# Federal Building and Fire Safety Investigation of the World Trade Center Disaster

## National Construction Safety Team Advisory Committee Meeting

# Project 6 – Structural Fire Response and Collapse Analysis

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# Disclaimer

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# Project Tasks

This project has the following tasks:

- Evaluate the structural response of floor and column subsystems under fire conditions.
- Evaluate the response of the WTC towers under fire conditions, both with and without aircraft impact damage.
- Identify and evaluate candidate hypotheses for initiation and propagation of collapse and estimate the uncertainty for probable collapse initiation and propagation mechanisms.
- Conduct tests of structural components and systems under fire conditions.
- Report on the performance of open-web steel trussed joist systems in fire.
- Analyze the response of WTC Building 7 under fire conditions.

# Relationship to other projects…

Project 6 relies heavily on information provided by other projects, specifically,

- Reference structural models of typical floor and exterior wall subsystems and of each WTC 1 and WTC 2 tower (Project 2)
- Extent of aircraft damage to WTC 1 and WTC 2 (Project 2)
- Mechanical properties of the steels, welds and bolts used in the construction of the towers including elastic, plastic and creep properties from 20ºC to 700ºC (Project 3)
- Thermal properties of spray-on fire resistant materials (SFRM) (Project 5)
- Temperature-time histories for various components, sub-systems and systems for both standard fires (e.g., ASTM E-119) and real fires based on fire dynamics simulations (Project 5).

# Objectives

To determine the structural response of the WTC Towers to aircraft impact and internal fires and to identify the most probable structural collapse mechanisms.

- ❑ Task 1: Components and Subsystems
- ❑ Task 2: Global Analysis without Impact Damage
- ❑ Task 3: Global Analysis with Impact Damage
- ❑ Task 4: Evaluation of Collapse Hypotheses

# Task 1: Components and Subsystems

Develop detailed nonlinear structural models of the floor system and exterior wall section and evaluate performance for service loads and elevated structural temperatures.

- Single exterior panel section for strength under thermal effects
- Floor section behavior for strength under thermal effects (80-in wide section)
- Truss seat connection for strength under thermal effects
- Full floor models of mechanical floor and typical office floor
- Multi-panel exterior wall section with connections

Identify dominant failure modes and parameters that strongly influence the analysis results for critical components and subsystems.

Develop approaches to simplify structural analyses for global modeling and analyses.

# Status - Task 1

The truss model, with knuckle and seat components, includes all potential failure modes that may occur under loading and thermal conditions, though the actual sequence of failure may differ under other loading and fire conditions.

The truss model can capture the following:

- Temperature-dependent elastic material properties for both steel and concrete
- Temperature-dependent steel plasticity
- Buckling of truss members
- Failure of knuckle causing loss of composite action
- Failure of studs on the strap
- Failure of stud on the spandrel
- Failure of the exterior and interior truss seats

# Status - Task 1

The exterior wall model consists of 3x3 exterior wall panels (9 columns by 9 spandrel beams) and includes all potential failure modes (columns and splices) that may occur under loading and thermal conditions.

The exterior wall model can capture the following:

- Column collapse due to large lateral deflections
- Column buckling due to loss of lateral bracing at floors
- Failure of column splice bolts and spandrel splice bolts

# Status - Task 1

The full floor model consists of all steel trusses (main trusses and bridging trusses), truss connections, perimeter and core columns, core framing beams, and concrete floor slab and includes all potential failure modes that may occur under loading and thermal conditions.

The full floor model can capture the following:

- Floor sagging due to:
  - Loss of stiffness at high temperatures
  - Yielding or buckling of critical truss members
  - Loss of composite action due to knuckle failure
- Loss of floor support (failure of interior or exterior floor truss seated connections)
- Expansion of floor system and resulting column forces

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# Task 2: Global Analysis Without Impact Damage

Determine the structural response to large fires without impact damage.

- Develop global model of one tower without impact damage for nonlinear analysis of building regions affected by fire.
- Analyze the structural response to ASTM standard fires and one to three (1-3) representative building fire scenarios from Project 5.

Improve WTC Tower models for analysis with impact damage.

- Identify parameters that strongly influence analysis results.
- Develop approaches to simplify models for global analyses.

# Task 3: Global Analysis With Impact Damage

Develop global model of each WTC tower with impact damage for nonlinear analysis of building regions affected by fire.

Analyze three to five (3-5) building fire scenarios provided by Project 5 for each tower and determine:

- Time-sequence of events,
- Mode of failure or capacity reduction for each critical member in the sequence and associated temperatures,
- Load redistribution during the sequence of events, and
- Agreement between analysis and observed performance.

Conduct parametric studies of the global analyses to identify influential parameters.

Repeat analyses for final fire scenarios. Identify most probable collapse initiation sequence.

# Status – Tasks 2 and 3

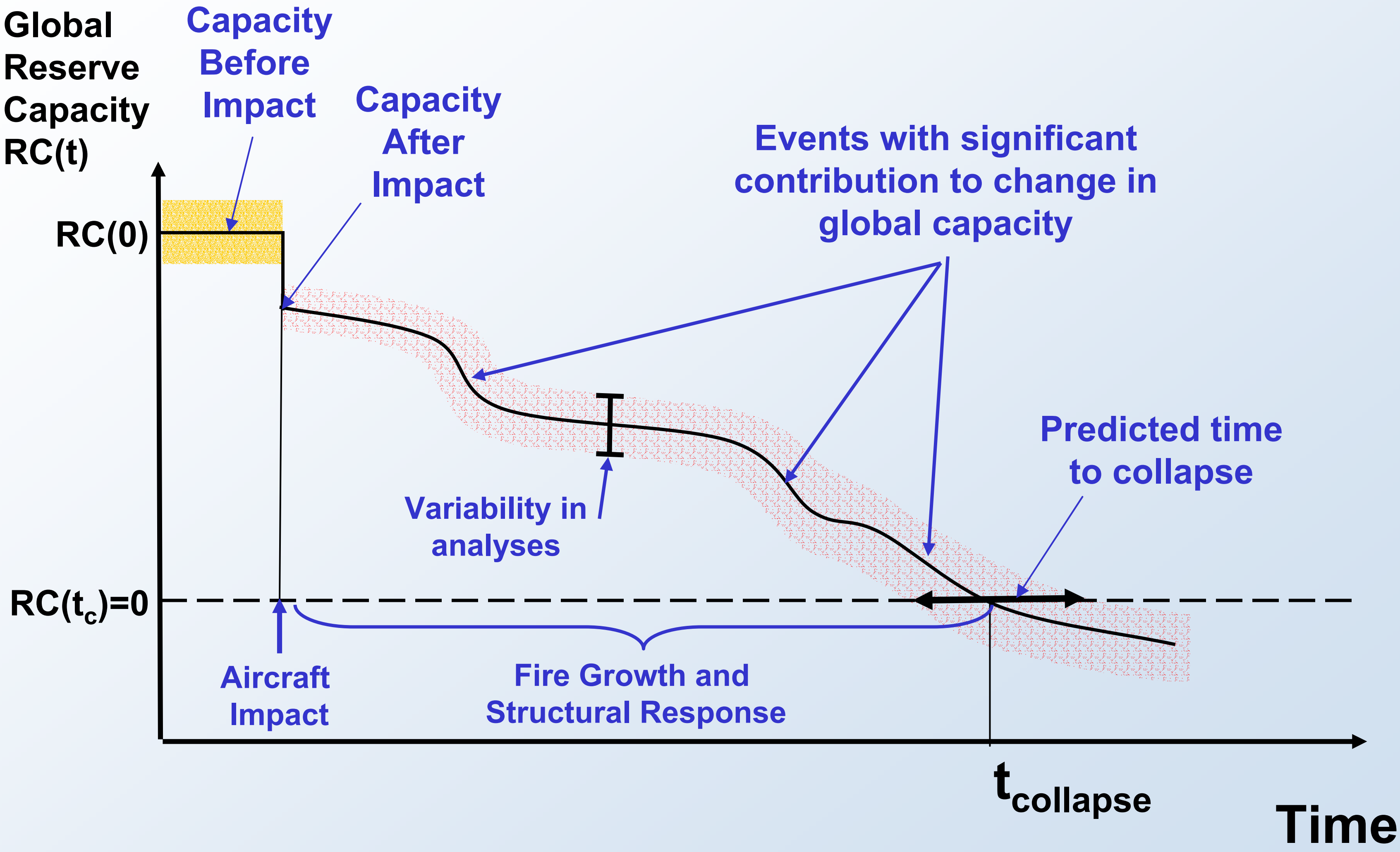
Work is under way to conduct global analyses:

- Global models have been developed in SAP and ANSYS, based upon the Project 2 Reference Models.
- Conditions include (median, upper bound, lower bound values):
  - Impact damage to structure
  - Impact damage to fireproofing
  - Debris distribution on floors
  - Structural time-temperature histories

# Status – Tasks 2 and 3

- ❑ Structural system capacity for the following states:
  - Before impact damage
  - After impact damage
  - During fire growth and spread
- ❑ Extent of load redistribution within and between core and exterior framing systems via hat truss and/or floor system.
- ❑ Conditions required for global instability (collapse initiation).

# Probabilistic Approach to Evaluate Changes in Global Capacity



# Task 4: Evaluation of Collapse Hypotheses

Identify candidate hypotheses for initiation and propagation of collapse.

Evaluate hypotheses for collapse initiation and propagation, including the role played by columns, floors, connections, and hat truss.

Estimate variability of probable collapse initiation and propagation mechanisms.

Identify most probable structural collapse sequence(s).

# Status – Task 4

NIST has developed a working hypothesis that identifies the chronological sequence of major events related to the collapses.

In progress…

- Specific load redistribution paths and damage scenarios are under analysis for the collapse of each tower.
- Timeline of fire and structural observations from photographic, video, and interview records is being developed.

# Review of Progress Under Task 1

The scope of work under Task 1 includes:

- Develop and validate ANSYS models of the full floor and exterior wall subsystems,
- Evaluate the structural responses of these subsystems under dead and live loads and elevated structural temperatures,
- Identify failure modes and failure sequences, and the associated temperatures and times-to-failure, and
- Identify simplifications for the global models and analyses.

# Review of Progress Under Task 1

**The following will be covered…**

Materials

- Concrete
- Steel

Full Floor Model

- Knuckle
- Truss Seats
- Truss

Exterior Wall Model

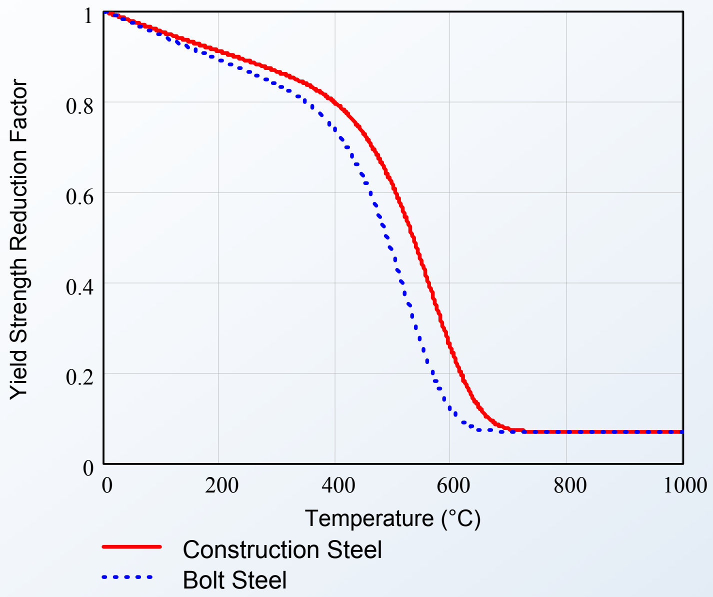
- Column panel
- Column Splice
- Exterior Wall

# Materials

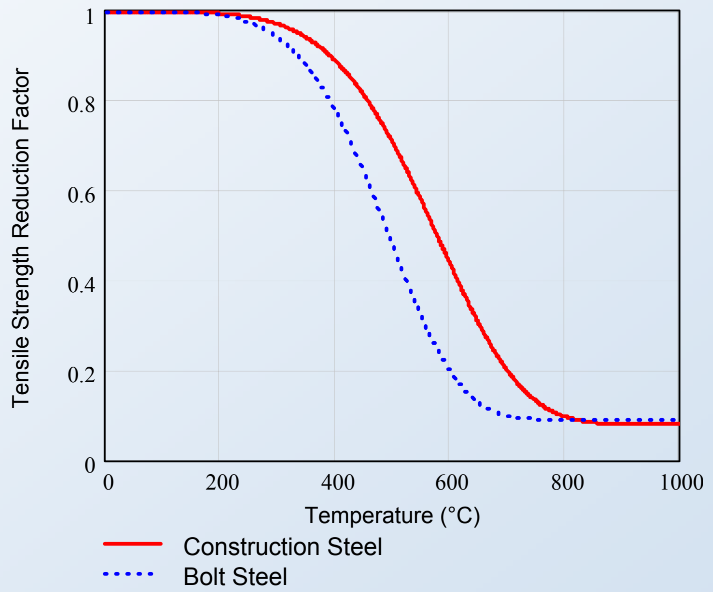
# Steel

- Project 3 has provided properties of 28 different types of steel used in WTC 1 and 2 and load-elongation test data of A325 bolts.
- Temperature-dependent properties that are the same for all types of steel
  - Modulus of elasticity,
  - Poisson's ratio,
  - Instantaneous coefficient of thermal expansion,
  - Yield strength reduction factor, and
  - Tensile strength reduction factor.

# Steel Properties at Elevated Temperature

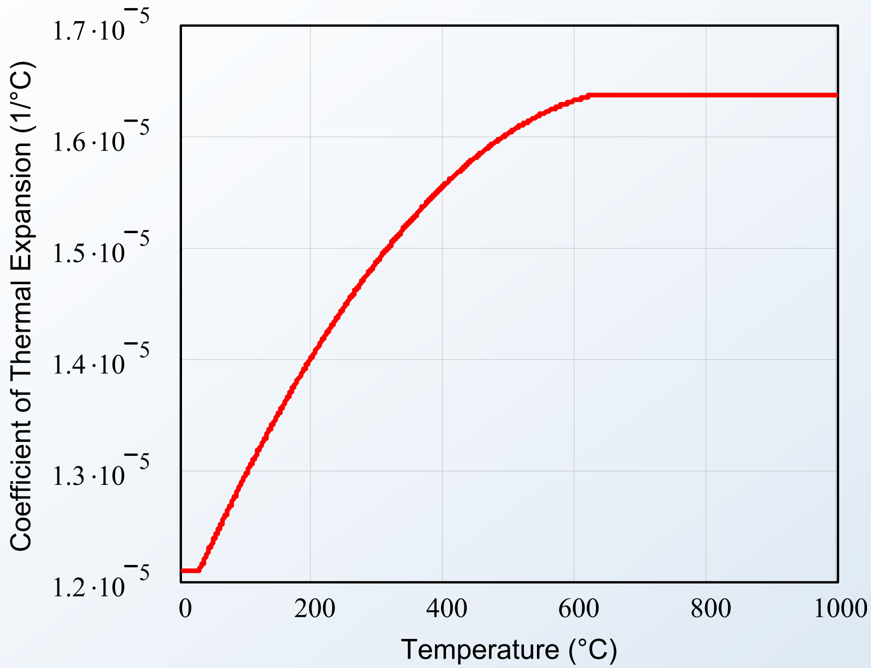



**Yield Strength Reduction Factor**

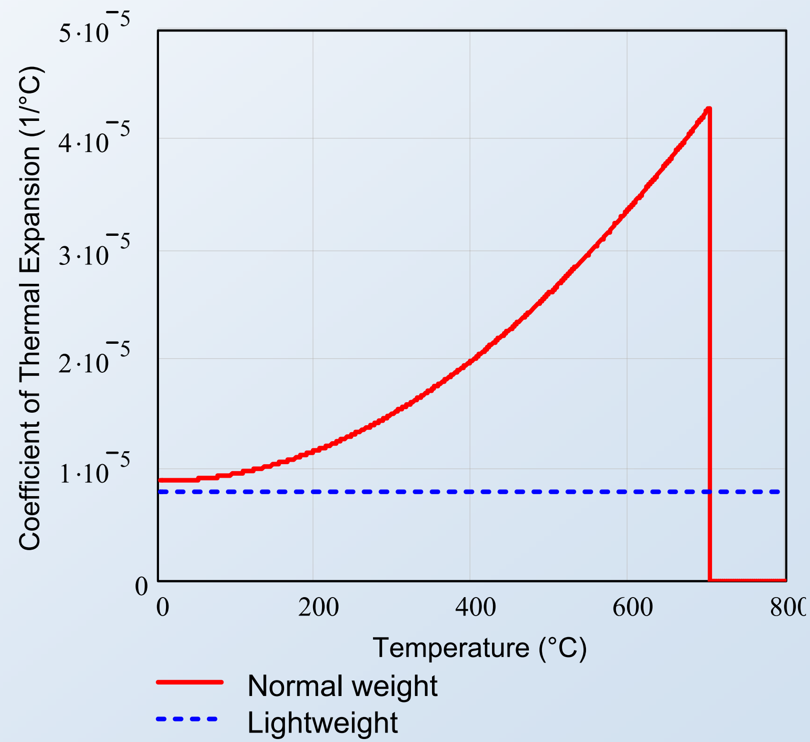



**Tensile Strength Reduction Factor**

# Instantaneous Coefficient of Thermal Expansion

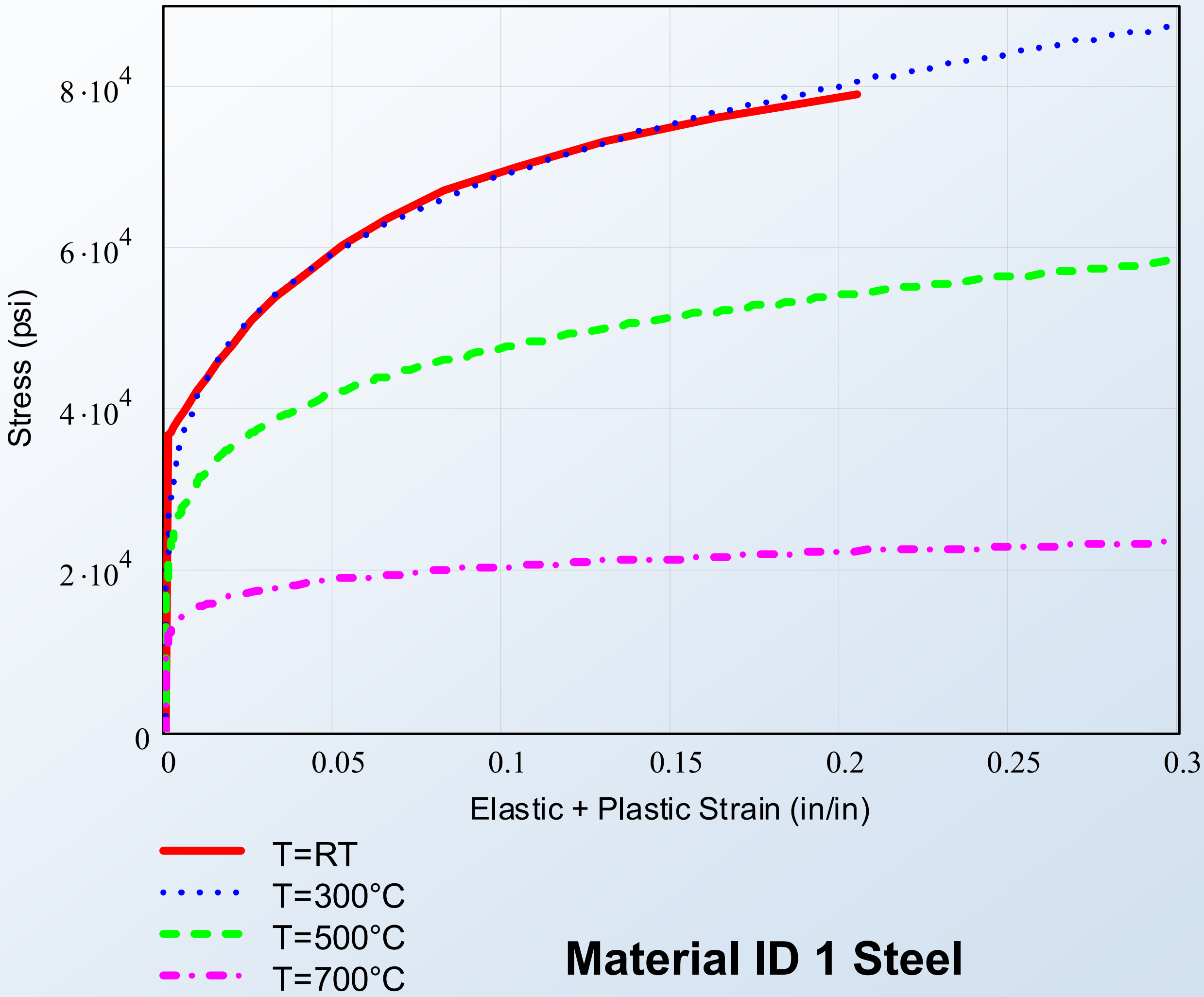



Steel




Concrete

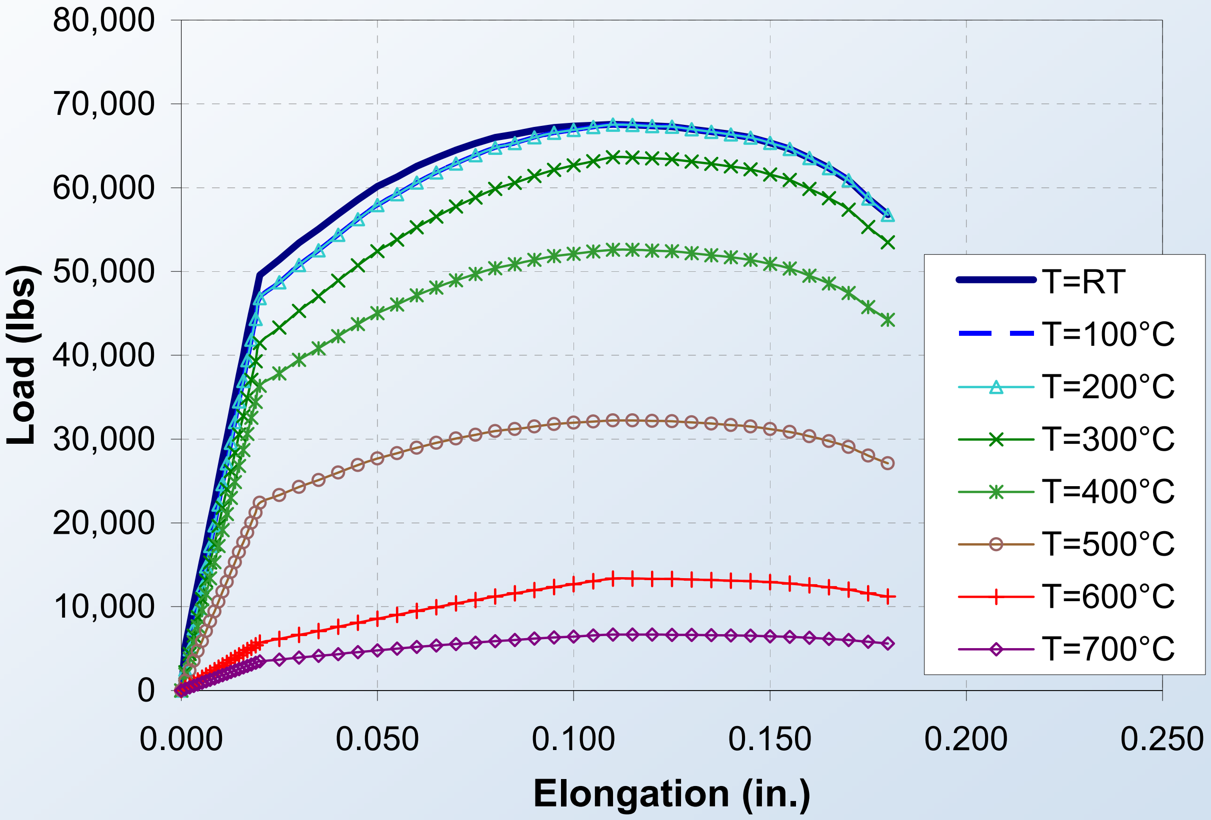
# Steel – Plasticity



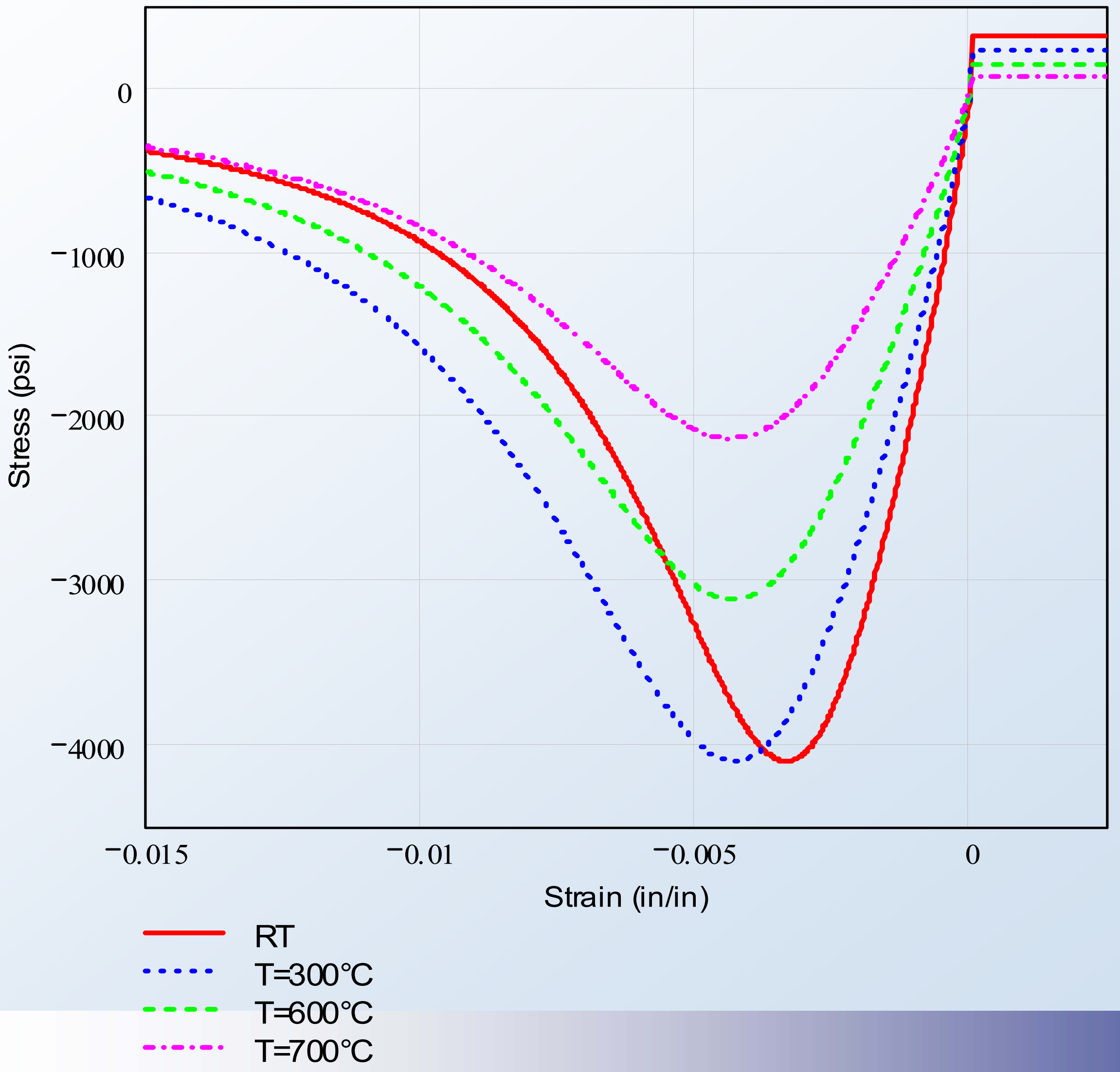

**Material ID 1 Steel**

# Bolts

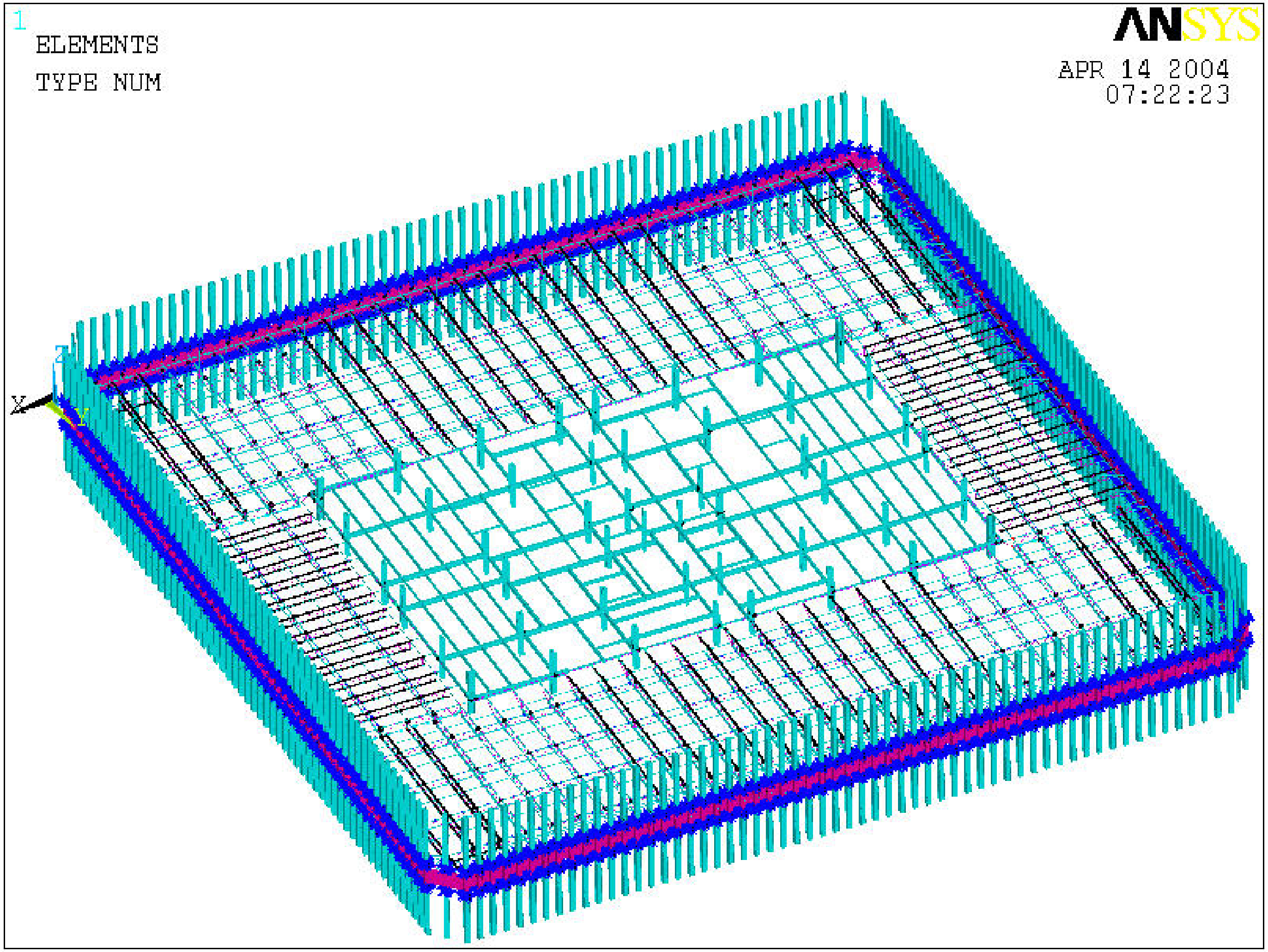
Based on test data for 7/8 in. diameter A325 bolt with a length of 4 in., load-elongation relationships at elevated temperatures of a 7/8 in. A325 bolt have been constructed.



# Concrete – Stress-Strain Relationship in ANSYS



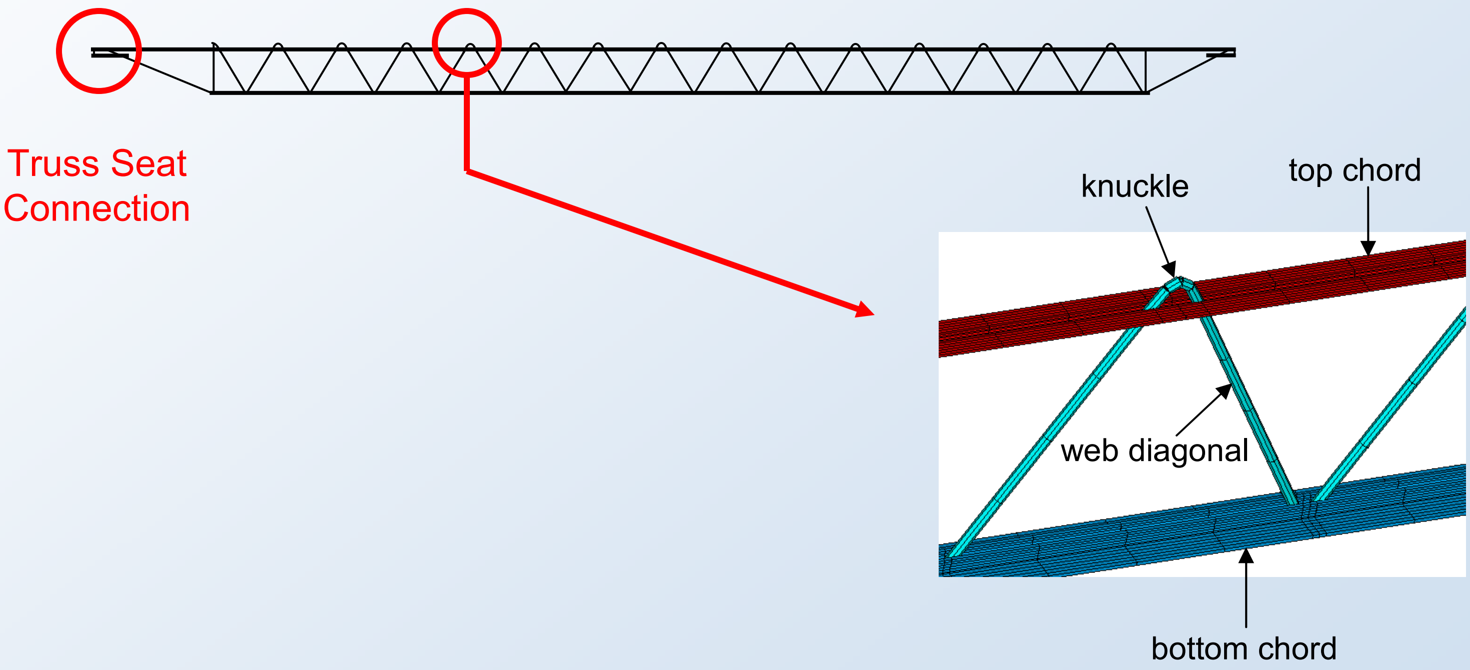
# Full Floor Model



# Full Floor Model

## Component Models

- Knuckle
- Truss Seat Connections
- Truss and Exterior Column



# Detailed Knuckle Analysis

Goals:

- Determine failure strength of knuckle-concrete composite connection at room and elevated temperatures.
- Develop a simplified representation for global model.

Failure Mode:

- Cracking and crushing of concrete leading to loss of composite action of floor system.

Validation:

- Comparison with available test data.

Analysis:

- ANSYS – LS Dyna
- Concrete Material Model:  Psuedo Tensor
- Knuckle/Concrete Interface
  - Bonded
  - No Friction Contact

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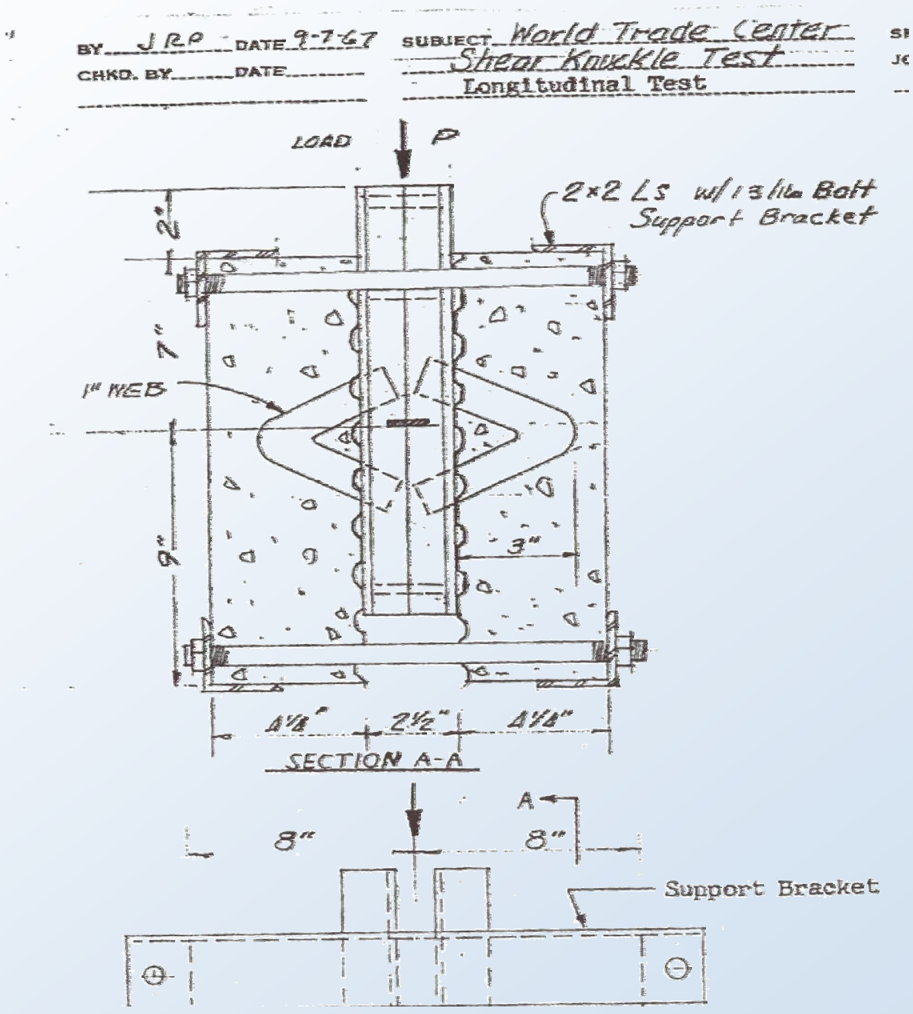
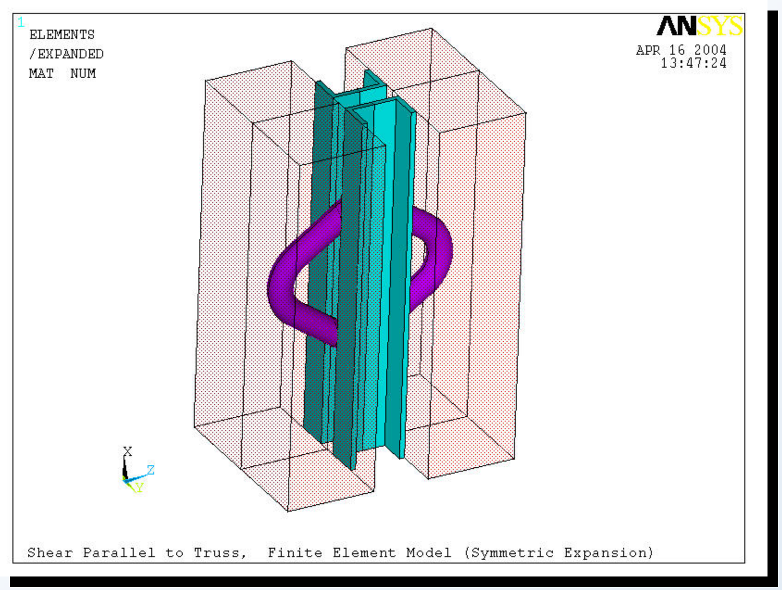
# Laclede Tests of 1967

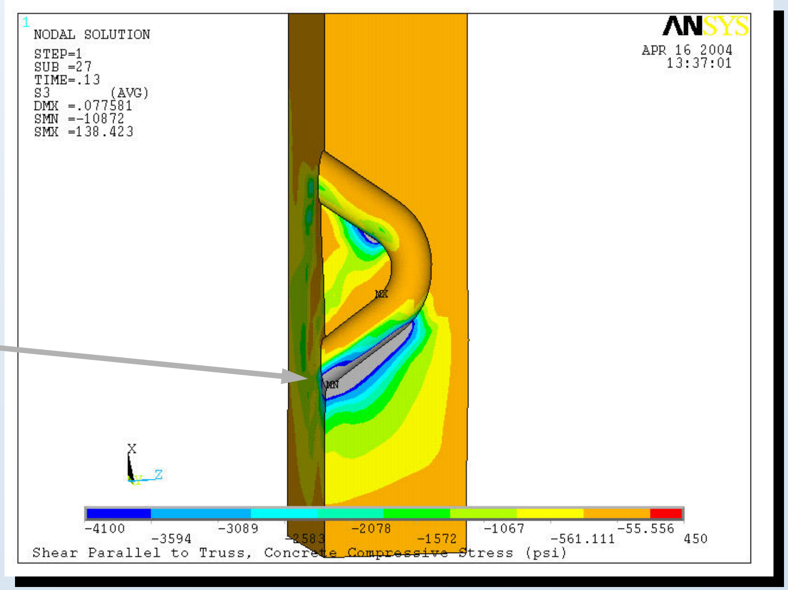



Drawing provided by Laclede Steel.

# Longitudinal Shear Model – Compressive Stress




Crush Region in Gray



# Knuckle Shear Strength

| Temperature ($^{o}$C) | | | | Shear Direction | |
|---|---|---|---|---|---|
| Hot Gas | Knuckle | Concrete | $f_c(T)/f_c$ | Longitudinal (kip) | Transverse (kip) |
| RT - 450 | <375 | 300 | 1.00 | 30 | 30 |
| 650 | 550 | 450 | 0.80 | 24 | 24 |
| 850 | 725 | 600 | 0.63 | 19 | 19 |
| 1050 | 900 | 750 | 0.50 | 15 | 15 |

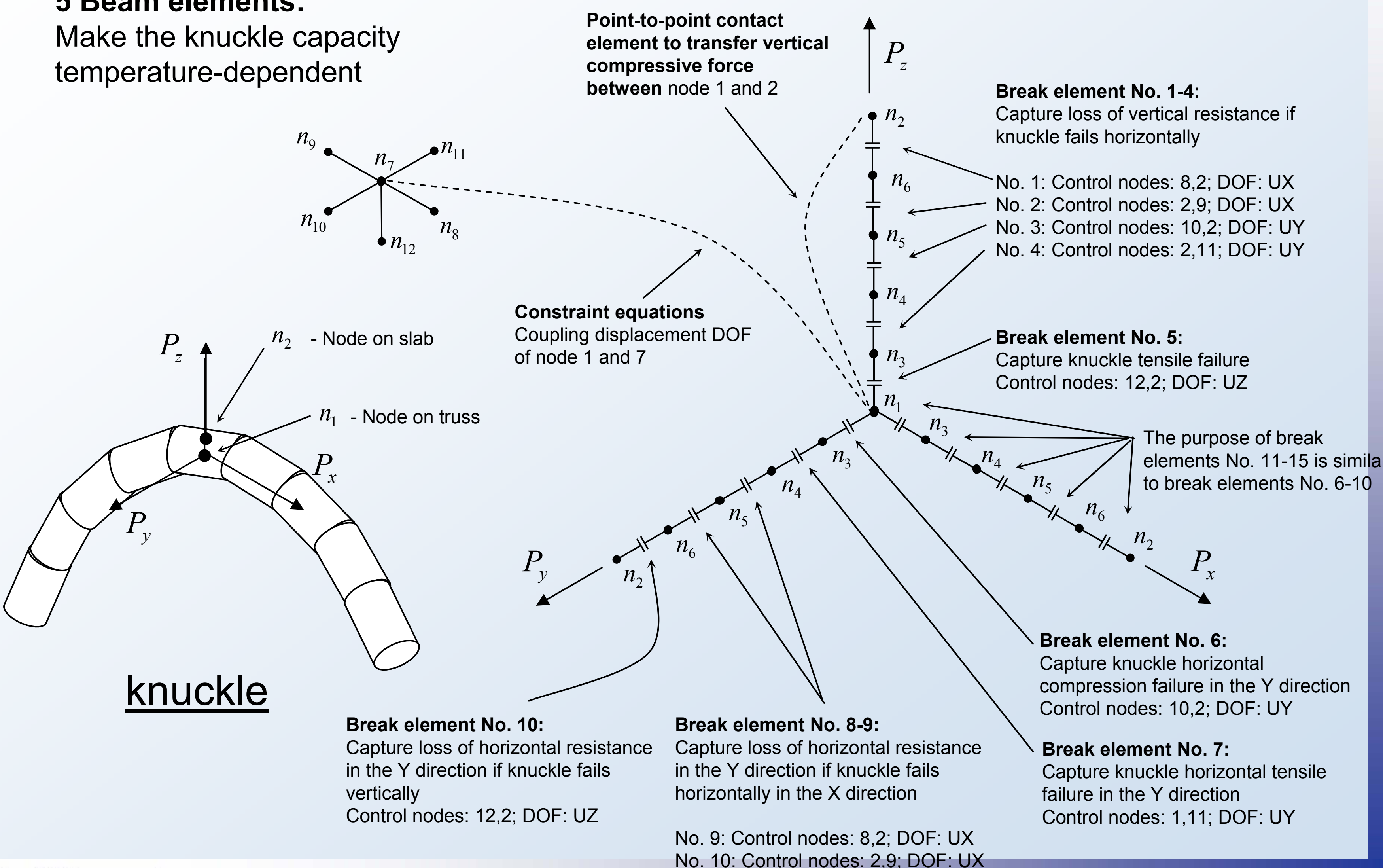
Knuckle shear strength is based on test /analysis results after adjusting for concrete strength.

Temperature effect on knuckle shear strength is proportional to concrete strength.

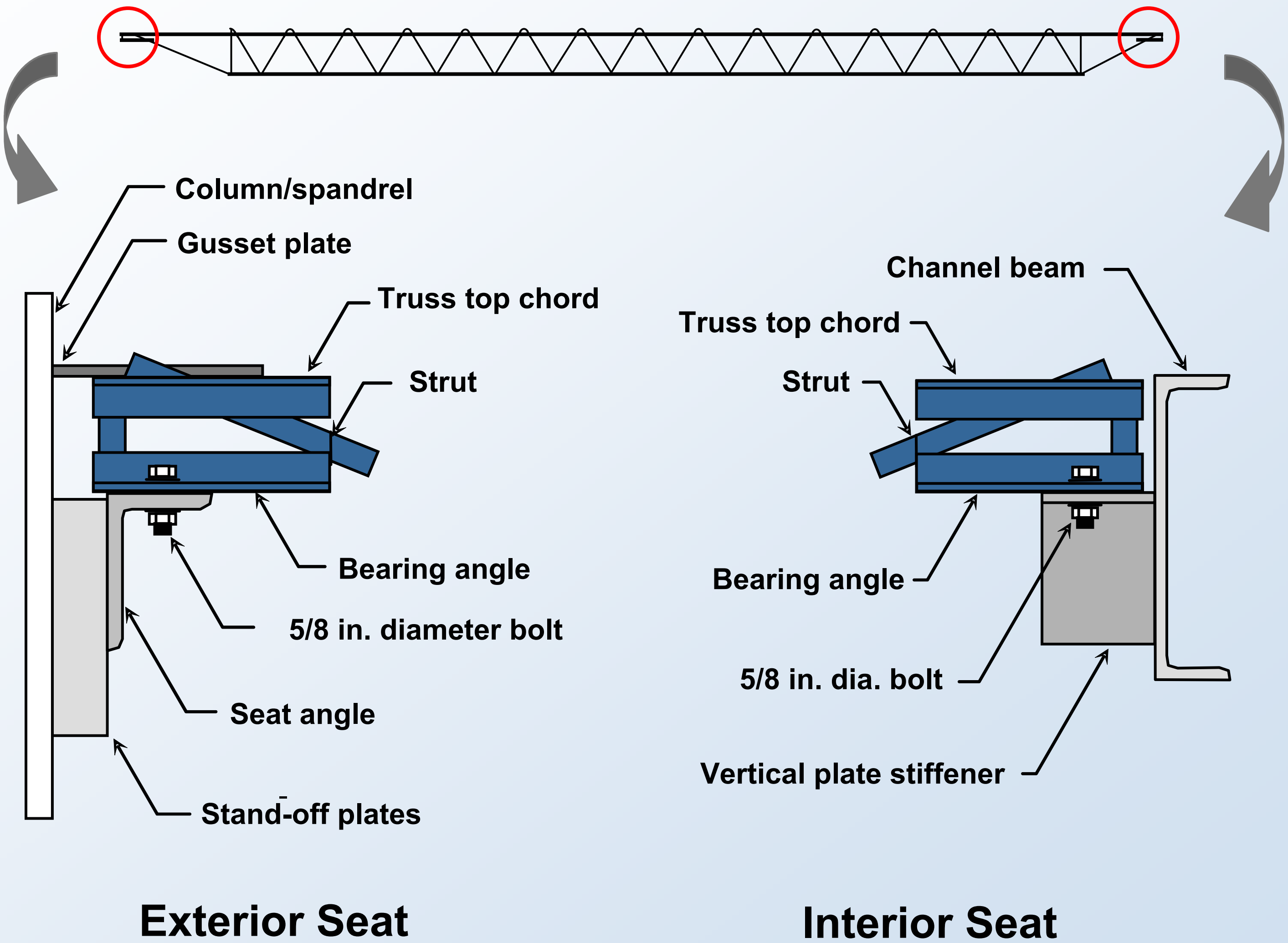
The knuckle is conductive and heats up the concrete in compression.

# Simplified model of knuckle

**5 Beam elements:**
Make the knuckle capacity temperature-dependent



# Truss Seat Connections



# Truss Seat Analysis

Goal:

- Determine failure of truss seats at room and elevated temperatures.

Failure Modes:

- Material yield or fracture
- Bolt shear failure
- Weld failure
- Bearing angles “walk off” support

Analysis:

- Linear elastic for load distribution
- Strength calculations per AISC LRFD

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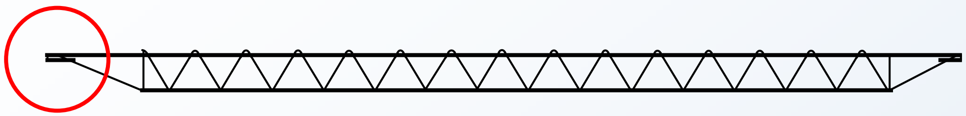
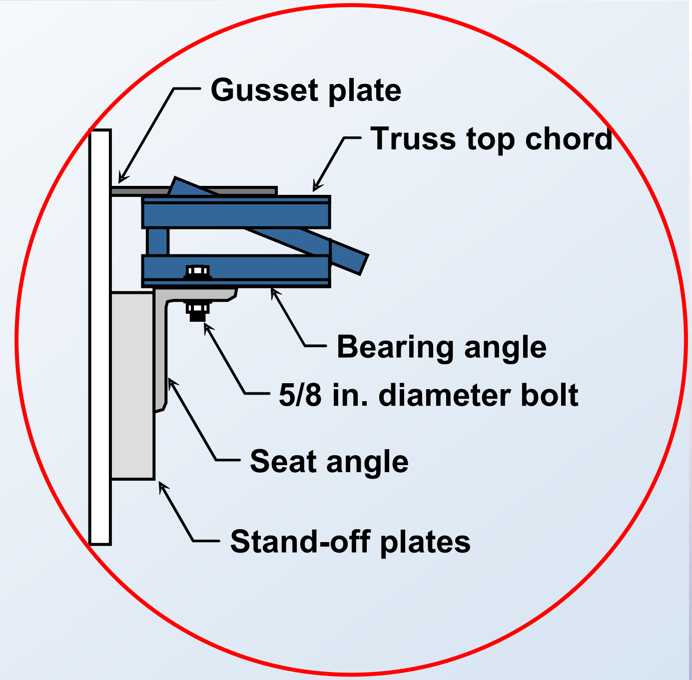
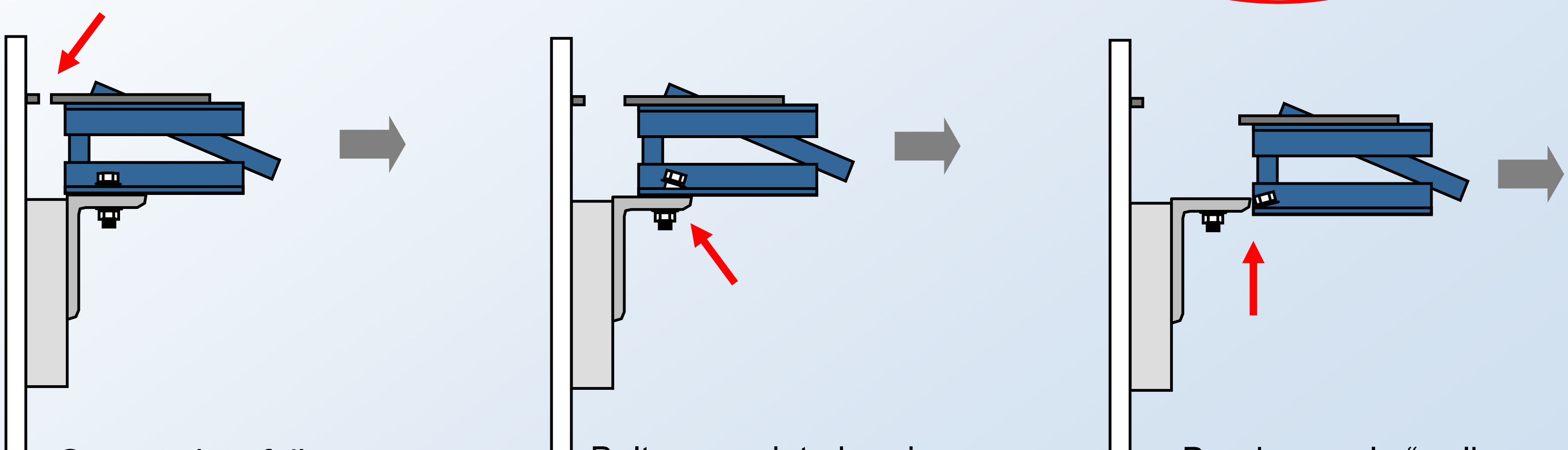
# Truss Seat Analysis






Possible failure sequence
under horizontal load…

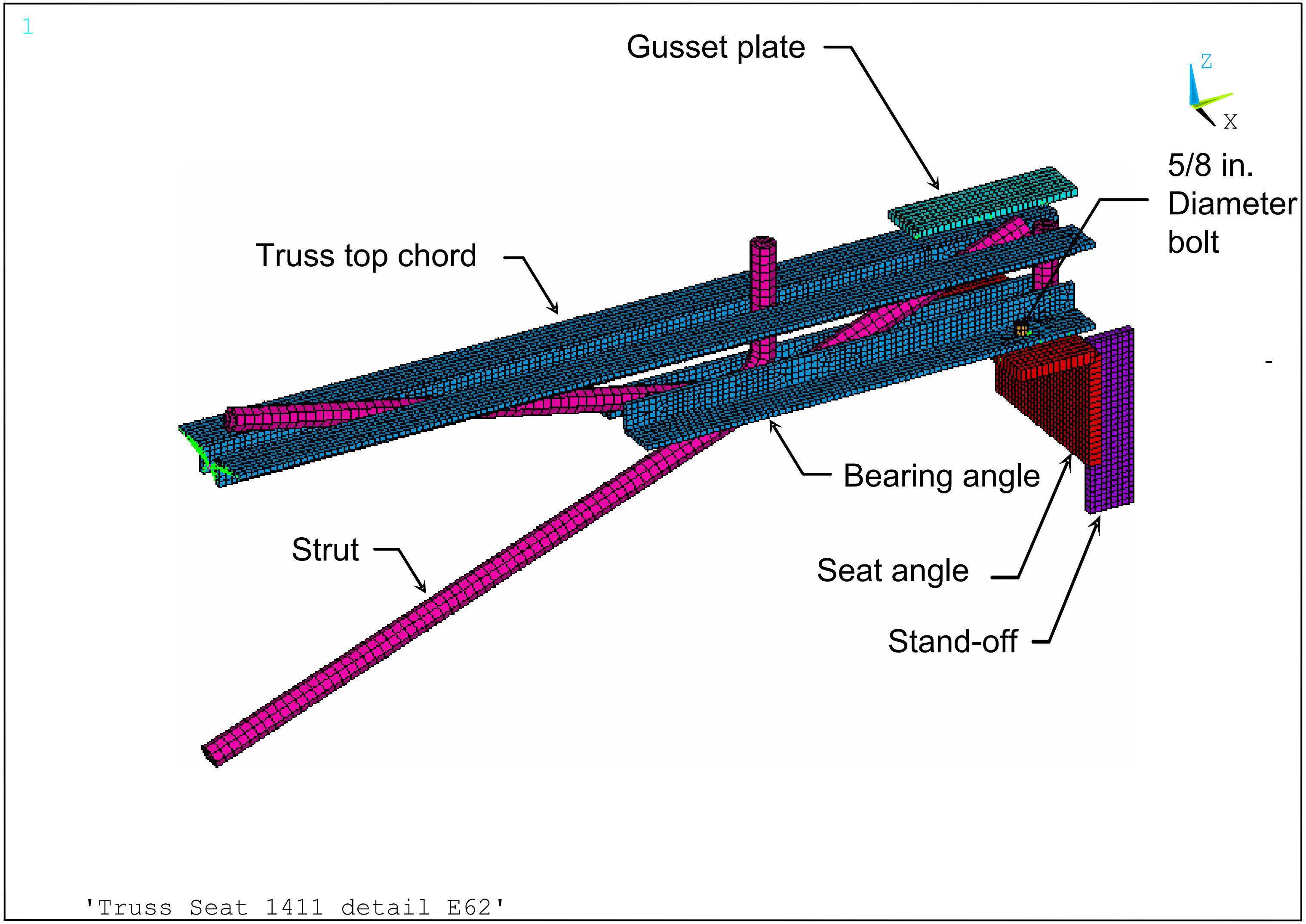


Gusset plate fails

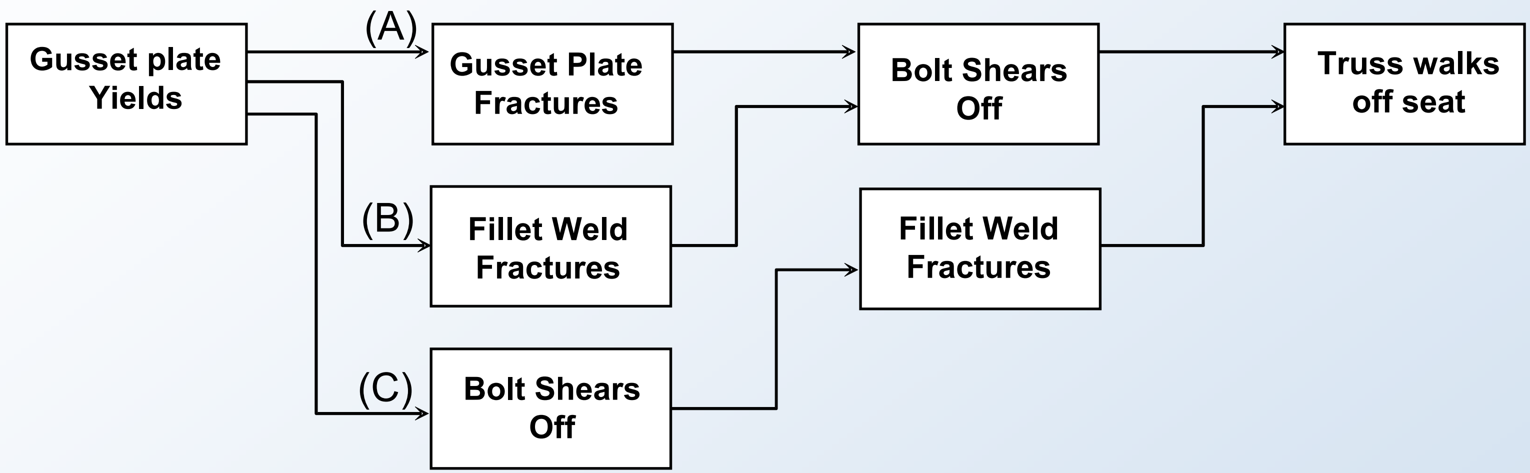
Bolt comes into bearing and shears off

Bearing angle “walks off” seat angle

# Finite Element Model of Exterior Seat

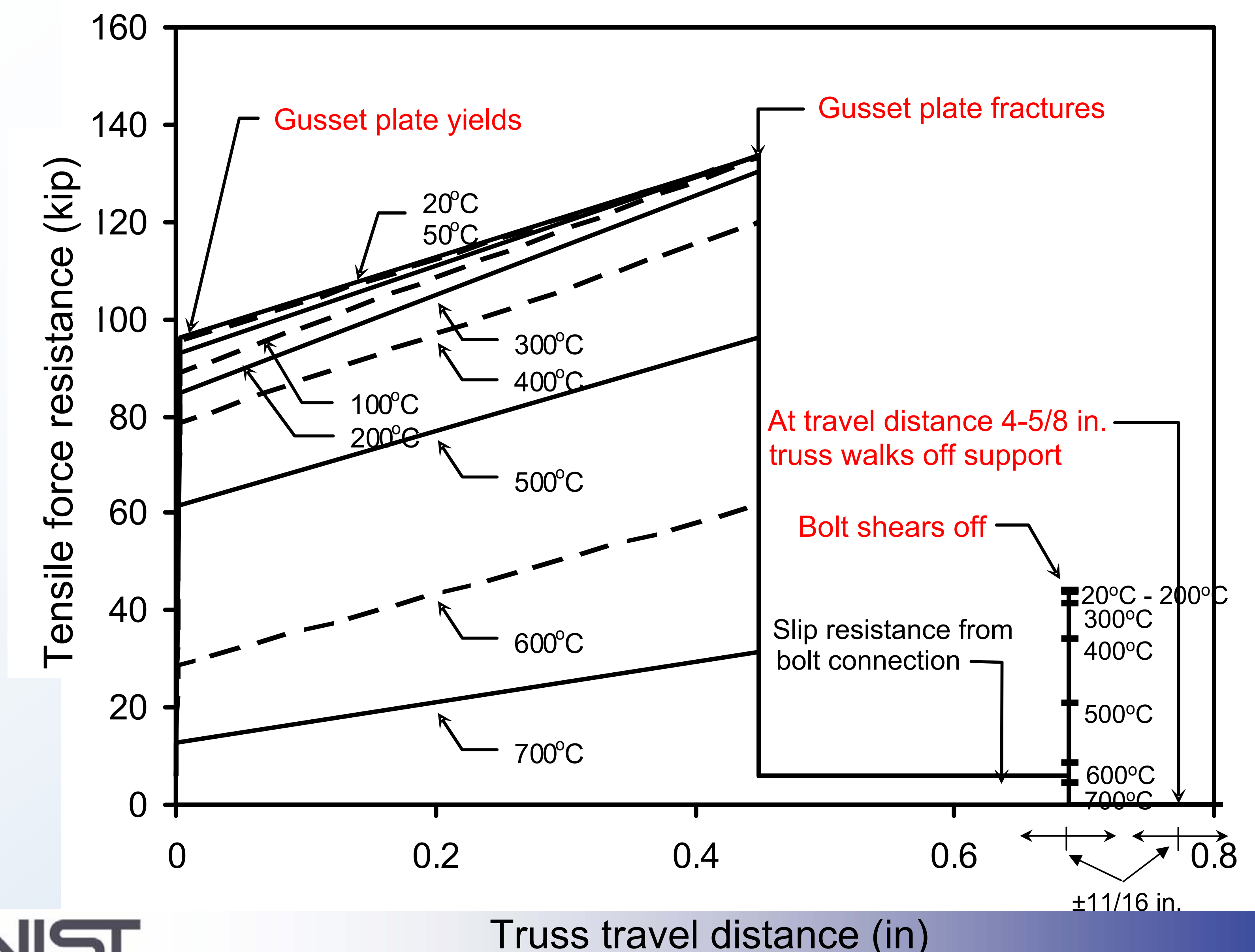


# Failure Sequence of Exterior Seats Against Tensile Force

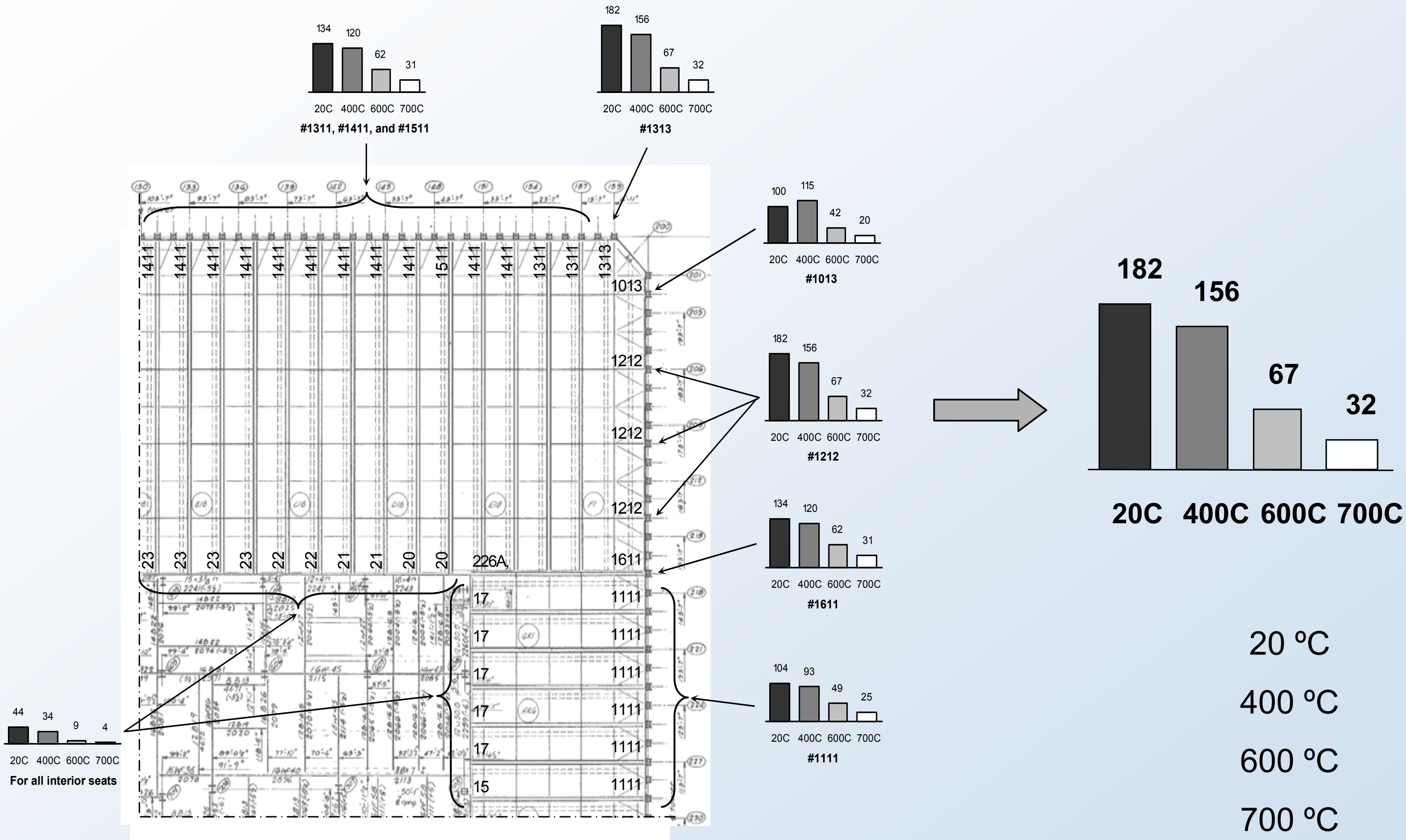



(A) Seat details 1111, 1311, 1411, 1511, and 1611 at all temperatures
(B) Seat detail 1013 at temperatures below 100$^{o}$C
(C) Seat details 1212 and 1313 at all temperatures, and detail 1013 at temperatures more than or equal to 100$^{o}$C

# Horizontal Tensile Force Resistance of Exterior Seat



# Horizontal Tensile Force Resistance of Exterior Seats

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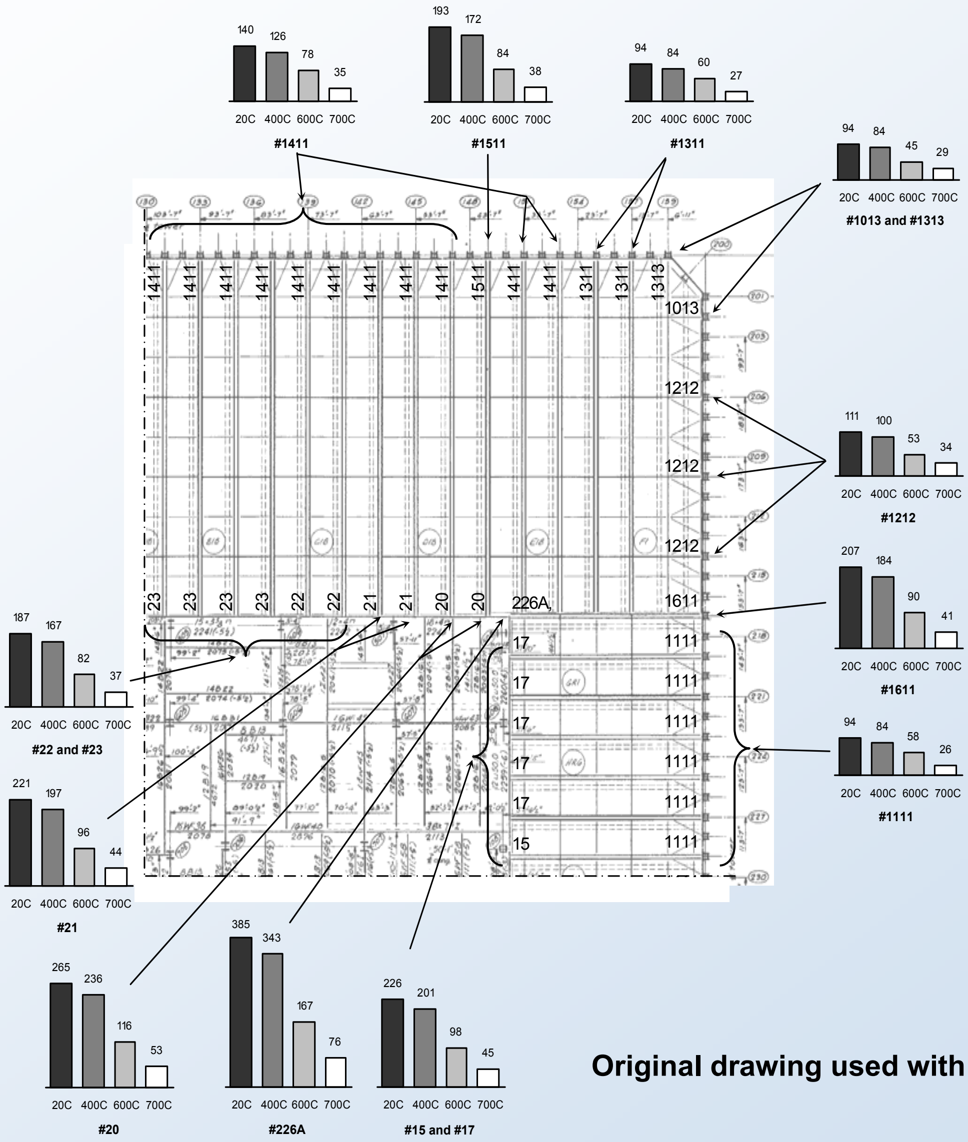
# Vertical Force Resistance of Exterior Seats




20 ºC
400 ºC
600 ºC
700 ºC

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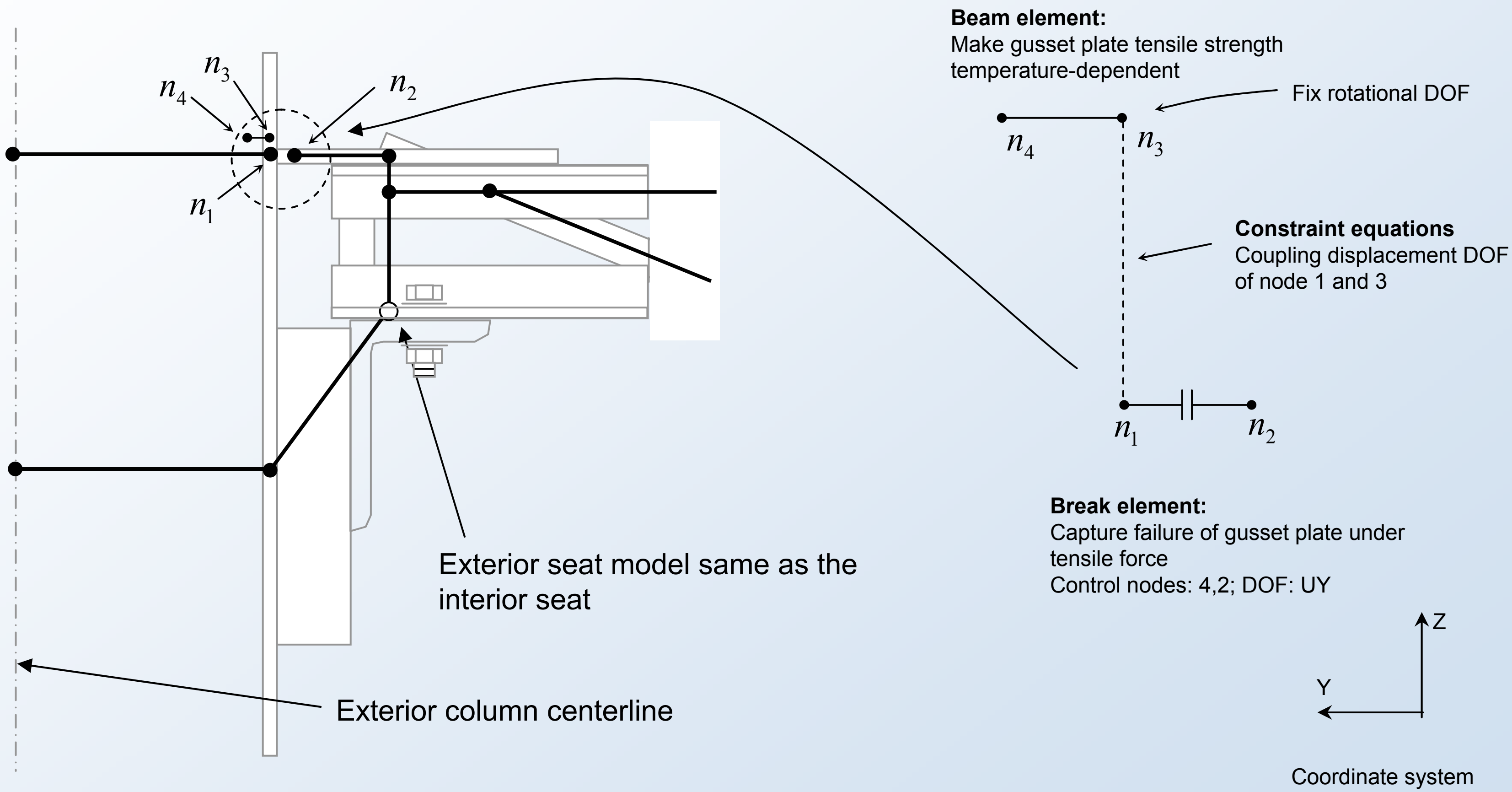
# Simplified Model of Exterior Truss Seat



# Single Truss with Floor Slab Analysis

Goals:

- Capture the potential failure modes and failure sequence of the truss under gravity when subjected to thermal load.
- Develop a simplified representation for full floor subsystem model.

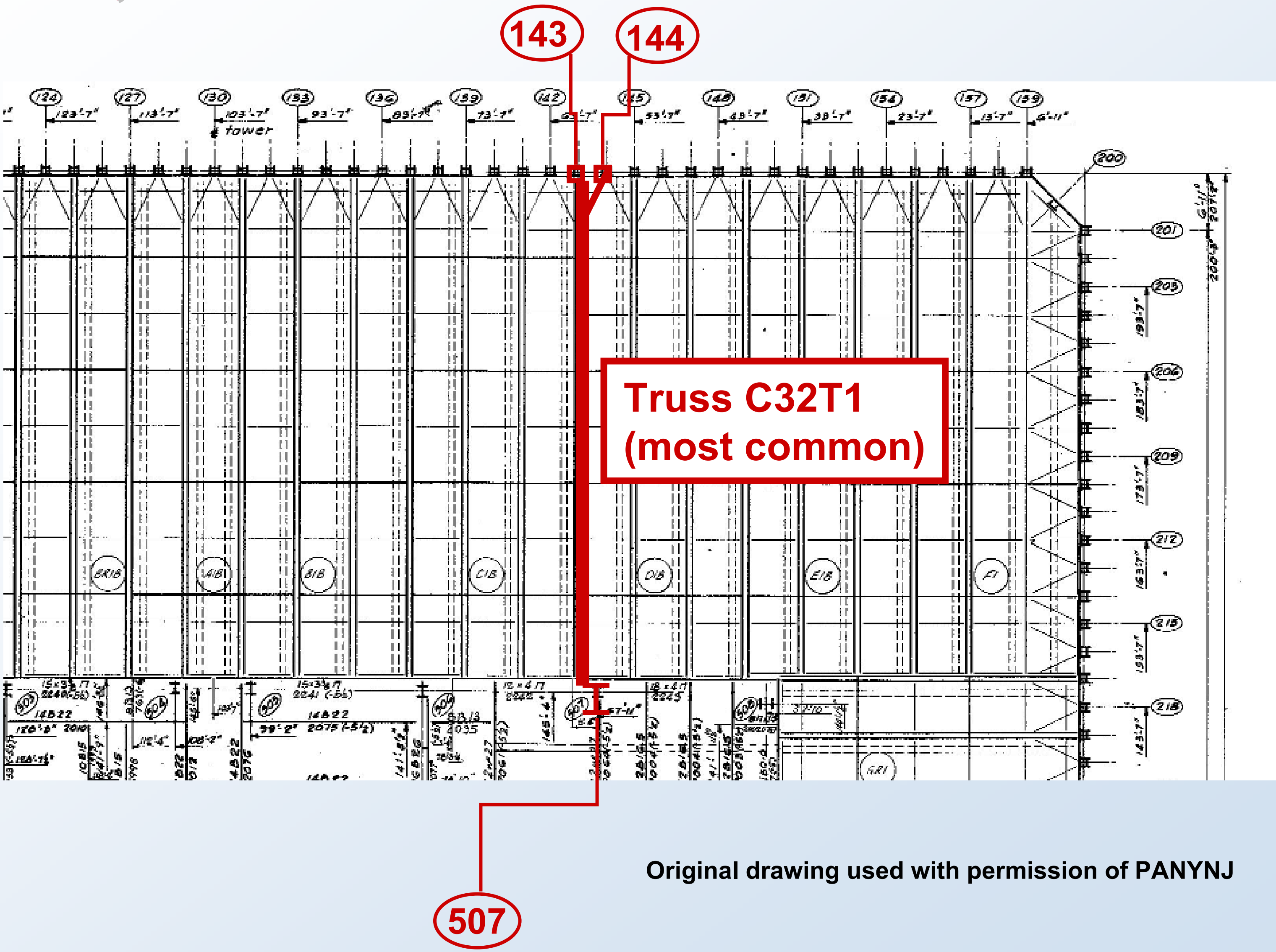
Failure Modes:

- Material yield
- Member buckling
- Knuckle failure
- Truss seat failures

Analysis:

- Nonlinear, inelastic analysis (ANSYS) under gravity and thermal load

# WTC1, Floor 96

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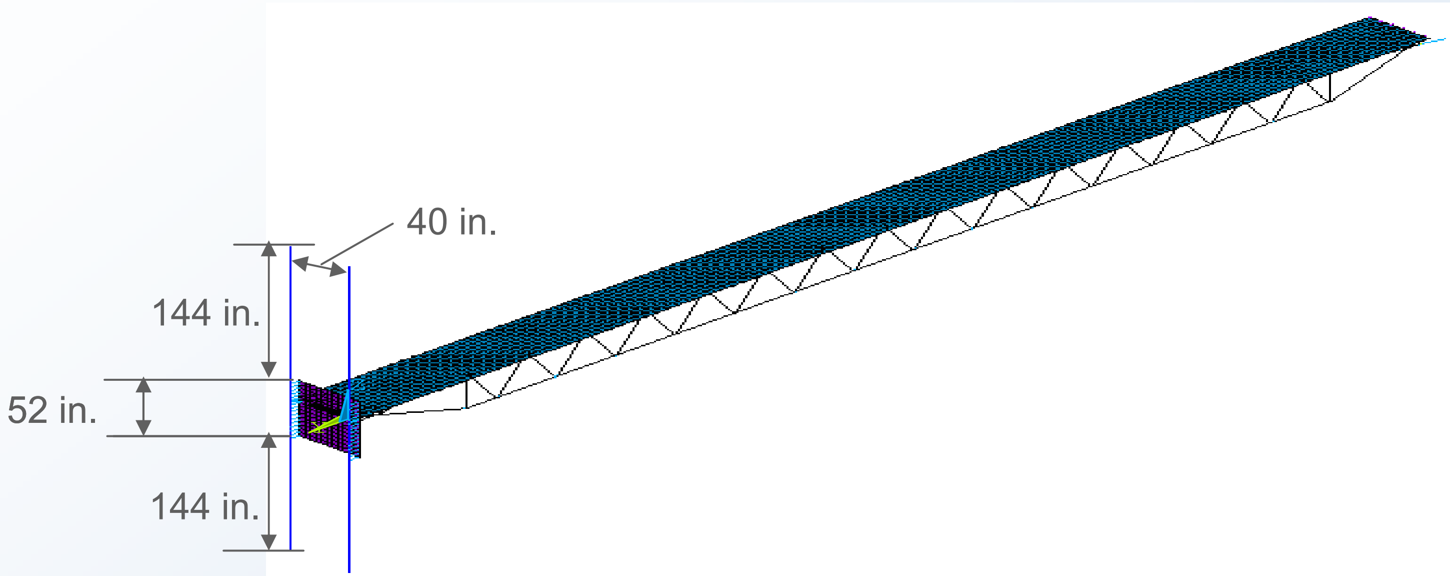
# Single Truss with Floor Slab Model




- Exterior columns are fixed at 12 ft above and below the top of 96$^{th}$ floor slab.
- Channel supporting the interior truss seat is not modeled and is assumed to be rigid.
- Bottom chord is supported laterally at bridging trusses
- Damper is not included in the model.
- Metal deck is not included in the model.
- Camber is not included in the model.

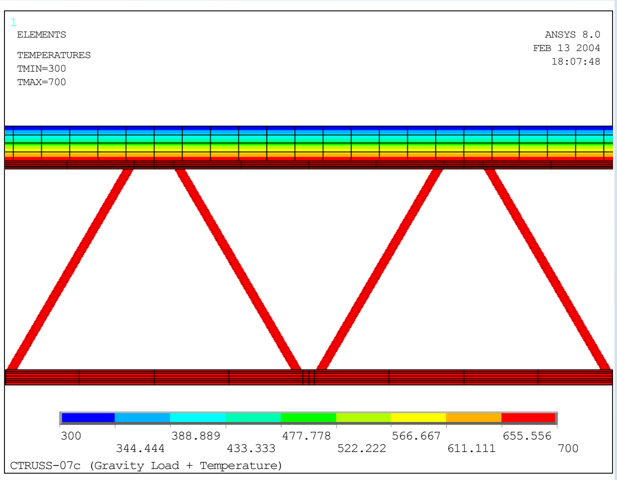
# Loading

Gravity loading includes:

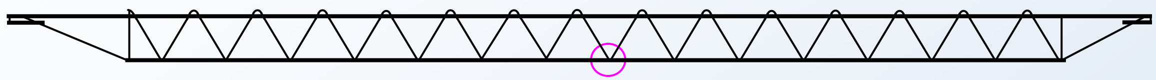
- Self-weight of structure
- 8 psf superimposed dead load (SDL)
- 13.75 psf service live load (25% of the design live load of 55 psf)

Thermal Loading:

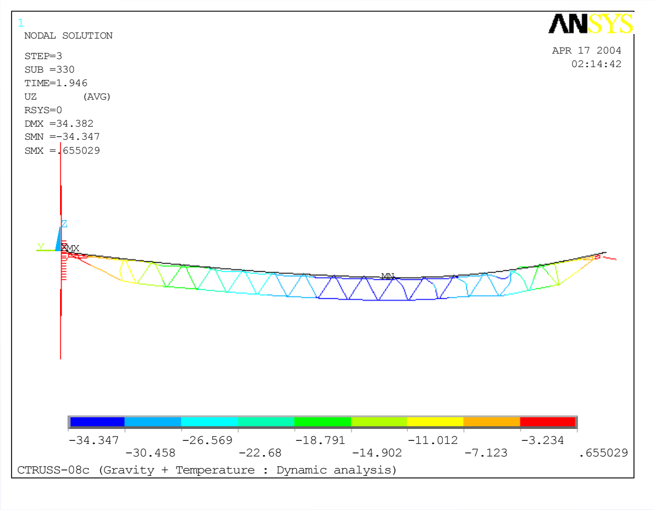
- Truss: ramped from 20°C to 700°C
- Slab: ramped from 20°C to 700°C at bottom of slab, and 20°C to 300°C at top of slab, linear gradient through thickness

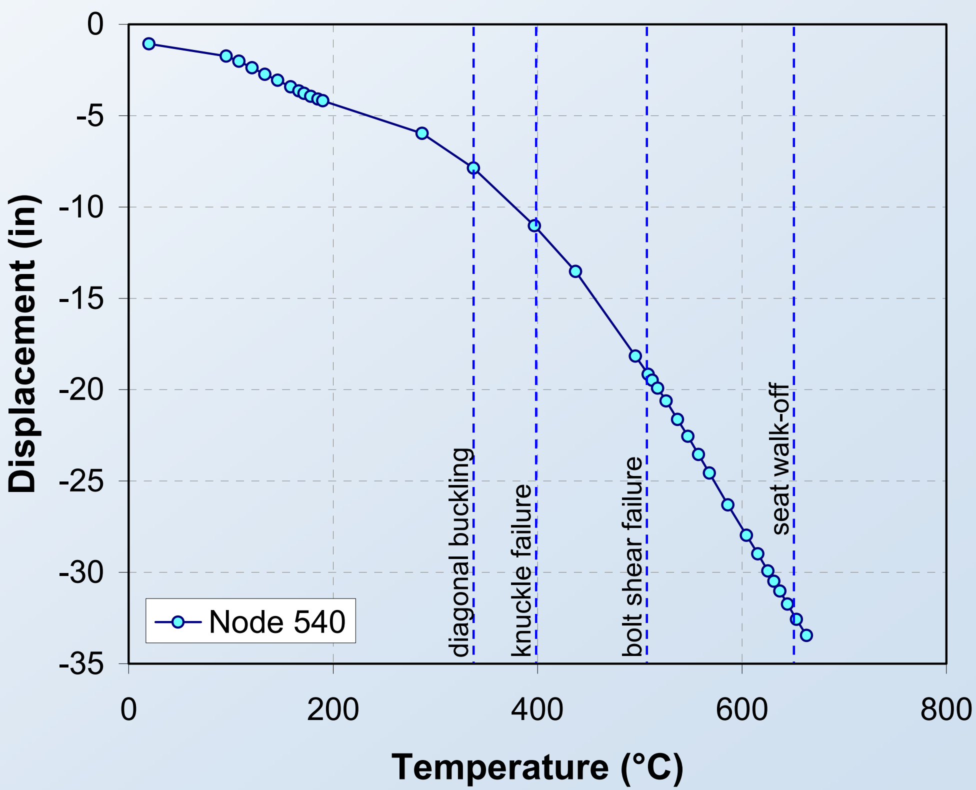


# Truss Vertical Deflection

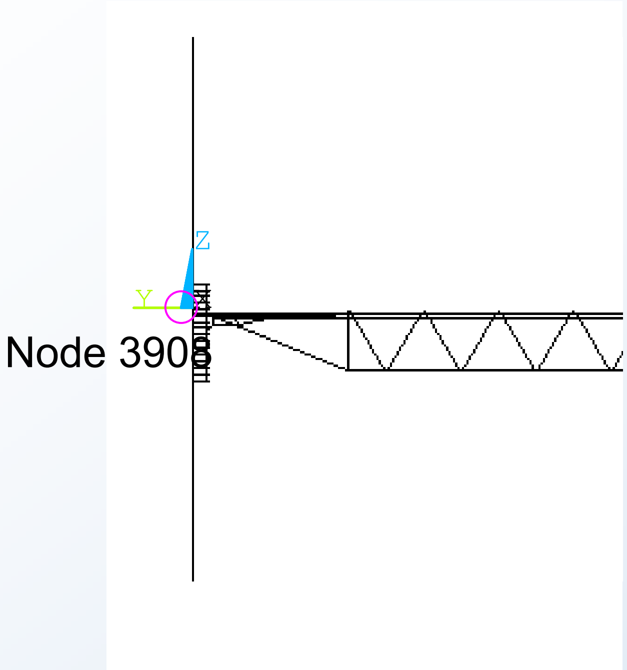


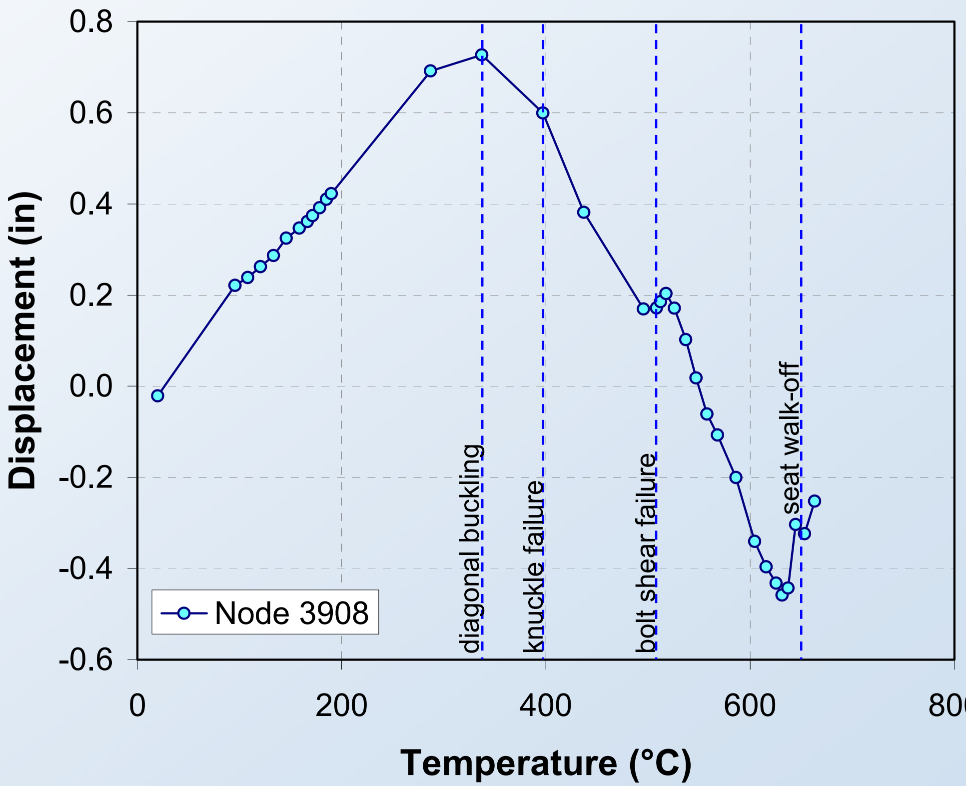
Node 540



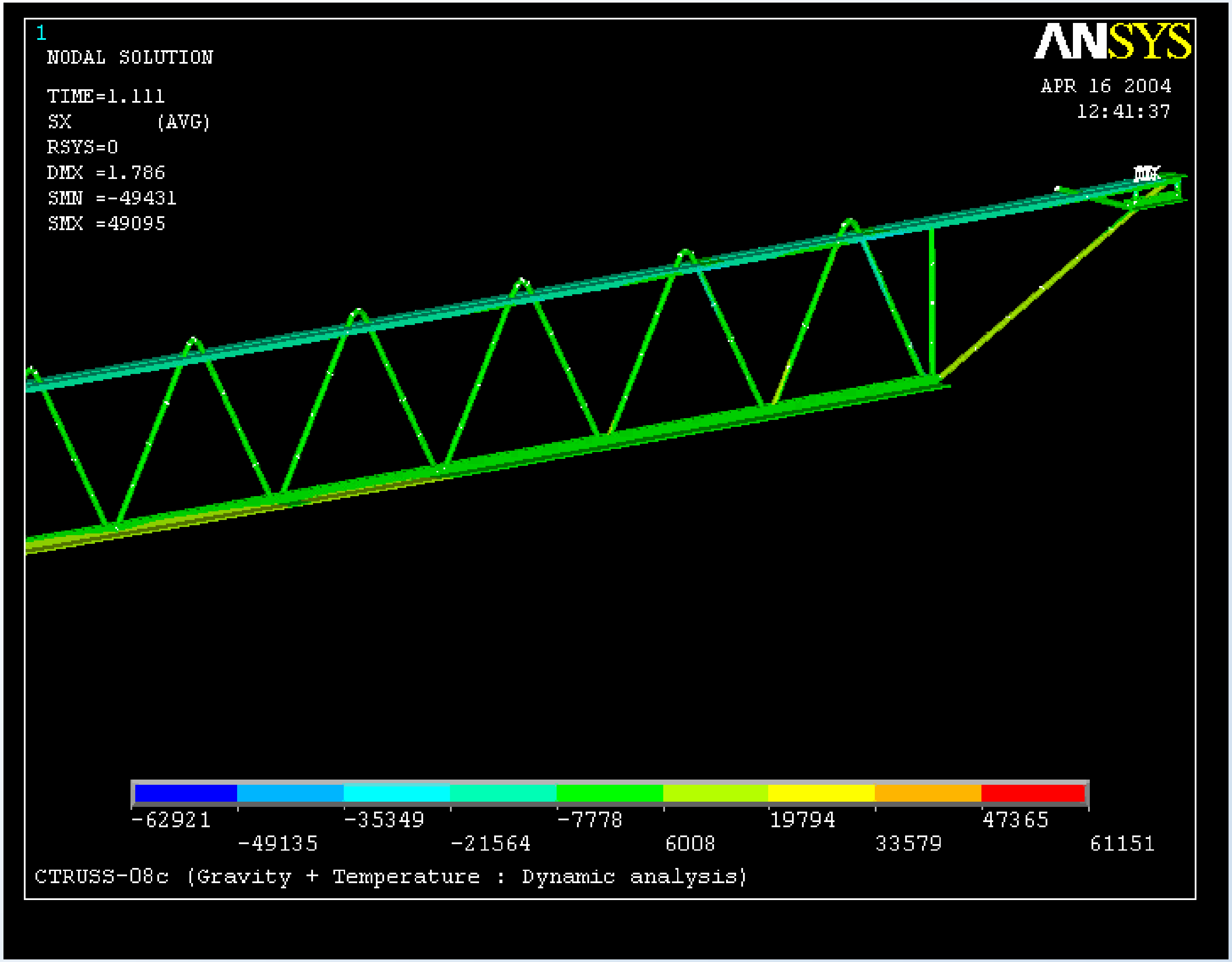



# Column Horizontal Deflection



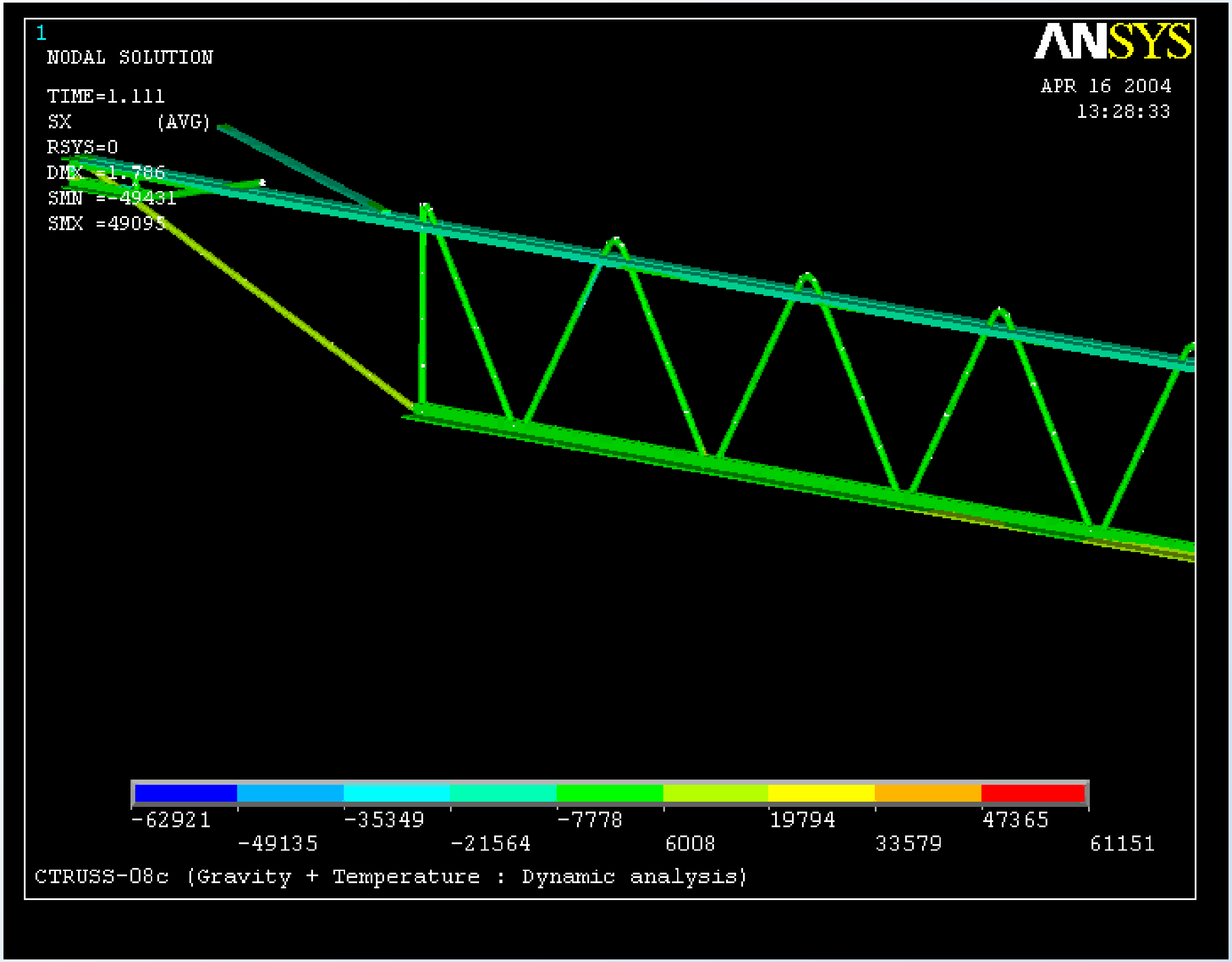



# Axial Stress Contour at Interior End




*Displacement magnification factor = 1.0*

# Axial Stress Contour at Exterior End




*Displacement magnification factor = 1.0*

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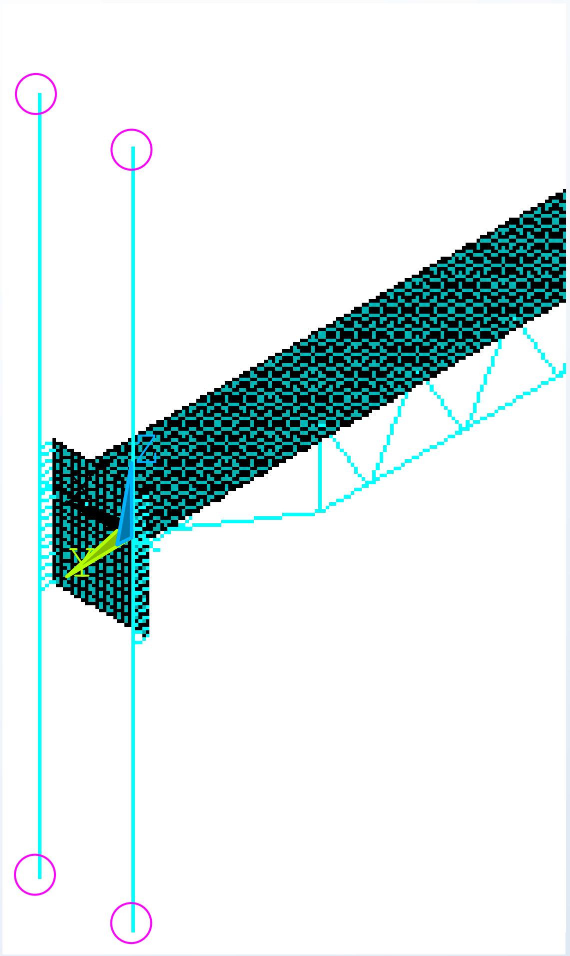
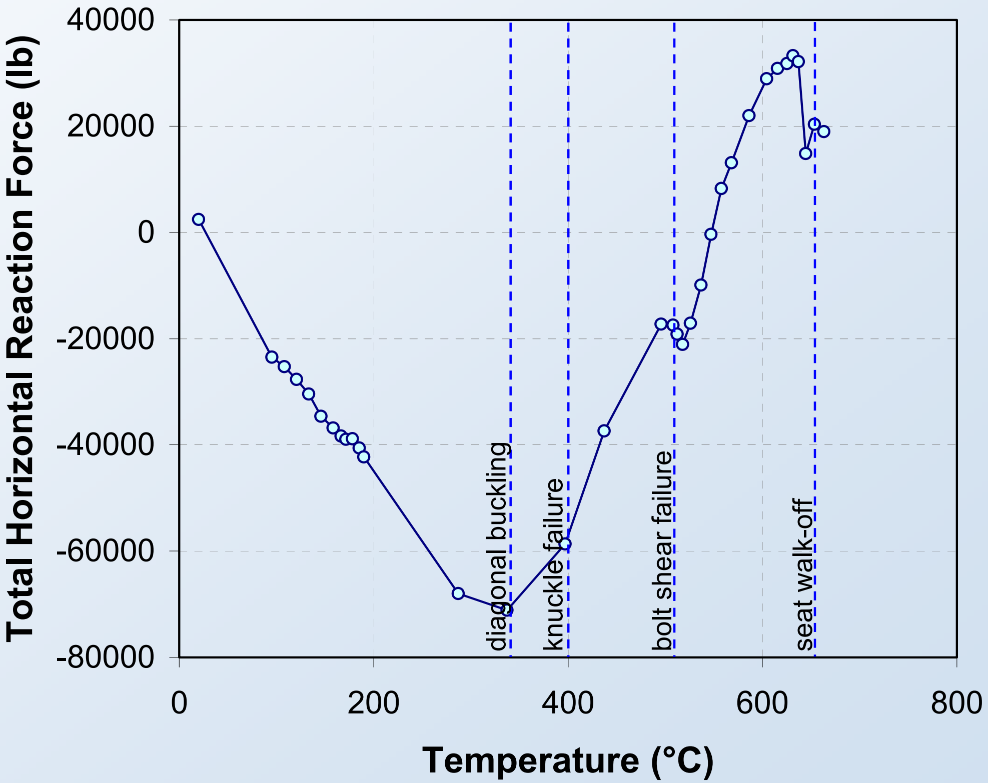
# Total Horizontal Reaction at Exterior Columns



# Thermal Response

**Diagonal bars start to buckle at ~340 $^{0}$C**

- Maximum vertical deflection at truss center 7.9 in.
- Exterior column is pushed out 0.7 in.
- Top chord of truss yields due to differential thermal expansion between steel and concrete.
- Truss pushes against interior and exterior seats.
- Concrete slab pushes against interior core and spandrel plate.

**Knuckles start to fail at ~400 $^{0}$C**

- Maximum vertical deflection at truss center 11.0 in.
- Exterior column is pushed out a maximum of 0.6 in.
- Shear studs on strap fail.

# Thermal Response (cont.)

**Interior Seat Bolt fails at ~500 $^{0}$C**

- Maximum vertical deflection at truss center 19.2 in.
- Exterior column push reverses direction and outward deflection is 0.2 in.
- Truss pulls at the interior seat, while concrete slab pushes against the interior core.
- Truss still pushes against the exterior seat and concrete slab also pushes against  the spandrel.
- Catenary truss no longer restrains column inward motion completely.

**Truss “walks off” the interior seat at ~650 $^{0}$C**

- Maximum vertical deflection at truss center is 32.6 in.
- Exterior column is pulled inward 0.3 in.
- Truss has no support at interior seat.  Concrete slab provides horizontal and vertical support against the interior core.
- Exterior seat provides vertical support for the truss.

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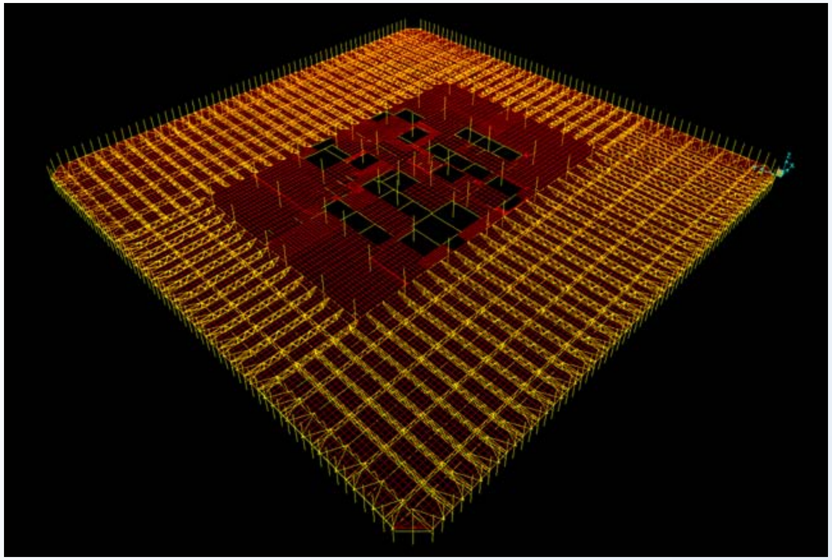
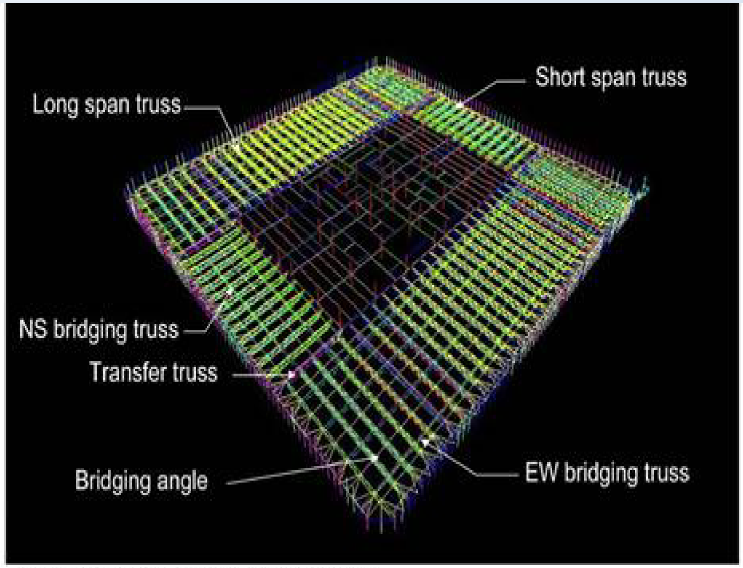
# Thermal Response (cont.)

**Truss support fails at exterior column at ~660 $^{0}$C**

- Gusset plate fails in tension at 660 $^{0}$C.
- Vertical load carrying capacity of the fillet welds at the seat standoffs reduce due to added bending moment.
- Strap breaks at 660 $^{o}$C.
- Fillet welds at the seat standoffs fail at 660 $^{o}$C.
- Truss loses the vertical support at the exterior column.
- Concrete slab provides vertical and horizontal support at interior core.

# Finite Element Model Translation



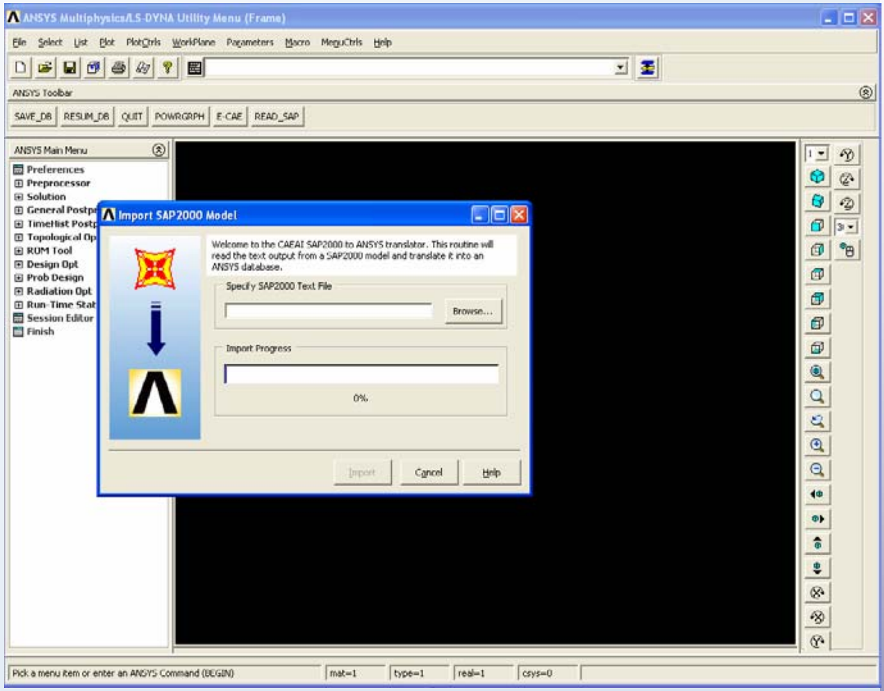


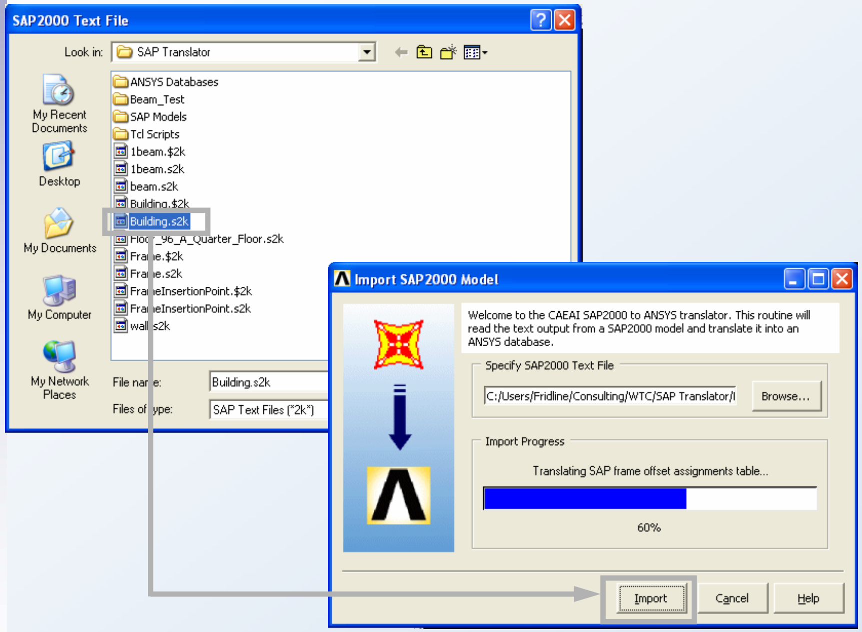
Shell elements and supports not shown

# Translator Features & Program Features

The model translator is written in a combination of ***Tcl/Tk*** and ***ANSYS APDL*** commands.

This allows the program to work seamlessly within the ANSYS Graphical User Interface.




The translator utilizes a wizard style format requiring minimal user interaction.

Translation status indicators allow user to track progress.

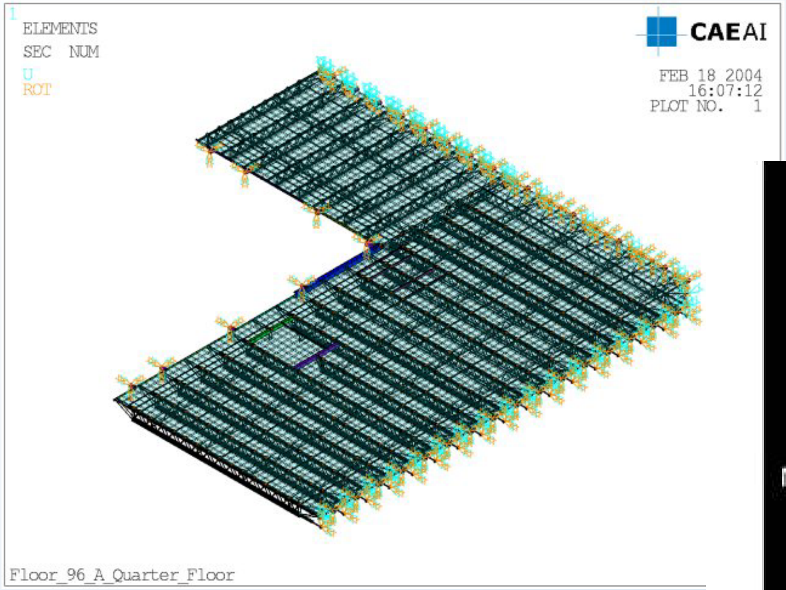
Summary report with translation tables.

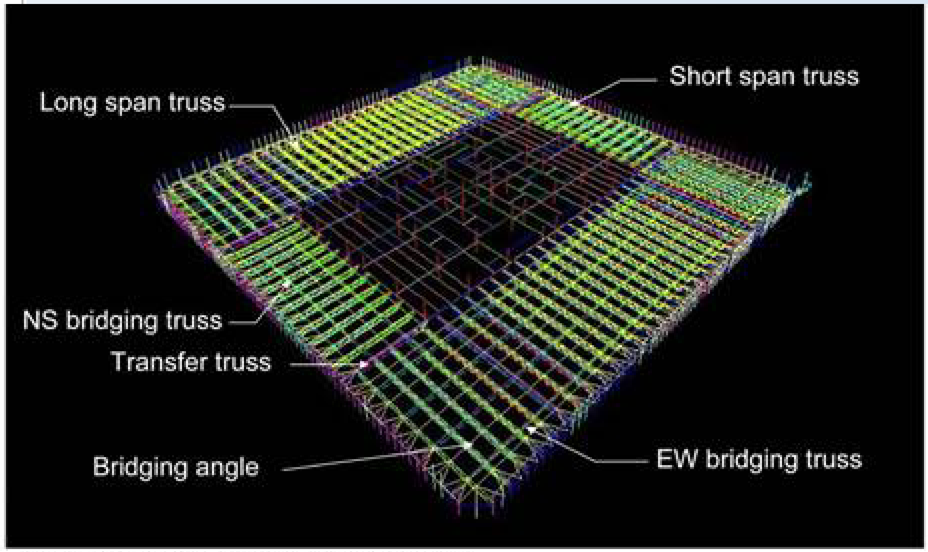
# WTC SAP-to-ANSYS Model Conversion

SAP2000 text file is used as input to the translator.

Specific models translated include:

- A Typical Truss Floor System
- WTC 1 or 2 simplified full building model (translation not complete yet)




Shell elements and supports not shown

# Validation of Converted Models

Validation through comparison of the converted ANSYS and SAP2000 reference models.

- Reactions due to gravity load,
- Deformations due to gravity load,
- Deformations due to arbitrary lateral load, and
- Natural frequencies and mode shapes.

| | SAP | ANSYS (BEAM 188) |
|---|---|---|
| Total Reaction (kip) | 2212.8<br>1 | 2210.85<br>(-0.09%) |
| Maximum Slab Displacement (in.) | 0.718 | 0.695<br>(-3.2%) |

| | SAP | ANSYS (BEAM 188) |
|---|---|---|
| Total Mass (lb-sec$^2$/in.) | 5448.7 | 5447.7<br>(-0.018%) |
| Dominant Natural Frequency of Floor (Hz) | 4.32 | 4.43<br>(+2.5%) |

# Full Floor Finite Element Model

# Full Floor Model for Nonlinear Analysis

Double-to-Single Truss

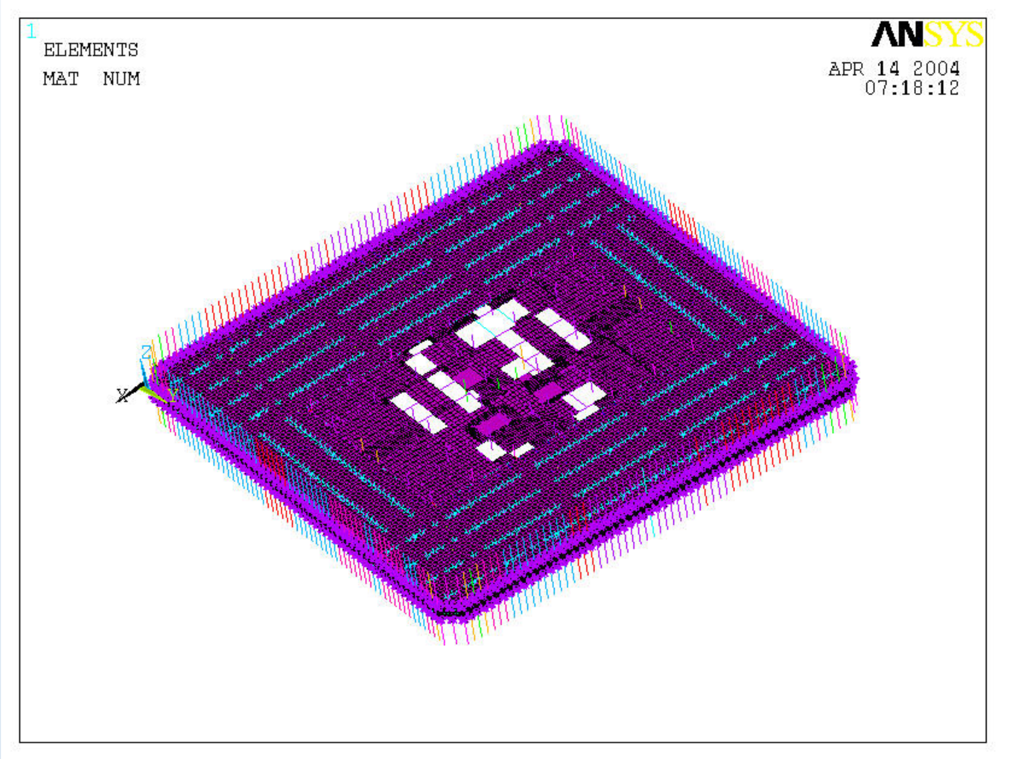
Beam Elements for Columns

Nonlinear Materials

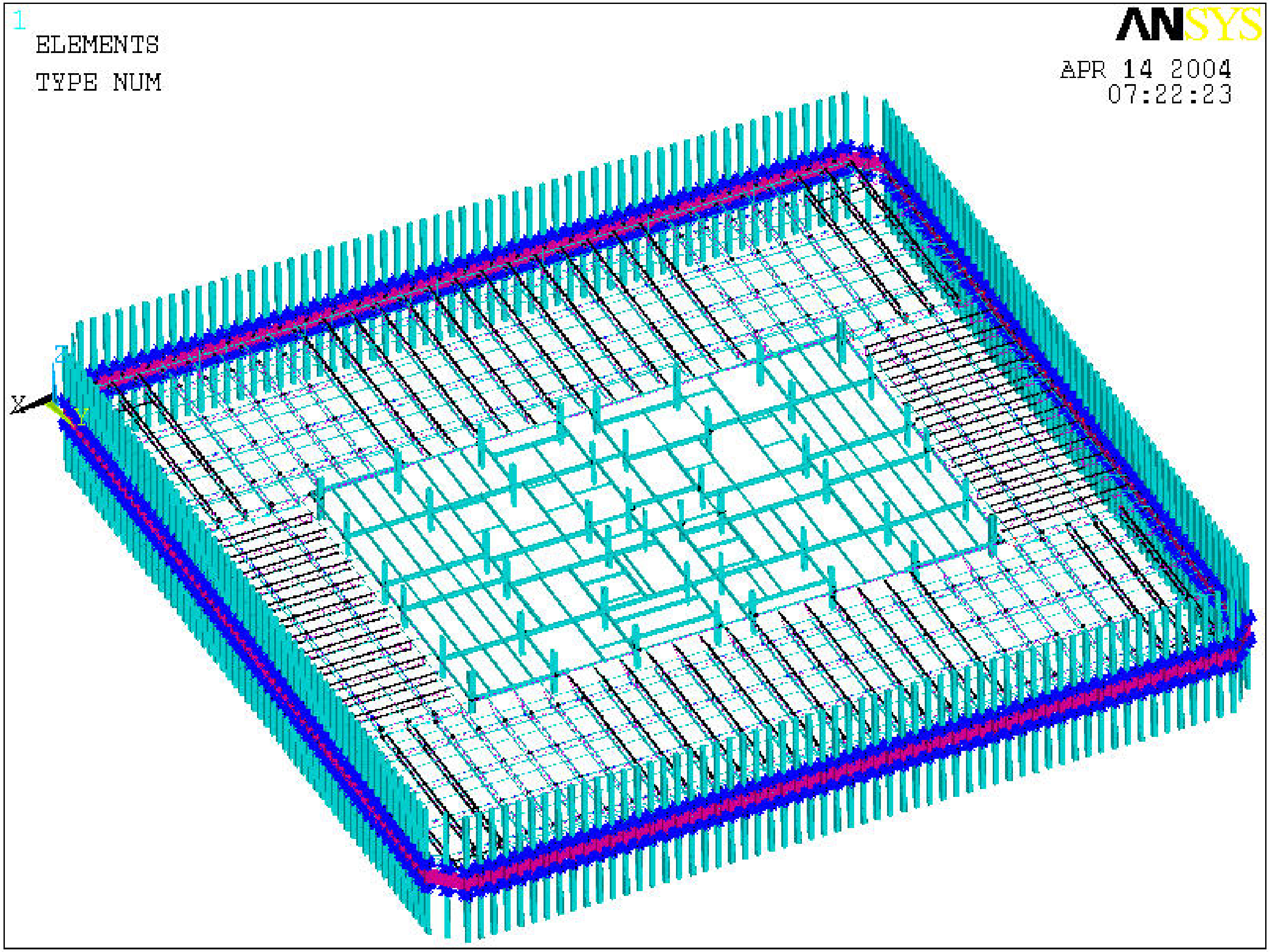
Shell Modeling of Spandrel & Local Column Vicinity

Break Elements

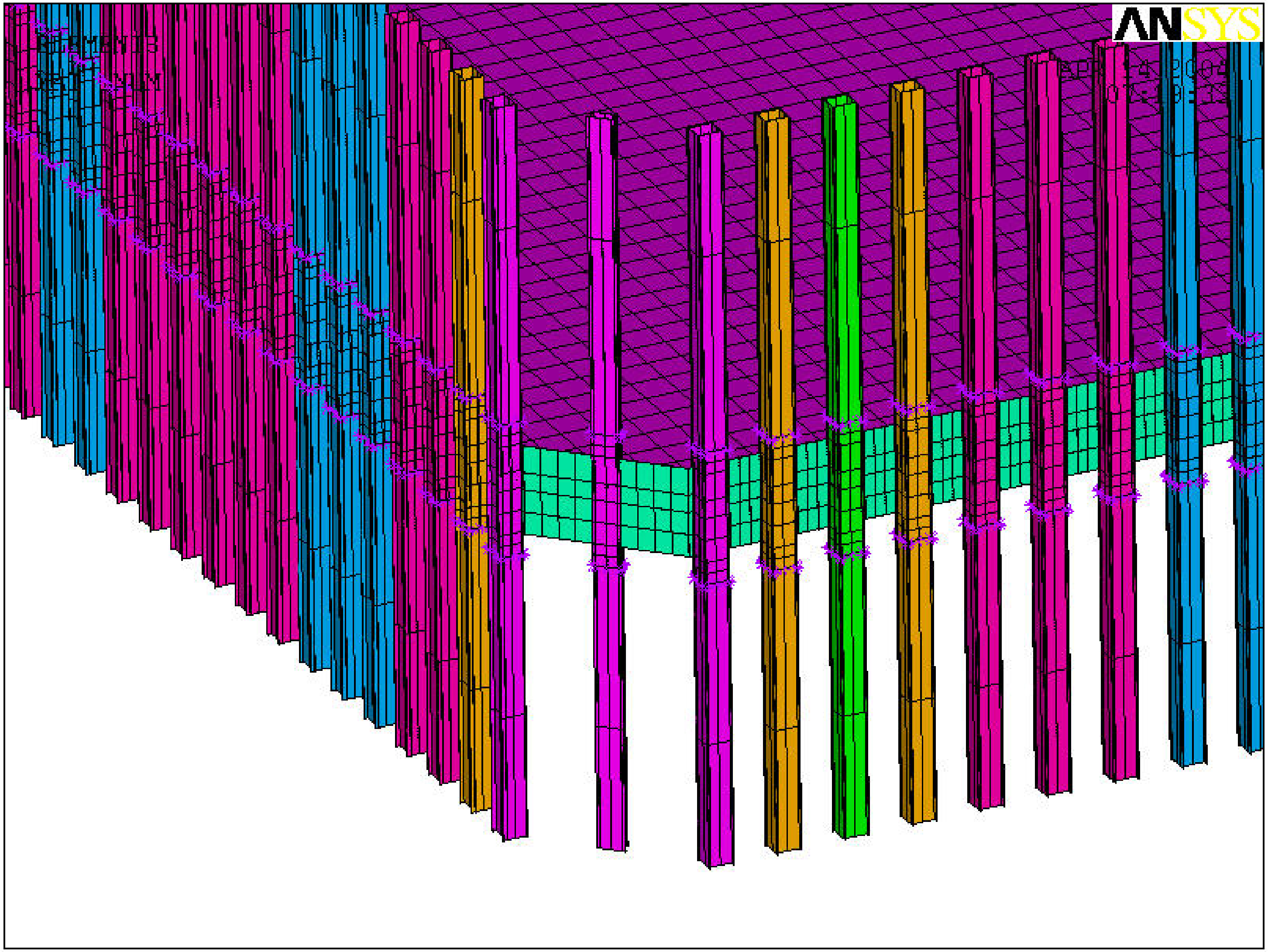
- Knuckles
- Truss Connections
- Interior and Exterior Truss Seats
- Slab-to-Spandrel Connection



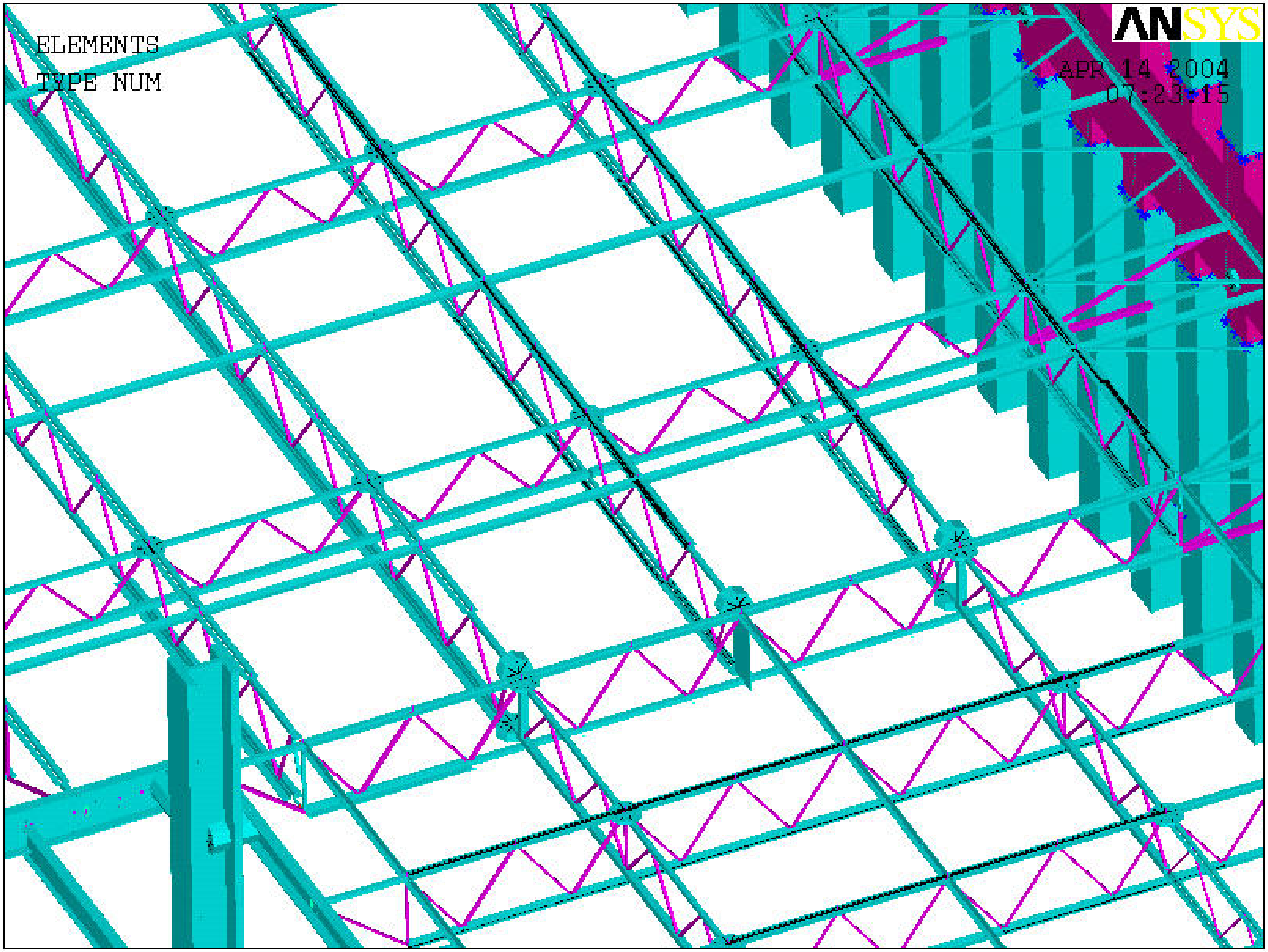
# Full Floor Model for Nonlinear Analysis



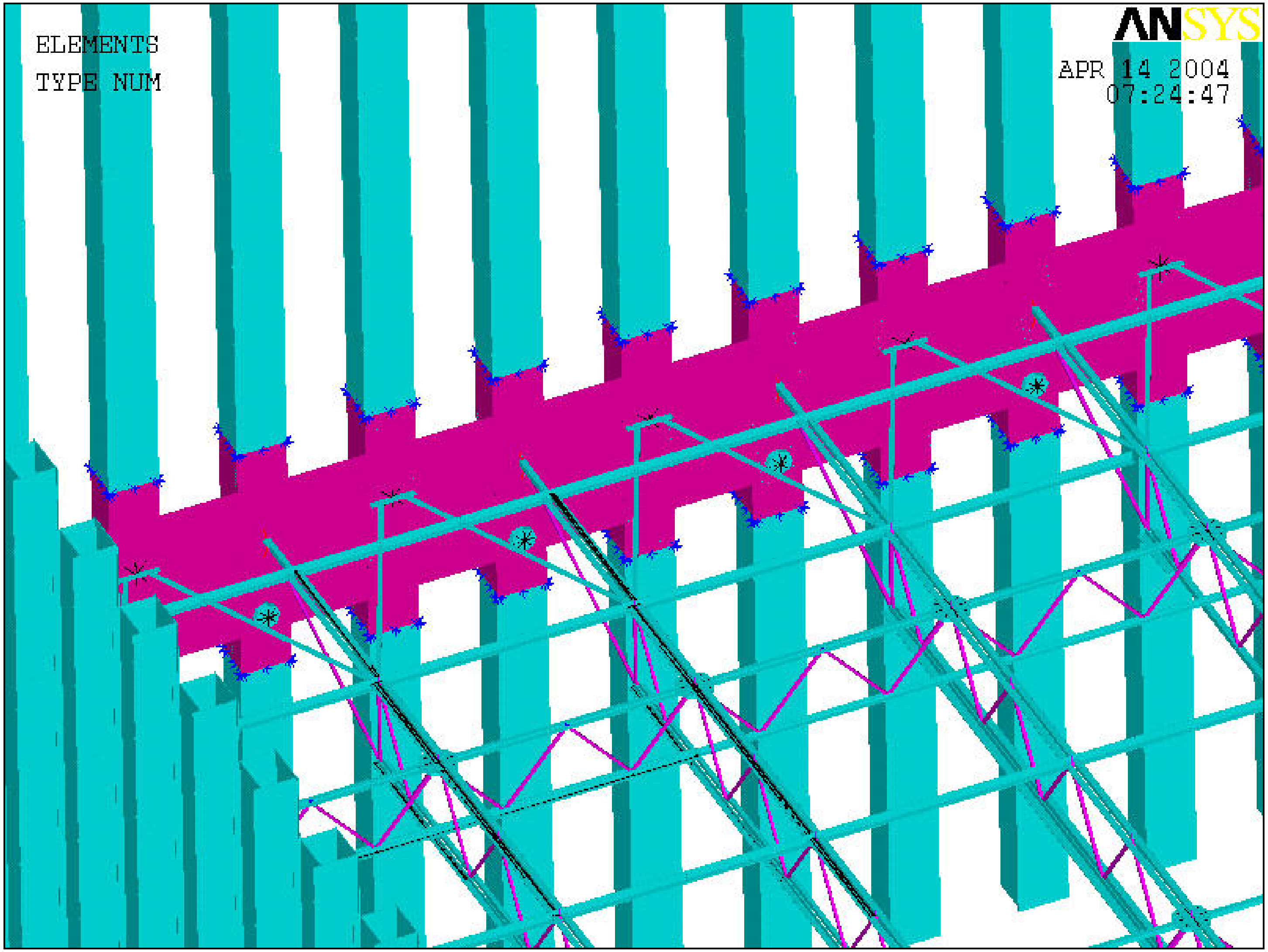
# Full Floor Model for Nonlinear Analysis



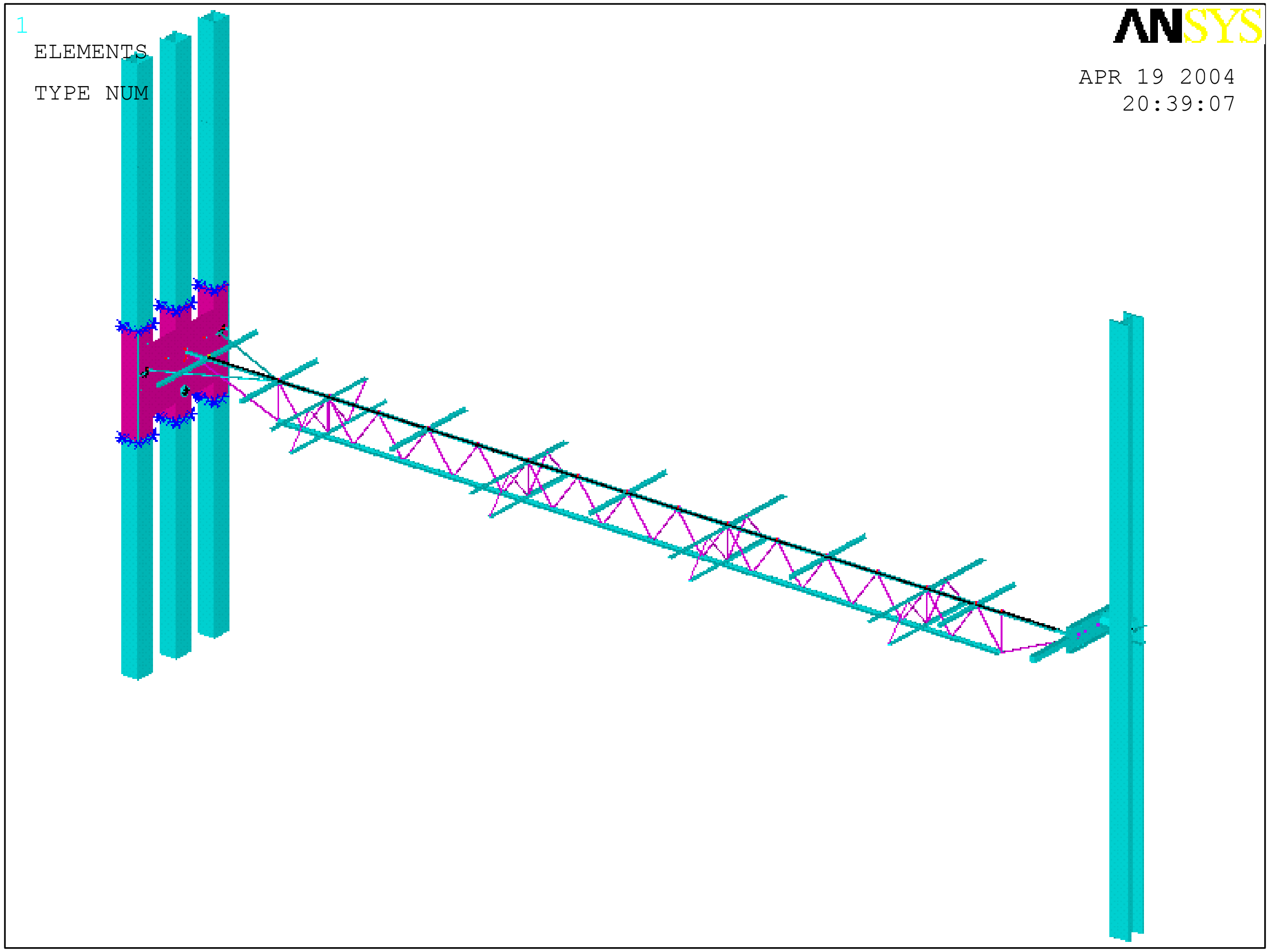
# Full Floor Model for Nonlinear Analysis



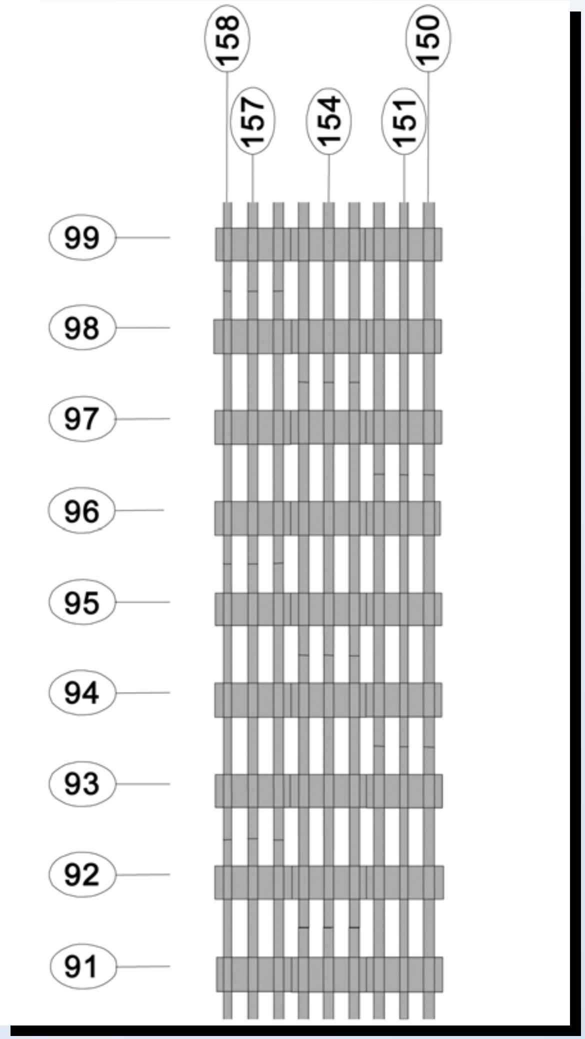
# Full Floor Model for Nonlinear Analysis



# Long Span Truss in Full Floor Model without Slab



# Exterior Wall Finite Element Model



# Exterior Wall Analysis

Goals:

- Capture the potential failure modes and failure sequence of the exterior columns under gravity loads and thermal load due to fires.
- Develop a simplified representation for global analysis.

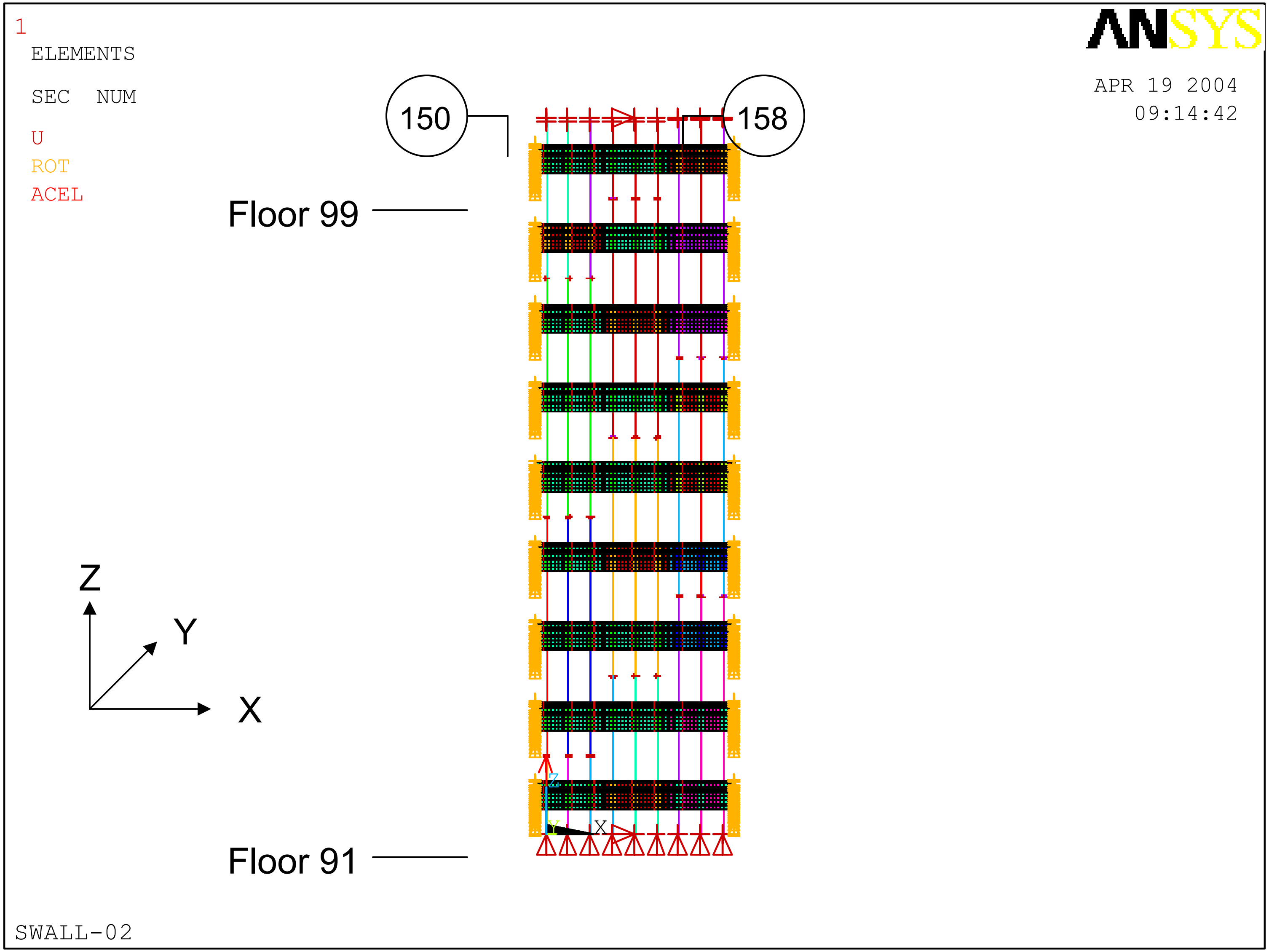
Failure Modes:

- Column collapse due to large lateral deflections.
- Column buckling due to loss of lateral bracing at floors.
- Failure of column splice bolts and spandrel splice bolts.

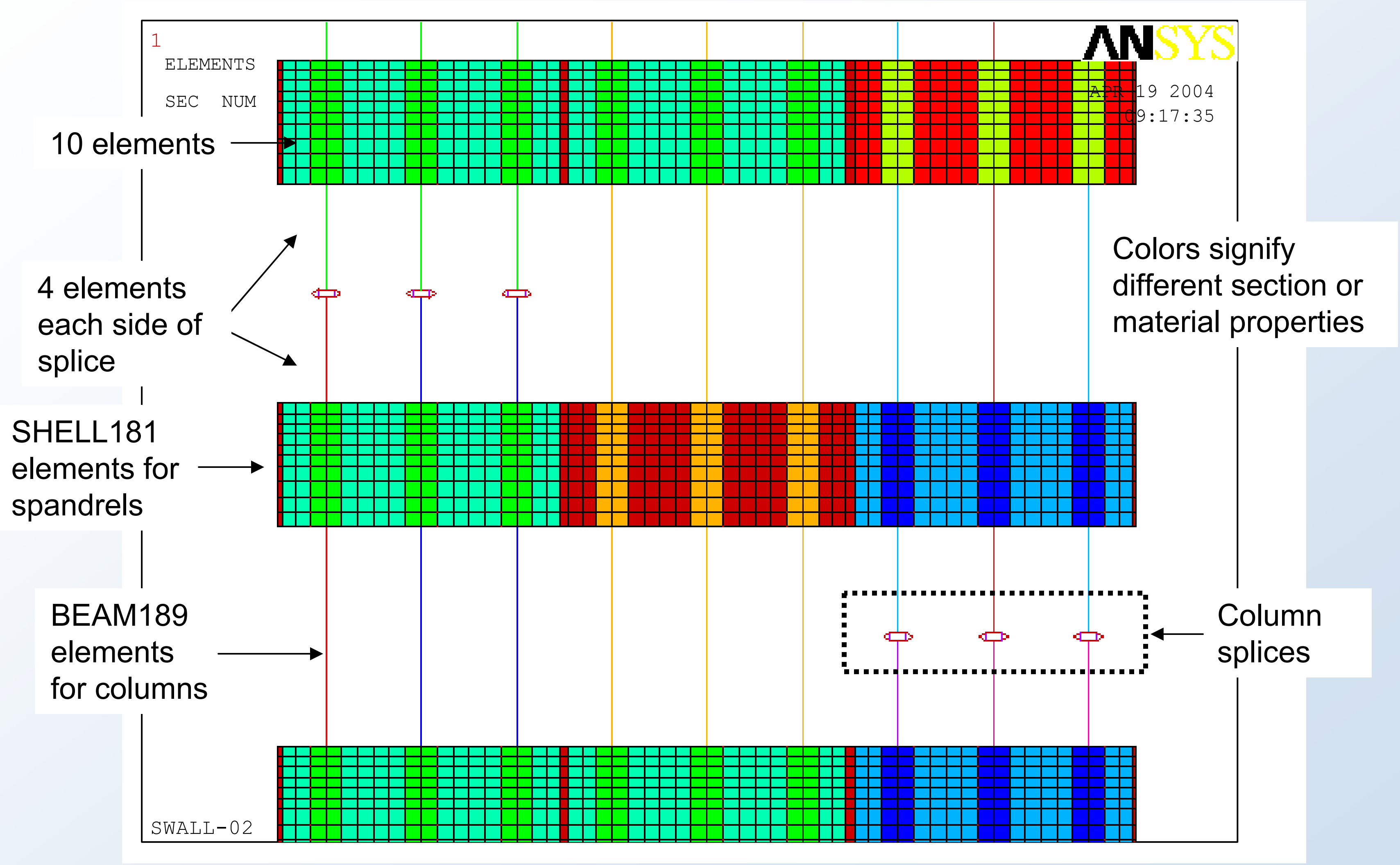
Analysis:

- Nonlinear, inelastic analysis (ANSYS) under gravity and thermal load.

# Exterior Wall Model

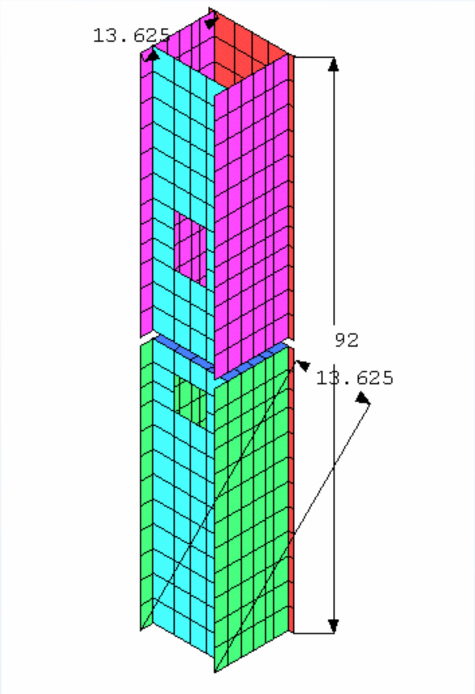


# Exterior Wall Model

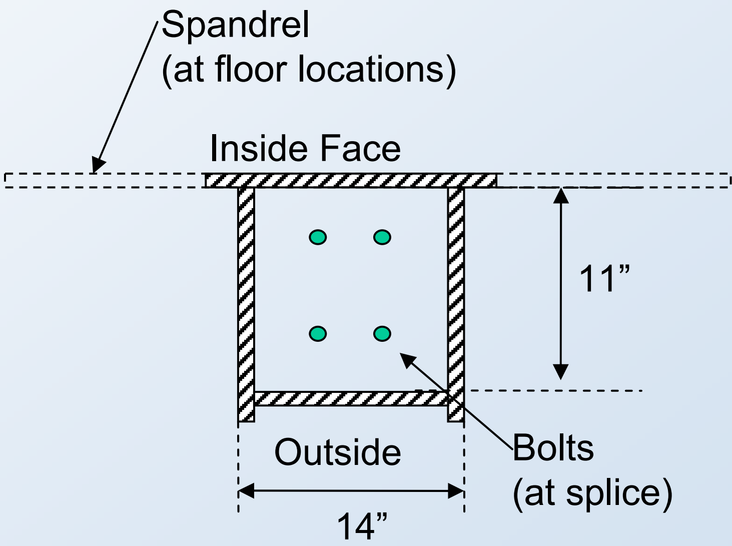


# Column Splice

- Exterior columns have column splices at every third floor.
- Each splice consists of a butt plate on each column with (typically) four bolts to connect the two plates.
- In the area of interest (floors 92 to 100) the butt plates are 1-3/8” thick, with 4 – 7/8” diameter A325 bolts.




View of Splice in Detailed FEM




Column Cross Section

Not to Scale

# Simplified Model of Column Splice

A simplified model of the column splice was developed to allow the critical splice properties to be added to the line-element column model.

- Tensile bolt flexibility.
- Rotational flexibility.
- Failure in rotation and axial tension due to bolt tensile failure.
- Temperature dependent bolt strength.
- Bolt shear failure is not modeled.
- Bolt pretension is not modeled as it plays only a minor role in bolt stiffness.

Bolt tensile response is based on bolt tests.

# Exterior Wall Model Loading

Gravity loads

- Self-weight.
- Superimposed dead and live loads from floors.
- Column loads from structure above model limits.

Transverse loads

- Loads from thermal expansion of floors.
- Loads from sagging floors.

Temperature loads

- Thermal-time history distributions for various fire scenarios, including ASTM standard E119.
- Different levels of fireproofing considered, including fully damaged fireproofing (bare steel).

# Exterior Wall Analysis

Analyses are in progress to determine failure modes and sequences:

- Under various fire scenarios, and
- For various conditions of fireproofing.

Results will be used to refine simplified wall behavior for global collapse analyses.

# Task 3…

Results to date provide:

- Understanding of truss behavior (including components) at elevated temperatures.

By the end of the month:

- Behavior and capacity of exterior columns under real fire scenarios.
- Behavior and capacity of floor system under real fire scenarios.

Work has started on Task 3 to:

- Include damage estimates (from Project 2).
- Identify specific load redistribution paths for each tower under impact and various fireproofing conditions.
- Determine the contribution of local and subsystem failures due to aircraft impact and fire growth to the deterioration of global stability.