

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

**Project 6: Structural Fire Response and
Collapse Analysis**

December 2, 2003

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William Fritz, Ph.D., Kuldeep Prasad, Ph.D.

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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

To determine the structural response of WTC 7 to debris damage and internal fires and to identify the most probable structural collapse mechanism.

- ❑ Task 1: Component, Subsystem and Global Analyses
- ❑ Task 2: Global Analysis of Collapse Hypotheses
- ❑ Task 3: Evaluation of Collapse Hypotheses

WTC Towers

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.

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
- 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.

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).

Examples of Key Factors in Collapse Hypotheses

- Thermal sagging, expansion of floor system
- Loss of lateral support to columns

- Load redistribution through hat truss
- Buckling/yielding of columns
- Core column failure in tension

- Failure of connections (e.g., truss seats, exterior column bolts...)
- Thermal effects (condition of fireproofing, thermal gradients, cooling cycle)

Status (1)

Contract awarded to Simpson Gumpertz & Heger (SGH) of Waltham, Massachusetts to develop component, subsystem and global models and to conduct thermal-structural analyses

- ❑ Contract awarded October 30, 2003
- ❑ Kickoff meeting held November 24, 2003

Fourth ASTM E119 test has been added to UL contract

- ❑ 35 ft span assembly, thermally restrained, $\frac{3}{4}$ -in fireproofing
- ❑ 35 ft span assembly, thermally unrestrained, $\frac{3}{4}$ -in fireproofing
- ❑ 17 ft span assembly, thermally restrained, $\frac{3}{4}$ -in fireproofing
- ❑ 17 ft span assembly, thermally restrained, $\frac{1}{2}$ -in fireproofing

Status (2)

For Task 1, work is underway (reported subsequently) to develop finite element models of components and subsystems for nonlinear thermal-structural analyses

- Single exterior panel section
- Floor section behavior for strength (80-in wide section)
- Truss seat connection for strength

For Task 2, work is underway to develop finite element models of floor systems and entire tower structure for nonlinear thermal-structural analyses

- Translate Reference Models to ANSYS
- Verify translated models against Reference Models
- Refine models for thermal-structural analysis

Status (3)

For Task 4, work is underway (reported subsequently) to conduct simplified analyses:

- a. Effect of thermal expansion of floor system
- b. Effect of loss of floors on column failure
- c. Effect of fire and fireproofing condition on time to weaken steel columns
- d. Load redistribution due to failure of column in tower structure

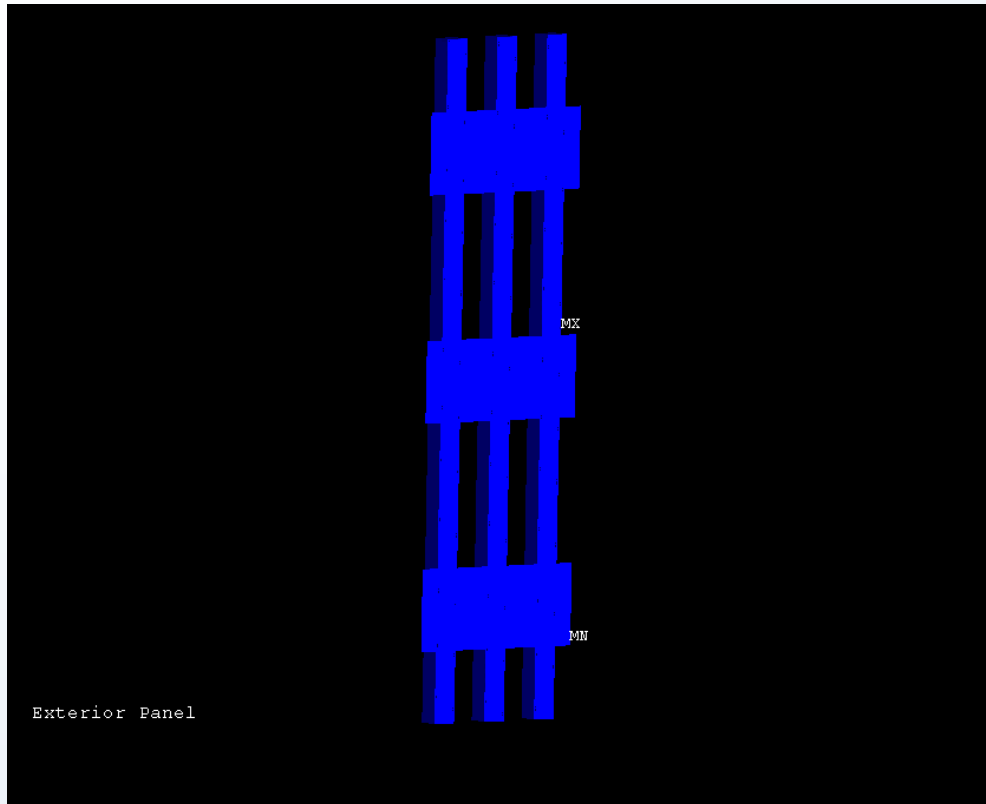
Task 1 Progress: Detailed Models of Components and Subsystems

NIST has developed detailed finite element models of

- ❑ Exterior Column Panel
- ❑ Floor Assembly (80-in section width)
- ❑ Seated Truss Connection

And is evaluating performance under load and elevated temperature

Task 1 Progress: Exterior Column Panel Buckling Behavior



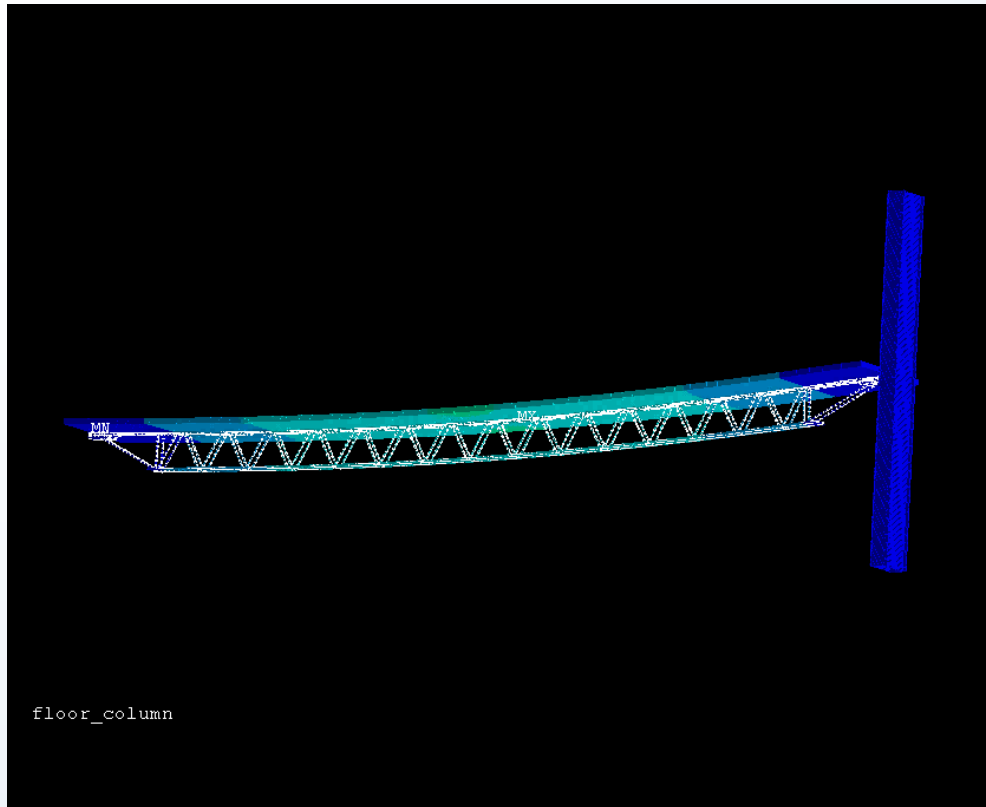
Computer Model (ANSYS)

- Geometric nonlinearity
- Material nonlinearity

Preliminary Studies

- Buckling of initially perfectly straight column

Task 1 Progress: Floor Section Behavior



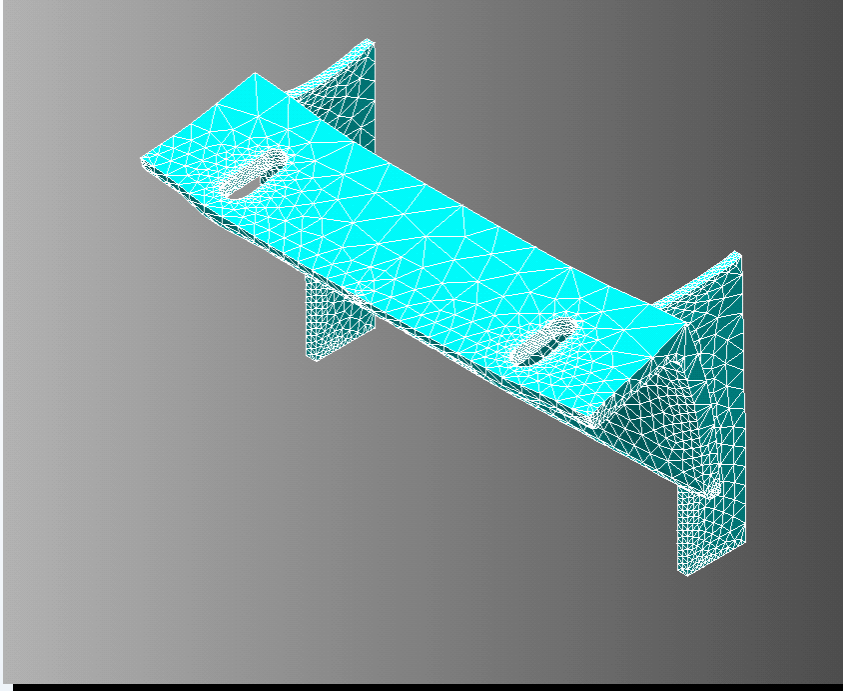
Computer Model (ANSYS)

- Geometric nonlinearity
- Material nonlinearity
- Uniform load (dead load + service load)

Preliminary Studies

- Buckling under lateral restraint
- Effect of fire conditions
 - Uniform heating
 - Representative fires (FDS)
- Effect of thermal restraint
 - Unrestrained
 - Fully restrained
 - Partially restrained (column stiffness)

Task 1 Progress: Seated Truss Connection



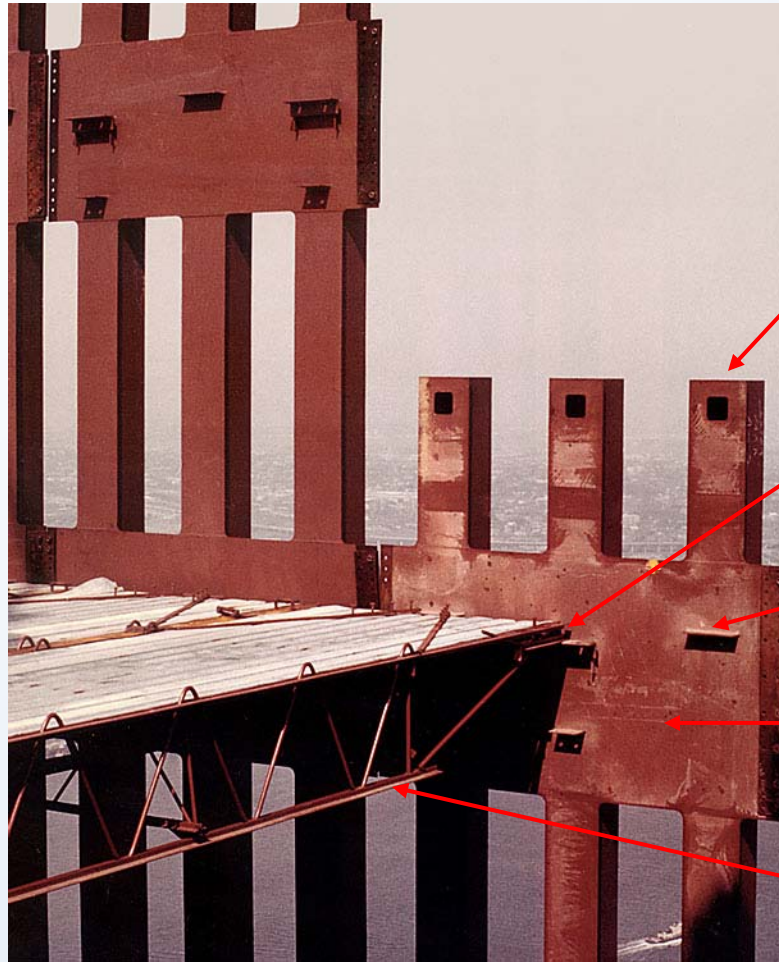
Computer Model (ANSYS)

- Geometric nonlinearity
- Material nonlinearity

Preliminary Studies

- Vertical load (gravity) plus bolt pull-out

Floor Truss System and Exterior Column Panels



Bolted column connection

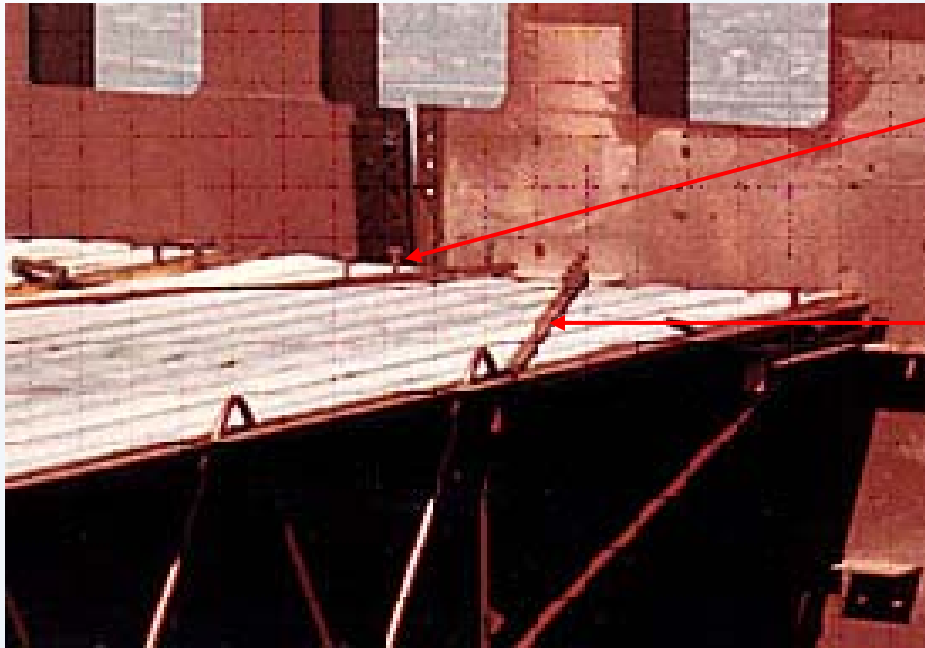
Floor truss seat connection

Strap attachment plate

Exterior column panel

Floor truss

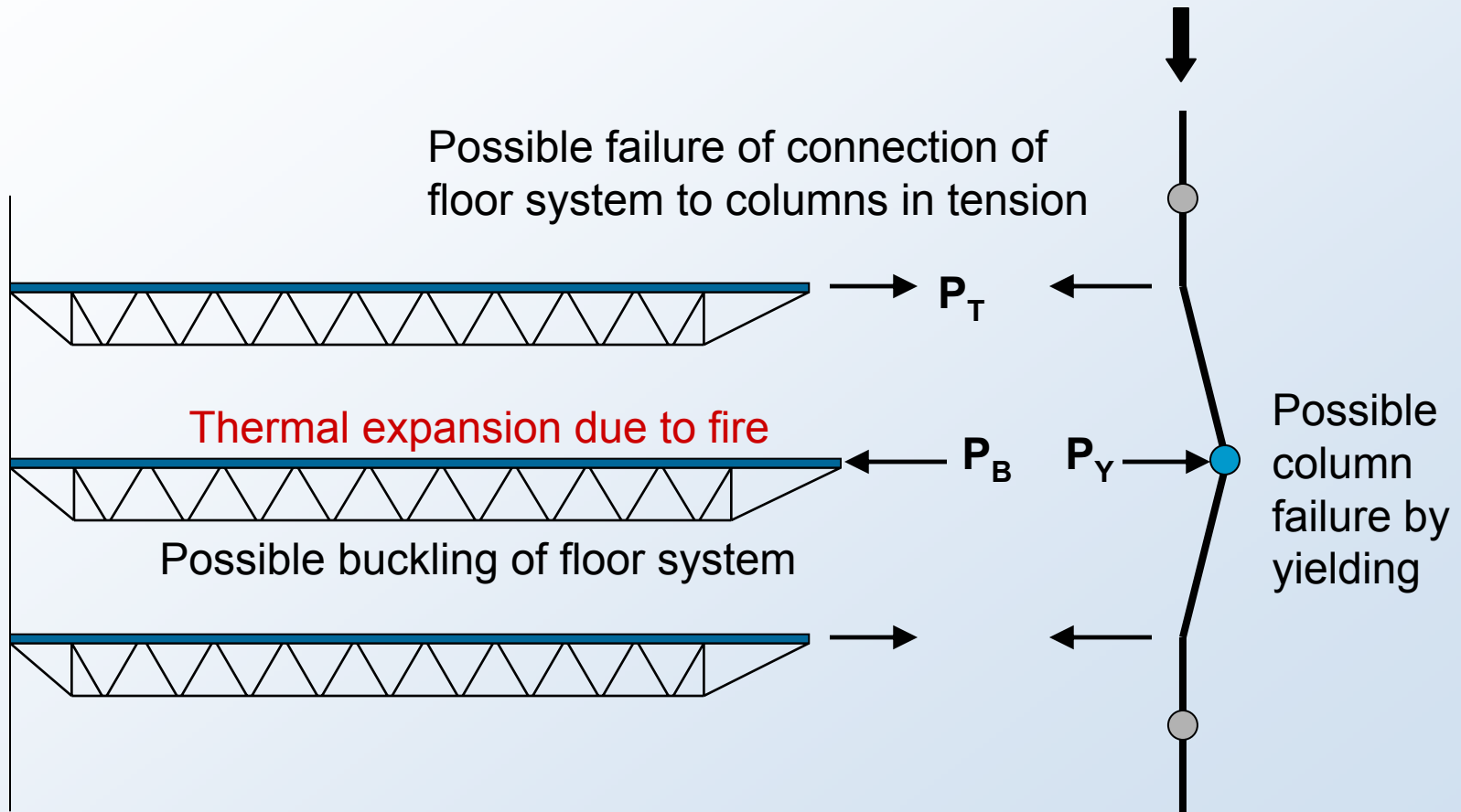
Floor Truss System and Exterior Column Panels



Shear studs

Diagonal straps

Task 4a Progress: Simplified Assessment of Failure Modes for Floor and Exterior Column Systems



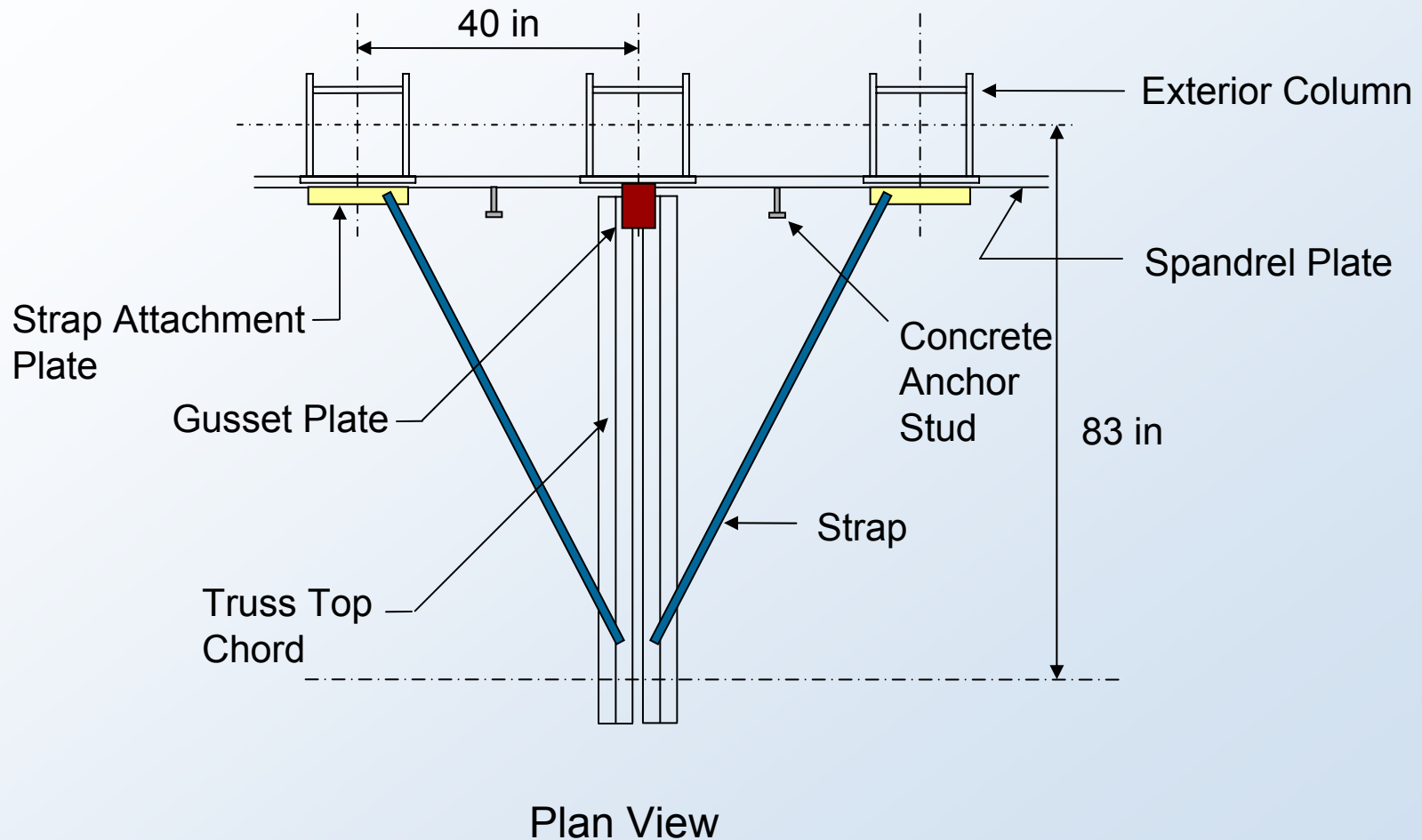
Lateral Bracing of Exterior Columns

Visual evidence that floor-to-exterior column connection failed

- ❑ Possibilities: lateral capacity, vertical capacity, or both exceeded

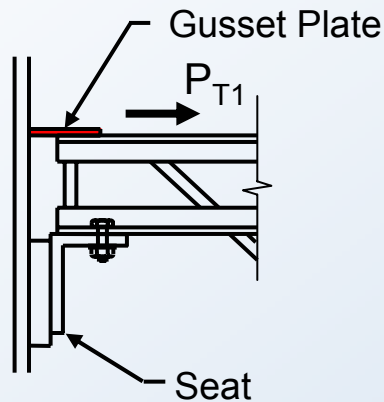


Task 4a Progress: Lateral Bracing of Exterior Column (P_T)

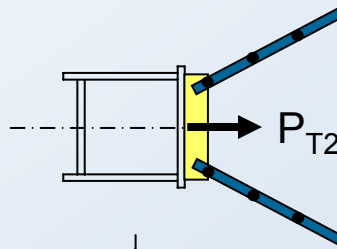


Task 4a Progress: Lateral Bracing of Exterior Columns (P_T)

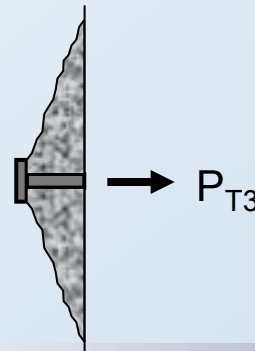
$$P_T = P_{T1} + P_{T2} + P_{T3}$$



Ultimate Strength of
Gusset Plate per
AISC Specification
(1999)



Ultimate Strength of
Gusset Plate per
AISC Specification
(1999)



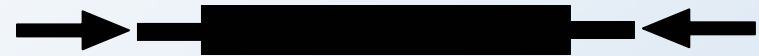
Concrete breakout
strength per ACI-
318 (2002)

Failure by
Concrete breakout

Task 4a Progress: Buckling of Floor System (P_B)

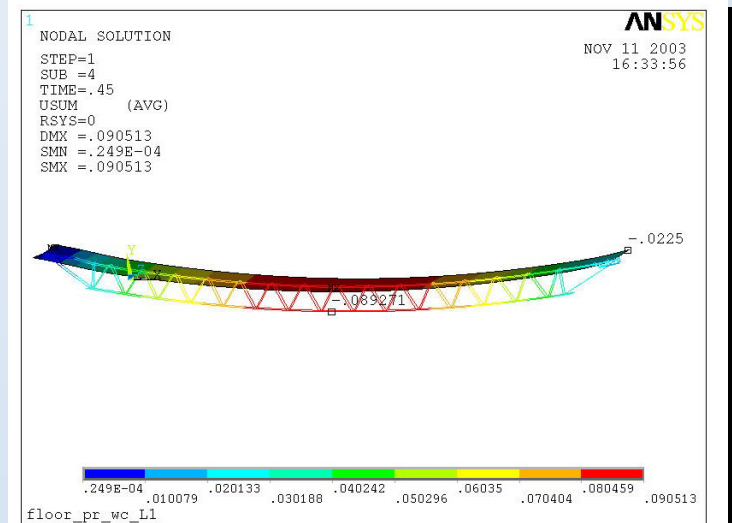
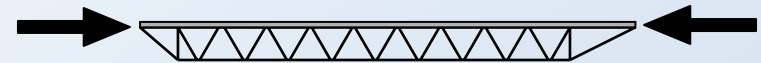
Analytical (Euler) Solution

- ❑ Sensitive to end condition assumptions



ANSYS Computer Solution

- ❑ 80 in wide panel (by symmetry)
- ❑ Geometric nonlinearities included
- ❑ Ambient temperature
- ❑ Preliminary results within bounds of simplified analytical solutions

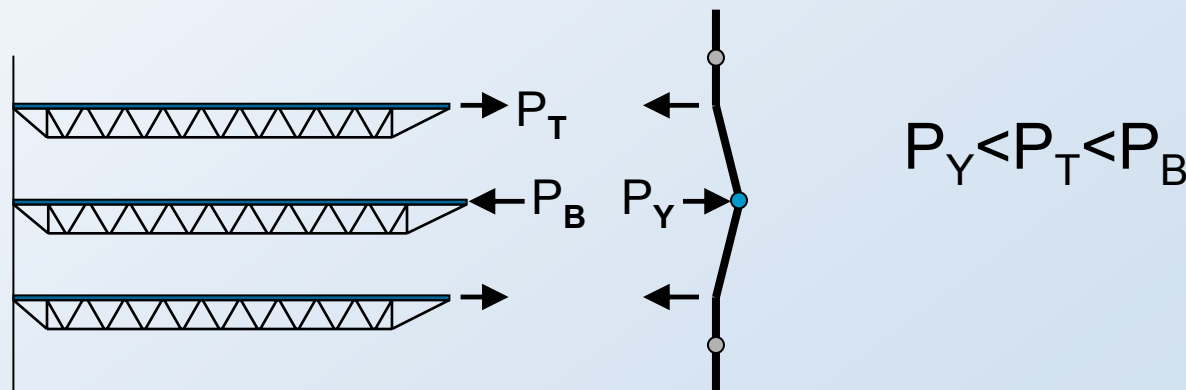


Task 4a Progress: In-Plane Failure Modes - Interim Findings of Simplified Analysis

Relative capacities (weakest to strongest) at room temperatures under lateral loads

- ❑ Exterior column yielding (P_Y)
- ❑ Floor-to-column connection failure (P_T)
- ❑ Floor system buckling (P_B)

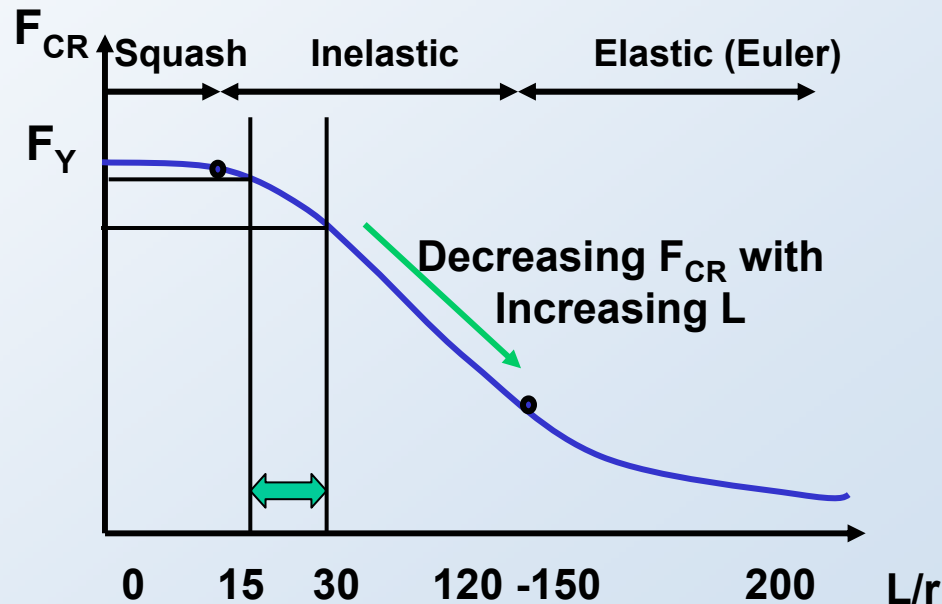
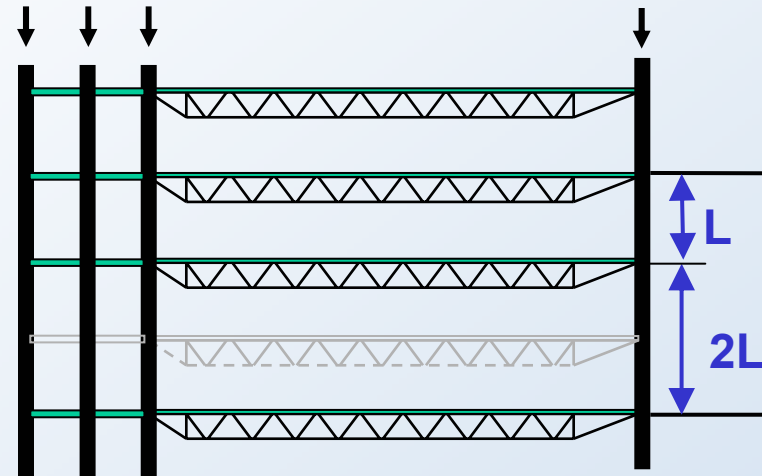
Capacities change with elevated temperature; relative order does not change.



Task 4b Progress: Simplified Analysis of Column Failure

Failure of core and exterior columns

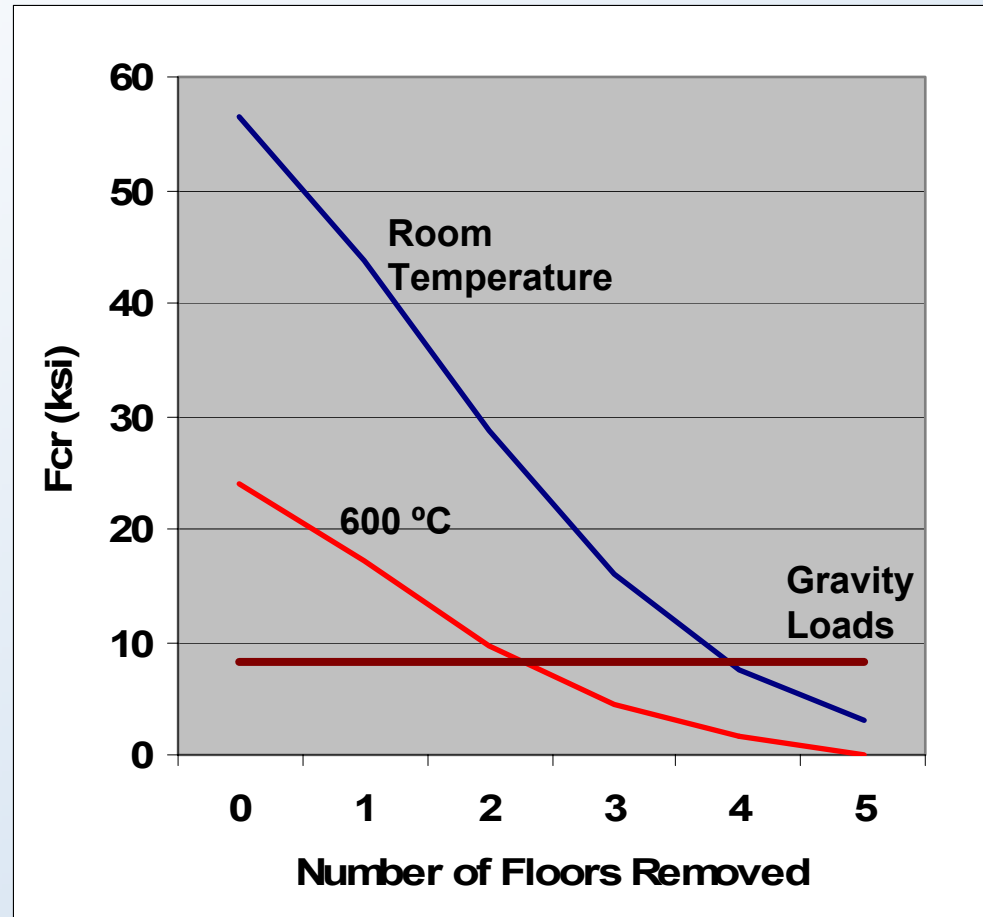
- ❑ Effect of floor removal
- ❑ Effect of elevated temperatures
- ❑ Increased loads



Task 4b Progress: Effect of Floor Removal on Column Failure – A Typical Example

Average for Exterior Columns

WTC 1 North Face
Floor 95 under
Service Loads



Task 4c Progress: Estimated Times for Core Columns to Reach 600 °C

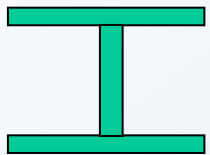
Typical Core Column

12WF133

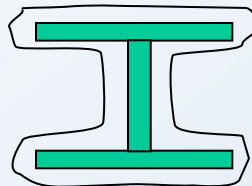
Floor 92-95

(2-3/16-in fireproofing)

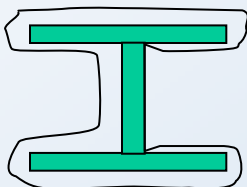
Bare Steel



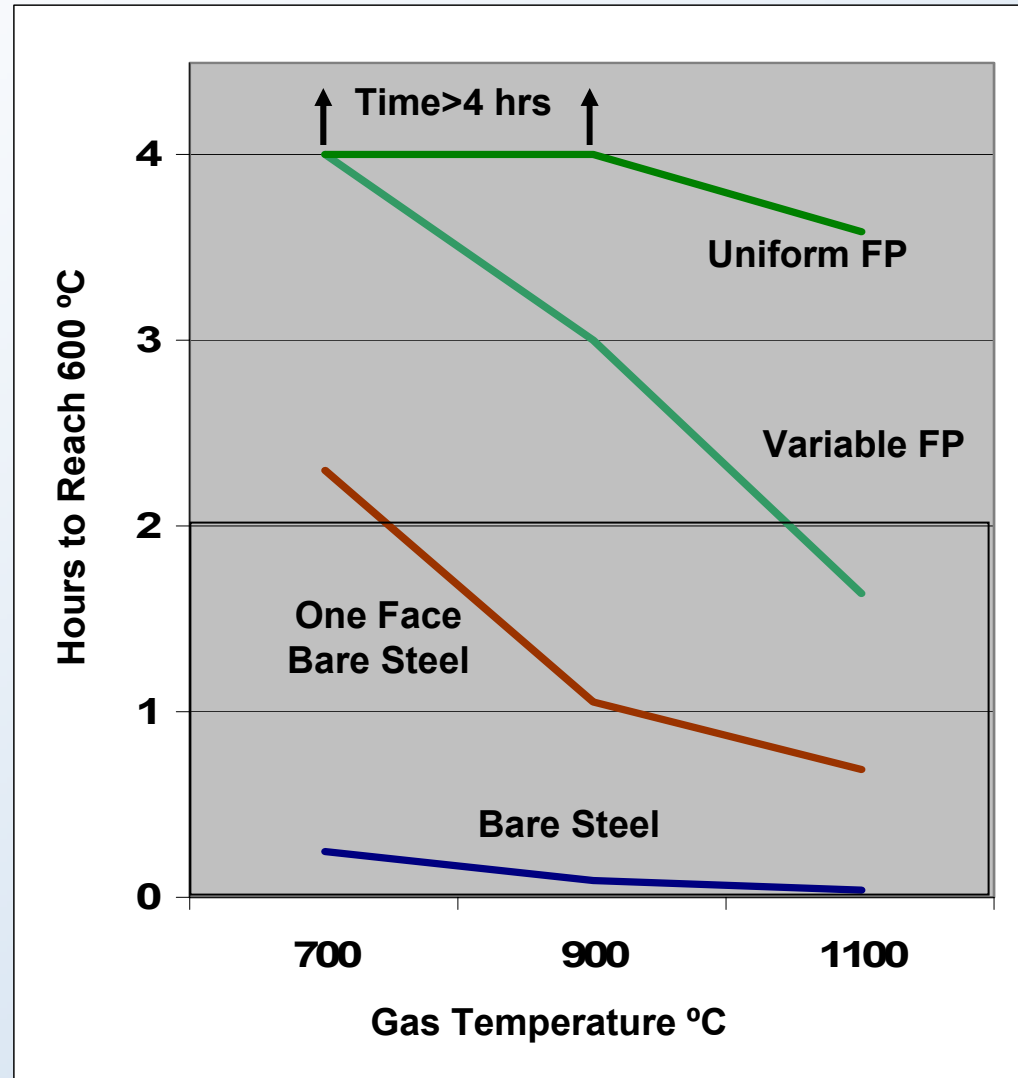
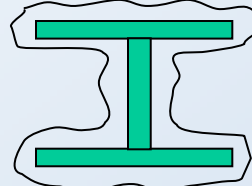
Uniform Thickness



One Face Bare Steel



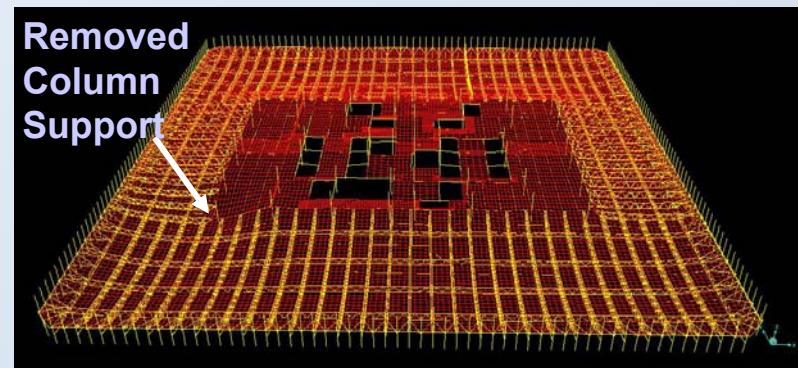
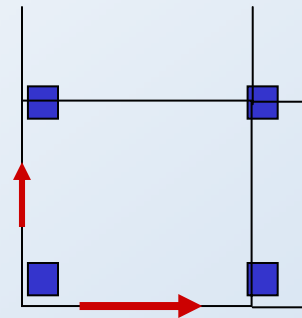
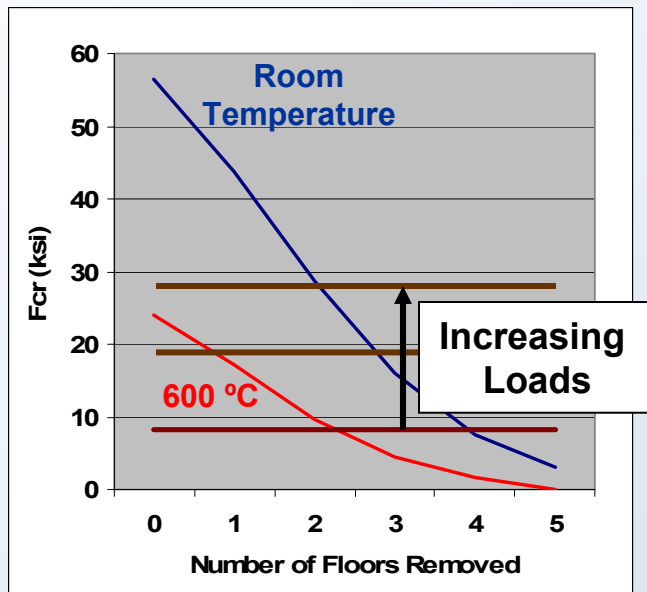
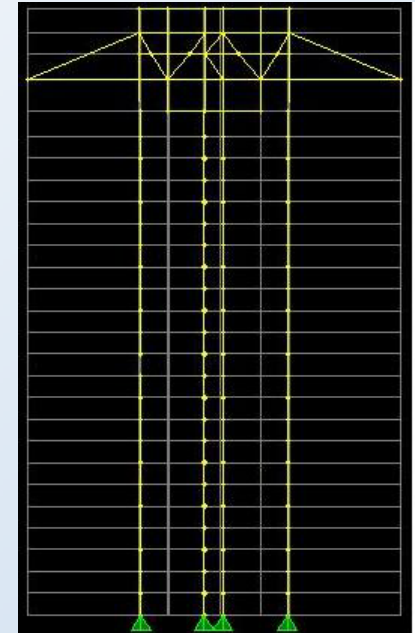
20% Variable Thickness



Task 4d Progress: Simplified Analysis of Load Redistribution Effects on Column Failure

Loads from severed or damaged columns are redistributed to the remaining columns. Columns will continue to redistribute loads as they fail during fires

As column loads increase, less damage (fire and loss of floors) is needed to fail columns



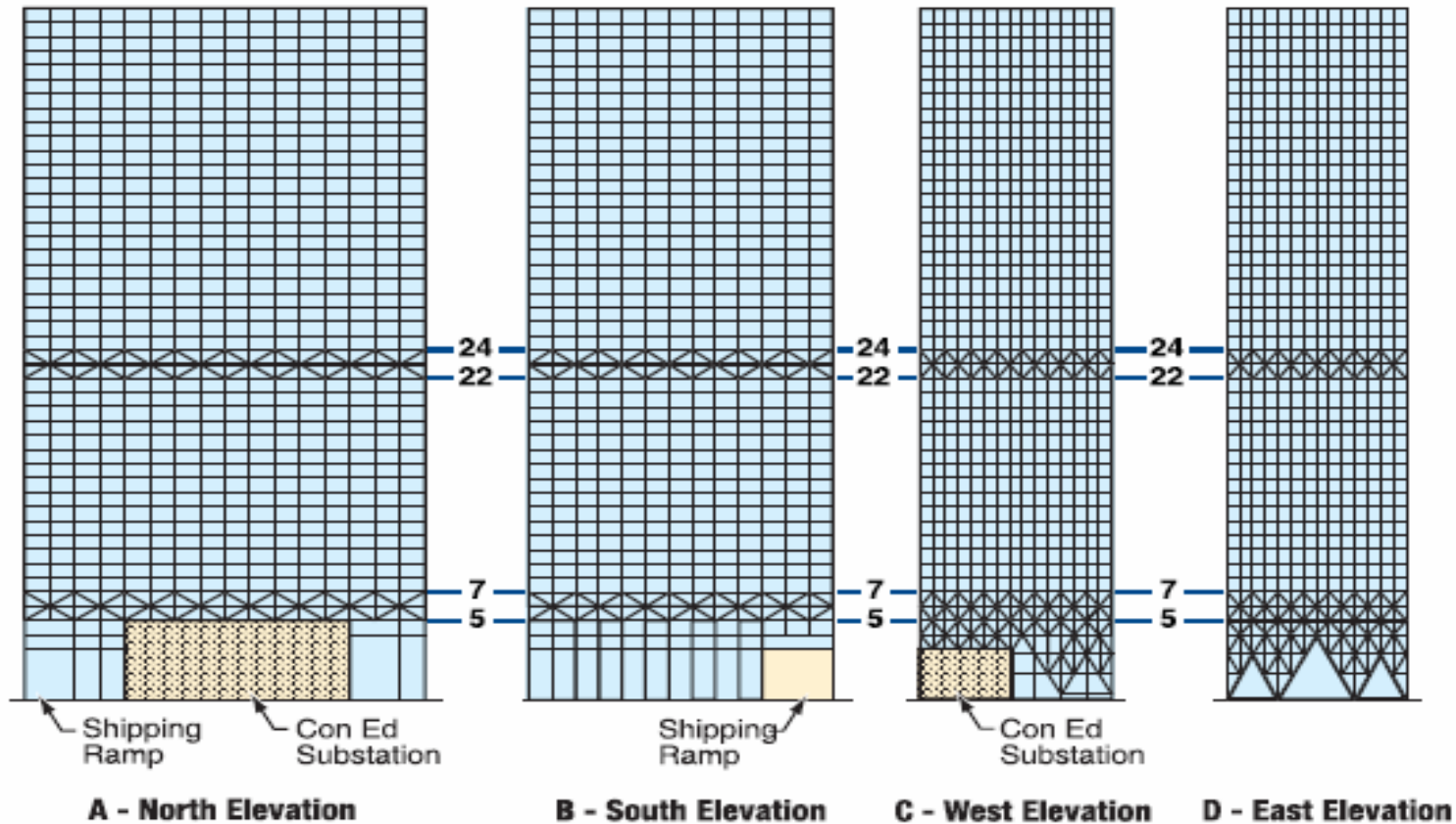
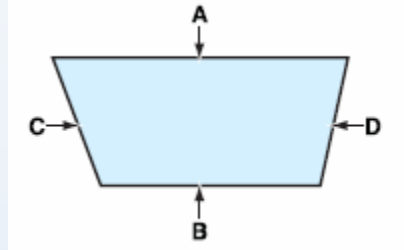
WTC 7

Objectives

To determine the structural response of WTC 7 to debris damage and internal fires and to identify the most probable structural collapse mechanism.

- ❑ Task 1: Component, Subsystem and Global Analyses
- ❑ Task 2: Global Analysis of Collapse Hypotheses
- ❑ Task 3: Evaluation of Collapse Hypotheses

WTC 7 Structural Features



NOTE: Belt trusses located at floors 5-7 and 22-24.

Source: FEMA 403

Significant Features of WTC 7

Differences to note from the WTC Towers

- ❑ Lack of evidence of significant damage to structural, fireproofing, or fuel supply systems
- ❑ Fuel distribution systems were located between floors 1 to 9



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Significant Features of WTC 7

Floor 5 is a 14-in slab reinforced with T-beams

Floor 7 is an 8-in reinforced slab

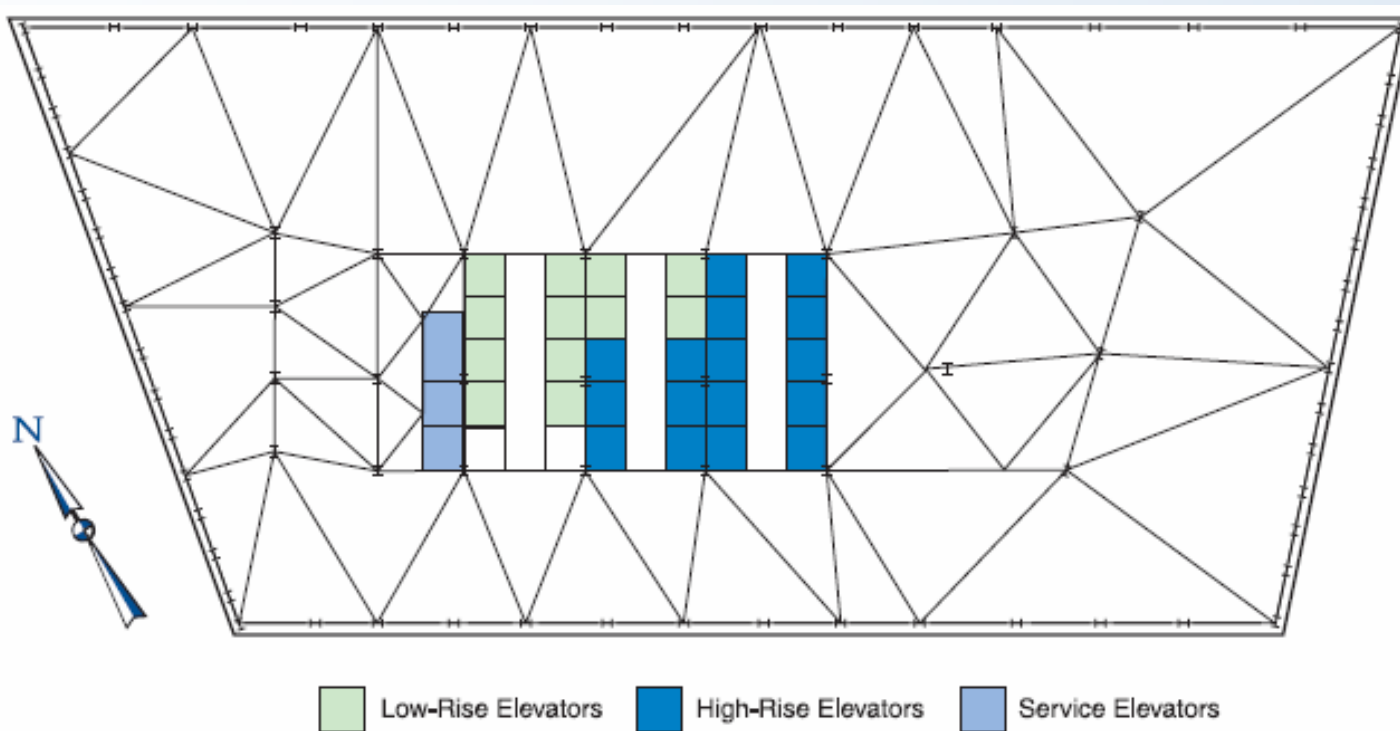


Figure 5-4 Fifth floor diaphragm plan showing T-sections embedded in 14-inch slab.

Source: FEMA 403

WTC 7 Transfer Trusses

Transfer trusses between floors 5 to 7 were large structural members (600-1000 plf)

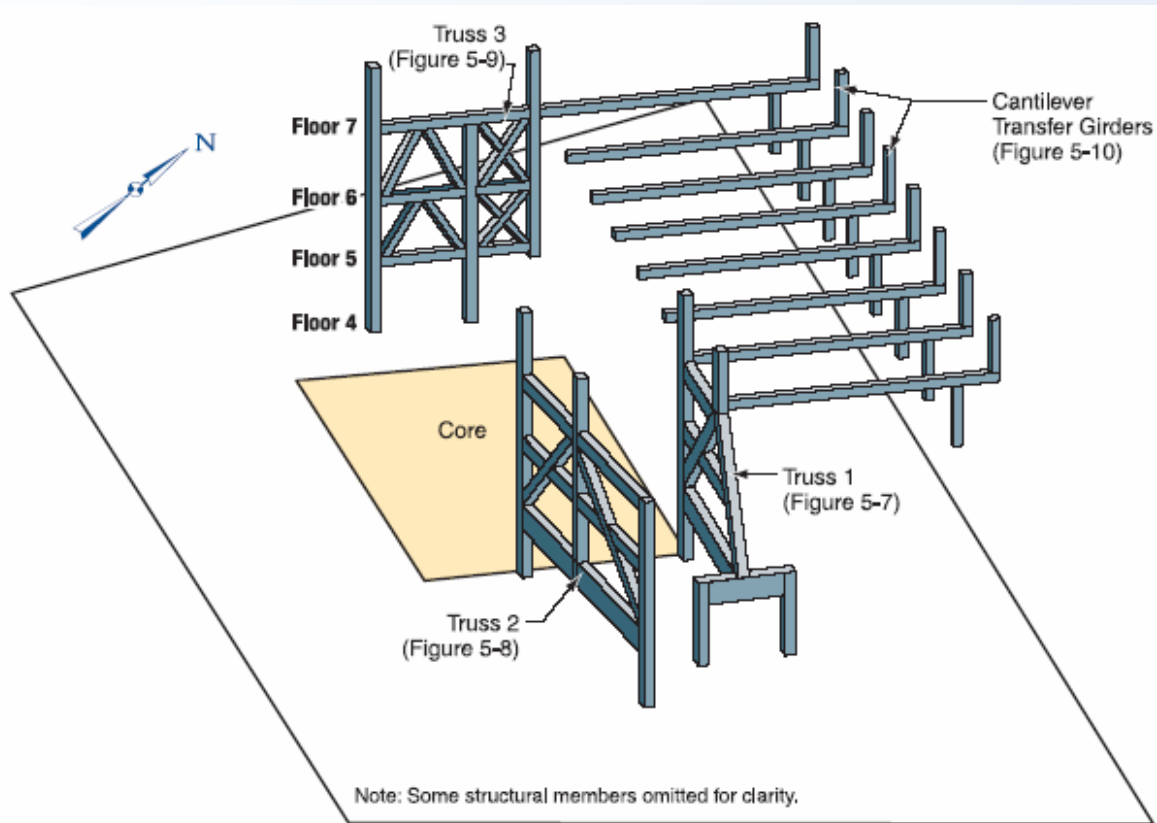


Figure 5-5 3-D diagram showing relation of trusses and transfer girders.

Source: FEMA 403

Task 1: Structural Response Analysis to Identify Critical Components

Develop a nonlinear global structural model of WTC 7 and evaluate its performance under design gravity loads.

Identify credible failure sequences using the structural model to analyze the effect of component failures on the structural system stability

Identify dominant failure modes for critical components and subsystems for service loads and elevated structural temperatures

Conduct parametric studies of critical subsystems to identify influential parameters

Develop approaches to simplify structural analyses for global modeling and analyses

Tasks 2 and 3: Structural Analysis of Collapse Initiation Hypotheses

Refine the global model of WTC 7 to support nonlinear structural analysis for building regions affected by fire.

Analyze three (3) collapse initiation sequences selected.

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

Identify the most probable collapse initiation sequence, based upon:

- 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
- Agreement between analysis and observed performance

Status (1)

Contract has been awarded to Gilsanz, Murray, and Steficek (GMS) of New York City to develop component, subsystem and global models and to conduct thermal-structural analyses

- Contract awarded October 27, 2003
- Kickoff Meeting November 7, 2003

Data collection

- Final design drawings
- Complete set of specifications
- Design and service loads
- Mechanical properties of steel (Project 3)
- Fireproofing materials (Projects 5 and 6)
- Fuel distribution system, tanks, and generators (Project 1)

Status (2)

Structural temperature time-histories for standard fires (e.g., ASTM E-119 and ASTM E-1529) and representative fires (Project 5).

Observables for collapse hypotheses (Project 5)

- ❑ Initial damage to WTC 7 structure from collapse of towers
- ❑ Timeline and locations of fire and smoke
- ❑ Timeline and location of exterior signs of collapse (penthouse, windows, fault-line, etc)



Structural Fire Response and Collapse Analysis of WTC 7

Expected Results

- ❑ Determine the structural response of components and systems to fires that contributed to the collapse of the building.
- ❑ Determine the effect of component failures on load redistribution and sequence of failures in the structure.
- ❑ Estimate the margin of safety for each critical component as a function of time.
- ❑ Identify the most probable collapse sequence that is consistent with the observed failure sequence in video and photographic records and other available observations.