji} is the value of the quantity at section point j and field point i;

s_{ji} is either the depth of section for a plane stress or strain element or the distance from the axis of symmetry for an axisymmetric element, of section point j at field point i;

w_i^f is the weighting for the evaluation of the field integration at point i;

w_j^s is the weighting for the evaluation of the section integration at point j;

j_i is the determinant of the Jacobian matrix at field point i.

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5.10.6 volume_3d_element_integrated_matrix

A **volume_3d_element_integrated_matrix** is the matrix to be integrated for a volume 3D element, and the method of integration.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_integrated_matrix;
  descriptor                : volume_3d_element_descriptor;
  property_type             : matrix_property_type;
  integration_description   : text;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **volume_3d_element_representation**.

property_type: the type of matrix being evaluated.

integration_description: the interpolation rule and integration method.

5.10.7 volume_3d_element_integrated_matrix_with_definition

A **volume_3d_element_integrated_matrix_with_definition** is the method of integration.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_integrated_matrix_with_definition
  SUBTYPE OF (volume_3d_element_integrated_matrix);
  integration_definition    : volume_3d_element_field_integration;
END_ENTITY;
(*
```

Attribute definitions:

integration_definition: a definition of the integration within the 3D volume.

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5.10.8 volume_3d_element_field_integration

A **volume_3d_element_field_integration** is a volume 3D field integration shall be either algebraic, by rule, or explicit.

EXPRESS specification:

```
*)
TYPE volume_3d_element_field_integration = SELECT
  (element_integration_algebraic,
   volume_3d_element_field_integration_rule,
   volume_3d_element_field_integration_explicit);
END_TYPE;
(*
```

5.10.9 element_integration_algebraic

An **element_integration_algebraic** is an element integration that is exact; therefore, no numerical integration information is required.

EXPRESS specification:

```
*)
TYPE element_integration_algebraic = ENUMERATION OF (algebraic);
END_TYPE;
(*
```

5.10.10 volume_3d_element_field_integration_rule

A **volume_3d_element_field_integration_rule** is the integration rule and order for a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_field_integration_rule;
  integration_method        : integration_rule;
  integration_order         : ARRAY [1:3] OF INTEGER;
END_ENTITY;
(*
```

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Attribute definitions:

integration_method: the integration rule for the quantity being integrated.

integration_order: the order of the specified rule for the quantity being integrated. A separate integration order is specified for each parametric axis direction established graphically in 5.8 in the sequence (ξ,η,ζ).

5.10.11 volume_3d_element_field_integration_explicit

A **volume_3d_element_field_integration_explicit** is the explicit numerical integration for a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_field_integration_explicit;
  integration_positions_and_weights: SET [1:?] OF volume_position_weight;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions_and_weights: the integration positions for the quantity being integrated, and the corresponding weights for each integration position.

5.10.12 volume_position_weight

A **volume_position_weight** is an integration position within a volume element, and its weighting factor.

EXPRESS specification:

```
*)
ENTITY volume_position_weight;
  integration_position      : volume_element_location;
  integration_weight        : context_dependent_measure;
END_ENTITY;
(*
```

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Attribute definitions:

integration_position: the integration position for the quantity being integrated.

integration_weight: the weight for the integration position.

5.10.13 volume_2d_element_integrated_matrix

A **volume_2d_element_integrated_matrix** is the matrix to be integrated for a volume 2D element, and the method of integration.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_integrated_matrix;
  descriptor                : volume_2d_element_descriptor;
  property_type             : matrix_property_type;
  integration_description   : text;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **volume_2d_element_representation**.

property_type: the type of matrix being evaluated.

integration_description: the interpolation rule and integration method.

5.10.14 volume_2d_element_integrated_matrix_with_definition

A **volume_2d_element_integrated_matrix_with_definition** is the method of integration.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_integrated_matrix_with_definition
  SUBTYPE OF (volume_2d_element_integrated_matrix);
  integration_definition    : volume_2d_element_field_integration;
END_ENTITY;
(*
```

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Attribute definitions:

integration_definition: a definition of the integration within the 2D volume.

5.10.15 volume_2d_element_field_integration

A **volume_2d_element_field_integration** is a volume 2D field integration that shall be either algebraic, by rule, or explicit.

EXPRESS specification:

```
*)
TYPE volume_2d_element_field_integration = SELECT
  (element_integration_algebraic,
   volume_2d_element_field_integration_rule,
   volume_2d_element_field_integration_explicit);
END_TYPE;
(*
```

5.10.16 volume_2d_element_field_integration_rule

A **volume_2d_element_field_integration_rule** is the integration rule and order for a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_field_integration_rule;
  integration_method        : integration_rule;
  integration_order         : ARRAY [1:2] OF INTEGER;
END_ENTITY;
(*
```

Attribute definitions:

integration_method: the integration rule for the quantity being integrated.

integration_order: the order of the specified rule for the quantity being integrated. A separate integration order is specified for each parametric axis direction established graphically in 5.8 in the sequence (ξ,η).

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5.10.17 volume_2d_element_field_integration_explicit

A **volume_2d_element_field_integration_explicit** is the explicit numerical integration for a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_field_integration_explicit;
  integration_positions_and_weights: SET [1:?] OF volume_position_weight;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions_and_weights: the integration positions for the quantity being integrated, and the corresponding weights for each integration position.

5.10.18 surface_3d_element_integrated_matrix

A **surface_3d_element_integrated_matrix** is the matrix to be integrated for a surface 3D element, and the method of integration.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_integrated_matrix;
  descriptor                : surface_3d_element_descriptor;
  property_type             : surface_matrix_property_type;
  integration_description   : text;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **surface_3d_element_representation**.

property_type: the type of matrix being evaluated.

integration_description: the interpolation rule and integration method.

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5.10.19 surface_3d_element_integrated_matrix_with_definition

A **surface_3d_element_integrated_matrix_with_definition** is the method of integration.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_integrated_matrix_with_definition
  SUBTYPE OF (surface_3d_element_integrated_matrix);
  integration_definition    : surface_3d_element_integration;
END_ENTITY;
(*
```

Attribute definitions:

integration_definition: a definition of the integration within the 3D surface.

5.10.20 surface_3d_element_integration

A **surface_3d_element_integration** is the method of integration for the field and section of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_integration;
  field                     : surface_3d_element_field_integration;
  section                   : surface_section_integration;
END_ENTITY;
(*
```

Attribute definitions:

field: the integration of the quantity being integrated over the field (surface) of the element.

section: the integration of the quantity being integrated through the section (thickness) of the element.

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5.10.21 surface_3d_element_field_integration

A **surface_3d_element_field_integration** is a surface 3D field integration that shall be either algebraic, by rule, or explicit.

EXPRESS specification:

```
*)
TYPE surface_3d_element_field_integration = SELECT
  (element_integration_algebraic,
   surface_3d_element_field_integration_rule,
   surface_3d_element_field_integration_explicit);
END_TYPE;
(*
```

5.10.22 surface_section_integration

A **surface_section_integration** is a surface 3D section integration that shall be either algebraic, by rule, or explicit.

EXPRESS specification:

```
*)
TYPE surface_section_integration = SELECT
  (element_integration_algebraic,
   surface_section_integration_rule,
   surface_section_integration_explicit);
END_TYPE;
(*
```

5.10.23 surface_3d_element_field_integration_rule

A **surface_3d_element_field_integration_rule** is the integration rule and order for a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_field_integration_rule;
  integration_method        : integration_rule;
  integration_order         : ARRAY [1:2] OF INTEGER;
END_ENTITY;
(*
```

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Attribute definitions:

integration_method: the integration rule for the quantity being integrated.

integration_order: the order of the specified rule for the quantity being integrated. A separate integration order is specified for each parametric axis direction established graphically in 5.8 in the sequence (ξ,η).

5.10.24 surface_3d_element_field_integration_explicit

A **surface_3d_element_field_integration_explicit** is the explicit numerical integration for a surface 3D element field.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_field_integration_explicit;
  integration_positions_and_weights: SET [1:?] OF surface_position_weight;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions_and_weights: the integration positions for the quantity being integrated, and the corresponding weights for each integration position.

5.10.25 surface_position_weight

A **surface_position_weight** is an integration position within a surface element, and its weighting factor.

EXPRESS specification:

```
*)
ENTITY surface_position_weight;
  integration_position      : surface_element_location;
  integration_weight        : context_dependent_measure;
END_ENTITY;
(*
```

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Attribute definitions:

integration_position: the integration position for the quantity being integrated.

integration_weight: the weight for the integration position.

5.10.26 surface_section_integration_rule

A **surface_section_integration_rule** is the integration rule and order for a surface element section.

EXPRESS specification:

```
*)
ENTITY surface_section_integration_rule;
  integration_method        : integration_rule;
  integration_order         : INTEGER;
END_ENTITY;
(*
```

Attribute definitions:

integration_method: the integration rule for the quantity being integrated.

integration_order: the order of the specified rule for the quantity being integrated.

5.10.27 surface_section_integration_explicit

A **surface_section_integration_explicit** is the explicit numerical integration through the section for a surface element.

EXPRESS specification:

```
*)
ENTITY surface_section_integration_explicit;
  integration_positions_and_weights : SET [1:?] OF
                                      surface_section_position_weight;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions_and_weights: the integration positions and weights through the thickness of the section for the quantity being integrated.

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5.10.28 surface_section_position_weight

A **surface_section_position_weight** is the integration weight and position in a surface element section.

EXPRESS specification:

```
*)
ENTITY surface_section_position_weight;
  integration_position      : surface_section_element_location;
  integration_weight        : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

integration_position: the integration position through the thickness of the surface section.

integration_weight: the weight for the integration position.

5.10.29 surface_2d_element_integrated_matrix

A **surface_2d_element_integrated_matrix** is the matrix to be integrated for a surface 2D element, and the method of integration.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_integrated_matrix;
  descriptor                : surface_2d_element_descriptor;
  property_type             : surface_matrix_property_type;
  integration_description   : text;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **surface_2d_element_representation**.

property_type: the type of matrix being evaluated.

integration_description: interpolation rule and integration method.

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5.10.30 surface_2d_element_integrated_matrix_with_definition

A **surface_2d_element_integrated_matrix_with_definition** is the method of integration.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_integrated_matrix_with_definition
  SUBTYPE OF (surface_2d_element_integrated_matrix);
  integration_definition    : surface_2d_element_integration;
END_ENTITY;
(*
```

Attribute definitions:

integration_definition: the integration within the surface.

5.10.31 surface_2d_element_integration

A **surface_2d_element_integration** is the method of integration for the length of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_integration;
  element_length            : surface_2d_element_length_integration;
  section                   : surface_section_integration;
END_ENTITY;
(*
```

Attribute definitions:

element_length: the integration of the quantity being integrated along the length of the curve that defines the surface 2D element in the 2D analysis plane.

section: the integration of the quantity being integrated through the section (thickness) of the element.

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5.10.32 surface_2d_element_length_integration

A **surface_2d_element_length_integration** is a surface 2D length integration that shall be either algebraic, by rule, or explicit.

EXPRESS specification:

```
*)
TYPE surface_2d_element_length_integration = SELECT
  (element_integration_algebraic,
   surface_2d_element_length_integration_rule,
   surface_2d_element_length_integration_explicit);
END_TYPE;
(*
```

5.10.33 surface_2d_element_length_integration_rule

A **surface_2d_element_length_integration_rule** is the integration rule and order for a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_length_integration_rule;
  integration_method        : integration_rule;
  integration_order         : INTEGER;
END_ENTITY;
(*
```

Attribute definitions:

integration_method: the integration rule for the quantity being integrated.

integration_order: the order of the specified rule for the quantity being integrated.

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5.10.34 surface_2d_element_length_integration_explicit

A **surface_2d_element_length_integration_explicit** is the explicit numerical integration for a surface 2D element length.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_length_integration_explicit;
  integration_positions_and_weights: SET [1:?] OF surface_position_weight;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions_and_weights: the integration positions for the quantity being integrated, and the corresponding weights for each integration position.

5.10.35 curve_3d_element_integrated_matrix

A **curve_3d_element_integrated_matrix** is the matrix to be integrated for a curve 3D element, and the method of integration.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_integrated_matrix;
  descriptor                : curve_3d_element_descriptor;
  property_type             : curve_matrix_property_type;
  integration_description   : text;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **curve_3d_element_representation**.

property_type: the type of matrix being evaluated.

integration_description: the interpolation rule and integration method.

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5.10.36 curve_3d_element_integrated_matrix_with_definition

A **curve_3d_element_integrated_matrix_with_definition** is the method of integration.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_integrated_matrix_with_definition
  SUBTYPE OF (curve_3d_element_integrated_matrix);
  integration_definition    : curve_3d_element_integration;
END_ENTITY;
(*
```

Attribute definitions:

integration_definition: a definition of the integration within the curve.

5.10.37 curve_3d_element_integration

A **curve_3d_element_integration** the method of integration for the length and section of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_integration;
  element_length            : curve_3d_element_length_integration;
  section                   : curve_section_integration_explicit;
END_ENTITY;
(*
```

Attribute definitions:

element_length: the integration of the quantity being integrated along the length of the element.

section: the integration of the quantity being integrated over the section of the element.

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5.10.38 curve_3d_element_length_integration

A **curve_3d_element_length_integration** is a curve 3D length integration that shall be either algebraic, by rule, or explicit.

EXPRESS specification:

```
*)
TYPE curve_3d_element_length_integration = SELECT
  (element_integration_algebraic,
   curve_3d_element_length_integration_rule,
   curve_3d_element_length_integration_explicit);
END_TYPE;
(*
```

5.10.39 curve_3d_element_length_integration_rule

A **curve_3d_element_length_integration_rule** is the integration rule and order for a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_length_integration_rule;
  integration_method        : integration_rule;
  integration_order         : INTEGER;
END_ENTITY;
(*
```

Attribute definitions:

integration_method: the integration rule for the quantity being integrated.

integration_order: the order of the specified rule for the quantity being integrated.

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5.10.40 curve_3d_element_length_integration_explicit

A **curve_3d_element_length_integration_explicit** is the explicit numerical integration for a curve 3D element length.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_length_integration_explicit;
  integration_positions_and_weights: SET [1:?] OF
                                     curve_3d_element_position_weight;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions_and_weights: the integration positions for the quantity being integrated, and the corresponding weights for each integration position.

5.10.41 curve_3d_element_position_weight

A **curve_3d_element_position_weight** is an integration position within a 3D curve element, and its weighting factor.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_position_weight;
  integration_position      : curve_volume_element_location;
  integration_weight        : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

integration_position: the integration positions for the quantity being integrated.

integration_weight: the weight for each integration position.

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5.10.42 curve_section_integration_explicit

A **curve_section_integration_explicit** is the explicit numerical integration for a curve element cross section.

EXPRESS specification:

```
*)
ENTITY curve_section_integration_explicit;
  integration_positions     : SET [1:?] OF curve_section_element_location;
END_ENTITY;
(*
```

Attribute definitions:

integration_positions: the integration positions across the section for the quantity being integrated.

5.10.43 curve_2d_element_integrated_matrix

A **curve_2d_element_integrated_matrix** is the matrix to be integrated for a curve 2D element, and the method of integration.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_integrated_matrix;
  descriptor                : curve_2d_element_descriptor;
  property_type             : curve_matrix_property_type;
  integration_description   : text;
END_ENTITY;
(*
```

Attribute definitions:

descriptor: the association to the information describing a **curve_2d_element_representation**.

property_type: the type of matrix being evaluated.

integration_description: the interpolation rule and integration method.

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5.10.44 curve_2d_element_integrated_matrix_with_definition

A **curve_2d_element_integrated_matrix_with_definition** is the method of integration.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_integrated_matrix_with_definition
  SUBTYPE OF (curve_2d_element_integrated_matrix);
  integration_definition    : curve_2d_element_integration;
END_ENTITY;
(*
```

Attribute definitions:

integration_definition: a definition of the integration within the curve.

5.10.45 curve_2d_element_integration

A **curve_2d_element_integration** is the method of integration for the section of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_integration;
  section                   : LIST [1:?] OF curve_section_element_location;
END_ENTITY;
(*
```

Attribute definitions:

section: a definition of the integration of the quantity being integrated over the section of the element.

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5.11 Structural response representation schema entity definitions: Element locations

A field variable may be evaluated for a list of locations within an element. This list of locations is specified by reference to the entity within this section, which is appropriate to the element type.

5.11.1 fea_parametric_point

An **fea_parametric_point** is a position within a finite element, and specifies its parametric coordinates ξ, η, and ζ.

EXPRESS specification:

```
*)
ENTITY fea_parametric_point
  SUBTYPE OF (point);
  coordinates              : LIST [1:3] OF parameter_value;
WHERE
  WR1: valid_parametric_coordinate (coordinates);
  WR2:  SIZEOF (TYPEOF (SELF) *
         ['GEOMETRY_SCHEMA.CARTESIAN_POINT',
          'GEOMETRY_SCHEMA.POINT_ON_CURVE',
          'GEOMETRY_SCHEMA.POINT_ON_SURFACE',
          'GEOMETRY_SCHEMA.DEGENERATE_PCURVE',
          'GEOMETRY_SCHEMA.POINT_REPLICA',
          'GEOMETRY_SCHEMA.SPHERICAL_POINT',
          'GEOMETRY_SCHEMA.CYLINDRICAL_POINT'])
         = 0;
END_ENTITY;
(*
```

Attribute definitions:

coordinates: the coordinates of the position. The first value of the coordinate is the ξ coordinate, the second the η coordinate, and the third the ζ coordinate (if applicable).

Formal propositions:

WR1: each coordinate shall lie in the range from -1.0 to +1.0.

WR2: only the SUBTYPE of **fea_parametric_point** shall exist in this instance.

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5.11.2 volume_element_location

A **volume_element_location** is a location within a volume element, and specifies its parametric coordinates ξ, η and ζ.

EXPRESS specification:

```
*)
ENTITY volume_element_location;
  coordinates               : fea_parametric_point;
END_ENTITY;
(*
```

Attribute definitions:

coordinates: the coordinates of the location. The first value of the coordinate is the ξ coordinate, the second the η coordinate, and the third the ζ coordinate (if applicable).

5.11.3 surface_volume_element_location

A **surface_volume_element_location** is a location within the volume of a surface element.

EXPRESS specification:

```
*)
ENTITY surface_volume_element_location;
  field_location            : surface_element_location;
  section_location          : surface_section_element_location;
END_ENTITY;
(*
```

Attribute definitions:

field_location: the location over the surface of the element.

section_location: the location on the section (through the thickness) of the element.

5.11.4 surface_element_location

A **surface_element_location** is a location on the surface of a surface element, that specifies its parametric coordinates ξ and, if appropriate, η.

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EXPRESS specification:

```
*)
ENTITY surface_element_location;
  coordinates                : fea_parametric_point;
END_ENTITY;
(*
```

Attribute definitions:

coordinates: the coordinates of the location. The first value of the pair is the ξ coordinate, and the second the η coordinate (if applicable).

5.11.5 surface_section_element_location

A **surface_section_element_location** is a location on the section (through the thickness) of a surface element. A section location can be specified as an offset from the nominal plane of the surface, or as a dimensionless section coordinate.

Within a surface of a composite material, a field variable may be discontinuous at a material boundary. If a section location is specified at a material boundary, a flag can be set to indicate whether the value of the variable is to be evaluated above or below the discontinuity.

EXPRESS specification:

```
*)
ENTITY surface_section_element_location
  SUPERTYPE OF (ONEOF (surface_section_element_location_absolute,
                       surface_section_element_location_dimensionless));
  above_material_discontinuity : LOGICAL;
END_ENTITY;
(*
```

Attribute definitions:

above_material_discontinuity: the side of a material discontinuity on which the field variable is to be evaluated.

If the value is TRUE, then the variable is evaluated on the side of the discontinuity in the direction of the positive z axis of the property coordinate system for the element. If the value is FALSE, then the variable is evaluated on the other side of the discontinuity. If the value is UNKNOWN, then there is no discontinuity.

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5.11.6 surface_section_element_location_absolute

A **surface_section_element_location_absolute** is a location on the section (through the thickness)of a surface element that is specified by giving a distance from the nominal plane of the surface.

EXPRESS specification:

```
*)
ENTITY surface_section_element_location_absolute
  SUBTYPE OF (surface_section_element_location);
  offset                    : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

offset: the distance of the location from the nominal plane of the element.

A positive value indicates an offset in the direction of the positive **z** axis of the property coordinate system for the element.

5.11.7 surface_section_element_location_dimensionless

A **surface_section_element_location_dimensionless** is a location on the section (through the thickness) of a surface element that is specified by giving a dimensionless section coordinate.

EXPRESS specification:

```
*)
ENTITY surface_section_element_location_dimensionless
  SUBTYPE OF (surface_section_element_location);
  coordinate                : LIST [1:1] OF parameter_value;
WHERE
  WR1: valid_parametric_coordinate (coordinate);
END_ENTITY;
(*
```

Attribute definitions:

coordinate: the section coordinate of the location. A section coordinate of 1.0 indicates the surface of the element in the direction of the positive **z** axis of the property coordinate system for the element. A section coordinate of -1.0 indicates the other surface.

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Formal propositions:

WR1: the section coordinate shall be within the range from -1.0 to +1.0.

5.11.8 curve_volume_element_location

A **curve_volume_element_location** is a location within the volume of a curve element.

EXPRESS specification:

```
*)
ENTITY curve_volume_element_location;
  field_location            : curve_element_location;
  section_location          : curve_section_element_location;
END_ENTITY;
(*
```

Attribute definitions:

field_location: the location along the length of the element.

section_location: the location on the section (through the thickness) of the element.

5.11.9 curve_element_location

A **curve_element_location** is a location along the length of a curve element, that is specified by its parametric coordinate ξ.

EXPRESS specification:

```
*)
ENTITY curve_element_location;
  coordinate                : fea_parametric_point;
END_ENTITY;
(*
```

Attribute definitions:

coordinate: the coordinate of the location. The value is the ξ coordinate.

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5.11.10 curve_section_element_location

A **curve_section_element_location** is a location on the section (through the thickness) of a curve element. A section location is specified by giving distances from the nominal axis of the curve.

EXPRESS specification:

```
*)
ENTITY curve_section_element_location;
  offsets                  : ARRAY [1:2] of context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

offsets: the distances of the location from the nominal axis of the element.

A positive value for the first coordinate indicates an offset in the direction of the positive **y** axis of the property coordinate system for the element.

A positive value for the second coordinate item indicates an offset in the direction of the positive **z** axis of the property coordinate system for the element.

5.12 Structural response representation schema entity definitions: Finite element analysis material properties

The material specifications and properties for an element are referenced through a set of **fea_material_property_representation** entities. The material specifications are inherited from entities associated with a **material_property_representation**, which in turn may have an **fea_material_property_representation** subtype.

NOTE See Figure 54 for a perspective on how the **fea_material_property_representation** entity associates finite element analysis model information with entities from ISO 10303-45.

EXAMPLE Each **fea_material_property_representation** is defined with respect to a **data_environment** entity that is specified by a reference from an instantiation of a **material_property_representation** and the associated material product **representation** related entities. The environment variables (such as temperature, moisture content) are associated to the **material_property_representation** by the set of **property_definition_representation** entities referenced by the **data_environment** entity. There is a single FEA material property representation item for each material property and associated environment variables per where rule WR1 in the **fea_material_property_representation** entity. An **element_material** aggregates together **material_property_representation** entities to represent all the material properties necessary to define an element.

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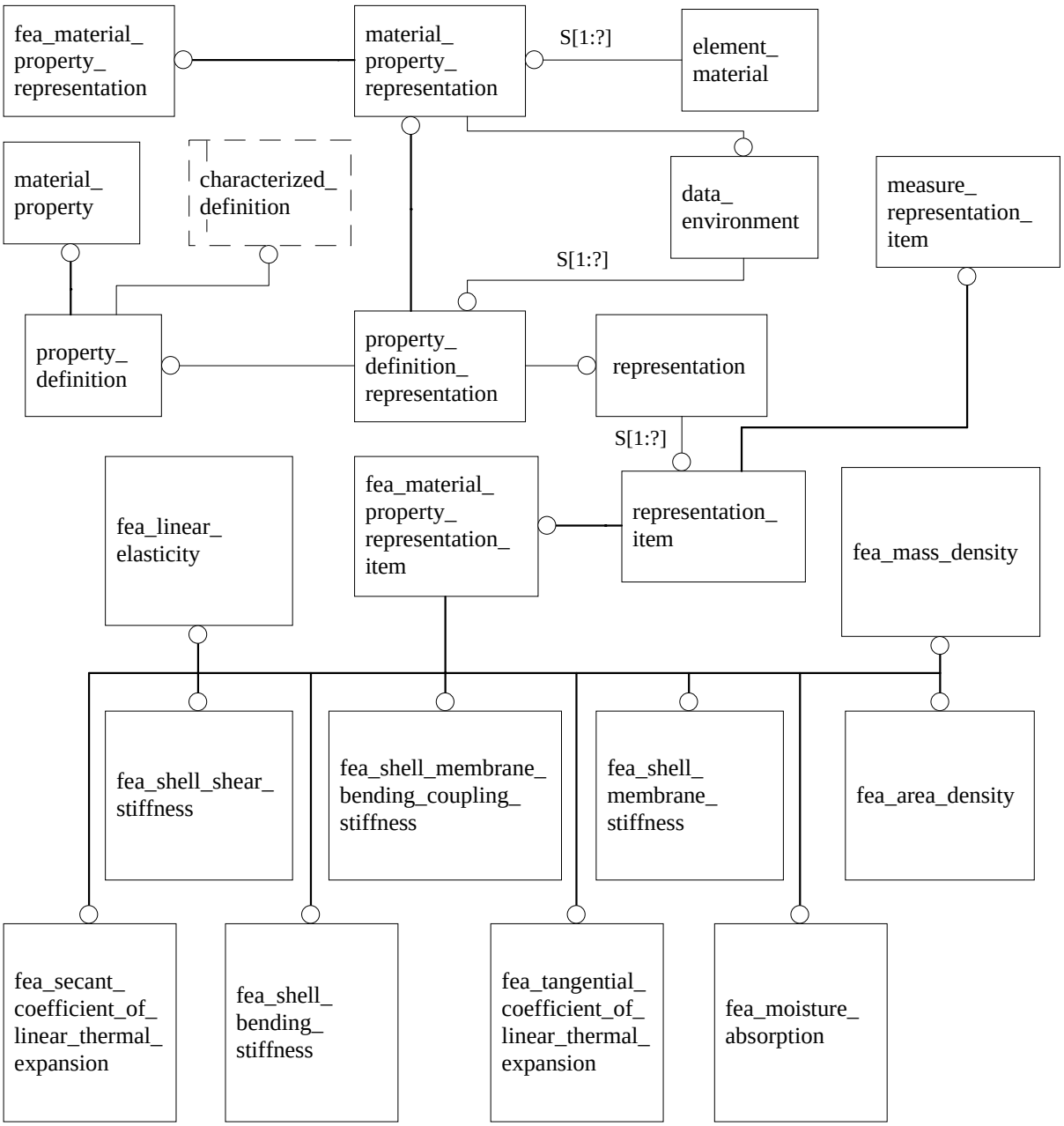

Figure 54 – Relationship between FEA and ISO 10303-45

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5.12.1 element_material

An **element_material** is the aggregation of the material properties of the continuum that a finite element represents.

EXPRESS specification:

```
*)
ENTITY element_material;
  material_id                : identifier;
  description                : text;
  properties                 : SET [1:?] OF material_property_representation;
END_ENTITY;
(*
```

Attribute definitions:

material_id: a unique application defined identifier for the material to be used during the finite element analysis.

description: a text narrative about the substance.

properties: the material properties that characterize a finite element.

Informal propositions:

IP1: the combination of **fea_model** referenced by an element using an **element_material** and **material_id** shall be unique within a finite element analysis model.

5.12.2 fea_material_property_geometric_relationship

An **fea_material_property_geometric_relationship** associates finite element material properties to a **geometric_representation_item** within the context of a particular representation.

EXPRESS specification:

```
*)
ENTITY fea_material_property_geometric_relationship;
  material_ref               : fea_material_property_representation;
  item                       : analysis_item_within_representation;
WHERE
  WR1: 'GEOMETRY_SCHEMA.GEOMETRIC_REPRESENTATION_ITEM' IN TYPEOF(item.item);
END_ENTITY;
(*
```

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Attribute definitions:

material_ref: the material properties to be associated.

item: the **geometric_representation_item** to which material properties are to be related.

Formal propositions:

WR1: there shall be a geometric shape representation item associated with the finite element material properties.

5.12.3 fea_material_property_representation

An **fea_material_property_representation** is a property of the substance of the continuum that a finite element represents. The property is defined with respect to the data environment specified in the **material_property_representation** supertype.

NOTE For layered composite material properties for surface elements the total thickness for the element is defined by adding up all the ply thicknesses in the material. The plies are defined by a defining Application Protocol.

EXPRESS specification:

```
*)
ENTITY fea_material_property_representation
  SUBTYPE OF (material_property_representation);
WHERE
  WR1: SIZEOF (QUERY (item <*
       SELF\property_definition_representation.used_representation.items |
         SIZEOF (['STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_LINEAR_ELASTICITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MASS_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_AREA_DENSITY',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_MOISTURE_ABSORPTION',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_MEMBRANE_STIFFNESS',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_BENDING_STIFFNESS',
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_MEMBRANE_BENDING_COUPLING_STIFFNESS',
```

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```
                  'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.' +
                  'FEA_SHELL_SHEAR_STIFFNESS'] * TYPEOF (item)
                  ) = 1
       )) = 1;
  WR2: 'MATERIAL_PROPERTY_DEFINITION_SCHEMA.MATERIAL_PROPERTY' IN
       TYPEOF (SELF\property_definition_representation.definition);
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be exactly one of the following **fea_material_property_representation_item** subtypes associated with an **fea_material_property_representation**:

— **fea_linear_elasticity**;

— **fea_mass_density**;

— **fea_area_density**;

— **fea_tangential_coefficient_of_linear_thermal_expansion**;

— **fea_secant_coefficient_of_linear_thermal_expansion**;

— **fea_moisture_absorption**;

— **fea_shell_membrane_stiffness**;

— **fea_shell_bending_stiffness**;

— **fea_shell_membrane_bending_coupling_stiffness**;

— **fea_shell_shear_stiffness**.

WR2: the **definition** attribute that is inherited from the **property_definition_representation** supertype of an **fea_material_property_representation** shall be a **material_property**.

5.12.4 fea_material_property_representation_item

An **fea_material_property_representation_item** is the representation of mechanical material properties suitably idealized for finite element analysis.

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EXPRESS specification:

```
*)
ENTITY fea_material_property_representation_item
  SUPERTYPE OF (ONEOF (fea_linear_elasticity,
                   fea_mass_density,
                   fea_area_density,
                   fea_tangential_coefficient_of_linear_thermal_expansion,
                   fea_secant_coefficient_of_linear_thermal_expansion,
                   fea_moisture_absorption,
                   fea_shell_membrane_stiffness,
                   fea_shell_bending_stiffness,
                   fea_shell_membrane_bending_coupling_stiffness,
                   fea_shell_shear_stiffness))
  SUBTYPE OF (representation_item);
END_ENTITY;
(*
```

5.12.5 fea_linear_elasticity

An **fea_linear_elasticity** is the collection of mechanical material properties representing a linear response of an **fea_material** to a small change in strain at a constant temperature. The response is a change in stress caused by a small change in strain as follows:

$$\Delta\sigma_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} d_{ijkl}\,\Delta\varepsilon_{kl}$$

where:

d: is the fourth order elasticity tensor;

$\Delta\sigma$: is a change in the stress tensor;

$\Delta\varepsilon$: is a change in the strain tensor.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_linear_elasticity
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor4_3d;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the values of the elasticity properties.

5.12.6 fea_mass_density

An **fea_mass_density** is the mass of **fea_material** per unit volume of an element in a strain free state.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_mass_density
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constant              : scalar;
END_ENTITY;
(*
```

Attribute definitions:

fea_constant: the value of the FEA mass density property.

5.12.7 fea_area_density

An **fea_area_density** is the mass of **fea_material** per unit area of a surface element in a strain free state.

NOTE This property is usually defined in a strain free state that has a reference temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_area_density
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constant              : scalar;
END_ENTITY;
(*
```

Attribute definitions:

fea_constant: the value of the FEA area density property.

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5.12.8 fea_tangential_coefficient_of_linear_thermal_expansion

An **fea_tangential_coefficient_of_linear_thermal_expansion** is the relationship of a change in thermal strain in an element to a small change in temperature as follows:

$$\Delta\varepsilon_{ij} = \alpha_{ij}(T)\,\Delta T$$

where:

α**:** is the tangential coefficient of linear thermal expansion for the material at temperature T;

$\Delta\varepsilon$**:** is the change in the strain tensor caused by the small change in temperature at temperature T;

ΔT**:** is a change in temperature in the neighborhood of T in which the incremental thermal expansion is linear;

T**:** is the temperature.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_tangential_coefficient_of_linear_thermal_expansion
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor2_3d;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the value of the FEA tangential coefficient of linear thermal expansion tensor.

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5.12.9 fea_secant_coefficient_of_linear_thermal_expansion

An **fea_secant_coefficient_of_linear_thermal_expansion** is the relationship of the thermal strain of an element caused by a change from a reference temperature to a specified temperature as follows:

$$\varepsilon_{ij} = \alpha_{ij}\,(T - T_o)$$

where:

$\alpha(T)$**:** is the secant coefficient of linear thermal expansion for the material at temperature T;

ε**:** is the thermal strain caused by a change in temperature from its reference value T_o to T;

T_o**:** is the reference temperature;

T**:** is the temperature.

The secant and the tangential coefficients of linear thermal expansion are different if the coefficients are temperature dependent.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_secant_coefficient_of_linear_thermal_expansion
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor2_3d;
  reference_temperature     : thermodynamic_temperature_measure;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the value of the FEA secant coefficient of linear thermal expansion tensor.

reference_temperature: the value of the reference temperature.

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5.12.10 fea_moisture_absorption

An **fea_moisture_absorption** is the relationship of a change in moisture strain in an element to a small change in moisture as follows:

$$\Delta\varepsilon_{ij} = \beta_{ij}(M)\,\Delta M$$

where:

β**:** is the coefficient of linear moisture expansion for the material at moisture content M;

$\Delta\varepsilon$**:** is the change in the strain tensor caused by the small change in moisture at moisture content M;

ΔM**:** is the change in moisture;

M**:** is the moisture content.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_moisture_absorption
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor2_3d;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the value of the FEA linear moisture expansion tensor.

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5.12.11 fea_shell_membrane_stiffness

An **fea_shell_membrane_stiffness** is the collection of mechanical properties representing a linear response of a **fea_material** to a small change in membrane strain. The response is a change in surface membrane force caused by a small change in membrane strain as follows:

$$\Delta N_{ij} = \sum_{k=1}^{2} \sum_{l=1}^{2} d_{ijkl} \, \Delta\varepsilon_{kl}$$

where:

d: is the shell membrane elasticity tensor;

N: is the 2D second order surface membrane force tensor;

ε: is the 2D second order membrane strain tensor:

$$\varepsilon = \frac{1}{2}(J + J^t)$$

where:

$$J = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial v}{\partial x} \\ \frac{\partial u}{\partial y} & \frac{\partial v}{\partial y} \end{pmatrix}$$

and where:

J: is the Jacobian;

J^t: is the transpose of the Jacobian;

u: is displacement in the x direction;

v: is displacement in the y direction.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_shell_membrane_stiffness
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor4_2d;
END_ENTITY;
(*
```

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Attribute definitions:

fea_constants: the value of the FEA surface membrane elasticity tensor.

5.12.12 fea_shell_bending_stiffness

An **fea_shell_bending_stiffness** is the collection of mechanical properties representing a linear response of an **fea_material** to a small change in curvature. The response is a change in surface aggregate bending moment caused by a small change in curvature as follows:

$$\Delta D_{ij} = \sum_{k=1}^{2} \sum_{l=1}^{2} d_{ijkl} \, \Delta c_{kl}$$

where:

d**:** is the shell bending elasticity tensor;

D**:** is the 2D second order aggregate surface bending moment tensor;

c**:** is the symmetric 2D second order surface curvature tensor:

$$\begin{pmatrix} -\dfrac{\partial^2 w}{\partial x^2} & -\dfrac{\partial^2 w}{\partial x \partial y} \\ -\dfrac{\partial^2 w}{\partial x \partial y} & -\dfrac{\partial^2 w}{\partial y^2} \end{pmatrix}$$

where:

w**:** is displacement in the z direction.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_shell_bending_stiffness
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor4_2d;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the value of the FEA shell bending elasticity tensor.

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5.12.13 fea_shell_membrane_bending_coupling_stiffness

An **fea_shell_membrane_bending_coupling_stiffness** is the collection of mechanical properties representing a linear response of an **fea_material** to a small change in curvature. The response is a change in surface membrane force caused by a small change in curvature as follows:

$$\Delta N_{ij} = \sum_{k=1}^{2} \sum_{l=1}^{2} d_{ijkl} \, \Delta c_{kl}$$

where:

d**:** is the shell membrane bending coupling elasticity tensor;

N**:** is the 2D second order surface membrane force tensor;

c**:** is the symmetric 2D second order surface curvature tensor.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_shell_membrane_bending_coupling_stiffness
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor4_2d;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the value of the FEA shell membrane bending coupling elasticity tensor.

5.12.14 fea_shell_shear_stiffness

An **fea_shell_shear_stiffness** is the collection of mechanical properties representing a linear response of an **fea_material** to a small change in surface out of plane shear strain. The response is a change in surface aggregate out of plane shear forces caused by a small change in surface out of plane shear strain as follows:

$$\Delta F_i = \sum_{j=1}^{2} s_{ij} \, \Delta \varepsilon_j$$

where:

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s: is the shell shear elasticity tensor;

F: is the 2D surface aggregate out of plane shear force vector;

ε: is the 2D surface out of plane shear strain vector:

$$\begin{pmatrix} \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \\ \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \end{pmatrix}$$

where:

u: is displacement in the x direction.

v: is displacement in the y direction.

w: is displacement in the z direction.

NOTE This property is usually a function of temperature and other independent variables.

EXPRESS specification:

```
*)
ENTITY fea_shell_shear_stiffness
  SUBTYPE OF (fea_material_property_representation_item);
  fea_constants             : symmetric_tensor2_2d;
END_ENTITY;
(*
```

Attribute definitions:

fea_constants: the value of the FEA shell shear elasticity tensor.

5.13 Structural response representation schema entity definitions: Element properties

Element properties are information associated with elements that are not derivable from the element connectivity and the associated node geometry.

Volume elements have no associated physical properties other than material properties, so no property entities exist for them. The volume elements refer directly to a material to supply all other needed property information.

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5.13.1 Surface element properties

Surface elements are idealised volumes, and as such require other property values, such as thickness, to complete their definition.

A surface element can model a volume of material where the geometry of the volume is specified by a reference surface which is defined by the positions of the nodes, the element shape functions, and a thickness at each point on the surface. The thickness is often defined by nodal values which are then interpolated by the element shape functions.

NOTE 1 Other independent definitions of thickness over the surface of an element are possible, such as one described by bicubic polynomials. These independent definitions are not in this part of ISO 10303 at the present, though a subtyping has been constructed to allow inclusion at a later date with minimum impact on the current information model.

Alternatively a surface may be a composite or fabricated shell for which the geometric and section properties may be separated in a simple way. A full description of the material and section shall be contained in a referencing application protocol. In this case an aggregate section thickness is not required within a finite element analysis model, and is not supplied.

The material model may contain constitutive matrices to describe directly the aggregate behaviour of a composite or fabricated surface.

It is also possible to specify constitutive matrices for a non-homogeneous surface within the finite element model. This is done by supplying a separate effective thickness and effective material for each of the membrane, bending, shear, and membrane-coupling matrices. A precise definition for these constitutive matrices and for the different effective thicknesses and effective materials is given in the paragraphs below.

The engineering theory for the thermo-mechanical behaviour of a shell defines the kinematics of deformation within the entire volume of the surface element with respect to variables defined with respect to the reference surface of an element. Classical thin shell theory assumes that normals remain straight and normal to the reference surface. The principal underlying the finite element method - the variational principal of minimum potential energy for the displacement formulation elements - is not affected by such kinematic assumptions. However the kinematic assumptions allow strains and stresses to be generalised to give quantities such as curvatures, and bending and twisting moments.

For an analysis of a surface that assumes linear material behaviour it is possible to consider separately the integration through the thickness and the integration over the surface. Consider the strain energy for a surface element is given by an integral of the form:

$$V = \frac{1}{2}\,\mathbf{u}^t \int_{surface} \int_{thickness} B^t\, D\, B\, dt\, ds\, \mathbf{u}$$

where:

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$\mathbf{u}$ represents the vector of nodal generalised displacements for the element;

B represents the element shape function derivatives which relate the nodal generalised displacements to strains at any point within the element such that:

$$\varepsilon = B\ \mathbf{u}$$

D represents the elasticity matrix for the material which relates the strains to the stresses at a point within the element such that:

$$\sigma = D\,\varepsilon$$

where:

σ is the stress tensor components in a vector form;

ε is the strain tensor components in a vector form.

Alternatively, for an analysis with linear material behaviour the integration through the thickness can be carried out algebraically so that the strain energy is given by an integral of the form:

$$V = \frac{1}{2}\,\mathbf{u}^t \int_{surface} B'^t\ D'\ B'\ ds\ \mathbf{u}$$

where:

B' represents the element shape function derivatives which relate the nodal generalised displacements to strains at any point within the element such that:

$$\varepsilon' = B'\ \mathbf{u}$$

D' represents the constitutive matrix for the surface which relates the generalised strains to generalised stresses at a point on the surface such that:

$$\sigma' = D'\,\varepsilon'$$

where:

σ' is the vector of membrane force and bending moment components:

$$\begin{pmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \end{pmatrix}$$

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within which:

N_{xx}, N_{yy}, N_{xy} are components of membrane force;

M_{xx}, M_{yy}, M_{xy} are components of bending moment.

ε' is the vector of membrane strain and curvature components:

$$\begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \chi_{xx} \\ \chi_{yy} \\ \tau_{xy} \end{pmatrix}$$

within which:

ε_{xx}, ε_{yy}, γ_{xy} are the components of membrane strain;

χ_{xx}, χ_{yy}, τ_{xy} are the components of curvature.

NOTE 2 The curvature components χ_{xx} and χ_{yy} are positive when the center of curvature is on the $+z$ side. The sign convention is shown in Figure 55.

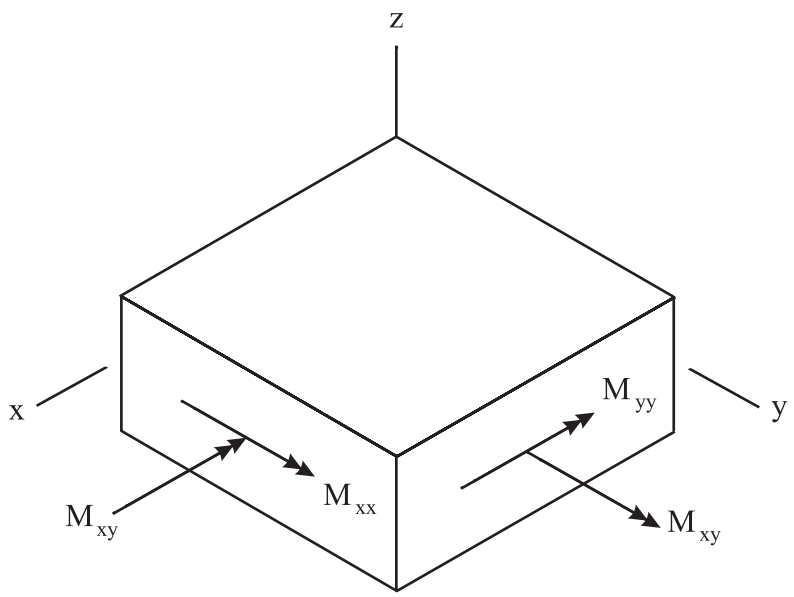

Figure 55 – Bending moments

At a point on the surface with thickness h and offset p, the limits for section integration are ($p - \frac{h}{2}$ to $p + \frac{h}{2}$). At this point the D' matrix is defined with respect to the coordinate axes for the surface section properties by:

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$$D' = \begin{pmatrix} h\,D_m & h\,p\,D_m \\ h\,p\,D_m & (\frac{1}{12}h^3 + h\,p^2)\,D_m \end{pmatrix}$$

where:

D_m is the membrane elasticity matrix, which for a isotropic material has the form:

$$D_m = \frac{E}{(1-\nu^2)} \begin{pmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{(1-\nu)}{2} \end{pmatrix}$$

where:

E is Young's modulus;

ν is Poisson's ratio.

For some applications it may be desired to use different material and section properties to define the different sub-matrices of D'. When this is desired, the following form of D' is obtained:

$$D' = \begin{pmatrix} h_m\,D_{mm} & h_b\,p\,D_{mc} \\ h_b\,p\,D_{mc} & (\frac{1}{12}h_b^3 + h_b\,p^2)\,D_{mb} \end{pmatrix}$$

where:

D_{mm} is the membrane elasticity matrix;

D_{mb} is the bending elasticity matrix;

D_{mc} is the membrane - bending coupling matrix;

h_m is the membrane thickness;

h_b is the bending thickness.

For some applications it may be desirable to use separate material and section properties for shear behaviour. In this case an aggregate constitutive matrix can be formed to relate shear strain to shear force as follows:

$$\begin{pmatrix} V_x \\ V_y \end{pmatrix} = h_s\,D_s \begin{pmatrix} \varepsilon_{xz} \\ \varepsilon_{yz} \end{pmatrix}$$

where:

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V_x, V_y are components of shear force;

$\varepsilon_{xz}, \varepsilon_{yz}$ are components of shear strain;

h_s is the effective shear thickness for transverse shear;

D_s is the elasticity matrix for shear.

For an isotropic material the elasticity matrix D_s has the form:

$$D_s = G \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

where:

G is the shear modulus.

NOTE 3 The relationships of the surface element property subtypes are shown in the EXPRESS-G Partial Model in Figure 56.

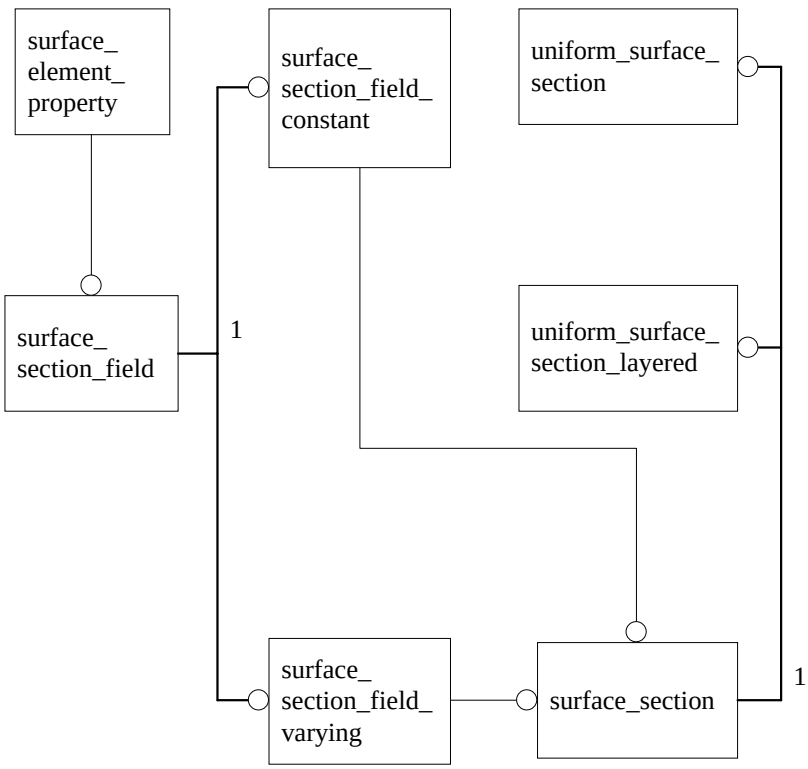

Figure 56 – Surface element properties EXPRESS-G partial model

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5.13.2 Curve element properties

Curve elements, like surface elements, are idealised volumes, and as such require other property values, such as cross-sectional area, to complete their definition.

A curve element has a single parametric axis that is established graphically in 5.8. The position of this axis is defined by the positions of the nodes of an element, the shape functions of an element, and any element end offsets.

The parametric axis runs between the end positions of the element.

NOTE 1 The end positions can be offset from the end nodes of an element as shown in Figure 57.

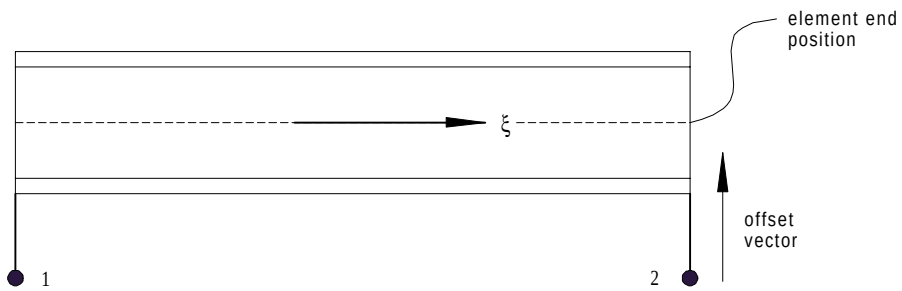

Figure 57 – Curve element end offsets

The parametric axis cannot be offset from the mid-span nodes of higher order curve elements.

Curve element section properties are defined with respect to the y and z axes of the property coordinate system of an element, whose origin is on the parametric axis of the element.

NOTE 2 Neither the section centroid or shear centre need to lie on the parametric axis of the element as shown in Figure 58.

A curve 3D element can be divided into intervals that may have different material and property specifications. The intervals within a curve element shall be defined in a sequence from node 1 to node 2. For each interval except the last, the position of the interval end that is closest to end 2 of the element shall be specified. A parametric position of 1.0 is specified for the last interval to ensure that it ends at the end of the element. A position within a curve element is defined with respect to the parametric coordinate system for the element such that:

— position -1.0 is the end of the element closest to node 1;

— position 1.0 is the end of the element closest to node 2.

NOTE 3 An element divided into 2 equal length intervals is shown in Figure 59.

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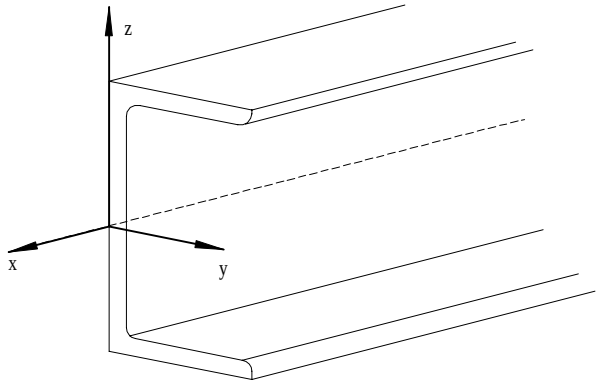

Figure 58 – Curve element property coordinate system origin orientation

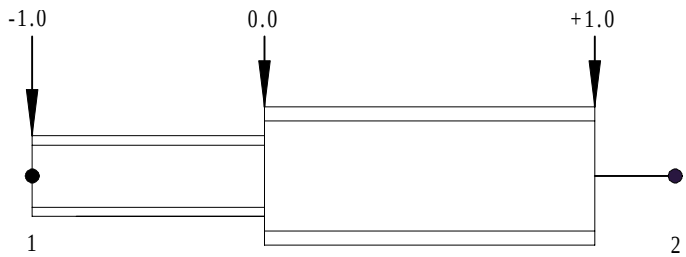

Figure 59 – Curve element interval specification conventions

The end fixings of a curve 3D element determine the way in which it is connected to its nodes. A fixing is described by an end offset and an end release, as described in the following two paragraphs.

The end of a curve element can be offset from its node so that a rigid body provides the link between the end of the element and the node. The offset is defined as the distance from the node to the end position of the element. This distance can be specified with respect to an arbitrary coordinate system or the property coordinate system at the end of the element. The orientation of the property coordinate system may itself depend on the offset.

One or more degrees of freedom can be released between a node and the end of the element. For each released degree of freedom, a connecting stiffness shall be specified (which may be zero). The released degrees of freedom may be specified with respect to an arbitrary coordinate system or the property coordinate system at the end of the element. The strain energy V associated with the release is given by:

$$V = \frac{1}{2}\, k\, d^2$$

where:

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k is the release stiffness;

d is the difference between the displacement for the degree of freedom on either side of the release.

If a release and offset are specified at the same end of the element then the release acts between the node and the rigid body linking the end of the element to the node.

NOTE 4 A release and offset are both shown in Figure 60.

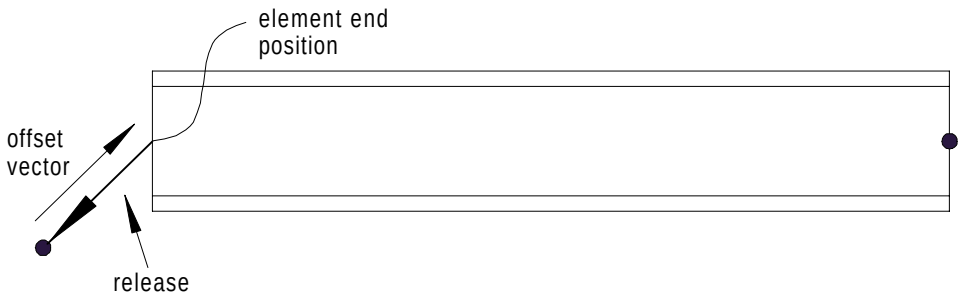

Figure 60 – Curve element end release and end offset

NOTE 5 The relationships of the surface element property subtypes are shown in the EXPRESS-G Partial Model in Figure 61.

5.13.3 surface_element_property

A **surface_element_property** is the section properties for a surface element.

NOTE The material of the surface is specified by subtypes of **fea_material_property_representation_-item**. Material property subtypes that apply to surface elements have a rule associating the property to an element. If several material property matrices are needed then each would be an instance of a separate environment in an **fea_material_property_representation_item**.

EXAMPLE Membrane, bending, membrane-bending coupling, or shear are types of material property matrices.

EXPRESS specification:

```
*)
ENTITY surface_element_property;
  property_id                : identifier;
  description                : text;
  section                    : surface_section_field;
END_ENTITY;
(*
```

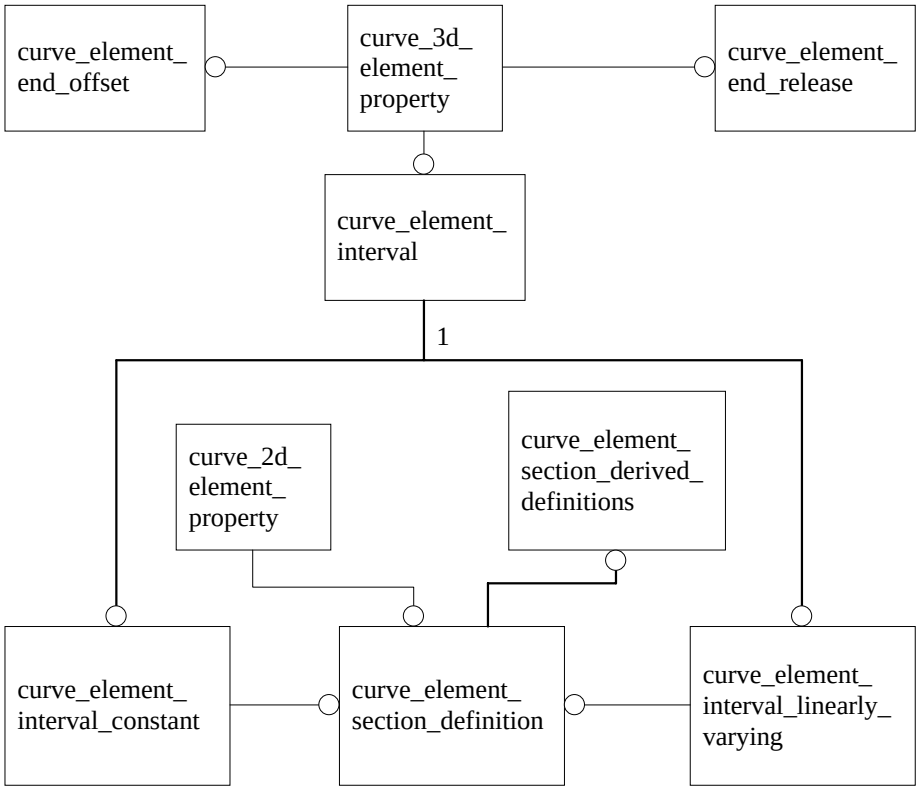

Figure 61 – Curve element properties EXPRESS-G partial model

Attribute definitions:

property_id: an application defined identifier of the surface element properties.

description: the surface element properties.

section: the properties over the field of the surface element.

Informal propositions:

IP1: the combination of an **fea_model** referenced by an element using a **surface_element_property** and **property_id** shall be unique within a finite element analysis model.

5.13.4 surface_section_field

A **surface_section_field** is a surface section field that shall be either constant or varying.

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EXPRESS specification:

```
*)
ENTITY surface_section_field
  SUPERTYPE OF (ONEOF (surface_section_field_constant,
                       surface_section_field_varying));
END_ENTITY;
(*
```

5.13.5 surface_section_field_constant

A **surface_section_field_constant** is a surface section field that has a constant value over the field of a surface element.

EXPRESS specification:

```
*)
ENTITY surface_section_field_constant
  SUBTYPE OF (surface_section_field);
  definition                : surface_section;
END_ENTITY;
(*
```

Attribute definitions:

definition: the surface section definition for the surface element. There is only one value that is constant over the entire surface.

5.13.6 surface_section_field_varying

A **surface_section_field_varying** is a surface section field that varies over the field of a surface element. The values in the surface section definition list (which correspond in order to the node list) are interpolated using the element shape functions.

EXPRESS specification:

```
*)
ENTITY surface_section_field_varying
  SUBTYPE OF (surface_section_field);
  definitions               : LIST [1:?] OF surface_section;
  additional_node_values    : BOOLEAN;
END_ENTITY;
(*
```

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Attribute definitions:

definition: the surface section definition for the surface element. The values in the surface section definition list (which correspond in order to the node list) are interpolated using the element shape functions.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or just the vertex nodes (FALSE).

5.13.7 surface_section

A **surface_section** is a surface section definition that shall be uniform, with or without layers.

EXPRESS specification:

```
*)
ENTITY surface_section
  SUPERTYPE OF (ONEOF (uniform_surface_section,
                       uniform_surface_section_layered));
  offset                     : measure_or_unspecified_value;
  non_structural_mass        : measure_or_unspecified_value;
  non_structural_mass_offset : measure_or_unspecified_value;
END_ENTITY;
(*
```

Attribute definitions:

offset: the distance between the neutral plane for bending and the reference surface which is defined by the positions of the nodes and the element shape functions. Surface element properties are defined with respect to the property coordinate system of the element. If the offset is positive, the neutral plane for bending is on the same side of the reference plane as the positive 3 direction of the property coordinate system.

non_structural_mass: the non-structural mass per unit area of the reference plane of the surface element. This mass is in addition to the structural mass which is calculated from the volume of the element and the density of the material of the element.

non_structural_mass_offset: the offset direction which is defined with respect to the reference plane of the surface which in turn is defined by the positions of the nodes and the element shape functions. Surface element properties are defined with respect to the property coordinate system of the element. If the offset is positive, the offset direction is on the same side of the reference plane as the positive 3 direction of the property coordinate system.

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5.13.8 uniform_surface_section

A **uniform_surface_section** is a surface section field that is uniform through the thickness of a surface element.

EXPRESS specification:

```
*)
ENTITY uniform_surface_section
  SUBTYPE OF (surface_section);
  thickness                 : context_dependent_measure;
  bending_thickness         : measure_or_unspecified_value;
  shear_thickness           : measure_or_unspecified_value;
END_ENTITY;
(*
```

Attribute definitions:

thickness: the membrane thickness of the surface element.

bending_thickness: this attribute specifies the effective thickness for bending of the surface. If it is not supplied, it is assumed to be of the same value as **thickness**.

shear_thickness: the effective thickness for transverse shear (shear normal to the reference plane). This attribute shall be supplied if the surface element permits shear deformation. If it is not supplied for an element that supports shear deformation, then the analysis program shall use the appropriate value for a uniform shell.

5.13.9 uniform_surface_section_layered

A **uniform_surface_section_layered** is a surface section field that is layered through the thickness of a surface element. All layer information shall be specified in a using application protocol. The thickness, and if necessary the bending and shear thickness of the element shall be specified by the sum of the layer thicknesses and the layer properties and orientations.

EXPRESS specification:

```
*)
ENTITY uniform_surface_section_layered
  SUBTYPE OF (surface_section);
END_ENTITY;
(*
```

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5.13.10 fea_surface_section_geometric_relationship

An **fea_surface_section_geometric_relationship** is the association of a surface section definition to a geometric shape representation item.

EXPRESS specification:

```
*)
ENTITY fea_surface_section_geometric_relationship;
  section_ref                : surface_section;
  item                       : analysis_item_within_representation;
WHERE
  WR1: 'GEOMETRY_SCHEMA.GEOMETRIC_REPRESENTATION_ITEM' IN TYPEOF(item.item);
END_ENTITY;
(*
```

Attribute definitions:

section_ref: the surface section definition being related to geometry.

item: the geometric representation item to which the surface section definition is being related.

Formal propositions:

WR1: the representation item associated with the surface section definition shall be a geometric representation item.

5.13.11 curve_3d_element_property

A **curve_3d_element_property** is a cross-section for a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_property;
  property_id                : identifier;
  description                : text;
  interval_definitions       : LIST [1:?] OF curve_element_interval;
  end_offsets                : ARRAY [1:2] OF curve_element_end_offset;
  end_releases               : ARRAY [1:2] OF curve_element_end_release;
END_ENTITY;
(*
```

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Attribute definitions:

property_id: an application defined identifier for the property, and is unique within the finite element analysis model.

description: the curve element properties.

interval_definitions: the material and section properties for each of the element intervals. The intervals shall be defined in sequence beginning with the interval closest to node 1 and ending with the interval closest to node 2.

end_offsets: the end offsets for the curve element. The item 1 of the array references the definition of the end offset at node 1 of the element. Item 2 references the definition of the end offset at node 2 of the element.

end_releases: the end releases for the curve element. The item 1 of the array references the definition of the end release at node 1 of the element. Item 2 references the definition of the end release at node 2 of the element.

Informal propositions:

IP1: the combination of an **fea_model** and **property_id** shall be unique within a finite element analysis model.

5.13.12 curve_element_interval

A **curve_element_interval** is a curve element interval that shall be either constant or linearly varying.

EXPRESS specification:

```
*)
ENTITY curve_element_interval
  SUPERTYPE OF (ONEOF (curve_element_interval_constant,
                       curve_element_interval_linearly_varying));
  finish_position           : curve_element_location;
  eu_angles                 : euler_angles;
END_ENTITY;
(*
```

Attribute definitions:

finish_position: the position of the end of the interval closest to node 2 of the curve element. The position is defined by the coordinate with respect to the parametric axis established graphically in 5.8. The intervals of a curve element are listed in the attribute **interval_definitions** of the curve_3d_element_-property. The start position for each interval in the list (except the first) is the finish position of the previous interval. The start position for the first interval in the list has a parametric coordinate -1.0. This

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is the end at node 1. The finish position for the last interval has a parametric coordinate of 1.0. A finish position of 1.0 shall be supplied for the last interval in the list.

eu_angles: three Euler angles that define a relative coordinate system with respect to the element parametric coordinate system that is used to define the material directions. The x material direction shall be aligned with the relative coordinate system x axis, similarly the material y direction shall be aligned with the relative coordinate system y axis, and the material z direction shall be aligned with the relative coordinate systems z axis.

5.13.13 curve_element_interval_constant

A **curve_element_interval_constant** is a curve section that is constant over an interval of a curve element.

EXPRESS specification:

```
*)
ENTITY curve_element_interval_constant
  SUBTYPE OF (curve_element_interval);
  section                : curve_element_section_definition;
END_ENTITY;
(*
```

Attribute definitions:

section: the section definition for the interval.

5.13.14 curve_element_interval_linearly_varying

A **curve_element_interval_linearly_varying** is a curve section that varies linearly over an interval of a curve element.

EXPRESS specification:

```
*)
ENTITY curve_element_interval_linearly_varying
  SUBTYPE OF (curve_element_interval);
  sections               : ARRAY [1:2] OF curve_element_section_definition;
END_ENTITY;
(*
```

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Attribute definitions:

sections: the section definitions at each end of the interval. Item 1 of the array references the section at the end of the interval nearest to node 1 of the element. Item 2 of the array references the section at the end of the interval nearest to node 2 of the element.

5.13.15 curve_2d_element_property

A **curve_2d_element_property** is the section properties of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_property;
  property_id                : identifier;
  description                : text;
  section                    : curve_element_section_definition;
END_ENTITY;
(*
```

Attribute definitions:

property_id: an application defined identifier for the property, which is unique within the finite element analysis model.

description: the curve element properties.

section: the section definition for the element.

Informal propositions:

IP1: the combination of an **fea_model** and **property_id** shall be unique within a finite element analysis model.

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5.13.16 curve_element_section_definition

A **curve_element_section_definition** is the section at a point on the curve element.

EXPRESS specification:

```
*)
ENTITY curve_element_section_definition
  SUPERTYPE OF (curve_element_section_derived_definitions);
  description               : text;
  section_angle             : plane_angle_measure;
END_ENTITY;
(*
```

Attribute definitions:

description: the curve element definition.

section_angle: the orientation angle of the curve element section about the curve element x axis. The angle is positive with respect to the right hand rule.

5.13.17 curve_element_section_derived_definitions

A **curve_element_section_derived_definitions** is cross-sectional information for a curve element.

EXPRESS specification:

```
*)
ENTITY curve_element_section_derived_definitions
  SUBTYPE OF (curve_element_section_definition);
  cross_sectional_area      : context_dependent_measure;
  shear_area                : ARRAY [1:2] OF measure_or_unspecified_value;
  second_moment_of_area     : ARRAY [1:3] OF context_dependent_measure;
  torsional_constant        : context_dependent_measure;
  warping_constant          : measure_or_unspecified_value;
  location_of_centroid      : ARRAY [1:2] OF measure_or_unspecified_value;
  location_of_shear_centre  : ARRAY [1:2] OF measure_or_unspecified_value;
  location_of_non_structural_mass
                            : ARRAY [1:2] OF measure_or_unspecified_value;
  non_structural_mass       : measure_or_unspecified_value;
  polar_moment              : measure_or_unspecified_value;
END_ENTITY;
(*
```

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Attribute definitions:

cross_sectional_area: the cross sectional area of the section.

shear_area: the shear area of the section. Array item 1 specifies the shear area effective for deformation in the xy plane of the property coordinate system. Array item 2 specifies the shear area effective for deformation in the xz plane of the property coordinate system. An Eulerian beam formulation assumes that there is no shear deformation, that is, the shear area is infinite. For such elements no shear area need be specified.

second_moment_of_area: the second moments of area about the section centroid. The components of the inertia tensor with respect to the y and z axes of the property coordinate system are stored as follows: array item 1 contains I_{yy}, array item 2 contains I_{zz}, array item 3 contains I_{yz}.

torsional_constant: the torsional stiffness of the section. A precise definition of this attribute without any warping contributions is as follows:

$$\frac{\Delta\theta}{\Delta L} = \frac{T}{J\,G}$$

where:

θ is the angle of twist;

T is the applied torsional moment;

L is the length of the curve;

J is the torsional constant whose units are $(length)^4$;

G is the shear modulus of the material.

warping_constant: the warping coefficient of the section. The torsional behaviour of a curve element is described by the torsional constant and the warping coefficient using the following equation:

$$T = G\,J\,\frac{\partial\theta}{\partial x} - E\,\frac{\partial^2}{\partial x^2}(C_w\,\frac{\partial\theta}{\partial x})$$

where:

T is the applied torsional moment;

J is the torsional constant;

G is the shear modulus of the material;

C_w is the warping constant whose units are $(length)^6$;

E is the elastic modulus of the material;

θ is the angle of twist;

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x is distance along the $\mathbf{x}$ axis of the curve element.

location_of_centroid: The distance of the section centroid from the parametric axis. Array item 1 specifies the distance in the direction of the property coordinate system $\mathbf{x}$ axis. Array item 2 specifies the distance in the direction of the property coordinate system $\mathbf{y}$ axis.

location_of_shear_centre: The distance of the section shear centre from the parametric axis. Array item 1 specifies the distance in the direction of the property coordinate system $\mathbf{x}$ axis. Array item 2 specifies the distance in the direction of the property coordinate system $\mathbf{y}$ axis.

location_of_non_structural_mass: The distance of the non-structural mass from the parametric axis. Array item 1 specifies the distance in the direction of the property coordinate system $\mathbf{x}$ axis. Array item 2 specifies the distance in the direction of the property coordinate system $\mathbf{y}$ axis.

non_structural_mass: the non-structural mass per unit length of the curve element parametric axis.

polar_moment: the polar moment of area of the curve element. This attribute is used to calculate the dynamic inertia of the curve element. It is NOT used to calculate the torsional stiffness. The polar moment is the sum of the perpendicular moments unless there are contributions from non-structural mass.

5.13.18 fea_curve_section_geometric_relationship

An **fea_curve_section_geometric_relationship** is the association of a curve section definition to a geometric shape representation item.

EXPRESS specification:

```
*)
ENTITY fea_curve_section_geometric_relationship;
  section_ref                : curve_element_section_definition;
  item                       : analysis_item_within_representation;
WHERE
  WR1: 'GEOMETRY_SCHEMA.GEOMETRIC_REPRESENTATION_ITEM' IN TYPEOF(item.item);
END_ENTITY;
(*
```

Attribute definitions:

section_ref: the curve section definition being related to geometry.

item: the geometric representation item to which the curve section definition is being related.

Formal propositions:

WR1: the representation item associated with the curve section definition shall be a geometric representation item.

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5.13.19 curve_element_end_offset

A **curve_element_end_offset** is the offset of the end attachment of a curve element.

EXPRESS specification:

```
*)
ENTITY curve_element_end_offset;
  coordinate_system         : curve_element_end_coordinate_system;
  offset_vector             : ARRAY [1:3] OF context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

coordinate_system: the coordinate system that is used to specify the end offset.

offset_vector: the distance from the node to the end position of the element with respect to the local orthogonal triad of the specified coordinate system at the node.

5.13.20 curve_element_end_release

A **curve_element_end_release** are the releases of a curve element end.

EXPRESS specification:

```
*)
ENTITY curve_element_end_release;
  coordinate_system        : curve_element_end_coordinate_system;
  releases                 : LIST [1:?] OF curve_element_end_release_packet;
END_ENTITY;
(*
```

Attribute definitions:

coordinate_system: the coordinate system that is used to specify the end release.

releases: pairs of the degrees of freedom released between the node and the element with respect to the orthogonal triad of the specified coordinate system evaluated at the node, and the associated release stiffness.

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5.13.21 curve_element_end_release_packet

A **curve_element_end_release_packet** is the release degree of freedom and stiffness of a curve element end. If a degree of freedom is not released then the joint stiffness is infinite.

EXPRESS specification:

```
*)
ENTITY curve_element_end_release_packet;
  release_freedom           : curve_element_freedom;
  release_stiffness         : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

release_freedom: the degrees of freedom released between the node and the element with respect to the orthogonal triad of the specified coordinate system evaluated at the node. If there are no releases then the enumeration of **none** shall be used.

release_stiffness: the stiffness associated with the degree of freedom. If no stiffnesses are desired, the value is set to 0.0.

5.13.22 axisymmetric_2d_element_property

An **axisymmetric_2d_element_property** defines the properties for all types of axisymmetric 2D elements.

EXPRESS specification:

```
*)
ENTITY axisymmetric_2d_element_property;
  angle                     : plane_angle_measure;
END_ENTITY;
(*
```

Attribute definitions:

angle: the segment considered in an axisymmetric analysis.

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5.13.23 plane_2d_element_property

A **plane_2d_element_property** defines the properties for all types of plane 2D elements.

EXPRESS specification:

```
*)
ENTITY plane_2d_element_property
  SUPERTYPE OF (simple_plane_2d_element_property);
  depth                    : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

depth: a depth of a plane stress or plane strain section.

5.13.24 simple_plane_2d_element_property

A **simple_plane_2d_element_property** has no further properties.

NOTE This entity is supplied for extensibility of the information model.

EXPRESS specification:

```
*)
ENTITY simple_plane_2d_element_property
  SUBTYPE OF (plane_2d_element_property);
END_ENTITY;
(*
```

5.14 Structural response representation schema entity definitions: Groups

A group is a set of elements, nodes or groups within the FEA information model. A group may be used to collect entities that have a common attribute such as colour.

5.14.1 fea_group

An **fea_group** is a group that shall be either be a group of elements or nodes.

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EXPRESS specification:

```
*)
ENTITY fea_group
  SUPERTYPE OF (ONEOF(element_group,
                      node_group))
  SUBTYPE OF (group);
  model_ref                 : fea_model;
END_ENTITY;
(*
```

Attribute definitions:

model_ref: an application definied identifier of the **fea_model** which possesses the group.

NOTE The group id, a unique application defined identifier of an **fea_group** is specified by the **name** attribute of the **group** supertype. Similarly a description is specified by the **description** attribute of the **group** supertype.

EXAMPLE The description may be whatever label the analyst chooses for group identification, such as 'Bu 1', 'AY_0328', or 'eseridir'.

Informal propositions:

IP1: the combination of an **fea_model** and group id shall be unique within a finite element analysis model.

5.14.2 element_group

An **element_group** is a group containing only elements.

EXPRESS specification:

```
*)
ENTITY element_group
  SUBTYPE OF (fea_group);
  elements                  : SET [1:?] OF element_representation;
END_ENTITY;
(*
```

Attribute definitions:

elements: the elements being grouped.

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5.14.3 node_group

A **node_group** is a group containing only nodes.

EXPRESS specification:

```
*)
ENTITY node_group
  SUBTYPE OF (fea_group);
  nodes                    : SET [1:?] OF node_representation;
END_ENTITY;
(*
```

Attribute definitions:

nodes: the nodes being grouped.

5.14.4 fea_group_relation

An **fea_group_relation** is an aggregation of FEA groups.

EXPRESS specification:

```
*)
ENTITY fea_group_relation
  SUBTYPE OF (group_relationship);
WHERE
  WR1: 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.FEA_GROUP'
       IN TYPEOF (SELF\group_relationship.relating_group);
  WR2: 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.FEA_GROUP'
       IN TYPEOF (SELF\group_relationship.related_group);
END_ENTITY;
(*
```

Formal propositions:

WR1: the relating_group attribute shall be associated with an **fea_group**.

WR2: the related_group attribute shall be associated with an **fea_group**.

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5.14.5 volume_3d_element_group

An **volume_3d_element_group** is a group containing only volume 3D elements.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_group
  SUBTYPE OF (element_group);
WHERE
  WR1: SIZEOF(query(item <* elements |
       NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
            'VOLUME_3D_ELEMENT_REPRESENTATION' IN TYPEOF (item))))=0;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be only **volume_3d_element_representation** entities in the group.

5.14.6 volume_2d_element_group

A **volume_2d_element_group** is a group containing only volume 2D elements.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_group
  SUBTYPE OF (element_group);
WHERE
  WR1: SIZEOF(QUERY(item <* elements |
       (NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
             'AXISYMMETRIC_VOLUME_2D_ELEMENT_REPRESENTATION'
              IN TYPEOF(item)) AND
        NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
             'PLANE_VOLUME_2D_ELEMENT_REPRESENTATION'
              IN TYPEOF(item)))))=0;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be only volume 2d element representation entities in the group.

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5.14.7 surface_3d_element_group

A **surface_3d_element_group** is a group containing only surface 3D elements.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_group
  SUBTYPE OF (element_group);
WHERE
  WR1: SIZEOF(query(item <* elements |
       NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
            'SURFACE_3D_ELEMENT_REPRESENTATION' IN TYPEOF (item))))=0;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be only **surface_3d_element_representation** entities in the group.

5.14.8 surface_2d_element_group

A **surface_2d_element_group** is a group containing only surface 2D elements.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_group
  SUBTYPE OF (element_group);
WHERE
  WR1: SIZEOF(QUERY(item <* elements |
       (NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
             'AXISYMMETRIC_SURFACE_2D_ELEMENT_REPRESENTATION'
              IN TYPEOF(item)) AND
        NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
             'PLANE_SURFACE_2D_ELEMENT_REPRESENTATION'
              IN TYPEOF(item)))))=0;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be only surface 2D element representation entities in the group.

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5.14.9 curve_3d_element_group

A **curve_3d_element_group** is a group containing only curve 3D elements.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_group
  SUBTYPE OF (element_group);
WHERE
  WR1: SIZEOF(query(item <* elements |
       NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
            'CURVE_3D_ELEMENT_REPRESENTATION' IN TYPEOF (item))))=0;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be only **curve_3d_element_representation** entities in the group.

5.14.10 curve_2d_element_group

A **curve_2d_element_group** is a group containing only curve 2D elements.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_group
  SUBTYPE OF (element_group);
WHERE
  WR1: SIZEOF(QUERY(item <* elements |
       (NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
             'AXISYMMETRIC_CURVE_2D_ELEMENT_REPRESENTATION'
              IN TYPEOF(item)) AND
        NOT ('STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.'+
             'PLANE_CURVE_2D_ELEMENT_REPRESENTATION'
              IN TYPEOF(item)))))=0;
END_ENTITY;
(*
```

Formal propositions:

WR1: there shall be only curve 2D element representation entities in the group.

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5.15 Structural response representation schema function definitions

These definitions are used to ensure the correctness of information in many of the finite element analysis model schema information model entities.

5.15.1 required_0d_nodes

A **required_0d_nodes** verifies that the node list for a 0D (point) element contains a single node.

EXPRESS specification:

```
*)
FUNCTION required_0d_nodes
  (node_list                : LIST [1:?] OF node_representation): BOOLEAN;

  RETURN (SIZEOF (node_list) = 1);

END_FUNCTION;
(*
```

Argument definitions:

node_list: input argument consisting of a list of one to many of the nodes in a 0D element.

5.15.2 required_1d_nodes

A **required_1d_nodes** verifies that the node list for a 1D (curve) element contains the proper number of nodes based on the order of the element. The number of nodes shall be equal to the number of end nodes, plus any additional nodes for the element.

EXPRESS specification:

```
*)
FUNCTION required_1d_nodes
  (node_list                : LIST [1:?] OF node_representation;
   order                    : element_order) : BOOLEAN;

  LOCAL
   end_nodes                : INTEGER;
   additional_nodes         : INTEGER;
  END_LOCAL;

  end_nodes := 2;
```

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```
  IF (order = linear) THEN
    additional_nodes := 0;
  END_IF;
  IF (order = quadratic) THEN
    additional_nodes := 1;
  END_IF;
  IF (order = cubic) THEN
    additional_nodes := 2;
  END_IF;

  RETURN (SIZEOF (node_list) = end_nodes + additional_nodes);

END_FUNCTION;
(*
```

Argument definitions:

node_list: input argument consisting of a list of one to many of the nodes in a 1D element.

order: input argument defining the geometric order of interpolation of the element.

5.15.3 required_2d_nodes

A **required_2d_nodes** verifies that the node list for a 2D element (triangle or quadrilateral) contains the proper number of nodes based on the shape and order of the element. The number of nodes shall be equal to either the sum of the vertex and edge nodes, or the sum of the vertex, edge, face, and body nodes for the element.

EXPRESS specification:

```
*)
FUNCTION required_2d_nodes
  (node_list                : LIST [1:?] OF node_representation;
   element_shape            : element_2d_shape;
   order                    : element_order) : BOOLEAN;
  LOCAL
    vertex_nodes            : INTEGER;
    edge_nodes              : INTEGER;
    edge_face_body_nodes    : INTEGER;
  END_LOCAL;

  IF (element_shape = triangle) THEN
    vertex_nodes := 3;
    IF (order = linear) THEN
      edge_nodes           := 0;
      edge_face_body_nodes := 0;
    END_IF;
    IF (order = quadratic) THEN
```

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```
      edge_nodes           := 3;
      edge_face_body_nodes := 3;
    END_IF;
    IF (order = cubic) THEN
      edge_nodes           := 6;
      edge_face_body_nodes := 7;
    END_IF;
  END_IF;

  IF (element_shape = quadrilateral) THEN
    vertex_nodes := 4;
    IF (order = linear) THEN
      edge_nodes           := 0;
      edge_face_body_nodes := 0;
    END_IF;
    IF (order = quadratic) THEN
      edge_nodes           := 4;
      edge_face_body_nodes := 5;
    END_IF;
    IF (order = cubic) THEN
      edge_nodes           := 8;
      edge_face_body_nodes := 12;
    END_IF;
  END_IF;

  RETURN ((SIZEOF (node_list) = vertex_nodes + edge_nodes) OR
          (SIZEOF (node_list) = vertex_nodes + edge_face_body_nodes));

END_FUNCTION;
(*
```

Argument definitions:

node_list: input argument consisting of a list of one to many of the nodes in a 2D element.

element_shape: input argument defining the geometric shape of the element.

order: input argument defining the geometric order of interpolation of the element.

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5.15.4 required_3d_nodes

A **required_3d_nodes** verifies that the node list for a 3D (hexahedron, wedge, tetrahedron, or pyramid) element contains the proper number of nodes based on the shape and order of the element. The number of nodes shall be equal to either the sum of the vertex and edge nodes, or the sum of the vertex, edge, face, and body nodes for the element.

EXPRESS specification:

```
*)
FUNCTION required_3d_nodes
  (node_list                : LIST [1:?] OF node_representation;
   element_shape            : volume_3d_element_shape;
   order                    : element_order) : BOOLEAN;
  LOCAL
    vertex_nodes            : INTEGER;
    edge_nodes              : INTEGER;
    edge_face_body_nodes    : INTEGER;
  END_LOCAL;

  IF (element_shape = hexahedron) THEN
    vertex_nodes := 8;
    IF (order = linear) THEN
      edge_nodes           := 0;
      edge_face_body_nodes := 0;
    END_IF;
    IF (order = quadratic) THEN
      edge_nodes           := 12;
      edge_face_body_nodes := 19;
    END_IF;
    IF (order = cubic) THEN
      edge_nodes           := 24;
      edge_face_body_nodes := 56;
    END_IF;
  END_IF;

  IF (element_shape = wedge) THEN
    vertex_nodes := 6;
    IF (order = linear) THEN
      edge_nodes           := 0;
      edge_face_body_nodes := 0;
    END_IF;
    IF (order = quadratic) THEN
      edge_nodes           := 9;
      edge_face_body_nodes := 12;
    END_IF;
    IF (order = cubic) THEN
      edge_nodes           := 18;
      edge_face_body_nodes := 34;
```

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```
    END_IF;
  END_IF;

  IF (element_shape = tetrahedron) THEN
    vertex_nodes := 4;
    IF (order = linear) THEN
      edge_nodes           := 0;
      edge_face_body_nodes := 0;
    END_IF;
    IF (order = quadratic) THEN
      edge_nodes           := 6;
      edge_face_body_nodes := 6;
    END_IF;
    IF (order = cubic) THEN
      edge_nodes           := 12;
      edge_face_body_nodes := 16;
    END_IF;
  END_IF;

  IF (element_shape = pyramid) THEN
    vertex_nodes := 5;
    IF (order = linear) THEN
      edge_nodes           := 0;
      edge_face_body_nodes := 0;
    END_IF;
    IF (order = quadratic) THEN
      edge_nodes           := 8;
      edge_face_body_nodes := 9;
    END_IF;
    IF (order = cubic) THEN
      edge_nodes           := 16;
      edge_face_body_nodes := 25;
    END_IF;
  END_IF;

  RETURN ((SIZEOF (node_list) = vertex_nodes + edge_nodes) OR
          (SIZEOF (node_list) = vertex_nodes + edge_face_body_nodes));

END_FUNCTION;
(*
```

Argument definitions:

node_list: input argument consisting of a list of one to many of the nodes in a 3D element.

element_shape: input argument defining the geometric shape of the element.

order: input argument defining the geometric order of interpolation of the element.

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5.15.5 number_of_terms

A **number_of_terms** is used to derive the number of terms in a matrix.

EXPRESS specification:

```
*)
FUNCTION number_of_terms
  (node_dof_list           : LIST [1:?] OF LIST [1:?] OF degree_of_freedom;
   matrix_type             : matrix_symmetry) : INTEGER;
  LOCAL
    num_terms              : INTEGER;
    number_of_freedoms     : INTEGER;
  END_LOCAL;

  number_of_freedoms := 0; (* loop for each item in the outer list*)

  REPEAT i := 1 TO SIZEOF (node_dof_list); (* find size of inner list*)
    number_of_freedoms := number_of_freedoms + SIZEOF (node_dof_list[i]);
  END_REPEAT;

  IF (matrix_type = symmetric) THEN
    num_terms := (number_of_freedoms * (number_of_freedoms+1)) DIV 2;
  END_IF;

  IF (matrix_type = diagonal) THEN
    num_terms := number_of_freedoms;
  END_IF;

RETURN (num_terms);

END_FUNCTION;
(*
```

Argument definitions:

node_dof_list: input argument consisting of a list of one to many of a list of one to many of the degrees of freedom in a matrix.

matrix_symmetry: input argument defining the type of symmetry for the matrix.

number_of_terms: integer output argument that is set to the total number of terms in the matrix.

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5.15.6 valid_parametric_coordinate

A **valid_parametric_coordinate** ensures each of the parametric coordinates lies in the range from -1.0 to +1.0.

EXPRESS specification:

```
*)
FUNCTION valid_parametric_coordinate
    (coordinates            :  LIST [1:3] OF parameter_value): BOOLEAN;

    LOCAL
      i                     : INTEGER;
    END_LOCAL;

    REPEAT i:=1 TO HIINDEX(coordinates);
      IF ((1.0 < coordinates[i]) OR (coordinates[i] < -1.0)) THEN
        RETURN (FALSE);
      END_IF;
    END_REPEAT;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

coordinates: input argument consisting of the element parametric coordinates that are being checked.

5.15.7 build_direction_node

A **build_direction_node** calculates the components of a direction that is defined by a vector from **node_-1** to **node_2**. The components are expressed in a cartesian coordinate space whose axes are coincident with those of the cartesian, cylindrical, or spherical coordinate space defining the location of the first node in the argument list.

EXPRESS specification:

```
*)
FUNCTION build_direction_node
    (node_1                 : node_representation;
     node_2                 : node_representation): LIST [2:3] OF REAL;

LOCAL
```

```
  nodal_direction_ratios    : LIST [2:3] OF REAL;
  u                         : direction;
  i                         : INTEGER;
  ndim                      : INTEGER;
  rep_items                 : SET [1:?] of representation_item;
  node_1_point              : cartesian_point;
  node_2_point              : cartesian_point;
END_LOCAL;

rep_items := node_1.items;
REPEAT i := 1 TO SIZEOF(rep_items);
  IF ('GEOMETRY_SCHEMA.CARTESIAN_POINT' IN TYPEOF(rep_items[i])) THEN
    node_1_point := rep_items[i];
    ESCAPE;
  END_IF;
END_REPEAT;

rep_items := node_2.items;
REPEAT i := 1 TO SIZEOF(rep_items);
  IF ('GEOMETRY_SCHEMA.CARTESIAN_POINT' IN TYPEOF(rep_items[i])) THEN
    node_2_point := rep_items[i];
    ESCAPE;
  END_IF;
END_REPEAT;

ndim := HIINDEX(node_2_point.coordinates);
REPEAT i := 1 TO ndim;
  u.direction_ratios[i] := node_2_point.coordinates[i] -
                           node_1_point.coordinates[i];
END_REPEAT;

u := normalise (u);
REPEAT i := 1 TO ndim;
  nodal_direction_ratios[i] := u.direction_ratios[i];
END_REPEAT;

RETURN (nodal_direction_ratios);

END_FUNCTION;
(*
```

Argument definitions:

node_1: identifies the first node defining the direction. This node is the origin point of the direction.

node_2: identifies the second node defining the direction. This node is the point defining the positive sense of the direction.

nodal_direction_ratios: output argument that contains the calculated direction.

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5.15.8 consistent_geometric_reference

A **consistent_geometric_reference** ensures that a given element aspect (volume, face, edge) is related to the appropriate type of geometric representation item. The element aspect **element_volume** shall be related to a solid model; element aspects **volume_3d_face**, **volume_2d_face**, **surface_3d_face**, and **surface_2d_face** shall be related to either a geometric surface or a topological face surface; and element aspects **volume_3d_edge**, **volume_2d_edge**, **surface_3d_edge**, and **surface_2d_edge** shall be related to either a geometric curve or a topological edge curve. The function shall return TRUE if the element aspect is paired with an appropriate geometric representation item, and return FALSE otherwise.

EXPRESS specification:

```
*)
FUNCTION consistent_geometric_reference (
  aspect                    : GENERIC;
  item                      : geometric_representation_item) : BOOLEAN;

LOCAL
  srrs                      : STRING;
  feacr                     : STRING;
  aspect_type               : SET [1:?] OF STRING;
  item_type                 : SET [1:?] OF STRING;
END_LOCAL;

srrs        := 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.';
feacr       := 'FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.';
aspect_type := TYPEOF (aspect);
item_type   := TYPEOF (item);

IF ('GEOMETRIC_MODEL_SCHEMA.SOLID_MODEL' IN item_type) THEN
  IF ((srrs + 'ELEMENT_VOLUME') IN aspect_type) THEN
    RETURN (TRUE);
  END_IF;
END_IF;

IF (('GEOMETRY_SCHEMA.SURFACE' IN item_type) OR
    ('TOPOLOGY_SCHEMA.FACE_SURFACE' IN item_type)) THEN
  IF SIZEOF ([(feacr + 'VOLUME_3D_FACE'),
              (feacr + 'VOLUME_2D_FACE'),
              (feacr + 'SURFACE_3D_FACE'),
              (feacr + 'SURFACE_2D_FACE')] *
               aspect_type ) = 1 THEN
    RETURN (TRUE);
  END_IF;
END_IF;

IF (('GEOMETRY_SCHEMA.CURVE' IN item_type) OR
    ('TOPOLOGY_SCHEMA.EDGE_CURVE' IN item_type)) THEN
  IF SIZEOF ([(feacr + 'VOLUME_3D_EDGE'),
```

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```
              (feacr + 'VOLUME_2D_EDGE'),
              (feacr + 'SURFACE_3D_EDGE'),
              (feacr + 'SURFACE_2D_EDGE'),
              (srrs  + 'CURVE_EDGE')] *
               aspect_type ) = 1 THEN
    RETURN (TRUE);
  END_IF;
END_IF;

RETURN (FALSE);

END_FUNCTION;
(*
```

Argument definitions:

aspect: identifies the element aspect.

item: identifies the geometric representation item.

5.15.9 consistent_element_or_group_reference

A **consistent_element_or_group_reference** ensures that a given element aspect (face, edge, volume) is consistent with the element type for a given element or set of elements. The function shall return TRUE if the element aspect is associated with the element type for a given element representation, or for all the elements in a given element group.

EXPRESS specification:

```
*)
FUNCTION consistent_element_or_group_reference (
  aspect                    : GENERIC;
  element                   : GENERIC) : BOOLEAN;

LOCAL
  srrs                      : STRING;
  i                         : INTEGER;
END_LOCAL;

srrs := 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.';

IF ((srrs + 'ELEMENT_REPRESENTATION') IN TYPEOF(element)) THEN
  RETURN (consistent_element_reference (aspect, element));
END_IF;

IF ((srrs + 'ELEMENT_GROUP') IN TYPEOF(element)) THEN
  REPEAT i := 1 TO HIINDEX (element.elements);
    IF NOT (consistent_element_reference (aspect, element.elements[i]))
```

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```
     THEN
      RETURN (FALSE);
    END_IF;
  END_REPEAT;
  RETURN (TRUE);
END_IF;

RETURN (FALSE);

END_FUNCTION;
(*
```

Argument definitions:

element: identifies the element or group of elements.

aspect: identifies the element aspect.

5.15.10 consistent_element_reference

A **consistent_element_reference** ensures that a given element aspect (face, edge, volume) is consistent with the element type for an **element_representation**. The element aspect **element_volume** may be associated with any element type; element aspects **volume_3d_face** and **volume_3d_edge** shall be associated with a volume 3D element; element aspects **volume_2d_face** and **volume_2d_edge** shall be associated with a volume 2D element; element aspects **surface_3d_face** and **surface_3d_edge** shall be associated with a surface 3D element; element aspects **surface_2d_face** and **surface_2d_edge** shall be associated with a surface 2D element; and the element aspect **curve_edge** shall be associated with a curve 2D or 3D element. The function shall return TRUE if the element aspect is paired with an appropriate element representation, and return FALSE otherwise.

EXPRESS specification:

```
*)
FUNCTION consistent_element_reference (
  aspect                    : GENERIC;
  element                   : element_representation) : BOOLEAN;

LOCAL
  srrs                      : STRING;
  feacr                     : STRING;
  aspect_type               : SET [1:?] OF STRING;
  element_type              : SET [1:?] OF STRING;
END_LOCAL;

srrs         := 'STRUCTURAL_RESPONSE_REPRESENTATION_SCHEMA.';
feacr        := 'FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.';
aspect_type  := TYPEOF (aspect);
```

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```
element_type := TYPEOF (element);

IF ((srrs + 'ELEMENT_REPRESENTATION')
    IN element_type) THEN
  IF ((srrs + 'ELEMENT_VOLUME') IN aspect_type) THEN
    RETURN (TRUE);
  END_IF;
END_IF;

IF ((srrs + 'VOLUME_3D_ELEMENT_REPRESENTATION')
    IN element_type) THEN
  IF (((feacr + 'VOLUME_3D_FACE') IN aspect_type) OR
      ((feacr + 'VOLUME_3D_EDGE') IN aspect_type)) THEN
    RETURN (TRUE);
  END_IF;
END_IF;

IF (((srrs + 'AXISYMMETRIC_VOLUME_2D_ELEMENT_REPRESENTATION')
     IN element_type) OR
    ((srrs + 'PLANE_VOLUME_2D_ELEMENT_REPRESENTATION')
     IN element_type)) THEN
  IF (((feacr + 'VOLUME_2D_FACE') IN aspect_type) OR
      ((feacr + 'VOLUME_2D_EDGE') IN aspect_type)) THEN
    RETURN (TRUE);
  END_IF;
END_IF;

IF ((srrs + 'SURFACE_3D_ELEMENT_REPRESENTATION')
    IN element_type) THEN
  IF (((feacr + 'SURFACE_3D_FACE') IN aspect_type) OR
      ((feacr + 'SURFACE_3D_EDGE') IN aspect_type)) THEN
    RETURN (TRUE);
  END_IF;
END_IF;

IF (((srrs + 'AXISYMMETRIC_SURFACE_2D_ELEMENT_REPRESENTATION')
    IN element_type) OR
    ((srrs + 'PLANE_SURFACE_2D_ELEMENT_REPRESENTATION')
     IN element_type)) THEN
  IF (((feacr + 'SURFACE_2D_FACE') IN aspect_type) OR
      ((feacr + 'SURFACE_2D_EDGE') IN aspect_type)) THEN
  RETURN (TRUE);
  END_IF;
END_IF;

IF (((srrs + 'CURVE_3D_ELEMENT_REPRESENTATION')
     IN element_type) OR
    ((srrs + 'AXISYMMETRIC_CURVE_2D_ELEMENT_REPRESENTATION')
     IN element_type) OR
    ((srrs + 'PLANE_CURVE_2D_ELEMENT_REPRESENTATION')
     IN element_type)) THEN
  IF ((srrs + 'CURVE_EDGE') IN aspect_type) THEN
```

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```
    RETURN (TRUE);
  END_IF;
END_IF;

RETURN (FALSE);

END_FUNCTION;
(*
```

Argument definitions:

element: identifies the element representation.

aspect: identifies the element aspect.

EXPRESS specification:

```
*)
END_SCHEMA; -- structural_response_representation_schema
(*
```

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6 Finite element analysis control and result schema

The following EXPRESS declaration begins the **finite_element_analysis_control_and_result_schema** and identifies the necessary external references.

EXPRESS specification:

```
*)
SCHEMA finite_element_analysis_control_and_result_schema;

  REFERENCE FROM fea_scalar_vector_tensor_schema
      (anisotropic_symmetric_tensor2_2d,
       anisotropic_symmetric_tensor2_3d,
       anisotropic_symmetric_tensor4_2d,
       isotropic_symmetric_tensor2_3d,
       orthotropic_symmetric_tensor2_3d,
       scalar,
       symmetric_tensor2_2d,
       symmetric_tensor2_3d,
       symmetric_tensor4_2d,
       tensor1,
       tensor1_2d,
       tensor1_3d);

  REFERENCE FROM geometric_model_schema
      (solid_model);

  REFERENCE FROM geometry_schema
      (curve,
       point,
       surface);

  REFERENCE FROM measure_schema
      (context_dependent_measure,
       count_measure,
       length_measure,
       plane_angle_measure);

  REFERENCE FROM structural_response_representation_schema
      (analysis_item_within_representation,
       axisymmetric_curve_2d_element_descriptor,
       axisymmetric_curve_2d_element_representation,
       axisymmetric_surface_2d_element_descriptor,
       axisymmetric_surface_2d_element_representation,
       axisymmetric_volume_2d_element_descriptor,
       axisymmetric_volume_2d_element_representation,
       curve_2d_element_coordinate_system,
       curve_2d_element_descriptor,
       curve_2d_element_group,
       curve_2d_element_representation,
```

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```
        curve_3d_element_coordinate_system,
        curve_3d_element_descriptor,
        curve_3d_element_group,
        curve_3d_element_representation,
        curve_element_location,
        curve_section_element_location,
        curve_volume_element_location,
        degree_of_freedom,
        directionally_explicit_element_representation,
        element_descriptor,
        element_group,
        element_representation,
        explicit_element_representation,
        fea_axis2_placement_3d,
        fea_model,
        node_group,
        node_representation,
        plane_curve_2d_element_descriptor,
        plane_curve_2d_element_representation,
        plane_surface_2d_element_descriptor,
        plane_surface_2d_element_representation,
        plane_volume_2d_element_descriptor,
        plane_volume_2d_element_representation,
        point_element_representation,
        substructure_element_representation,
        surface_2d_element_coordinate_system,
        surface_2d_element_descriptor,
        surface_2d_element_group,
        surface_2d_element_representation,
        surface_3d_element_coordinate_system,
        surface_3d_element_descriptor,
        surface_3d_element_group,
        surface_3d_element_representation,
        surface_element_location,
        surface_section_element_location,
        surface_volume_element_location,
        volume_2d_element_coordinate_system,
        volume_2d_element_descriptor,
        volume_2d_element_group,
        volume_2d_element_representation,
        volume_3d_element_coordinate_system,
        volume_3d_element_group,
        volume_3d_element_descriptor,
        volume_3d_element_representation,
        volume_element_location);

  REFERENCE FROM support_resource_schema
      (identifier,
       label,
       text);
(*
```

NOTE The schemas referenced above can be found in the following parts of ISO 10303:

fea_scalar_vector_tensor_schema	Clause 7 of this part of ISO 10303
geometric_model_schema	ISO 10303-42
geometry_schema	ISO 10303-42
measure_schema	ISO 10303-41
structural_response_representation_schema	Clause 5 of this part of ISO 10303
support_resource_schema	ISO 10303-41

6.1 Introduction

The subjects of the **finite_element_analysis_control_and_result_schema** are the controls necessary to perform a finite element analysis, and the analysis output generated from the analysis of a combination of a finite element model and a control.

6.2 Fundamental concepts and assumptions

The fundamental concepts and assumptions include the concepts of control, step, state, process, result, the roles of a **state_definition** in defining and containing analysis output information, and units and measures.

NOTE An EXPRESS-G Partial Model illustrating the control and result relationships is shown in Figure 62.

6.2.1 Control

A control for a finite element analysis describes the operations carried out upon the model as a set of analysis steps. A model may have one or more sets of control information.

The control information also includes the administrative and configuration control information, and the constraints upon the model at each analysis step.

6.2.2 Control process

A control process defines the way in which a model is caused to depart from its initial state. For linear analysis (no other type is within scope) a control process specifies a final model state.

The objective for the finite element analysis application is to calculate the response of the model to the change from the initial state to the final state of the following model state information:

— external loads;

EXAMPLE 1 Forces and moments in a stress/displacement analysis are types of external loads.

— independent field variables that effect the material of an element;

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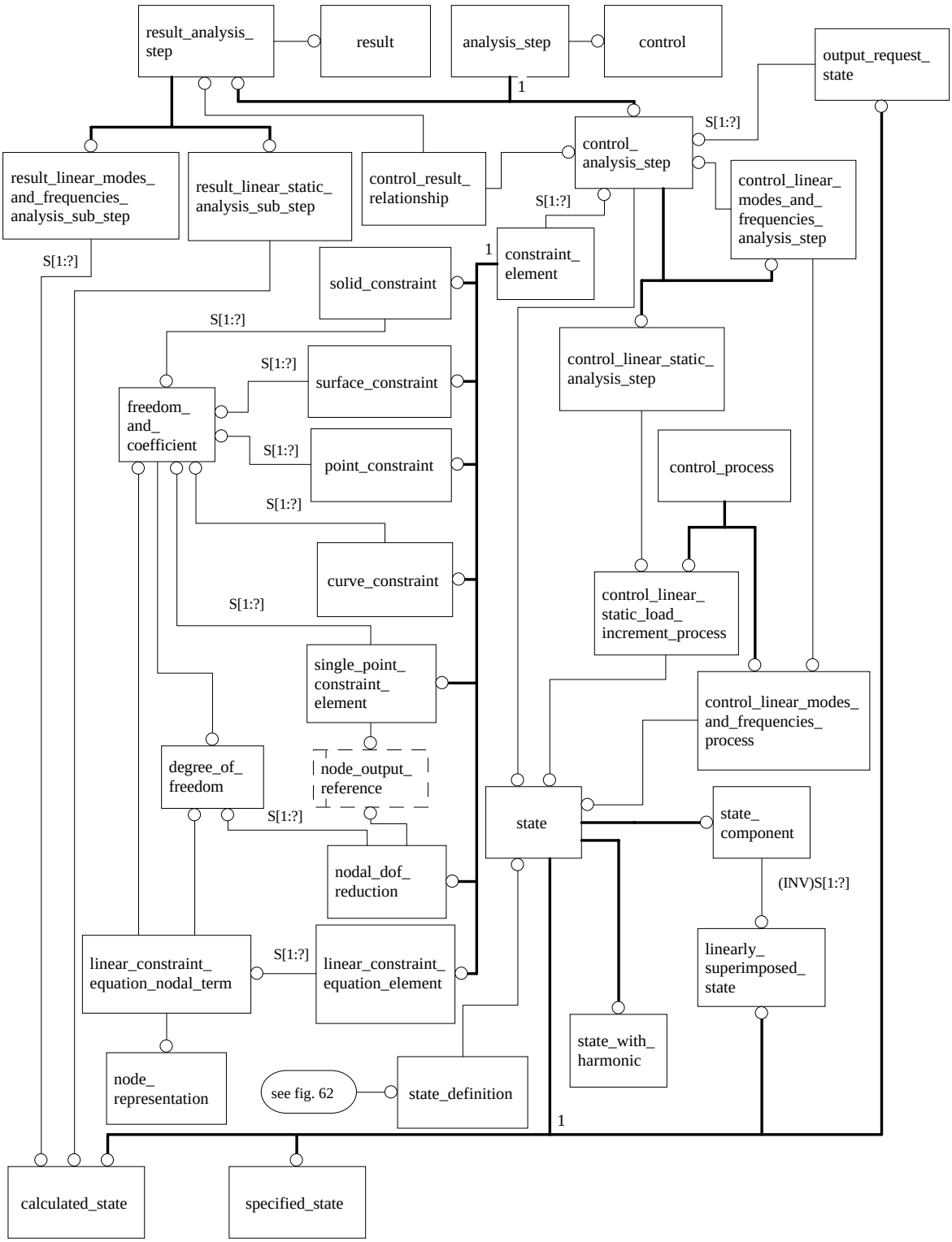

Figure 62 – Finite element analysis control EXPRESS-G partial model

EXAMPLE 2 Temperature and moisture are independent field variables that effect the material of an element by causing initial stresses or strains.

— the values of constraints.

6.2.3 Result

A result for a finite element analysis consists of the response of a model to a control as calculated by a finite element analysis application.

A result has the following structure:

— a control has one or more sets of result information. Each set of result information corresponds to a separate execution of an finite element analysis application.

— a result has one or more analysis sub-steps for nonlinear analyses. The finite element analysis application divides the analysis steps specified by the control into sub-steps in order to carry out the calculation. For a linear analysis (no other type is in scope), each analysis step has a single sub-step.

— for each analysis sub-step there is a single state that describes the model at the end of the sub-step.

6.2.4 Analysis step

An analysis step may either be a **control_analysis_step** or a **result_analysis_step**. A **control_analysis_-step** defines an operation on the model by specifying an initial state and a process. Nodal constraints are associated with a **control_analysis_step**, as are output requests. A **result_analysis_step** may only reference a **calculated_state**.

6.2.5 State

A state is the aggregation of the information known or requested about the analysis variables of a model at an instant.

The state information includes:

— the nodal variable values;

— the field variable values within the elements;

— the values of constraints.

The state information is defined in **state_definition**s. When a **state** describes an analysis that requires a symmetry and harmonic specification then a complex instantiation of **state** with **state_with_harmonic** is required. The component of a **linearly_superimposed_state** is specified by a **state_component** that in itself is a **state**.

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6.2.6 State definition

A state definition describes the values of the analysis variables of a model.

A state definition refers to either an output request state, specified state, calculated state, or linearly superimposed state. The type of information to be output is specified by a **state_definition** entity which references an **output_request_state**. Control state or analysis output state information are contained in a **state_definition** entity which references a **specified_state**, **calculated_state**, or a **linearly_-superimposed_state**.

A **state_definition** therefore either:

— defines an output request set by specifying the variable for which values are to be calculated;

— defines a state of a node, element, or a portion of the model by specifying the values of a variable;

— defines an analysis output message.

The variable may be:

— a variable expressed with respect to solution degrees of freedom at a node of the model;

— a field variable at a point within an element of the model, or aggregated within one or more elements;

— analysis status messages.

EXAMPLE Errors, warnings, or notes are analysis status messages.

In each type of **state_definition** there is a where-rule constraint that enforces the correct combinations of value and variable.

6.2.7 Units and measures

Units are assigned in a context, and the value of the measure is assigned directly.

6.3 Finite element analysis control and result schema type definitions

The following are a resource for the entities in the finite element analysis control and result schema of the FEA information model.

NOTE The types in this clause are organized in groups of similar subject matter.

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6.3.1 model_or_control_element

A **model_or_control_element** enables an attribute to reference either a control (constraint element) or a model element.

EXPRESS specification:

```
*)
TYPE model_or_control_element = SELECT
     (element_representation,
      constraint_element);
END_TYPE;
(*
```

6.3.2 cylindrical_harmonic_number

A **cylindrical_harmonic_number** is a number identifying the harmonic for a **cylindrical_harmonic_-control** and a **state** in an axisymmetric analysis.

EXPRESS specification:

```
*)
TYPE cylindrical_harmonic_number = INTEGER;
WHERE
  WR1: SELF >= 0;
END_TYPE;
(*
```

Formal propositions:

WR1: a harmonic number shall be positive or zero.

6.3.3 volume_3d_face

A **volume_3d_face** is an element face of a volume 3D element.

Figures 27, 31, 35, and 39 in 5.8 establish graphically the relationship between the element face number and the positions in the volume 3D element **required_node_list** for the vertex nodes. The element faces are in the same positions with respect to this list for each element order.

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EXPRESS specification:

```
*)
TYPE volume_3d_face = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 6);
END_TYPE;
(*
```

Formal propositions:

WR1: a volume 3D element face shall be in the range from 1 to 6.

6.3.4 volume_2d_face

A **volume_2d_face** is an element face of a volume 2D element.

Figures 18 and 23 in 5.8 establish graphically the relationship between the element face number and the positions in the volume 2D element **required_node_list** for the vertex nodes. The element faces are in the same positions with respect to this list for each element order.

EXPRESS specification:

```
*)
TYPE volume_2d_face = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 4);
END_TYPE;
(*
```

Formal propositions:

WR1: a 2D volume element face shall be in the range from 1 to 4.

6.3.5 volume_3d_edge

A **volume_3d_edge** is an element edge of a volume 3D element.

Figures 27, 31, 35, and 39 in 5.8 establish graphically the relationship between the element edge number and the element edge positions in the volume 3D element. The element edges are in the same positions with respect to this list for each element order.

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EXPRESS specification:

```
*)
TYPE volume_3d_edge = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 12);
END_TYPE;
(*
```

Formal propositions:

WR1: a volume 3D edge shall be in the range from 1 to 12.

6.3.6 volume_2d_edge

A **volume_2d_edge** is an element edge of a volume 2D element.

Figures 18 and 23 in 5.8 establish graphically the relationship between the element edge number and the element edge positions in the volume 2D element. The element edges are in the same positions with respect to this list for each element order.

EXPRESS specification:

```
*)
TYPE volume_2d_edge = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 4);
END_TYPE;
(*
```

Formal propositions:

WR1: a volume 2D edge shall be in the range from 1 to 4.

6.3.7 surface_3d_face

A **surface_3d_face** is a top or bottom of a surface 3D element.

Figures 17 and 22 in 5.8 establish graphically the relationship between the element face number, and the top and bottom of a surface 3D element. The element faces are in the same positions with respect to this list for each element order.

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EXPRESS specification:

```
*)
TYPE surface_3d_face = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 2);
END_TYPE;
(*
```

Formal propositions:

WR1: a surface 3D element face shall be in the range from 1 to 2.

Informal propositions:

IP1: an element face of 1 shall be the positive z parametric axis side of the element, the 2 element face shall be the negative z parametric axis side of the element.

6.3.8 surface_3d_edge

A **surface_3d_edge** is an element edge of a surface 3D element.

Figures 17 and 22 in 5.8 establish graphically the relationship between the element edge number and the element edge positions in the surface 3D element. The element edges are in the same positions with respect to this list for each element order.

EXPRESS specification:

```
*)
TYPE surface_3d_edge = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 4);
END_TYPE;
(*
```

Formal propositions:

WR1: a surface 3D element edge shall be in the range from 1 to 4.

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6.3.9 surface_2d_face

A **surface_2d_face** is the top or bottom of a surface 2D element.

Figure 13 in 5.8 establishes graphically the relationship between the face number, and the top and bottom of a surface 2D element. The faces are in the same positions with respect to this list for each element order.

EXPRESS specification:

```
*)
TYPE surface_2d_face = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 2);
END_TYPE;
(*
```

Formal propositions:

WR1: a surface 2D face shall be in the range from 1 to 2.

Informal propositions:

IP1: an element face of 1 shall be the positive **z** parametric axis side of the element, an element face of 2 shall be the negative **z** parametric axis side of the element.

6.3.10 surface_2d_edge

A **surface_2d_edge** is an element edge of a surface 2D element.

Figure 13 in 5.8 establishes graphically the relationship between the element edge number and the edge positions in the surface 2D element. The element edges are in the same positions with respect to this list for each element order.

EXPRESS specification:

```
*)
TYPE surface_2d_edge = INTEGER;
WHERE
  WR1: (SELF >= 1) AND (SELF <= 2);
END_TYPE;
(*
```

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Formal propositions:

WR1: a surface 2D element edge shall be in the range from 1 to 2.

6.3.11 field_value

A **field_value** is the value of a field variable.

EXPRESS specification:

```
*)
TYPE field_value = SELECT
  (unspecified_value,
   scalar,
   tensor1_2d,
   tensor1_3d,
   anisotropic_symmetric_tensor2_2d,
   isotropic_symmetric_tensor2_3d,
   orthotropic_symmetric_tensor2_3d,
   anisotropic_symmetric_tensor2_3d);
END_TYPE;
(*
```

6.3.12 unspecified_value

An **unspecified_value** is a type that specifies an undefined value.

EXPRESS specification:

```
*)
TYPE unspecified_value = ENUMERATION OF
  (unspecified);
END_TYPE;
(*
```

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6.3.13 measure_or_unspecified_value

A **measure_or_unspecified_value** is a measure value or is not specified.

EXPRESS specification:

```
*)
TYPE measure_or_unspecified_value = SELECT
  (context_dependent_measure,
   unspecified_value);
END_TYPE;
(*
```

6.3.14 boundary_variable

A **boundary_variable** is a field variable on a boundary of an element.

EXPRESS specification:

```
*)
TYPE boundary_variable = SELECT
   (boundary_surface_scalar_variable,
   boundary_surface_vector_3d_variable,
   application_defined_scalar_variable,
   application_defined_vector_3d_variable);
END_TYPE;
(*
```

6.3.15 boundary_aggregated_variable

A **boundary_aggregated_variable** is an aggregated field variable on a boundary of an element.

EXPRESS specification:

```
*)
TYPE boundary_aggregated_variable = SELECT
   (aggregated_vector_3d_variable,
   application_defined_vector_3d_variable);
END_TYPE;
(*
```

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6.3.16 volume_variable

A **volume_variable** is a field variable within the volume of an element.

EXPRESS specification:

```
*)
TYPE volume_variable = SELECT
  (volume_scalar_variable,
   volume_angular_variable,
   volume_vector_3d_variable,
   volume_tensor2_3d_variable,
   application_defined_scalar_variable,
   application_defined_vector_3d_variable,
   application_defined_tensor2_3d_variable);
END_TYPE;
(*
```

6.3.17 volume_aggregated_variable

A **volume_aggregated_variable** is an aggregated field variable within an element.

EXPRESS specification:

```
*)
TYPE volume_aggregated_variable = SELECT
  (aggregated_scalar_variable,
   aggregated_angular_variable,
   aggregated_vector_3d_variable,
   aggregated_tensor2_3d_variable,
   application_defined_scalar_variable,
   application_defined_vector_3d_variable,
   application_defined_tensor2_3d_variable);
END_TYPE;
(*
```

6.3.18 surface_element_variable

A **surface_element_variable** is a field variable at a point on the surface of an element.

NOTE Many application defined variables are selected in the **volume_variable**.

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EXPRESS specification:

```
*)
TYPE surface_element_variable = SELECT
  (volume_variable,
   surface_scalar_variable,
   surface_vector_2d_variable,
   surface_vector_3d_variable,
   surface_tensor2_2d_variable,
   application_defined_tensor2_2d_variable);
END_TYPE;
(*
```

6.3.19 boundary_edge_variable

A **boundary_edge_variable** is a field variable on an element edge of a surface.

EXPRESS specification:

```
*)
TYPE boundary_edge_variable = SELECT
   (boundary_curve_scalar_variable,
    boundary_curve_vector_3d_variable,
    application_defined_scalar_variable,
    application_defined_vector_3d_variable);
END_TYPE;
(*
```

6.3.20 curve_element_variable

A **curve_element_variable** is a field variable at a point on a curve element.

NOTE Many application defined variables are selected in the **volume_variable**.

EXPRESS specification:

```
*)
TYPE curve_element_variable = SELECT
  (volume_variable,
   curve_scalar_variable,
   curve_vector_2d_variable,
   application_defined_vector_2d_variable,
   curve_vector_3d_variable);
END_TYPE;
(*
```

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6.3.21 curve_scalar_variable

A **curve_scalar_variable** is a scalar field variable that is aggregated over the section of a curve element at a point along its length.

EXPRESS specification:

```
*)
TYPE curve_scalar_variable = ENUMERATION OF
     (curve_axial_force,
      curve_axial_strain,
      torque,
      curve_warping,
      bi_moment,
      twist);
END_TYPE;
(*
```

Enumerated item definitions:

curve_axial_force: the total direct force acting across a plane normal to the axis of a curve element. A positive value denotes tension.

curve_axial_strain: the elastic strain along the axis of a curve element. This is given by:

$$\varepsilon = \frac{\partial u}{\partial x}$$

where:

u is translation of the element axis in the x direction of the curve element axis system;

x is the axis of the curve element axis system tangential to the element.

torque: the total moment of shear force about the axis of a curve element acting across a plane normal to the axis. A positive value results from a deformation such that the rotation of the section about a direction tangential to the axis increases with distance in that direction.

curve_warping: the warping of the section of a curve element.

bi_moment: the conjugate of warping of the section of a curve element.

twist: the torsional (twisting) of a curve element which is given by:

$$\phi = \frac{\partial \theta}{\partial x}$$

where:

θ is rotation of the element section about the x direction of the curve element axis system;

x is the axis of the curve element axis system tangential to the element.

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6.3.22 surface_scalar_variable

A **surface_scalar_variable** is a scalar field variable that is aggregated through the section of a surface element at a point on its surface.

EXPRESS specification:

```
*)
TYPE surface_scalar_variable = ENUMERATION OF
     (thickness,
      surface_thermal_gradient,
      reference_surface_thermal_gradient);
END_TYPE;
(*
```

Enumerated item definitions:

thickness: the thickness at a point on the surface of a surface element.

surface_thermal_gradient: a scalar quantity that is defined over a surface element. The surface thermal gradient is defined as follows:

$$\frac{\partial \theta}{\partial z}$$

where:

θ**:** is the temperature at a point within the thickness of the surface.

z**:** is distance through the thickness in the surface element z axis direction.

reference_surface_thermal_gradient: the reference temperature for the surface thermal gradient.

6.3.23 volume_scalar_variable

A **volume_scalar_variable** is a scalar field variable that is evaluated at a point within the volume of an element.

EXPRESS specification:

```
*)
TYPE volume_scalar_variable = ENUMERATION OF
     (temperature,
      moisture,
      reference_temperature,
      strain_energy_per_unit_volume);
END_TYPE;
(*
```

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Enumerated item definitions:

temperature: the temperature at a point.

moisture: the moisture content at a point.

reference_temperature: the reference temperature at a point.

strain_energy_per_unit_volume: the strain energy density evaluated at a point.

6.3.24 boundary_curve_scalar_variable

A **boundary_curve_scalar_variable** is a scalar field variable that is evaluated at a point along the element edge of a surface 3D element.

EXPRESS specification:

```
*)
TYPE boundary_curve_scalar_variable = ENUMERATION OF
     (normal_force_per_unit_length);
END_TYPE;
(*
```

Enumerated item definitions:

normal_force_per_unit_length: a scalar that is defined over a boundary element edge. The normal force per unit length acts into the element.

Normal_force_per_unit_length is a special case of **applied_force_per_unit_length**.

6.3.25 boundary_surface_scalar_variable

A **boundary_surface_scalar_variable** is a scalar field variable that is evaluated at a point on the element face a surface or volume element.

EXPRESS specification:

```
*)
TYPE boundary_surface_scalar_variable = ENUMERATION OF
     (pressure);
END_TYPE;
(*
```

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Enumerated item definitions:

pressure: a scalar that is defined over a boundary surface or element edge. The pressure is the force per unit area acting normal to the surface into the element.

Pressure is a special case of **applied_force_per_unit_area**.

6.3.26 aggregated_scalar_variable

An **aggregated_scalar_variable** is a scalar variable that is obtained by aggregation of a field within an element or over an element boundary. The variable may be evaluated for an element face, a single element, an element group or an entire model.

EXPRESS specification:

```
*)
TYPE aggregated_scalar_variable = ENUMERATION OF
     (total_strain_energy,
      mass,
      volume);
END_TYPE;
(*
```

Enumerated item definitions:

total_strain_energy: the total strain energy within a volume of the model.

mass: the mass of a single element, an element group, or an entire model.

volume: the volume of a single element, an element group, or an entire model.

6.3.27 volume_angular_variable

A **volume_angular_variable** is a scalar variable that is applied to a volume about the origin of the founding placement of the using entity, and about the Z axis of that placement.

EXPRESS specification:

```
*)
TYPE volume_angular_variable = ENUMERATION OF
     (constant_angular_acceleration,
      application_defined_angular_scalar_variable);
END_TYPE;
(*
```

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Enumerated item definitions:

constant_angular_acceleration: a constant angular acceleration applied to a volume.

application_defined_angular_scalar_variable: a scalar variable that is arbitrarily defined.

6.3.28 aggregated_angular_variable

An **aggregated_angular_variable** is an aggregated scalar variable that is applied to a volume about the origin of the founding placement of the using entity, and about the Z axis of that placement.

EXPRESS specification:

```
*)
TYPE aggregated_angular_variable = ENUMERATION OF
      (total_applied_moment,
       application_defined_aggregated_angular_scalar_variable);
END_TYPE;
(*
```

Enumerated item definitions:

total_applied_moment: the total applied moment applied to a volume.

application_defined_aggregated_angular_scalar_variable: A scalar variable that is arbitrarily defined.

6.3.29 application_defined_scalar_variable

A **application_defined_scalar_variable** is a scalar variable that is arbitrarily defined. The string shall be suitable for human interpretation.

EXPRESS specification:

```
*)
TYPE application_defined_scalar_variable = STRING;
END_TYPE;
(*
```

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6.3.30 curve_vector_2d_variable

A **curve_vector_2d_variable** is a 2D vector field variable that is aggregated over the section of a curve element at a point along its length.

EXPRESS specification:

```
*)
TYPE curve_vector_2d_variable = ENUMERATION OF
     (curve_shear_force,
      curve_bending_moment,
      curve_element_curvature,
      curve_thermal_gradient,
      reference_curve_thermal_gradient);
END_TYPE;
(*
```

Enumerated item definitions:

curve_shear_force: the aggregate shear force at a point on a curve element. The sign convention is defined by the following equation:

$$f = \mathbf{F}^t \begin{pmatrix} n_y \\ n_z \end{pmatrix}$$

where:

$\mathbf{F}$ is the aggregate shear force vector at a point on the curve with respect to the specified curve coordinate system;

f is the force applied by the curve on the side of the point with the higher x coordinate of the specified system to the side with the lower x coordinate, in the direction of unit vector $\mathbf{n}$ normal to the curve;

n_y **and** n_z denote the components of unit vector $\mathbf{n}$ in the directions of the axes y and z of the specified curve coordinate system.

The first component of $\mathbf{F}$ is the force in the direction of the curve coordinate system $\mathbf{y}$ axis, and the second component of $\mathbf{F}$ is the force in the direction of the curve coordinate system $\mathbf{z}$ axis.

curve_bending_moment: the aggregate bending moment at a point on a curve element. The sign convention is defined by the following equation:

$$m = \mathbf{M}^t \begin{pmatrix} n_y \\ n_z \end{pmatrix}$$

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where:

M is the aggregate bending moment at a point on the curve with respect to the specified curve coordinate system;

m is the moment applied by the curve on the side of the point with the higher x coordinate of the specified system to the side with the lower x coordinate, evaluated about the unit vector $\mathbf{n}$ normal to the curve;

n_y **and** n_z denote the components of unit vector $\mathbf{n}$ in the directions of the axes y and z of the specified curve coordinate system.

The first component of M is the moment about the curve coordinate system $\mathbf{y}$ axis, and the second component of M is the moment about the curve coordinate system $\mathbf{z}$ axis.

curve_element_curvature: this is the curvature vector for a curve which is defined as:

$$\mathbf{c} = \begin{pmatrix} -\dfrac{\partial^2 v}{\partial x^2} \\ -\dfrac{\partial^2 w}{\partial x^2} \end{pmatrix}$$

where:

$\mathbf{c}$ is the curvature vector;

v is displacement in the direction of the $\mathbf{y}$ axis of the specified curve coordinate system;

w is displacement in the direction of the $\mathbf{z}$ axis of the specified curve coordinate system.

This definition of curvature is only valid for small deformations to a curve with a small initial curvature.

curve_thermal_gradient: a 2D vector that is defined over a curve element. The curve thermal gradient is defined as follows:

$$\begin{pmatrix} \dfrac{\partial \theta}{\partial y} \\ \dfrac{\partial \theta}{\partial z} \end{pmatrix}$$

where:

θ**:** is the temperature at a point within the section of the curve;

y**:** is distance through the section in the curve element y axis direction;

z**:** is distance through the section in the curve element z axis direction.

reference_curve_thermal_gradient: the reference temperature for the curve thermal gradient.

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6.3.31 surface_vector_2d_variable

A **surface_vector_2d_variable** is a 2D vector field variable that is aggregated through the section of a surface element at a point on its surface.

EXPRESS specification:

```
*)
TYPE surface_vector_2d_variable = ENUMERATION OF
     (surface_out_of_plane_shear_force,
      surface_out_of_plane_shear_strain);
END_TYPE;
(*
```

Enumerated item definitions:

surface_out_of_plane_shear_force: the aggregate out-of-plane shear force at a point on a curve element. The sign convention is defined by the following equation:

$$f = \mathbf{F}^t \begin{pmatrix} n_x \\ n_y \end{pmatrix}$$

where:

$\mathbf{F}$ is the aggregate out-of-plane shear force at a point on the surface with respect to the specified surface coordinate system;

f is the force in the direction of the $\mathbf{z}$ axis of the specified coordinate system, applied across a unit width of surface normal to the unit vector $\mathbf{n}$ in the plane of the surface. The force is applied by the surface on the side of the unit width in the direction of the normal $\mathbf{n}$ to the side away from the normal;

n_x **and** n_y denote the components of unit vector $\mathbf{n}$ in the directions of the axes x and y of the specified surface coordinate system.

surface_out_of_plane_shear_strain: this is the out of plane shear strain vector for a surface, which is defined as:

$$\varepsilon = \begin{pmatrix} \dfrac{\partial w}{\partial x} + \dfrac{\partial u}{\partial z} \\ \dfrac{\partial w}{\partial y} + \dfrac{\partial v}{\partial z} \end{pmatrix}$$

where:

x is distance over the surface in the direction of the $\mathbf{x}$ axis of the specified surface coordinate system;

y is distance over the surface in the direction of the $\mathbf{y}$ axis of the specified surface coordinate system;

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u is displacement in the direction of the $\mathbf{x}$ axis of the specified surface coordinate system;

v is displacement in the direction of the $\mathbf{y}$ axis of the specified surface coordinate system;

w is displacement in the direction of the $\mathbf{z}$ axis of the specified surface coordinate system.

6.3.32 application_defined_vector_2d_variable

A **application_defined_vector_2d_variable** is a 2D vector variable that is arbitrarily defined. The string shall be suitable for human interpretation.

EXPRESS specification:

```
*)
TYPE application_defined_vector_2d_variable = STRING;
END_TYPE;
(*
```

6.3.33 curve_vector_3d_variable

A **curve_vector_3d_variable** is a 3D vector field variable that is aggregated over the section of a curve element at a point along its length.

EXPRESS specification:

```
*)
TYPE curve_vector_3d_variable = ENUMERATION OF
     (applied_force_per_unit_length,
      applied_moment_per_unit_length);
END_TYPE;
(*
```

Enumerated item definitions:

applied_force_per_unit_length: the force per unit length of an element applied to the model.

applied_moment_per_unit_length: the moment per unit length of an element applied to the model.

6.3.34 surface_vector_3d_variable

A **surface_vector_3d_variable** is a 3D vector field variable that is aggregated through the section of a surface element at a point on its surface.

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EXPRESS specification:

```
*)
TYPE surface_vector_3d_variable = ENUMERATION OF
     (applied_force_per_unit_area,
      applied_moment_per_unit_area);
END_TYPE;
(*
```

Enumerated item definitions:

applied_force_per_unit_area: force per unit area of an element applied to the model.

applied_moment_per_unit_area: moment per unit area of an element applied to the model.

6.3.35 volume_vector_3d_variable

A **volume_vector_3d_variable** is a 3D vector field variable at a point within the volume an element.

EXPRESS specification:

```
*)
TYPE volume_vector_3d_variable = ENUMERATION OF
     (position,
      applied_force_per_unit_volume,
      applied_moment_per_unit_volume,
      displacement,
      infinitesimal_rotation,
      acceleration);
END_TYPE;
(*
```

Enumerated item definitions:

position: the position of a point within the volume of an element.

applied_force_per_unit_volume: the force per unit volume of an element applied to the model.

applied_moment_per_unit_volume: the moment per unit volume of an element applied to the model.

displacement: the displacement of a point within an element.

infinitesimal_rotation: the infinitesimal rotation of fibres embedded within the material of an element at a point. These rotations are assumed to be small for a linear analysis, so that they can be regarded as a vector quantity.

acceleration: a 3D vector that is defined over a volume of an element.

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6.3.36 boundary_curve_vector_3d_variable

A **boundary_curve_vector_3d_variable** is a 3D vector field variable that is evaluated at a point along the element edge of a 3D surface element.

EXPRESS specification:

```
*)
TYPE boundary_curve_vector_3d_variable = ENUMERATION OF
     (applied_force_per_unit_length,
      applied_moment_per_unit_length);
END_TYPE;
(*
```

Enumerated item definitions:

applied_force_per_unit_length: the force per unit length of element edge applied to the model.

applied_moment_per_unit_length: the moment per unit length of element edge applied to the model.

6.3.37 boundary_surface_vector_3d_variable

A **boundary_surface_vector_3d_variable** is a 3D vector field variable that is evaluated at a point on the element face of a volume element.

EXPRESS specification:

```
*)
TYPE boundary_surface_vector_3d_variable = ENUMERATION OF
     (applied_force_per_unit_area,
      applied_moment_per_unit_area);
END_TYPE;
(*
```

Enumerated item definitions:

applied_force_per_unit_area: the force per unit area of element face applied to the model.

applied_moment_per_unit_length: the moment per unit area of element face applied to the model.

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6.3.38 aggregated_vector_3d_variable

An **aggregated_vector_3d_variable** is a 3D vector variable that is obtained by aggregation of a field within an element or over an element boundary. The variable may be evaluated for an element face, a single element, an element group or an entire model.

EXPRESS specification:

```
*)
TYPE aggregated_vector_3d_variable = ENUMERATION OF
     (total_applied_force,
      centre_of_mass_offset);
END_TYPE;
(*
```

Enumerated item definitions:

total_applied_force: the total applied force applied to a volume of the model.

centre_of_mass_offset: a 3D vector that is obtained by integration over an element, element group or whole model. The offset is the distance of the centre of mass from the origin of the master coordinate system for the model.

6.3.39 application_defined_vector_3d_variable

A **application_defined_vector_3d_variable** is a 3D vector variable that is arbitrarily defined. The string shall be suitable for human interpretation.

EXPRESS specification:

```
*)
TYPE application_defined_vector_3d_variable = STRING;
END_TYPE;
(*
```

6.3.40 surface_tensor2_2d_variable

A **surface_tensor2_2d_variable** is a 2D second order tensor field variable, that is aggregated through the section of a surface element at a point on its surface.

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EXPRESS specification:

```
*)
TYPE surface_tensor2_2d_variable = ENUMERATION OF
     (surface_membrane_force,
      surface_membrane_strain,
      surface_bending_moment,
      surface_curvature);
END_TYPE;
(*
```

Enumerated item definitions:

surface_membrane_force: the aggregate membrane force at a point on a surface element. The sign convention is defined by the following equation:

$$\mathbf{f} = \mathcal{F} \begin{pmatrix} n_x \\ n_y \end{pmatrix}$$

where:

$\mathcal{F}$ is the aggregate membrane force tensor at a point on the surface with respect to the specified surface coordinate system;

$\mathbf{f}$ is the force in the plane of the surface with respect to the x and y axes of the specified coordinate system, applied across a unit width of surface normal to the unit vector $\mathbf{n}$ in the plane of the surface. The force is applied by the surface on the side of the unit width in the direction of the normal $\mathbf{n}$ to the side away from the normal;

n_x **and** n_y denote the components of unit vector $\mathbf{n}$ in the directions of the axes x and y of the specified surface coordinate system.

surface_membrane_strain: the aggregate membrane strain for the surface, which is defined as:

$$\varepsilon = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{pmatrix}$$

where:

u is displacement in the direction of the $\mathbf{x}$ axis of the specified surface coordinate system;

v is displacement in the direction of the $\mathbf{y}$ axis of the specified surface coordinate system.

This tensor is symmetrical and only three components are stored. The engineering convention, in which the off-diagonal components are summed, is not used.

This definition of strain is only valid for small deformations to a surface with a small initial strain.

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surface_bending_moment: the aggregate bending moment at a point on a surface element. The sign convention is defined by the following equation:

$$\mathbf{m} = \mathcal{M} \begin{pmatrix} n_x \\ n_y \end{pmatrix}$$

where:

$\mathcal{M}$ is the aggregate membrane force tensor at a point on the surface with respect to the specified surface coordinate system;

$\mathbf{m}$ is the moment about the x and y axes of the specified coordinate system, applied across a unit width of surface normal to the unit vector $\mathbf{n}$ in the plane of the surface. The moment is applied by the surface on the side of the unit width in the direction of the normal $\mathbf{n}$ to the side away from the normal;

n_x **and** n_y denote the components of unit vector $\mathbf{n}$ in the directions of the axes x and y of the specified surface coordinate system.

surface_curvature: the curvature tensor for a surface which is defined as:

$$c = \begin{pmatrix} -\dfrac{\partial^2 w}{\partial x^2} & -\dfrac{\partial^2 w}{\partial x \partial y} \\ -\dfrac{\partial^2 w}{\partial x \partial y} & -\dfrac{\partial^2 w}{\partial y^2} \end{pmatrix}$$

where:

c is curvature tensor;

x is distance over the surface in the direction of the $\mathbf{x}$ axis of the specified surface coordinate system;

y is distance over the surface in the direction of the $\mathbf{y}$ axis of the specified surface coordinate system;

w is displacement in the direction of the $\mathbf{z}$ axis of the specified surface coordinate system.

This tensor is symmetrical and only three components are stored. The engineering convention, in which the off-diagonal components are summed, is not used.

This definition of curvature is only valid for small deformations to a surface with a small initial curvature.

6.3.41 application_defined_tensor2_2d_variable

A **application_defined_tensor2_2d_variable** is 2D second order tensor variable that is arbitrarily defined. The string shall be suitable for human interpretation.

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EXPRESS specification:

```
*)
TYPE application_defined_tensor2_2d_variable = STRING;
END_TYPE;
(*
```

6.3.42 volume_tensor2_3d_variable

A **volume_tensor2_3d_variable** is a 3D second order tensor field variable, that is evaluated at a point within the volume of an element.

EXPRESS specification:

```
*)
TYPE volume_tensor2_3d_variable = ENUMERATION OF
     (total_strain,
      stress);
END_TYPE;
(*
```

Enumerated item definitions:

total_strain: the elastic strain tensor ε that is the sum of the elastic strain ε^E and the thermal strain ε^T. All strains are expressed using the mathematical convention.

For a linear elastic analysis the elastic strains are given by:

$$\varepsilon_{ij}^E = 1/2 \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

where:

$\mathbf{v}$ is the translation at a point within the element;

$\mathbf{x}$ is the position at a point within the element.

For a linear elastic analysis the thermal strains are given by:

$$\varepsilon_{ij}^T = \alpha_{ij}(T - T_0)$$

where:

α is the tensor of secant thermal expansion coefficients at a point within the element;

T the temperature at a point within the element;

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T_0 the reference temperature.

For a linear elastic analysis the total strains are given by:

$$\varepsilon_{ij} = \varepsilon_{ij}^E + \varepsilon_{ij}^T$$

This tensor is symmetrical and only six components are stored. The engineering convention, in which pairs of off-diagonal components are summed, is not used.

stress: the stress tensor σ that is defined so that for a linear elastic analysis, the total strain energy per unit volume is given by:

$$\Delta v = \sum_i \sum_j \sigma_{ij} \Delta\varepsilon_{ij}$$

where:

Δv is the change of the strain energy per unit volume at a point within the element;

$\Delta\varepsilon$ is the change of the strain tensor.

6.3.43 aggregated_tensor2_3d_variable

An **aggregated_tensor2_3d_variable** is an aggregated 3D second order tensor field variable that is evaluated at a point within the volume of an element.

EXPRESS specification:

```
*)
TYPE aggregated_tensor2_3d_variable = ENUMERATION OF
     (rotational_inertia);
END_TYPE;
(*
```

Enumerated item definitions:

rotational_inertia: a 3D second order tensor that is obtained by integration over an element, element group or whole model. The rotational inertia is evaluated about the centre of mass for the domain of integration.

This tensor is symmetrical and only six components are stored.

6.3.44 application_defined_tensor2_3d_variable

A **application_defined_tensor2_3d_variable** is a 3D second order tensor variable that is arbitrarily defined. The string shall be suitable for human interpretation.

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EXPRESS specification:

```
*)
TYPE application_defined_tensor2_3d_variable = STRING;
END_TYPE;
(*
```

6.3.45 message_level

A **message_level** is the severity of the message.

EXPRESS specification:

```
*)
TYPE message_level = ENUMERATION OF
     (error,
      warning,
      note);
END_TYPE;
(*
```

Enumerated item definitions:

error: the message is an error message.

warning: the message is an warning message.

note: the message is an informative note.

6.3.46 surface_3d_state_coordinate_system

A **surface_3d_state_coordinate_system** is the valid types of coordinate systems in a state definition for a surface 3D element.

EXPRESS specification:

```
*)
TYPE surface_3d_state_coordinate_system = SELECT
     (fea_axis2_placement_3d,
      surface_3d_element_coordinate_system);
END_TYPE;
(*
```

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6.3.47 surface_2d_state_coordinate_system

A **surface_2d_state_coordinate_system** is the valid types of coordinate systems in a state definition for a surface 2D element.

EXPRESS specification:

```
*)
TYPE surface_2d_state_coordinate_system = SELECT
     (fea_axis2_placement_3d,
      surface_2d_element_coordinate_system);
END_TYPE;
(*
```

6.3.48 curve_3d_state_coordinate_system

A **curve_3d_state_coordinate_system** is the valid types of coordinate systems in a state definition for a curve 3D element.

EXPRESS specification:

```
*)
TYPE curve_3d_state_coordinate_system = SELECT
     (fea_axis2_placement_3d,
      curve_3d_element_coordinate_system);
END_TYPE;
(*
```

6.3.49 curve_2d_state_coordinate_system

A **curve_2d_state_coordinate_system** is the valid types of coordinate systems in a state definition for a curve 2D element.

EXPRESS specification:

```
*)
TYPE curve_2d_state_coordinate_system = SELECT
     (fea_axis2_placement_3d,
      curve_2d_element_coordinate_system);
END_TYPE;
(*
```

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6.3.50 action_type

An **action_type** is the valid types of nodal actions, that are either forces or moments.

EXPRESS specification:

```
*)
TYPE action_type = ENUMERATION OF
     (applied_loads,
      residual_loads);
END_TYPE;
(*
```

Enumerated item definitions:

applied_loads: the actions upon the node are applied loads.

residual_loads: the actions upon the node are residual loads resulting from a lack of equilibrium at the node.

6.3.51 volume_3d_element_output_reference

A **volume_3d_element_output_reference** is an output request or specification for an element representation, an element group, an element descriptor, or a geometric representation item within the context of a representation, for volume 3D elements. If an element descriptor is referenced then all elements that reference that descriptor will have the same output request or specification.

EXPRESS specification:

```
*)
TYPE volume_3d_element_output_reference = SELECT
     (volume_3d_element_representation,
      volume_3d_element_descriptor,
      volume_3d_element_group,
      volume_3d_substructure_element_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

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6.3.52 volume_2d_element_output_reference

A **volume_2d_element_output_reference** is an output request or specification for an element representation, an element group, an element descriptor, or a geometric representation item within the context of a representation, for volume 2D elements. If an element descriptor is referenced then all elements that reference that descriptor will have the same output request or specification.

EXPRESS specification:

```
*)
TYPE volume_2d_element_output_reference = SELECT
     (volume_2d_element_representation,
      volume_2d_element_descriptor,
      volume_2d_element_group,
      volume_2d_substructure_element_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

6.3.53 surface_3d_element_output_reference

A **surface_3d_element_output_reference** is an output request or specification for an element representation, an element group, an element descriptor, or a geometric representation item within the context of a representation, for surface 3D elements. If an element descriptor is referenced then all elements that reference that descriptor will have the same output request or specification.

EXPRESS specification:

```
*)
TYPE surface_3d_element_output_reference = SELECT
     (surface_3d_element_representation,
      surface_3d_element_descriptor,
      surface_3d_element_group,
      surface_3d_substructure_element_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

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6.3.54 surface_2d_element_output_reference

A **surface_2d_element_output_reference** is an output request or specification for an element representation, an element group, an element descriptor, or a geometric representation item within the context of a representation, for surface 2D elements. If an element descriptor is referenced then all elements that reference that descriptor will have the same output request or specification.

EXPRESS specification:

```
*)
TYPE surface_2d_element_output_reference = SELECT
     (surface_2d_element_representation,
      surface_2d_element_descriptor,
      surface_2d_element_group,
      surface_2d_substructure_element_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

6.3.55 curve_3d_element_output_reference

A **curve_3d_element_output_reference** is an output request or specification for an element representation, an element group, an element descriptor, or a geometric representation item within the context of a representation, for curve 3D elements. If an element descriptor is referenced then all elements that reference that descriptor will have the same output request or specification.

EXPRESS specification:

```
*)
TYPE curve_3d_element_output_reference = SELECT
     (curve_3d_element_representation,
      curve_3d_element_descriptor,
      curve_3d_element_group,
      curve_3d_substructure_element_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

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6.3.56 curve_2d_element_output_reference

A **curve_2d_element_output_reference** is an output request or specification for an element representation, an element group, an element descriptor, or a geometric representation item within the context of a representation, for curve 2D elements. If an element descriptor is referenced then all elements that reference that descriptor will have the same output request or specification.

EXPRESS specification:

```
*)
TYPE curve_2d_element_output_reference = SELECT
     (curve_2d_element_representation,
      curve_2d_element_descriptor,
      curve_2d_element_group,
      curve_2d_substructure_element_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

6.3.57 node_output_reference

A **node_output_reference** is an output reference or specification for a node representation, a node group, a node within a substructure element, or a geometric representation item within the context of a representation.

EXPRESS specification:

```
*)
TYPE node_output_reference = SELECT
     (node_representation,
      node_group,
      substructure_node_reference,
      analysis_item_within_representation);
END_TYPE;
(*
```

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6.4 Finite element analysis control and result entity definitions: Analysis control

A control for a finite element analysis describes the operations carried out upon the model. A finite element analysis application calculates the response of the model to these operations.

NOTE The entities in this clause are organized in groups of similar subject matter.

6.4.1 control

A **control** is administrative information for a model, and associates analysis controls and results with a unique model.

EXPRESS specification:

```
*)
ENTITY control;
  model_ref                 : fea_model;
  control_id                : identifier;
  creating_software         : text;
  description               : text;
  user_defined_control      : SET [1:?] OF text;
  intended_analysis_code    : SET [1:?] of text;
UNIQUE
  UR1: model_ref, control_id;
END_ENTITY;
(*
```

Attribute definitions:

model_ref: the model to which the control applies.

control_id: the identifier for the control information.

creating_software: the software used to create the control.

description: additional information about the purpose of this control.

user_defined_control: additional information about the analysis control parameters.

EXAMPLE Analysis code specific information may be input with this attribute, such as solution paramaters, singularity criteria, and restart instructions.

intended_analysis_code: the set of one or many names of the intended analysis code that an **fea_model** was created for. Each intended analysis code shall have the vendor, version, computer system, operating system and descriptions specified.

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Formal propositions:

UR1: the control identifier shall be unique for the model.

6.4.2 analysis_step

An **analysis_step** is a single step or sub-step in an analysis.

EXPRESS specification:

```
*)
ENTITY analysis_step
  SUPERTYPE OF (ONEOF (control_analysis_step,
                       result_analysis_step));
  analysis_control          : control;
END_ENTITY;
(*
```

Attribute definitions:

analysis_control: the control which governs the the analysis step.

6.4.3 control_analysis_step

A **control_analysis_step** is a single step in an analysis.

EXPRESS specification:

```
*)
ENTITY control_analysis_step
  SUPERTYPE OF (ONEOF(control_linear_static_analysis_step,
               control_linear_modes_and_frequencies_analysis_step))
  SUBTYPE OF (analysis_step);
  step_id                   : identifier;
  sequence                  : integer;
  initial_state             : state;
  description               : text;
UNIQUE
  UR1: SELF\analysis_step.analysis_control, sequence;
  UR2: SELF\analysis_step.analysis_control, step_id;
END_ENTITY;
(*
```

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Attribute definitions:

step_id: the identifier for the step.

sequence: a sequence number that determines the order of processing for the control analysis step.

initial_state: the state of the model at the beginning of the step. This includes information such as reference temperatures and initial strains or stresses. For an initial equilibrium state of zero stress or strain it is only necessary to identify the initial state. The initial state will then have no referencing state definitions.

description: additional information about the purpose of this control.

Formal propositions:

UR1: the sequence number shall be unique for the control.

UR2: the step identifier shall be unique for the control.

6.4.4 symmetry_control

A **symmetry_control** is the type of symmetry in an analysis.

EXPRESS specification:

```
*)
ENTITY symmetry_control
  SUPERTYPE OF (ONEOF (no_symmetry_control,
                       cylindrical_symmetry_control));
END_ENTITY;
(*
```

6.4.5 no_symmetry_control

A **no_symmetry_control** is an indication of lack of symmetry control in the analysis.

EXPRESS specification:

```
*)
ENTITY no_symmetry_control
  SUBTYPE OF (symmetry_control);
END_ENTITY;
(*
```

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6.4.6 cylindrical_symmetry_control

A **cylindrical_symmetry_control** is an indication of cylindrical harmonic symmetry in the analysis.

EXPRESS specification:

```
*)
ENTITY cylindrical_symmetry_control
  SUBTYPE OF (symmetry_control);
  harmonic                  : cylindrical_harmonic_number;
  phase                     : measure_or_unspecified_value;
END_ENTITY;
(*
```

Attribute definitions:

harmonic: the cylindrical harmonic number for an axisymmetric analysis. The initial state may be the zero harmonic, whatever the harmonic of the final state.

phase: the angle θ measured from the i axis, which gives a factor cos θ in the amplitude of all field variables for an axisymmetric analysis.

6.4.7 control_linear_static_analysis_step

A **control_linear_static_analysis_step** is an analysis step in a linear static analysis.

EXPRESS specification:

```
*)
ENTITY control_linear_static_analysis_step
  SUBTYPE OF (control_analysis_step);
  process                   : control_linear_static_load_increment_process;
END_ENTITY;
(*
```

Attribute definitions:

process: the load increment process for the linear static analysis.

6.4.8 control_linear_static_analysis_step_with_harmonic

A **control_linear_static_analysis_step_with_harmonic** is an analysis step in a linear static analysis with cylindrical symmetry.

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EXPRESS specification:

```
*)
ENTITY control_linear_static_analysis_step_with_harmonic
  SUBTYPE OF (control_linear_static_analysis_step);
  symmetry                  : cylindrical_symmetry_control;
END_ENTITY;
(*
```

Attribute definitions:

symmetry: the type of symmetry for an analysis.

Informal propositions:

IP1: the harmonic for a linear static analysis step shall be the same as that for its final state.

IP2: a harmonic number shall be supplied for a state of an axisymmetric model.

6.4.9 control_linear_modes_and_frequencies_analysis_step

A **control_linear_modes_and_frequencies_analysis_step** is an analysis step in a linear nodes and frequencies analysis.

EXPRESS specification:

```
*)
ENTITY control_linear_modes_and_frequencies_analysis_step
  SUBTYPE OF (control_analysis_step);
  process                   : control_linear_modes_and_frequencies_process;
  number_of_modes           : count_measure;
  frequency_range           : ARRAY [1:2] OF context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

process: the load increment process for the linear modes and frequencies analysis.

number_of_modes: the number of modes to be calculated for a step.

frequency_range: the range of frequencies to consider for a step.

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6.4.10 constraint_element

A **constraint_element** is a constraint applied to a node or between many nodes.

EXPRESS specification:

```
*)
ENTITY constraint_element
  SUPERTYPE OF (ONEOF (single_point_constraint_element,
                       linear_constraint_equation_element,
                       nodal_dof_reduction,
                       point_constraint,
                       curve_constraint,
                       surface_constraint,
                       solid_constraint));
  element_id                : identifier;
  steps                     : SET [1:?] OF control_analysis_step;
END_ENTITY;
(*
```

Attribute definitions:

element_id: the identifier for the constraint element.

steps: the analysis control steps to which the constraint element applies.

Informal propositions:

IP1: the constraint element identifier shall be unique for the model.

6.4.11 single_point_constraint_element

A **single_point_constraint_element** is a single point constraint which sets values for one or more degrees of freedom at a single node. This equation has the form:

$$a_i \cdot x_i = b_i$$

where:

x_i are the n nodal freedom values;

a_i are the n nodal freedom coefficients;

b_i are the constraint equation coefficients.

The values of this constraint are set by a **single_point_constraint_element_values** entity.

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EXPRESS specification:

```
*)
ENTITY single_point_constraint_element
  SUBTYPE OF (constraint_element);
  required_node             : node_output_reference;
  coordinate_system         : fea_axis2_placement_3d;
  freedoms_and_values       : SET [1:?] OF freedom_and_coefficient;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

required_node: the node that is being constrained.

coordinate_system: the coordinate system with respect to which the constraint freedoms are defined.

freedoms_and_values: the degrees of freedom and their coefficients for each term of the linear constraint equation.

description: additional information about the single point constraint element.

6.4.12 linear_constraint_equation_element

A **linear_constraint_equation_element** is a linear multi-point constraint specified as a constraint equation. This equation has the form:

$$\sum_{i=1}^{n} (a_i \cdot x_i) = b$$

where:

x_i are the n nodal freedom values;

a_i are the n nodal freedom coefficients;

b is the constraint equation coefficient.

The value the constraint equation coefficient b above is set by a **linear_constraint_equation_element_value** entity.

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EXPRESS specification:

```
*)
ENTITY linear_constraint_equation_element
  SUBTYPE OF (constraint_element);
  freedoms_and_coefficients : SET [1:?] OF
                                 linear_constraint_equation_nodal_term;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

freedoms_and_coefficients: the degrees of freedom and their coefficients for each term of the linear constraint equation.

description: additional information about the element.

6.4.13 linear_constraint_equation_nodal_term

A **linear_constraint_equation_nodal_term** is the degrees of freedom and their coefficients at a node of the constraint.

EXPRESS specification:

```
*)
ENTITY linear_constraint_equation_nodal_term;
  node                      : node_representation;
  coordinate_system         : fea_axis2_placement_3d;
  freedom_and_coefficient_term : freedom_and_coefficient;
  dependent                 : LOGICAL;
END_ENTITY;
(*
```

Attribute definitions:

node: the node that is associated with the degree of freedom.

coordinate_system: the coordinate system in which the constraint freedom is being defined.

freedom_and_coefficient_term: the constrained freedom at the node, and the coefficient for the constrained freedom at the node (denoted a_i in the constraint equation shown above in **linear_constraint_-equation_element**).

dependent: a flag that indicates whether or not the freedom is to be considered dependent by the analysis application, as follows: TRUE it is the dependent degree of freedom, FALSE it is not.

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6.4.14 freedom_and_coefficient

A **freedom_and_coefficient** is the degree of freedom and the corresponding coefficient value of a constraint equation.

EXPRESS specification:

```
*)
ENTITY freedom_and_coefficient;
  freedom                    : degree_of_freedom;
  a                          : measure_or_unspecified_value;
END_ENTITY;
(*
```

Attribute definitions:

freedom: the degree of freedom that the value is associated with.

a: the nodal freedom coefficient a associated with the degree of freedom, as defined in 6.4.12.

6.4.15 nodal_dof_reduction

A **nodal_dof_reduction** is a definition of the degrees of freedom that are to be reduced out for the specified node in dynamic and substructuring analyses.

EXPRESS specification:

```
*)
ENTITY nodal_dof_reduction
  SUBTYPE OF (constraint_element);
  required_node              : node_output_reference;
  coordinate_system          : fea_axis2_placement_3d;
  freedoms                   : SET [1:?] OF degree_of_freedom;
  description                : text;
END_ENTITY;
(*
```

Attribute definitions:

required_node: the node that is being reduced.

coordinate_system: the coordinate system with respect to which the constraint freedoms are defined.

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freedoms: the freedoms to be reduced.

description: additional information about the reduction definition.

6.4.16 point_constraint

A **point_constraint** sets the values for one or more degrees of freedom for all nodes that may be related to the specified point.

EXPRESS specification:

```
*)
ENTITY point_constraint
  SUBTYPE OF (constraint_element);
  required_point            : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  freedoms_and_coefficients : SET [1:?] OF freedom_and_coefficient;
  description               : text;
WHERE
  WR1: ('GEOMETRY_SCHEMA.POINT' IN TYPEOF (required_point.item)) OR
       ('TOPOLOGY_SCHEMA.VERTEX_POINT' IN TYPEOF (required_point.item));
END_ENTITY;
(*
```

Attribute definitions:

required_point: the point whose associated nodes are being constrained.

coordinate_system: the coordinate system with respect to which the constraint freedoms are defined.

freedoms_and_coefficients: the freedom and coefficient pairs imposed by the constraint.

description: additional information about the point constraint.

Formal propositions:

WR1: the **geometric_representation_item** shall be a point or a vertex point.

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6.4.17 curve_constraint

A **curve_constraint** sets the values for one or more degrees of freedom for all nodes that may be related to the specified curve.

EXPRESS specification:

```
*)
ENTITY curve_constraint
  SUBTYPE OF (constraint_element);
  required_curve            : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  freedoms_and_coefficients : SET [1:?] OF freedom_and_coefficient;
  description               : text;
WHERE
  WR1: ('GEOMETRY_SCHEMA.CURVE' IN TYPEOF (required_curve.item)) OR
       ('TOPOLOGY_SCHEMA.EDGE_CURVE' IN TYPEOF (required_curve.item));
END_ENTITY;
(*
```

Attribute definitions:

required_curve: the curve whose associated nodes are being constrained.

coordinate_system: the coordinate system with respect to which the constraint freedoms are defined.

freedoms_and_coefficients: the freedom and coefficient pairs imposed by the constraint.

description: additional information about the curve constraint.

Formal propositions:

WR1: the **geometric_representation_item** shall be a curve or an edge curve.

6.4.18 surface_constraint

A **surface_constraint** sets the values for one or more degrees of freedom for all nodes that may be related to the specified surface.

EXPRESS specification:

```
*)
ENTITY surface_constraint
  SUBTYPE OF (constraint_element);
  required_surface          : analysis_item_within_representation;
```

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```
  coordinate_system         : fea_axis2_placement_3d;
  freedoms_and_coefficients : SET [1:?] OF freedom_and_coefficient;
  description               : text;
WHERE
  WR1: ('GEOMETRY_SCHEMA.SURFACE' IN TYPEOF (required_surface.item)) OR
       ('TOPOLOGY_SCHEMA.FACE_SURFACE' IN TYPEOF (required_surface.item));
END_ENTITY;
(*
```

Attribute definitions:

required_surface: the surface whose associated nodes are being constrained.

coordinate_system: the coordinate system with respect to which the constraint freedoms are defined.

freedoms_and_coefficients: the freedom and coefficient pairs imposed by the constraint.

description: additional information about the surface constraint.

Formal propositions:

WR1: the **geometric_representation_item** shall be a surface or a face surface.

6.4.19 solid_constraint

A **solid_constraint** sets the values for one or more degrees of freedom for all nodes that may be related to the specified solid model.

EXPRESS specification:

```
*)
ENTITY solid_constraint
  SUBTYPE OF (constraint_element);
  required_solid            : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  freedoms_and_coefficients : SET [1:?] OF freedom_and_coefficient;
  description               : text;
WHERE
  WR1: 'GEOMETRIC_MODEL_SCHEMA.SOLID_MODEL' IN TYPEOF (required_solid.item);
END_ENTITY;
(*
```

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Attribute definitions:

required_solid: the solid whose associated nodes are being constrained.

coordinate_system: the coordinate system with respect to which the constraint freedoms are defined.

freedoms_and_coefficients: the freedom and coefficient pairs imposed by the constraint.

description: additional information about the solid constraint.

Formal propositions:

WR1: the **geometric_representation_item** shall be a solid.

6.4.20 control_process

A **control_process** is the way in which the model is caused to depart from its initial state.

EXPRESS specification:

```
*)
ENTITY control_process
  SUPERTYPE OF (ONEOF (control_linear_static_load_increment_process,
                       control_linear_modes_and_frequencies_process));
  process_id                : identifier;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

process_id: the identifier for the process.

description: additional information about the process.

Informal propositions:

IP1: the process identifier shall be unique for the model.

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6.4.21 control_linear_static_load_increment_process

A **control_linear_static_load_increment_process** is a process that is a static load increment, and specifies the final state. All loads other than those that specify the initial state (before the process of applying load for the step) are specified with this entity.

The load increment is the difference between the loads for the final state specified by this entity, and those for the initial state specified by entity **control_analysis_step**. The load increment shall include any changes in the constraints.

EXPRESS specification:

```
*)
ENTITY control_linear_static_load_increment_process
  SUBTYPE OF (control_process);
  final_input_state         : state;
END_ENTITY;
(*
```

Attribute definitions:

final_input_state: the final equilibrium state for the static load increment. The final state includes all field and node state definitions applied to the model. This state is a specified state without any analysis output information until an analysis has been carried out.

6.4.22 control_linear_modes_and_frequencies_process

A **control_linear_modes_and_frequencies_process** is a process that is a dynamic loading process, and specifies the final state. All loads other than those that specify the initial state (before the process of applying load for the step) are specified with this entity.

The load increment is the difference between the loads for the final state specified by this entity, and those for the initial state specified by entity **control_analysis_step**. The load increment shall include any changes in the constraints.

EXPRESS specification:

```
*)
ENTITY control_linear_modes_and_frequencies_process
  SUBTYPE OF (control_process);
  final_input_state         : state;
END_ENTITY;
(*
```

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Attribute definitions:

final_input_state: the final equilibrium state for the dynamic analysis process. The final state includes all field and node state definitions applied to the model. This state is a specified state without any analysis output information until an analysis has been carried out.

6.4.23 element_sequence

An **element_sequence** is an ordered list of elements.

NOTE Typical uses of the ordered list will be solution optimization or controlling the presentation of results.

EXPRESS specification:

```
*)
ENTITY element_sequence;
  order_id                  : identifier;
  control_ref               : control;
  purpose                   : text;
  elements                  : LIST [1:?] OF model_or_control_element;
UNIQUE
  UR1: order_id, control_ref;
END_ENTITY;
(*
```

Attribute definitions:

order_id: the identifier for the ordered element list.

control_ref: the control for the ordered element list.

purpose: additional information about the ordered element list specifying its use.

elements: the ordered list of elements.

Formal propositions:

UR1: the ordered list identifier shall be unique for the control reference in each of the steps.

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6.4.24 node_sequence

A **node_sequence** is an ordered list of nodes.

NOTE Typical uses of the ordered list will be solution optimization or controlling the presentation of results.

EXPRESS specification:

```
*)
ENTITY node_sequence;
  order_id                  : identifier;
  control_ref               : control;
  purpose                   : text;
  nodes                     : LIST [1:?] OF node_representation;
UNIQUE
  UR1: order_id, control_ref;
END_ENTITY;
(*
```

Attribute definitions:

order_id: the identifier for the ordered node list.

control_ref: the control for the ordered node list.

purpose: additional information about the ordered node list specifying its use.

nodes: the ordered list of nodes.

Formal propositions:

UR1: the ordered list identifier shall be unique for the control reference in each of the steps.

6.5 Finite element analysis control and result entity definitions: Analysis results

Analysis results for a finite element analysis consists of the response of a model to a control as calculated by a finite element analysis application. All model states calculated by the analysis application shall be linked to a result.

6.5.1 result

A **result** is the administrative information for analysis results.

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EXPRESS specification:

```
*)
ENTITY result;
  result_id                 : identifier;
  creating_software         : text;
  description               : text;
END_ENTITY;
(*
```

Attribute definitions:

result_id: the identifier for the result.

creating_software: the software that is used to create the result.

description: additional information about the result.

Informal propositions:

IP1: the result identifier shall be unique for the model.

6.5.2 result_analysis_step

A **result_analysis_step** is an analysis sub-step. As results are calculated, the analysis step specified by the control is divided into one or more analysis sub-steps. The resulting model state is stored for the end of each sub-step.

For a linear static and dynamic analyses, analysis calculations produce a single analysis sub-step which is the final state.

EXPRESS specification:

```
*)
ENTITY result_analysis_step
  SUPERTYPE OF (ONEOF (result_linear_static_analysis_sub_step,
                 result_linear_modes_and_frequencies_analysis_sub_step))
  SUBTYPE OF (analysis_step);
  analysis_result           : result;
UNIQUE
  UR1: SELF\analysis_step.analysis_control, analysis_result;
END_ENTITY;
(*
```

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Attribute definitions:

analysis_result: the result in which the step was calculated.

Formal propositions:

UR1: the result shall be unique for the control.

6.5.3 result_linear_static_analysis_sub_step

A **result_linear_static_analysis_sub_step** is a sub-step that is calculated by a linear static analysis, and represents the final state of the step.

EXPRESS specification:

```
*)
ENTITY result_linear_static_analysis_sub_step
  SUBTYPE OF (result_analysis_step);
  state                     : calculated_state;
END_ENTITY;
(*
```

Attribute definitions:

state: the calculated state resulting from the linear static analysis sub-step.

6.5.4 result_linear_modes_and_frequencies_analysis_sub_step

A **result_linear_modes_and_frequencies_analysis_sub_step** is a sub-step that is calculated by a linear modes and frequencies analysis, and represents the final state of the step. The final state is described by a series of calculated states, one state for each mode and frequency pair.

EXPRESS specification:

```
*)
ENTITY result_linear_modes_and_frequencies_analysis_sub_step
  SUBTYPE OF (result_analysis_step);
  states                    : SET [1:?] OF calculated_state;
END_ENTITY;
(*
```

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Attribute definitions:

states: the set of calculated states resulting from the linear modes and frequencies analysis sub-step. There is one **calculated_state** per mode and frequency pair.

Informal propositions:

IP1: there shall be exactly one **whole_model_modes_and_frequencies_analysis_message** for each **result_linear_modes_and_frequencies_analysis_sub_step** that defines the mode number and frequency value.

6.5.5 control_result_relationship

A **control_result_relationship** is the relationship of a result step to a control step (and the associated model) that formed the input to the analysis that created the calculated state for the result step.

EXPRESS specification:

```
*)
ENTITY control_result_relationship;
  control                   : control_analysis_step;
  result                    : result_analysis_step;
END_ENTITY;
(*
```

Attribute definitions:

control: the control for a given analysis step.

result: the result for a given analysis control.

6.6 Finite element analysis control and result entity definitions: Model state

At any instant, a model has a state. All information defining or requesting analysis variables within a model, including stress, strain or deflections are associated with a state. Any field within the scope of the analysis, but which is not defined for a state has a value of zero.

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6.6.1 state

A **state** is an aggregation of state definitions that describe the model at an instant as follows:

— the attributes of the entity provide administrative information for the state;

— details of the state are supplied by the **state_definition** entities that reference it.

EXPRESS specification:

```
*)
ENTITY state
  SUPERTYPE OF (ONEOF (specified_state,
                       calculated_state,
                       linearly_superimposed_state,
                       output_request_state));
  state_id                 : identifier;
  description              : text;
END_ENTITY;
(*
```

Attribute definitions:

state_id: the identifier for the state.

description: additional information about the state.

Informal propositions:

IP1: the state identifier shall be unique for the model.

6.6.2 state_with_harmonic

A **state_with_harmonic** is the state of a model for an analysis that requires the specification of the type of symmetry and a corresponding harmonic.

EXPRESS specification:

```
*)
ENTITY state_with_harmonic
  SUBTYPE OF (state);
  symmetry                 : cylindrical_symmetry_control;
END_ENTITY;
(*
```

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Attribute definitions:

symmetry: the type of symmetry for an analysis.

6.6.3 specified_state

A **specified_state** is all the information for the state that is specified, and that none of it is the result of a previous calculation represented within the information model.

EXPRESS specification:

```
*)
ENTITY specified_state
  SUBTYPE OF (state);
END_ENTITY;
(*
```

6.6.4 calculated_state

A **calculated_state** is some of the information for the state that is calculated by a previous analysis step.

EXPRESS specification:

```
*)
ENTITY calculated_state
  SUBTYPE OF (state);
END_ENTITY;
(*
```

6.6.5 linearly_superimposed_state

A **linearly_superimposed_state** is some of the information for the state that is calculated by a combination of previously calculated and/or specified steps.

EXPRESS specification:

```
*)
ENTITY linearly_superimposed_state
  SUBTYPE OF (state);
INVERSE
  components                : SET [1:?] OF state_component FOR state;
END_ENTITY;
(*
```

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Attribute definitions:

components: the states from which this state is created.

6.6.6 state_component

A **state_component** is a component of a linearly superimposed state.

EXPRESS specification:

```
*)
ENTITY state_component
  SUBTYPE OF (state);
  state                     : linearly_superimposed_state;
  factor                    : context_dependent_measure;
END_ENTITY;
(*
```

Attribute definitions:

state: the state that aggregates the state components.

factor: a weighting factor to scale information in the state.

6.6.7 output_request_state

An **output_request_state** is the computer readable output to be produced by an finite element analysis system as follows:

— the attributes of the entity provide administrative information for the state of output;

— details of the information to be produced by the finite element analysis system are supplied by the **state_definition** entities that reference it.

EXPRESS specification:

```
*)
ENTITY output_request_state
  SUBTYPE OF (state);
  steps                     : SET [1:?] OF control_analysis_step;
END_ENTITY;
(*
```

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Attribute definitions:

steps: the analysis control steps to which the output requests apply.

6.6.8 state_relationship

A **state_relationship** is an association between a relating state and a related state, such that all the information about the related state is also about the relating state. The related state is an aspect of the relating state.

EXAMPLE The **state_relationship** may be used to associate **state** entities to one or more **state - control_-analysis_step** pairs thereby providing an unordered grouping capability for **state_definition**s.

NOTE A **state_relationship** enables different aspects of a state such as boundary conditions, external loads, and thermal loads to be managed as separate states. The initial state for a **control_analysis_step** can be defined as a combination of different aspects. The partitioning of a state into aspects is solely for information management convenience, and has no engineering significance.

EXPRESS specification:

```
*)
ENTITY state_relationship;
  name                      : label;
  description               : text;
  relating_state            : state;
  related_state             : state;
END_ENTITY;
(*
```

Attribute definitions:

name: the word or group of words by which the **state_relationship** is referred to.

description: text that relates the nature of the **state_relationship**.

relating_state: one of the **state**s which is a part of the relationship.

related_state: the other **state** which is a part of the relationship. If one state in the relationship is dependent upon the other, then this attribute shall be the dependent one.

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6.7 Finite element analysis control and result entity definitions: State definition

A state definition has two roles:

— as a state definition with a value that contains numeric information, it can reference a **specified_-state**, **calculated_state**, or **linearly_superimposed_state** entity, thereby defining the variables within the model for that state;

— as a state definition with a value that is unspecified, it can reference an **output_request_state** entity to define the information to be calculated by the finite element analysis application for one or more **control_analysis_step**s.

NOTE An EXPRESS-G Partial Model illustrating the relationships of the state definitions is shown in Figure 63.

6.7.1 state_definition

A **state_definition** is both information known before and after an analysis and therefore either requests or represents information calculated by the analysis. In this manner a **state_definition** output from one **step** may be used as input for a subsequent **state_definition**.

EXAMPLE 1 External loadings and prescribed values of variables at a boundary are types of information known before and after an analysis.

EXAMPLE 2 Element stresses and values of variables at unconstrained nodes are types of information calculated by the analysis.

EXPRESS specification:

```
*)
ENTITY state_definition
  SUPERTYPE OF (ONEOF (field_variable_definition,
                       nodal_freedom_and_value_definition,
                       element_nodal_freedom_actions,
                       point_freedom_and_value_definition,
                       curve_freedom_and_value_definition,
                       surface_freedom_and_value_definition,
                       solid_freedom_and_value_definition,
                       linear_constraint_equation_element_value,
                       single_point_constraint_element_values,
                       analysis_message));
  defined_state             : state;
END_ENTITY;
(*
```

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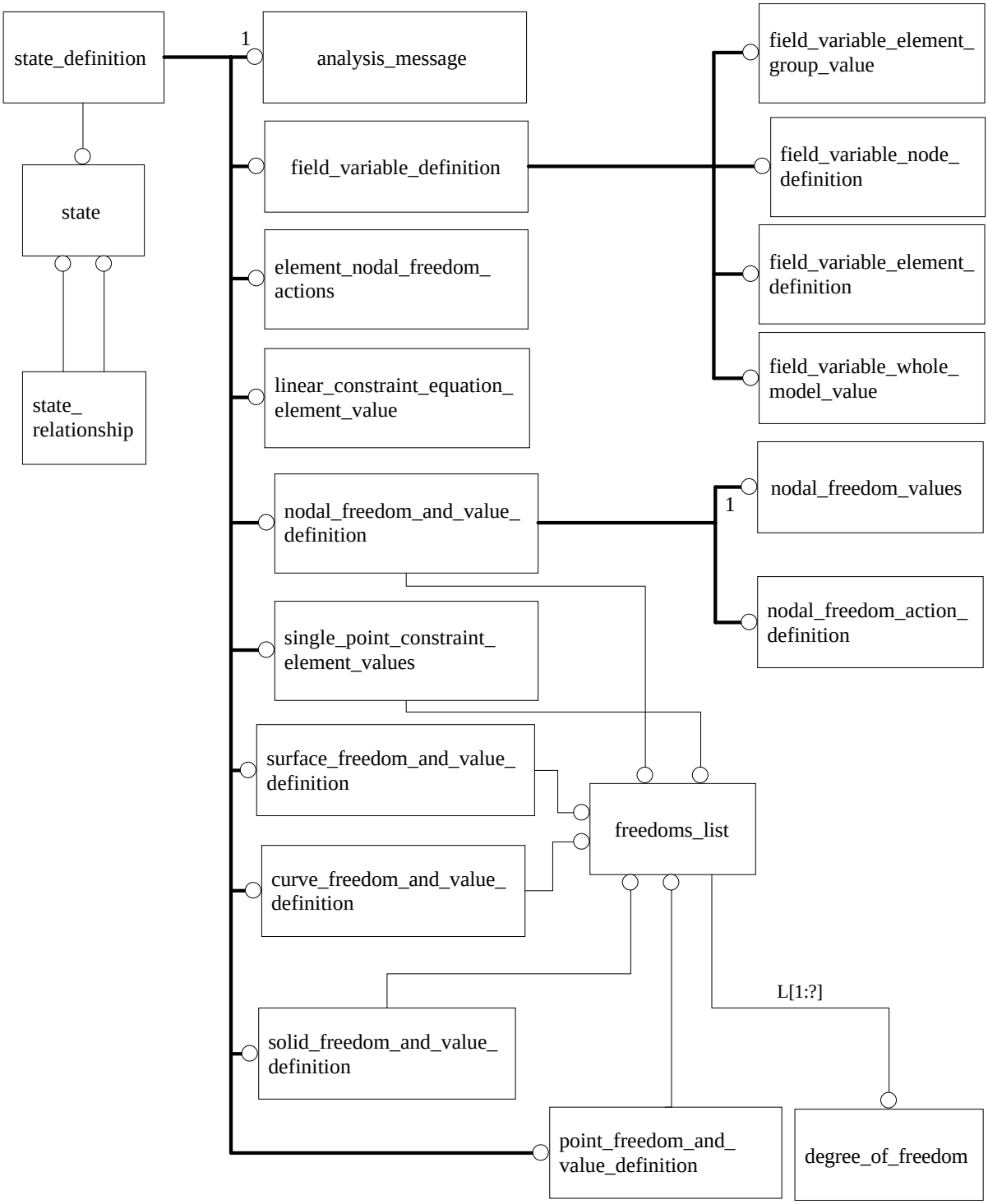

Figure 63 – State definition EXPRESS-G partial model

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Attribute definitions:

defined_state: the model state that aggregated the state definitions.

6.7.2 field_variable_definition

A **field_variable_definition** is a state of the model that specifies values for a field variable pertaining to the elements of the model.

The field variable information shall be either:

— evaluated a point within the volume of an element;

— aggregated through the section of a surface or curve element at a point on the element;

— aggregated within an element, a group of elements, or an entire model;

— evaluated at a point on an element boundary (element face of a volume element or element edge of a surface element);

— aggregated over an element boundary.

EXPRESS specification:

```
*)
ENTITY field_variable_definition
  SUPERTYPE OF (ONEOF (field_variable_element_definition,
                       field_variable_element_group_value,
                       field_variable_whole_model_value,
                       field_variable_node_definition))
  SUBTYPE OF (state_definition);
END_ENTITY;
(*
```

6.7.3 field_variable_element_definition

A **field_variable_element_definition** defines the state of the model by specifying the values of a variable within an element.

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EXPRESS specification:

```
*)
ENTITY field_variable_element_definition
  SUPERTYPE OF (ONEOF (volume_3d_element_field_variable_definition,
                       volume_2d_element_field_variable_definition,
                       surface_3d_element_field_variable_definition,
                       surface_2d_element_field_variable_definition,
                       curve_3d_element_field_variable_definition,
                       curve_2d_element_field_variable_definition))
  SUBTYPE OF (field_variable_definition);
END_ENTITY;
(*
```

6.7.4 volume_3d_element_field_variable_definition

A **volume_3d_element_field_variable_definition** is a state of the model that specifies the values of a variable within a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_field_variable_definition
  SUPERTYPE OF (ONEOF (
   volume_3d_element_location_point_variable_values,
   volume_3d_whole_element_variable_value,
   volume_3d_element_constant_specified_variable_value,
   volume_3d_element_nodal_specified_variable_values,
   volume_3d_element_boundary_location_point_variable_values,
   volume_3d_element_boundary_whole_face_variable_value,
   volume_3d_element_boundary_constant_specified_variable_value,
   volume_3d_element_boundary_nodal_specified_variable_values,
   volume_3d_element_boundary_edge_location_point_volume_variable_values,
   volume_3d_element_boundary_edge_whole_edge_variable_value,
   volume_3d_element_boundary_edge_constant_specified_volume_variable_value,
   volume_3d_element_boundary_edge_nodal_specified_variable_values))

  SUBTYPE OF (field_variable_element_definition);
  element                   : volume_3d_element_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified, or the element for which values are to be calculated.

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6.7.5 volume_3d_element_location_point_variable_values

A **volume_3d_element_location_point_variable_values** is a state of the model that specifies the values of a variable at location points within a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_location_point_variable_values
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              volume_3d_element_value_and_location;
  variable                  : volume_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the value shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.6 volume_3d_element_value_and_location

A **volume_3d_element_value_and_location** is the value of a variable at a location point within a volume 3D element.

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EXPRESS specification:

```
*)
ENTITY volume_3d_element_value_and_location;
  simple_value              : field_value;
  location                  : volume_element_location;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.7 volume_3d_whole_element_variable_value

A **volume_3d_whole_element_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over a volume 3D element. The value represented by this entity does not include a contribution from the aggregation of boundary variables.

EXPRESS specification:

```
*)
ENTITY volume_3d_whole_element_variable_value
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the value shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.8 volume_3d_element_constant_specified_variable_value

A **volume_3d_element_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant over a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_constant_specified_variable_value
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the value shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.9 volume_3d_element_nodal_specified_variable_values

A **volume_3d_element_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes of a volume 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for either the vertex nodes or all nodes of the element, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_nodal_specified_variable_values
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : volume_variable;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

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WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.10 volume_3d_element_boundary_location_point_variable_values

A **volume_3d_element_boundary_location_point_variable_values** is a state of the model that specifies the values of a variable at location points over the element face of a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_boundary_location_point_variable_values
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               volume_3d_element_value_and_location;
  variable                   : boundary_variable;
  element_face               : volume_3d_face;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_face: the element face for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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Informal propositions:

IP1: each location in the list shall lie on the specified element face.

6.7.11 volume_3d_element_boundary_whole_face_variable_value

A **volume_3d_element_boundary_whole_face_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over the element face of a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_boundary_whole_face_variable_value
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_face              : volume_3d_face;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face for which the values are specified.

coordinate_system: the coordinate system for the value.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the value shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.12 volume_3d_element_boundary_constant_specified_variable_-value

A **volume_3d_element_boundary_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant over the whole of a volume 3D element face.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_boundary_constant_specified_variable_value
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_variable;
  element_face              : volume_3d_face;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.13 volume_3d_element_boundary_nodal_specified_variable_-values

A **volume_3d_element_boundary_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes on an element face of a volume 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for the nodes on the element face, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_boundary_nodal_specified_variable_values
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_variable;
  element_face              : volume_3d_face;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_face: the element face for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the value shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.14 volume_3d_element_boundary_edge_location_point_volume_-variable_values

A **volume_3d_element_boundary_edge_location_point_volume_variable_values** is a state of the model that specifies the variable values along an edge of a volume 3D element.

EXPRESS specification:

```
*)
ENTITY
 volume_3d_element_boundary_edge_location_point_volume_variable_values
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               volume_3d_element_value_and_location;
  variable                   : boundary_edge_variable;
  element_edge               : volume_3d_edge;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: TRUE if the value set has only basis locations for the field variable within the element.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified. The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

Informal propositions:

IP1: each location in the list shall lie on the specified element edge.

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6.7.15 volume_3d_element_boundary_edge_whole_edge_variable_-value

A **volume_3d_element_boundary_edge_whole_edge_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation along an element edge of a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_boundary_edge_whole_edge_variable_value
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_edge              : volume_3d_edge;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.16 volume_3d_element_boundary_edge_constant_specified_-volume_variable_value

A **volume_3d_element_boundary_edge_constant_specified_volume_variable_value** is a state of the model that is defined by specifying the value of a variable at a point on a volume, which is constant along a volume 3D element edge.

EXPRESS specification:

```
*)
ENTITY
 volume_3d_element_boundary_edge_constant_specified_volume_variable_value
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_edge_variable;
  element_edge              : volume_3d_edge;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.17 volume_3d_element_boundary_edge_nodal_specified_-variable_values

A **volume_3d_element_boundary_edge_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes along an element edge of a volume 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for the nodes on the element edge, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY volume_3d_element_boundary_edge_nodal_specified_variable_values
  SUBTYPE OF (volume_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_edge_variable;
  element_edge              : volume_3d_edge;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.18 volume_2d_element_field_variable_definition

A **volume_2d_element_field_variable_definition** is a state of the model that specifies the values of a variable within a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_field_variable_definition
  SUPERTYPE OF (ONEOF (
   volume_2d_element_location_point_variable_values,
   volume_2d_whole_element_variable_value,
   volume_2d_element_constant_specified_variable_value,
   volume_2d_element_nodal_specified_variable_values,
   volume_2d_element_boundary_location_point_variable_values,
   volume_2d_element_boundary_whole_face_variable_value,
   volume_2d_element_boundary_constant_specified_variable_value,
   volume_2d_element_boundary_nodal_specified_variable_values,
   volume_2d_element_boundary_edge_location_point_volume_variable_values,
   volume_2d_element_boundary_edge_whole_edge_variable_value,
   volume_2d_element_boundary_edge_constant_specified_volume_variable_value,
   volume_2d_element_boundary_edge_nodal_specified_variable_values))

  SUBTYPE OF (field_variable_element_definition);
  element                   : volume_2d_element_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified, or the element for which values are to be calculated.

6.7.19 volume_2d_element_location_point_variable_values

A **volume_2d_element_location_point_variable_values** is a state of the model that specifies the values of a variable at location points within a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_location_point_variable_values
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
```

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```
                                volume_2d_element_value_and_location;
  variable                    : volume_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.20 volume_2d_element_value_and_location

A **volume_2d_element_value_and_location** is a value of a variable at a location point within a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_value_and_location;
  simple_value                : field_value;
  location                    : volume_element_location;
  coordinate_system           : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.21 volume_2d_whole_element_variable_value

A **volume_2d_whole_element_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over a volume 2D element.

The value represented by this entity does not include a contribution from the aggregation of boundary variables.

EXPRESS specification:

```
*)
ENTITY volume_2d_whole_element_variable_value
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.22 volume_2d_element_constant_specified_variable_value

A **volume_2d_element_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant over the whole of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_constant_specified_variable_value
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.23 volume_2d_element_nodal_specified_variable_values

A **volume_2d_element_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes of a volume 2D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for either the vertex nodes or all nodes of the element, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_nodal_specified_variable_values
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : volume_variable;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.24 volume_2d_element_boundary_location_point_variable_values

A **volume_2d_element_boundary_location_point_variable_values** is a state of the model that specifies the values of a variable at points over the element face of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_boundary_location_point_variable_values
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               volume_2d_element_value_and_location;
  variable                   : boundary_variable;
  element_face               : volume_2d_face;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_face: the element face for which the values are specified. The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

Informal propositions:

IP1: each location in the list shall lie on the specified element face.

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6.7.25 volume_2d_element_boundary_whole_face_variable_value

A **volume_2d_element_boundary_whole_face_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over the element face of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_boundary_whole_face_variable_value
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_face              : volume_2d_face;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.26 volume_2d_element_boundary_constant_specified_variable_-value

A **volume_2d_element_boundary_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant over the whole of a volume 2D element face.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_boundary_constant_specified_variable_value
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_variable;
  element_face              : volume_2d_face;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.27 volume_2d_element_boundary_nodal_specified_variable_-values

A **volume_2d_element_boundary_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes on an element face of a volume 2D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for the nodes on the element face, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_boundary_nodal_specified_variable_values
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  variable                  : boundary_variable;
  additional_node_values    : BOOLEAN;
  element_face              : volume_2d_face;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

variable: the type of field variable being specified.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

element_face: the element face for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.28 volume_2d_element_boundary_edge_location_point_volume_-variable_values

A **volume_2d_element_boundary_edge_location_point_volume_variable_values** is a state of the model that specifies the variable values along an edge of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY
 volume_2d_element_boundary_edge_location_point_volume_variable_values
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               volume_2d_element_value_and_location;
  variable                   : boundary_edge_variable;
  element_edge               : volume_2d_edge;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: TRUE if the value set has only basis locations for the field variable within the element.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified. The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

Informal propositions:

IP1: each location in the list shall lie on the specified element edge.

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6.7.29 volume_2d_element_boundary_edge_whole_edge_variable_-value

A **volume_2d_element_boundary_edge_whole_edge_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation along an element edge of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_boundary_edge_whole_edge_variable_value
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_edge              : volume_2d_edge;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.30 volume_2d_element_boundary_edge_constant_specified_-volume_variable_value

A **volume_2d_element_boundary_edge_constant_specified_volume_variable_value** is a state of the model that is defined by specifying the value of a variable at a point on a volume, which is constant along a volume 2D element edge.

EXPRESS specification:

```
*)
ENTITY
 volume_2d_element_boundary_edge_constant_specified_volume_variable_value
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_edge_variable;
  element_edge              : volume_2d_edge;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.31 volume_2d_element_boundary_edge_nodal_specified_-variable_values

A **volume_2d_element_boundary_edge_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes along an element edge of a volume 2D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for the nodes on the element edge, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY volume_2d_element_boundary_edge_nodal_specified_variable_values
  SUBTYPE OF (volume_2d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_edge_variable;
  element_edge              : volume_2d_edge;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_edge: the element edge of the volume for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.32 surface_3d_element_field_variable_definition

A **surface_3d_element_field_variable_definition** is a state of the model that specifies the values of a variable within a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_field_variable_definition
  SUPERTYPE OF (ONEOF (
  surface_3d_element_location_point_volume_variable_values,
  surface_3d_element_location_point_variable_values,
  surface_3d_whole_element_variable_value,
  surface_3d_element_constant_specified_variable_value,
  surface_3d_element_constant_specified_volume_variable_value,
  surface_3d_element_nodal_specified_variable_values,
  surface_3d_element_boundary_location_point_surface_variable_values,
  surface_3d_element_boundary_whole_face_variable_value,
  surface_3d_element_boundary_constant_specified_variable_value,
  surface_3d_element_boundary_constant_specified_surface_variable_value,
  surface_3d_element_boundary_nodal_specified_variable_values,
  surface_3d_element_boundary_edge_location_point_surface_variable_values,
  surface_3d_element_boundary_edge_location_point_variable_values,
  surface_3d_element_boundary_edge_whole_edge_variable_value,
  surface_3d_element_boundary_edge_constant_specified_variable_value,
  surface_3d_element_boundary_edge_constant_specified_surface_variable_value,
  surface_3d_element_boundary_edge_nodal_specified_variable_values))

  SUBTYPE OF (field_variable_element_definition);
  element                   : surface_3d_element_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified, or the element for which values are to be calculated.

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6.7.33 surface_3d_element_location_point_volume_variable_values

A **surface_3d_element_location_point_volume_variable_values** is a state of the model that specifies the values of a variable at location points within the volume of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_location_point_volume_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_3d_element_value_and_volume_location;
  variable                   : volume_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));

END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.34 surface_3d_element_value_and_location

A **surface_3d_element_value_and_location** is a value of a variable at a location point within the 2D field of a surface 3D element.

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EXPRESS specification:

```
*)
ENTITY surface_3d_element_value_and_location;
  simple_value              : field_value;
  location                  : surface_element_location;
  coordinate_system         : OPTIONAL surface_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.35 surface_3d_element_value_and_volume_location

A **surface_3d_element_value_and_volume_location** is a value of a variable at a location point within the volume of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_value_and_volume_location;
  simple_value              : field_value;
  location                  : surface_volume_element_location;
  coordinate_system         : OPTIONAL surface_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.36 surface_3d_element_location_point_variable_values

A **surface_3d_element_location_point_variable_values** is a state of the model that specifies the values of a variable at location points over the surface of a surface 3D element. The variables are obtained by aggregation through the section at each surface point.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_location_point_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              surface_3d_element_value_and_location;
  variable                  : surface_element_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

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Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.37 surface_3d_whole_element_variable_value

A **surface_3d_whole_element_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over a surface 3D element. The value represented by this entity does not include a contribution from the aggregation of boundary variables.

EXPRESS specification:

```
*)
ENTITY surface_3d_whole_element_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.38 surface_3d_element_constant_specified_variable_value

A **surface_3d_element_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant over the surface of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_constant_specified_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : surface_element_variable;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.39 surface_3d_element_constant_specified_volume_variable_value

A **surface_3d_element_constant_specified_volume_variable_value** is a state of the model that specifies the value of a variable which is constant within the volume of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_constant_specified_volume_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.40 surface_3d_element_nodal_specified_variable_values

A **surface_3d_element_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes of a surface 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for either the vertex nodes or all nodes of the element, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_nodal_specified_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : surface_element_variable;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.41 surface_3d_element_boundary_location_point_surface_-variable_values

A **surface_3d_element_boundary_location_point_surface_variable_values** is a state of the model that specifies the values of a variable at location points on the surface of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY
 surface_3d_element_boundary_location_point_surface_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_3d_element_value_and_location;
  variable                   : boundary_variable;
  element_face               : surface_3d_face;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.42 surface_3d_element_boundary_whole_face_variable_value

A **surface_3d_element_boundary_whole_face_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation on the surface of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_boundary_whole_face_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_face              : surface_3d_face;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being output.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.43 surface_3d_element_boundary_constant_specified_surface_-variable_value

A **surface_3d_element_boundary_constant_specified_surface_variable_value** is a state of the model that specifies the value of a variable at a point on a surface, which is constant over the surface of the surface 3D element.

EXPRESS specification:

```
*)
ENTITY
 surface_3d_element_boundary_constant_specified_surface_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_variable;
  element_face              : surface_3d_face;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically shown in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.44 surface_3d_element_boundary_constant_specified_variable_-value

A **surface_3d_element_boundary_constant_specified_variable_value** is a state of the model that specifies the value of a variable aggregated through the section, which is constant on the surface of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_boundary_constant_specified_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_face              : surface_3d_face;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.45 surface_3d_element_boundary_nodal_specified_variable_-values

A **surface_3d_element_boundary_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes on the surface of a surface 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_boundary_nodal_specified_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_variable;
  element_face              : surface_3d_face;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.46 surface_3d_element_boundary_edge_location_point_surface_-variable_values

A **surface_3d_element_boundary_edge_location_point_surface_variable_values** is a state of the model that specifies the values of a variable at location points within the surface along an element edge of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY
 surface_3d_element_boundary_edge_location_point_surface_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_3d_element_value_and_volume_location;
  variable                   : boundary_edge_variable;
  element_edge               : surface_3d_edge;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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Informal propositions:

IP1: each location in the list shall lie on the specified element edge.

6.7.47 surface_3d_element_boundary_edge_location_point_-variable_values

A **surface_3d_element_boundary_edge_location_point_variable_values** is a state of the model that specifies the values of a variable aggregated through the section at location points along an element edge of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY
 surface_3d_element_boundary_edge_location_point_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_3d_element_value_and_location;
  variable                   : boundary_edge_variable;
  element_edge               : surface_3d_edge;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

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WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

Informal propositions:

IP1: each location in the list shall lie on the specified element edge.

6.7.48 surface_3d_element_boundary_edge_whole_edge_variable_-value

A **surface_3d_element_boundary_edge_whole_edge_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation along an element edge of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_boundary_edge_whole_edge_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_edge              : surface_3d_edge;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.49 surface_3d_element_boundary_edge_constant_specified_-surface_variable_value

A **surface_3d_element_boundary_edge_constant_specified_surface_variable_value** is a state of the model that is defined by specifying the value of a variable at a point on a surface, which is constant along a surface 3D element edge.

EXPRESS specification:

```
*)
ENTITY
 surface_3d_element_boundary_edge_constant_specified_surface_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_edge_variable;
  element_edge              : surface_3d_edge;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.50 surface_3d_element_boundary_edge_constant_specified_-variable_value

A **surface_3d_element_boundary_edge_constant_specified_variable_value** is a state of the model that specifies the value of a variable aggregated through the section, which is constant along a surface 3D element edge.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_boundary_edge_constant_specified_variable_value
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_edge_variable;
  element_edge              : surface_3d_edge;
  coordinate_system         : OPTIONAL surface_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.51 surface_3d_element_boundary_edge_nodal_specified_-variable_values

A **surface_3d_element_boundary_edge_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes along an element edge of a surface 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for the nodes on the element edge, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY surface_3d_element_boundary_edge_nodal_specified_variable_values
  SUBTYPE OF (surface_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_edge_variable;
  element_edge              : surface_3d_edge;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

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Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.52 surface_2d_element_field_variable_definition

A **surface_2d_element_field_variable_definition** is a state of the model that specifies the values of a variable within a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_field_variable_definition
  SUPERTYPE OF (ONEOF (
  surface_2d_element_location_point_volume_variable_values,
  surface_2d_element_location_point_variable_values,
  surface_2d_whole_element_variable_value,
  surface_2d_element_constant_specified_variable_value,
  surface_2d_element_constant_specified_volume_variable_value,
  surface_2d_element_nodal_specified_variable_values,
  surface_2d_element_boundary_location_point_surface_variable_values,
  surface_2d_element_boundary_whole_face_variable_value,
  surface_2d_element_boundary_constant_specified_variable_value,
  surface_2d_element_boundary_constant_specified_surface_variable_value,
  surface_2d_element_boundary_nodal_specified_variable_values,
  surface_2d_element_boundary_edge_location_point_surface_variable_values,
  surface_2d_element_boundary_edge_location_point_variable_values,
  surface_2d_element_boundary_edge_whole_edge_variable_value,
  surface_2d_element_boundary_edge_constant_specified_variable_value,
  surface_2d_element_boundary_edge_constant_specified_surface_variable_value,
  surface_2d_element_boundary_edge_nodal_specified_variable_values))

  SUBTYPE OF (field_variable_element_definition);
  element                   : surface_2d_element_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified, or the element for which values are to be calculated.

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6.7.53 surface_2d_element_location_point_volume_variable_values

A **surface_2d_element_location_point_volume_variable_values** is a state of the model that specifies the values of a variable at location points within the volume of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_location_point_volume_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_2d_element_value_and_volume_location;
  variable                   : volume_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.54 surface_2d_element_value_and_location

A **surface_2d_element_value_and_location** is a value of a variable at a location point within the 2D field of a surface 2D element.

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EXPRESS specification:

```
*)
ENTITY surface_2d_element_value_and_location;
  simple_value              : field_value;
  location                  : surface_element_location;
  coordinate_system         : OPTIONAL surface_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.55 surface_2d_element_value_and_volume_location

A **surface_2d_element_value_and_volume_location** is a value of a variable at a location point within the volume of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_value_and_volume_location;
  simple_value              : field_value;
  location                  : surface_volume_element_location;
  coordinate_system         : OPTIONAL surface_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.56 surface_2d_element_location_point_variable_values

A **surface_2d_element_location_point_variable_values** is a state of the model that specifies the values of a variable at location points over the surface of a surface 2D element. The variables are obtained by aggregation through the section at each surface point.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_location_point_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              surface_2d_element_value_and_location;
  variable                  : surface_element_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

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Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.57 surface_2d_whole_element_variable_value

A **surface_2d_whole_element_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over a surface 2D element. The value represented by this entity does not include a contribution from the aggregation of boundary variables.

EXPRESS specification:

```
*)
ENTITY surface_2d_whole_element_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: The coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.58 surface_2d_element_constant_specified_variable_value

A **surface_2d_element_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant over the surface of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_constant_specified_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : surface_element_variable;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.59 surface_2d_element_constant_specified_volume_variable_value

A **surface_2d_element_constant_specified_volume_variable_value** is a state of the model that specifies the value of a variable which is a constant within the volume of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_constant_specified_volume_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.60 surface_2d_element_nodal_specified_variable_values

A **surface_2d_element_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes of a surface 2D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for either the vertex nodes or all nodes of the element, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_nodal_specified_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : surface_element_variable;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.61 surface_2d_element_boundary_location_point_surface_-variable_values

A **surface_2d_element_boundary_location_point_surface_variable_values** is a state of the model that specifies the values of a variable at location points on the surface of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY
 surface_2d_element_boundary_location_point_surface_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_2d_element_value_and_location;
  variable                   : boundary_variable;
  element_face               : surface_2d_face;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.62 surface_2d_element_boundary_whole_face_variable_value

A **surface_2d_element_boundary_whole_face_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation on the surface of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_boundary_whole_face_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_face              : surface_2d_face;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.63 surface_2d_element_boundary_constant_specified_surface_-variable_value

A **surface_2d_element_boundary_constant_specified_surface_variable_value** is a state of the model that specifies the value of a variable at a point on a surface, which is constant over the surface of the surface 2D element.

EXPRESS specification:

```
*)
ENTITY
 surface_2d_element_boundary_constant_specified_surface_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_variable;
  element_face              : surface_2d_face;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.64 surface_2d_element_boundary_constant_specified_variable_-value

A **surface_2d_element_boundary_constant_specified_variable_value** is a state of the model that specifies the value of a variable aggregated through the section, which is constant on the surface of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_boundary_constant_specified_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_face              : surface_2d_face;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.65 surface_2d_element_boundary_nodal_specified_variable_-values

A **surface_2d_element_boundary_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes on the surface of a surface 2D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_boundary_nodal_specified_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_variable;
  element_face              : surface_2d_face;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_face: the element face of the surface for which the values are specified.

The relationship between the element face number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.66 surface_2d_element_boundary_edge_location_point_surface_-variable_values

A **surface_2d_element_boundary_edge_location_point_surface_variable_values** is a state of the model that specifies the values of a variable at location points along an element edge of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY
 surface_2d_element_boundary_edge_location_point_surface_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_2d_element_value_and_volume_location;
  variable                   : boundary_edge_variable;
  element_edge               : surface_2d_edge;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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6.7.67 surface_2d_element_boundary_edge_location_point_-variable_values

A **surface_2d_element_boundary_edge_location_point_variable_values** is a state of the model that specifies the values of a variable aggregated through the section at location points along an element edge of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY
 surface_2d_element_boundary_edge_location_point_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  basis                      : BOOLEAN;
  values_and_locations       : SET [1:?] OF
                               surface_2d_element_value_and_location;
  variable                   : boundary_edge_variable;
  element_edge               : surface_2d_edge;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

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Informal propositions:

IP1: each location in the list shall lie on the specified element edge.

6.7.68 surface_2d_element_boundary_edge_whole_edge_variable_-value

A **surface_2d_element_boundary_edge_whole_edge_variable_value** that specifies a state of the model that specifies the value of a variable which is obtained by aggregation along an element edge of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_boundary_edge_whole_edge_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_aggregated_variable;
  element_edge              : surface_2d_edge;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.69 surface_2d_element_boundary_edge_constant_specified_-surface_variable_value

A **surface_2d_element_boundary_edge_constant_specified_surface_variable_value** is a state of the model that specifies the value of a variable at a point on a surface, which is a constant along a surface 2D element edge.

EXPRESS specification:

```
*)
ENTITY
 surface_2d_element_boundary_edge_constant_specified_surface_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_edge_variable;
  element_edge              : surface_2d_edge;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.70 surface_2d_element_boundary_edge_constant_specified_-variable_value

A **surface_2d_element_boundary_edge_constant_specified_variable_value** is a state of the model that specifies the value of a variable aggregated through the section, which is constant along a surface 2D element edge.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_boundary_edge_constant_specified_variable_value
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : boundary_edge_variable;
  element_edge              : surface_2d_edge;
  coordinate_system         : OPTIONAL surface_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.71 surface_2d_element_boundary_edge_nodal_specified_-variable_values

A **surface_2d_element_boundary_edge_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes along an element edge of a surface 2D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for the nodes on the element edge, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY surface_2d_element_boundary_edge_nodal_specified_variable_values
  SUBTYPE OF (surface_2d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : boundary_edge_variable;
  element_edge              : surface_2d_edge;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

element_edge: the element edge of the surface for which the values are specified.

The relationship between the element edge number and the element node sequence numbers is established graphically in 5.8.

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Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.72 curve_3d_element_field_variable_definition

A **curve_3d_element_field_variable_definition** is a state of the model that specifies the values of a variable within a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_field_variable_definition
  SUPERTYPE OF (ONEOF (
            curve_3d_element_location_point_volume_variable_values,
            curve_3d_element_location_point_variable_values,
            curve_3d_whole_element_variable_value,
            curve_3d_element_constant_specified_variable_value,
            curve_3d_element_constant_specified_volume_variable_value,
            curve_3d_element_nodal_specified_variable_values))

  SUBTYPE OF (field_variable_element_definition);
  element                   : curve_3d_element_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified, or for which the values are to be calculated.

6.7.73 curve_3d_element_location_point_volume_variable_values

A **curve_3d_element_location_point_volume_variable_values** is a state of the model that specifies the values of a variable at location points within the volume of a curve 3D element.

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EXPRESS specification:

```
*)
ENTITY curve_3d_element_location_point_volume_variable_values
  SUBTYPE OF (curve_3d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              curve_3d_element_value_and_volume_location;
  variable                  : volume_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.74 curve_3d_element_value_and_location

A **curve_3d_element_value_and_location** is a value of a variable along the 1D field of a curve 3D element.

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EXPRESS specification:

```
*)
ENTITY curve_3d_element_value_and_location;
  simple_value              : field_value;
  location                  : curve_element_location;
  coordinate_system         : OPTIONAL curve_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.75 curve_3d_element_value_and_volume_location

A **curve_3d_element_value_and_volume_location** is an aggregated value of a variable at a location point in the volume of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_value_and_volume_location;
  simple_value              : field_value;
  location                  : curve_volume_element_location;
  coordinate_system         : OPTIONAL curve_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.76 curve_3d_element_location_point_variable_values

A **curve_3d_element_location_point_variable_values** is a state of the model that specifies the values of a variable at location points over the curve of a curve 3D element. The variables are obtained by aggregation through the section at each curve point.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_location_point_variable_values
  SUBTYPE OF (curve_3d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              curve_3d_element_value_and_location;
  variable                  : curve_element_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

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Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.77 curve_3d_whole_element_variable_value

A **curve_3d_whole_element_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over a curve 3D element. The value represented by this entity does not include a contribution from the aggregation of boundary variables.

EXPRESS specification:

```
*)
ENTITY curve_3d_whole_element_variable_value
  SUBTYPE OF (curve_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL curve_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.78 curve_3d_element_constant_specified_variable_value

A **curve_3d_element_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant along the length of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_constant_specified_variable_value
  SUBTYPE OF (curve_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : curve_element_variable;
  coordinate_system         : OPTIONAL curve_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.79 curve_3d_element_constant_specified_volume_variable_value

A **curve_3d_element_constant_specified_volume_variable_value** is a state of the model that specifies the value of a variable at a point within a volume which is constant within the volume of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_constant_specified_volume_variable_value
  SUBTYPE OF (curve_3d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL curve_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.80 curve_3d_element_nodal_specified_variable_values

A **curve_3d_element_nodal_specified_variable_values** is a state of the model that specifies the value of a variable for the nodes of a curve 3D element. The variable is interpolated within the element using the appropriate shape functions specified for the variable.

Values are supplied for either the vertex nodes or all nodes of the element, in the order established graphically in 5.8.

EXPRESS specification:

```
*)
ENTITY curve_3d_element_nodal_specified_variable_values
  SUBTYPE OF (curve_3d_element_field_variable_definition);
  values                    : LIST [1:?] OF field_value;
  additional_node_values    : BOOLEAN;
  variable                  : curve_element_variable;
WHERE
  WR1: consistent_list_values (values, variable);
  WR2: appropriate_list_value_existence (values,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

values: the values of the field variable.

additional_node_values: indicates whether values are given for all nodes of the element (TRUE), or for just the vertex nodes (FALSE).

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.81 curve_2d_element_field_variable_definition

A **curve_2d_element_field_variable_definition** is a state of the model that specifies the values of a variable within a curve 2D element.

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EXPRESS specification:

```
*)
ENTITY curve_2d_element_field_variable_definition
  SUPERTYPE OF (ONEOF (
            curve_2d_element_location_point_volume_variable_values,
            curve_2d_element_location_point_variable_values,
            curve_2d_whole_element_variable_value,
            curve_2d_element_constant_specified_variable_value,
            curve_2d_element_constant_specified_volume_variable_value))
  SUBTYPE OF (field_variable_element_definition);
  element                   : curve_2d_element_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified, or for which the values are to be calculated.

6.7.82 curve_2d_element_location_point_volume_variable_values

A **curve_2d_element_location_point_volume_variable_values** is a state of the model that specifies the values of a variable at location points within the volume of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_location_point_volume_variable_values
  SUBTYPE OF (curve_2d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              curve_2d_element_value_and_volume_location;
  variable                  : curve_element_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

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variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.83 curve_2d_element_value_and_location

A **curve_2d_element_value_and_location** is a value of a variable along the 1D field of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_value_and_location;
  simple_value              : field_value;
  location                  : curve_section_element_location;
  coordinate_system         : OPTIONAL curve_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.84 curve_2d_element_value_and_volume_location

A **curve_2d_element_value_and_volume_location** is an aggregated value of a variable at a location point in the volume of a curve 2D element.

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EXPRESS specification:

```
*)
ENTITY curve_2d_element_value_and_volume_location;
  simple_value              : field_value;
  location                  : curve_volume_element_location;
  coordinate_system         : OPTIONAL curve_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
END_ENTITY;
(*
```

Attribute definitions:

simple_values: the value of the field variable.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

6.7.85 curve_2d_element_location_point_variable_values

A **curve_2d_element_location_point_variable_values** is a state of the model that specifies the value of a variable aggregated through the section of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_location_point_variable_values
  SUBTYPE OF (curve_2d_element_field_variable_definition);
  basis                     : BOOLEAN;
  values_and_locations      : SET [1:?] OF
                              curve_2d_element_value_and_location;
  variable                  : curve_element_variable;
WHERE
  WR1: consistent_set_values (values_and_locations, variable);
  WR2: appropriate_set_value_existence (values_and_locations,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

basis: if **basis** is TRUE then the value set contains only basis locations for the field variable within the element, and no others.

values_and_locations: the values and locations of the field variable.

variable: the type of field variable being specified.

Formal propositions:

WR1: each variable shall have a corresponding value of the proper type.

WR2: the values shall be unspecified when the **state_definition.defined_state** is an **output_request_-state**.

6.7.86 curve_2d_whole_element_variable_value

A **curve_2d_whole_element_variable_value** is a state of the model that specifies the value of a variable which is obtained by aggregation over a curve 2D element. The value represented by this entity does not include a contribution from the aggregation of boundary variables.

EXPRESS specification:

```
*)
ENTITY curve_2d_whole_element_variable_value
  SUBTYPE OF (curve_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL curve_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.87 curve_2d_element_constant_specified_variable_value

A **curve_2d_element_constant_specified_variable_value** is a state of the model that specifies the value of a variable which is constant along the length of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_constant_specified_variable_value
  SUBTYPE OF (curve_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : surface_element_variable;
  coordinate_system         : OPTIONAL curve_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.88 curve_2d_element_constant_specified_volume_variable_value

A **curve_2d_element_constant_specified_volume_variable_value** is a state of the model that specifies the value of a variable at a point within a volume, which is constant throughout the volume of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_element_constant_specified_volume_variable_value
  SUBTYPE OF (curve_2d_element_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL curve_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.89 field_variable_element_group_value

A **field_variable_element_group_value** is a state of the model that specifies the value of a variable aggregated over a group of elements.

The value represented by this entity includes a contribution from variables aggregated within the elements and over their boundaries.

EXPRESS specification:

```
*)
ENTITY field_variable_element_group_value
  SUBTYPE OF (field_variable_definition);
  group                     : element_group;
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL fea_axis2_placement_3d;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

group: the element group for which the values are specified, or the element groups for which values are to be calculated.

simple_value: the value of the field variable at the aggregate centroid of the element group.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

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6.7.90 field_variable_whole_model_value

A **field_variable_whole_model_value** is a state of the model that specifies the value of a variable aggregated over all the elements in the model.

The value represented by this entity includes a contribution from variables aggregated within the elements and over their boundaries.

EXPRESS specification:

```
*)
ENTITY field_variable_whole_model_value
  SUBTYPE OF (field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL fea_axis2_placement_3d;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable at the centroid of the model.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.91 field_variable_node_definition

A **field_variable_node_definition** is a state of the model that specifies the values of a field variable at nodes to represent nodal averaged values.

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EXPRESS specification:

```
*)
ENTITY field_variable_node_definition
  SUPERTYPE OF (ONEOF (volume_3d_node_field_variable_definition,
                       volume_2d_node_field_variable_definition,
                       surface_3d_node_field_variable_definition,
                       surface_2d_node_field_variable_definition,
                       curve_3d_node_field_variable_definition,
                       curve_2d_node_field_variable_definition))
  SUBTYPE OF (field_variable_definition);
  node                      : node_output_reference;
  group                     : OPTIONAL element_group;
END_ENTITY;
(*
```

Attribute definitions:

node: the node for which the value is specified, or the node for which the value is to be calculated.

group: the elements connected to the node for which the field variable value is valid. If this attribute is omitted then the variable is valid for all elements connected to the node.

6.7.92 volume_3d_node_field_variable_definition

A **volume_3d_node_field_variable_definition** is a state of the model that specifies the values of a variable at the nodes of a volume 3D element.

EXPRESS specification:

```
*)
ENTITY volume_3d_node_field_variable_definition
  SUBTYPE OF (field_variable_node_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL volume_3d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.93 volume_2d_node_field_variable_definition

A **volume_2d_node_field_variable_definition** is a state of the model that specifies the values of a variable at the nodes of a volume 2D element.

EXPRESS specification:

```
*)
ENTITY volume_2d_node_field_variable_definition
  SUBTYPE OF (field_variable_node_definition);
  simple_value              : field_value;
  variable                  : volume_variable;
  coordinate_system         : OPTIONAL volume_2d_element_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.94 surface_3d_node_field_variable_definition

A **surface_3d_node_field_variable_definition** is a state of the model that specifies the values of a variable at the nodes of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_node_field_variable_definition
  SUPERTYPE OF (ONEOF (
            surface_3d_node_field_section_variable_values,
            surface_3d_node_field_aggregated_variable_values))
  SUBTYPE OF (field_variable_node_definition);
END_ENTITY;
(*
```

6.7.95 surface_3d_node_field_section_variable_values

A **surface_3d_node_field_section_variable_values** is a state of the model that specifies the values of a variable through the section at the nodes of a surface 3D element.

EXPRESS specification:

```
*)
ENTITY surface_3d_node_field_section_variable_values
  SUBTYPE OF (surface_3d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : surface_element_variable;
  location                  : surface_section_element_location;
  coordinate_system         : OPTIONAL surface_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.96 surface_3d_node_field_aggregated_variable_values

A **surface_3d_node_field_aggregated_variable_values** is a state of the model that specifies the values of a variable at the nodes of a surface 3D element. The variables are obtained by aggregation through the section at each node.

EXPRESS specification:

```
*)
ENTITY surface_3d_node_field_aggregated_variable_values
  SUBTYPE OF (surface_3d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL surface_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.97 surface_2d_node_field_variable_definition

A **surface_2d_node_field_variable_definition** is a state of the model that specifies the values of a variable at the nodes of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_node_field_variable_definition
  SUPERTYPE OF (ONEOF (
            surface_2d_node_field_section_variable_values,
            surface_2d_node_field_aggregated_variable_values))
  SUBTYPE OF (field_variable_node_definition);
END_ENTITY;
(*
```

6.7.98 surface_2d_node_field_section_variable_values

A **surface_2d_node_field_section_variable_values** is a state of the model that specifies the values of a variable through the section at the nodes of a surface 2D element.

EXPRESS specification:

```
*)
ENTITY surface_2d_node_field_section_variable_values
  SUBTYPE OF (surface_2d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : surface_element_variable;
  location                  : surface_section_element_location;
  coordinate_system         : OPTIONAL surface_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.99 surface_2d_node_field_aggregated_variable_values

A **surface_2d_node_field_aggregated_variable_values** is a state of the model that specifies the values of a variable at the nodes of a surface 2D element. The variables are obtained by aggregation through the section at each node.

EXPRESS specification:

```
*)
ENTITY surface_2d_node_field_aggregated_variable_values
  SUBTYPE OF (surface_2d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL surface_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.100 curve_3d_node_field_variable_definition

A **curve_3d_node_field_variable_definition** is a state of the model that specifies the values of a variable at the nodes of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_node_field_variable_definition
  SUPERTYPE OF (ONEOF (
            curve_3d_node_field_section_variable_values,
            curve_3d_node_field_aggregated_variable_values))
  SUBTYPE OF (field_variable_node_definition);
END_ENTITY;
(*
```

6.7.101 curve_3d_node_field_section_variable_values

A **curve_3d_node_field_section_variable_values** is a state of the model that specifies the values of a variable through the section at the nodes of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_node_field_section_variable_values
  SUBTYPE OF (curve_3d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : curve_element_variable;
  location                  : curve_section_element_location;
  coordinate_system         : OPTIONAL curve_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.102 curve_3d_node_field_aggregated_variable_values

A **curve_3d_node_field_aggregated_variable_values** is a state of the model that specifies the values of a variable aggregated through the cross-section of the curve at the nodes of a curve 3D element.

EXPRESS specification:

```
*)
ENTITY curve_3d_node_field_aggregated_variable_values
  SUBTYPE OF (curve_3d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL curve_3d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.103 curve_2d_node_field_variable_definition

A **curve_2d_node_field_variable_definition** is a state of the model that specifies the values of a variable at the nodes of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_node_field_variable_definition
  SUPERTYPE OF (ONEOF (
            curve_2d_node_field_section_variable_values,
            curve_2d_node_field_aggregated_variable_values))
  SUBTYPE OF (field_variable_node_definition);
END_ENTITY;
(*
```

6.7.104 curve_2d_node_field_section_variable_values

A **curve_2d_node_field_section_variable_values** is a state of the model that specifies the values of a variable across the section at the nodes of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_node_field_section_variable_values
  SUBTYPE OF (curve_2d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : curve_element_variable;
  location                  : curve_section_element_location;
  coordinate_system         : OPTIONAL curve_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

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Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

location: the location at which the value of the field variable is specified.

coordinate_system: the coordinate system for the value.

Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.105 curve_2d_node_field_aggregated_variable_values

A **curve_2d_node_field_aggregated_variable_values** is a state of the model that specifies the values of a variable aggregated through the cross-section at the nodes of a curve 2D element.

EXPRESS specification:

```
*)
ENTITY curve_2d_node_field_aggregated_variable_values
  SUBTYPE OF (curve_2d_node_field_variable_definition);
  simple_value              : field_value;
  variable                  : volume_aggregated_variable;
  coordinate_system         : OPTIONAL curve_2d_state_coordinate_system;
WHERE
  WR1: necessary_value_coordinate_system (simple_value, coordinate_system);
  WR2: consistent_value (simple_value, variable);
  WR3: appropriate_value_existence (simple_value,
       TYPEOF (SELF\state_definition.defined_state));
END_ENTITY;
(*
```

Attribute definitions:

simple_value: the value of the field variable.

variable: the type of field variable being specified.

coordinate_system: the coordinate system for the value.

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Formal propositions:

WR1: the coordinate system shall be specified if any of the specified values are not scalar.

WR2: each variable shall have a corresponding value of the proper type.

WR3: the simple value shall be unspecified when the **state_definition.defined_state** is an **output_-request_state**.

6.7.106 nodal_freedom_and_value_definition

A **nodal_freedom_and_value_definition** is a state of the model that specifies information at a node of the model with respect to the solution degrees of freedom that are not a part of an element field discretization. The information may be:

— values for the solution degrees of freedom, such as x translation, or z rotation;

— loads applied in the direction of the solutions degrees of freedom such as values for x force, or z moment. These may be loads applied to a node by elements of the model, or loads applied to a node from outside the model.

NOTE The purpose of this entity IS to represent information such as loads and displacements at nodes. The purpose of this entity is NOT to represent an element field that has been discretized at the model nodes. The **field_variable_node_definition** should be used for that purpose.

EXPRESS specification:

```
*)
ENTITY nodal_freedom_and_value_definition
  SUPERTYPE OF (ONEOF (nodal_freedom_values,
                       nodal_freedom_action_definition))
  SUBTYPE OF (state_definition);
  node                      : node_output_reference;
  coordinate_system         : fea_axis2_placement_3d;
  degrees_of_freedom        : freedoms_list;
  values                    : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (values);
END_ENTITY;
(*
```

Attribute definitions:

node: the node for which the values are specified, or the node for which the values are to be calculated.

coordinate_system: the coordinate system in which the nodal degrees of freedom are defined.

degrees_of_freedom: the degrees of freedom at the node.

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values: the matching values at the node.

Formal propositions:

WR1: the number of degrees of freedom shall match the number of values.

6.7.107 nodal_freedom_values

A **nodal_freedom_values** is a state of the model that specifies the values for degrees of freedom at a node.

EXPRESS specification:

```
*)
ENTITY nodal_freedom_values
  SUBTYPE OF (nodal_freedom_and_value_definition);
END_ENTITY;
(*
```

6.7.108 nodal_freedom_action_definition

A **nodal_freedom_action_definition** is a state of the model that specifies the values for the actions applied directly to a node of the model. The type of action is indicated with the **action** attribute.

EXPRESS specification:

```
*)
ENTITY nodal_freedom_action_definition
  SUBTYPE OF (nodal_freedom_and_value_definition);
  action                    : action_type;
END_ENTITY;
(*
```

Attribute definitions:

action: the type of values (external applied loads or residual loads at the node) that the action represents.

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6.7.109 element_nodal_freedom_actions

An **element_nodal_freedom_actions** is the values of nodal action for an element. This action is applied by the element to the node.

NOTE This entity is used to represent the reactions of a single or multi-point constraint.

EXPRESS specification:

```
*)
ENTITY element_nodal_freedom_actions
  SUBTYPE OF (state_definition);
  element                   : model_or_control_element;
  nodal_action              : LIST [1:?] OF
                                 element_nodal_freedom_terms;
END_ENTITY;
(*
```

Attribute definitions:

element: the element for which the values are specified or calculated. This can be either an element or a constraint.

nodal_action: the values and associated degrees of freedom at the nodes of an element. The terms in the LIST correspond to the nodes in the **required_node_list** and the **additional_node_list** for the element.

6.7.110 element_nodal_freedom_terms

An **element_nodal_freedom_terms** is a list of degrees of freedom and corresponding values at a node of an element, and a reference coordinate system in which the values are defined.

EXPRESS specification:

```
*)
ENTITY element_nodal_freedom_terms;
  coordinate_system         : fea_axis2_placement_3d;
  degrees_of_freedom        : freedoms_list;
  values                    : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (values);
END_ENTITY;
(*
```

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Attribute definitions:

coordinate_system: the coordinate system in which the values are defined.

degrees_of_freedom: the degrees of freedom at the node.

values: the values corresponding to the degrees of freedom at the node.

6.7.111 point_freedom_and_value_definition

A **point_freedom_and_value_definition** is a state of the model that specifies information at all nodes that may be associated with a point with respect to the solution degrees of freedom that are not a part of an element field discretization. The intent of this entity is identical to a **nodal_freedom_and_value_-definition**, however it is applied to all nodes associated to a point, rather than to a single node.

EXPRESS specification:

```
*)
ENTITY point_freedom_and_value_definition
  SUPERTYPE OF (ONEOF (point_freedom_values,
                       point_freedom_action_definition))
  SUBTYPE OF (state_definition);
  required_point            : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  degrees_of_freedom        : freedoms_list;
  values                    : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (values);
  WR2: ('GEOMETRY_SCHEMA.POINT' IN TYPEOF (required_point.item)) OR
       ('TOPOLOGY_SCHEMA.VERTEX_POINT' IN TYPEOF (required_point.item));
END_ENTITY;
(*
```

Attribute definitions:

required_point: the point whose associated nodes are for which the values are specified, or whose associated nodes for which the values are to be calculated.

coordinate_system: the coordinate system in which the nodal degrees of freedom are defined.

degrees_of_freedom: the degrees of freedom at the node.

values: the matching values at the node.

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Formal propositions:

WR1: the number of degrees of freedom shall match the number of values.

WR2: the **geometric_representation_item** shall be a point or a vertex point.

6.7.112 point_freedom_values

A **point_freedom_values** is a state of the model that specifies the values for degrees of freedom at a node that is associated with a point.

EXPRESS specification:

```
*)
ENTITY point_freedom_values
  SUBTYPE OF (point_freedom_and_value_definition);
END_ENTITY;
(*
```

6.7.113 point_freedom_action_definition

A **point_freedom_action_definition** is a state of the model that specifies the values for the actions applied directly to nodes associated with a point. The type of action is indicated with the **action** attribute.

EXPRESS specification:

```
*)
ENTITY point_freedom_action_definition
  SUBTYPE OF (point_freedom_and_value_definition);
  action                    : action_type;
END_ENTITY;
(*
```

Attribute definitions:

action: the type of values (external applied loads or residual loads at the nodes associated with the point) that the action represents.

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6.7.114 curve_freedom_and_value_definition

A **curve_freedom_and_value_definition** is a state of the model that specifies information at all nodes that may be associated with a curve with respect to the solution degrees of freedom that are not a part of an element field discretization. The intent of this entity is identical to a **nodal_freedom_and_value_-definition**, however it is applied to all nodes associated to a curve, rather than to a single node.

EXPRESS specification:

```
*)
ENTITY curve_freedom_and_value_definition
  SUPERTYPE OF (ONEOF (curve_freedom_values,
                       curve_freedom_action_definition))
  SUBTYPE OF (state_definition);
  required_curve            : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  degrees_of_freedom        : freedoms_list;
  values                    : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (values);
  WR2: ('GEOMETRY_SCHEMA.CURVE' IN TYPEOF (required_curve.item)) OR
       ('TOPOLOGY_SCHEMA.EDGE_CURVE' IN TYPEOF (required_curve.item));
END_ENTITY;
(*
```

Attribute definitions:

required_curve: the curve whose associated nodes have the values specified, or whose associated node values are to be calculated.

coordinate_system: the coordinate system in which the nodal degrees of freedom are defined.

degrees_of_freedom: the degrees of freedom at the node.

values: the matching values at the node.

Formal propositions:

WR1: the number of degrees of freedom shall match the number of values.

WR2: the **geometric_representation_item** shall be a curve or an edge curve.

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6.7.115 curve_freedom_values

A **curve_freedom_values** is a state of the model that specifies the values for degrees of freedom at a node that is associated with a curve.

EXPRESS specification:

```
*)
ENTITY curve_freedom_values
  SUBTYPE OF (curve_freedom_and_value_definition);
END_ENTITY;
(*
```

6.7.116 curve_freedom_action_definition

A **curve_freedom_action_definition** is a state of the model that specifies the values for the actions applied directly to nodes associated with a curve. The type of action is indicated with the **action** attribute.

EXPRESS specification:

```
*)
ENTITY curve_freedom_action_definition
  SUBTYPE OF (curve_freedom_and_value_definition);
  action                    : action_type;
END_ENTITY;
(*
```

Attribute definitions:

action: the type of values (external applied loads or residual loads at the nodes associated with the curve) that the action represents.

6.7.117 surface_freedom_and_value_definition

A **surface_freedom_and_value_definition** is a state of the model that specifies information at all nodes that may be associated with a surface with respect to the solution degrees of freedom that are not a part of an element field discretization. The intent of this entity is identical to a **nodal_freedom_and_value_-definition**, however it is applied to all nodes associated to a surface, rather than to a single node.

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EXPRESS specification:

```
*)
ENTITY surface_freedom_and_value_definition
  SUPERTYPE OF (ONEOF (surface_freedom_values,
                       surface_freedom_action_definition))
  SUBTYPE OF (state_definition);
  required_surface          : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  degrees_of_freedom        : freedoms_list;
  values                    : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (values);
  WR2: ('GEOMETRY_SCHEMA.SURFACE' IN TYPEOF (required_surface.item)) OR
       ('TOPOLOGY_SCHEMA.FACE_SURFACE' IN TYPEOF (required_surface.item));
END_ENTITY;
(*
```

Attribute definitions:

required_surface: the surface whose associated nodes are have the values specified, or whose associated node values are to be calculated.

coordinate_system: the coordinate system in which the nodal degrees of freedom are defined.

degrees_of_freedom: the degrees of freedom at the node.

values: the matching values at the node.

Formal propositions:

WR1: the number of degrees of freedom shall match the number of values.

WR2: the **geometric_representation_item** shall be a surface or a face surface.

6.7.118 surface_freedom_values

A **surface_freedom_values** is a state of the model that specifies the values for degrees of freedom at a node that is associated with a surface.

EXPRESS specification:

```
*)
ENTITY surface_freedom_values
  SUBTYPE OF (surface_freedom_and_value_definition);
END_ENTITY;
(*
```

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6.7.119 surface_freedom_action_definition

A **surface_freedom_action_definition** is a state of the model that specifies the values for the actions applied directly to nodes associated with a surface. The type of action is indicated with the **action** attribute.

EXPRESS specification:

```
*)
ENTITY surface_freedom_action_definition
  SUBTYPE OF (surface_freedom_and_value_definition);
  action                    : action_type;
END_ENTITY;
(*
```

Attribute definitions:

action: the type of values (external applied loads or residual loads at the nodes associated with the surface) that the action represents.

6.7.120 solid_freedom_and_value_definition

A **solid_freedom_and_value_definition** is a state of the model that specifies information at all nodes that may be associated with a solid with respect to the solution degrees of freedom that are not a part of an element field discretization. The intent of this entity is identical to a **nodal_freedom_and_value_-definition**, however it is applied to all nodes associated to a solid, rather than to a single node.

EXPRESS specification:

```
*)
ENTITY solid_freedom_and_value_definition
  SUPERTYPE OF (ONEOF (solid_freedom_values,
                       solid_freedom_action_definition))
  SUBTYPE OF (state_definition);
  required_solid            : analysis_item_within_representation;
  coordinate_system         : fea_axis2_placement_3d;
  degrees_of_freedom        : freedoms_list;
  values                    : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (values);
  WR2: 'GEOMETRIC_MODEL_SCHEMA.SOLID_MODEL' IN TYPEOF (required_solid.item);
END_ENTITY;
(*
```

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Attribute definitions:

required_solid: the solid whose associated nodes have the values specified, or whose associated node values are to be calculated.

coordinate_system: the coordinate system in which the nodal degrees of freedom are defined.

degrees_of_freedom: the degrees of freedom at the node.

values: the matching values at the node.

Formal propositions:

WR1: the number of degrees of freedom shall match the number of values.

WR2: the **geometric_representation_item** shall be a solid model.

6.7.121 solid_freedom_values

A **solid_freedom_values** is a state of the model that specifies the values for degrees of freedom at a node that is associated with a solid.

EXPRESS specification:

```
*)
ENTITY solid_freedom_values
  SUBTYPE OF (solid_freedom_and_value_definition);
END_ENTITY;
(*
```

6.7.122 solid_freedom_action_definition

A **solid_freedom_action_definition** is a state of the model that specifies the values for the actions applied directly to nodes associated with a solid. The type of action is indicated with the **action** attribute.

EXPRESS specification:

```
*)
ENTITY solid_freedom_action_definition
  SUBTYPE OF (solid_freedom_and_value_definition);
  action                    : action_type;
END_ENTITY;
(*
```

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Attribute definitions:

action: the type of values (external applied loads or residual loads at the nodes associated with the solid) that the action represents.

6.7.123 freedoms_list

A **freedoms_list** is a list of the degrees of freedom at a node.

EXPRESS specification:

```
*)
ENTITY freedoms_list;
  freedoms                  : LIST [1:?] OF degree_of_freedom;
END_ENTITY;
(*
```

Attribute definitions:

freedoms: the degrees of freedom.

6.7.124 linear_constraint_equation_element_value

A **linear_constraint_equation_element_value** is the specified constraint equation coefficient b associated with the freedoms (x_i) and coefficients (a_i) as shown in the equation in 6.4.12.

EXPRESS specification:

```
*)
ENTITY linear_constraint_equation_element_value
  SUBTYPE OF (state_definition);
  element                   : linear_constraint_equation_element;
  b                         : measure_or_unspecified_value;
END_ENTITY;
(*
```

Attribute definitions:

element: the linear constraint equation element to which the coefficient is applied.

b: the constraint equation coefficient b as above.

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6.7.125 single_point_constraint_element_values

A **single_point_constraint_element_values** is the set of specified constraint equation coefficients and corresponding freedoms for a single point constraint.

NOTE The freedoms are specified with the values to allow the correlation of the constraint coefficient with the nodal freedom coefficient in a **single_point_constraint_element** entity.

EXPRESS specification:

```
*)
ENTITY single_point_constraint_element_values
  SUBTYPE OF (state_definition);
  element                   : single_point_constraint_element;
  degrees_of_freedom        : freedoms_list;
  b                         : LIST [1:?] OF measure_or_unspecified_value;
WHERE
  WR1: SIZEOF(degrees_of_freedom.freedoms) = SIZEOF (b);
END_ENTITY;
(*
```

Attribute definitions:

element: the single point constraint element to which the coefficients and freedoms are applied.

degrees_of_freedom: the degrees of freedom at the node of the element.

b: the constraint equation coefficients corresponding to the freedoms list.

Formal propositions:

WR1: the number of degrees of freedom shall match the number of values.

6.7.126 analysis_message

An **analysis_message** is message information that may be attached to an element, a node, or an entire model.

EXPRESS specification:

```
*)
ENTITY analysis_message
  SUPERTYPE OF (ONEOF (whole_model_analysis_message,
                       element_analysis_message,
```

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```
                        node_analysis_message,
                        element_group_analysis_message))
  SUBTYPE OF (state_definition);
  level                     : message_level;
  message_text              : text;
END_ENTITY;
(*
```

Attribute definitions:

level: the severity of analysis message.

message_text: the message text.

6.7.127 whole_model_analysis_message

A **whole_model_analysis_message** is message information that may be attached to the entire **fea_-model**.

EXPRESS specification:

```
*)
ENTITY whole_model_analysis_message
  SUPERTYPE OF (whole_model_modes_and_frequencies_analysis_message)
  SUBTYPE OF (analysis_message);
END_ENTITY;
(*
```

6.7.128 whole_model_modes_and_frequencies_ analysis_message

A **whole_model_modes_and_frequencies_ analysis_message** is message information about a mode number and matching frequency that may be attached to the entire **fea_model**.

EXPRESS specification:

```
*)
ENTITY whole_model_modes_and_frequencies_analysis_message
  SUBTYPE OF (whole_model_analysis_message);
  mode                      : count_measure;
  frequency                 : context_dependent_measure;
END_ENTITY;
(*
```

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Attribute definitions:

mode: the mode number that the message concerns.

frequency: the frequency that matches the mode number that the message concerns.

6.7.129 element_analysis_message

An **element_analysis_message** is message information that may be attached to an element.

EXPRESS specification:

```
*)
ENTITY element_analysis_message
  SUBTYPE OF (analysis_message);
  element                    : element_representation;
END_ENTITY;
(*
```

Attribute definitions:

element: the element that the message concerns.

6.7.130 node_analysis_message

A **node_analysis_message** is message information that may be attached to a node.

EXPRESS specification:

```
*)
ENTITY node_analysis_message
  SUBTYPE OF (analysis_message);
  node                       : node_output_reference;
END_ENTITY;
(*
```

Attribute definitions:

node: the node or node group that the message concerns.

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6.7.131 element_group_analysis_message

An **element_group_analysis_message** is message information that may be attached to an element group.

EXPRESS specification:

```
*)
ENTITY element_group_analysis_message
  SUBTYPE OF (analysis_message);
  group                     : element_group;
END_ENTITY;
(*
```

Attribute definitions:

group: the group of elements that the message concerns.

6.7.132 volume_3d_substructure_element_reference

An **volume_3d_substructure_element_reference** is the reference of a volume 3D element within the contet of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY volume_3d_substructure_element_reference;
  substructure_element_ref  : substructure_element_representation;
  element_ref               : volume_3d_element_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the volume 3D element information references.

element_ref: the volume 3D element for output request or specification.

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6.7.133 volume_2d_substructure_element_reference

An **volume_2d_substructure_element_reference** is the reference of a volume 2D element within the context of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY volume_2d_substructure_element_reference;
  substructure_element_ref  : substructure_element_representation;
  element_ref               : volume_2d_element_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the volume 2D element information references.

element_ref: the volume 2D element for output request or specification.

6.7.134 surface_3d_substructure_element_reference

An **surface_3d_substructure_element_reference** is the reference of a surface 3D element within the context of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY surface_3d_substructure_element_reference;
  substructure_element_ref  : substructure_element_representation;
  element_ref               : surface_3d_element_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the surface 3D element information references.

element_ref: the surface 3D element for output request or specification.

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6.7.135 surface_2d_substructure_element_reference

An **surface_2d_substructure_element_reference** is the reference of a surface 2D element within the context of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY surface_2d_substructure_element_reference;
  substructure_element_ref  : substructure_element_representation;
  element_ref               : surface_2d_element_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the surface 2D element information references.

element_ref: the surface 2D element for output request or specification.

6.7.136 curve_3d_substructure_element_reference

An **curve_3d_substructure_element_reference** is the reference of a curve 3D element within the context of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY curve_3d_substructure_element_reference;
  substructure_element_ref  : substructure_element_representation;
  element_ref               : curve_3d_element_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the curve 3D element information references.

element_ref: the curve 3D element for output request or specification.

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6.7.137 curve_2d_substructure_element_reference

An **curve_2d_substructure_element_reference** is the reference of a curve 2D element within the context of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY curve_2d_substructure_element_reference;
  substructure_element_ref  : substructure_element_representation;
  element_ref               : curve_2d_element_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the curve 2D element information references.

element_ref: the curve 2D element for output request or specification.

6.7.138 substructure_node_reference

An **substructure_node_reference** is the reference of a node within the context of a substructure for output request or specification.

EXPRESS specification:

```
*)
ENTITY substructure_node_reference;
  substructure_element_ref  : substructure_element_representation;
  node_ref                  : node_representation;
END_ENTITY;
(*
```

Attribute definitions:

substructure_element_ref: the substructure element that the node information references.

node_ref: the node for output request or specification.

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6.8 Finite element analysis control and result schema function definitions

These definitions are used to ensure the correctness of information in many of the finite element analysis control and result schema information model entities.

6.8.1 necessary_value_coordinate_system

A **necessary_value_coordinate_system** ensures that a coordinate system is supplied for the value of a non-scalar variable.

EXPRESS specification:

```
*)
FUNCTION necessary_value_coordinate_system
    (cs_value               : field_value;
     coordinate_system      : GENERIC): BOOLEAN;

    IF (SIZEOF (
        ['FEA_SCALAR_VECTOR_TENSOR_SCHEMA.TENSOR1_2D',
         'FEA_SCALAR_VECTOR_TENSOR_SCHEMA.TENSOR1_3D',
         'FEA_SCALAR_VECTOR_TENSOR_SCHEMA.SYMMETRIC_TENSOR2_2D',
         'FEA_SCALAR_VECTOR_TENSOR_SCHEMA.SYMMETRIC_TENSOR2_3D'] *
        TYPEOF (cs_value)) = 1) THEN
        IF (NOT EXISTS (coordinate_system) ) THEN
            RETURN (FALSE);
        END_IF;
    END_IF;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

value: identifies the value being checked.

coordinate_system: identifies the coordinate system being checked for existence.

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6.8.2 consistent_set_values

A **consistent_set_values** ensures the SET of variables and values are consistent.

EXPRESS specification:

```
*)
FUNCTION consistent_set_values
    (values_and_locations   : SET [1:?] OF GENERIC;
     variable               : GENERIC) : BOOLEAN;

    LOCAL
     vv_type                : STRING;
     fv_type                : SET [1:?] OF STRING;
     i                      : INTEGER;
    END_LOCAL;

    vv_type := variable_value_type (variable);

    REPEAT i := 1 TO HIINDEX (values_and_locations);

       fv_type := TYPEOF (values_and_locations[i].simple_value);

       IF NOT (('FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.' +
           'UNSPECIFIED_VALUE') IN fv_type) THEN

          IF NOT (vv_type IN fv_type) THEN
             RETURN (FALSE);
          END_IF;

       END_IF;

    END_REPEAT;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

values_and_locations: identifies the SET of values to be compared with the variable to ensure consistency.

variable: identifies the variable to be compared with the SET of values to ensure a consistency.

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6.8.3 consistent_list_values

A **consistent_list_values** ensures the LIST of variables and values are consistent.

EXPRESS specification:

```
*)
FUNCTION consistent_list_values
    (values                 : LIST [1:?] OF field_value;
     variable               : GENERIC) : BOOLEAN;

    LOCAL
     vv_type                : STRING;
     fv_type                : SET [1:?] OF STRING;
     i                      : INTEGER;
    END_LOCAL;

    vv_type := variable_value_type (variable);

    REPEAT i := 1 TO HIINDEX (values);

       fv_type := TYPEOF (values[i]);

       IF NOT (('FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.' +
           'UNSPECIFIED_VALUE') IN fv_type) THEN

          IF NOT (vv_type IN fv_type) THEN
             RETURN (FALSE);
          END_IF;

       END_IF;

    END_REPEAT;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

values_and_locations: identifies the LIST of values to be compared with the variable to ensure consistency.

variable: identifies the variable to be compared with the LIST of values to ensure a consistency.

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6.8.4 consistent_value

A **consistent_value** ensures the variable and value are consistent.

EXPRESS specification:

```
*)
FUNCTION consistent_value
    (c_value                : field_value;
     variable               : GENERIC) : BOOLEAN;

    LOCAL
     vv_type                : STRING;
     fv_type                : SET [1:?] OF STRING;
    END_LOCAL;

    vv_type := variable_value_type (variable);

    fv_type := TYPEOF (c_value);

    IF NOT (('FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.' +
       'UNSPECIFIED_VALUE') IN fv_type) THEN

       IF NOT (vv_type IN fv_type) THEN
          RETURN (FALSE);
       END_IF;

    END_IF;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

value: identifies the value to be compared with the variable to ensure consistency.

variable: identifies the variable to be compared with the value to ensure a consistency.

6.8.5 variable_value_type

A **variable_value_type** calculates the corresponding value for a supplied variable.

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EXPRESS specification:

```
*)
FUNCTION variable_value_type
    (variable                : GENERIC) : STRING;

    LOCAL
     svt                     : STRING;
     feacr                   : STRING;
     variable_typeof         : SET [1:?] OF STRING;
    END_LOCAL;

    svt     := 'FEA_SCALAR_VECTOR_TENSOR_SCHEMA.';
    feacr   := 'FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.';
    variable_typeof := TYPEOF (variable);

    IF SIZEOF ([(feacr + 'CURVE_SCALAR_VARIABLE'),
                (feacr + 'SURFACE_SCALAR_VARIABLE'),
                (feacr + 'VOLUME_SCALAR_VARIABLE'),
                (feacr + 'BOUNDARY_CURVE_SCALAR_VARIABLE'),
                (feacr + 'BOUNDARY_SURFACE_SCALAR_VARIABLE'),
                (feacr + 'AGGREGATED_SCALAR_VARIABLE'),
                (feacr + 'VOLUME_ANGULAR_VARIABLE'),
                (feacr + 'AGGREGATED_ANGULAR_VARIABLE'),
                (feacr + 'APPLICATION_DEFINED_SCALAR_VARIABLE')] *
               variable_typeof ) = 1 THEN
        RETURN (svt + 'SCALAR');
    END_IF;

    IF SIZEOF ([(feacr + 'CURVE_VECTOR_2D_VARIABLE'),
                (feacr + 'SURFACE_VECTOR_2D_VARIABLE'),
                (feacr + 'APPLICATION_DEFINED_VECTOR_2D_VARIABLE')] *
               variable_typeof ) = 1 THEN
        RETURN (svt + 'TENSOR1_2D');
    END_IF;

    IF SIZEOF ([(feacr + 'CURVE_VECTOR_3D_VARIABLE'),
                (feacr + 'SURFACE_VECTOR_3D_VARIABLE'),
                (feacr + 'VOLUME_VECTOR_3D_VARIABLE'),
                (feacr + 'BOUNDARY_CURVE_VECTOR_3D_VARIABLE'),
                (feacr + 'BOUNDARY_SURFACE_VECTOR_3D_VARIABLE'),
                (feacr + 'AGGREGATED_VECTOR_3D_VARIABLE'),
                (feacr + 'APPLICATION_DEFINED_VECTOR_3D_VARIABLE')] *
               variable_typeof ) = 1 THEN
        RETURN (svt + 'TENSOR1_3D');
    END_IF;

    IF SIZEOF ([(feacr + 'SURFACE_TENSOR2_2D_VARIABLE'),
                (feacr + 'APPLICATION_DEFINED_TENSOR2_2D_VARIABLE')] *
               variable_typeof ) = 1 THEN
        RETURN (svt + 'SYMMETRIC_TENSOR2_3D');
```

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```
    END_IF;

    IF SIZEOF ([(feacr + 'VOLUME_TENSOR2_3D_VARIABLE'),
                (feacr + 'AGGREGATED_TENSOR2_3D_VARIABLE'),
                (feacr + 'APPLICATION_DEFINED_TENSOR2_3D_VARIABLE')] *
               variable_typeof ) = 1 THEN
        RETURN (svt + 'SYMMETRIC_TENSOR2_3D');
    END_IF;

    RETURN ('NO_MATCH');

END_FUNCTION;
(*
```

Argument definitions:

variable: identifies used to calculate the appropriately corresponding type of value.

vv_type: output argument that is the value for a corresponding variable.

6.8.6 appropriate_set_value_existence

A **appropriate_set_value_existence** ensures the value is unspecified only when the **state_-definition.defined_state** is an **output_request_state** for a SET of **values_and_locations**.

EXPRESS specification:

```
*)
FUNCTION appropriate_set_value_existence
    (values_and_locations   : SET [1:?] OF GENERIC;
     type_self              : SET [1:?] OF STRING) : BOOLEAN;

    LOCAL
     i                      : INTEGER;
    END_LOCAL;

    REPEAT i := 1 TO HIINDEX (values_and_locations);
       IF NOT (appropriate_value_existence
                (values_and_locations[i].simple_value, type_self))
          THEN
          RETURN (FALSE);
       END_IF;
    END_REPEAT;

    RETURN (TRUE);

END_FUNCTION;
(*
```

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Argument definitions:

values_and_locations: identifies the SET of values to be checked for existence.

type_self: identifies the **state_definition**.

6.8.7 appropriate_list_value_existence

A **appropriate_set_value_existence** ensures the value is unspecified only when the **state_-definition.defined_state** is an **output_request_state** for a LIST of **values_and_locations**.

EXPRESS specification:

```
*)
FUNCTION appropriate_list_value_existence
    (values                 : LIST [1:?] OF GENERIC;
     type_self              : SET [1:?] OF STRING) : BOOLEAN;

    LOCAL
     i                      : INTEGER;
    END_LOCAL;

    REPEAT i := 1 TO HIINDEX (values);
       IF NOT (appropriate_value_existence (values[i], type_self)) THEN
          RETURN (FALSE);
       END_IF;
    END_REPEAT;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

values: identifies the LIST of values to be checked for existence.

type_self: identifies the **state_definition**.

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6.8.8 appropriate_value_existence

An **appropriate_value_existence** ensures the value is unspecified only when the **state_-definition.defined_state** is an **output_request_state**.

EXPRESS specification:

```
*)
FUNCTION appropriate_value_existence
    (a_value_e              : GENERIC;
     type_self              : SET [1:?] OF STRING) : BOOLEAN;

    LOCAL
     feacr                  : STRING;
     value_typeof           : SET [1:?] OF STRING;
    END_LOCAL;

    feacr := 'FINITE_ELEMENT_ANALYSIS_CONTROL_AND_RESULT_SCHEMA.';
    value_typeof := TYPEOF(a_value_e);

    IF (((feacr + 'OUTPUT_REQUEST_STATE') IN type_self) AND
       NOT ((feacr + 'UNSPECIFIED_VALUE') IN value_typeof)) THEN
       RETURN (FALSE);
    END_IF;

    RETURN (TRUE);

END_FUNCTION;
(*
```

Argument definitions:

a_value_e: identifies the value to be checked for proper type.

type_self: identifies the **state_definition**.

EXPRESS specification:

```
*)
END_SCHEMA; -- finite_element_analysis_control_and_result_schema
(*
```

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7 FEA scalar vector tensor schema

The following EXPRESS declaration begins the **fea_scalar_vector_tensor_schema** and identifies the necessary external references.

EXPRESS specification:

```
*)
SCHEMA fea_scalar_vector_tensor_schema;

  REFERENCE FROM measure_schema
      (context_dependent_measure);

  REFERENCE FROM representation_schema
      (representation_item);
(*
```

NOTE The schemas referenced above can be found in the following parts of ISO 10303:

measure_schema	ISO 10303-41
representation_schema	ISO 10303-43

7.1 Introduction

The subject of the **fea_scalar_vector_tensor_schema** is the definition of the scalars, vectors (first order tensors) and tensors that are necessary to represent the input and output of finite element analyses.

7.2 Fundamental concepts and assumptions

The fundamental concepts and assumptions include the concept that units are assigned in a context, and the value of the measure is assigned directly.

7.3 FEA scalar vector tensor schema type definitions: The FEA representation of scalars, vectors, and tensors

Finite element analysis requires scalars, 2D and 3D vectors, and 2D and 3D second and fourth order tensors to represent the input and output of finite element analyses. The 3D fourth order tensors are used for material response, and are documented in 7.4.

NOTE The types in this clause are organized in groups of similar subject matter.

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7.3.1 angular_value

An **angular_value** is a zero order tensor representing the magnitude of an angular value about an axis.

Informal propositions:

IP1: the axis shall be the $Z - axis$ of the founding placement of the referencing entity.

EXPRESS specification:

```
*)
TYPE angular_value =
     context_dependent_measure;
END_TYPE;
(*
```

7.3.2 scalar

A **scalar** is a zero order tensor.

EXPRESS specification:

```
*)
TYPE scalar =
     context_dependent_measure;
END_TYPE;
(*
```

7.3.3 tensor1

A **tensor1** is a first order tensor, or vector.

EXPRESS specification:

```
*)
TYPE tensor1 = SELECT
  (tensor1_2d,
   tensor1_3d);
END_TYPE;
(*
```

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7.3.4 tensor1_2d

A **tensor1_2d** is a first order tensor, or vector in 2D space.

EXPRESS specification:

```
*)
TYPE tensor1_2d =
     ARRAY [1:2] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the 1 component of the tensor.

ARRAY[2]: the 2 component of the tensor.

7.3.5 tensor1_3d

A **tensor1_3d** is a first order tensor, or vector, in 3D space.

EXPRESS specification:

```
*)
TYPE tensor1_3d =
  ARRAY [1:3] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the 1 component of the tensor.

ARRAY[2]: the 2 component of the tensor.

ARRAY[3]: the 3 component of the tensor.

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7.3.6 symmetric_tensor2_2d

A **symmetric_tensor2_2d** is a symmetric second order tensor in 2D space.

A 2D second order tensor s_{ij} is the relationship between two 2D vectors f_i and n_i, as shown below:

$$f_i = \sum_{j=1}^{2} s_{ij} n_j \quad \text{for} \quad i = 1, 2$$

EXPRESS specification:

```
*)
TYPE symmetric_tensor2_2d = SELECT
  (anisotropic_symmetric_tensor2_2d);
END_TYPE;
(*
```

7.3.7 anisotropic_symmetric_tensor2_2d

An **anisotropic_symmetric_tensor2_2d** is an anisotropic symmetric second order tensor in 2D space.

EXPRESS specification:

```
*)
TYPE anisotropic_symmetric_tensor2_2d =
  ARRAY [1:3] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the 11 component of the tensor.

ARRAY[2]: the 22 component of the tensor.

ARRAY[3]: the 12 component of the tensor.

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7.3.8 symmetric_tensor2_3d

A **symmetric_tensor2_3d** is a symmetric second order tensor in 3D space.

A 3D second order tensor s_{ij} is the relationship between two 3D vectors f_i and n_i, as shown below:

$$f_i = \sum_{j=1}^{3} s_{ij} n_j \quad \text{for} \quad i = 1,3$$

EXPRESS specification:

```
*)
TYPE symmetric_tensor2_3d = SELECT
  (isotropic_symmetric_tensor2_3d,
   orthotropic_symmetric_tensor2_3d,
   anisotropic_symmetric_tensor2_3d);
END_TYPE;
(*
```

7.3.9 isotropic_symmetric_tensor2_3d

An **isotropic_symmetric_tensor2_3d** is an isotropic symmetric second order tensor in 3D space, which is characterized by one independent value.

The value s is a term in the tensor as follows:

$$\begin{pmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{pmatrix}$$

EXPRESS specification:

```
*)
TYPE isotropic_symmetric_tensor2_3d =
     context_dependent_measure;
END_TYPE;
(*
```

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7.3.10 orthotropic_symmetric_tensor2_3d

An **orthotropic_symmetric_tensor2_3d** is an orthotropic symmetric second order tensor in 3D space, which is characterized by three independent values.

The values s_{11}, s_{22}, and s_{33} are terms in the tensor as follows:

$$\begin{pmatrix} s_{11} & 0 & 0 \\ 0 & s_{22} & 0 \\ 0 & 0 & s_{33} \end{pmatrix}$$

EXPRESS specification:

```
*)
TYPE orthotropic_symmetric_tensor2_3d =
     ARRAY [1:3] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the tensor components s_{11} defined above.

ARRAY[2]: the tensor components s_{22} defined above.

ARRAY[3]: the tensor components s_{33} defined above.

7.3.11 anisotropic_symmetric_tensor2_3d

An **anisotropic_symmetric_tensor2_3d** is an anisotropic symmetric second order tensor in 3D space.

EXPRESS specification:

```
*)
TYPE anisotropic_symmetric_tensor2_3d =
     ARRAY [1:6] OF context_dependent_measure;
END_TYPE;
(*
```

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Enumerated item definitions:

ARRAY[1]: the 11 component of the tensor.

ARRAY[2]: the 12 component of the tensor.

ARRAY[3]: the 13 component of the tensor.

ARRAY[4]: the 22 component of the tensor.

ARRAY[5]: the 23 component of the tensor.

ARRAY[6]: the 33 component of the tensor.

7.3.12 symmetric_tensor4_2d

A **symmetric_tensor4_2d** is a symmetric fourth order tensor in 2D space.

A 2D fourth order tensor d_{ijkl} is the relationship between two 2D second order tensors s_{ij} and e_{ij}, as shown below:

$$s_{ij} = \sum_{k=1}^{2} \sum_{l=1}^{2} d_{ijkl} e_{kl} \text{ for } i = 1,2 \text{ and } j = 1,2$$

EXPRESS specification:

```
*)
TYPE symmetric_tensor4_2d = SELECT
  (anisotropic_symmetric_tensor4_2d);
END_TYPE;
(*
```

7.3.13 anisotropic_symmetric_tensor4_2d

An **anisotropic_symmetric_tensor4_2d** is an anisotropic symmetric fourth order tensor in 2D space.

EXPRESS specification:

```
*)
TYPE anisotropic_symmetric_tensor4_2d =
     ARRAY [1:6] OF context_dependent_measure;
END_TYPE;
(*
```

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Enumerated item definitions:

ARRAY[1]: the 1111 component of the tensor.

ARRAY[2]: the 1122 component of the tensor.

ARRAY[3]: the 1112 component of the tensor.

ARRAY[4]: the 2222 component of the tensor.

ARRAY[5]: the 2212 component of the tensor.

ARRAY[6]: the 1212 component of the tensor.

7.3.14 tensor_type

A **tensor_type** is the value of a field variable.

EXPRESS specification:

```
*)
TYPE tensor_type = SELECT
  (scalar,
   angular_value,
   tensor1_2d,
   tensor1_3d,
   anisotropic_symmetric_tensor2_2d,
   isotropic_symmetric_tensor2_3d,
   orthotropic_symmetric_tensor2_3d,
   anisotropic_symmetric_tensor2_3d,
   anisotropic_symmetric_tensor4_2d,
   anisotropic_symmetric_tensor4_3d,
   fea_isotropic_symmetric_tensor4_3d,
   fea_iso_orthotropic_symmetric_tensor4_3d,
   fea_transverse_isotropic_symmetric_tensor4_3d,
   fea_column_normalised_orthotropic_symmetric_tensor4_3d,
   fea_column_normalised_monoclinic_symmetric_tensor4_3d);
END_TYPE;
(*
```

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7.4 FEA scalar vector tensor schema type definitions: The FEA representation of a fourth order material response tensor

The following TYPEs are used to specify material response in 3D space.

7.4.1 symmetric_tensor4_3d

A **symmetric_tensor4_3d** is a symmetric fourth order material response tensor in 3D space. A 3D fourth order tensor d_{ijkl} represents the relationship between two 3D second order tensors s_{ij} and e_{ij}, as shown below:

$$s_{ij} = \sum_{k=1}^{3} \sum_{l=1}^{3} d_{ijkl} e_{kl} \text{ for } i = 1,3 \text{ and } j = 1,3$$

In finite element analysis it is common to represent a symmetric 3D second order tensor s_{ij} as a (6) array S_i, with terms:

$$\begin{pmatrix} s_{11} \\ s_{22} \\ s_{33} \\ s_{12} \\ s_{23} \\ s_{31} \end{pmatrix}$$

Correspondingly, a symmetric 3D fourth order tensor d_{ijkl} is represented as a symmetric (6×6) matrix D_{ij} with terms:

$$\begin{pmatrix} d_{1111} & d_{1122} & d_{1133} & d_{1112} & d_{1123} & d_{1131} \\ & d_{2222} & d_{2233} & d_{2212} & d_{2223} & d_{2231} \\ & & d_{3333} & d_{3312} & d_{3323} & d_{3331} \\ & & & d_{1212} & d_{1223} & d_{1231} \\ & symmetric & & & d_{2323} & d_{2331} \\ & & & & & d_{3131} \end{pmatrix}$$

Note that if:

— σ_{ij} is stress, with (6) array representation S_i;

— ε_{ij} is strain;

— α_{kl} is the coefficient of linear thermal expansion;

— T is temperature;

— β_{kl} is the coefficient of linear moisture expansion;

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— M is moisture content;

— d_{ijkl} is elasticity, with (6×6) matrix representation D_{ij},

then:

$$\Delta\sigma_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} d_{ijkl}(\Delta\varepsilon_{kl} - \alpha_{kl}\Delta T - \beta_{kl}\Delta M) \text{ for } i = 1,3 \text{ and } j = 1,3$$

and in contracted notation:

$$S_i = \sum_{j=1}^{6} D_{ij}(E_j - {E_j}^T - {E_j}^M) \text{ for } i = 1,6$$

where E_j is the engineering representation of the strain with components:

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{12} \\ 2\varepsilon_{23} \\ 2\varepsilon_{31} \end{pmatrix}$$

A second order tensor shall be represented by its true mathematical components, and not by the components of its engineering representation.

EXPRESS specification:

```
*)
TYPE symmetric_tensor4_3d = SELECT
 (anisotropic_symmetric_tensor4_3d,
  fea_isotropic_symmetric_tensor4_3d,
  fea_iso_orthotropic_symmetric_tensor4_3d,
  fea_transverse_isotropic_symmetric_tensor4_3d,
  fea_column_normalised_orthotropic_symmetric_tensor4_3d,
  fea_column_normalised_monoclinic_symmetric_tensor4_3d);
END_TYPE;
(*
```

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7.4.2 anisotropic_symmetric_tensor4_3d

An **anisotropic_symmetric_tensor4_3d** is an anisotropic symmetric fourth order tensor in 3D space.

EXPRESS specification:

```
*)
TYPE anisotropic_symmetric_tensor4_3d =
     ARRAY [1:21] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the 1111 component of the tensor.

ARRAY[2]: the 1122 component of the tensor.

ARRAY[3]: the 1133 component of the tensor.

ARRAY[4]: the 1112 component of the tensor.

ARRAY[5]: the 1123 component of the tensor.

ARRAY[6]: the 1131 component of the tensor.

ARRAY[7]: the 2222 component of the tensor.

ARRAY[8]: the 2233 component of the tensor.

ARRAY[9]: the 2212 component of the tensor.

ARRAY[10]: the 2223 component of the tensor.

ARRAY[11]: the 2231 component of the tensor.

ARRAY[12]: the 3333 component of the tensor.

ARRAY[13]: the 3312 component of the tensor.

ARRAY[14]: the 3323 component of the tensor.

ARRAY[15]: the 3331 component of the tensor.

ARRAY[16]: the 1212 component of the tensor.

ARRAY[17]: the 1223 component of the tensor.

ARRAY[18]: the 1231 component of the tensor.

ARRAY[19]: the 2323 component of the tensor.

ARRAY[20]: the 2331 component of the tensor.

ARRAY[21]: the 3131 component of the tensor.

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7.4.3 fea_isotropic_symmetric_tensor4_3d

An **fea_isotropic_symmetric_tensor4_3d** is an isotropic symmetric fourth order tensor in 3D space, which is characterized by two independent values.

The values E and ν give terms in the (6×6) array representation of the **inverse** of the tensor as follows:

$$\begin{pmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ & & \frac{1}{E} & 0 & 0 & 0 \\ & & & \frac{1}{G} & 0 & 0 \\ & symmetric & & & \frac{1}{G} & 0 \\ & & & & & \frac{1}{G} \end{pmatrix}$$

where

$$G = \frac{E}{2(1+\nu)}$$

For an elasticity tensor:

— E is the Young's modulus;

— ν is the Poisson's ratio;

— G is the shear modulus;

— the terms are shown for the inverse of an elasticity tensor, which is a compliance tensor.

EXPRESS specification:

```
*)
TYPE fea_isotropic_symmetric_tensor4_3d =
     ARRAY [1:2] OF context_dependent_measure;
END_TYPE;
(*
```

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Enumerated item definitions:

ARRAY[1]: the term E defined above, which is the Young's modulus for an elasticity tensor.

ARRAY[2]: the term ν defined above, which is the Poisson's ratio for an elasticity tensor.

7.4.4 fea_iso_orthotropic_symmetric_tensor4_3d

An **fea_iso_orthotropic_symmetric_tensor4_3d** is an iso-orthotropic symmetric fourth order tensor in 3D space, which is characterized by three independent values.

The values E, ν, and G give terms in the (6×6) array representation of the **inverse** of the tensor as follows:

$$\begin{pmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ & & \frac{1}{E} & 0 & 0 & 0 \\ & & & \frac{1}{G} & 0 & 0 \\ & symmetric & & & \frac{1}{G} & 0 \\ & & & & & \frac{1}{G} \end{pmatrix}$$

For an elasticity tensor:

— E is the Young's modulus;

— ν is the Poisson's ratio;

— G is the shear modulus;

— the terms are shown for the inverse of an elasticity tensor, which is a compliance tensor.

EXPRESS specification:

```
*)
TYPE fea_iso_orthotropic_symmetric_tensor4_3d =
     ARRAY [1:3] OF context_dependent_measure;
END_TYPE;
(*
```

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Enumerated item definitions:

ARRAY[1]: the term E defined above, which is the Young's modulus for an elasticity tensor.

ARRAY[2]: the term ν defined above, which is the Poisson's ratio for an elasticity tensor.

ARRAY[3]: the term G defined above, which is the shear modulus for an elasticity tensor.

7.4.5 fea_transverse_isotropic_symmetric_tensor4_3d

An **fea_transverse_isotropic_symmetric_tensor4_3d** is a transverse isotropic symmetric fourth order tensor in 3D space, which is characterized by five independent values.

The values E_{ll}, E_{tt}, ν_{tt}, ν_{tl}, and G_{lt} give terms in the (6×6) array representation of the **inverse** of the tensor as follows:

$$\begin{pmatrix} \frac{1}{E_{ll}} & -\frac{\nu_{tl}}{E_{tt}} & -\frac{\nu_{tl}}{E_{tt}} & 0 & 0 & 0 \\ & \frac{1}{E_{tt}} & -\frac{\nu_{tt}}{E_{tt}} & 0 & 0 & 0 \\ & & \frac{1}{E_{tt}} & 0 & 0 & 0 \\ & & & \frac{1}{G_{lt}} & 0 & 0 \\ & symmetric & & & \frac{1}{G_{tt}} & 0 \\ & & & & & \frac{1}{G_{lt}} \end{pmatrix}$$

where

$$G_{tt} = \frac{E_{tt}}{2(1+\nu_{tt})}$$

.

For an elasticity tensor:

— E_{ll} is the longitudinal Young's modulus;

— ν_{tt} is the Poisson's ratio for strains in the transverse direction when uniaxially stressed in a transverse direction;

— E_{tt} is the transverse Young's modulus;

— ν_{tl} is the ratio between strain in a transverse direction to strain in the longitudinal direction when uniaxially strained in the longitudinal direction;

— G_{lt} is the modulus for shear in the longitudinal - transverse plane;

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— the 1 axis is longitudinal;

— the 2 and 3 axes are transverse;

— the terms are shown for the inverse of an elasticity tensor, which is a compliance tensor.

EXPRESS specification:

```
*)
TYPE fea_transverse_isotropic_symmetric_tensor4_3d =
     ARRAY [1:5] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the term E_{ll} defined above, which is the Young's modulus in the longitudinal direction for an elasticity tensor.

ARRAY[2]: the term ν_{tt} defined above, which is the Poisson's ratio in the transverse plane for an elasticity tensor.

ARRAY[3]: the term E_{tt} defined above, which is the Young's modulus in a transverse direction for an elasticity tensor.

ARRAY[4]: the term ν_{tl} defined above, which is the Poisson's ratio between transverse and longitudinal directions for an elasticity tensor.

ARRAY[5]: the term G_{lt} defined above, which is the modulus for shear between longitudinal and transverse directions for an elasticity tensor.

7.4.6 fea_column_normalised_orthotropic_symmetric_tensor4_3d

An **fea_column_normalised_orthotropic_symmetric_tensor4_3d** is a column normalised orthotropic symmetric fourth order tensor in 3D space, characterized by nine independent values.

The values E_{11}, E_{22}, E_{33}, ν_{12}, ν_{23}, ν_{31}, G_{12}, G_{23}, and G_{31} give terms in the (6×6) array representation of the **inverse** of the tensor as follows:

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$$\begin{pmatrix} \frac{1}{E_{11}} & -\frac{\nu_{12}}{E_{22}} & -\frac{\nu_{13}}{E_{33}} & 0 & 0 & 0 \\ & \frac{1}{E_{22}} & -\frac{\nu_{23}}{E_{33}} & 0 & 0 & 0 \\ & & \frac{1}{E_{33}} & 0 & 0 & 0 \\ & & & \frac{1}{G_{12}} & 0 & 0 \\ & symmetric & & & \frac{1}{G_{23}} & 0 \\ & & & & & \frac{1}{G_{31}} \end{pmatrix}$$

For an elasticity tensor:

— E_{11} is the Young's modulus in the 1 axis direction;

— E_{22} is the Young's modulus in the 2 axis direction;

— E_{33} is the Young's modulus in the 3 axis direction;

— ν_{12} is the Poisson's ratio for transverse strain in the 2 direction when uniaxially stressed in the 1 direction, $\nu_{12} = -\varepsilon_2/\varepsilon_1$ when $s_{ij} = 0$ for $i, j \neq 1$;

— ν_{13} is the Poisson's ratio for transverse strain in the 3 direction when uniaxially stressed in the 1 direction, $\nu_{13} = -\varepsilon_3/\varepsilon_1$ when $s_{ij} = 0$ for $i, j \neq 1$;

— ν_{23} is the Poisson's ratio for transverse strain in the 3 direction when uniaxially stressed in the 2 direction; $\nu_{23} = -\varepsilon_3/\varepsilon_2$ when $s_{ij} = 0$ for $i, j \neq 2$;

— G_{12} is the modulus for shear in the 1-2 plane;

— G_{23} is the modulus for shear in the 2-3 plane;

— G_{31} is the modulus for shear in the 3-1 plane;

— the terms are shown for the inverse of an elasticity tensor, which is a compliance tensor.

NOTE The Poisson's ratio convention used here and symmetry results in $E_{ii}\nu_{ji} = E_{jj}\nu_{ij}$.

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EXPRESS specification:

```
*)
TYPE fea_column_normalised_orthotropic_symmetric_tensor4_3d =
     ARRAY [1:9] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the term E_{11} defined above, which is the Young's modulus in the 1 direction for an elasticity tensor.

ARRAY[2]: the term E_{22} defined above, which is the Young's modulus in the 2 direction for an elasticity tensor.

ARRAY[3]: the term E_{33} defined above, which is the Young's modulus in the 3 direction for an elasticity tensor.

ARRAY[4]: the term ν_{12} defined above, which is the Poisson's ratio between the 1 and 2 directions for an elasticity tensor.

ARRAY[5]: the term ν_{13} defined above, which is the Poisson's ratio between the 1 and 3 directions for an elasticity tensor.

ARRAY[6]: the term ν_{23} defined above, which is the Poisson's ratio between the 2 and 3 directions for an elasticity tensor.

ARRAY[7]: the term G_{12} defined above, which is the modulus between the 1 and 2 directions for an elasticity tensor.

ARRAY[8]: the term G_{23} defined above, which is the modulus between the 2 and 3 directions for an elasticity tensor.

ARRAY[9]: the term G_{31} defined above, which is the modulus between the 3 and 1 directions for an elasticity tensor.

7.4.7 fea_column_normalised_monoclinic_symmetric_tensor4_3d

An **fea_column_normalised_monoclinic_symmetric_tensor4_3d** is a column normalised monoclinic symmetric fourth order tensor in 3D space, which is characterized by thirteen independent values.

The values E_{11}, E_{22}, E_{33}, ν_{12}, ν_{13}, ν_{23}, G_{23}, G_{31}, G_{12}, $\nu_{1,12}$, $\nu_{2,12}$, $\nu_{3,12}$, and $\nu_{23,31}$ give terms in the (6×6) array representation of the **inverse** of the tensor as follows:

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$$\begin{pmatrix} \frac{1}{E_{11}} & -\frac{\nu_{12}}{E_{22}} & -\frac{\nu_{13}}{E_{33}} & \frac{\nu_{1,12}}{G_{12}} & 0 & 0 \\ & \frac{1}{E_{22}} & -\frac{\nu_{23}}{E_{22}} & \frac{\nu_{2,12}}{G_{12}} & 0 & 0 \\ & & \frac{1}{E_{33}} & \frac{\nu_{3,12}}{G_{12}} & 0 & 0 \\ & & & \frac{1}{G_{12}} & 0 & 0 \\ & symmetric & & & \frac{1}{G_{23}} & \frac{\nu_{23,31}}{G_{31}} \\ & & & & & \frac{1}{G_{31}} \end{pmatrix}$$

For an elasticity tensor:

— E_{11} is the Young's modulus in the 1 axis direction;

— E_{22} is the Young's modulus in the 2 axis direction;

— E_{33} is the Young's modulus in the 3 axis direction;

— ν_{12} is the Poisson's ratio for transverse strain in the 2 direction when uniaxially stressed in the 1 direction, $E_{11}\nu_{21} = E_{22}\nu_{12}$;

— ν_{13} is the Poisson's ratio for transverse strain in the 3 direction when uniaxially stressed in the 1 direction, $E_{11}\nu_{31} = E_{33}\nu_{13}$;

— ν_{23} is the Poisson's ratio for transverse strain in the 3 direction when uniaxially stressed in the 2 direction, $E_{22}\nu_{32} = E_{33}\nu_{23}$;

— G_{23} is the modulus for shear in the 2-3 plane;

— G_{31} is the modulus for shear in the 3-1 plane;

— G_{12} is the modulus for shear in the 1-2 plane;

— $\nu_{1,12}$ is the coupling between the 1 axis extension and shear in the 1-2 plane, $E_{11}\nu_{1,12} = G_{12}\nu_{12,1}$;

— $\nu_{2,12}$ is the coupling between the 2 axis extension and shear in the 1-2 plane, $E_{22}\nu_{2,12} = G_{12}\nu_{12,2}$;

— $\nu_{3,12}$ is the coupling between the 3 axis extension and shear in the 1-2 plane, $E_{33}\nu_{3,12} = G_{12}\nu_{12,3}$;

— $\nu_{23,31}$ is the coupling between shears in the 2-3 and the 3-1 planes, $G_{23}\nu_{23,31} = G_{13}\nu_{31,23}$;

— the terms are shown for the inverse of an elasticity tensor, which is a compliance tensor.

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EXPRESS specification:

```
*)
TYPE fea_column_normalised_monoclinic_symmetric_tensor4_3d =
     ARRAY [1:13] OF context_dependent_measure;
END_TYPE;
(*
```

Enumerated item definitions:

ARRAY[1]: the term E_{11} defined above, which is the Young's modulus in the 1 direction for an elasticity tensor.

ARRAY[2]: the term E_{22} defined above, which is the Young's modulus in the 2 direction for an elasticity tensor.

ARRAY[3]: the term E_{33} defined above, which is the Young's modulus in the 3 direction for an elasticity tensor.

ARRAY[4]: the term ν_{12} defined above, which is the Poisson's ratio between the 1 and 2 directions for an elasticity tensor.

ARRAY[5]: the term ν_{13} defined above, which is the Poisson's ratio between the 1 and 3 directions for an elasticity tensor.

ARRAY[6]: the term ν_{23} defined above, which is the Poisson's ratio between the 2 and 3 directions for an elasticity tensor.

ARRAY[7]: the term G_{23} defined above, which is the modulus between the 2 and 3 directions for an elasticity tensor.

ARRAY[8]: the term G_{31} defined above, which is the modulus between the 3 and 1 directions for an elasticity tensor.

ARRAY[9]: the term G_{12} defined above, which is the modulus between the 1 and 2 directions for an elasticity tensor.

ARRAY[10]: the term $\nu_{1,12}$ defined above, which is the coupling between 1 extension and 1/2 plane shear for an elasticity tensor.

ARRAY[11]: the term $\nu_{2,12}$ defined above, which is the coupling between 2 extension and 1/2 plane shear for an elasticity tensor.

ARRAY[12]: the term $\nu_{3,12}$ defined above, which is the coupling between 3 extension and 1/2 plane shear for an elasticity tensor.

ARRAY[13]: the term $\nu_{23,31}$ defined above, which is the coupling between 2/3 and 3/1 plane shear for an elasticity tensor.

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7.5 FEA scalar vector tensor schema entity definitions: Tensor representation

7.5.1 tensor_representation_item

A **tensor_representation_item** is the value of a field variable within the context of a representation.

EXPRESS specification:

```
*)
ENTITY tensor_representation_item
  SUBTYPE OF (representation_item);
  tensor_value              : tensor_type;
END_ENTITY;
(*
```

Attribute definitions:

tensor_value: the value for the field variable.

EXPRESS specification:

```
*)
END_SCHEMA; -- fea_scalar_vector_tensor_schema
(*
```

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Annex A
(normative)

Short names of entities

Table A.1 provides the short names of entities specified in this part of ISO 10303. Requirements on the use of short names are found in the implementation methods included in ISO 10303.

Table A.1 – Short names of entities

Entity names	Short names
ALIGNED_AXIS_TOLERANCE	ALAXTL
ALIGNED_CURVE_3D_ELEMENT_COORDINATE_SYSTEM	AC3ECS
ALIGNED_SURFACE_2D_ELEMENT_COORDINATE_SYSTEM	AS2ECS
ALIGNED_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM	AS3ECS
ANALYSIS_ITEM_WITHIN_REPRESENTATION	AIWR
ANALYSIS_MESSAGE	ANLMSS
ANALYSIS_STEP	ANLSTP
ARBITRARY_VOLUME_2D_ELEMENT_COORDINATE_SYSTEM	AV2ECS
ARBITRARY_VOLUME_3D_ELEMENT_COORDINATE_SYSTEM	AV3ECS
AXISYMMETRIC_2D_ELEMENT_PROPERTY	A2EP
AXISYMMETRIC_CURVE_2D_ELEMENT_DESCRIPTOR	AC2ED
AXISYMMETRIC_CURVE_2D_ELEMENT_REPRESENTATION	AC2ER
AXISYMMETRIC_SURFACE_2D_ELEMENT_DESCRIPTOR	AS2ED
AXISYMMETRIC_SURFACE_2D_ELEMENT_REPRESENTATION	AS2ER
AXISYMMETRIC_VOLUME_2D_ELEMENT_DESCRIPTOR	AV2ED
AXISYMMETRIC_VOLUME_2D_ELEMENT_REPRESENTATION	AV2ER
CALCULATED_STATE	CLCSTT
CONSTANT_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM	CS3ECS
CONSTRAINT_ELEMENT	CNSELM
CONTROL	CNTRL
CONTROL_ANALYSIS_STEP	CNANST
CONTROL_LINEAR_MODES_AND_FREQUENCIES_ANALYSIS_STEP	CLMAFA
CONTROL_LINEAR_MODES_AND_FREQUENCIES_PROCESS	CLMAFP
CONTROL_LINEAR_STATIC_ANALYSIS_STEP	CLSAS
CONTROL_LINEAR_STATIC_ANALYSIS_STEP_WITH_HARMONIC	CLSASW
CONTROL_LINEAR_STATIC_LOAD_INCREMENT_PROCESS	CLSLIP
CONTROL_PROCESS	CNTPRC
CONTROL_RESULT_RELATIONSHIP	CNRSRL
CURVE_2D_ELEMENT_BASIS	C2EB
CURVE_2D_ELEMENT_CONSTANT_SPECIFIED_VARIABLE_VALUE	C2CSV
CURVE_2D_ELEMENT_CONSTANT_SPECIFIED_VOLUME_VARIABLE_-VALUE	C2ECSV

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Table A.1 (continued)

Entity names	Short names
CURVE_2D_ELEMENT_COORDINATE_SYSTEM	C2ECS
CURVE_2D_ELEMENT_FIELD_VARIABLE_DEFINITION	C2EFVD
CURVE_2D_ELEMENT_GROUP	C2EG
CURVE_2D_ELEMENT_INTEGRATED_MATRIX	C2EIM
CURVE_2D_ELEMENT_INTEGRATED_MATRIX_WITH_DEFINITION	C2EIMW
CURVE_2D_ELEMENT_INTEGRATION	C2EI
CURVE_2D_ELEMENT_LOCATION_POINT_VARIABLE_VALUES	C2E0
CURVE_2D_ELEMENT_LOCATION_POINT_VOLUME_VARIABLE_-VALUES	C2ELPV
CURVE_2D_ELEMENT_PROPERTY	C2EP
CURVE_2D_ELEMENT_VALUE_AND_LOCATION	C2EVAL
CURVE_2D_ELEMENT_VALUE_AND_VOLUME_LOCATION	C2EVAV
CURVE_2D_NODE_FIELD_AGGREGATED_VARIABLE_VALUES	C2NFAV
CURVE_2D_NODE_FIELD_SECTION_VARIABLE_VALUES	C2NFSV
CURVE_2D_NODE_FIELD_VARIABLE_DEFINITION	C2NFVD
CURVE_2D_SUBSTRUCTURE_ELEMENT_REFERENCE	C2SER
CURVE_2D_WHOLE_ELEMENT_VARIABLE_VALUE	C2WEVV
CURVE_3D_ELEMENT_BASIS	C3EB
CURVE_3D_ELEMENT_CONSTANT_SPECIFIED_VARIABLE_VALUE	C3ECSV
CURVE_3D_ELEMENT_CONSTANT_SPECIFIED_VOLUME_VARIABLE_-VALUE	C3CSV
CURVE_3D_ELEMENT_DESCRIPTOR	C3ED
CURVE_3D_ELEMENT_FIELD_VARIABLE_DEFINITION	C3EFVD
CURVE_3D_ELEMENT_GROUP	C3EG
CURVE_3D_ELEMENT_INTEGRATED_MATRIX	C3EIM
CURVE_3D_ELEMENT_INTEGRATED_MATRIX_WITH_DEFINITION	C3EIMW
CURVE_3D_ELEMENT_INTEGRATION	C3EI
CURVE_3D_ELEMENT_LENGTH_INTEGRATION_EXPLICIT	C3ELIE
CURVE_3D_ELEMENT_LENGTH_INTEGRATION_RULE	C3ELIR
CURVE_3D_ELEMENT_LOCATION_POINT_VARIABLE_VALUES	C3LPV
CURVE_3D_ELEMENT_LOCATION_POINT_VOLUME_VARIABLE_-VALUES	C3ELPV
CURVE_3D_ELEMENT_NODAL_SPECIFIED_VARIABLE_VALUES	C3ENSV
CURVE_3D_ELEMENT_POSITION_WEIGHT	C3EPW
CURVE_3D_ELEMENT_PROPERTY	C3EP
CURVE_3D_ELEMENT_REPRESENTATION	C3ER
CURVE_3D_ELEMENT_VALUE_AND_LOCATION	C3EVAL
CURVE_3D_ELEMENT_VALUE_AND_VOLUME_LOCATION	C3EVAV
CURVE_3D_NODE_FIELD_AGGREGATED_VARIABLE_VALUES	C3NFAV

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Table A.1 (continued)

Entity names	Short names
CURVE_3D_NODE_FIELD_SECTION_VARIABLE_VALUES	C3NFSV
CURVE_3D_NODE_FIELD_VARIABLE_DEFINITION	C3NFVD
CURVE_3D_SUBSTRUCTURE_ELEMENT_REFERENCE	C3SER
CURVE_3D_WHOLE_ELEMENT_VARIABLE_VALUE	C3WEVV
CURVE_CONSTRAINT	CRVCNS
CURVE_ELEMENT_END_OFFSET	CEEO
CURVE_ELEMENT_END_RELEASE	CEER
CURVE_ELEMENT_END_RELEASE_PACKET	CEERP
CURVE_ELEMENT_INTERVAL	CRELIN
CURVE_ELEMENT_INTERVAL_CONSTANT	CEIC
CURVE_ELEMENT_INTERVAL_LINEARLY_VARYING	CEILV
CURVE_ELEMENT_LOCATION	CRELLC
CURVE_ELEMENT_SECTION_DEFINITION	CESD
CURVE_ELEMENT_SECTION_DERIVED_DEFINITIONS	CESDD
CURVE_FREEDOM_ACTION_DEFINITION	CFAD
CURVE_FREEDOM_AND_VALUE_DEFINITION	CFAVD
CURVE_FREEDOM_VALUES	CRFRVL
CURVE_SECTION_ELEMENT_LOCATION	CSEL
CURVE_SECTION_INTEGRATION_EXPLICIT	CSIE
CURVE_VOLUME_ELEMENT_LOCATION	CVEL
CYLINDRICAL_SYMMETRY_CONTROL	CYSYCN
DIRECTIONALLY_EXPLICIT_ELEMENT_COEFFICIENT	DEEC
DIRECTIONALLY_EXPLICIT_ELEMENT_COORDINATE_SYSTEM_-ALIGNED	DCS
DIRECTIONALLY_EXPLICIT_ELEMENT_COORDINATE_SYSTEM_-ARBITRARY	DEECSA
DIRECTIONALLY_EXPLICIT_ELEMENT_REPRESENTATION	DEER
DIRECTION_NODE	DRCND
DUMMY_NODE	DMMND
ELEMENT_ANALYSIS_MESSAGE	ELANMS
ELEMENT_DEFINITION	ELMDFN
ELEMENT_DESCRIPTOR	ELMDSC
ELEMENT_GEOMETRIC_RELATIONSHIP	ELGMRL
ELEMENT_GROUP	ELMGRP
ELEMENT_GROUP_ANALYSIS_MESSAGE	EGAM
ELEMENT_MATERIAL	ELMMTR
ELEMENT_NODAL_FREEDOM_ACTIONS	ENFA
ELEMENT_NODAL_FREEDOM_TERMS	ENFT

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Table A.1 (continued)

Entity names	Short names
ELEMENT_REPRESENTATION	ELMRPR
ELEMENT_SEQUENCE	ELMSQN
EULER_ANGLES	ELRANG
EXPLICIT_ELEMENT_MATRIX	EXELMT
EXPLICIT_ELEMENT_REPRESENTATION	EXELRP
FEA_AREA_DENSITY	FARDN
FEA_AXIS2_PLACEMENT_2D	FAP2
FEA_AXIS2_PLACEMENT_3D	FAP3
FEA_CURVE_SECTION_GEOMETRIC_RELATIONSHIP	FCSGR
FEA_GROUP	FGRP
FEA_GROUP_RELATION	FGRRL
FEA_LINEAR_ELASTICITY	FLNEL
FEA_MASS_DENSITY	FMSDN
FEA_MATERIAL_PROPERTY_GEOMETRIC_RELATIONSHIP	FMPGR
FEA_MATERIAL_PROPERTY_REPRESENTATION	FMPR
FEA_MATERIAL_PROPERTY_REPRESENTATION_ITEM	FMPRI
FEA_MODEL	FMDL
FEA_MODEL_2D	FMD2D
FEA_MODEL_3D	FMD3D
FEA_MODEL_DEFINITION	FMDDF
FEA_MOISTURE_ABSORPTION	FMSAB
FEA_PARAMETRIC_POINT	FPRPN
FEA_REPRESENTATION_ITEM	FRPIT
FEA_SECANT_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION	FSCOLT
FEA_SHELL_BENDING_STIFFNESS	FSBS
FEA_SHELL_MEMBRANE_BENDING_COUPLING_STIFFNESS	FSMBCS
FEA_SHELL_MEMBRANE_STIFFNESS	FSMS
FEA_SHELL_SHEAR_STIFFNESS	FSSS
FEA_SURFACE_SECTION_GEOMETRIC_RELATIONSHIP	FSSGR
FEA_TANGENTIAL_COEFFICIENT_OF_LINEAR_THERMAL_EXPANSION	FTCOLT
FIELD_VARIABLE_DEFINITION	FLVRDF
FIELD_VARIABLE_ELEMENT_DEFINITION	FVED
FIELD_VARIABLE_ELEMENT_GROUP_VALUE	FVEGV
FIELD_VARIABLE_NODE_DEFINITION	FVND
FIELD_VARIABLE_WHOLE_MODEL_VALUE	FVWMV
FREEDOMS_LIST	FRDLST
FREEDOM_AND_COEFFICIENT	FRANCF
GEOMETRIC_NODE	GMTND

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Table A.1 (continued)

Entity names	Short names
GROUNDED_DAMPER	GRNDMP
GROUNDED_SPRING	GRNSPR
LINEARLY_SUPERIMPOSED_STATE	LNSPST
LINEAR_CONSTRAINT_EQUATION_ELEMENT	LCEE
LINEAR_CONSTRAINT_EQUATION_ELEMENT_VALUE	LCEEV
LINEAR_CONSTRAINT_EQUATION_NODAL_TERM	LCENT
NODAL_DOF_REDUCTION	NDDFRD
NODAL_FREEDOM_ACTION_DEFINITION	NFAD
NODAL_FREEDOM_AND_VALUE_DEFINITION	NFAVD
NODAL_FREEDOM_VALUES	NDFRVL
NODE	NODE
NODE_ANALYSIS_MESSAGE	NDANMS
NODE_DEFINITION	NDDFN
NODE_GEOMETRIC_RELATIONSHIP	NDGMRL
NODE_GROUP	NDGRP
NODE_REPRESENTATION	NDRPR
NODE_SEQUENCE	NDSQN
NODE_SET	NDST
NODE_WITH_SOLUTION_COORDINATE_SYSTEM	NWSCS
NODE_WITH_VECTOR	NDWTVC
NO_SYMMETRY_CONTROL	NSYCN
OUTPUT_REQUEST_STATE	OTRQST
PARAMETRIC_CURVE_3D_ELEMENT_COORDINATE_DIRECTION	PC3ECD
PARAMETRIC_CURVE_3D_ELEMENT_COORDINATE_SYSTEM	PC3ECS
PARAMETRIC_SURFACE_2D_ELEMENT_COORDINATE_SYSTEM	PS2ECS
PARAMETRIC_SURFACE_3D_ELEMENT_COORDINATE_SYSTEM	PS3ECS
PARAMETRIC_VOLUME_2D_ELEMENT_COORDINATE_SYSTEM	PV2ECS
PARAMETRIC_VOLUME_3D_ELEMENT_COORDINATE_SYSTEM	PV3ECS
PLANE_2D_ELEMENT_PROPERTY	P2EP
PLANE_CURVE_2D_ELEMENT_DESCRIPTOR	PC2ED
PLANE_CURVE_2D_ELEMENT_REPRESENTATION	PC2ER
PLANE_SURFACE_2D_ELEMENT_DESCRIPTOR	PS2ED
PLANE_SURFACE_2D_ELEMENT_REPRESENTATION	PS2ER
PLANE_VOLUME_2D_ELEMENT_DESCRIPTOR	PV2ED
PLANE_VOLUME_2D_ELEMENT_REPRESENTATION	PV2ER
POINT_CONSTRAINT	PNTCNS
POINT_ELEMENT_MATRIX	PNELMT
POINT_ELEMENT_REPRESENTATION	PNELRP

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Table A.1 (continued)

Entity names	Short names
POINT_FREEDOM_ACTION_DEFINITION	PFAD
POINT_FREEDOM_AND_VALUE_DEFINITION	PFAVD
POINT_FREEDOM_VALUES	PNFRVL
RESULT	RESULT
RESULT_ANALYSIS_STEP	RSANST
RESULT_LINEAR_MODES_AND_FREQUENCIES_ANALYSIS_SUB_STEP	RLMAFA
RESULT_LINEAR_STATIC_ANALYSIS_SUB_STEP	RLSASS
SIMPLE_PLANE_2D_ELEMENT_PROPERTY	SP2EP
SINGLE_POINT_CONSTRAINT_ELEMENT	SPCE
SINGLE_POINT_CONSTRAINT_ELEMENT_VALUES	SPCEV
SOLID_CONSTRAINT	SLDCNS
SOLID_FREEDOM_ACTION_DEFINITION	SFD
SOLID_FREEDOM_AND_VALUE_DEFINITION	SFVD
SOLID_FREEDOM_VALUES	SLFRVL
SPECIFIED_STATE	SPCSTT
STATE	STATE
STATE_COMPONENT	STTCMP
STATE_RELATIONSHIP	STTRLT
STATE_WITH_HARMONIC	STWTHR
STATIONARY_MASS	STTMSS
STRUCTURAL_RESPONSE_PROPERTY	STRSPR
STRUCTURAL_RESPONSE_PROPERTY_DEFINITION_REPRESENTATION	SRPDR
SUBSTRUCTURE_ELEMENT_REPRESENTATION	SBELRP
SUBSTRUCTURE_NODE_REFERENCE	SBNDRF
SUBSTRUCTURE_NODE_RELATIONSHIP	SBNDRL
SURFACE_2D_ELEMENT_BASIS	S2EB
SURFACE_2D_ELEMENT_BOUNDARY_CONSTANT_SPECIFIED_-SURFACE_VARIABLE_VALUE	S2BCS
SURFACE_2D_ELEMENT_BOUNDARY_CONSTANT_SPECIFIED_-VARIABLE_VALUE	S2EBCS
SURFACE_2D_ELEMENT_BOUNDARY_EDGE_CONSTANT_SPECIFIED_-SURFACE_VARIABLE_VALUE	S2BC
SURFACE_2D_ELEMENT_BOUNDARY_EDGE_CONSTANT_SPECIFIED_-VARIABLE_VALUE	S2EBEC
SURFACE_2D_ELEMENT_BOUNDARY_EDGE_LOCATION_POINT_-SURFACE_VARIABLE_VALUES	S2BL
SURFACE_2D_ELEMENT_BOUNDARY_EDGE_LOCATION_POINT_-VARIABLE_VALUES	S2EBEL

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Table A.1 (continued)

Entity names	Short names
SURFACE_2D_ELEMENT_BOUNDARY_EDGE_NODAL_SPECIFIED_-VARIABLE_VALUES	S2EBEN
SURFACE_2D_ELEMENT_BOUNDARY_EDGE_WHOLE_EDGE_-VARIABLE_VALUE	S2EBEW
SURFACE_2D_ELEMENT_BOUNDARY_LOCATION_POINT_SURFACE_-VARIABLE_VALUES	S2EBLP
SURFACE_2D_ELEMENT_BOUNDARY_NODAL_SPECIFIED_VARIABLE_-VALUES	S2EBNS
SURFACE_2D_ELEMENT_BOUNDARY_WHOLE_FACE_VARIABLE_-VALUE	S2EBWF
SURFACE_2D_ELEMENT_CONSTANT_SPECIFIED_VARIABLE_VALUE	S2ECSV
SURFACE_2D_ELEMENT_CONSTANT_SPECIFIED_VOLUME_-VARIABLE_VALUE	S2CSV
SURFACE_2D_ELEMENT_FIELD_VARIABLE_DEFINITION	S2EFVD
SURFACE_2D_ELEMENT_GROUP	S2EG
SURFACE_2D_ELEMENT_INTEGRATED_MATRIX	S2EIM
SURFACE_2D_ELEMENT_INTEGRATED_MATRIX_WITH_DEFINITION	S2EIMW
SURFACE_2D_ELEMENT_INTEGRATION	S2EI
SURFACE_2D_ELEMENT_LENGTH_INTEGRATION_EXPLICIT	S2ELIE
SURFACE_2D_ELEMENT_LENGTH_INTEGRATION_RULE	S2ELIR
SURFACE_2D_ELEMENT_LOCATION_POINT_VARIABLE_VALUES	S2ELPV
SURFACE_2D_ELEMENT_LOCATION_POINT_VOLUME_VARIABLE_-VALUES	S2LPV
SURFACE_2D_ELEMENT_NODAL_SPECIFIED_VARIABLE_VALUES	S2ENSV
SURFACE_2D_ELEMENT_VALUE_AND_LOCATION	S2EVAL
SURFACE_2D_ELEMENT_VALUE_AND_VOLUME_LOCATION	S2EVAV
SURFACE_2D_NODE_FIELD_AGGREGATED_VARIABLE_VALUES	S2NFAV
SURFACE_2D_NODE_FIELD_SECTION_VARIABLE_VALUES	S2NFSV
SURFACE_2D_NODE_FIELD_VARIABLE_DEFINITION	S2NFVD
SURFACE_2D_SUBSTRUCTURE_ELEMENT_REFERENCE	S2SER
SURFACE_2D_WHOLE_ELEMENT_VARIABLE_VALUE	S2WEVV
SURFACE_3D_ELEMENT_BASIS	S3EB
SURFACE_3D_ELEMENT_BOUNDARY_CONSTANT_SPECIFIED_-SURFACE_VARIABLE_VALUE	S3EBCS
SURFACE_3D_ELEMENT_BOUNDARY_CONSTANT_SPECIFIED_-VARIABLE_VALUE	S3BCS
SURFACE_3D_ELEMENT_BOUNDARY_EDGE_CONSTANT_SPECIFIED_-SURFACE_VARIABLE_VALUE	S3EBEC

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Table A.1 (continued)

Entity names	Short names
SURFACE_3D_ELEMENT_BOUNDARY_EDGE_CONSTANT_SPECIFIED_-VARIABLE_VALUE	S3BC
SURFACE_3D_ELEMENT_BOUNDARY_EDGE_LOCATION_POINT_-SURFACE_VARIABLE_VALUES	S3BL
SURFACE_3D_ELEMENT_BOUNDARY_EDGE_LOCATION_POINT_-VARIABLE_VALUES	S3EBEL
SURFACE_3D_ELEMENT_BOUNDARY_EDGE_NODAL_SPECIFIED_-VARIABLE_VALUES	S3EBEN
SURFACE_3D_ELEMENT_BOUNDARY_EDGE_WHOLE_EDGE_-VARIABLE_VALUE	S3EBEW
SURFACE_3D_ELEMENT_BOUNDARY_LOCATION_POINT_SURFACE_-VARIABLE_VALUES	S3EBLP
SURFACE_3D_ELEMENT_BOUNDARY_NODAL_SPECIFIED_VARIABLE_-VALUES	S3EBNS
SURFACE_3D_ELEMENT_BOUNDARY_WHOLE_FACE_VARIABLE_-VALUE	S3EBWF
SURFACE_3D_ELEMENT_CONSTANT_SPECIFIED_VARIABLE_VALUE	S3ECSV
SURFACE_3D_ELEMENT_CONSTANT_SPECIFIED_VOLUME_-VARIABLE_VALUE	S3CSV
SURFACE_3D_ELEMENT_DESCRIPTOR	S3ED
SURFACE_3D_ELEMENT_FIELD_INTEGRATION_EXPLICIT	S3EFIE
SURFACE_3D_ELEMENT_FIELD_INTEGRATION_RULE	S3EFIR
SURFACE_3D_ELEMENT_FIELD_VARIABLE_DEFINITION	S3EFVD
SURFACE_3D_ELEMENT_GROUP	S3EG
SURFACE_3D_ELEMENT_INTEGRATED_MATRIX	S3EIM
SURFACE_3D_ELEMENT_INTEGRATED_MATRIX_WITH_DEFINITION	S3EIMW
SURFACE_3D_ELEMENT_INTEGRATION	S3EI
SURFACE_3D_ELEMENT_LOCATION_POINT_VARIABLE_VALUES	S3ELPV
SURFACE_3D_ELEMENT_LOCATION_POINT_VOLUME_VARIABLE_-VALUES	S3LPV
SURFACE_3D_ELEMENT_NODAL_SPECIFIED_VARIABLE_VALUES	S3ENSV
SURFACE_3D_ELEMENT_REPRESENTATION	S3ER
SURFACE_3D_ELEMENT_VALUE_AND_LOCATION	S3EVAL
SURFACE_3D_ELEMENT_VALUE_AND_VOLUME_LOCATION	S3EVAV
SURFACE_3D_NODE_FIELD_AGGREGATED_VARIABLE_VALUES	S3NFAV
SURFACE_3D_NODE_FIELD_SECTION_VARIABLE_VALUES	S3NFSV
SURFACE_3D_NODE_FIELD_VARIABLE_DEFINITION	S3NFVD
SURFACE_3D_SUBSTRUCTURE_ELEMENT_REFERENCE	S3SER
SURFACE_3D_WHOLE_ELEMENT_VARIABLE_VALUE	S3WEVV

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Table A.1 (continued)

Entity names	Short names
SURFACE_CONSTRAINT	SRFCNS
SURFACE_ELEMENT_LOCATION	SRELLC
SURFACE_ELEMENT_PROPERTY	SRELPR
SURFACE_FREEDOM_ACTION_DEFINITION	SFAD
SURFACE_FREEDOM_AND_VALUE_DEFINITION	SFAVD
SURFACE_FREEDOM_VALUES	SRFRVL
SURFACE_POSITION_WEIGHT	SRPSWG
SURFACE_SECTION	SRFSCT
SURFACE_SECTION_ELEMENT_LOCATION	SSEL
SURFACE_SECTION_ELEMENT_LOCATION_ABSOLUTE	SSELA
SURFACE_SECTION_ELEMENT_LOCATION_DIMENSIONLESS	SSELD
SURFACE_SECTION_FIELD	SRSCFL
SURFACE_SECTION_FIELD_CONSTANT	SSFC
SURFACE_SECTION_FIELD_VARYING	SSFV
SURFACE_SECTION_INTEGRATION_EXPLICIT	SSIE
SURFACE_SECTION_INTEGRATION_RULE	SSIR
SURFACE_SECTION_POSITION_WEIGHT	SSPW
SURFACE_VOLUME_ELEMENT_LOCATION	SVEL
SYMMETRY_CONTROL	SYMCNT
SYSTEM_AND_FREEDOM	SYANFR
TENSOR_REPRESENTATION_ITEM	TNRPIT
UNIFORM_SURFACE_SECTION	UNSRSC
UNIFORM_SURFACE_SECTION_LAYERED	USSL
VOLUME_2D_ELEMENT_BASIS	V2EB
VOLUME_2D_ELEMENT_BOUNDARY_CONSTANT_SPECIFIED_-VARIABLE_VALUE	V2EBCS
VOLUME_2D_ELEMENT_BOUNDARY_EDGE_CONSTANT_SPECIFIED_-VOLUME_VARIABLE_VALUE	V2EBEC
VOLUME_2D_ELEMENT_BOUNDARY_EDGE_LOCATION_POINT_-VOLUME_VARIABLE_VALUES	V2EBEL
VOLUME_2D_ELEMENT_BOUNDARY_EDGE_NODAL_SPECIFIED_-VARIABLE_VALUES	V2EBEN
VOLUME_2D_ELEMENT_BOUNDARY_EDGE_WHOLE_EDGE_-VARIABLE_VALUE	V2EBEW
VOLUME_2D_ELEMENT_BOUNDARY_LOCATION_POINT_VARIABLE_-VALUES	V2EBLP
VOLUME_2D_ELEMENT_BOUNDARY_NODAL_SPECIFIED_VARIABLE_-VALUES	V2EBNS

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Table A.1 (continued)

Entity names	Short names
VOLUME_2D_ELEMENT_BOUNDARY_WHOLE_FACE_VARIABLE_-VALUE	V2EBWF
VOLUME_2D_ELEMENT_CONSTANT_SPECIFIED_VARIABLE_VALUE	V2ECSV
VOLUME_2D_ELEMENT_FIELD_INTEGRATION_EXPLICIT	V2EFIE
VOLUME_2D_ELEMENT_FIELD_INTEGRATION_RULE	V2EFIR
VOLUME_2D_ELEMENT_FIELD_VARIABLE_DEFINITION	V2EFVD
VOLUME_2D_ELEMENT_GROUP	V2EG
VOLUME_2D_ELEMENT_INTEGRATED_MATRIX	V2EIM
VOLUME_2D_ELEMENT_INTEGRATED_MATRIX_WITH_DEFINITION	V2EIMW
VOLUME_2D_ELEMENT_LOCATION_POINT_VARIABLE_VALUES	V2ELPV
VOLUME_2D_ELEMENT_NODAL_SPECIFIED_VARIABLE_VALUES	V2ENSV
VOLUME_2D_ELEMENT_VALUE_AND_LOCATION	V2EVAL
VOLUME_2D_NODE_FIELD_VARIABLE_DEFINITION	V2NFVD
VOLUME_2D_SUBSTRUCTURE_ELEMENT_REFERENCE	V2SER
VOLUME_2D_WHOLE_ELEMENT_VARIABLE_VALUE	V2WEVV
VOLUME_3D_ELEMENT_BASIS	V3EB
VOLUME_3D_ELEMENT_BOUNDARY_CONSTANT_SPECIFIED_-VARIABLE_VALUE	V3EBCS
VOLUME_3D_ELEMENT_BOUNDARY_EDGE_CONSTANT_SPECIFIED_-VOLUME_VARIABLE_VALUE	V3EBEC
VOLUME_3D_ELEMENT_BOUNDARY_EDGE_LOCATION_POINT_-VOLUME_VARIABLE_VALUES	V3EBEL
VOLUME_3D_ELEMENT_BOUNDARY_EDGE_NODAL_SPECIFIED_-VARIABLE_VALUES	V3EBEN
VOLUME_3D_ELEMENT_BOUNDARY_EDGE_WHOLE_EDGE_-VARIABLE_VALUE	V3EBEW
VOLUME_3D_ELEMENT_BOUNDARY_LOCATION_POINT_VARIABLE_-VALUES	V3EBLP
VOLUME_3D_ELEMENT_BOUNDARY_NODAL_SPECIFIED_VARIABLE_-VALUES	V3EBNS
VOLUME_3D_ELEMENT_BOUNDARY_WHOLE_FACE_VARIABLE_-VALUE	V3EBWF
VOLUME_3D_ELEMENT_CONSTANT_SPECIFIED_VARIABLE_VALUE	V3ECSV
VOLUME_3D_ELEMENT_DESCRIPTOR	V3ED
VOLUME_3D_ELEMENT_FIELD_INTEGRATION_EXPLICIT	V3EFIE
VOLUME_3D_ELEMENT_FIELD_INTEGRATION_RULE	V3EFIR
VOLUME_3D_ELEMENT_FIELD_VARIABLE_DEFINITION	V3EFVD
VOLUME_3D_ELEMENT_GROUP	V3EG
VOLUME_3D_ELEMENT_INTEGRATED_MATRIX	V3EIM

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Table A.1 (concluded)

Entity names	Short names
VOLUME_3D_ELEMENT_INTEGRATED_MATRIX_WITH_DEFINITION	V3EIMW
VOLUME_3D_ELEMENT_LOCATION_POINT_VARIABLE_VALUES	V3ELPV
VOLUME_3D_ELEMENT_NODAL_SPECIFIED_VARIABLE_VALUES	V3ENSV
VOLUME_3D_ELEMENT_REPRESENTATION	V3ER
VOLUME_3D_ELEMENT_VALUE_AND_LOCATION	V3EVAL
VOLUME_3D_NODE_FIELD_VARIABLE_DEFINITION	V3NFVD
VOLUME_3D_SUBSTRUCTURE_ELEMENT_REFERENCE	V3SER
VOLUME_3D_WHOLE_ELEMENT_VARIABLE_VALUE	V3WEVV
VOLUME_ELEMENT_LOCATION	VLELLC
VOLUME_POSITION_WEIGHT	VLPSWG
WHOLE_MODEL_ANALYSIS_MESSAGE	WMAM
WHOLE_MODEL_MODES_AND_FREQUENCIES_ANALYSIS_MESSAGE	WMMAFA

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Annex B
(normative)

Information object registration

B.1 Document identification

To provide for unambiguous identification of an information object in an open system, the object identifier

```
{ iso standard 10303 part(104) version(1) }
```

is assigned to this part of ISO 10303. The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

B.2 Schema identification

B.2.1 structural_response_definition_schema identification

To provide for unambiguous identification of the structural-response-definition-schema in an open information system, the object identifier

```
{ iso standard 10303 part(104) version(1) object(1)
    structural-response-definition-schema(1) }
```

is assigned to the **structural_response_definition_schema** (see clause 4). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

B.2.2 structural_response_representation_schema identification

To provide for unambiguous identification of the structural-response-representation-schema in an open information system, the object identifier

```
{ iso standard 10303 part(104) version(1) object(1)
  structural-response-representation-schema(2) }
```

is assigned to the **structural_response_representation_schema** (see clause 5). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

B.2.3 finite_element_analysis_control_and_result_schema identification

To provide for unambiguous identification of the finite-element-analysis-control-and-result-schema in an open information system, the object identifier

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```
{ iso standard 10303 part(104) version(1) object(1)
finite-element-analysis-control-and-result-schema(3) }
```

is assigned to the **finite_element_analysis_control_and_result_schema** (see clause 6). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

B.2.4 fea_scalar_vector_tensor_schema identification

To provide for unambiguous identification of the fea-scalar-vector-tensor-schema in an open information system, the object identifier

```
{ iso standard 10303 part(104) version(1) object(1)
       fea-scalar-vector-tensor-schema(4) }
```

is assigned to the **fea_scalar_vector_tensor_schema** (see clause 7). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

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Annex C
(informative)

Computer-interpretable listings

This annex references a listing of the EXPRESS entity names and corresponding short names as specified in this part of ISO 10303. It also references a listing of each EXPRESS schema specified in this part of ISO 10303, without comments or other explanatory text. These listings are available in computer-interpretable form and can be found at the following URLs:

Short names: `<http://www.mel.nist.gov/div826/subject/spde/snr/>`
EXPRESS: `<http://www.mel.nist.gov/step/parts/part104/is/>`

If there is difficulty accessing these sites contact ISO Central Secretariat or contact the ISO TC 184/SC4 Secretariat directly at: `sc4sec@cme.nist.gov`.

NOTE The information provided in computer-interpretable form at the above URLs is informative. The information that is contained in the body of this part of ISO 10303 is normative.

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Annex D
(informative)

EXPRESS-G diagrams

Figures D.1 through D.86 correspond to the EXPRESS listing given in annex C. The diagrams use the EXPRESS-G graphical notation for the EXPRESS language. EXPRESS-G is defined in annex D of ISO 10303-11.

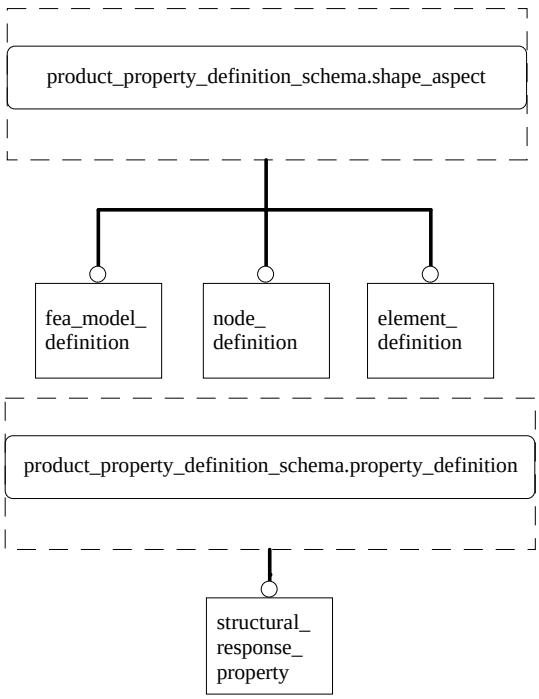

Figure D.1 – Structural response definition schema EXPRESS-G diagram, 1 of 86.

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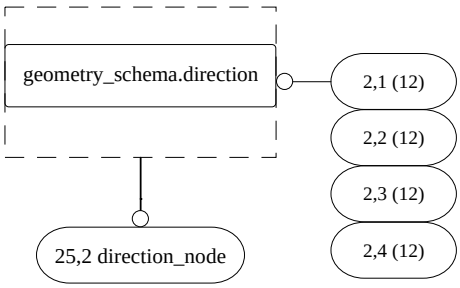

Figure D.2 – Structural response representation schema EXPRESS-G diagram, 2 of 86.

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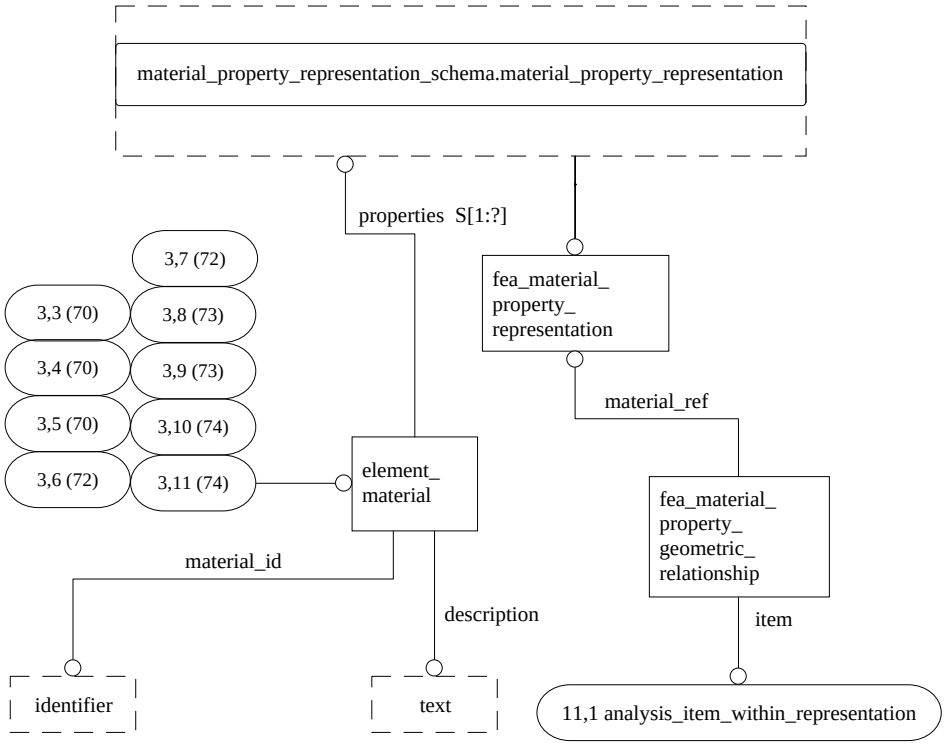

Figure D.3 – Structural response representation schema EXPRESS-G diagram, 3 of 86.

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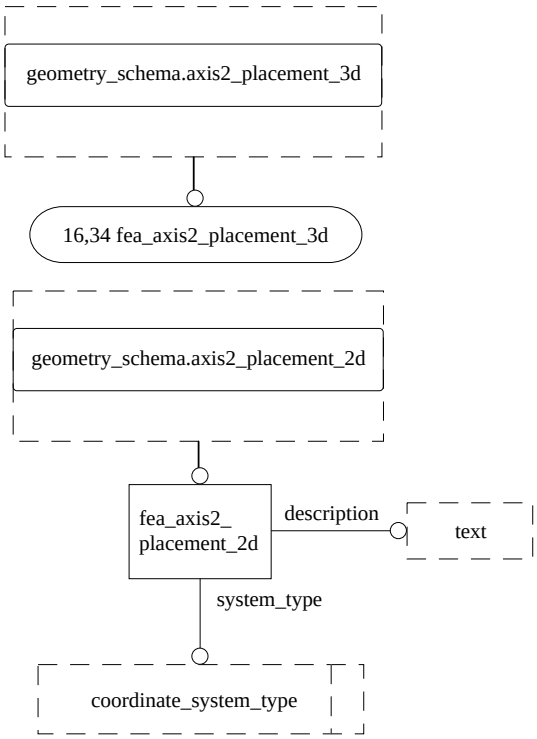

Figure D.4 – Structural response representation schema EXPRESS-G diagram, 4 of 86.

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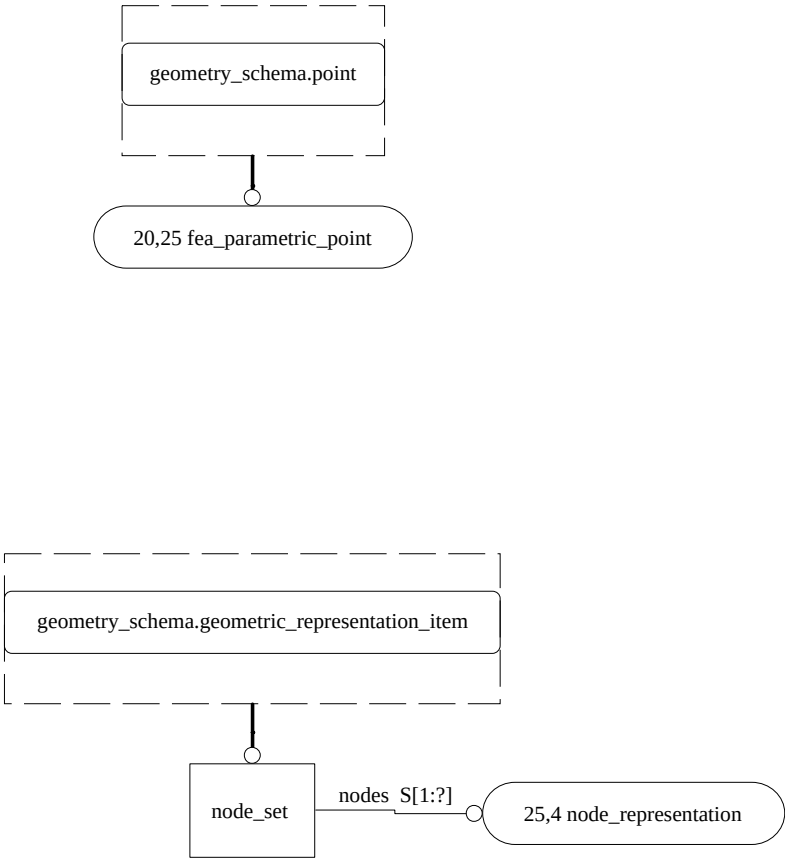

Figure D.5 – Structural response representation schema EXPRESS-G diagram, 5 of 86.

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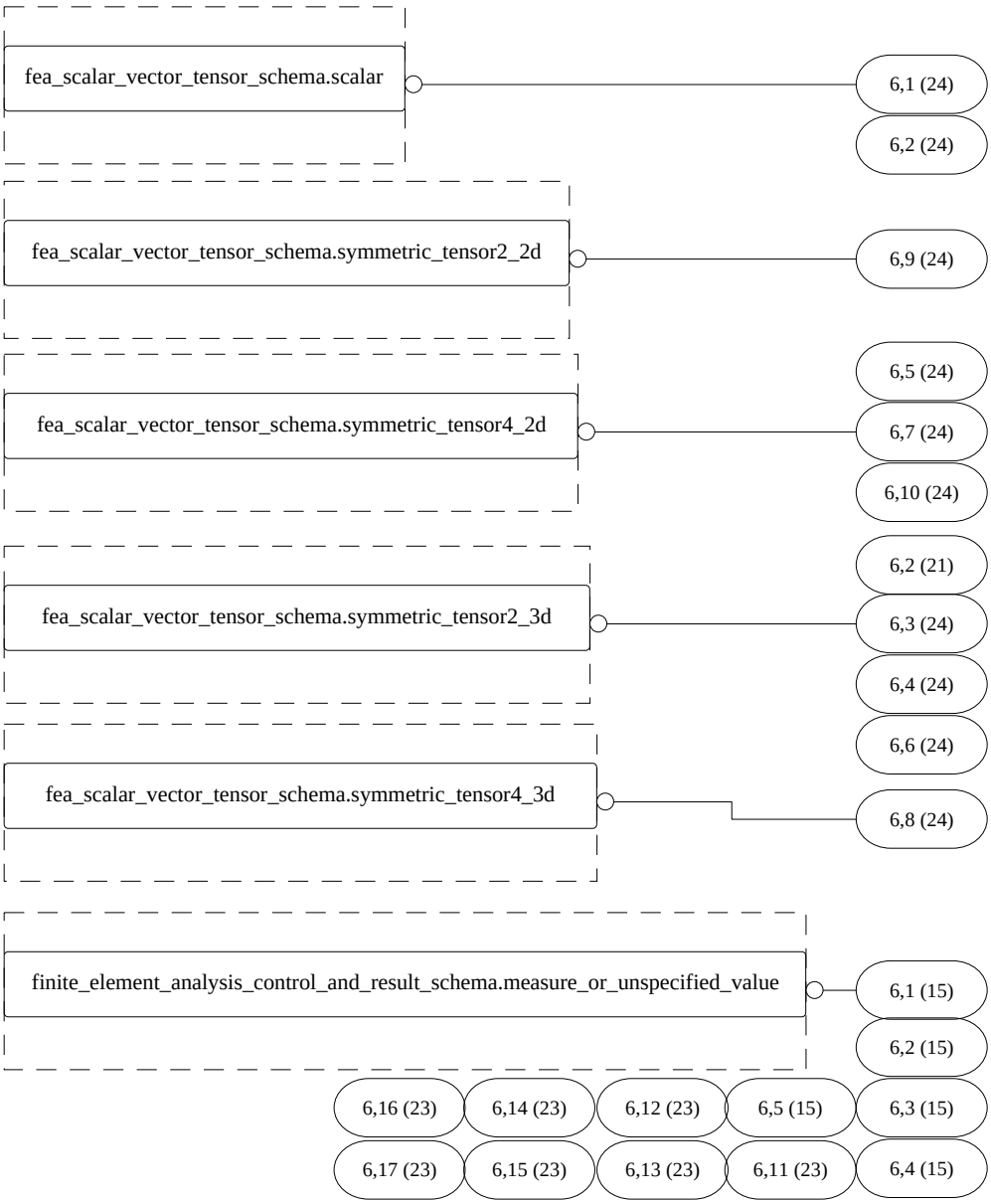

Figure D.6 – Structural response representation schema EXPRESS-G diagram, 6 of 86.

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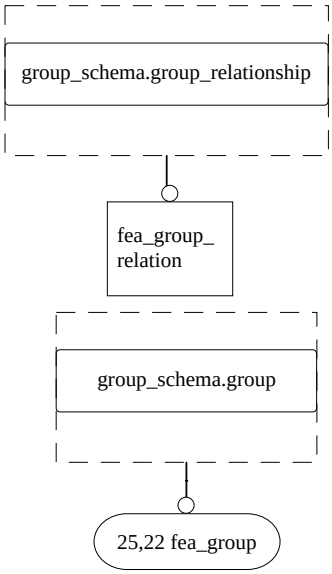

Figure D.7 – Structural response representation schema EXPRESS-G diagram, 7 of 86.

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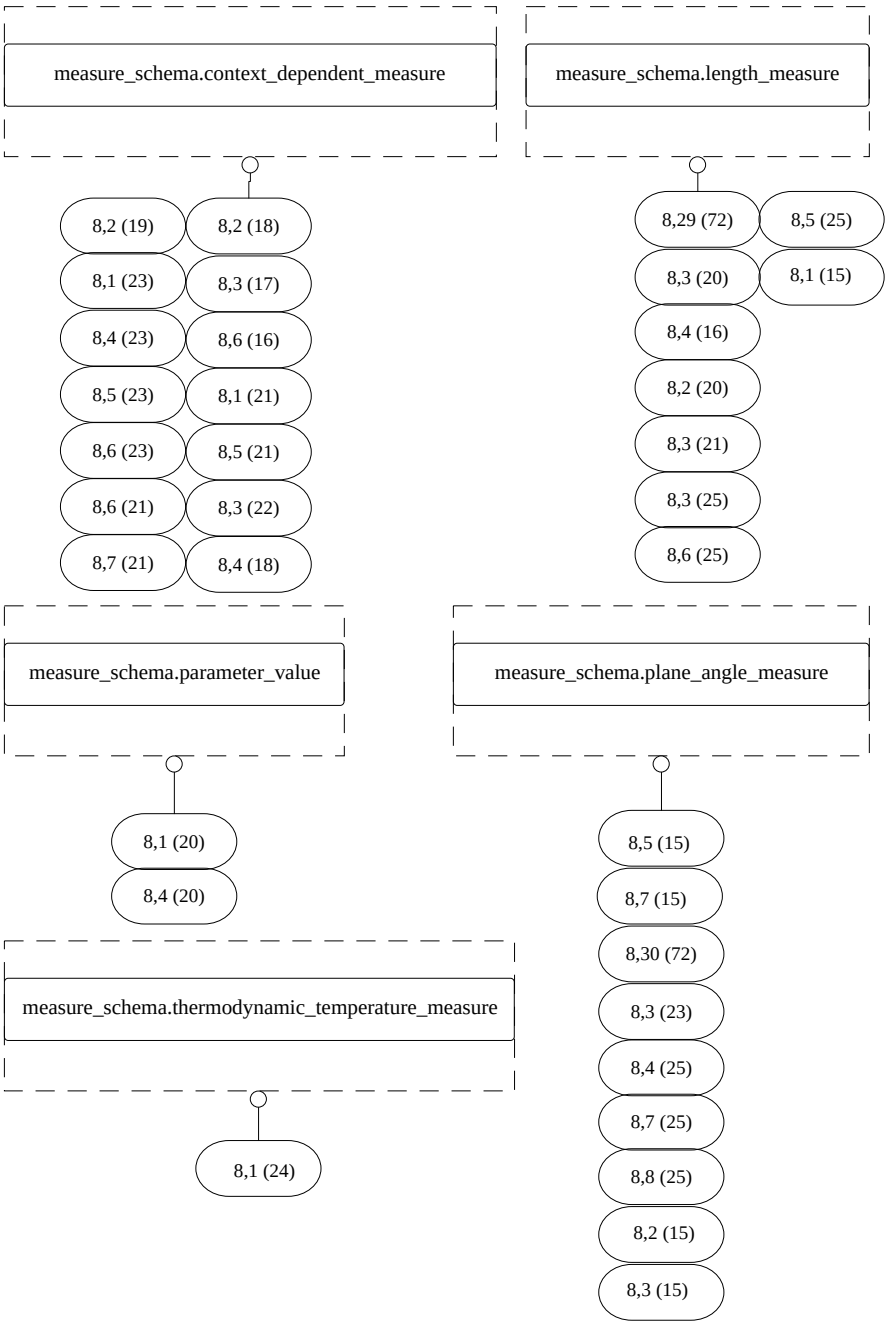

Figure D.8 – Structural response representation schema EXPRESS-G diagram, 8 of 86.

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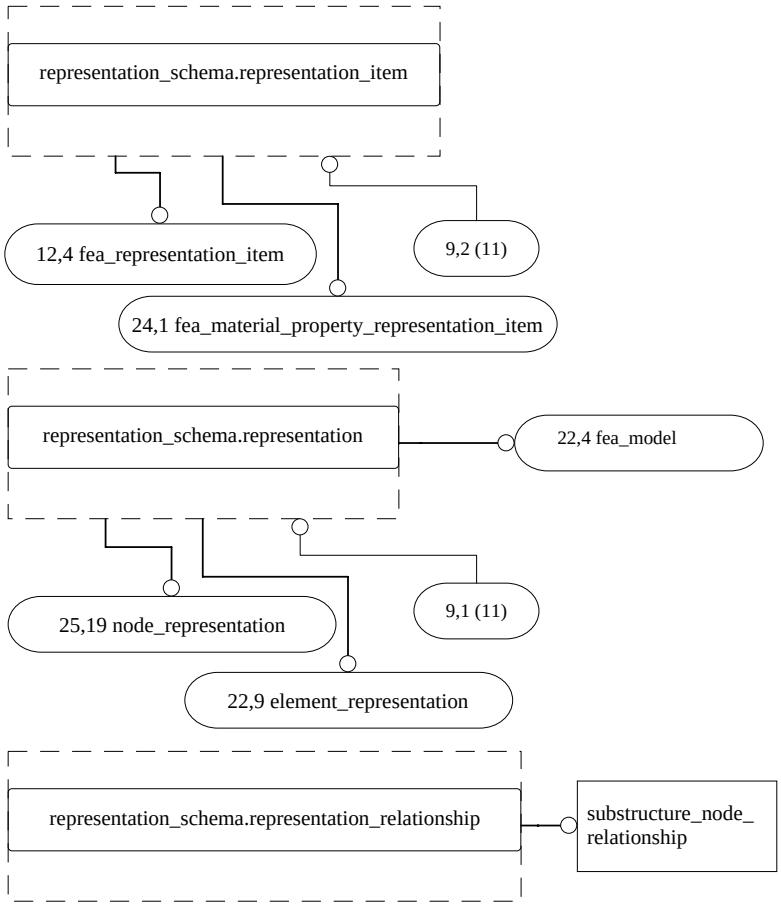

Figure D.9 – Structural response representation schema EXPRESS-G diagram, 9 of 86.

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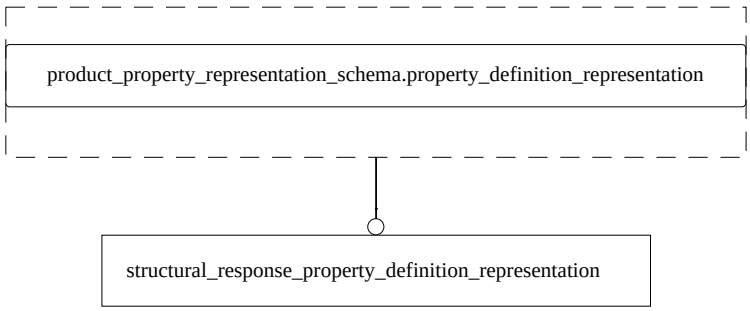

Figure D.10 – Structural response representation schema EXPRESS-G diagram, 10 of 86.

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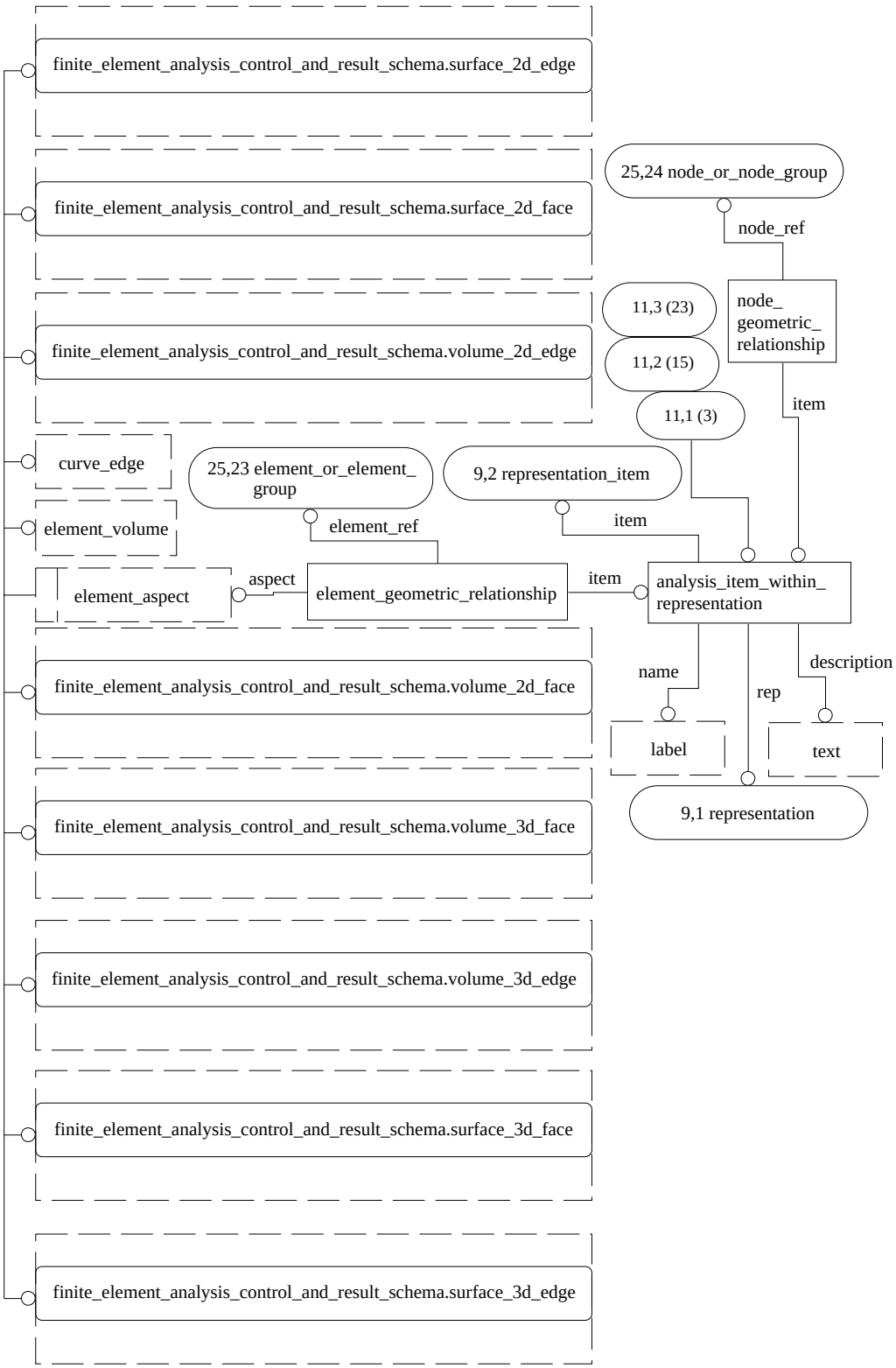

Figure D.11 – Structural response representation schema EXPRESS-G diagram, 11 of 86.

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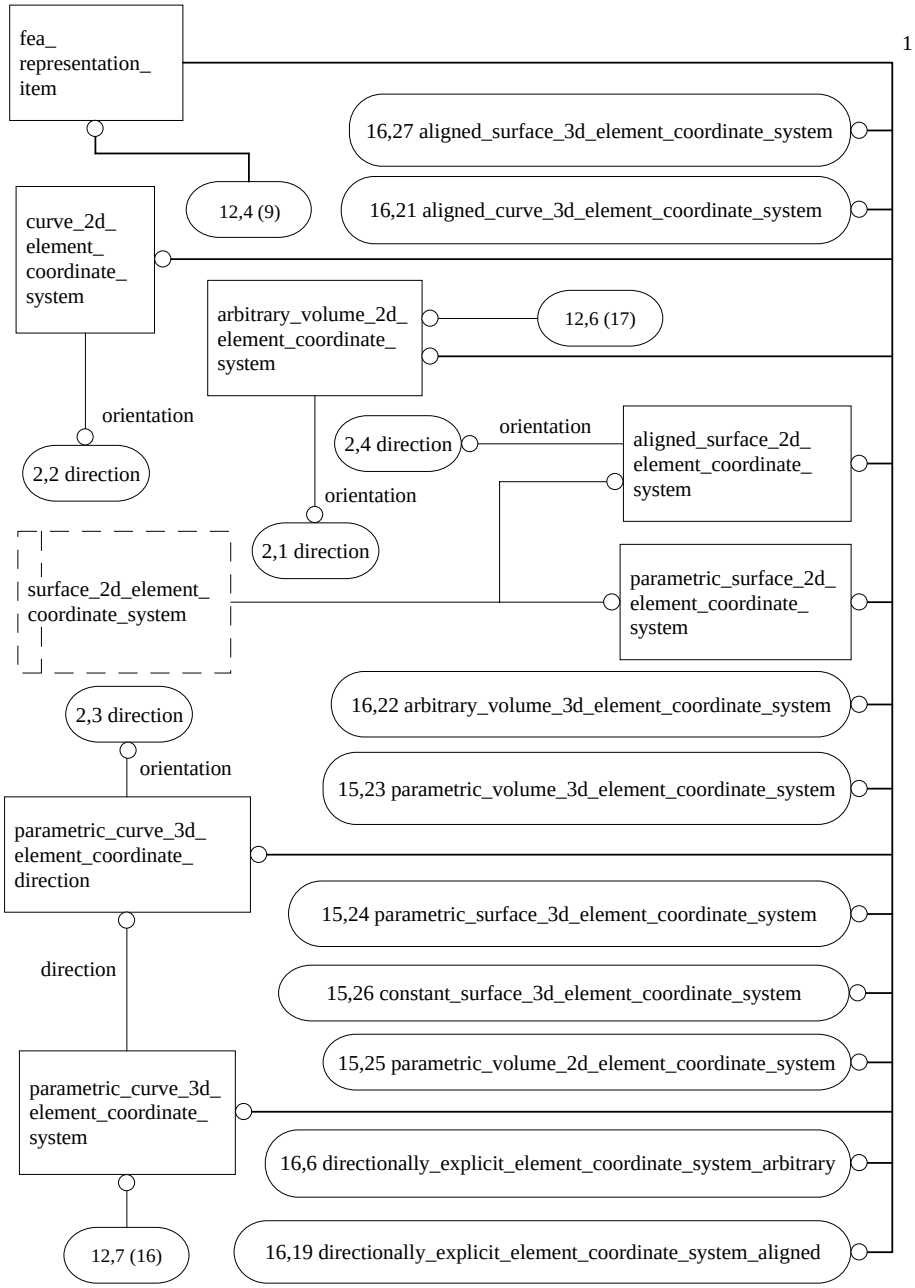

Figure D.12 – Structural response representation schema EXPRESS-G diagram, 12 of 86.

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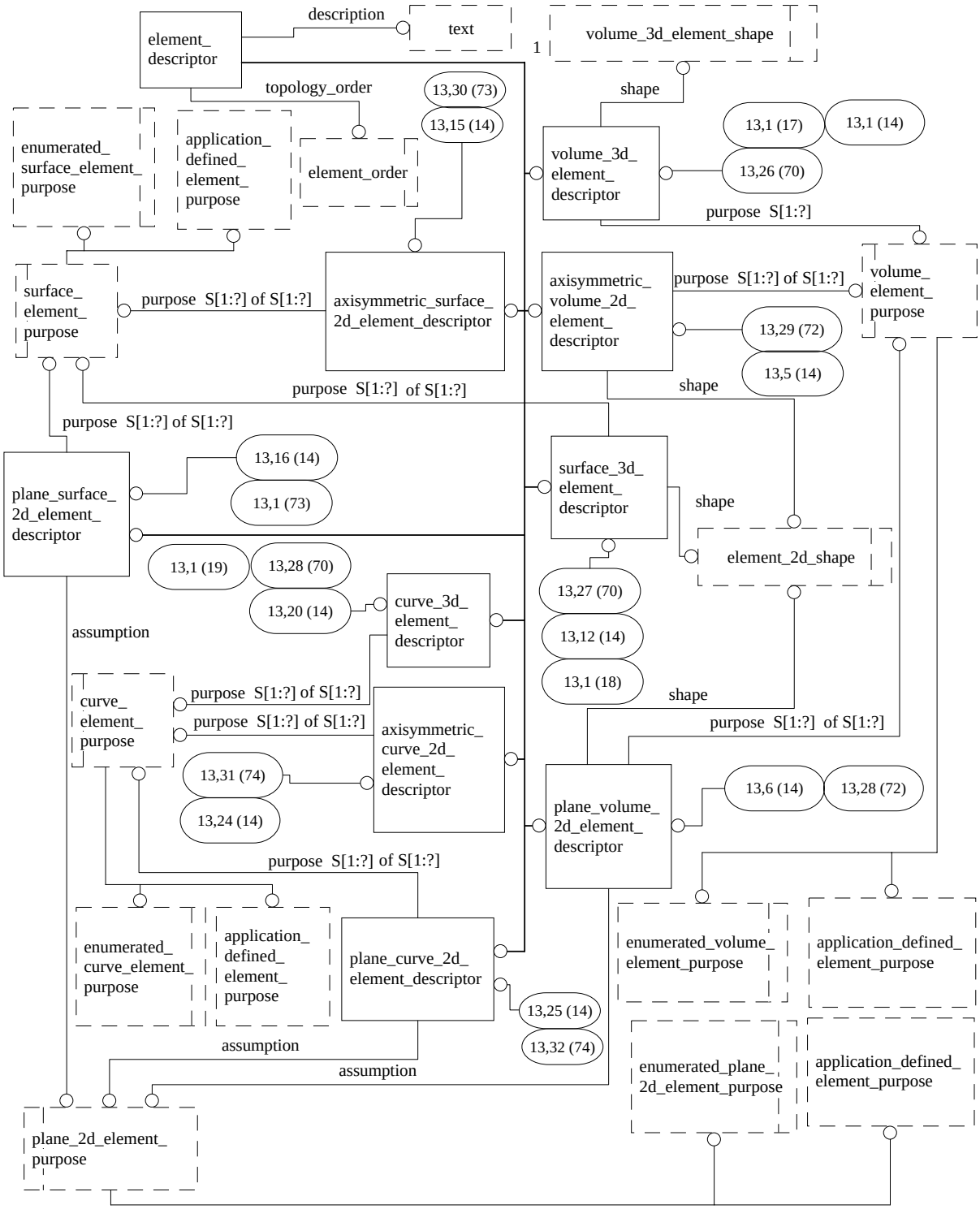

Figure D.13 – Structural response representation schema EXPRESS-G diagram, 13 of 86.

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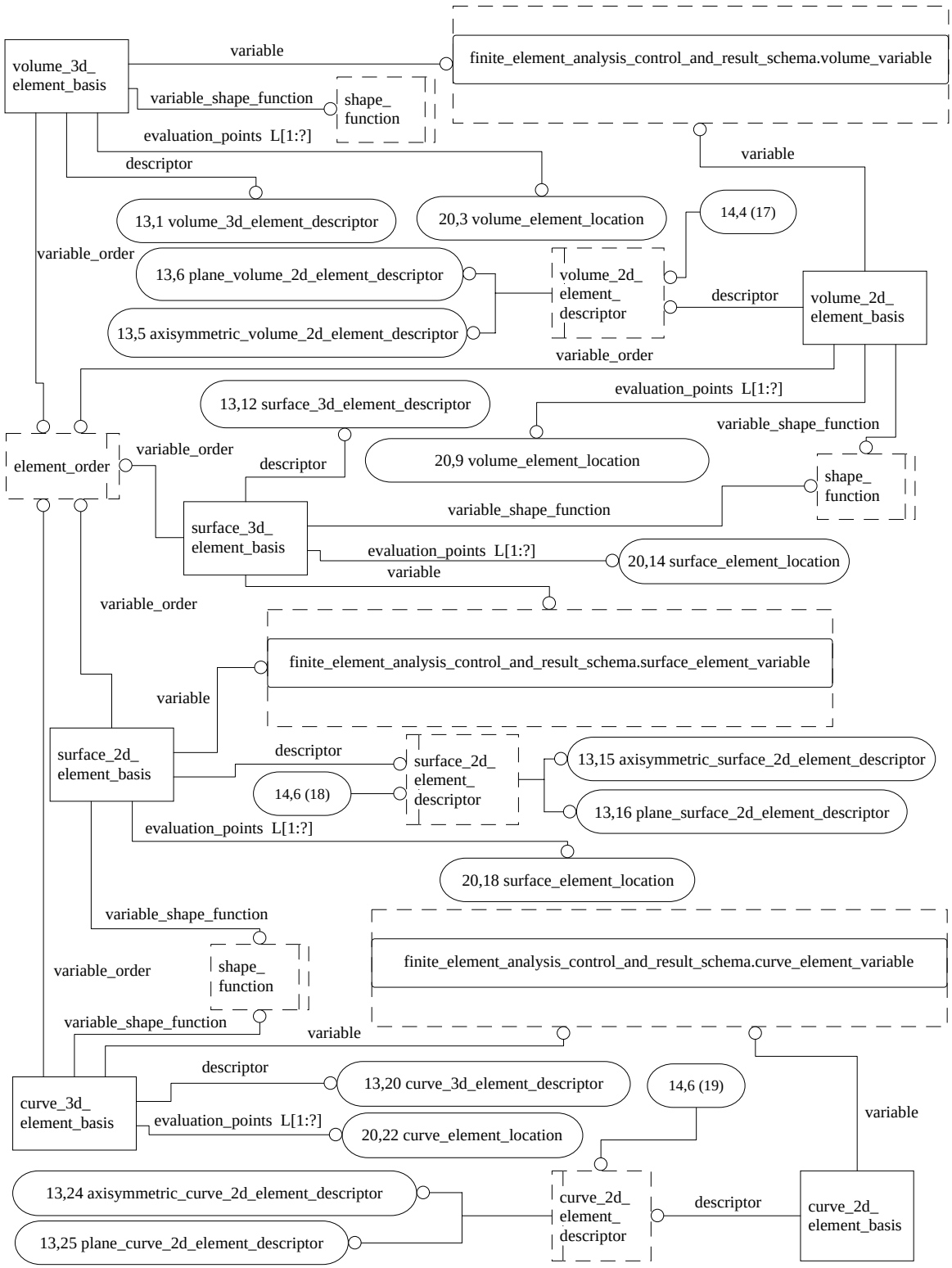

Figure D.14 – Structural response representation schema EXPRESS-G diagram, 14 of 86.

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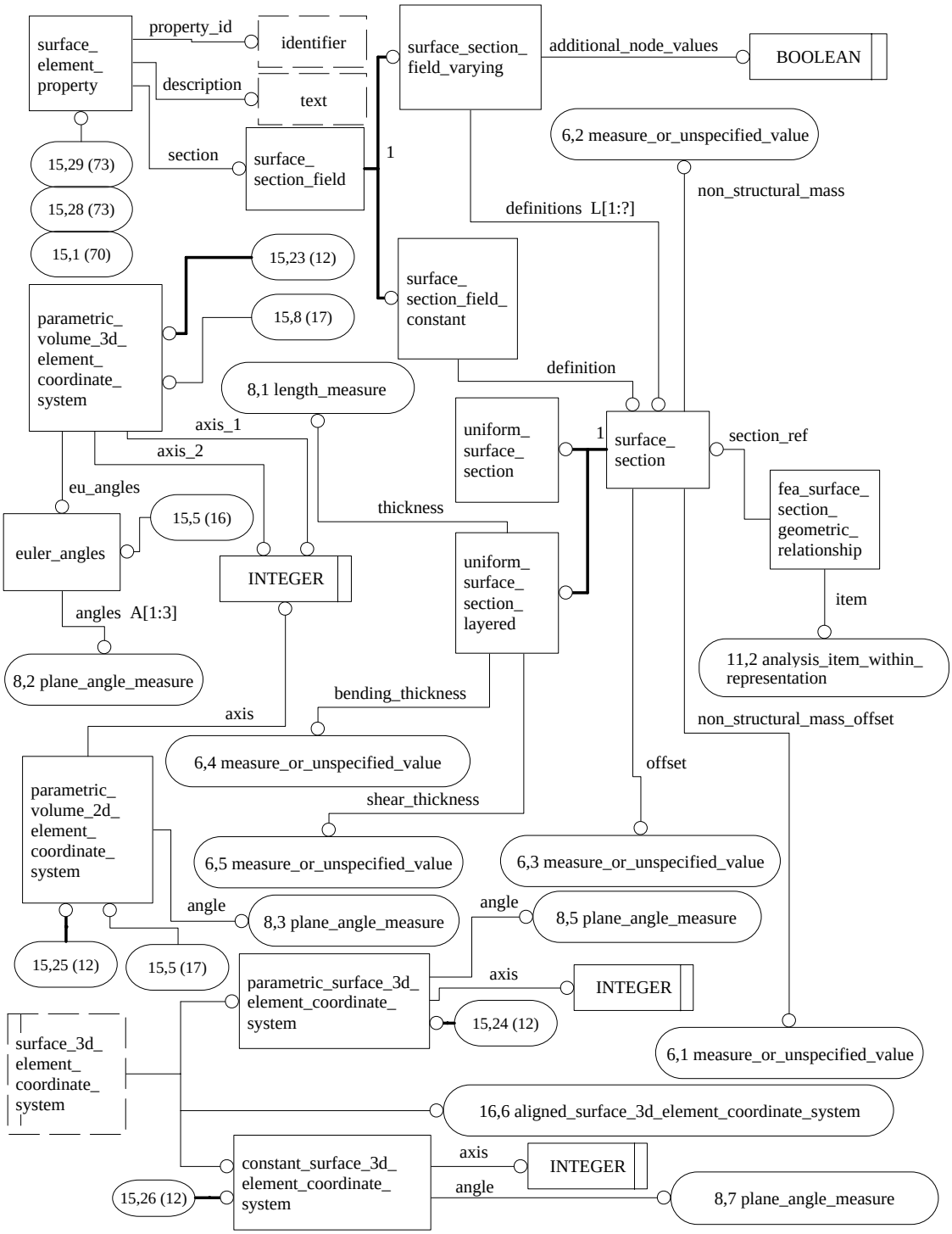

Figure D.15 – Structural response representation schema EXPRESS-G diagram, 15 of 86.

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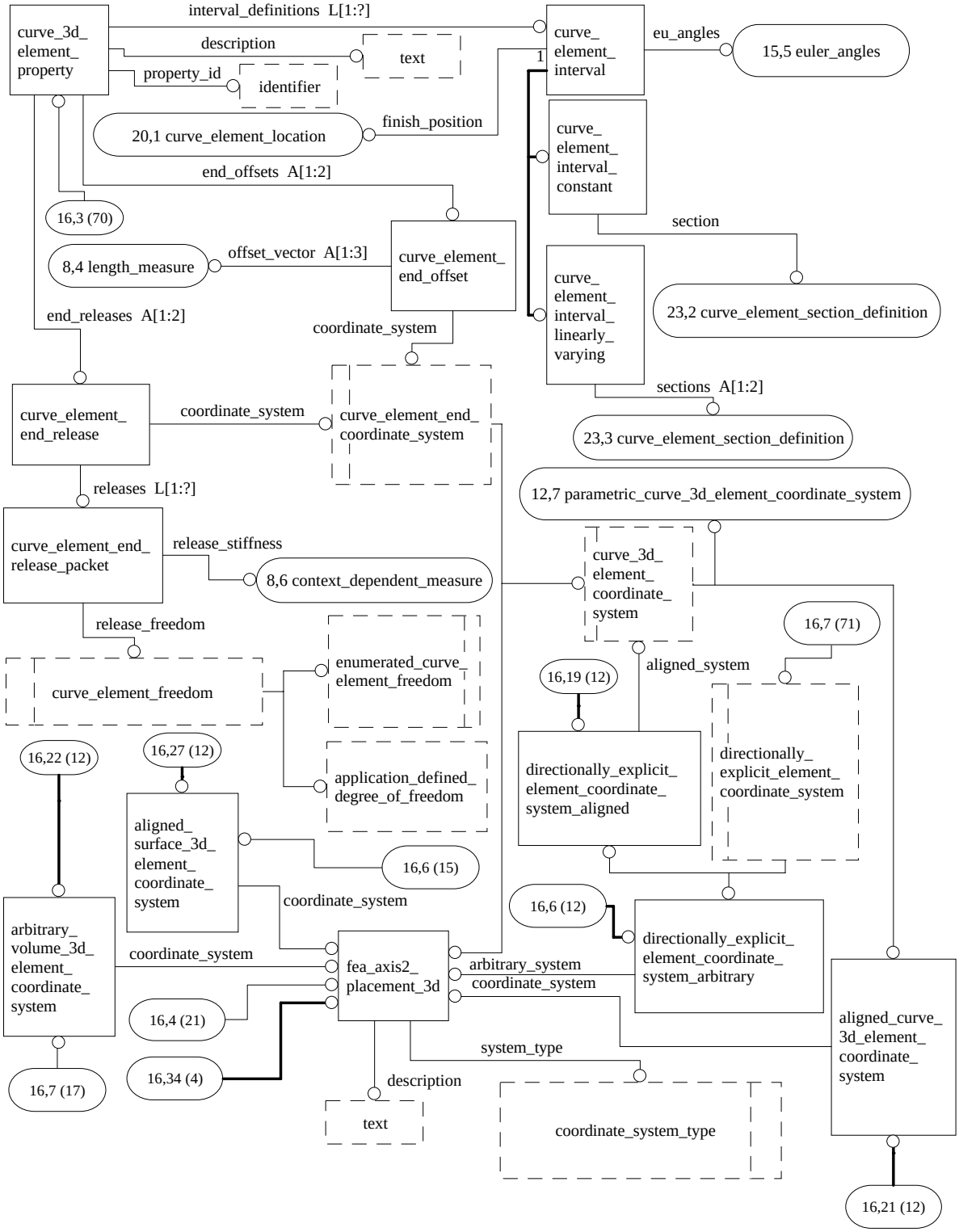

Figure D.16 – Structural response representation schema EXPRESS-G diagram, 16 of 86.

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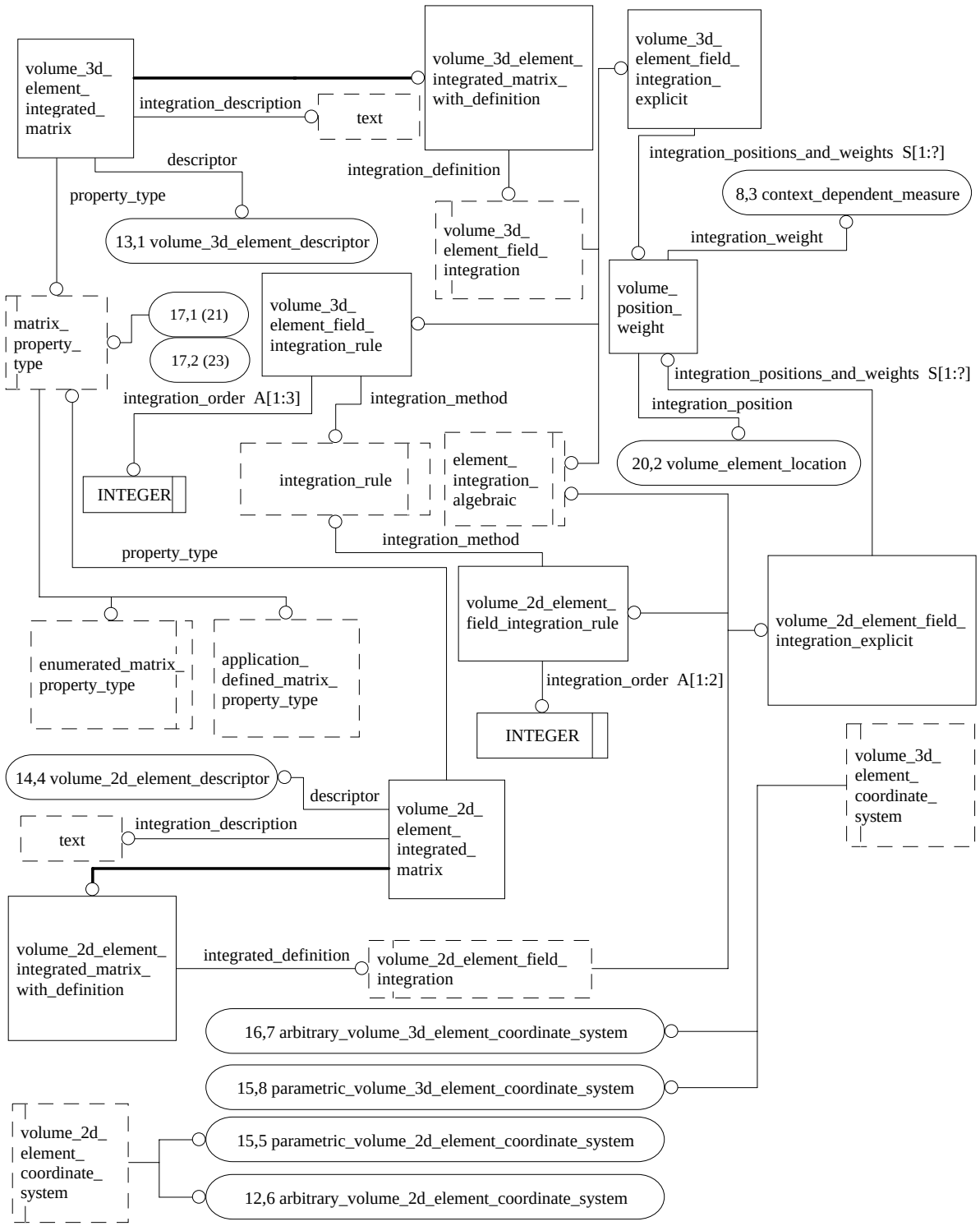

Figure D.17 – Structural response representation schema EXPRESS-G diagram, 17 of 86.

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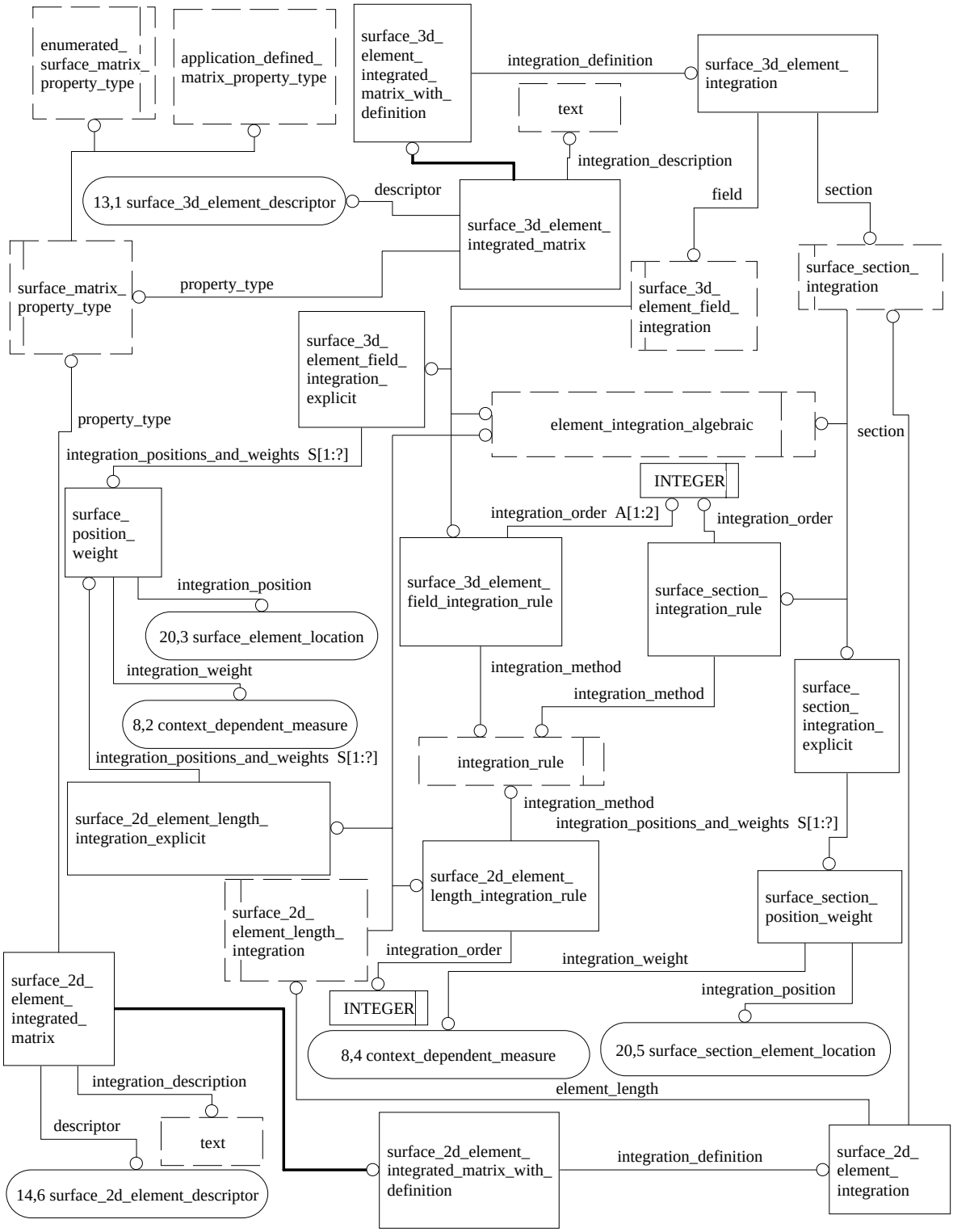

Figure D.18 – Structural response representation schema EXPRESS-G diagram, 18 of 86.

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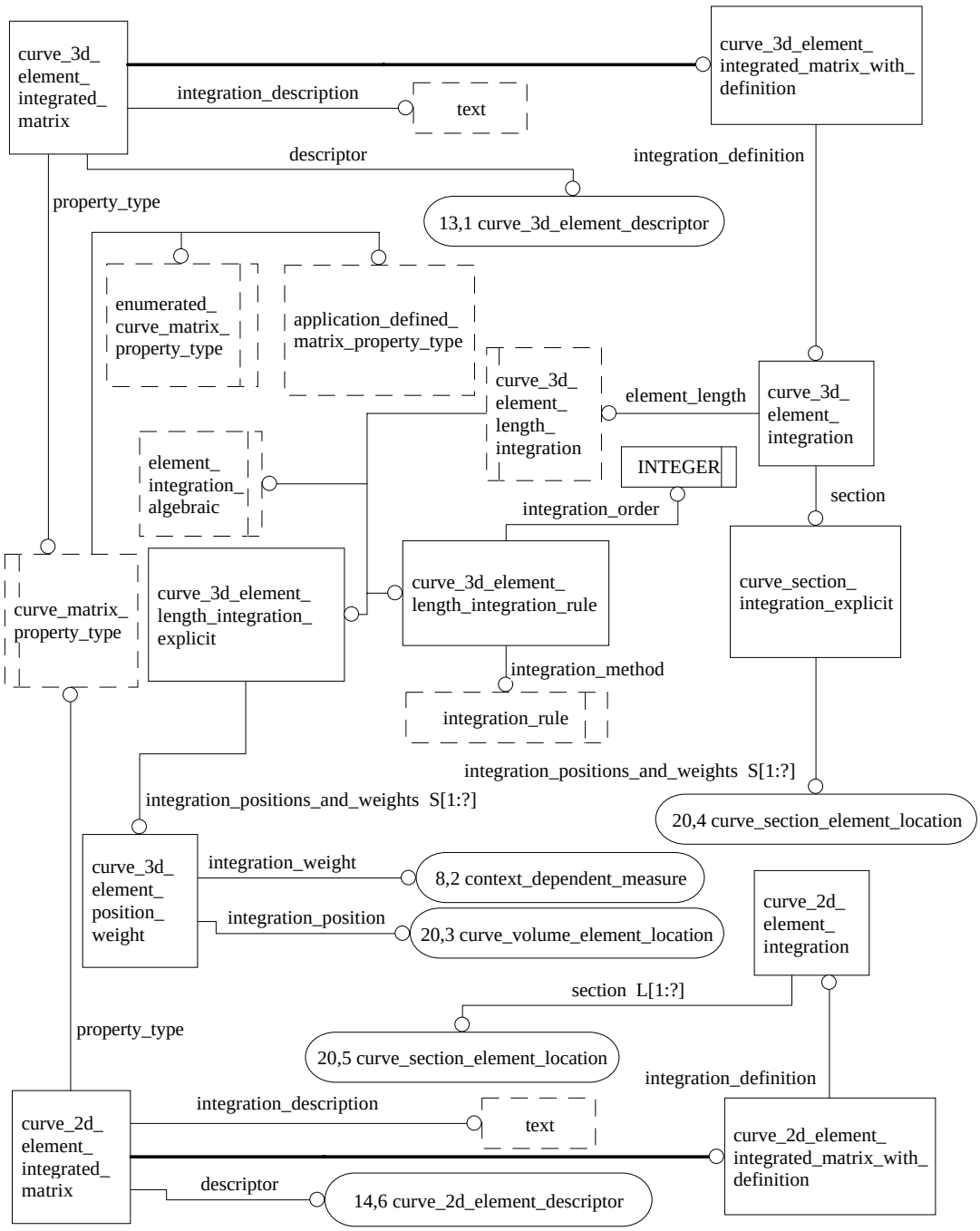

Figure D.19 – Structural response representation schema EXPRESS-G diagram, 19 of 86.

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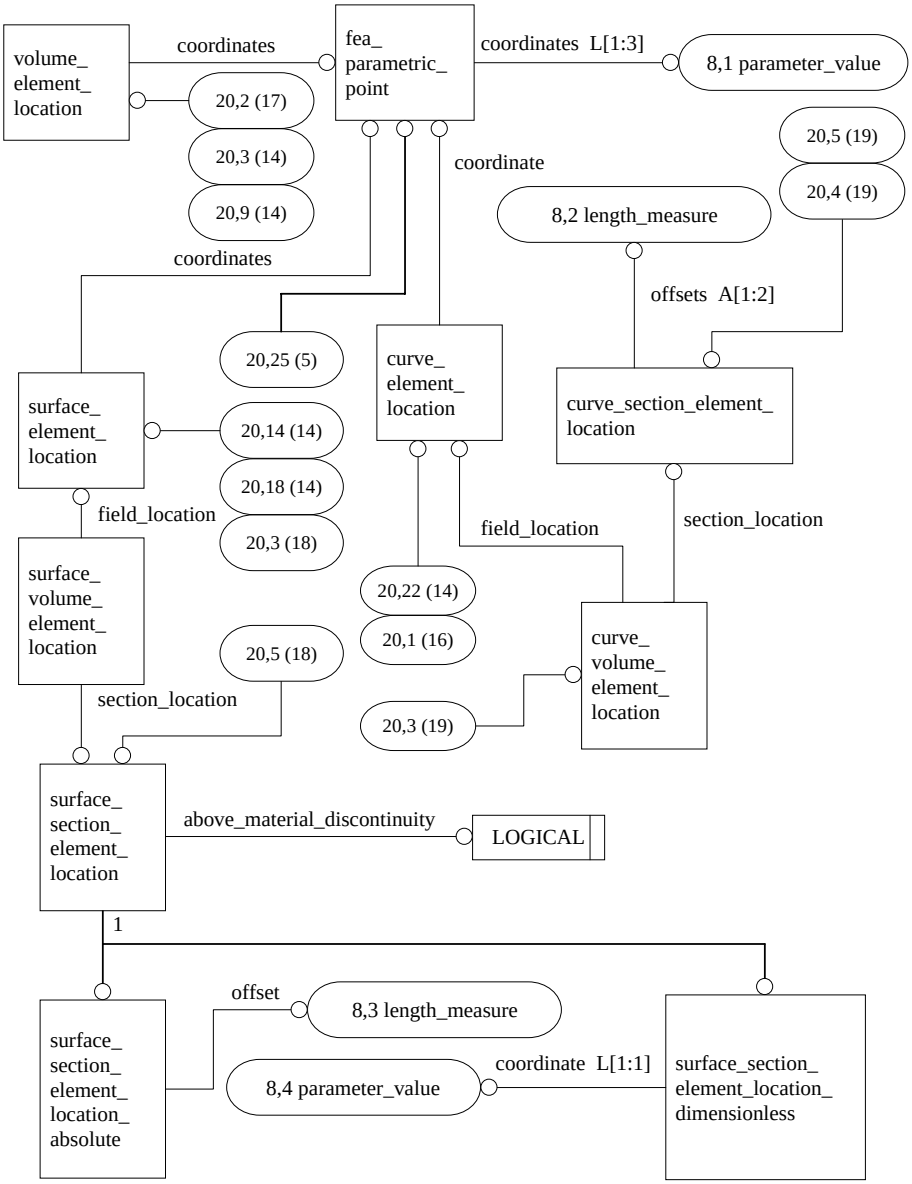

Figure D.20 – Structural response representation schema EXPRESS-G diagram, 20 of 86.

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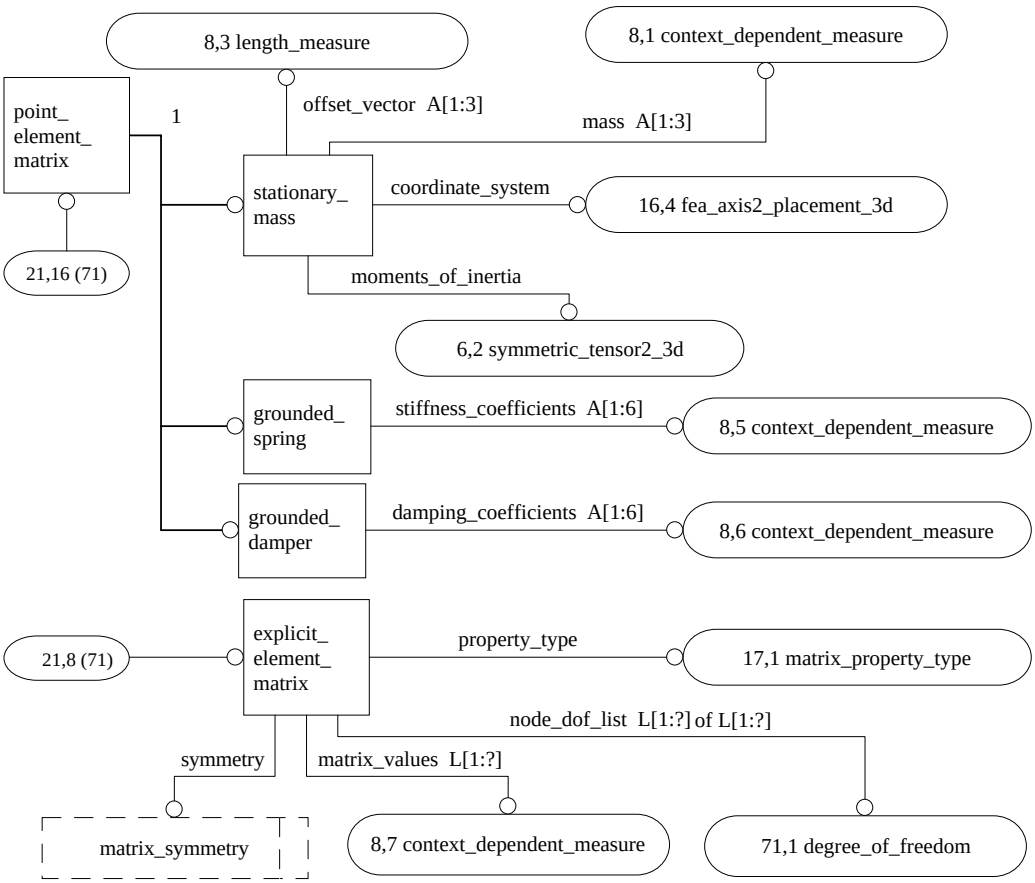

Figure D.21 – Structural response representation schema EXPRESS-G diagram, 21 of 86.

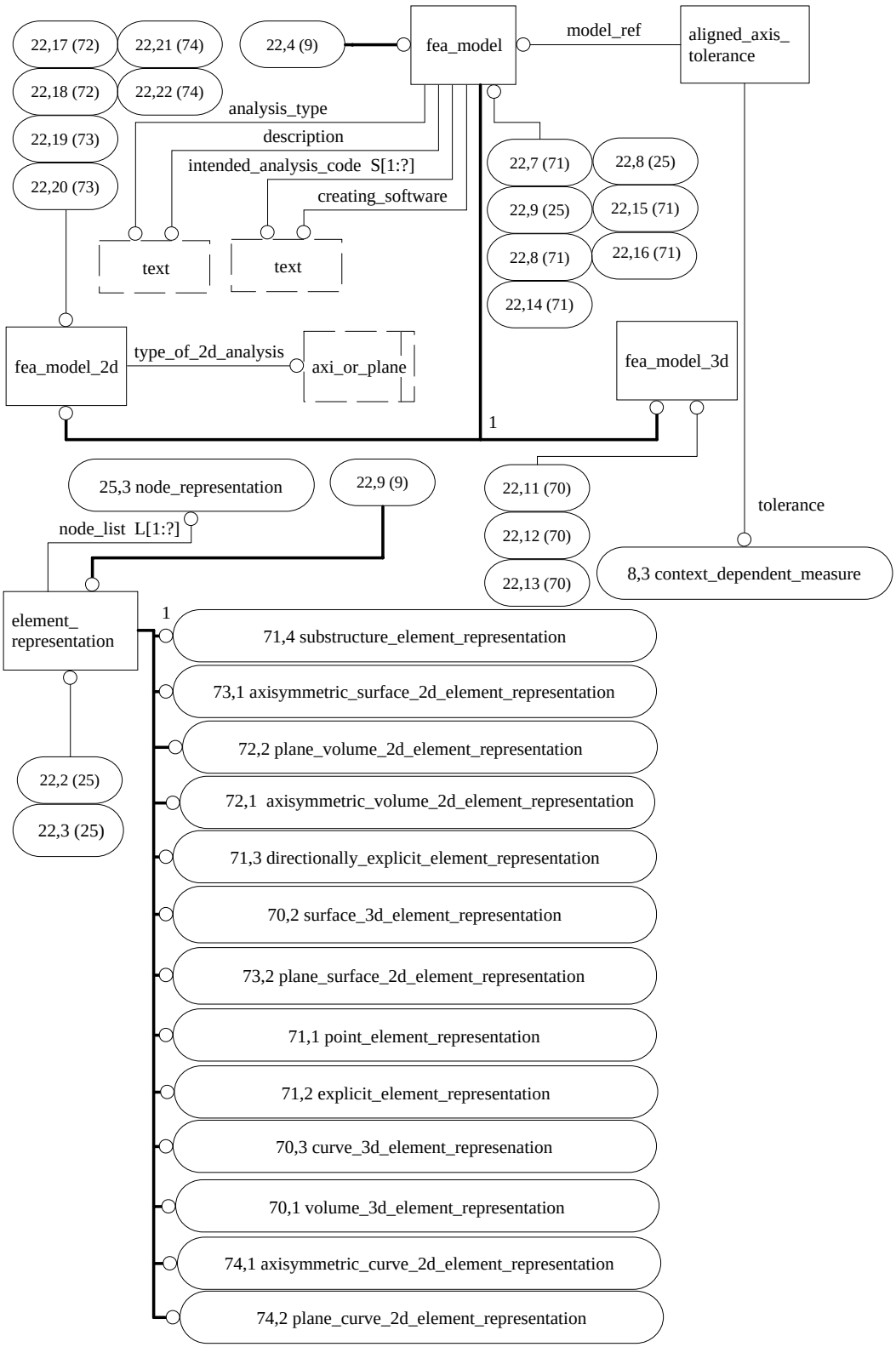

Figure D.22 – Structural response representation schema EXPRESS-G diagram, 22 of 86.

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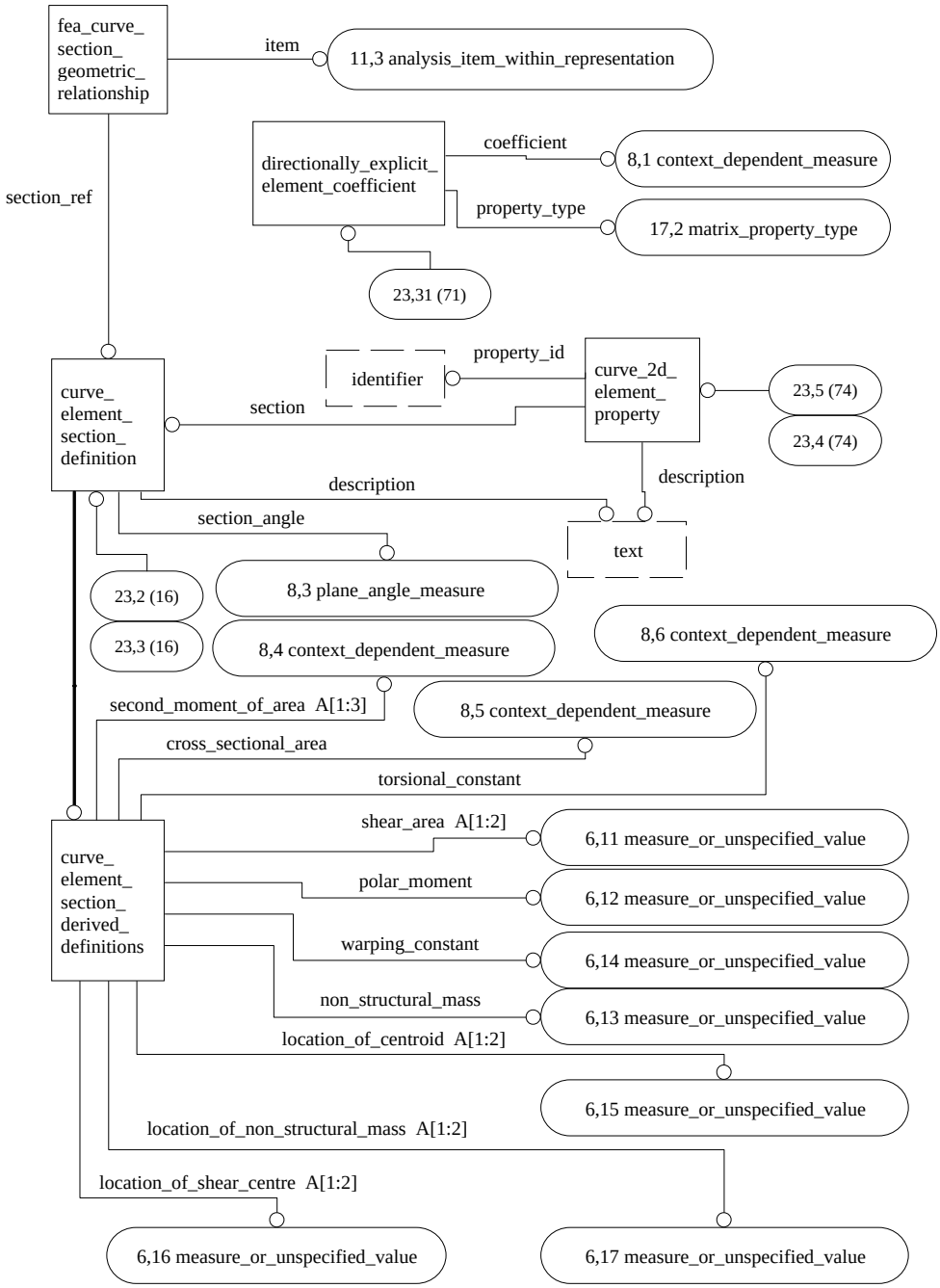

Figure D.23 – Structural response representation schema EXPRESS-G diagram, 23 of 86.

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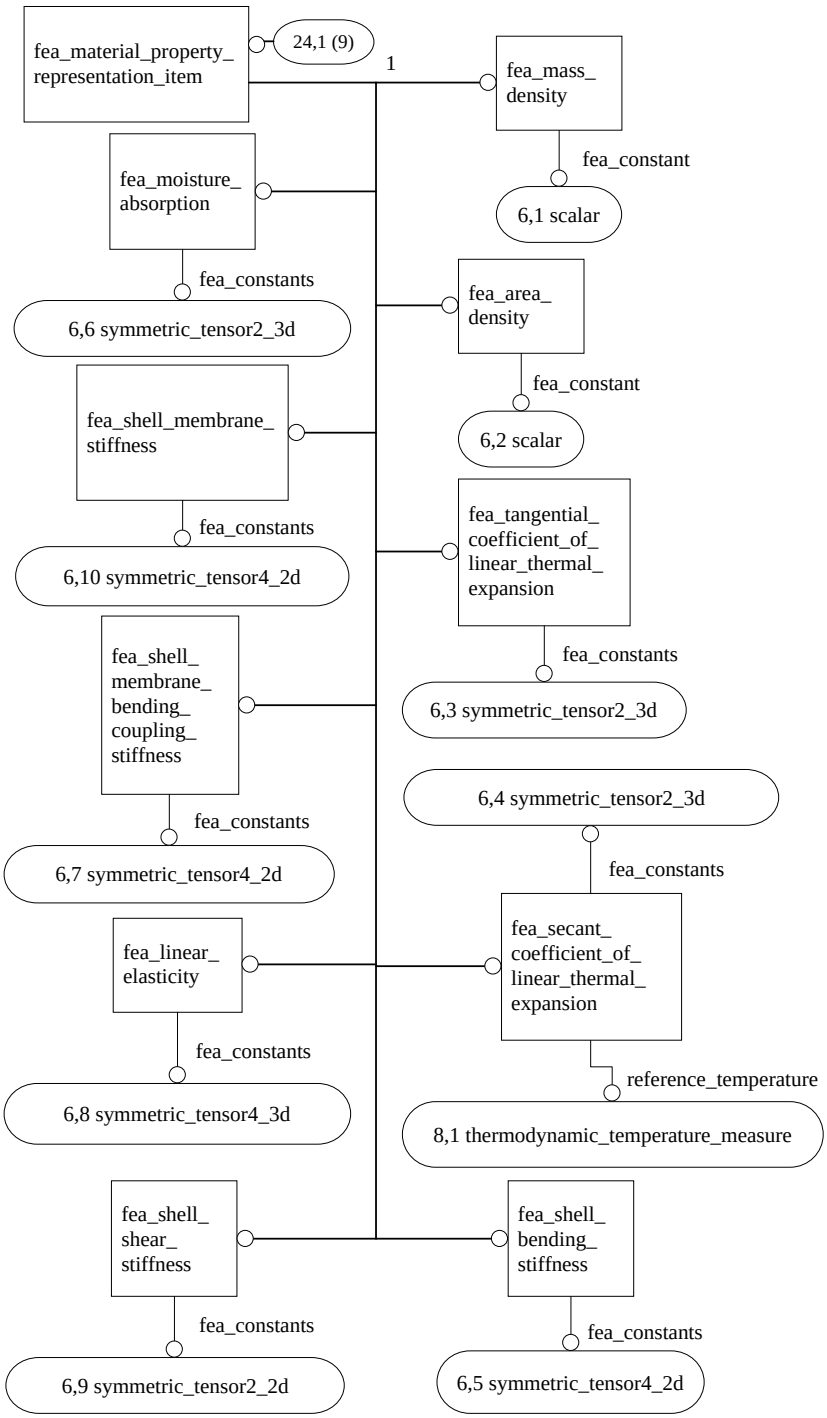

Figure D.24 – Structural response representation schema EXPRESS-G diagram, 24 of 86.

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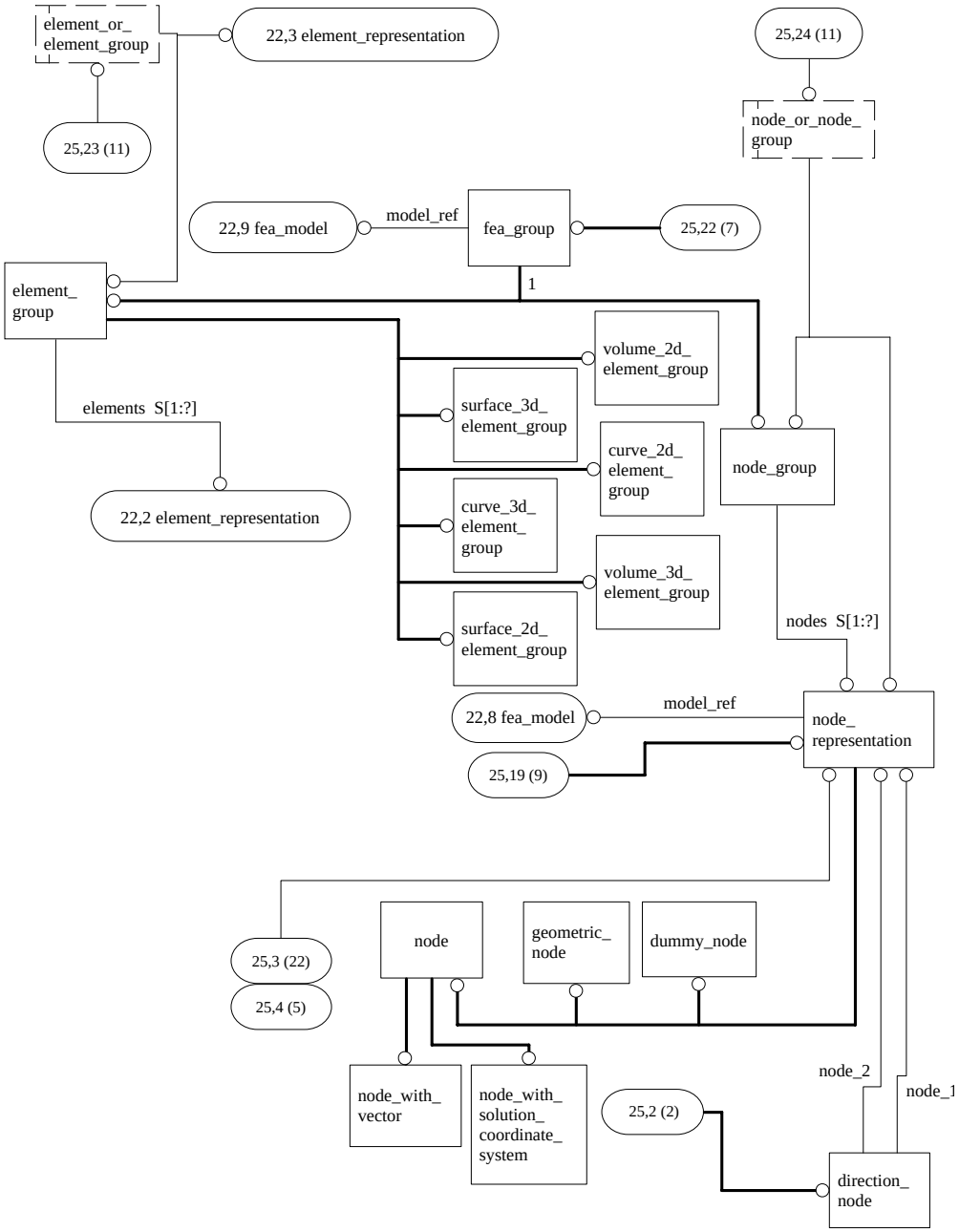

Figure D.25 – Structural response representation schema EXPRESS-G diagram, 25 of 86.

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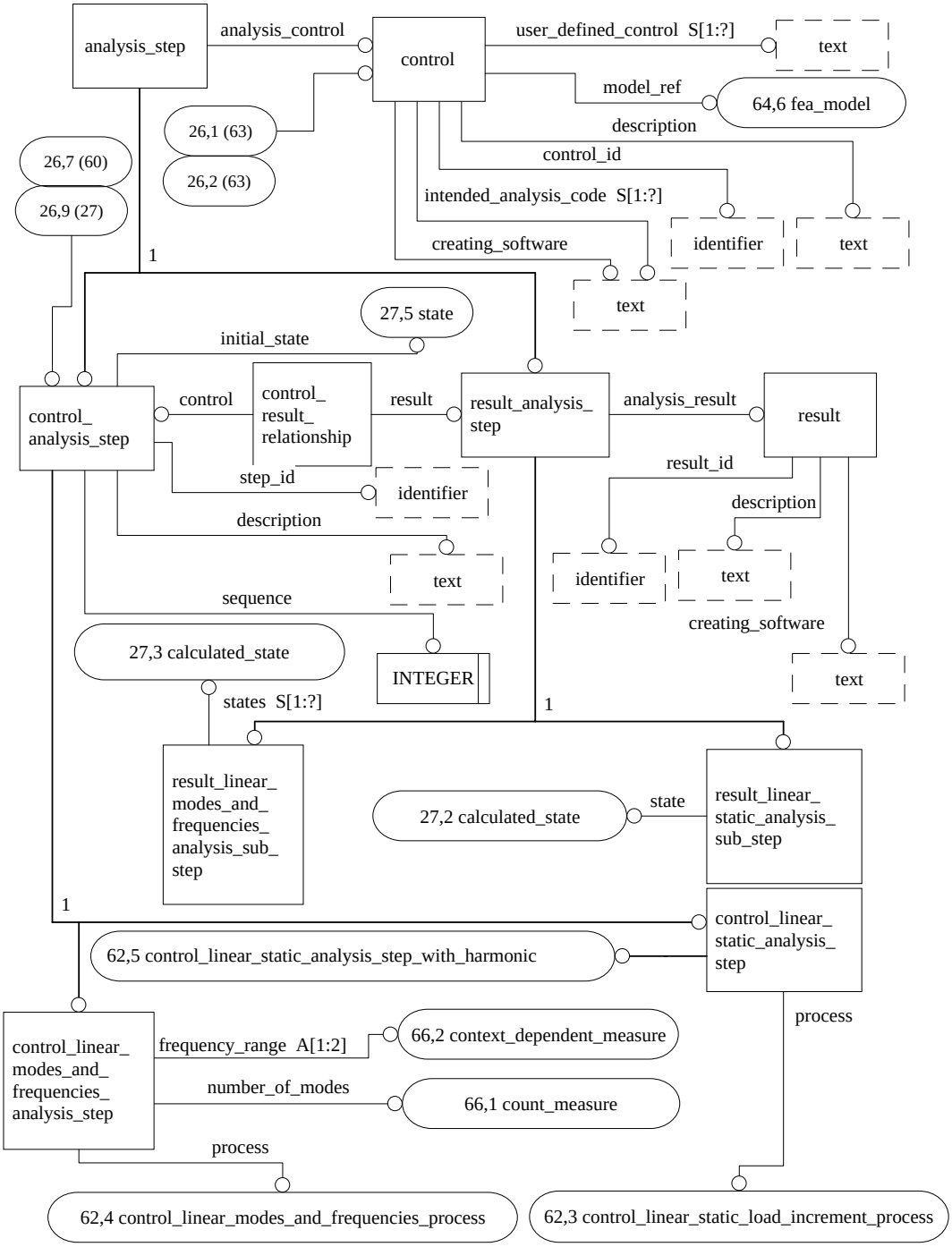

Figure D.26 – Finite element analysis control and result schema EXPRESS-G diagram, 26 of 86.

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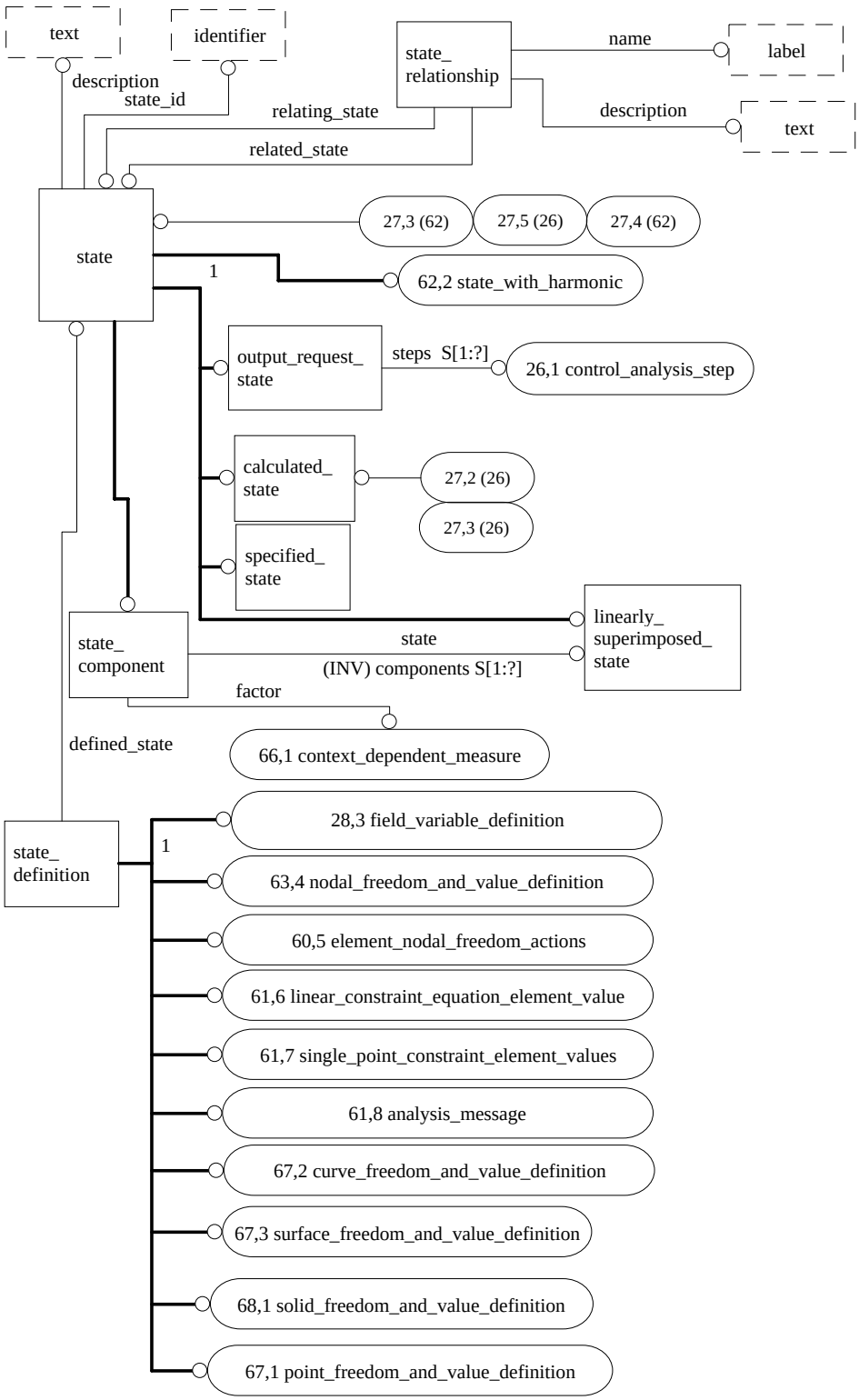

Figure D.27 – Finite element analysis control and result schema EXPRESS-G diagram, 27 of 86.

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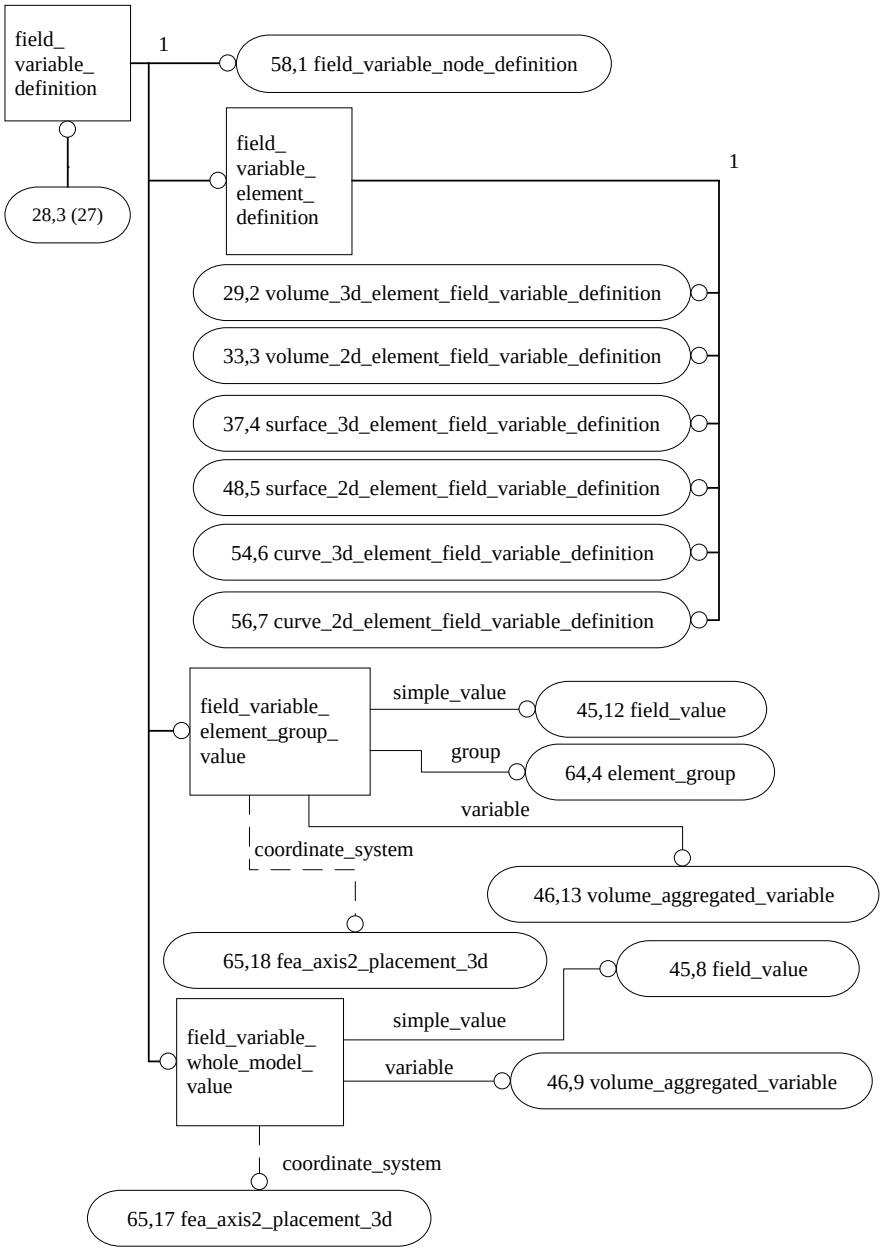

Figure D.28 – Finite element analysis control and result schema EXPRESS-G diagram, 28 of 86.

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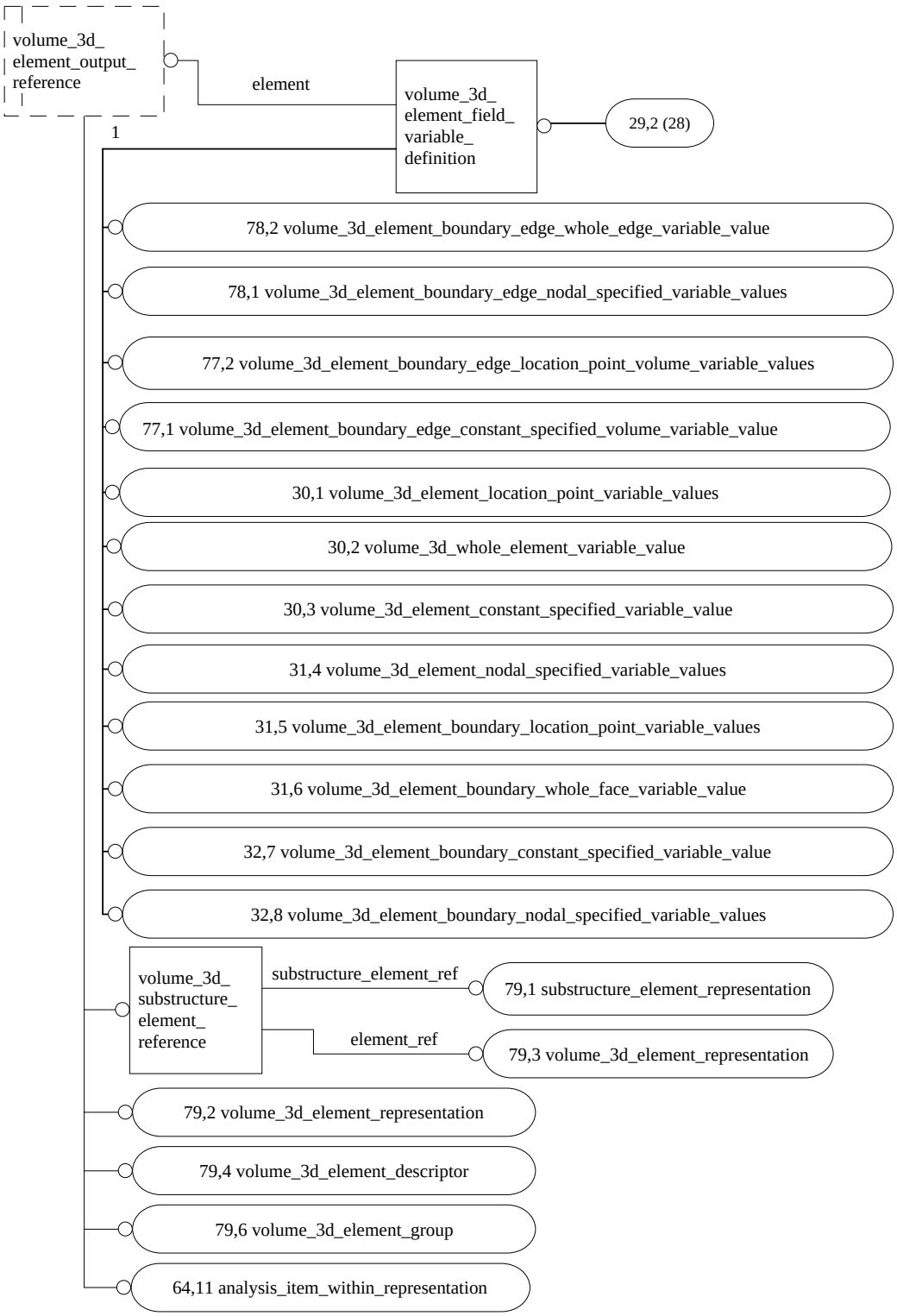

Figure D.29 – Finite element analysis control and result schema EXPRESS-G diagram, 29 of 86.

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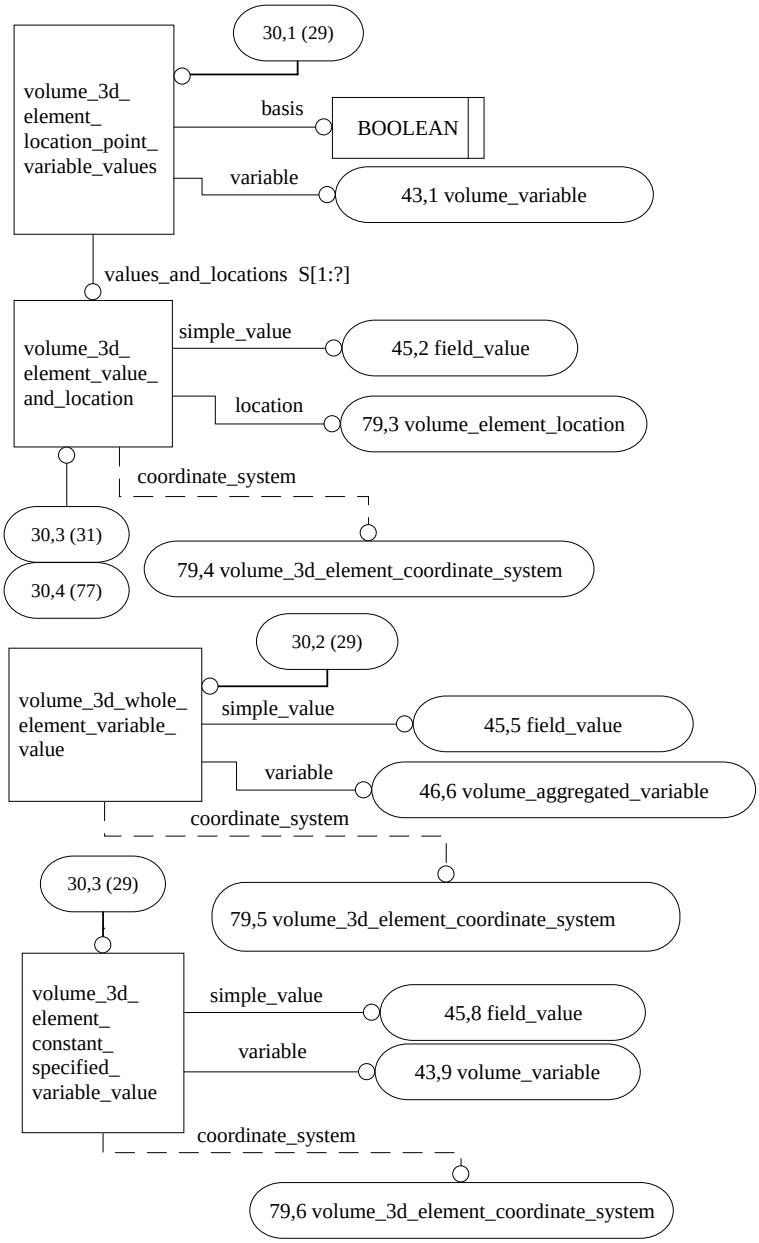

Figure D.30 – Finite element analysis control and result schema EXPRESS-G diagram, 30 of 86.

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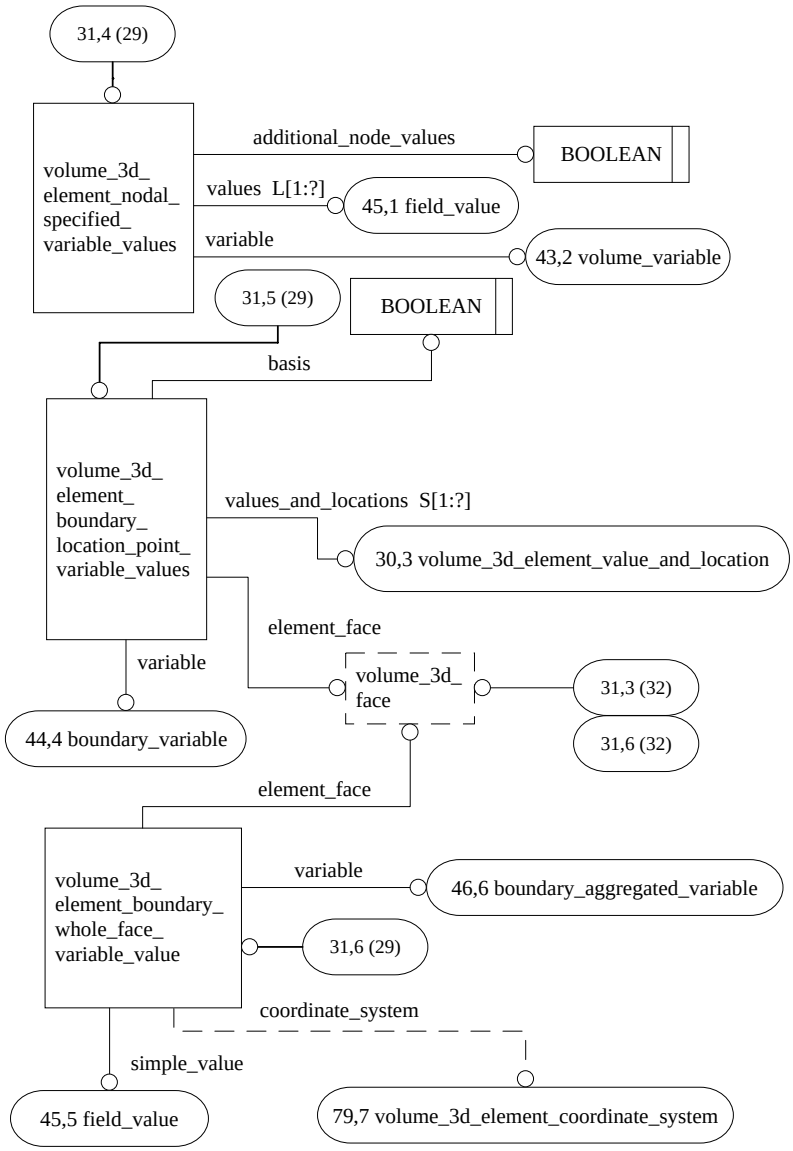

Figure D.31 – Finite element analysis control and result schema EXPRESS-G diagram, 31 of 86.

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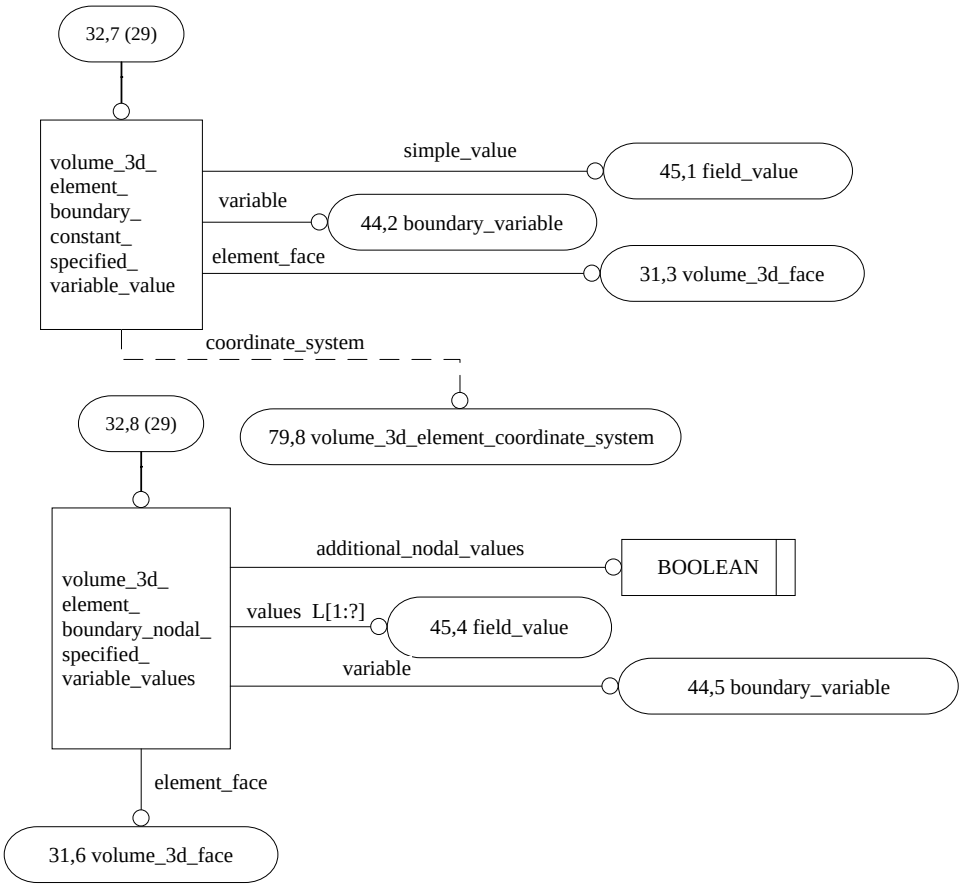

Figure D.32 – Finite element analysis control and result schema EXPRESS-G diagram, 32 of 86.

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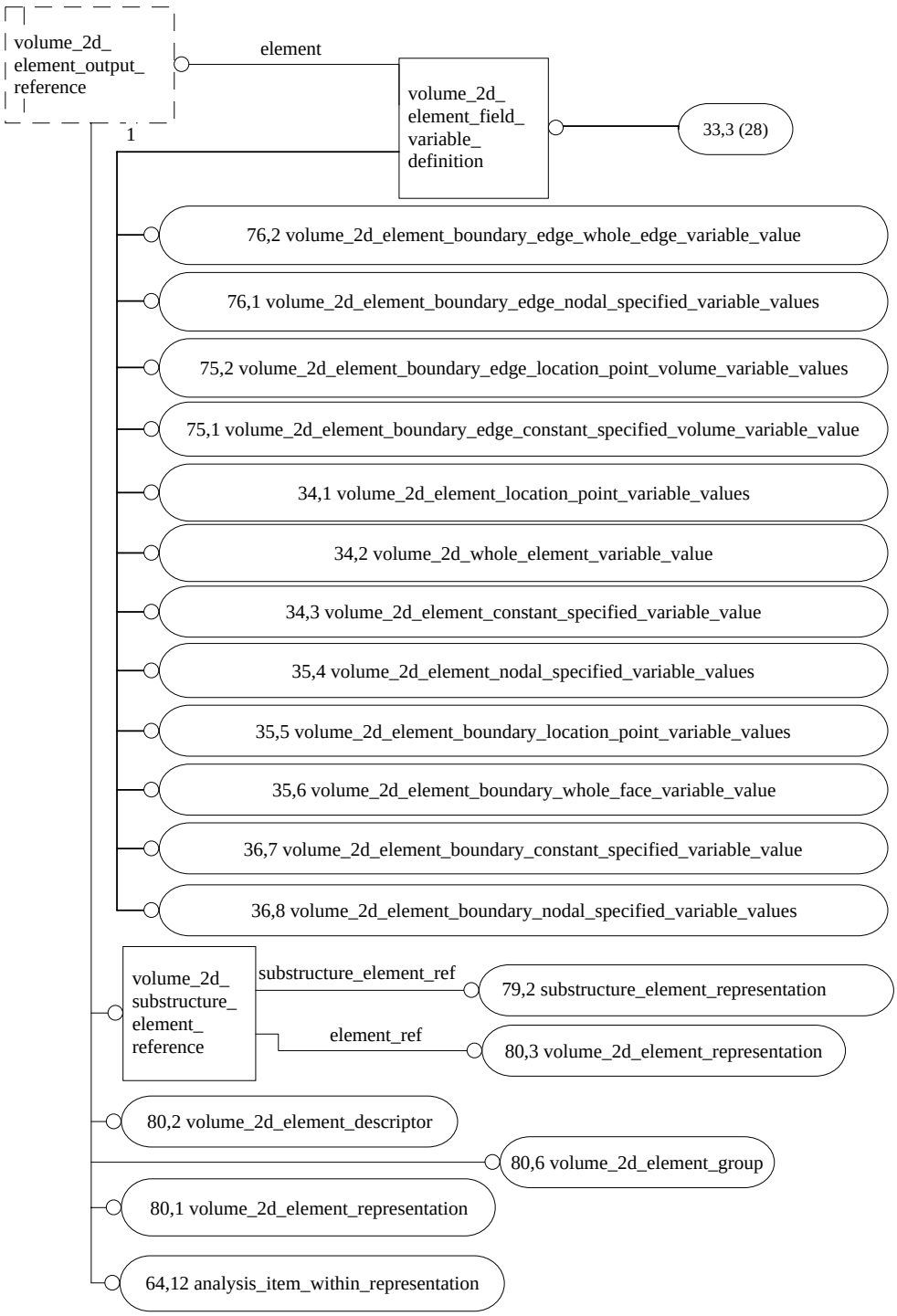

Figure D.33 – Finite element analysis control and result schema EXPRESS-G diagram, 33 of 86.

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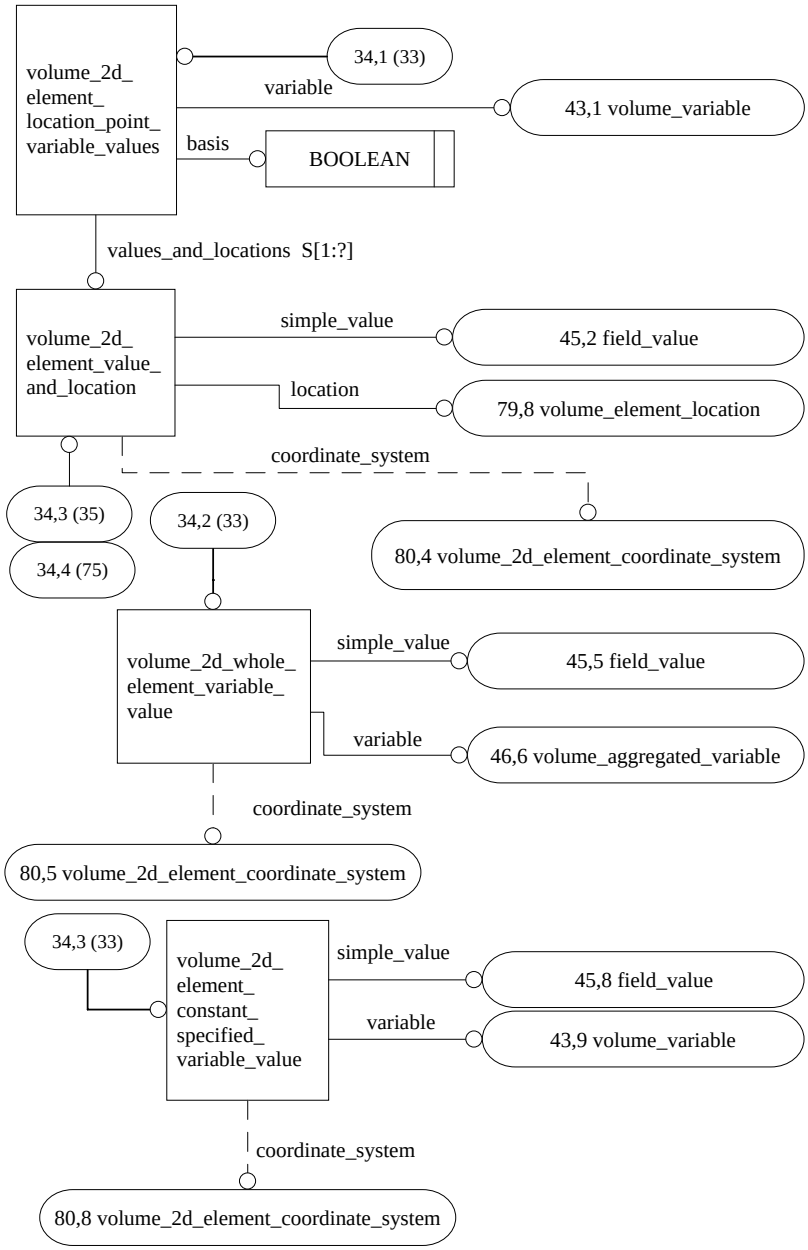

Figure D.34 – Finite element analysis control and result schema EXPRESS-G diagram, 34 of 86.

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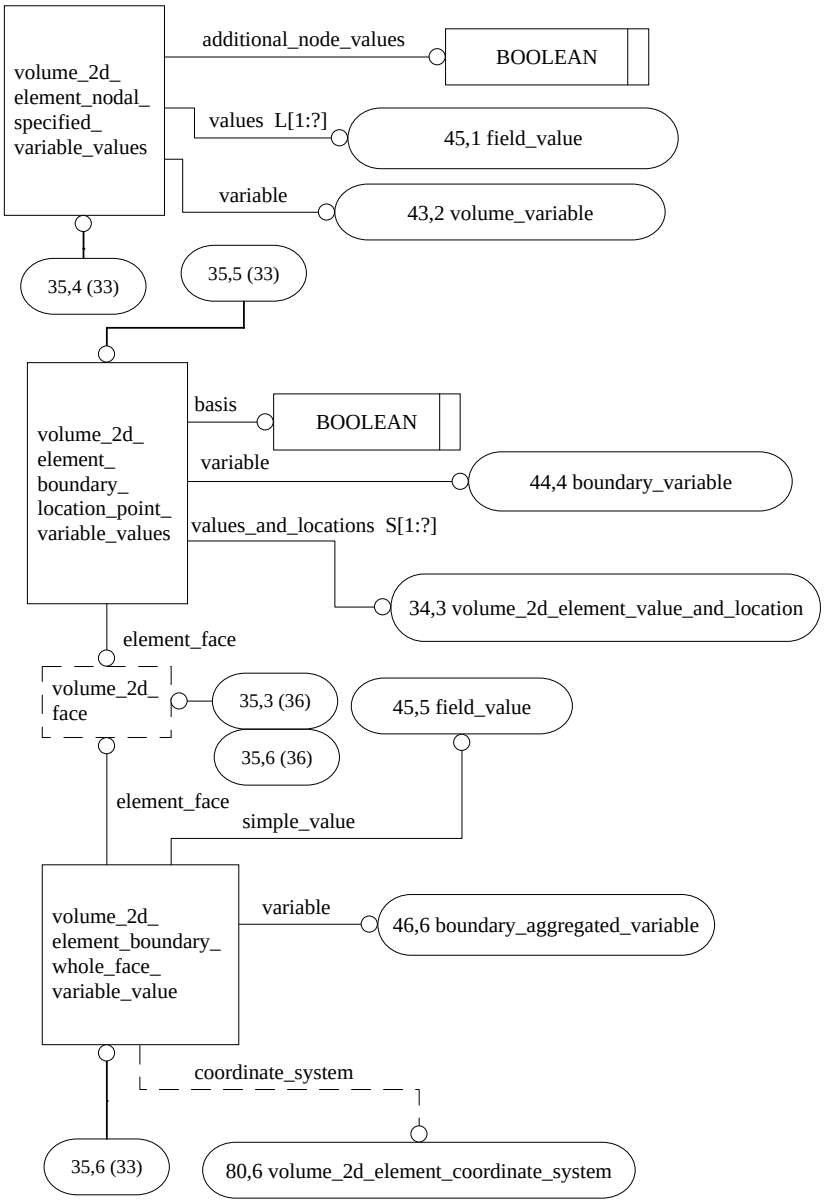

Figure D.35 – Finite element analysis control and result schema EXPRESS-G diagram, 35 of 86.

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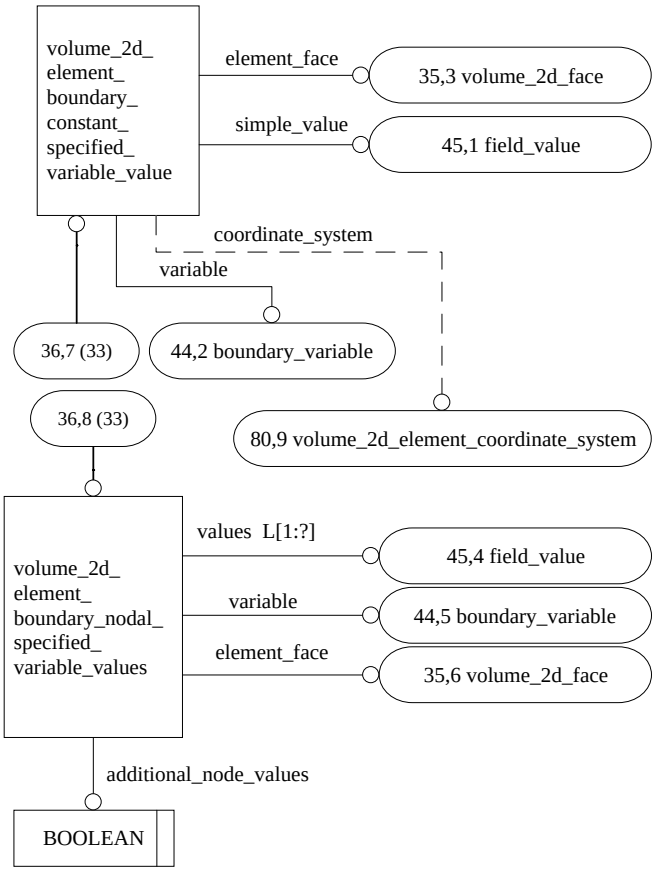

Figure D.36 – Finite element analysis control and result schema EXPRESS-G diagram, 36 of 86.

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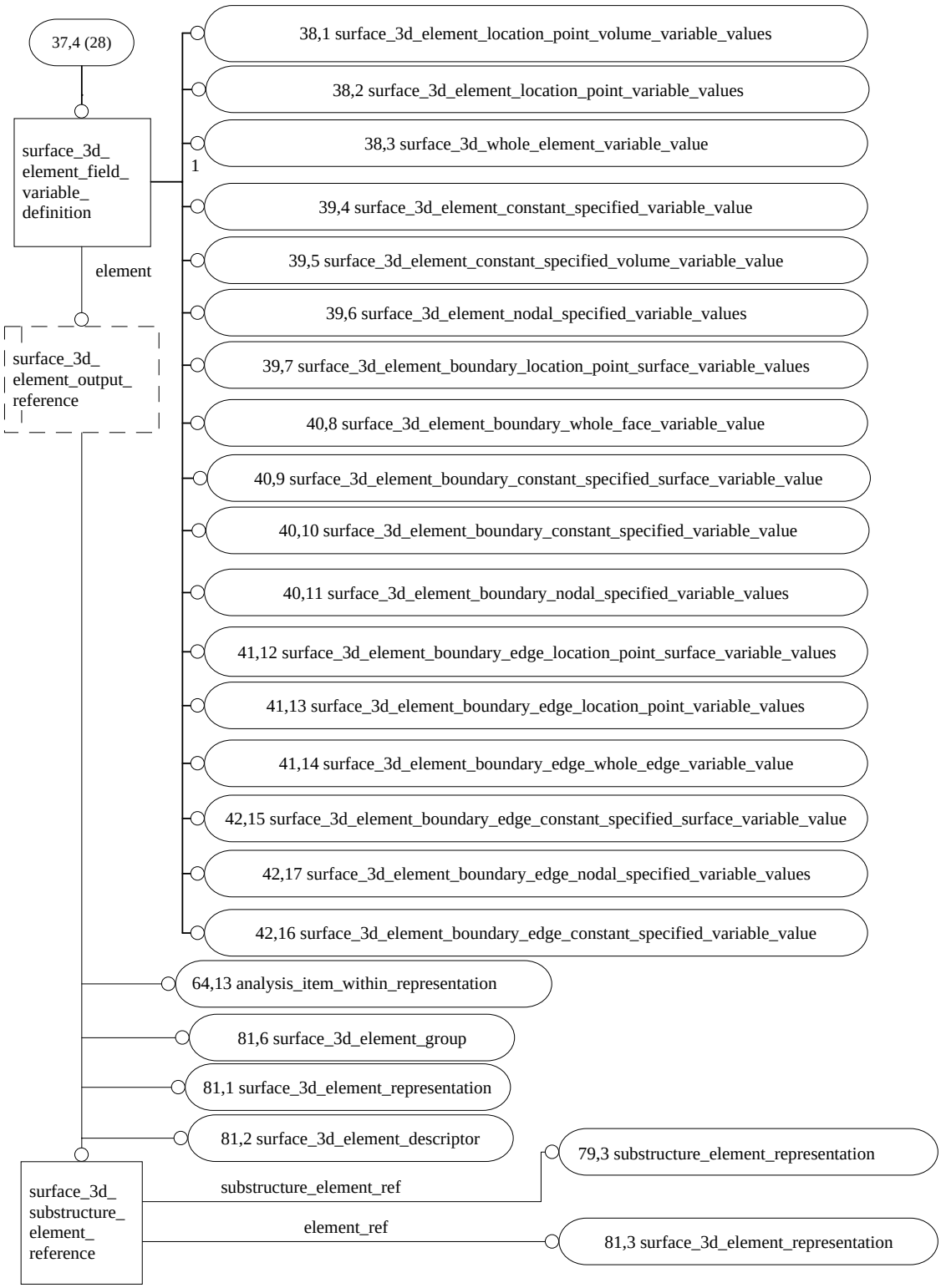

Figure D.37 – Finite element analysis control and result schema EXPRESS-G diagram, 37 of 86.

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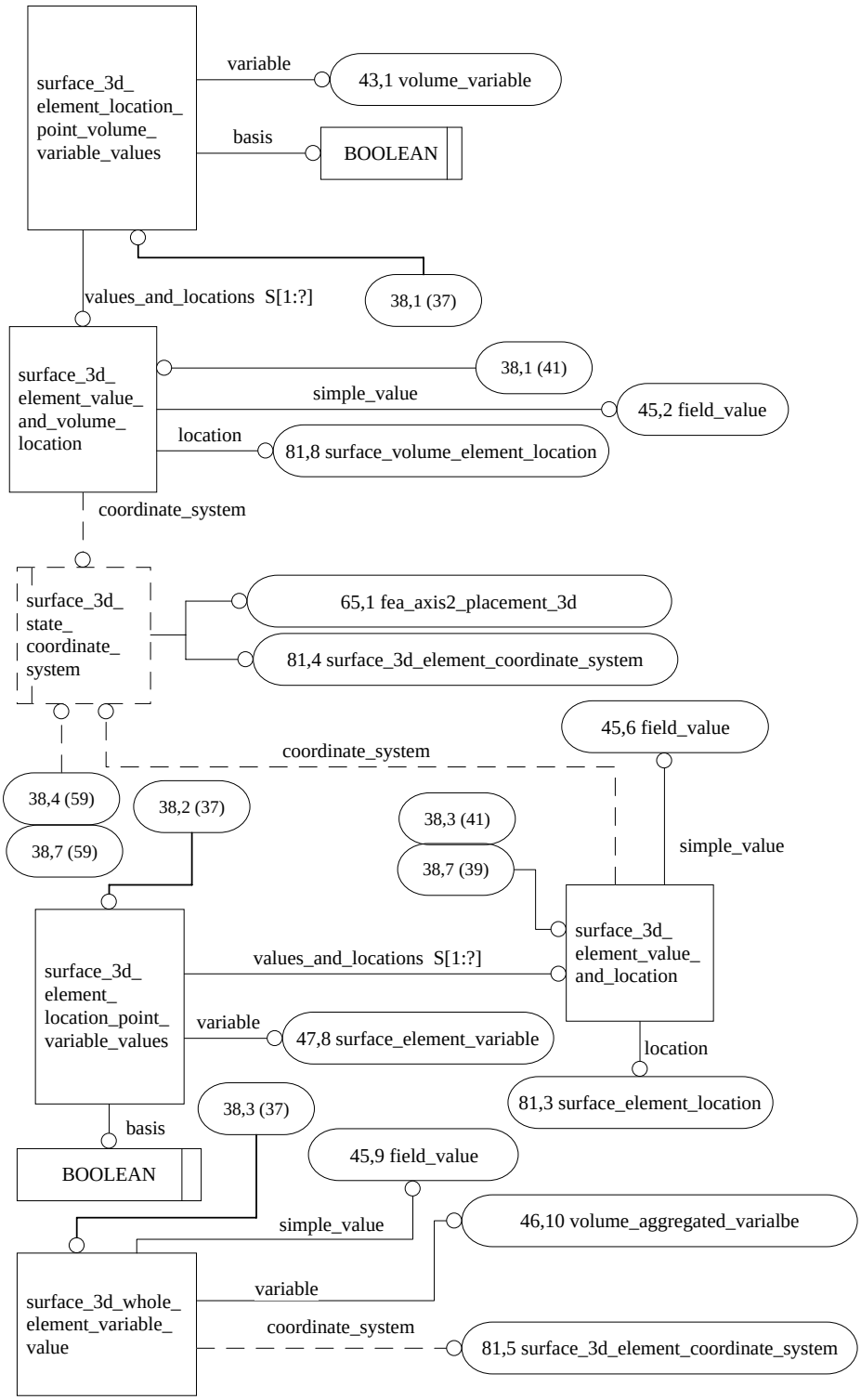

Figure D.38 – Finite element analysis control and result schema EXPRESS-G diagram, 38 of 86.

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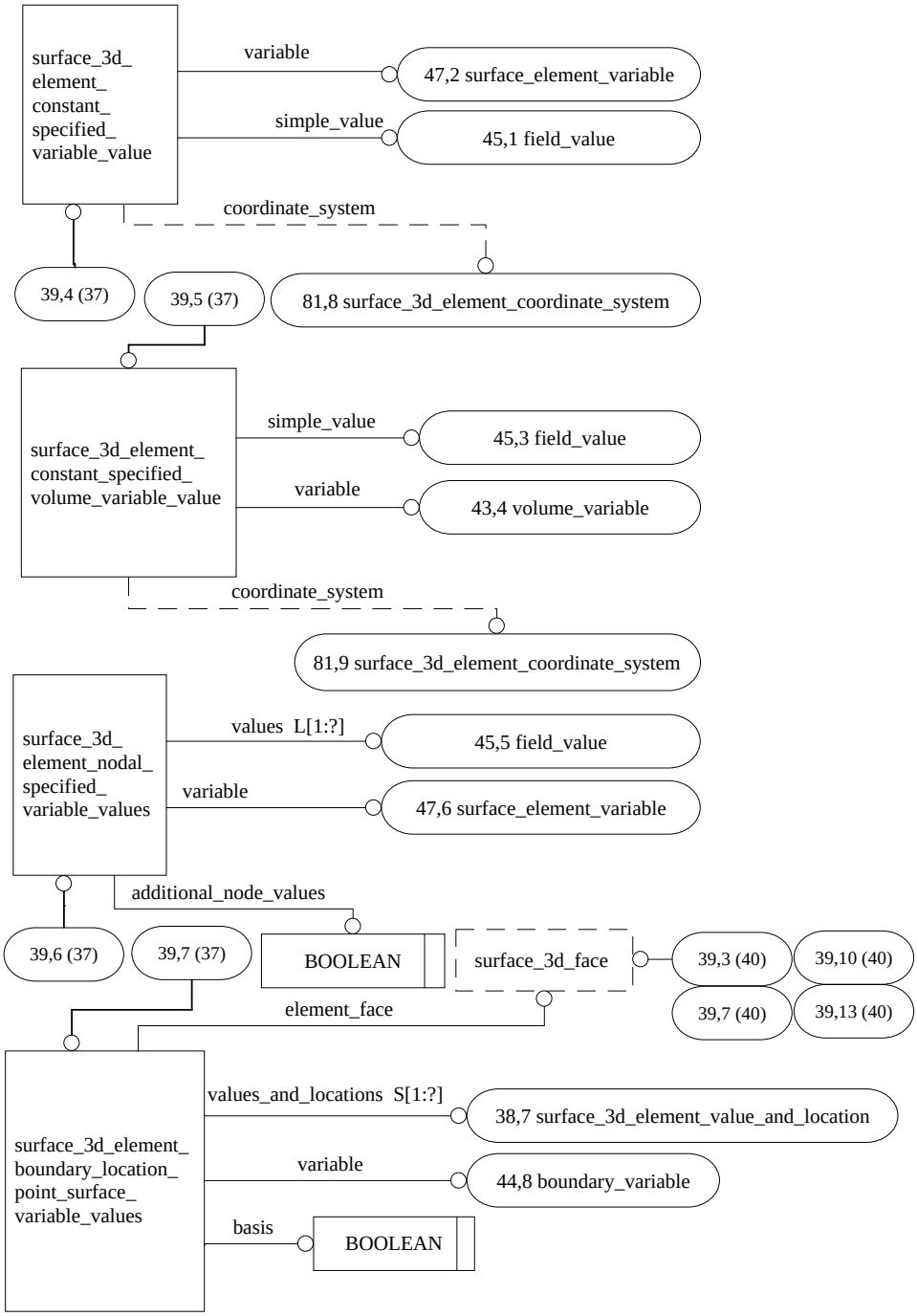

Figure D.39 – Finite element analysis control and result schema EXPRESS-G diagram, 39 of 86.

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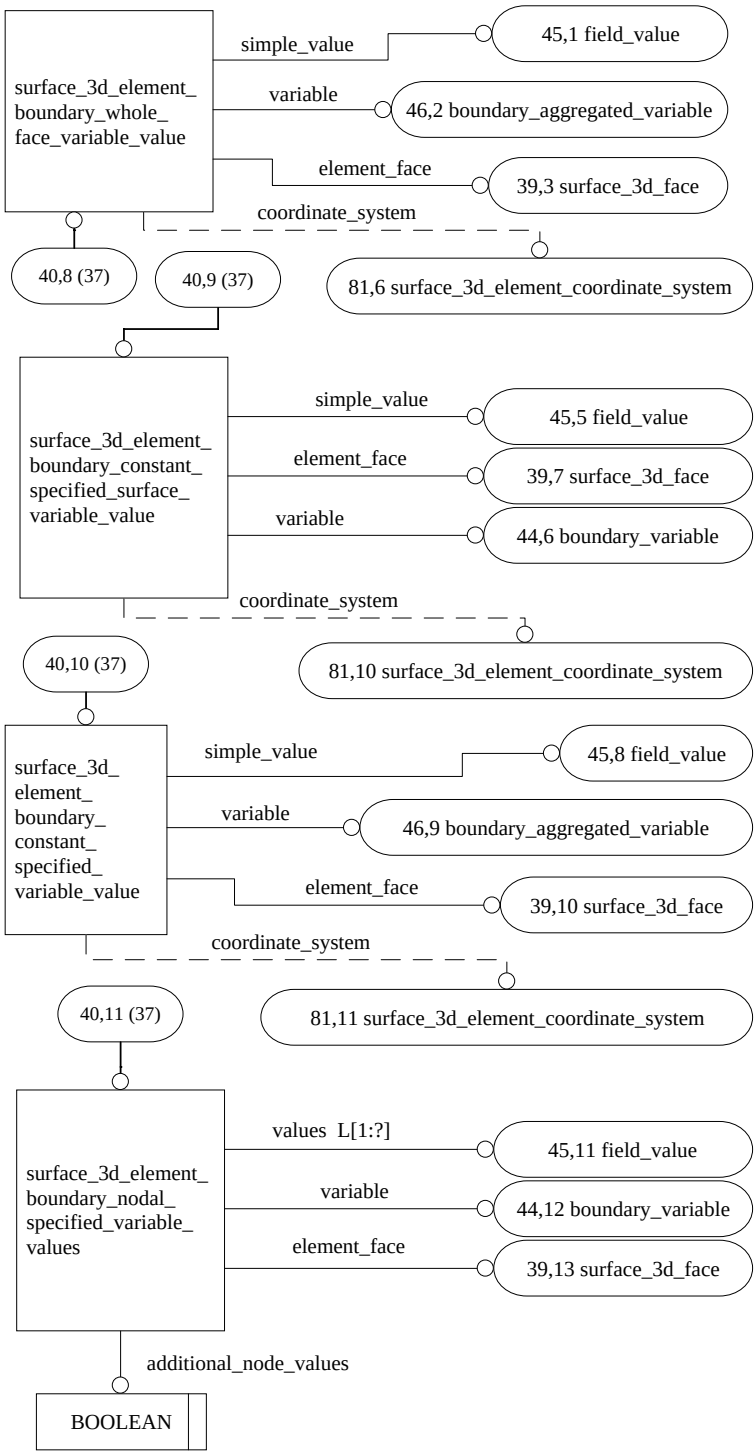

Figure D.40 – Finite element analysis control and result schema EXPRESS-G diagram, 40 of 86.

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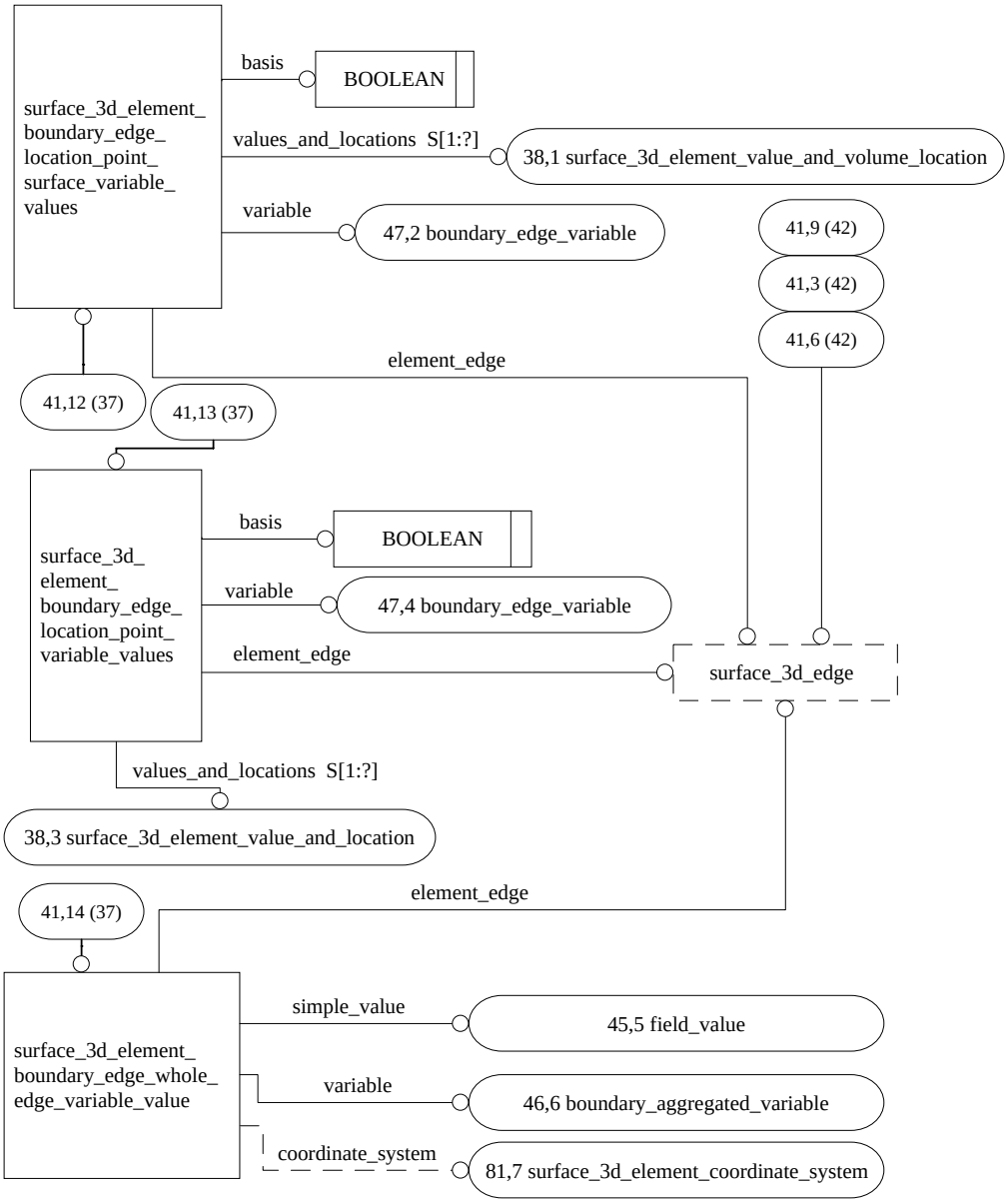

Figure D.41 – Finite element analysis control and result schema EXPRESS-G diagram, 41 of 86.

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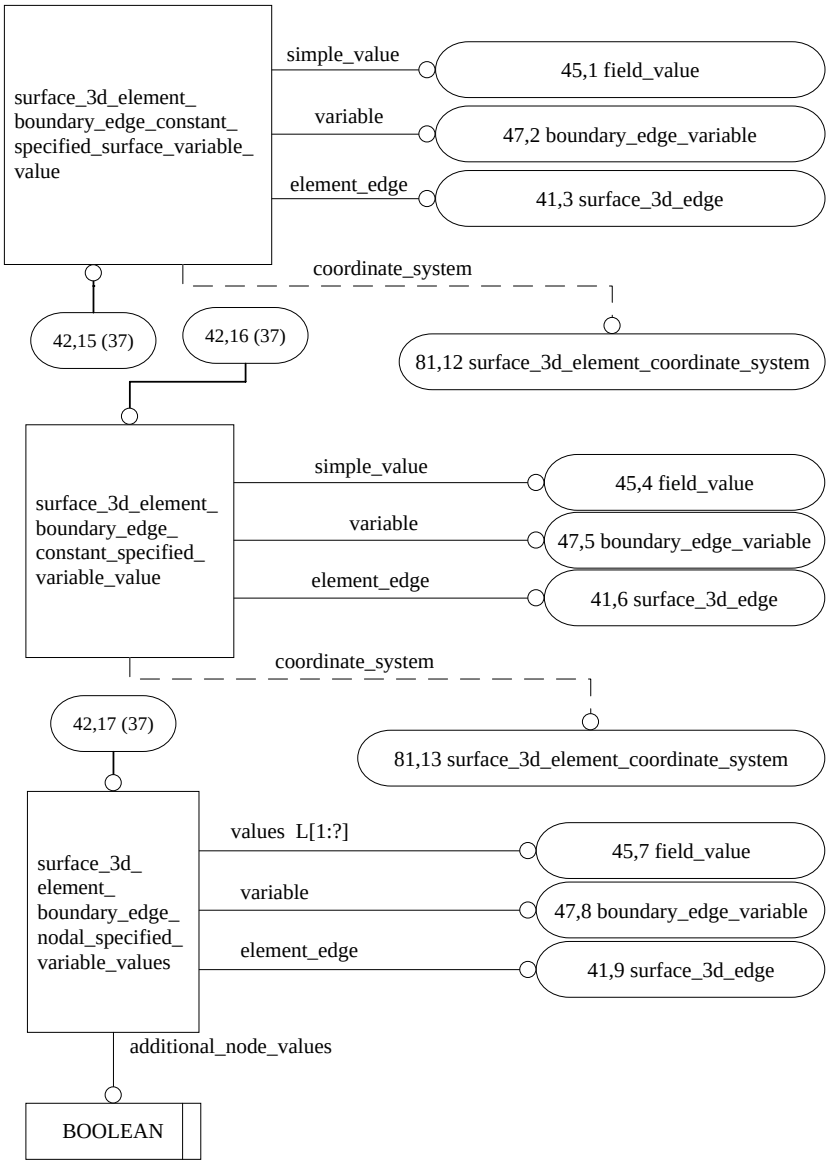

Figure D.42 – Finite element analysis control and result schema EXPRESS-G diagram, 42 of 86.

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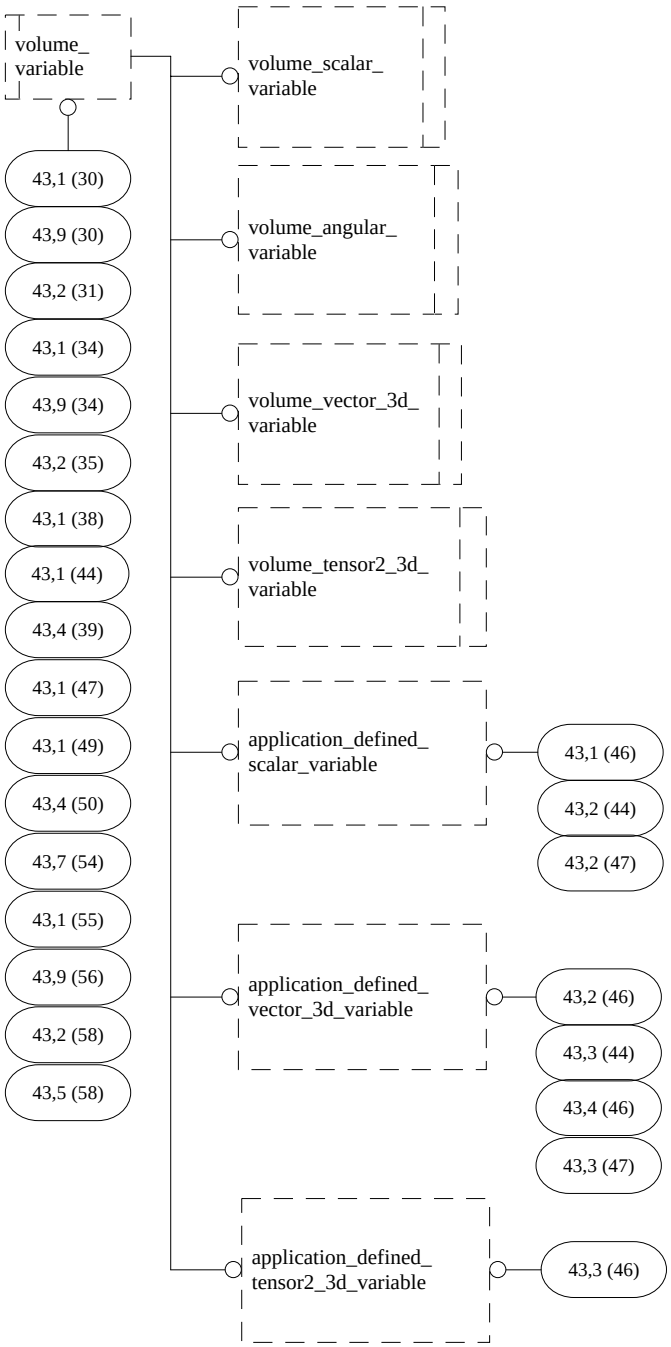

Figure D.43 – Finite element analysis control and result schema EXPRESS-G diagram, 43 of 86.

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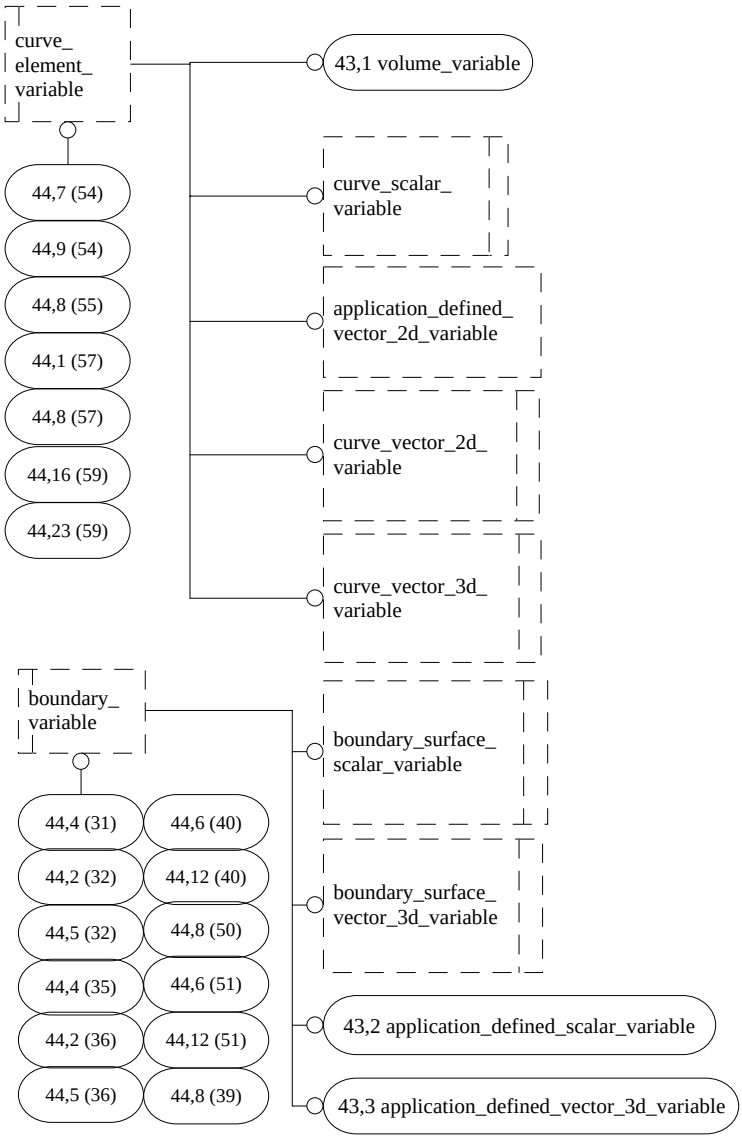

Figure D.44 – Finite element analysis control and result schema EXPRESS-G diagram, 44 of 86.

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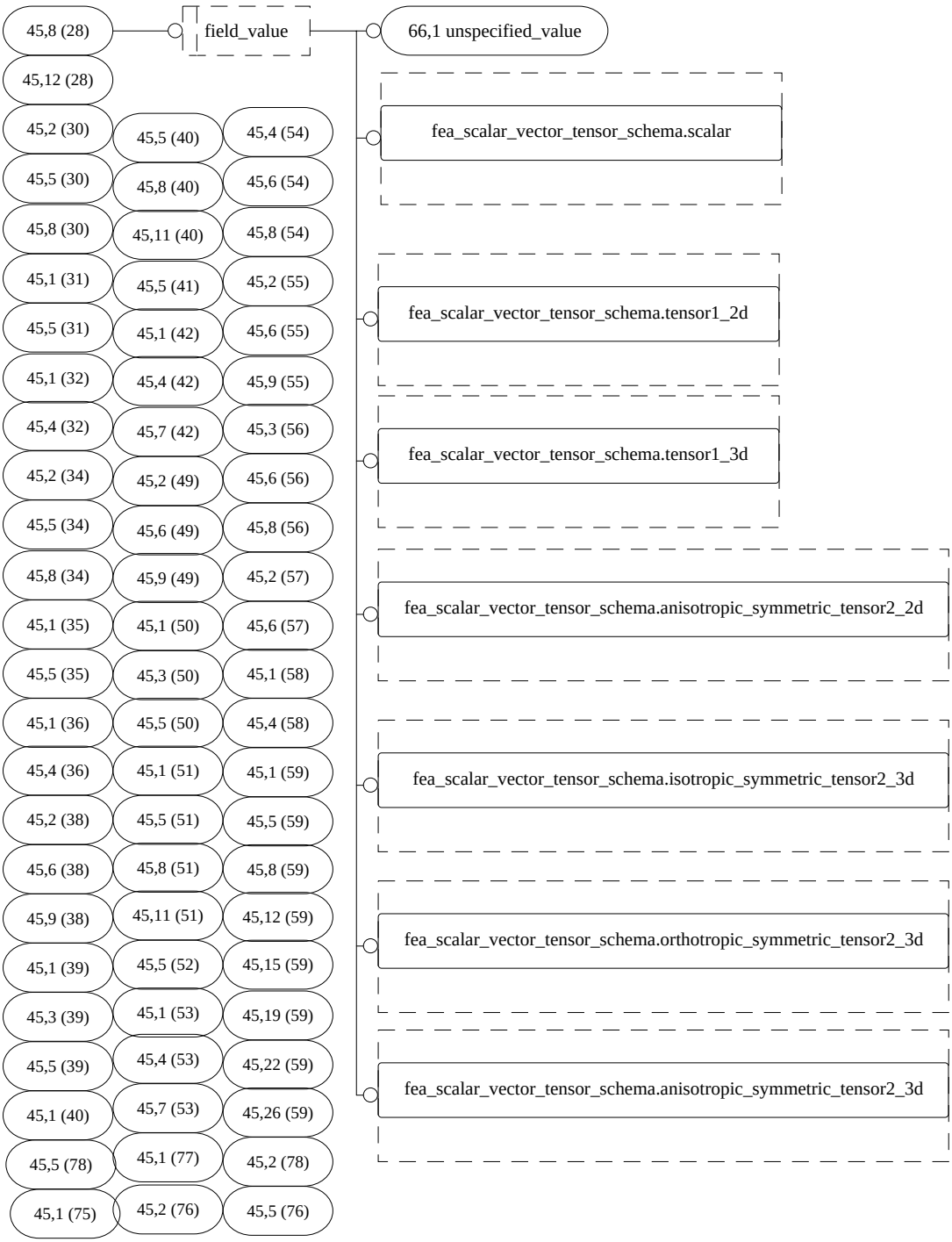

Figure D.45 – Finite element analysis control and result schema EXPRESS-G diagram, 45 of 86.

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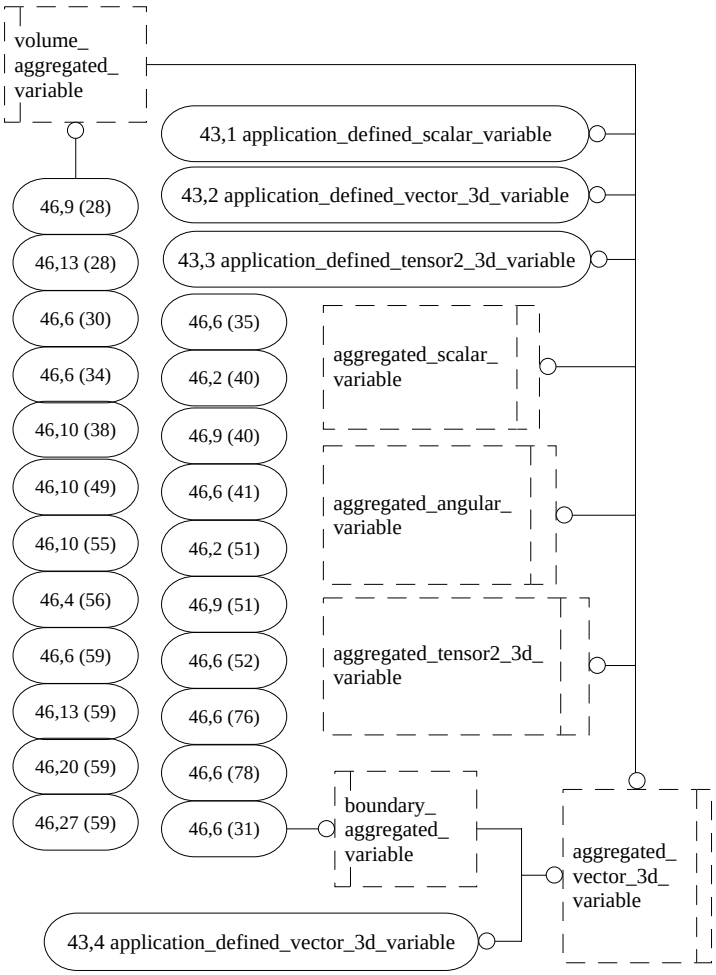

Figure D.46 – Finite element analysis control and result schema EXPRESS-G diagram, 46 of 86.

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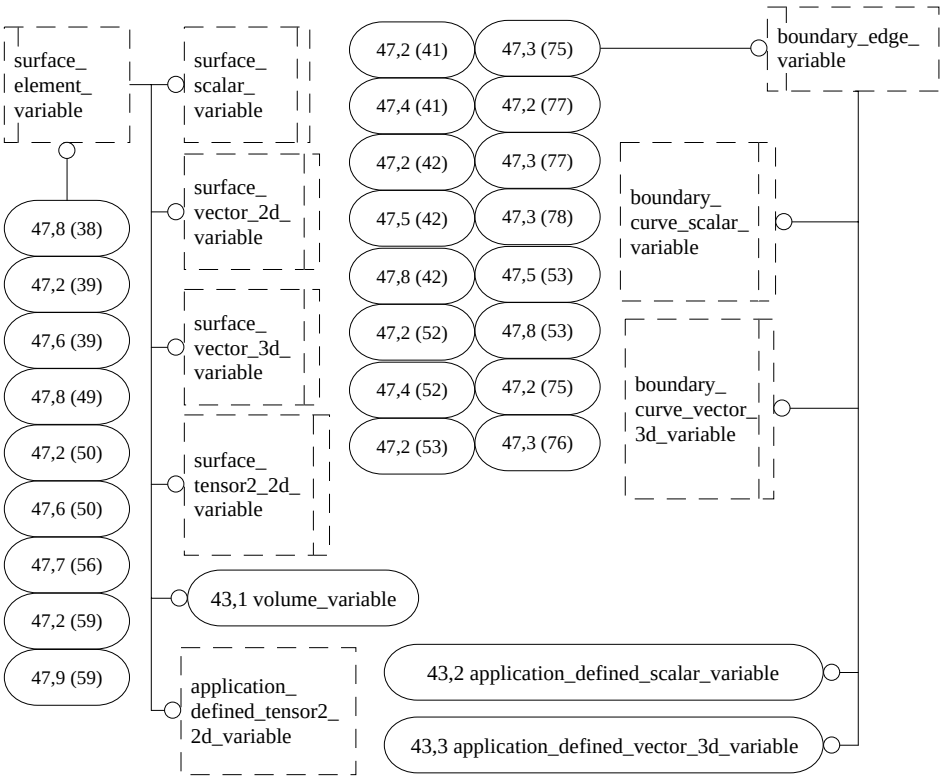

Figure D.47 – Finite element analysis control and result schema EXPRESS-G diagram, 47 of 86.

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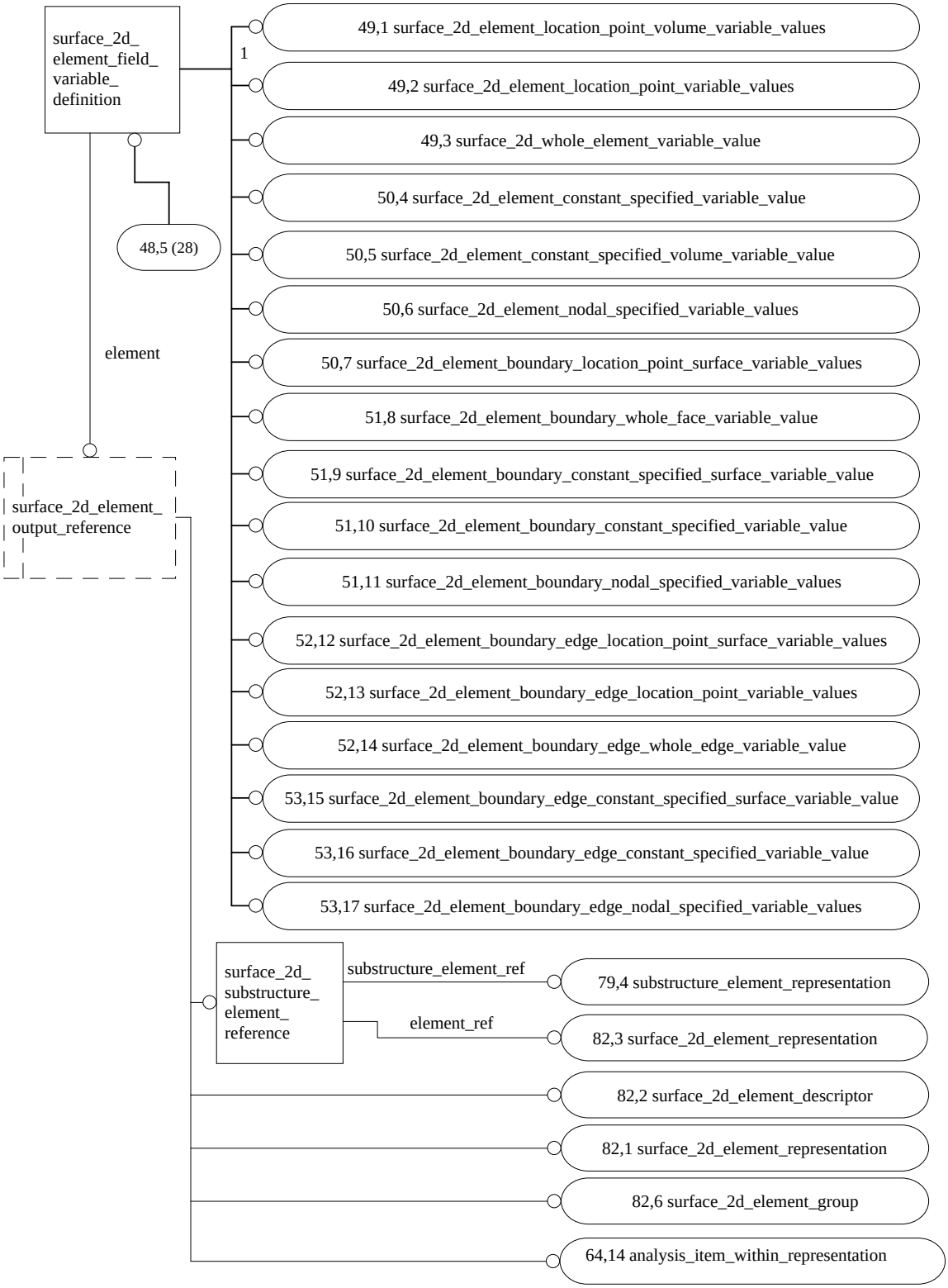

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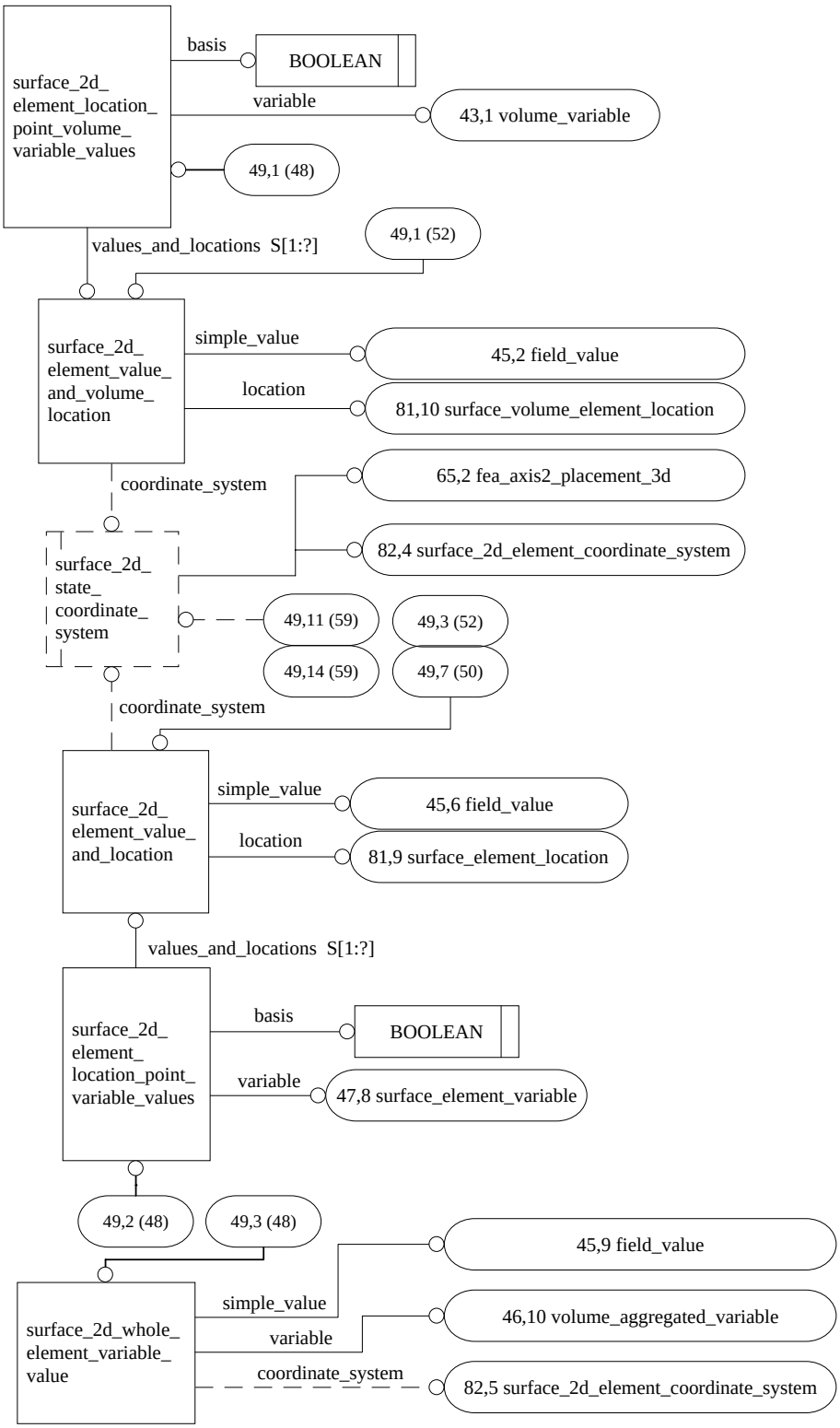

Figure D.49 – Finite element analysis control and result schema EXPRESS-G diagram, 49 of 86.

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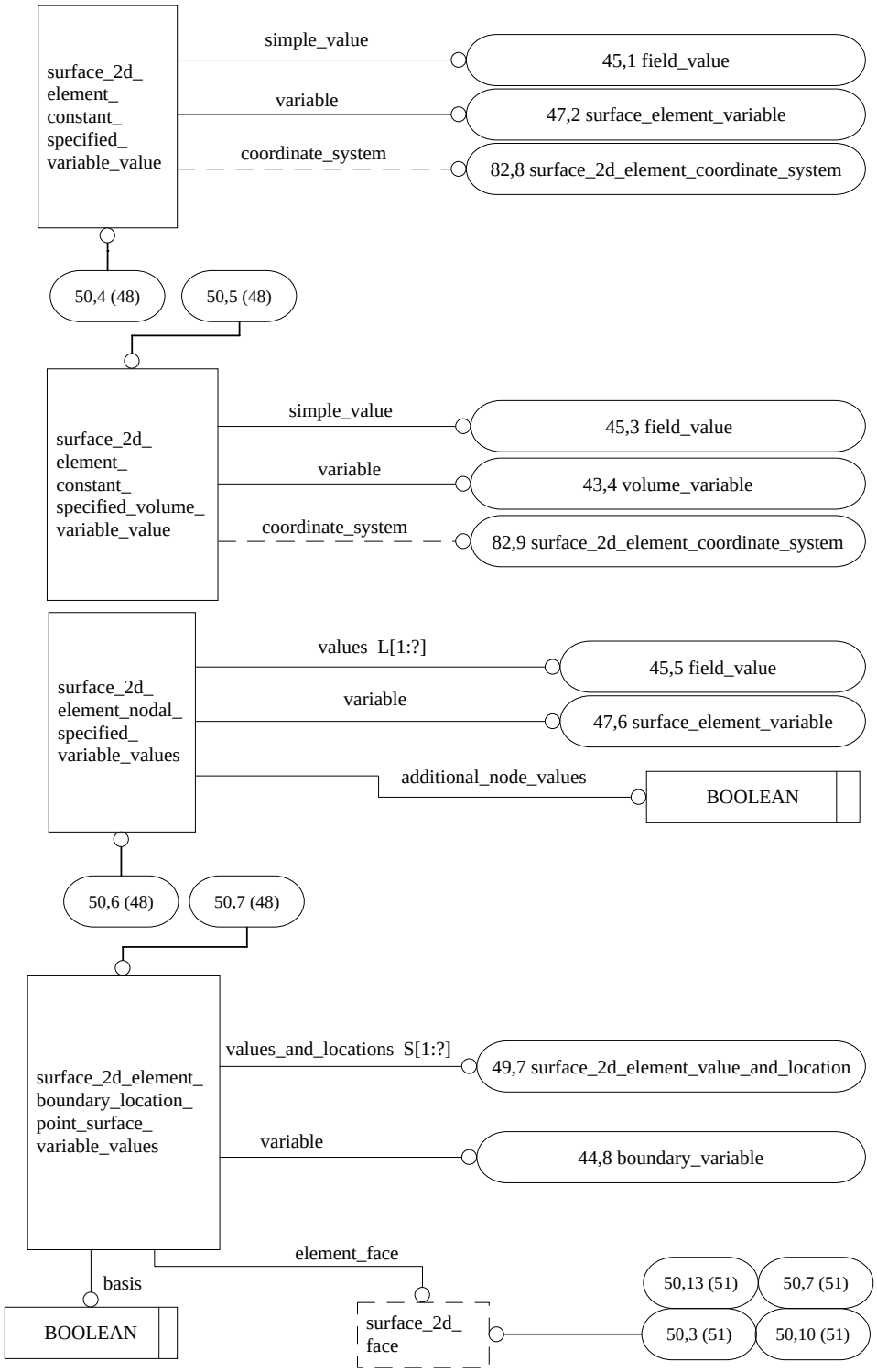

Figure D.50 – Finite element analysis control and result schema EXPRESS-G diagram, 50 of 86.

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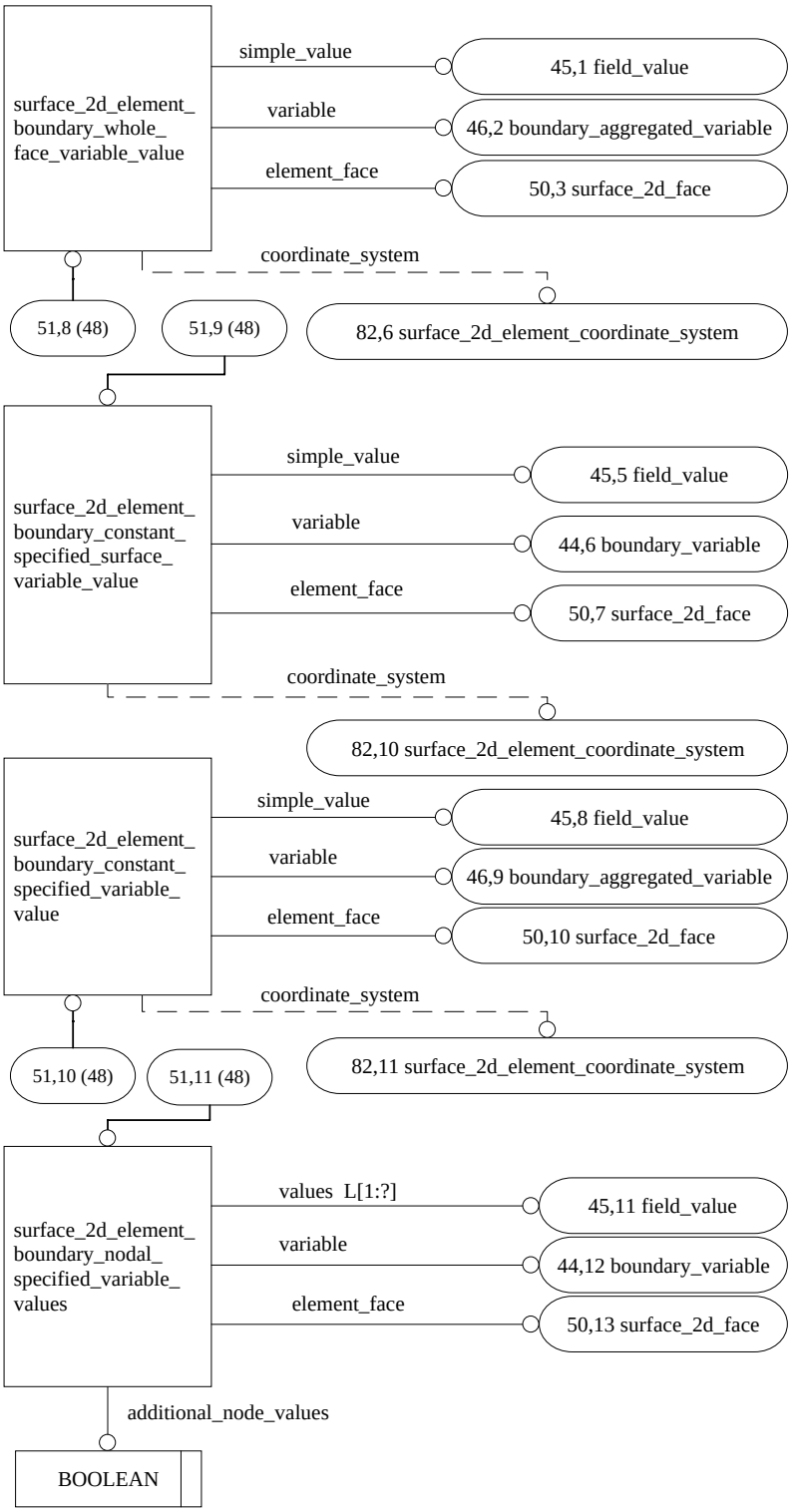

Figure D.51 – Finite element analysis control and result schema EXPRESS-G diagram, 51 of 86.

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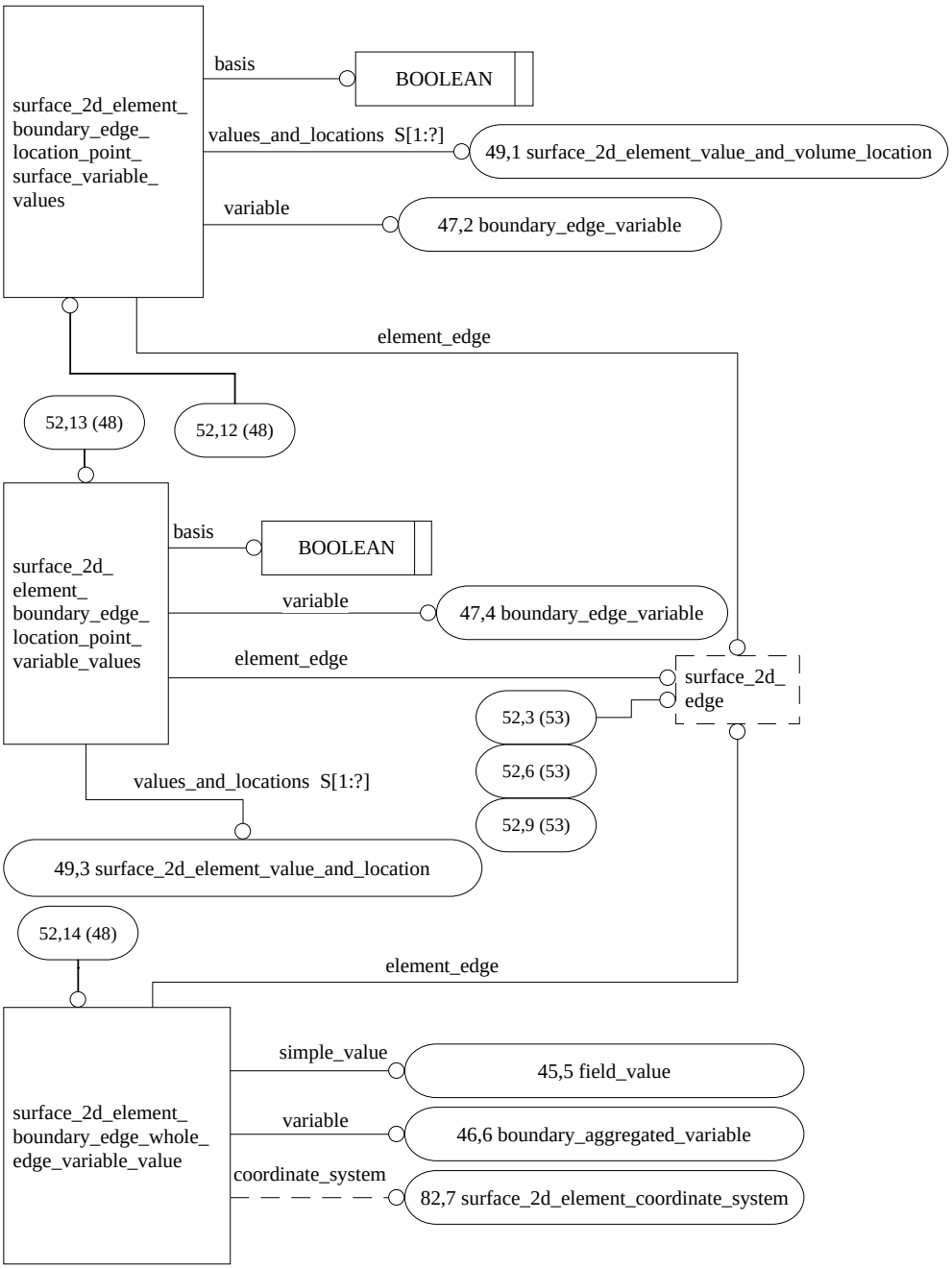

Figure D.52 – Finite element analysis control and result schema EXPRESS-G diagram, 52 of 86.

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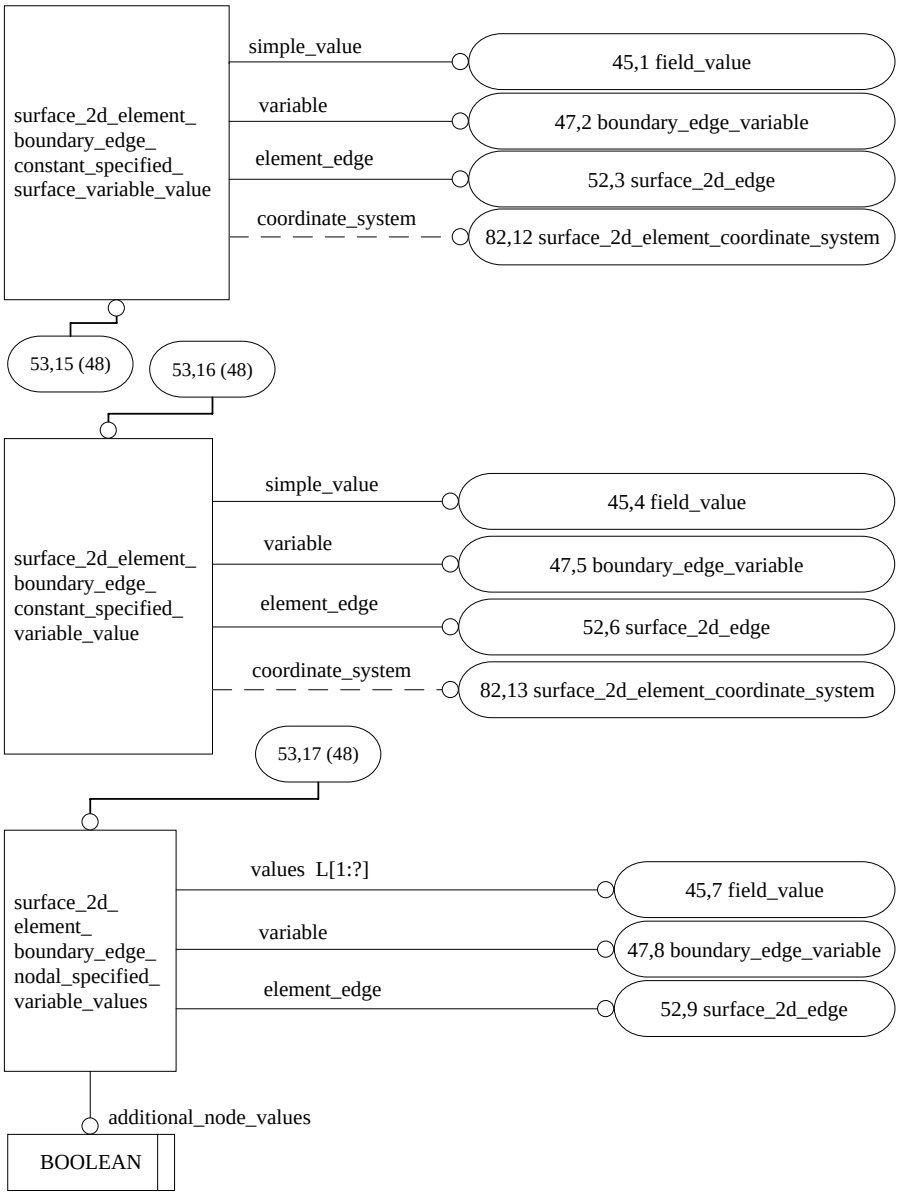

Figure D.53 – Finite element analysis control and result schema EXPRESS-G diagram, 53 of 86.

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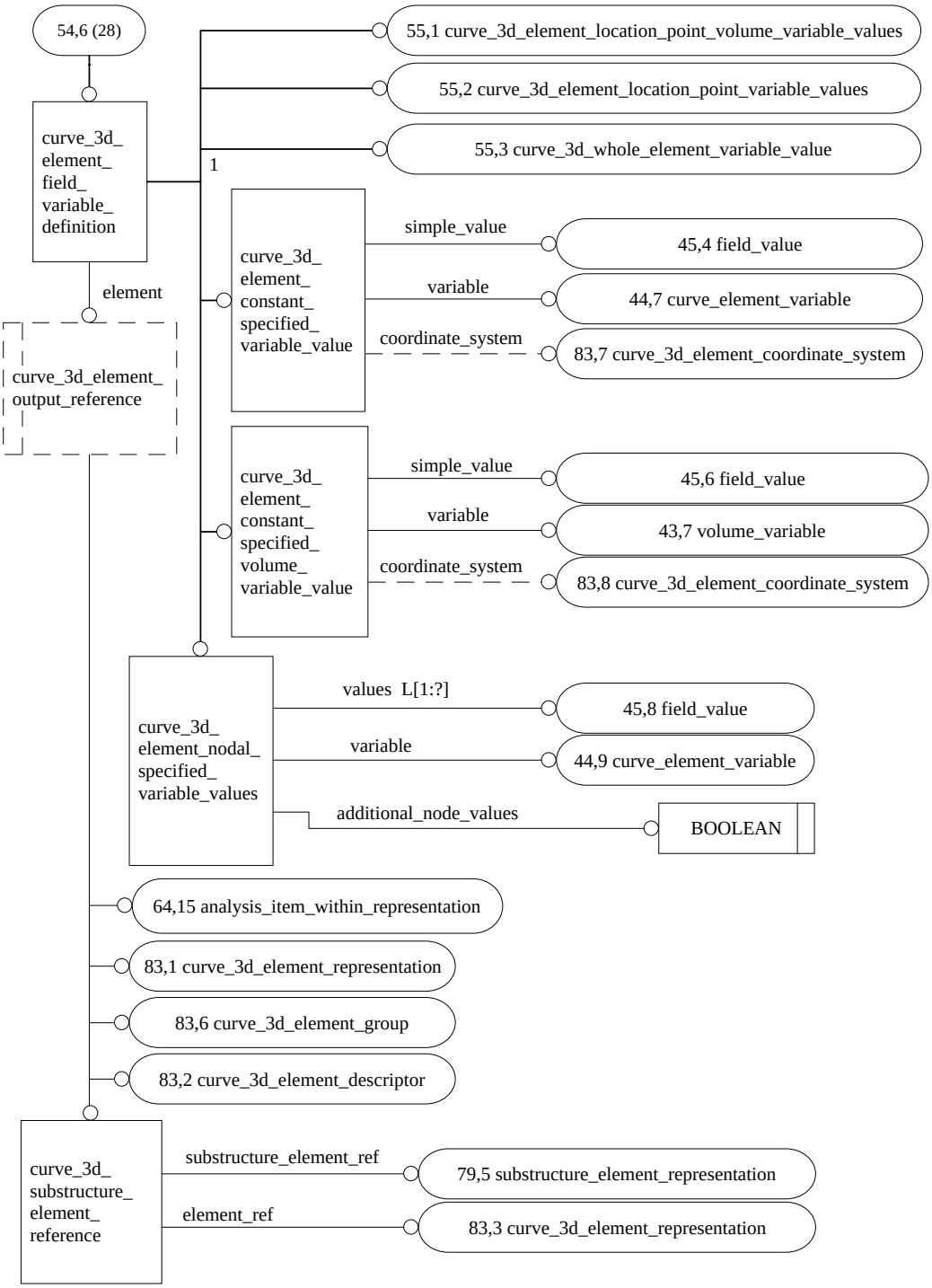

Figure D.54 – Finite element analysis control and result schema EXPRESS-G diagram, 54 of 86.

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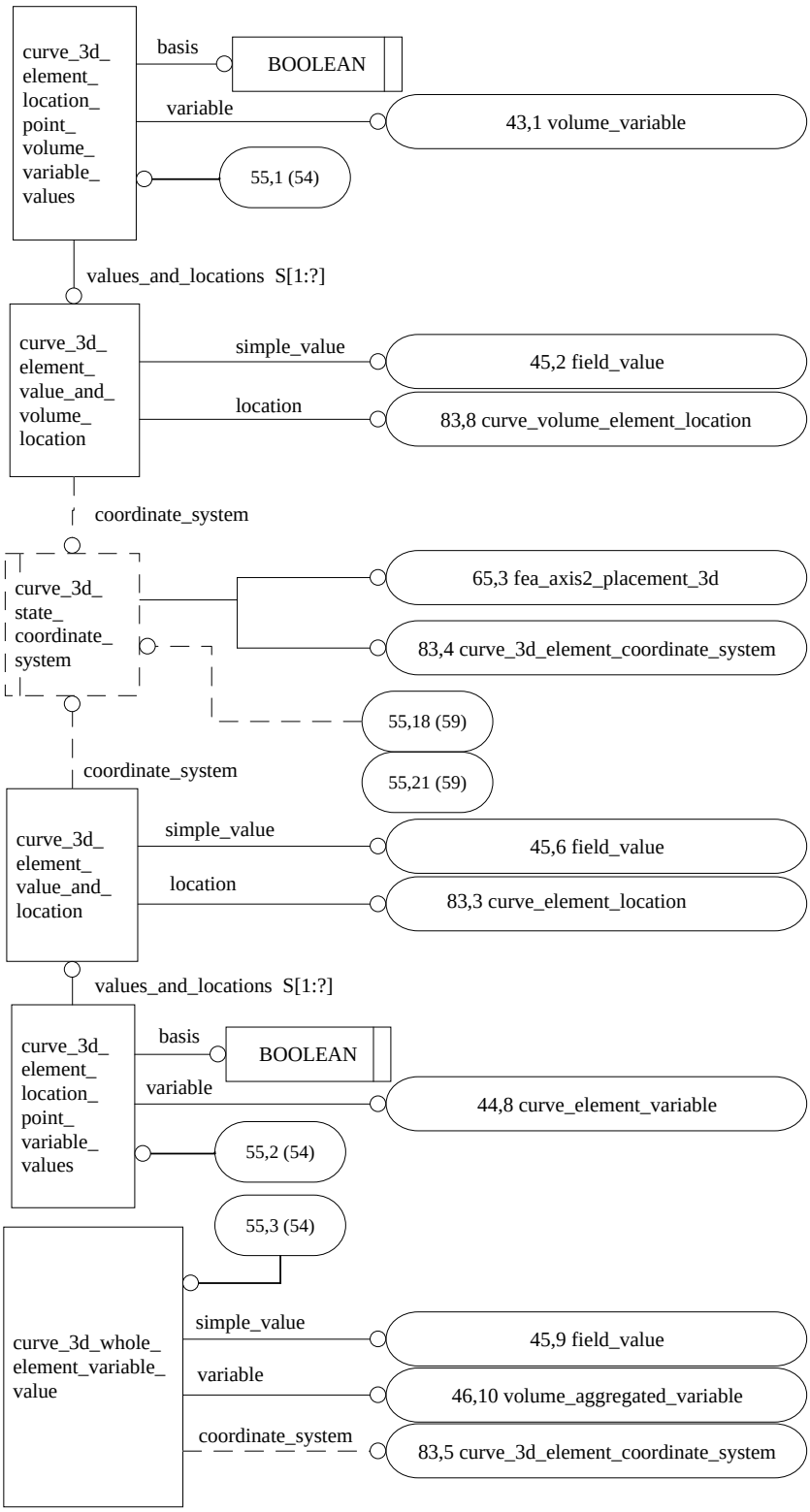

Figure D.55 – Finite element analysis control and result schema EXPRESS-G diagram, 55 of 86.

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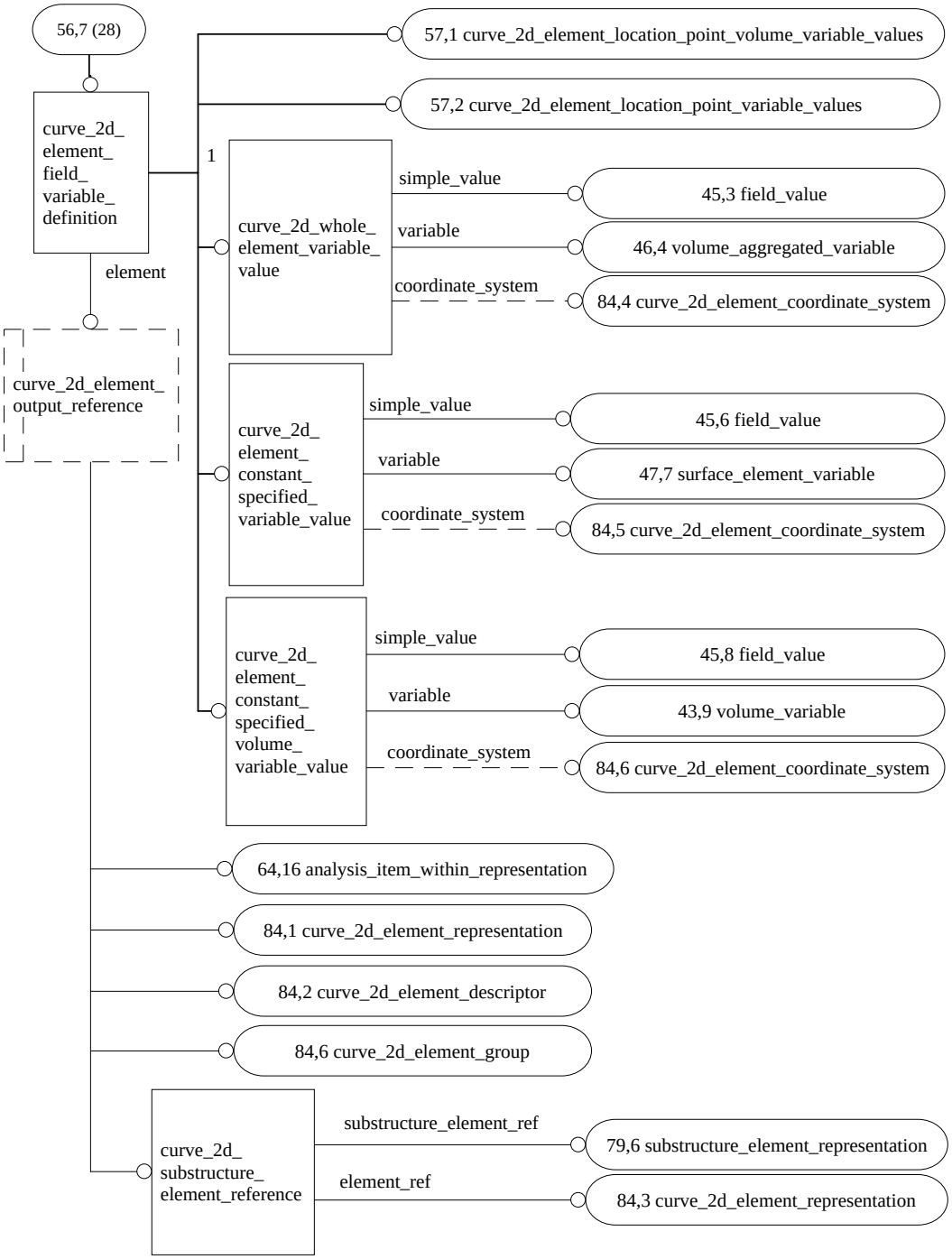

Figure D.56 – Finite element analysis control and result schema EXPRESS-G diagram, 56 of 86.

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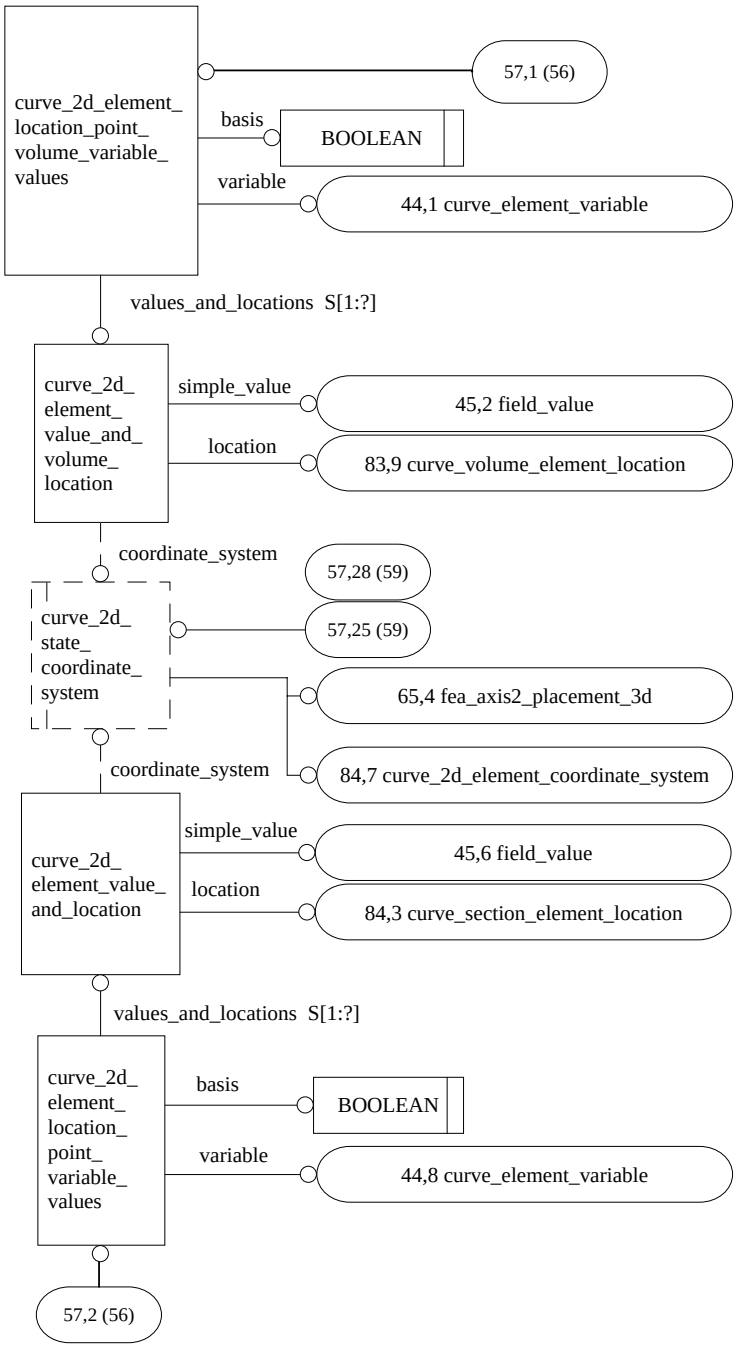

Figure D.57 – Finite element analysis control and result schema EXPRESS-G diagram, 57 of 86.

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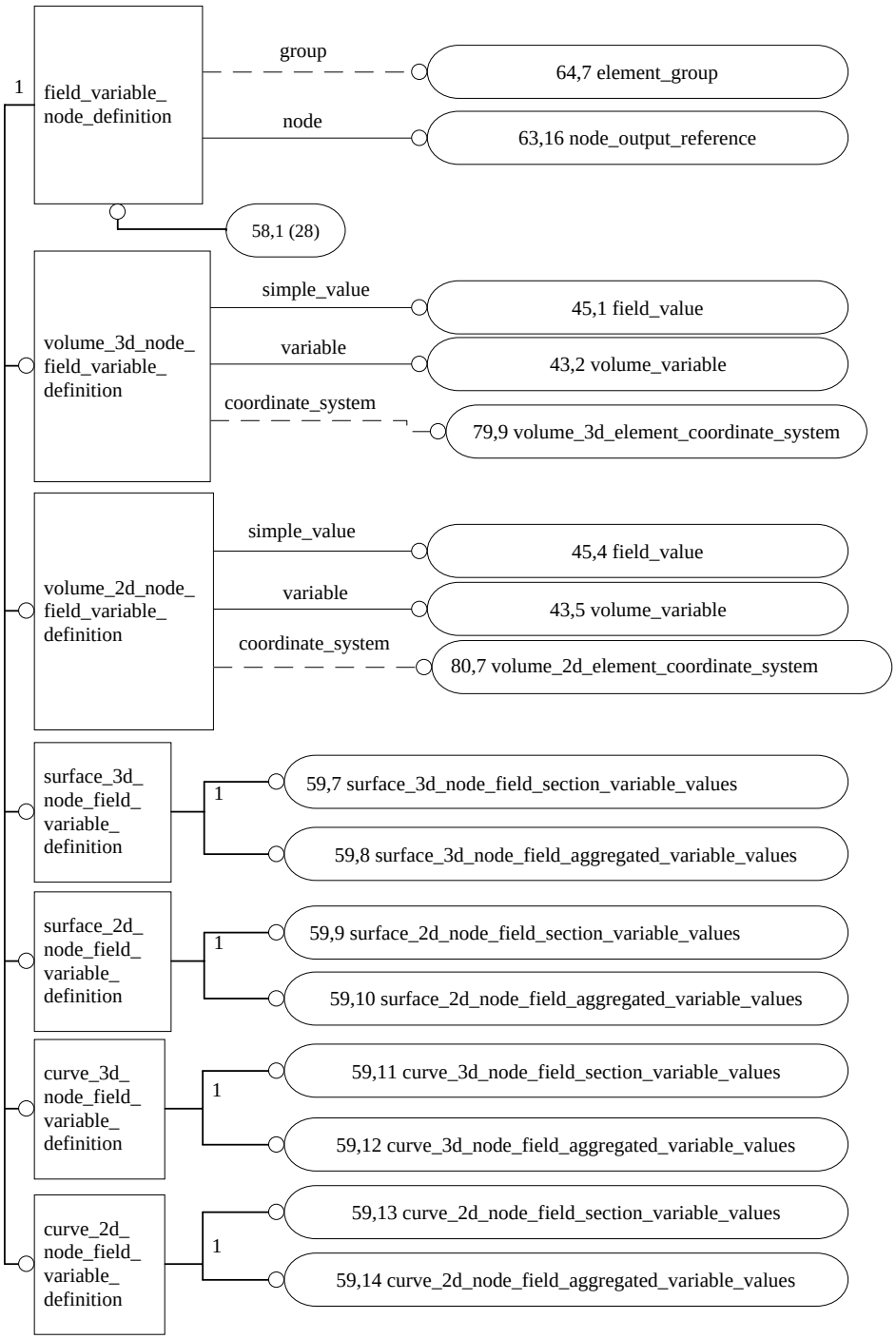

Figure D.58 – Finite element analysis control and result schema EXPRESS-G diagram, 58 of 86.

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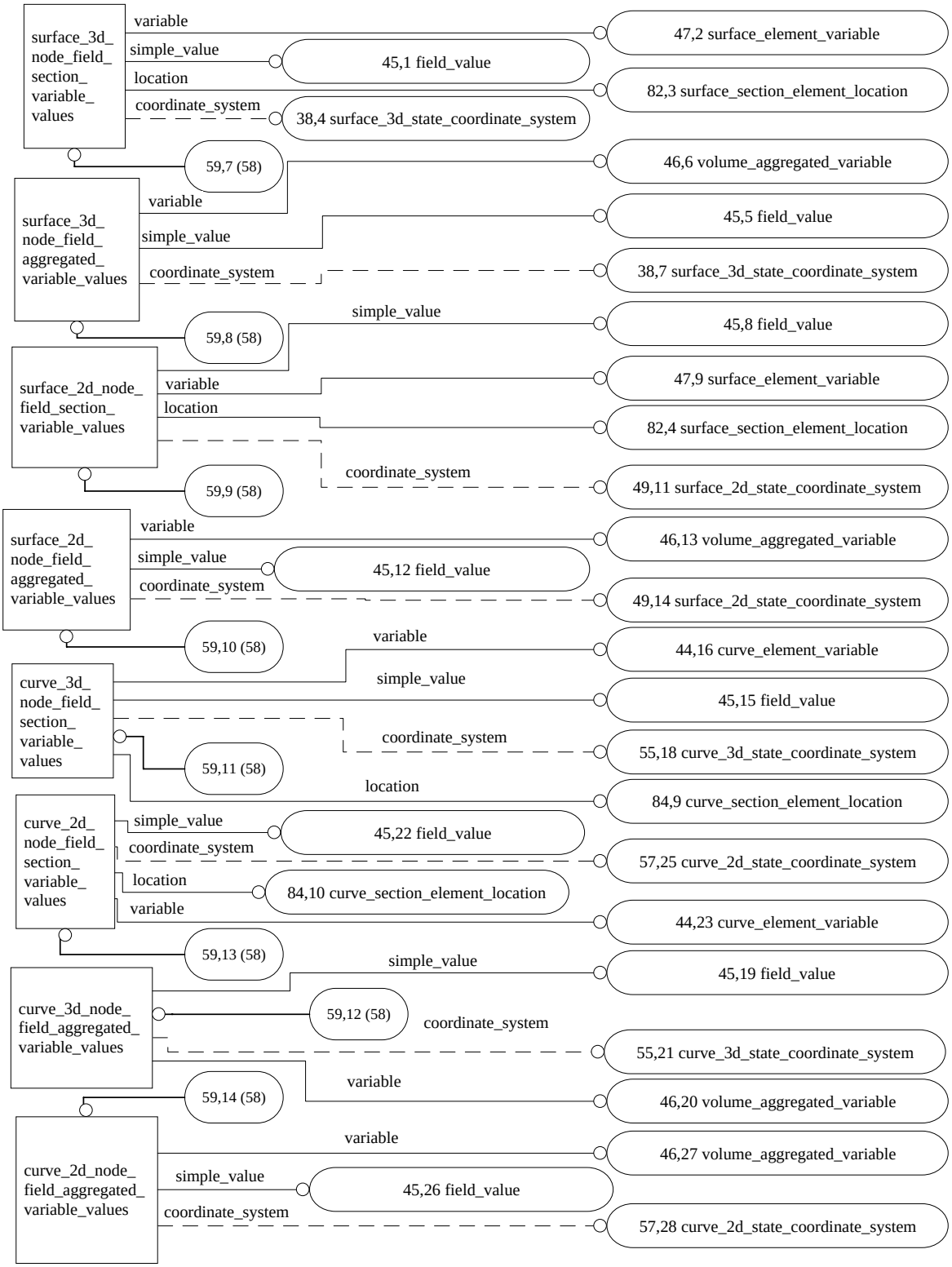

Figure D.59 – Finite element analysis control and result schema EXPRESS-G diagram, 59 of 86.

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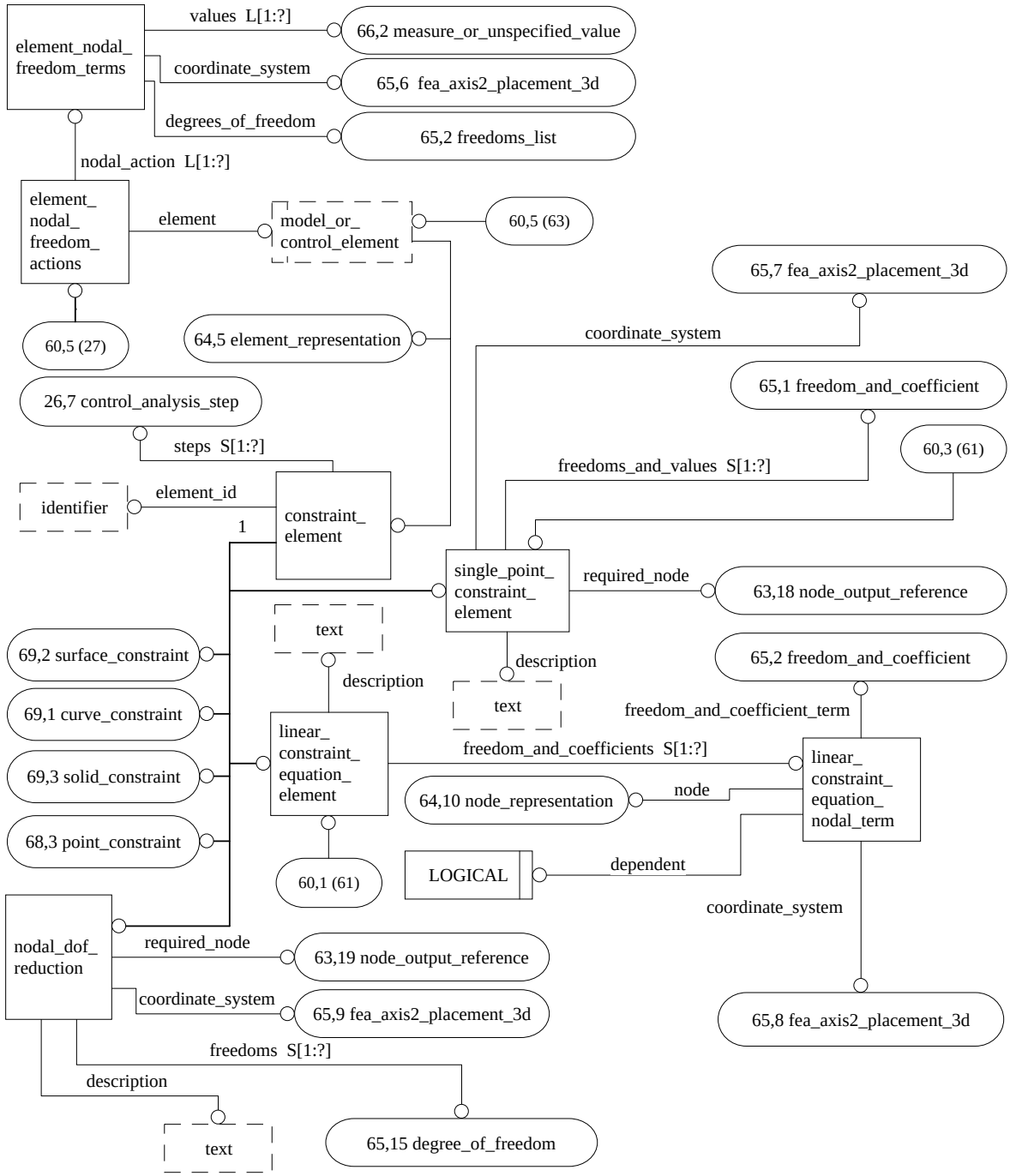

Figure D.60 – Finite element analysis control and result schema EXPRESS-G diagram, 60 of 86.

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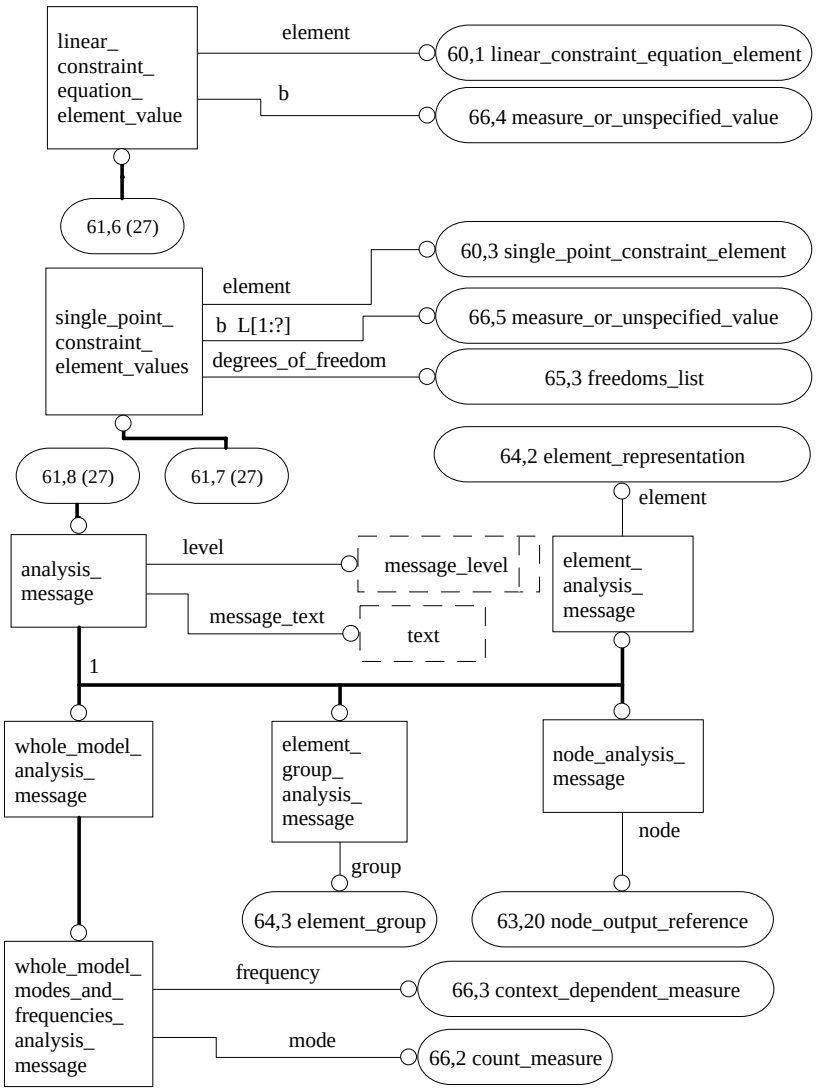

Figure D.61 – Finite element analysis control and result schema EXPRESS-G diagram, 61 of 86.

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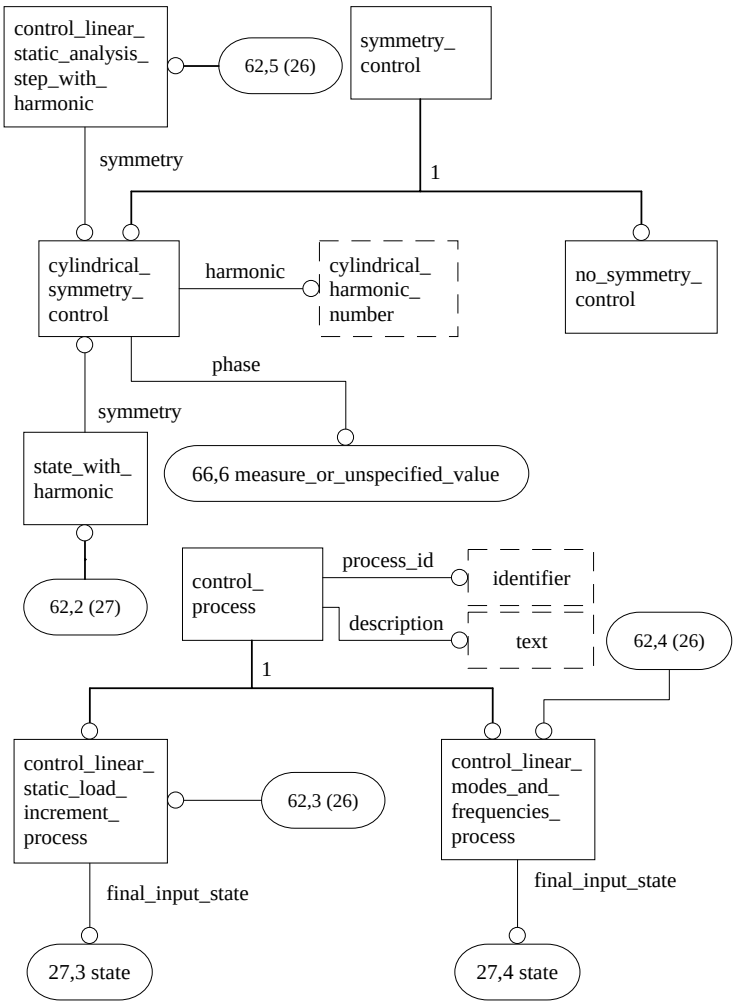

Figure D.62 – Finite element analysis control and result schema EXPRESS-G diagram, 62 of 86.

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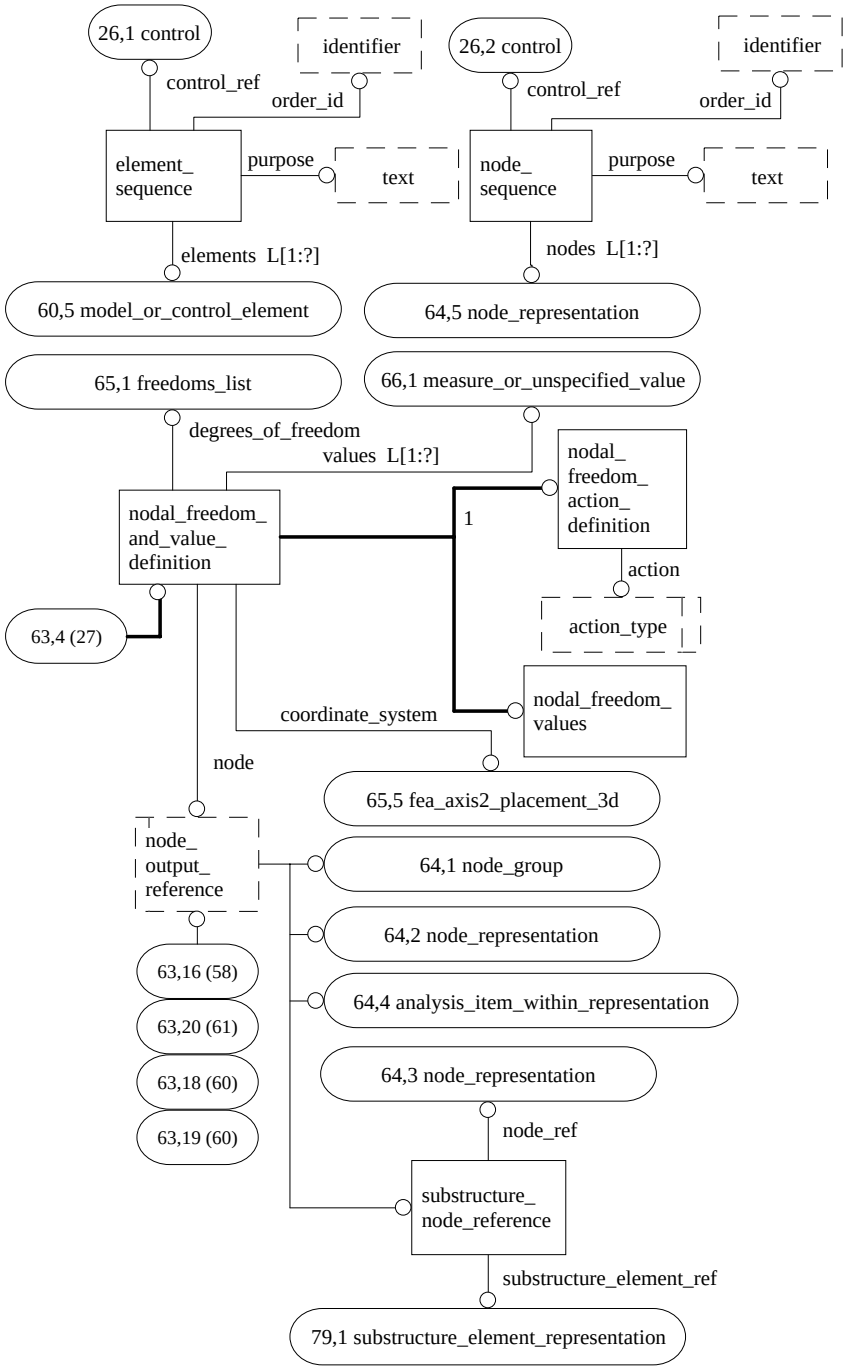

Figure D.63 – Finite element analysis control and result schema EXPRESS-G diagram, 63 of 86.

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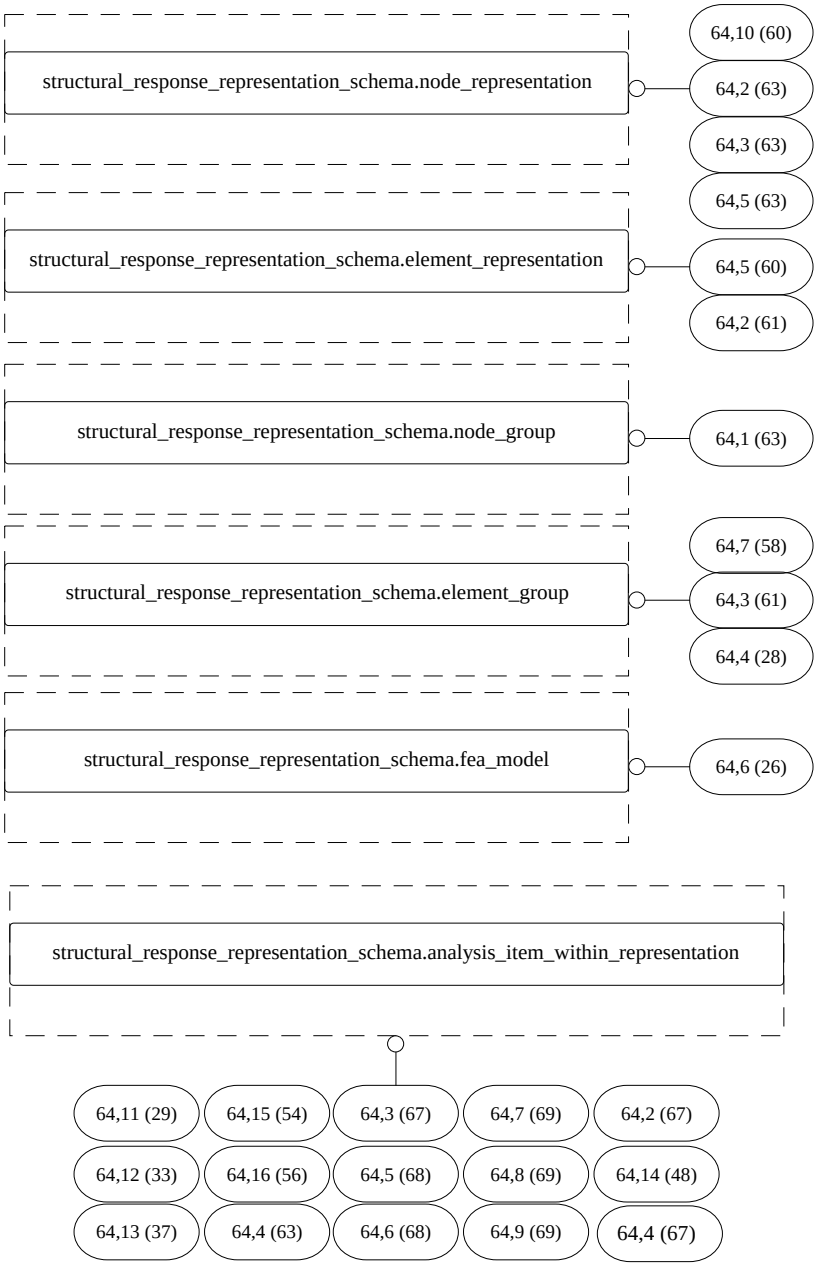

Figure D.64 – Finite element analysis control and result schema EXPRESS-G diagram, 64 of 86.

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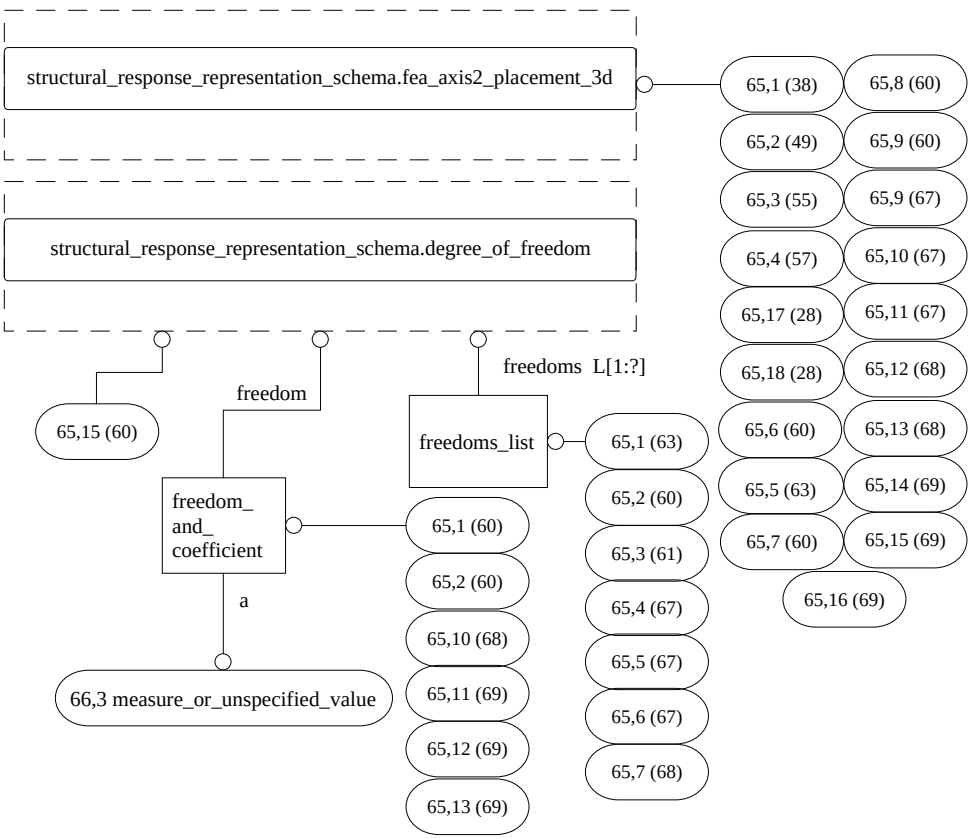

Figure D.65 – Finite element analysis control and result schema EXPRESS-G diagram, 65 of 86.

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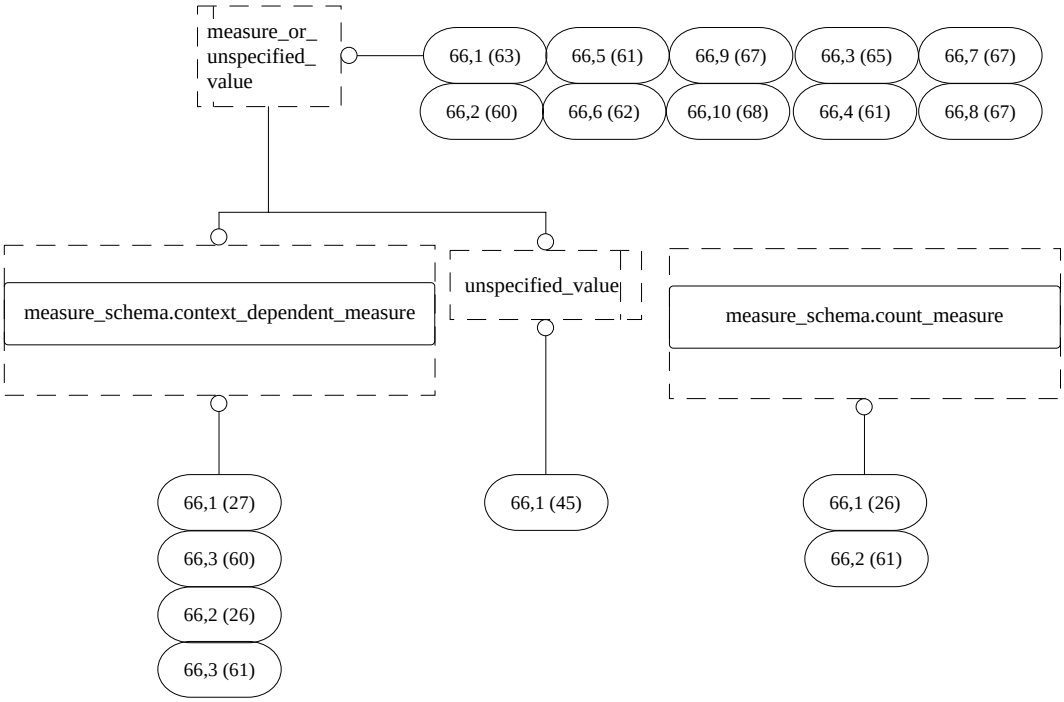

Figure D.66 – Finite element analysis control and result schema EXPRESS-G diagram, 66 of 86.

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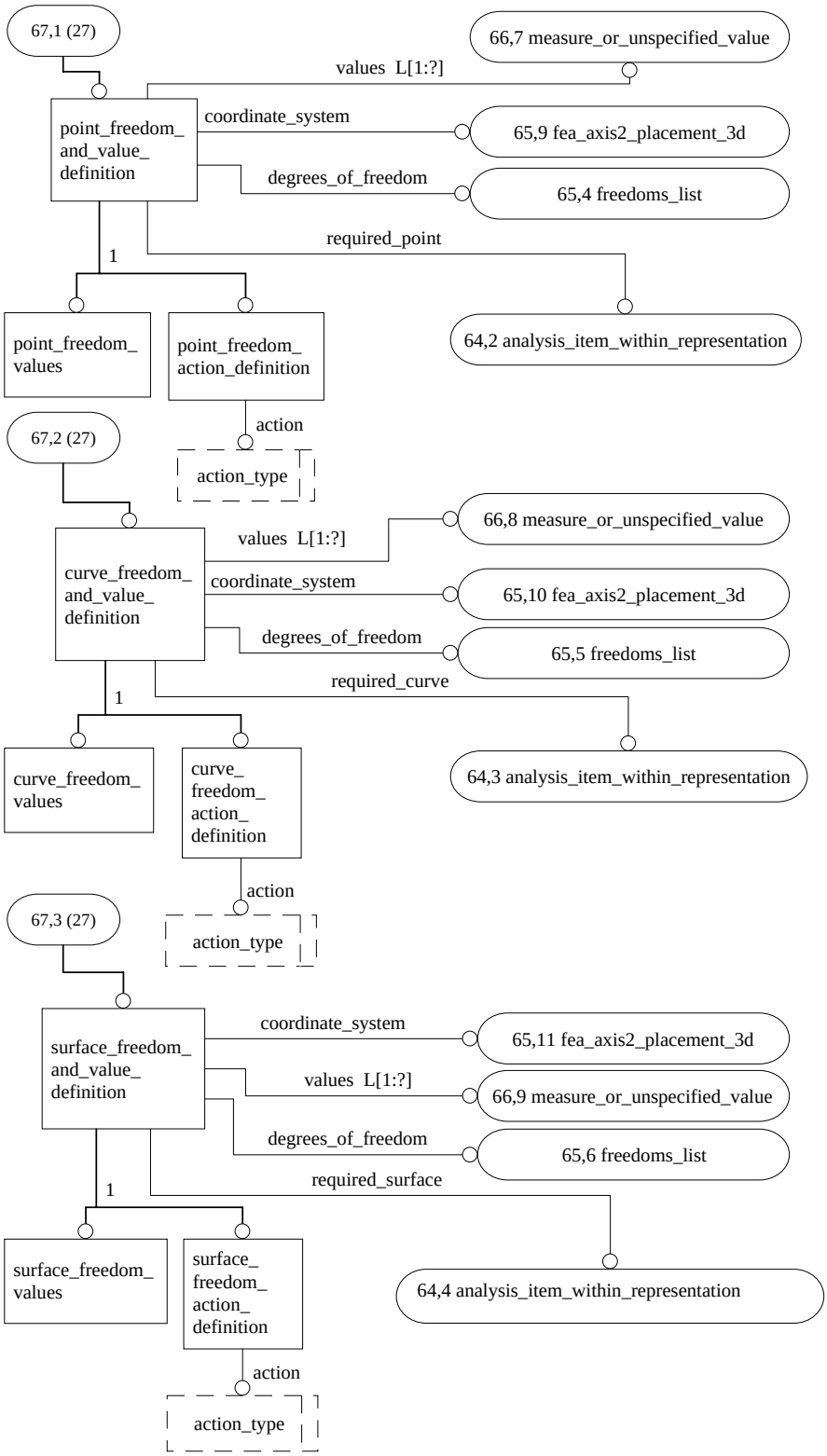

Figure D.67 – Finite element analysis control and result schema EXPRESS-G diagram, 67 of 86.

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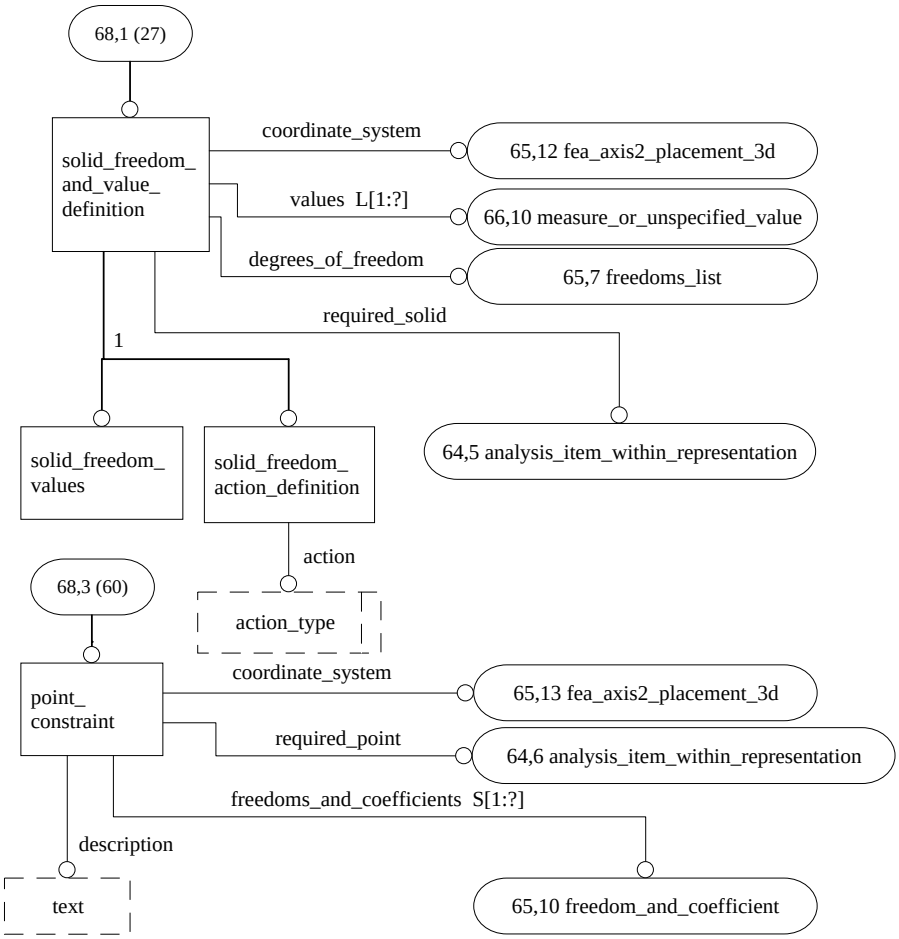

Figure D.68 – Finite element analysis control and result schema EXPRESS-G diagram, 68 of 86.

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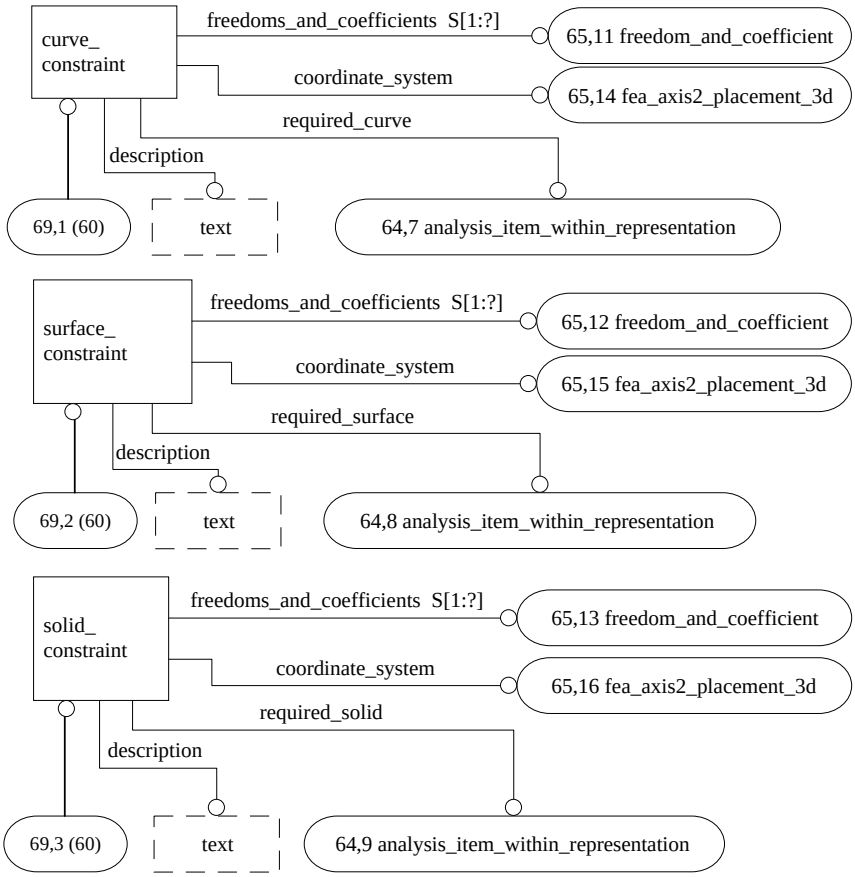

Figure D.69 – Finite element analysis control and result schema EXPRESS-G diagram, 69 of 86.

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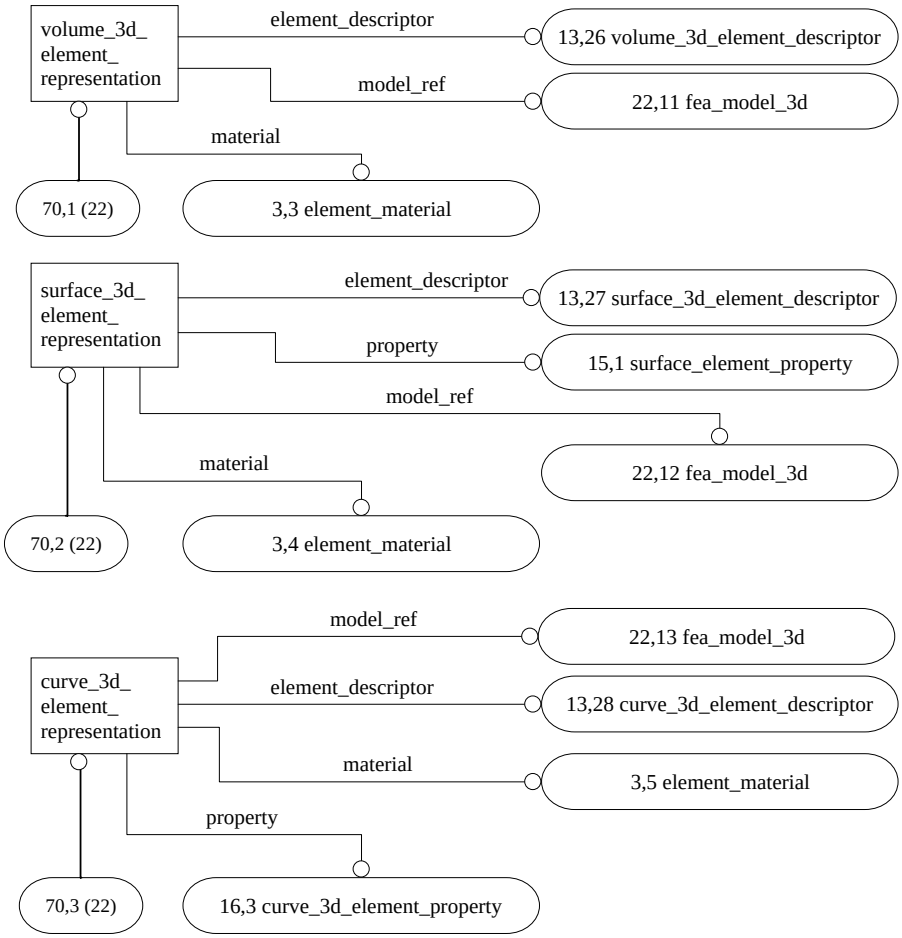

Figure D.70 – Structural response representation schema EXPRESS-G diagram, 70 of 86.

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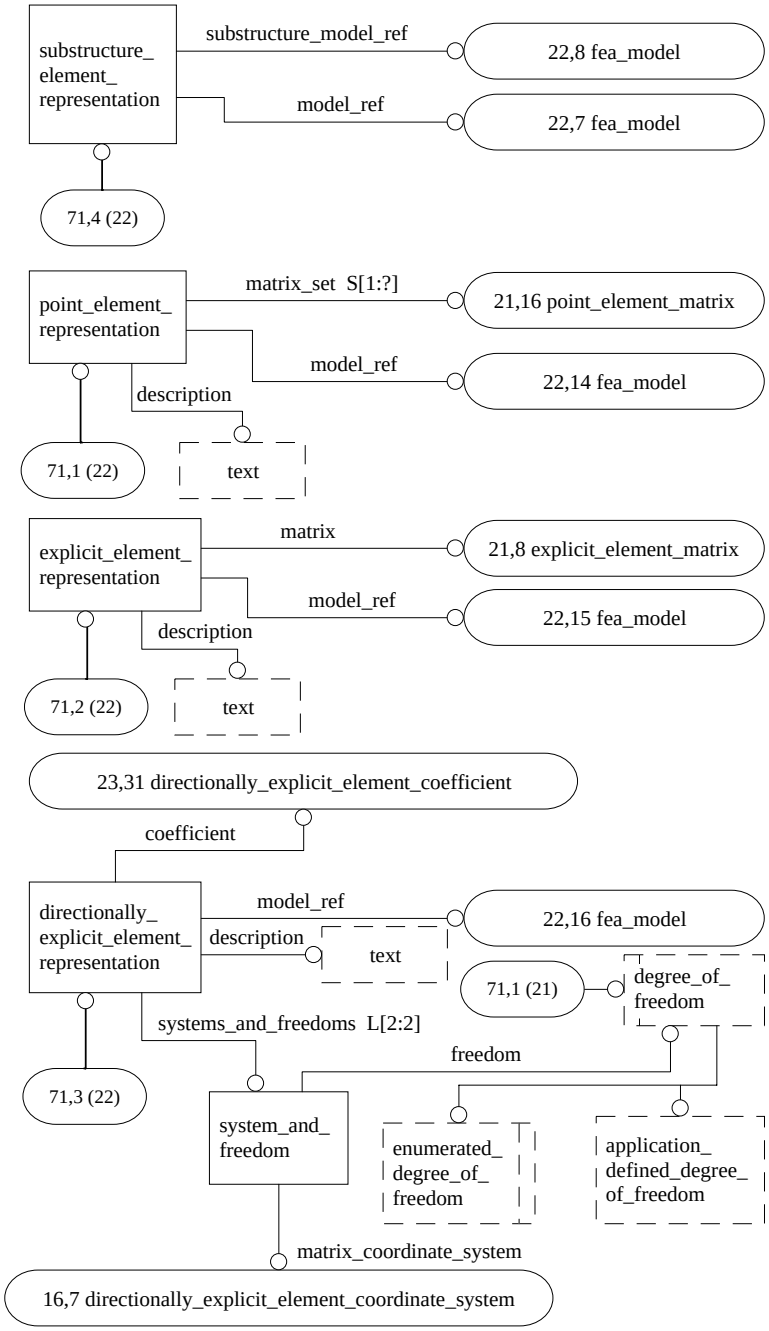

Figure D.71 – Structural response representation schema EXPRESS-G diagram, 71 of 86.

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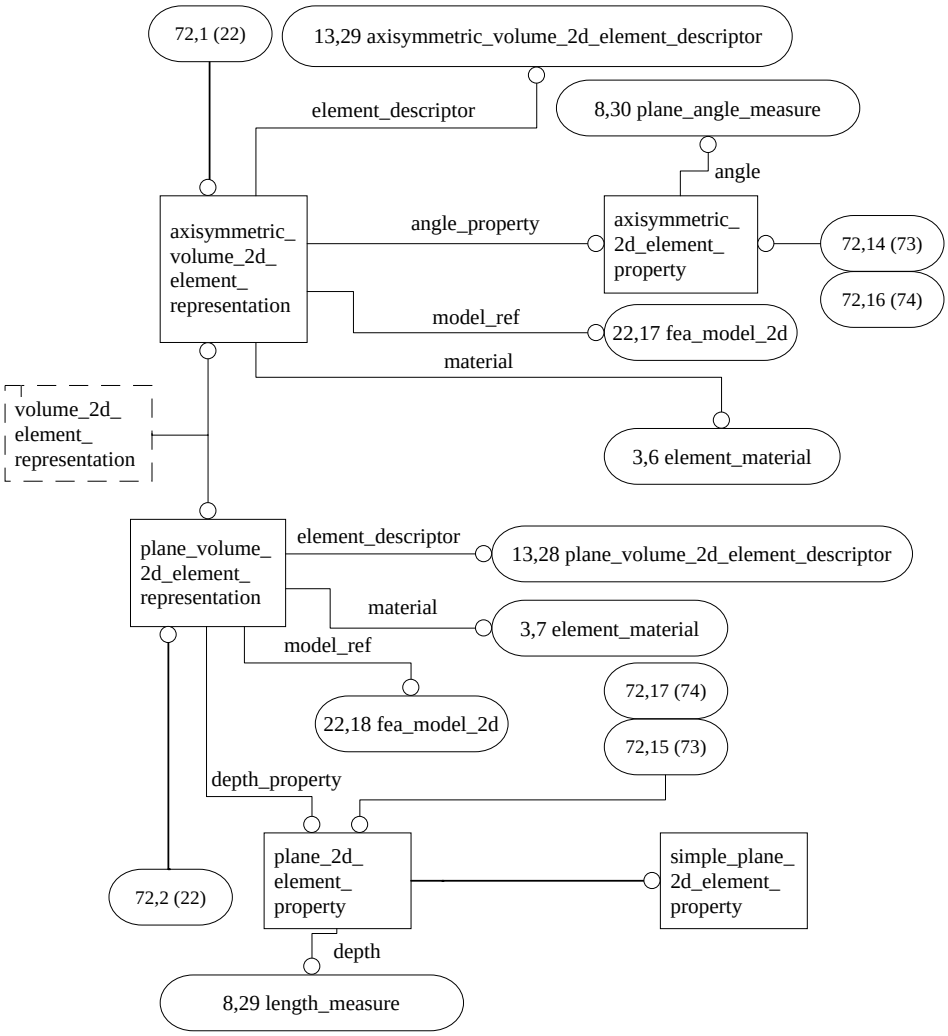

Figure D.72 – Structural response representation schema EXPRESS-G diagram, 72 of 86.

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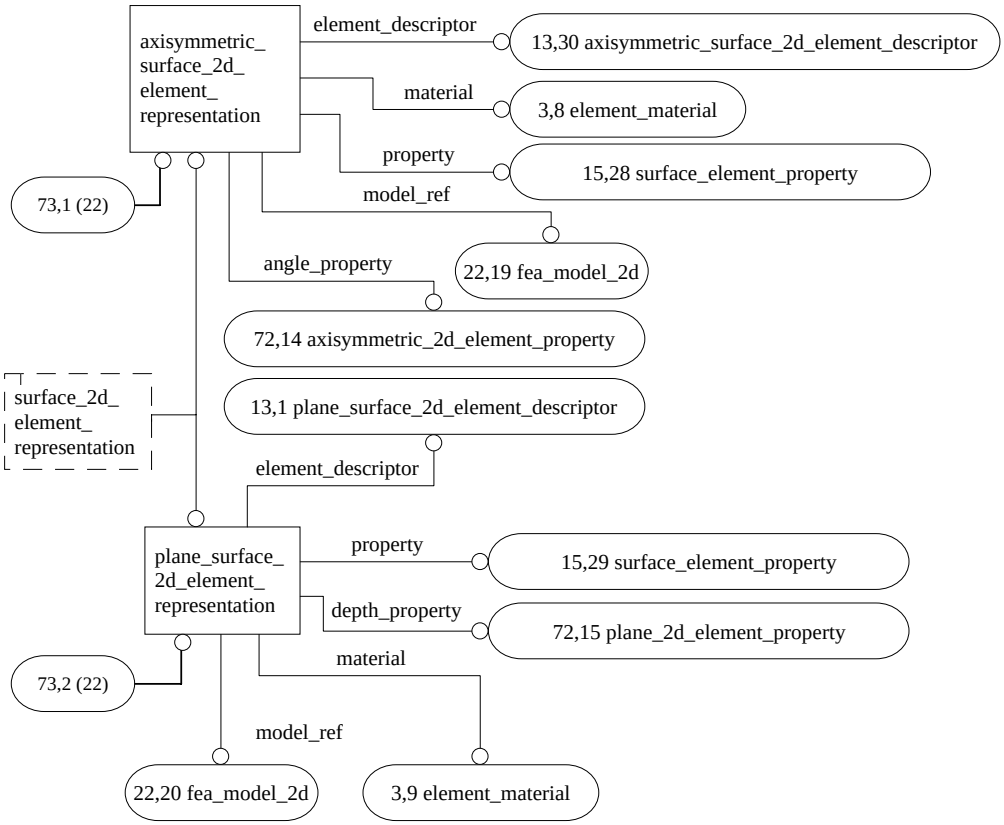

Figure D.73 – Structural response representation schema EXPRESS-G diagram, 73 of 86.

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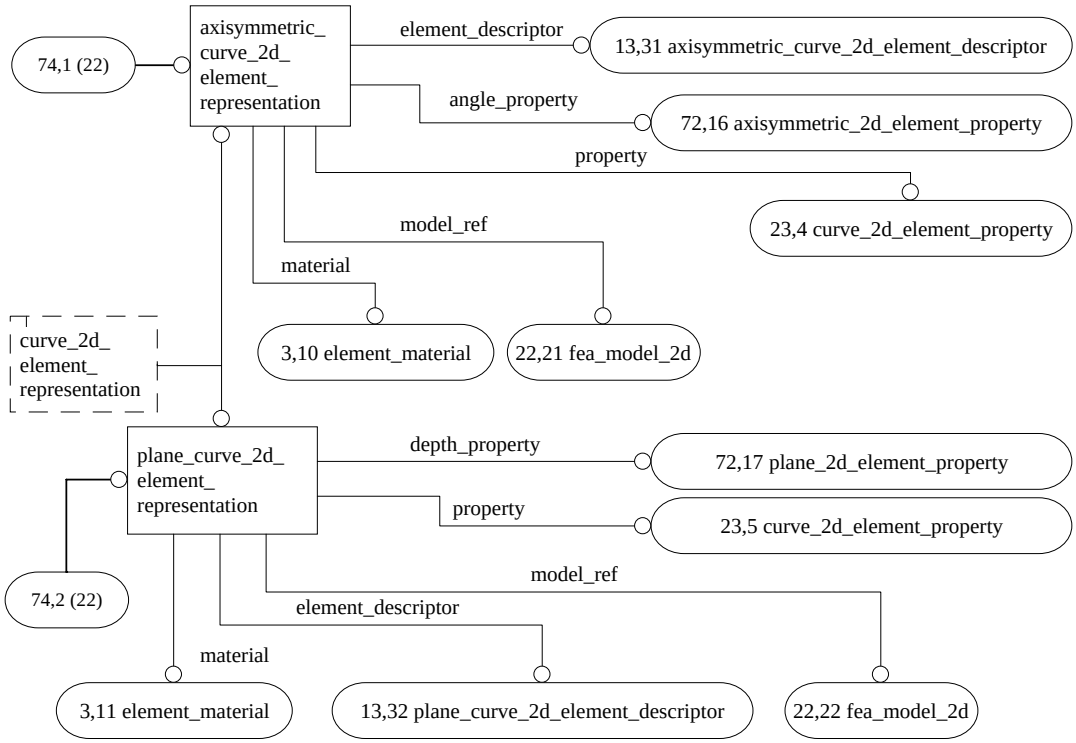

Figure D.74 – Structural response representation schema EXPRESS-G diagram, 74 of 86.

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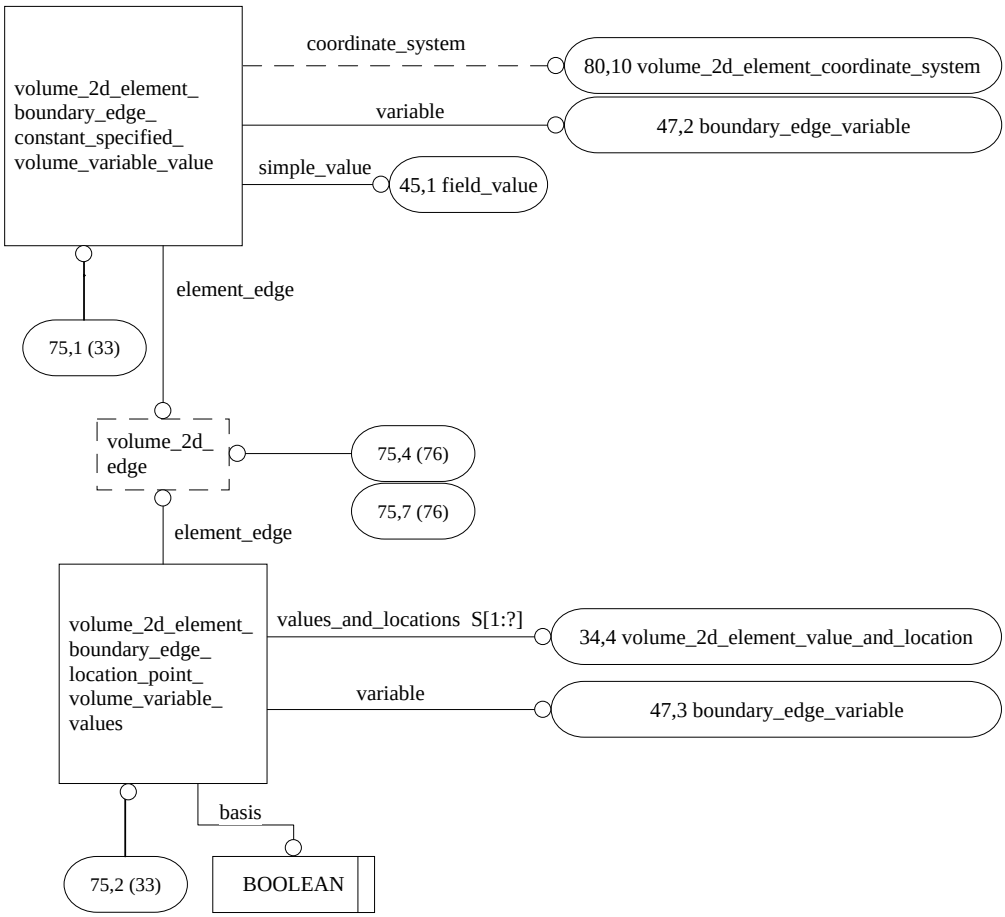

Figure D.75 – Structural response representation schema EXPRESS-G diagram, 75 of 86.

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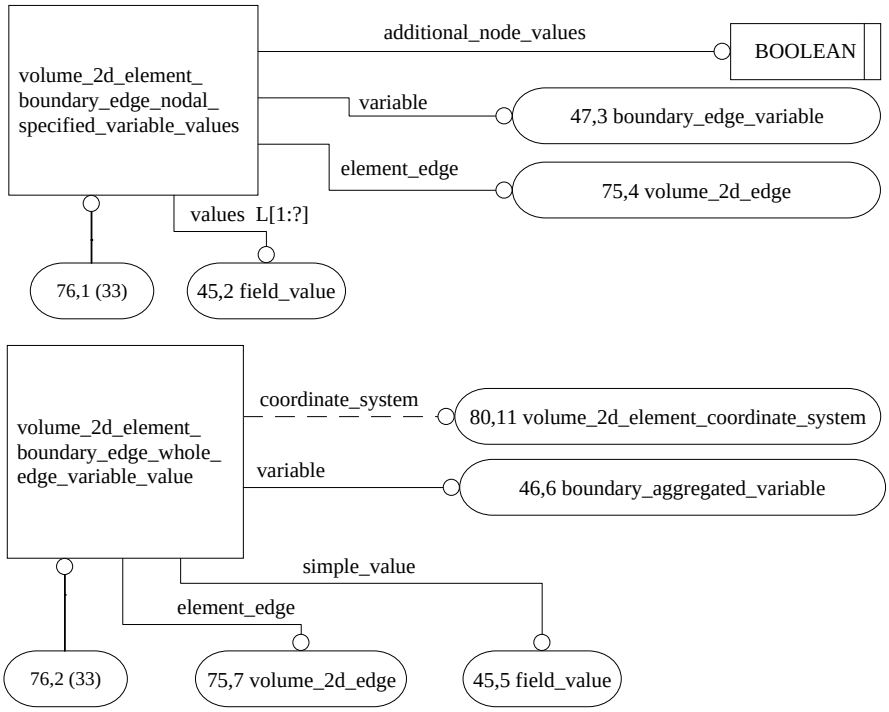

Figure D.76 – Structural response representation schema EXPRESS-G diagram, 76 of 86.

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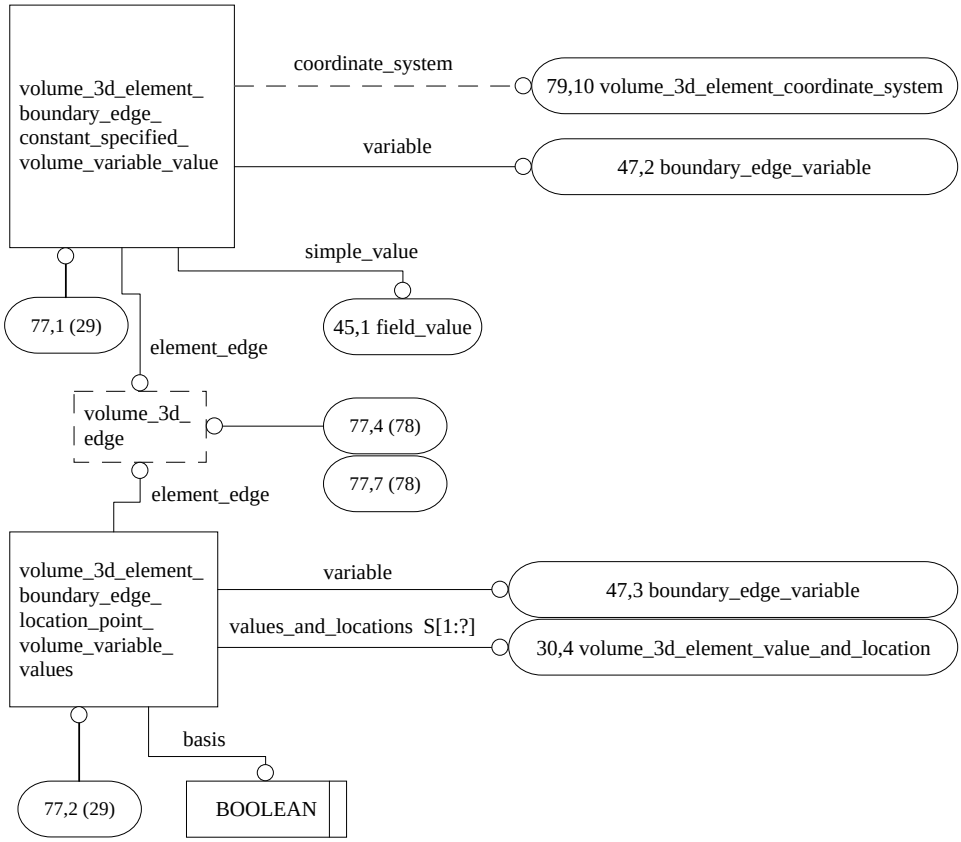

Figure D.77 – Finite element analysis control and result schema EXPRESS-G diagram, 77 of 86.

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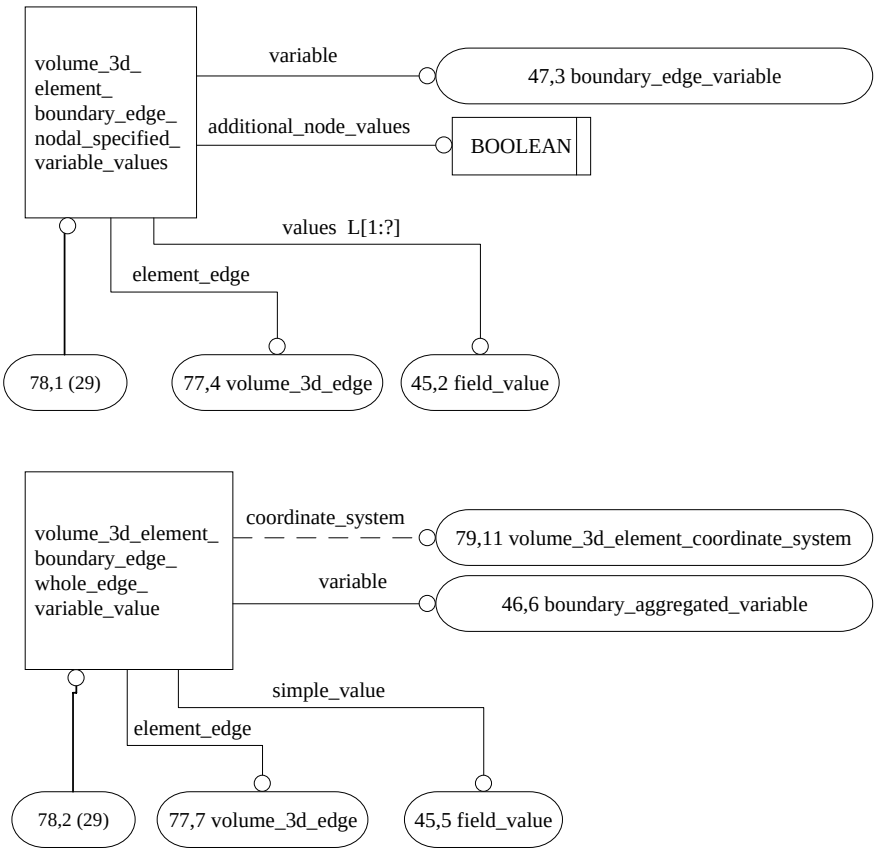

Figure D.78 – Finite element analysis control and result schema EXPRESS-G diagram, 78 of 86.

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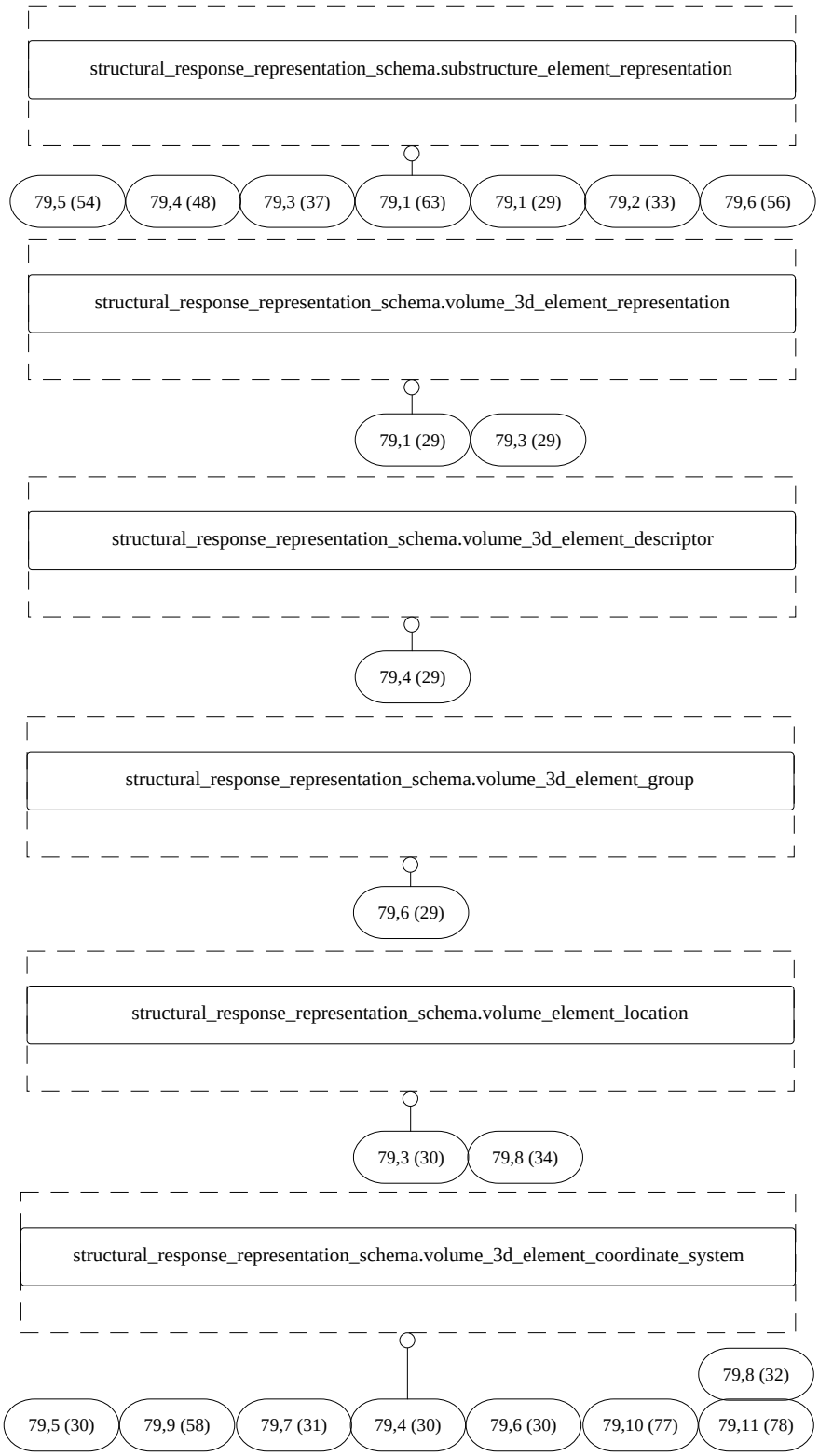

Figure D.79 – Finite element analysis control and result schema EXPRESS-G diagram, 79 of 86.

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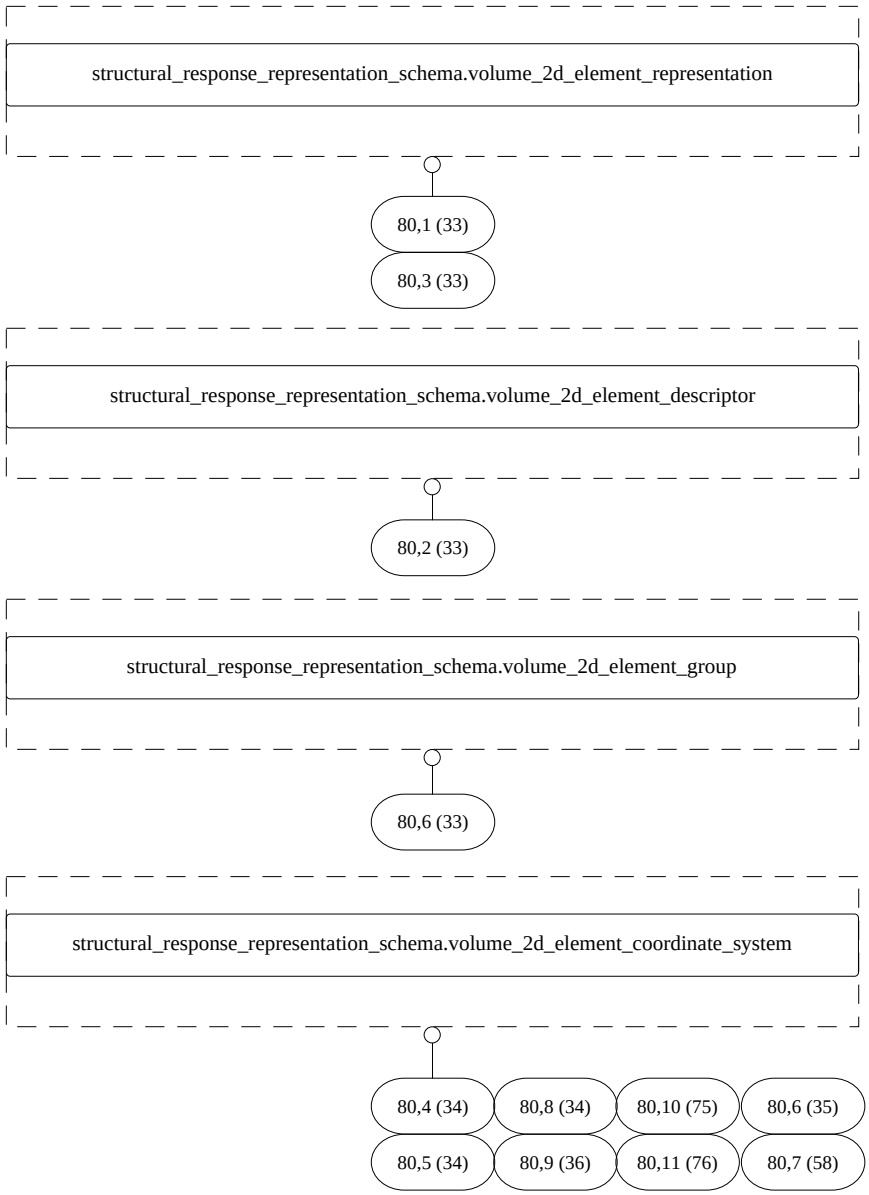

Figure D.80 – Finite element analysis control and result schema EXPRESS-G diagram, 80 of 86.

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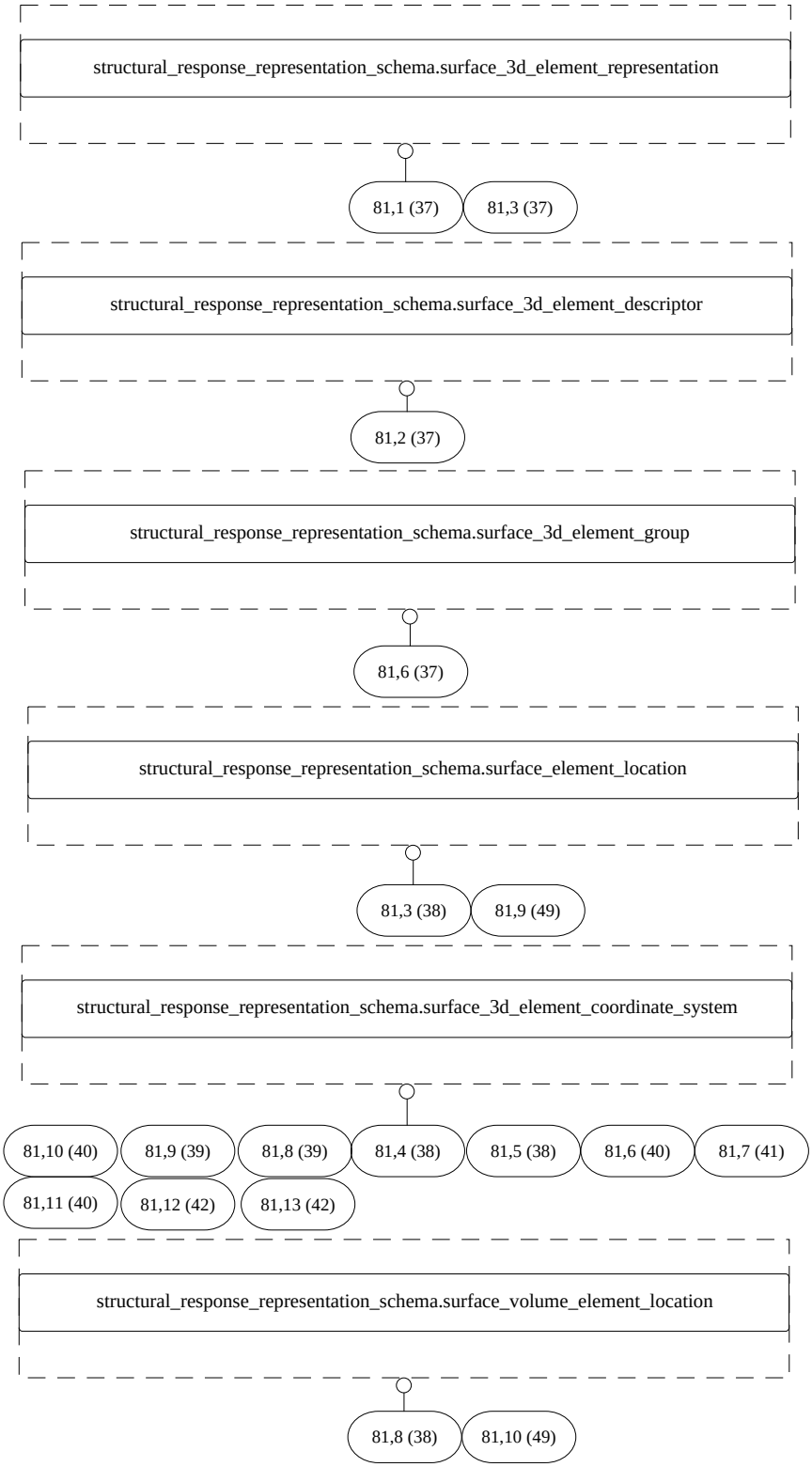

Figure D.81 – Finite element analysis control and result schema EXPRESS-G diagram, 81 of 86.

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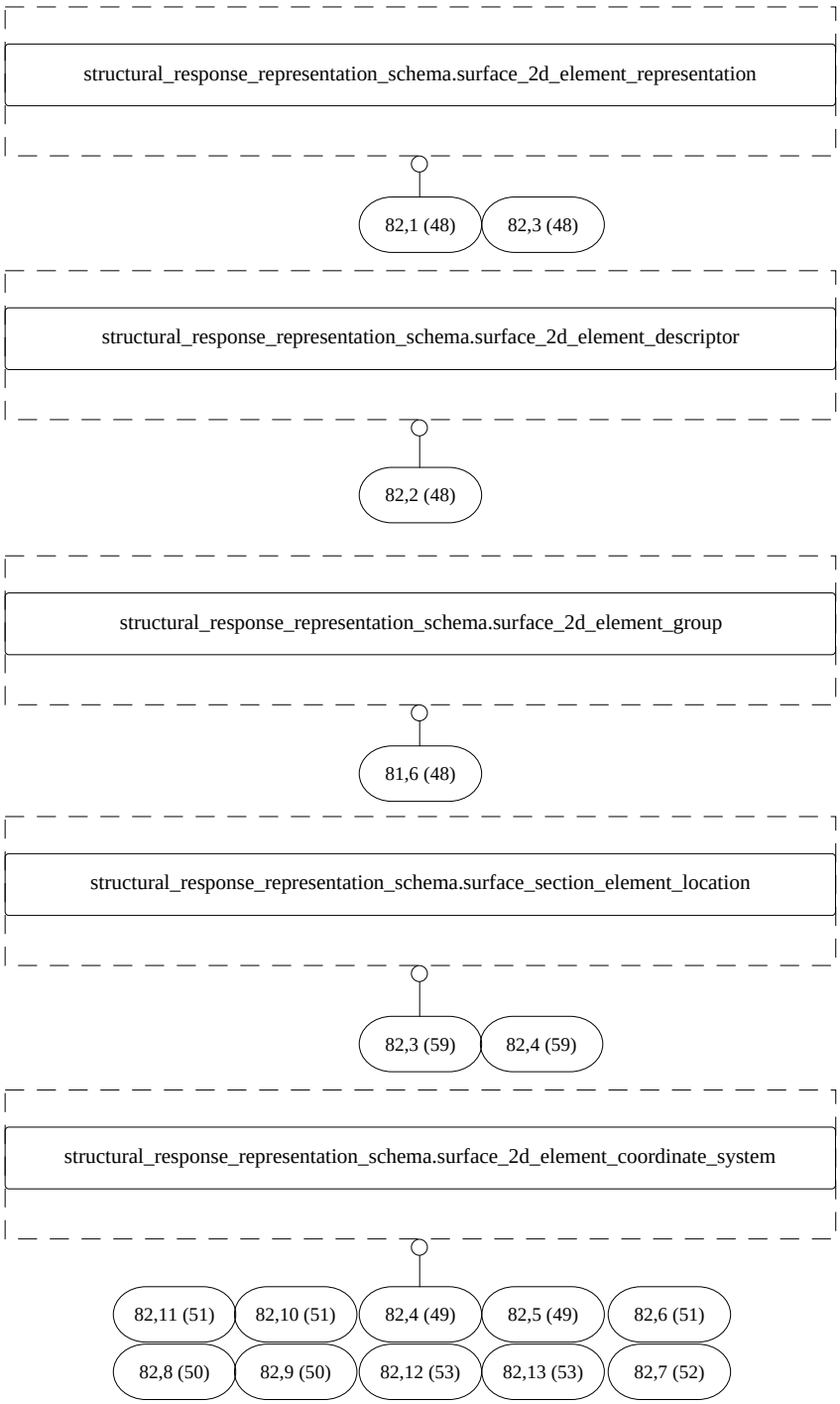

Figure D.82 – Finite element analysis control and result schema EXPRESS-G diagram, 82 of 86.

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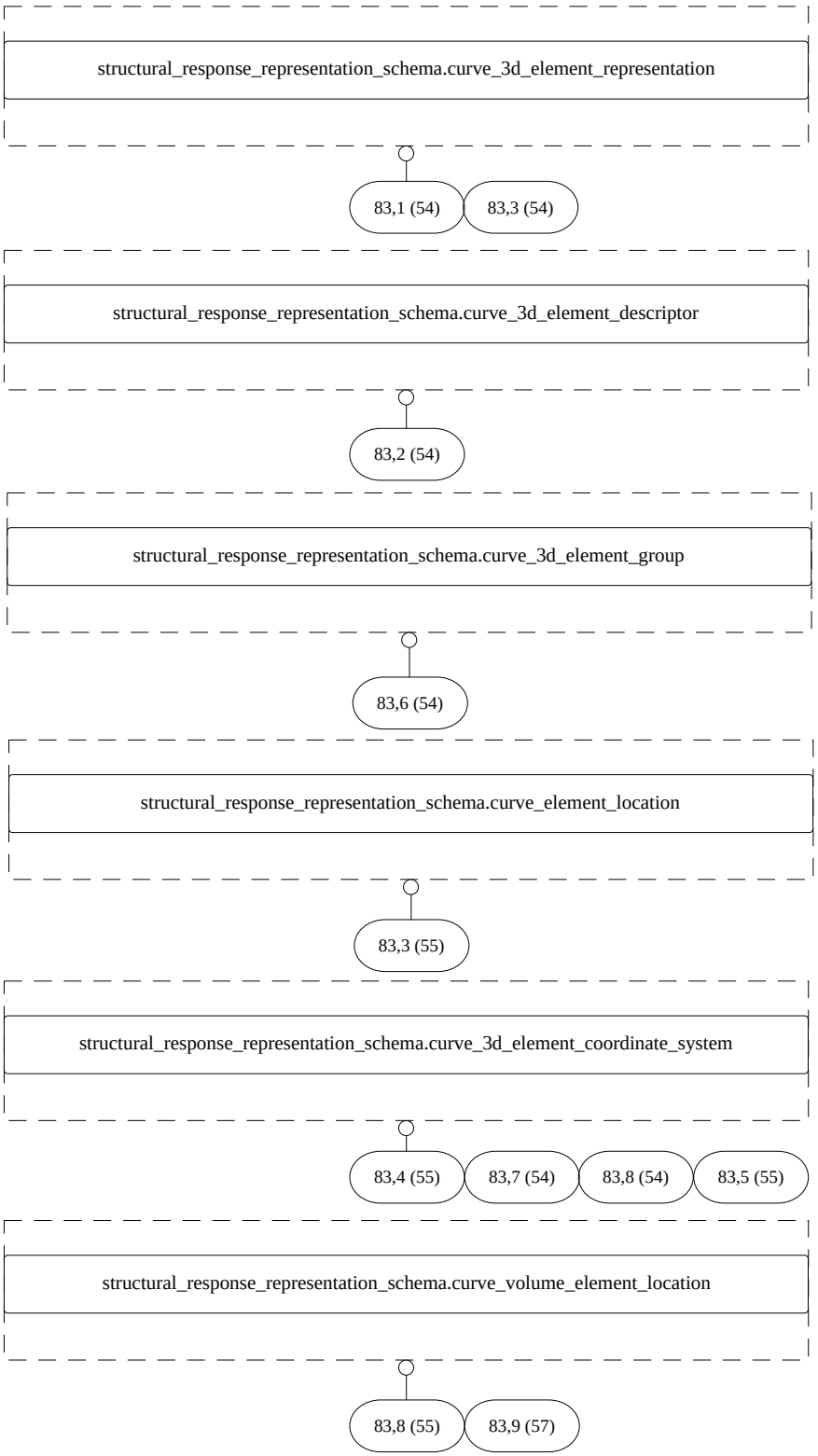

Figure D.83 – Finite element analysis control and result schema EXPRESS-G diagram, 83 of 86.

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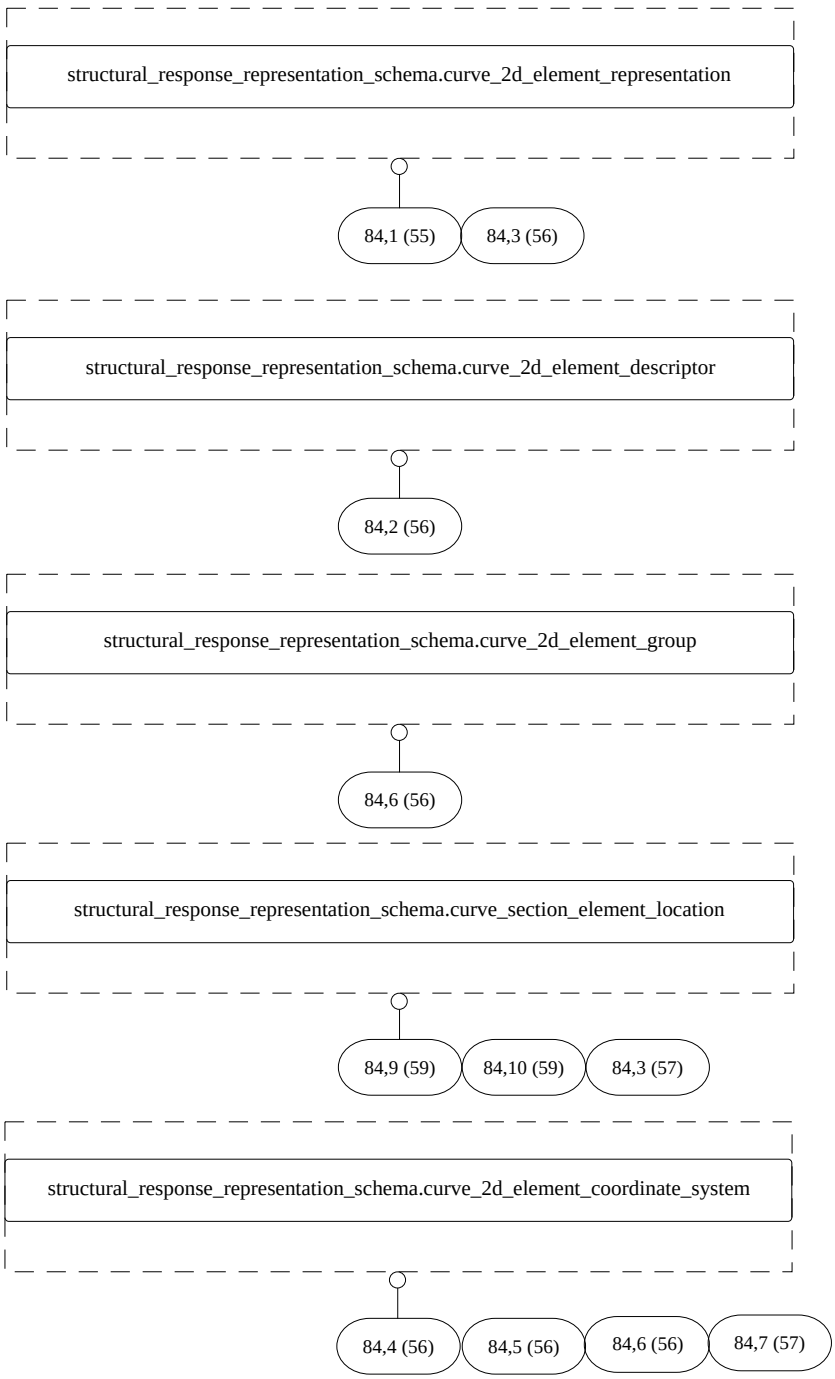

Figure D.84 – Finite element analysis control and result schema EXPRESS-G diagram, 84 of 86.

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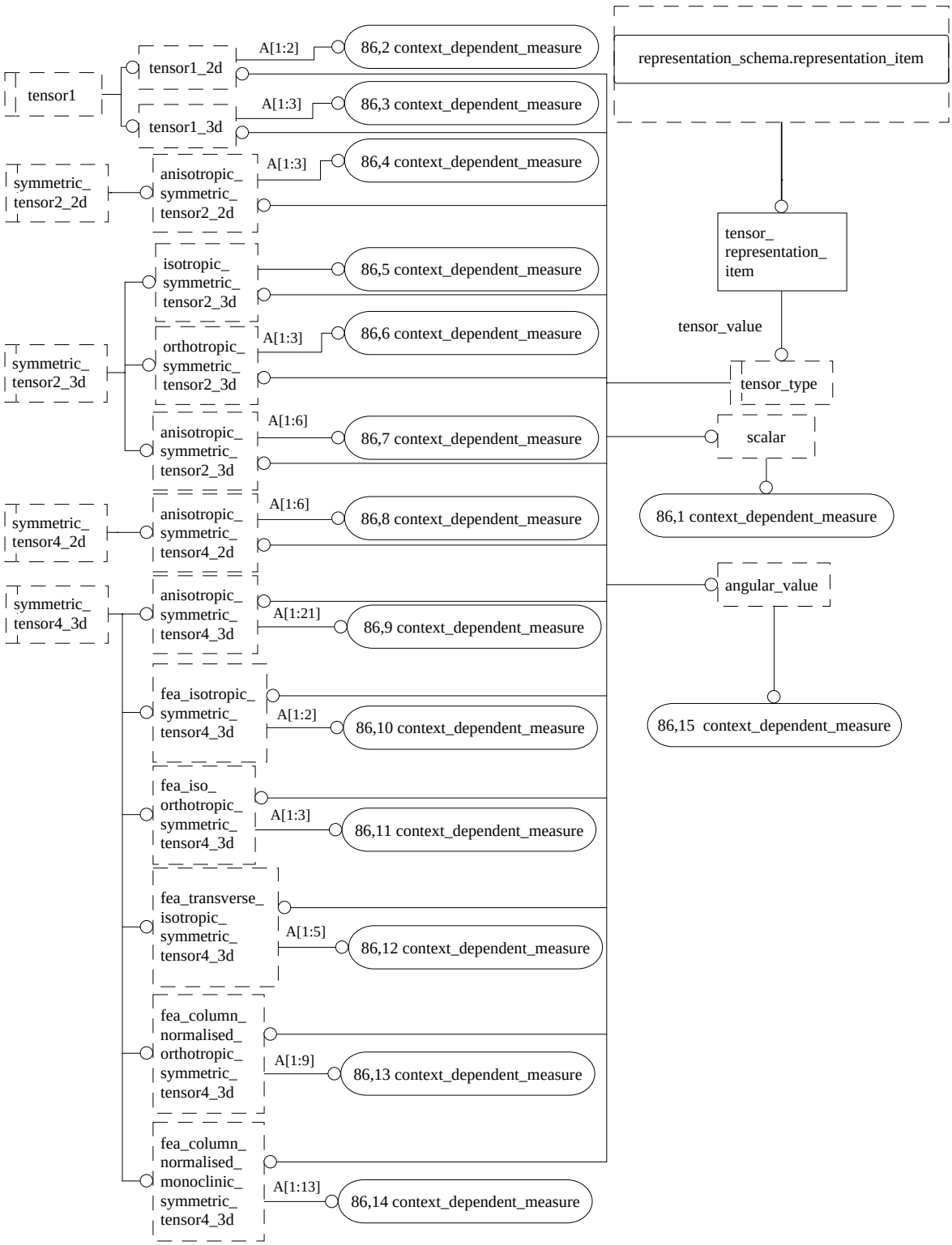

Figure D.85 – Scalar vector tensor schema EXPRESS-G diagram, 85 of 86.

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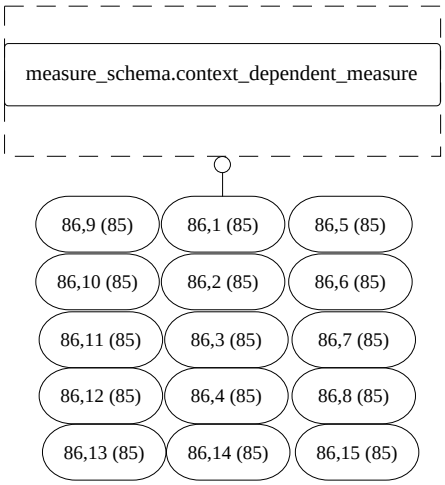

Figure D.86 – Scalar vector tensor schema EXPRESS-G diagram, 86 of 86.

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Annex E
(informative)

Finite element multi-disciplinary and nonlinear analysis extensions

The purpose of this annex is to provide a top-level description of how the FEA information model will eventually support an integrated analysis environment. The scope of the FEA information model is multi-disciplinary, extending across all analysis disciplines necessary for design verification as illustrated in Figure E.1. In addition this annex will describe how the FEA information model was designed to be easily adapted to nonlinear analyses.

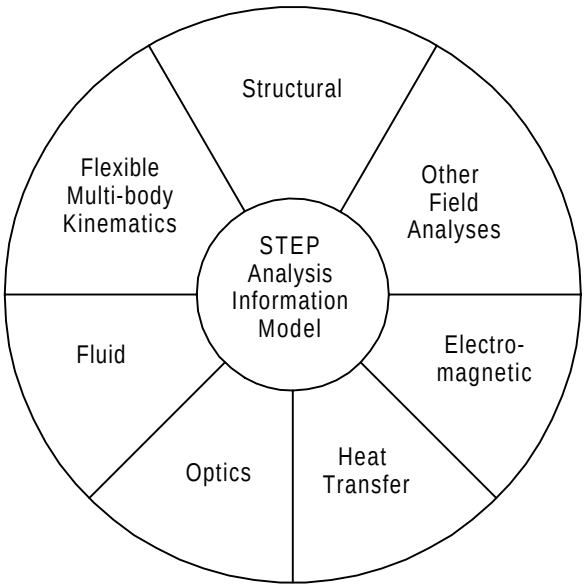

Figure E.1 – Multi-disciplinary analysis environment

Each of the disciplines has existing or potential FEA application, either uncoupled or coupled to other disciplines, with bounding interface information requirements as shown in Figure 1. While this part of ISO 10303 of the STEP FEA information model emphasises structural analysis applications, the architecture is sufficiently generic and open to accommodate other disciplines as required. The FEA information model will cover all the informational needs of the analyst and include all the information pertaining to definition of the finite element models, controls and results. The model will accommodate multi-level substructuring within an analysis discipline as well as across disciplines.

Multi-levelled substructuring was considered in the design of the FEA information model by implementing an approach that “wraps around” the existing information model. This approach was selected for

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minimum impact on the existing model so that a usable portion of the FEA information model could be published without the prospect of a large scale revision to support substructuring.

Within each analysis discipline a hierarchy of analysis types is planned. The goal is to provide as common an analysis architecture as practical. The results state definition packet concept forms the interdisciplinary interface. Note that the interpolation of information to this common information structure is out of scope. As multi-disciplinary analysis is addressed this architecture will be expanded. Candidate analysis types to be supported by the FEA information model include:

a) Analysis - Structural

    1) Linear

        i) Static thermo-structural;

        ii) Bifurcation buckling;

        iii) Transient response;

        iv) Frequency response.

    2) Nonlinear

        i) Static thermo-structural;

        ii) Buckling;

        iii) Transient response;

        iv) Frequency response;

        v) Creep.

b) Analysis - Heat Transfer

c) Analysis - Fluid

d) Analysis - Electromagnetic

e) Analysis - Flexible Multi-body Kinematics

f) Analysis - Optic

The FEA information model has been intentionally designed to accommodate nonlinear analyses. The areas to be detailed to complete this expansion include the definition of nonlinear element types, material property representations, and element output scalars, vectors, and tensors. The basic structure to

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represent the input and output of a nonlinear analysis, however, has been accounted for in the information model design. Each of these areas has been designed to be easily expanded without impacting the current information model.

One of the main aspects of nonlinear analyses is the use of output information from a previous iteration to serve as input for the next. This information representation capability has been included in the specification of analysis control and state definition. The extensions for nonlinear analyses to this area would need only be the delineation of specific types of nonlinear analysis steps and states. Because of this approach the majority of the information needed to exchange a nonlinear analysis is currently in place.

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