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

June 22, 2004

John L. Gross, Ph.D., P.E.
Building and Fire Research Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce
John.Gross@nist.gov
Disclaimer

Certain commercial entities, equipment, products, or materials are identified in this presentation in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose.
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.
- 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 20°C to 700°C (Project 3)
- Thermal properties of spray-on fire resistant materials (SFRM) (Project 5)
- Temperature-time histories for various components, subsystems 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**
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

Global Reserve Capacity $RC(t)$

- Capacity Before Impact
- Capacity After Impact

Events with significant contribution to change in global capacity

Variability in analyses

Predicted time to collapse

$t_{\text{collapse}}$

Time
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

Exterior Wall Model
- Column panel
- Column Splice
- Exterior Wall

Full Floor Model
- Knuckle
- Truss Seats
- Truss
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

Temperature (°C)

Coefficient of Thermal Expansion (1/°C)

Normal weight

Lightweight
Steel – Plasticity

Material ID 1 Steel

Elastic + Plastic Strain (in/in)

Stress (psi)

T=RT
T=300°C
T=500°C
T=700°C
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

-RT
-T=300°C
-T=600°C
-T=700°C
Full Floor Model
Full Floor Model

Component Models

- Knuckle
- Truss Seat Connections
- Truss and Exterior Column

Truss Seat Connection

- knuckle
- top chord
- web diagonal
- bottom chord
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
Laclede Tests of 1967

Drawing provided by Laclede Steel.
Longitudinal Shear Model – Compressible Stress

Crush Region in Gray
Knuckle Shear Strength

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Shear Direction</th>
<th>Hot Gas</th>
<th>Knuckle</th>
<th>Concrete</th>
<th>$f_c(T)/f_c$</th>
<th>Longitudinal (kip)</th>
<th>Transverse (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RT - 450</td>
<td>&lt;375</td>
<td>300</td>
<td>1.00</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>650</td>
<td>550</td>
<td>450</td>
<td>0.80</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>850</td>
<td>725</td>
<td>600</td>
<td>0.63</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1050</td>
<td>900</td>
<td>750</td>
<td>0.50</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

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

Constraint equations
Coupling displacement DOF of node 1 and 7

Break element No. 1-4:
Capture loss of vertical resistance if knuckle fails horizontally
No. 1: Control nodes: 8,2; DOF: UX
No. 2: Control nodes: 2,9; DOF: UX
No. 3: Control nodes: 10,2; DOF: UY
No. 4: Control nodes: 2,11; DOF: UY

Break element No. 5:
Capture knuckle tensile failure
Control nodes: 12,2; DOF: UZ

Break element No. 6:
Capture knuckle horizontal compression failure in the Y direction
Control nodes: 10,2; DOF: UY

Break element No. 7:
Capture knuckle horizontal tensile failure in the Y direction
Control nodes: 1,11; DOF: UY

The purpose of break elements No. 11-15 is similar to break elements No. 6-10

Break element No. 8-9:
Capture loss of horizontal resistance in the Y direction if knuckle fails horizontally in the X direction
No. 9: Control nodes: 8,2; DOF: UX
No. 10: Control nodes: 2,9; DOF: UX

Break element No. 10:
Capture loss of horizontal resistance in the Y direction if knuckle fails vertically
Control nodes: 12,2; DOF: UZ

Point-to-point contact element to transfer vertical compressive force between node 1 and 2

- Node on slab
- Node on truss

Knuckle
Truss Seat Connections

Exterior Seat
- Column/spandrel
- Gusset plate
- Truss top chord
- Strut
- Bearing angle
- 5/8 in. diameter bolt
- Seat angle
- Stand-off plates

Interior Seat
- Channel beam
- Truss top chord
- Strut
- Bearing angle
- 5/8 in. dia. bolt
- Vertical plate stiffener
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
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

- Gusset plate
- Truss top chord
- Strut
- Bearing angle
- Seat angle
- Stand-off
- 5/8 in. Diameter bolt

'Truss Seat 1411 detail E62'
Failure Sequence of Exterior Seats Against Tensile Force

(A) Gusset plate Yields
    → Gusset Plate Fractures

(B) Fillet Weld Fractures

    → Bolt Shears Off

(C) Bolt Shears Off

    → Truss walks off seat

(A) Seat details 1111, 1311, 1411, 1511, and 1611 at all temperatures
(B) Seat detail 1013 at temperatures below 100°C
(C) Seat details 1212 and 1313 at all temperatures, and detail 1013 at temperatures more than or equal to 100°C
Horizontal Tensile Force Resistance of Exterior Seat

![Graph showing tensile force resistance at different temperatures]

- **Gusset plate yields**
- **Gusset plate fractures**
- **Bolt shears off**
- **Slip resistance from bolt connection**

At travel distance 4-5/8 in., truss walks off support

Temperatures:
- 20°C - 200°C
- 300°C
- 400°C
- 500°C
- 600°C
- 700°C

Truss travel distance (in)

Tensile force resistance (kip)

±11/16 in.
Horizontal Tensile Force Resistance of Exterior Seats

Original drawing used with permission of PANYNJ
Vertical Force Resistance of Exterior Seats

Original drawing used with permission of PANYNJ

20 °C
400 °C
600 °C
700 °C
Simplified Model of Exterior Truss Seat

Exterior column centerline

Constraint equations
Coupling displacement DOF of node 1 and 3

Beam element:
Make gusset plate tensile strength temperature-dependent

Break element:
Capture failure of gusset plate under tensile force
Control nodes: 4,2; DOF: UY

Exterior seat model same as the interior seat

Coordinate system
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

Original drawing used with permission of PANYNJ

Truss C32T1 (most common)
Exterior columns are fixed at 12 ft above and below the top of 96th 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

- Displacement (in)
- Temperature (°C)

Diagonal buckling
Knuckle failure
Bolt shear failure
Seat walk-off

Node 540

0 200 400 600 800

-35 -30 -25 -20 -15 -10 -5 0

0 400 600 800

Column Horizontal Deflection

Node 3908

Displacement (in) vs. Temperature (°C)

-0.6 to 0.6

Temperature (°C) 0 to 800

- diagonal buckling
- knuckle failure
- bolt shear failure
- seat walk-off

NIST
Axial Stress Contour at Interior End

Displacement magnification factor = 1.0
Axial Stress Contour at Exterior End

Displacement magnification factor = 1.0
Total Horizontal Reaction at Exterior Columns

![Diagram of total horizontal reaction at exterior columns with a graph showing temperature (°C) vs. total horizontal reaction force (lb). The graph highlights critical points such as diagonal buckling, knuckle failure, bolt shear failure, and seat walk-off.]
Thermal Response

Diagonal bars start to buckle at ~340 °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 °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 °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 °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.
Thermal Response (cont.)

Truss support fails at exterior column at ~660 °C

- Gusset plate fails in tension at 660 °C.
- Vertical load carrying capacity of the fillet welds at the seat standoffs reduce due to added bending moment.
- Strap breaks at 660 °C.
- Fillet welds at the seat standoffs fail at 660 °C.
- Truss loses the vertical support at the exterior column.
- Concrete slab provides vertical and horizontal support at interior core.
Finite Element Model Translation

[Diagram showing a finite element model with labels for different elements: Long span truss, Short span truss, NS bridging truss, Transfer truss, Bridging angle, EW bridging truss. Note: 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)
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.

<table>
<thead>
<tr>
<th></th>
<th>SAP</th>
<th>ANSYS (BEAM 188)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Reaction (kip)</td>
<td>2212.8</td>
<td>2210.85 (-0.09%)</td>
</tr>
<tr>
<td>Maximum Slab Displacement (in.)</td>
<td>0.718</td>
<td>0.695 (-3.2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SAP</th>
<th>ANSYS (BEAM 188)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass (lb-sec²/in.)</td>
<td>5448.7</td>
<td>5447.7 (-0.018%)</td>
</tr>
<tr>
<td>Dominant Natural Frequency of Floor (Hz)</td>
<td>4.32</td>
<td>4.43 (+2.5%)</td>
</tr>
</tbody>
</table>
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

Colors signify different section or material properties.

- **BEAM189 elements for columns**
- **SHELL181 elements for spandrels**
- **10 elements**
- **4 elements each side of splice**

Column splices
**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.
**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.