Structural Response of Components, Subsystems, and Global Models of WTC Towers to Aircraft Impact and Fire

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Objective and Approach

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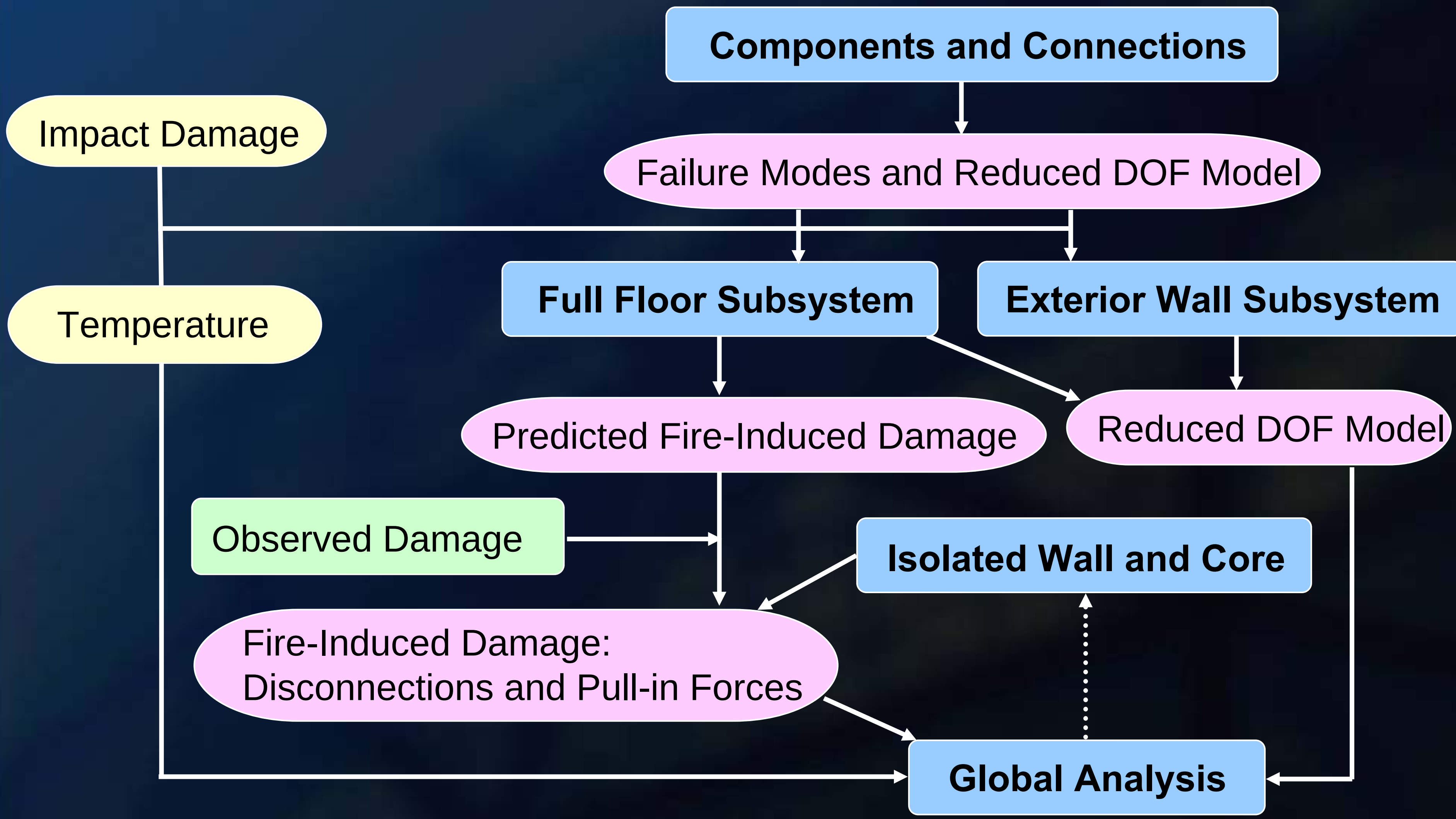
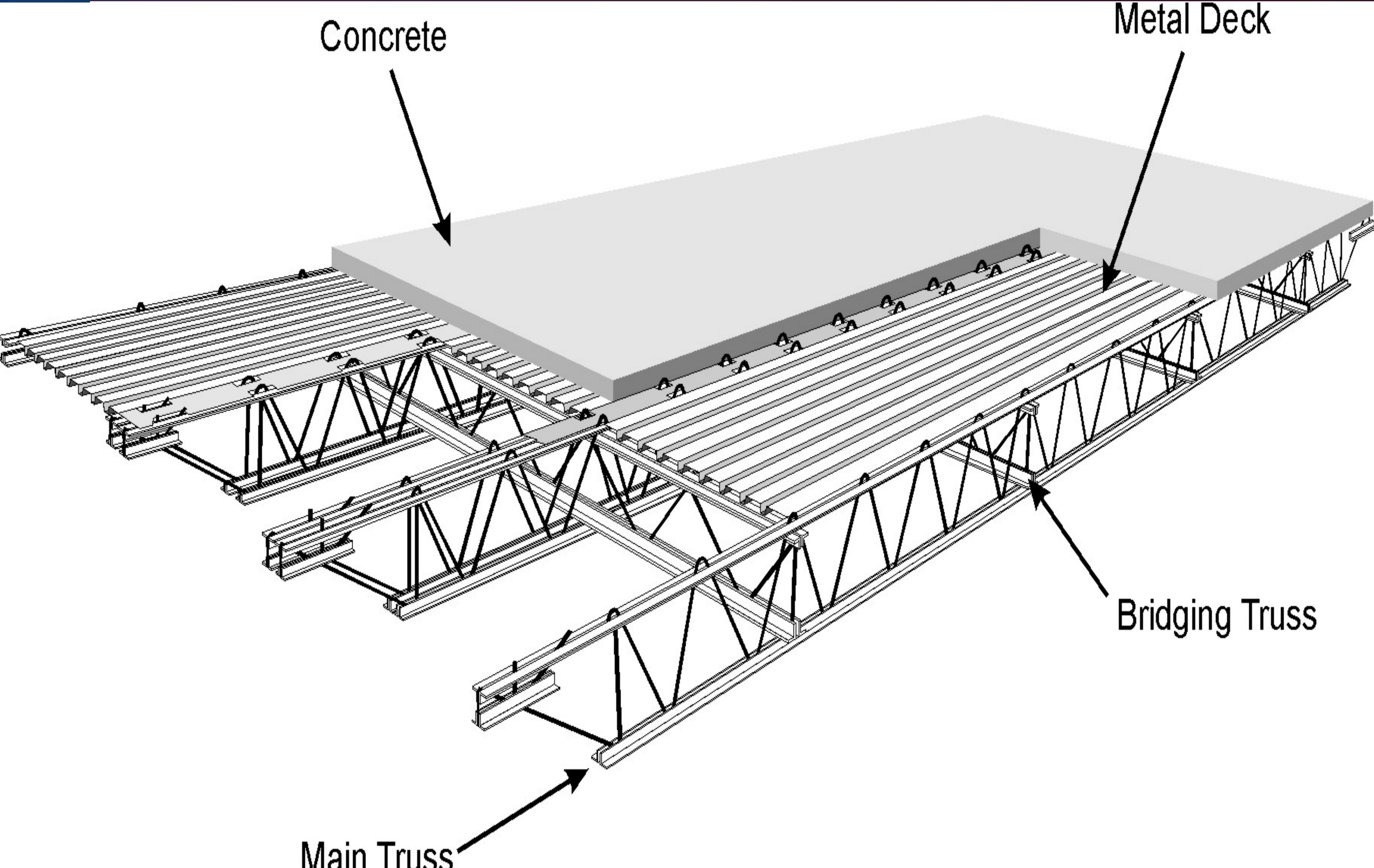
- Objective: Present the results of the finite element analyses performed for each of the WTC towers to determine their structural response to aircraft impact damage and subsequent fires.

- Approach: For components, subsystems, and towers
  - Identify probable failure modes and key structural responses
  - Improve numerical efficiency in larger subsystem and global analyses by developing reduced degree of freedom (DOF) models that capture essential behavior and failure modes
  - Guide and validate structural response using key observations

Method of Approach



Floors



Floor Truss with Concrete Slab

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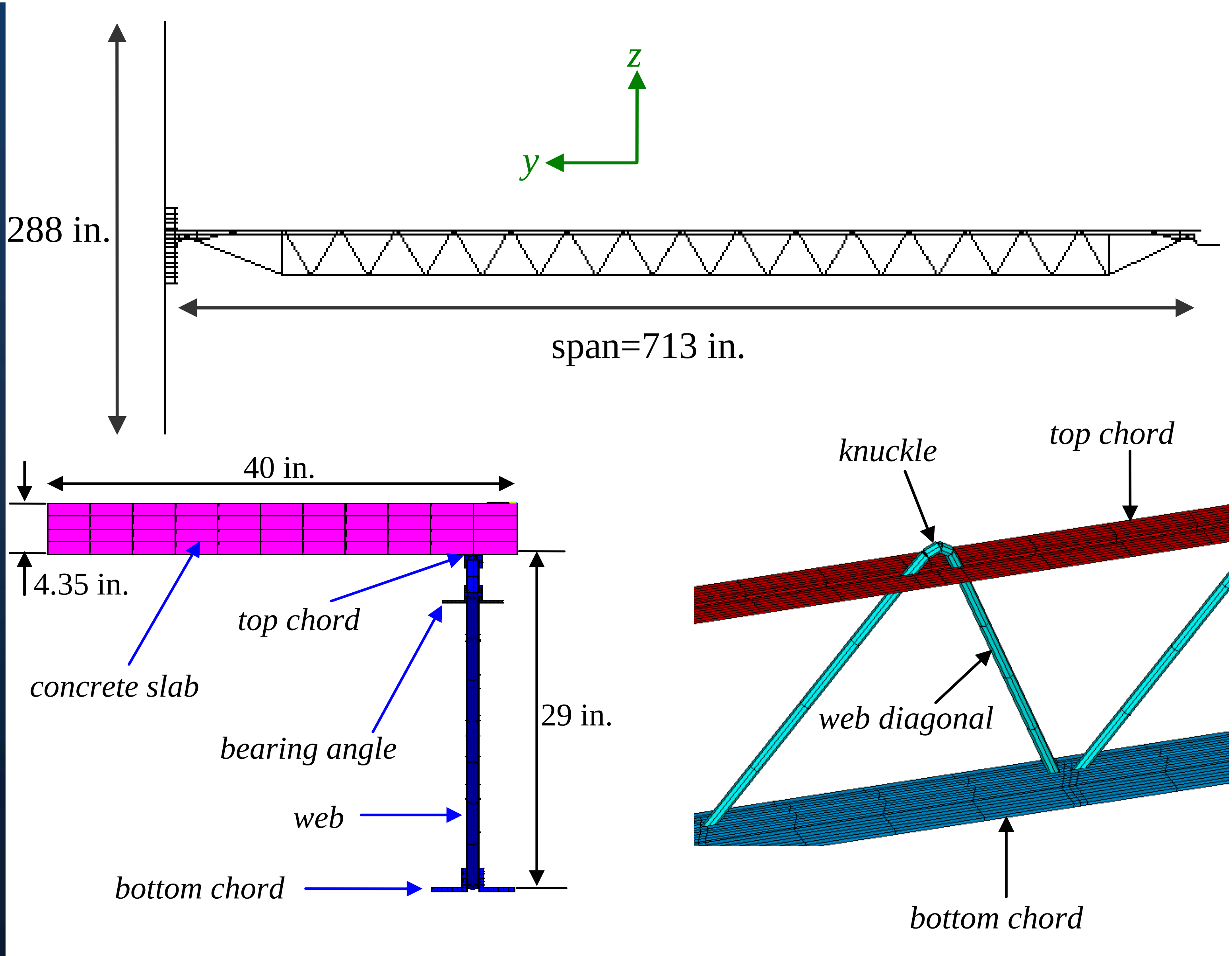

Temperature-Dependent Material Properties

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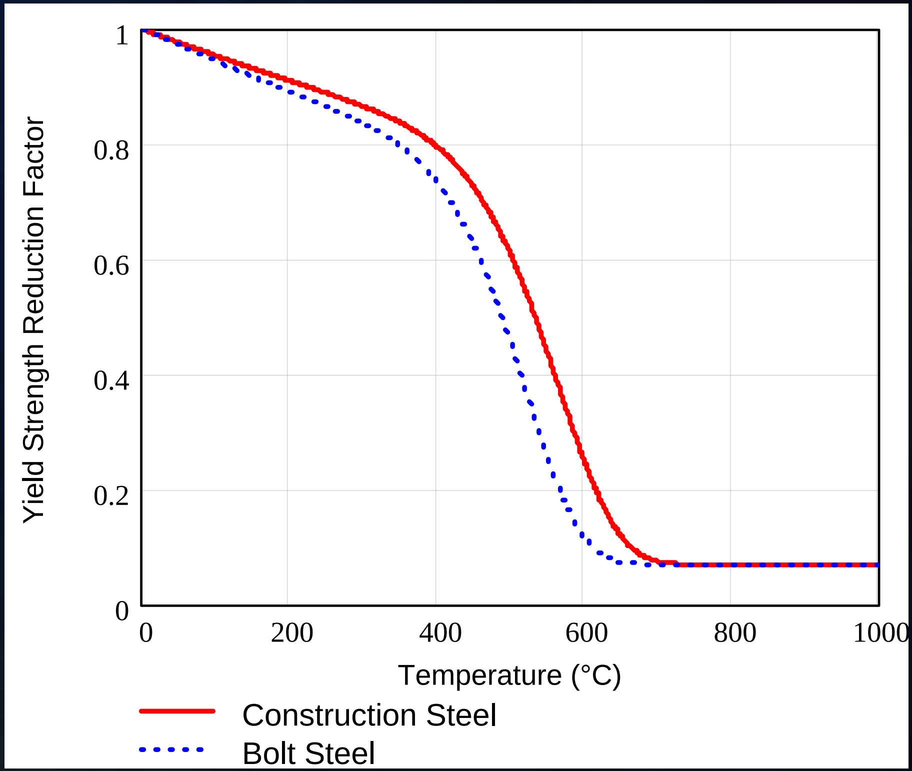
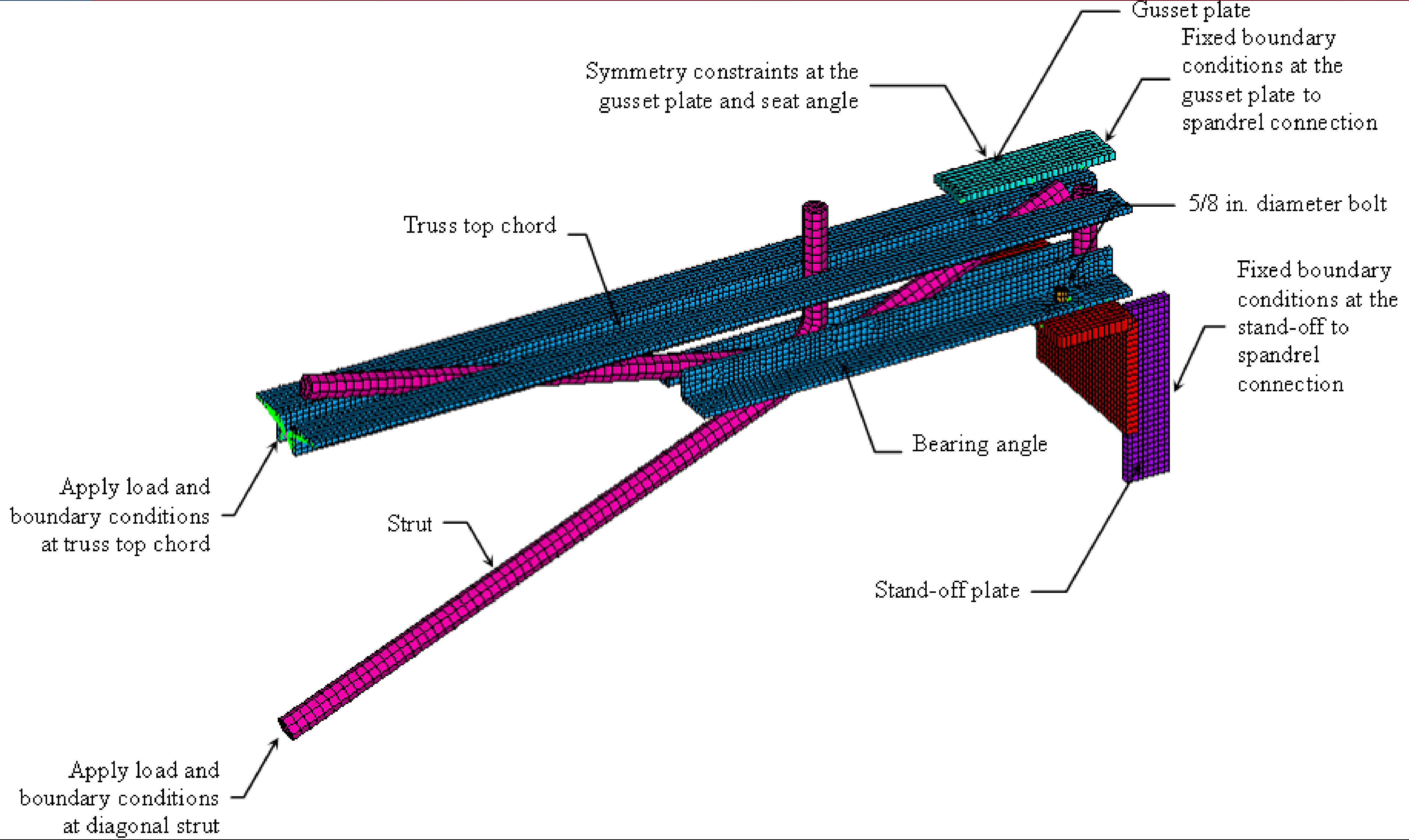
- Steel
  - Modulus of Elasticity
  - Yield Strength
  - Tensile Strength
  - Coefficient of Thermal Expansion
  - Creep
  - $\varepsilon_{tot} = \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{creep} + \varepsilon_{\Delta T}$
- Concrete
  - Modulus of Elasticity
  - Compressive Strength
  - Tensile Strength
  - Coefficient of Thermal Expansion



Exterior Truss Seat Model



Truss Seat Failure Modes

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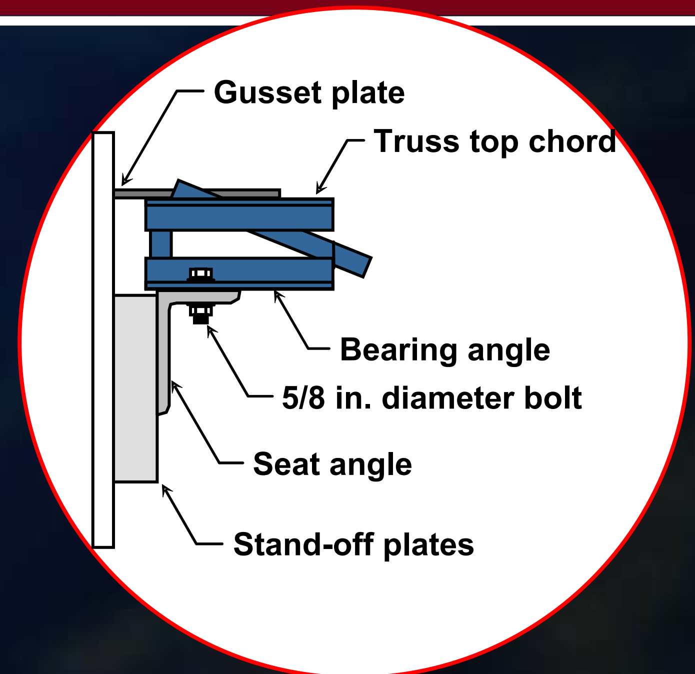
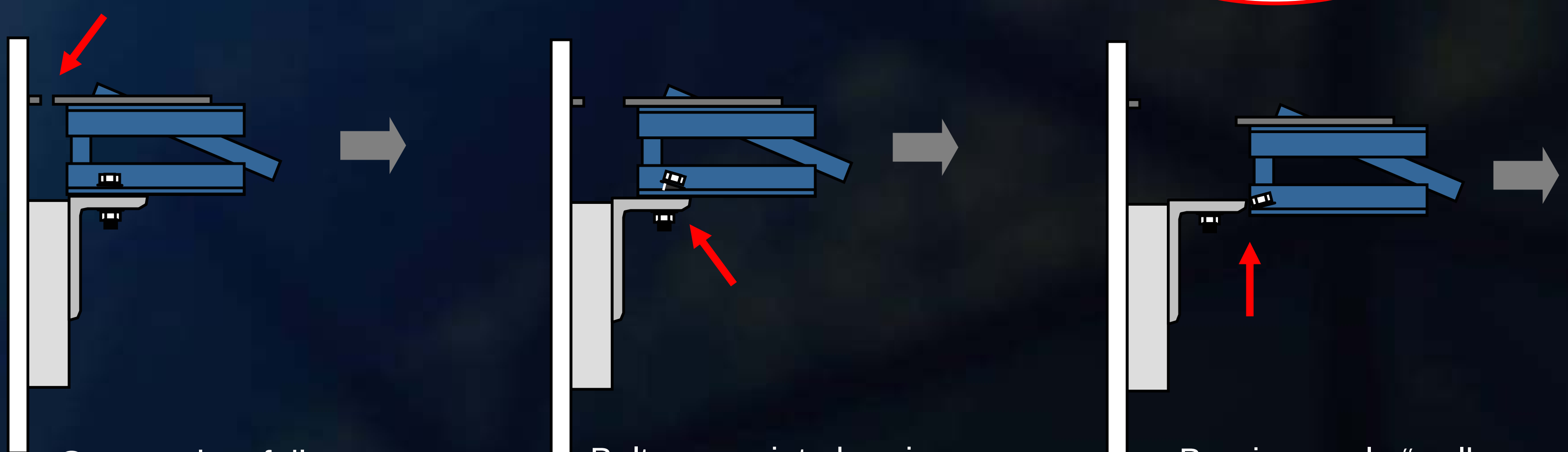


Possible failure sequence under horizontal load…



Gusset plate fails

Bolt comes into bearing and shears off

Bearing angle “walks off” seat angle

Break Element Model for Interior Truss Seat

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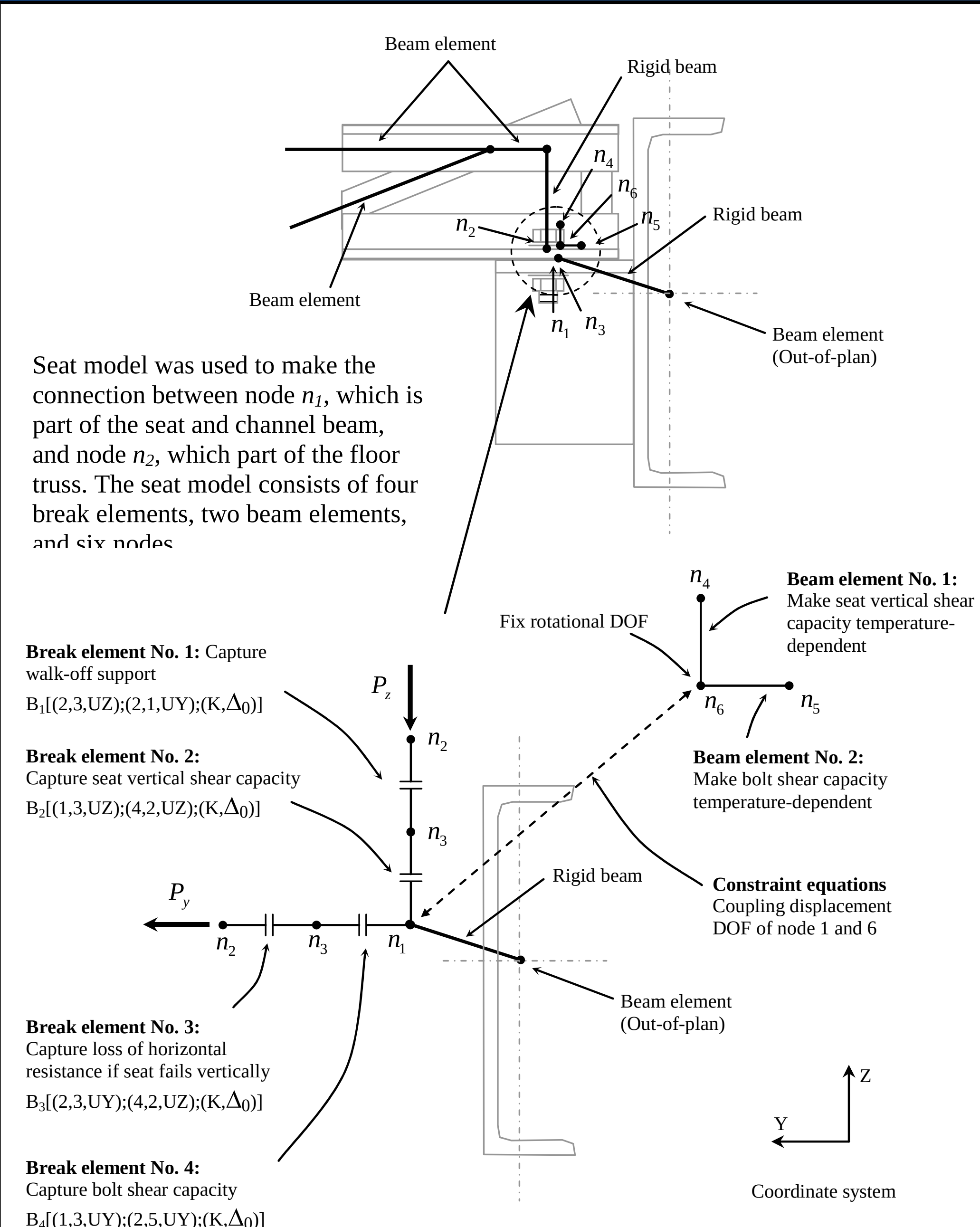

- Break elements were defined as the elements that capture loss of stiffness resulting from a certain failure mode.
- Break elements had temperature-dependent capacities.

Knuckle Analysis

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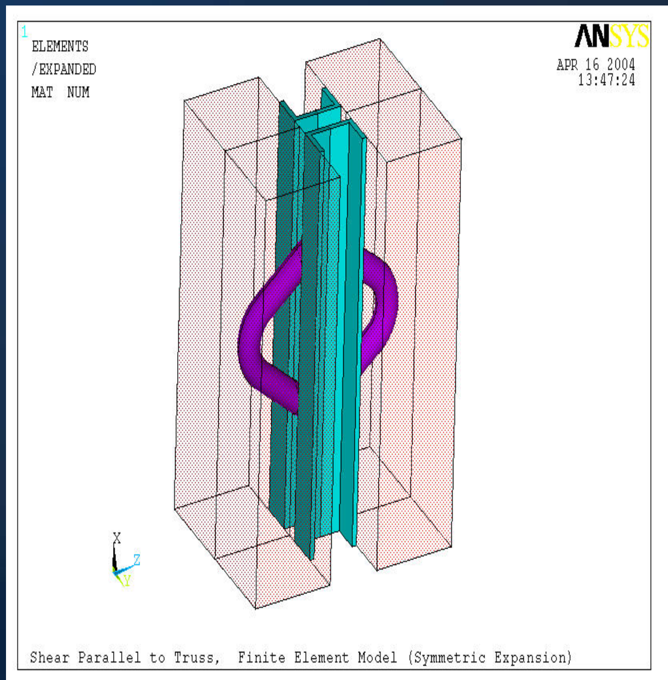
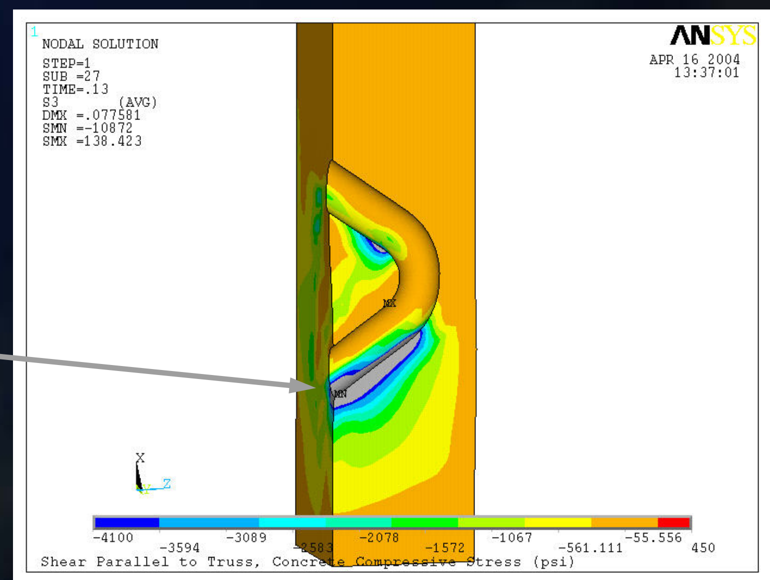


Crush Region in Gray



Axial Stress in Truss Members Near the Interior End

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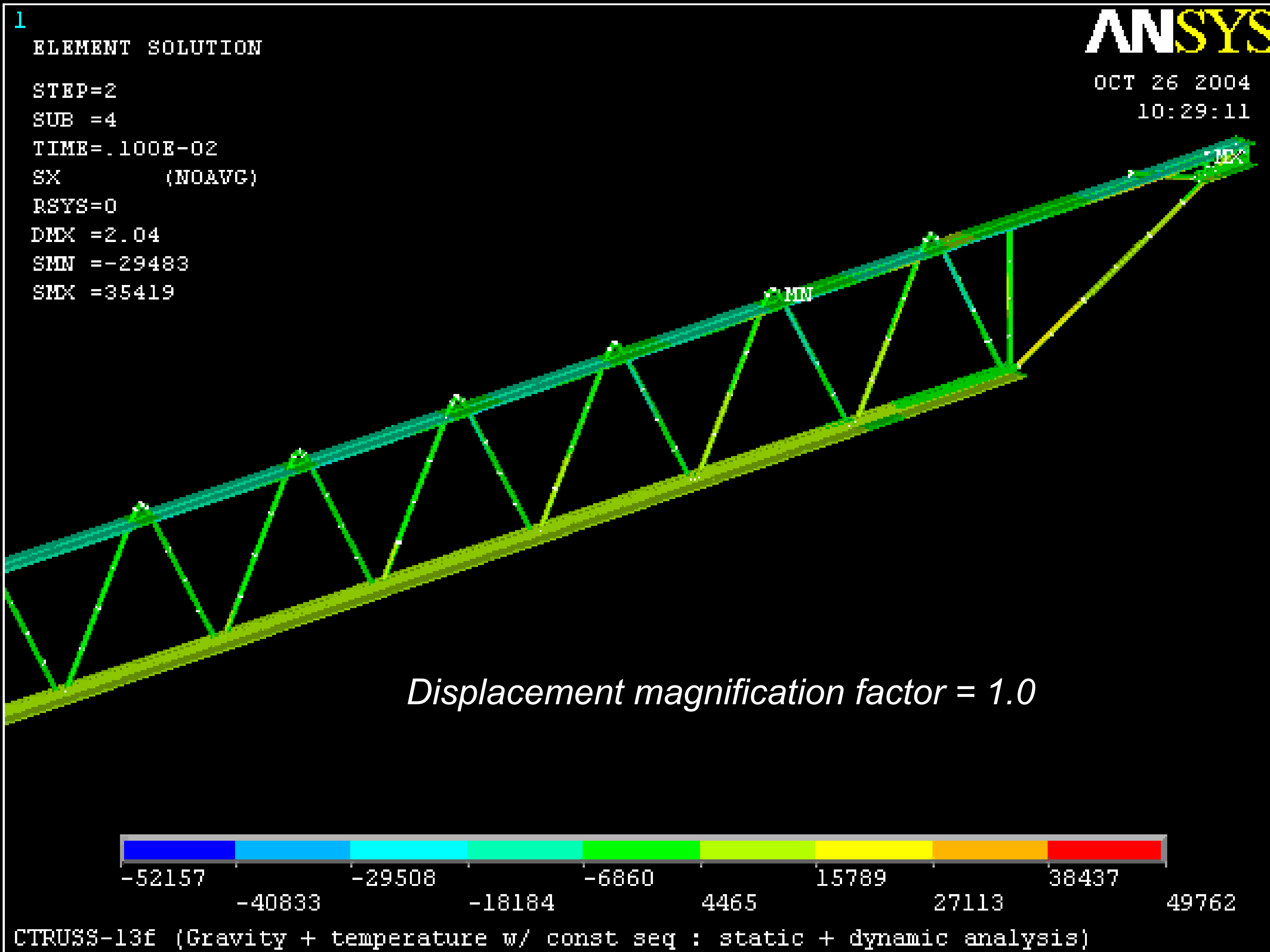
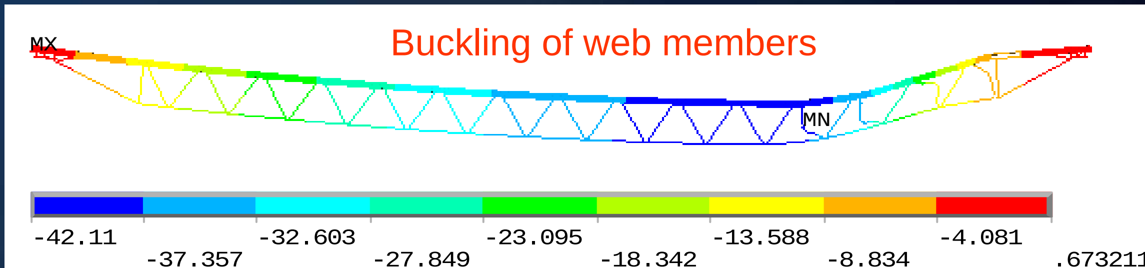
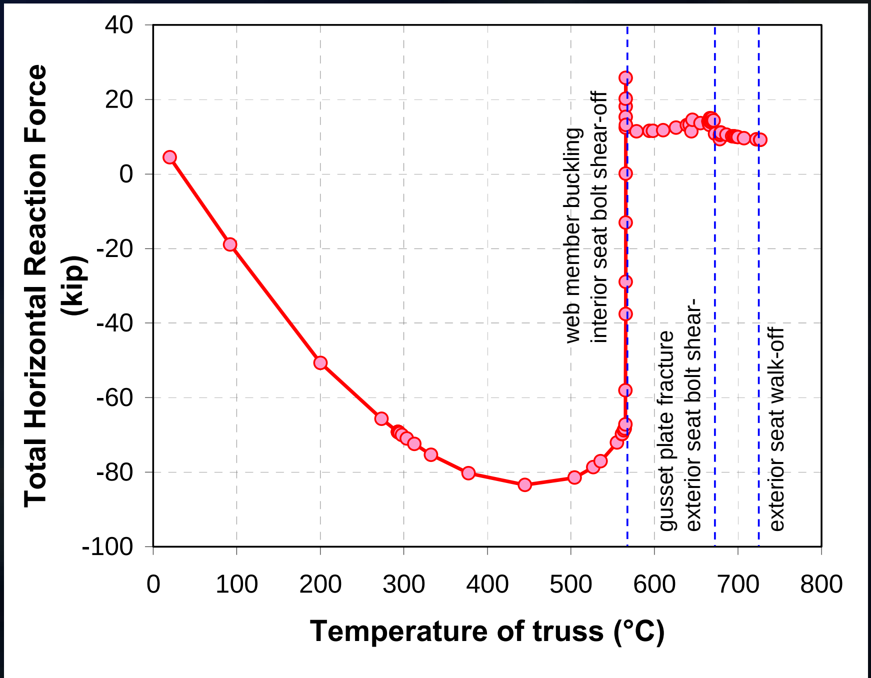


Sagging Observed in the Detailed Truss Model

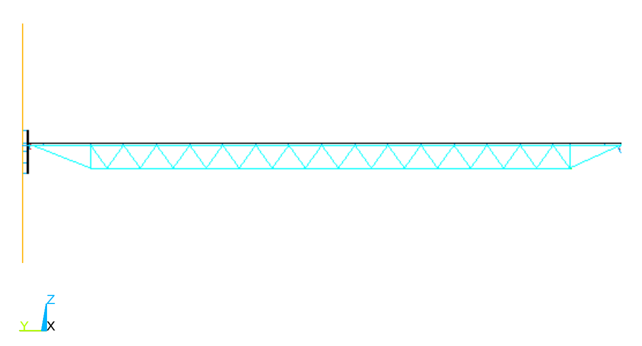
Vertical displacement contour at 700 ˚C

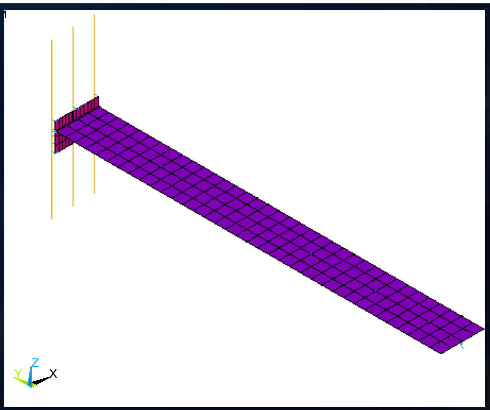


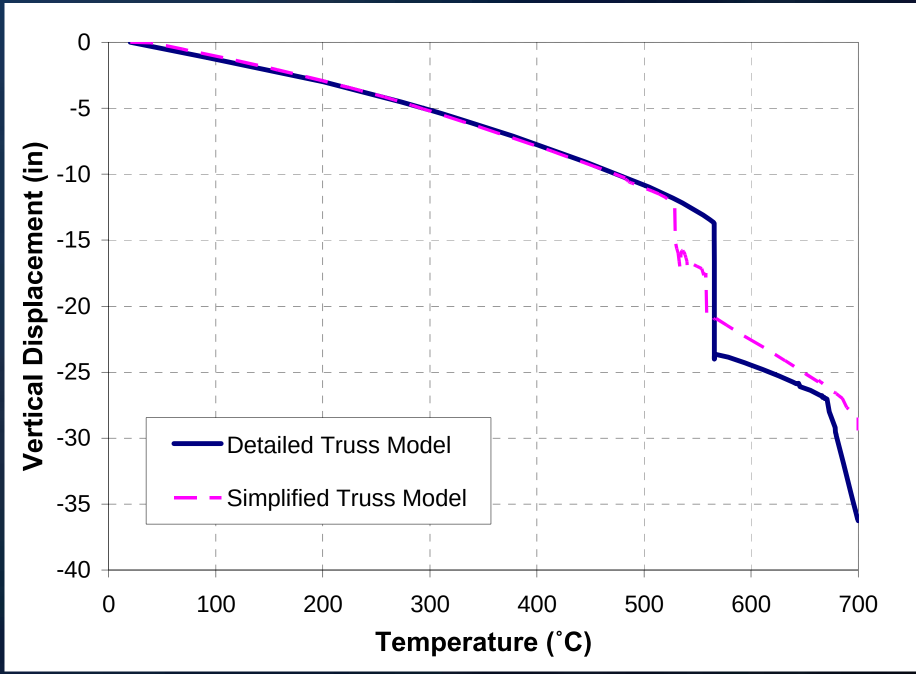
- After web members buckled, the truss pulled exterior columns in.
- The tension force ranged from 9 kip to 14 kip per column in this model.



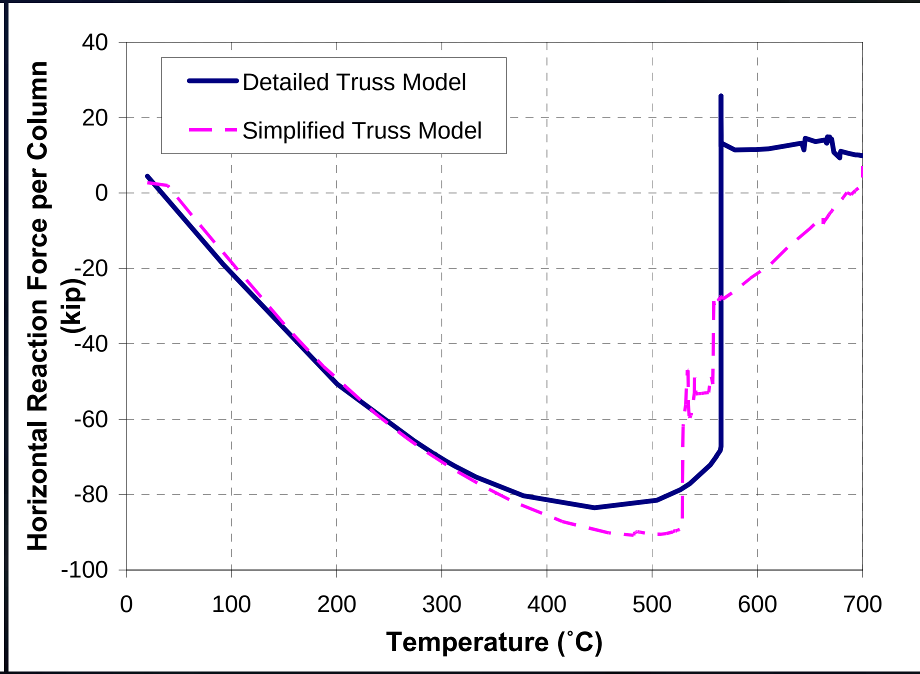
Response of Reduced DOF Truss Model to Temperatures







Vertical displacement at midspan



Horizontal reaction per exterior column

Creep Effect on Vertical Displacement of Truss Model

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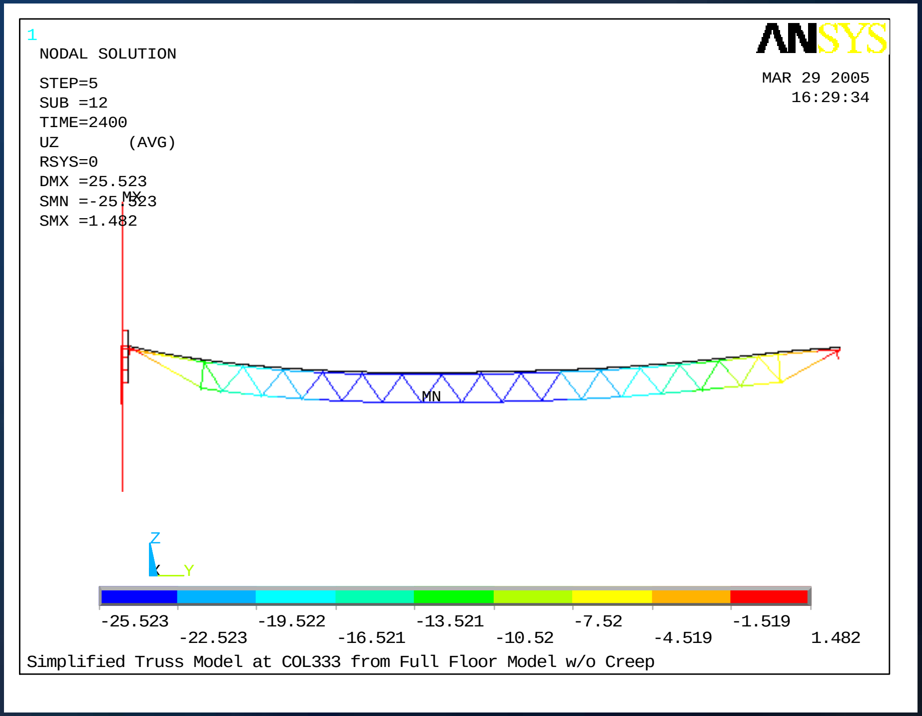
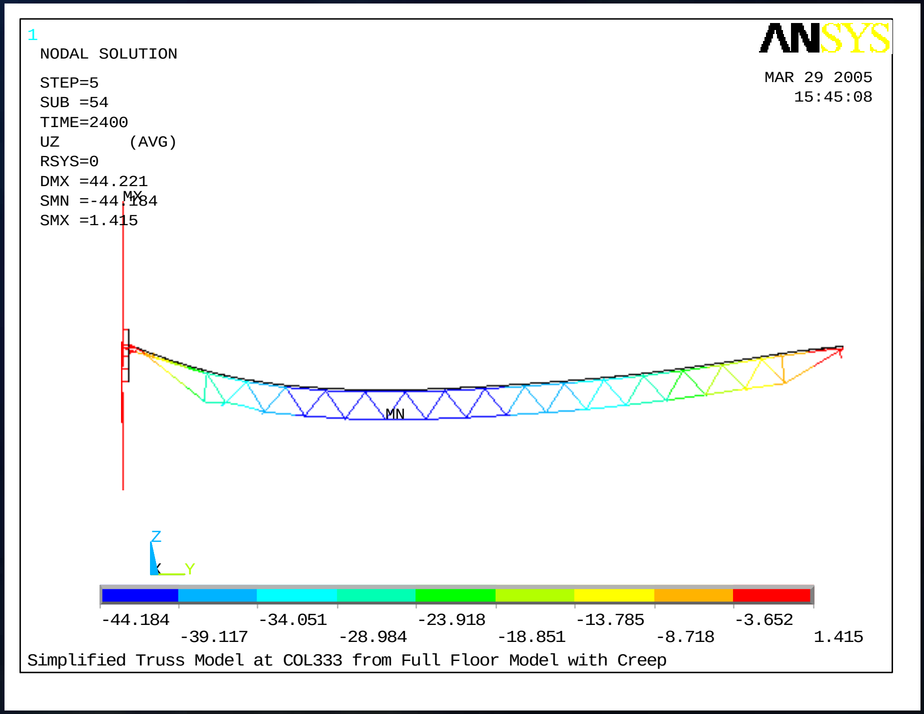
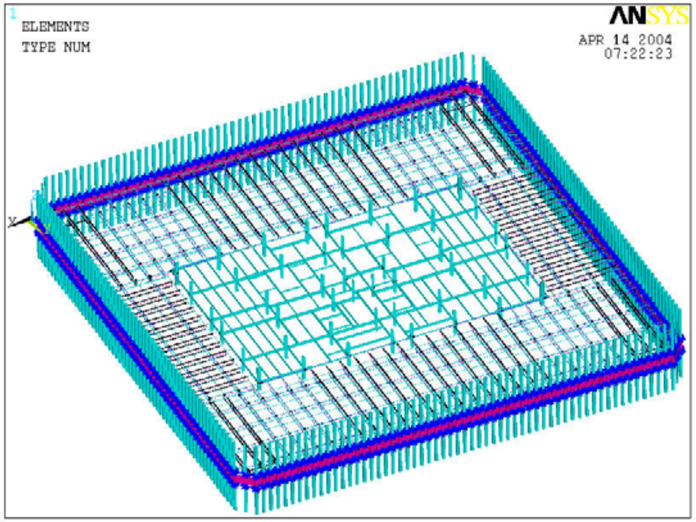


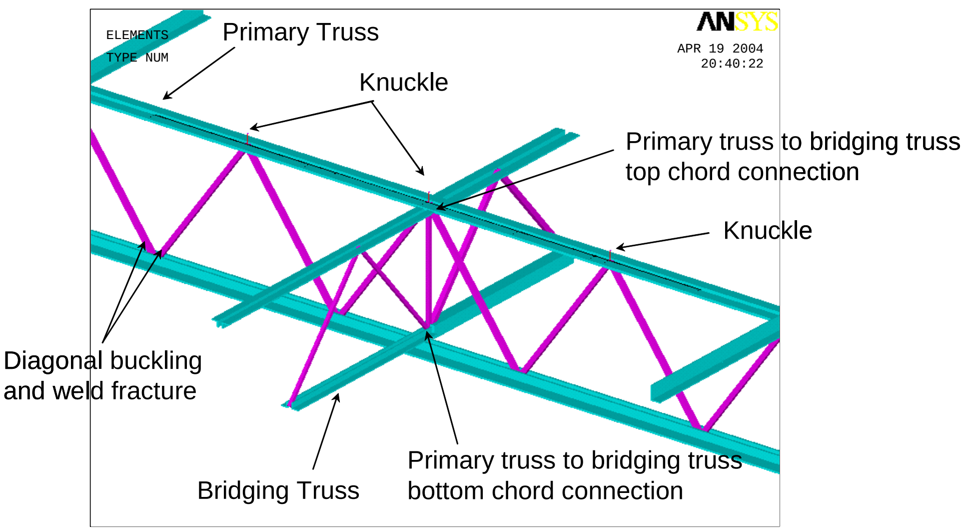


w/o Creep at 2,400 s
Max. = 25.5 in.

w/ Creep at 2,400 s
Max. = 44.2 in.

Full Floor Model





Component Models:

- Knuckle
- Truss Seat/Connections
- Truss/Exterior Column

Subsystem Model: Full Floor

- Concrete slab
- Primary floor trusses
- Bridging trusses
- Transfer trusses
- Strap anchors
- Interior and exterior columns
- Spandrels
- Core beams

Finite Element Model of Full Floor

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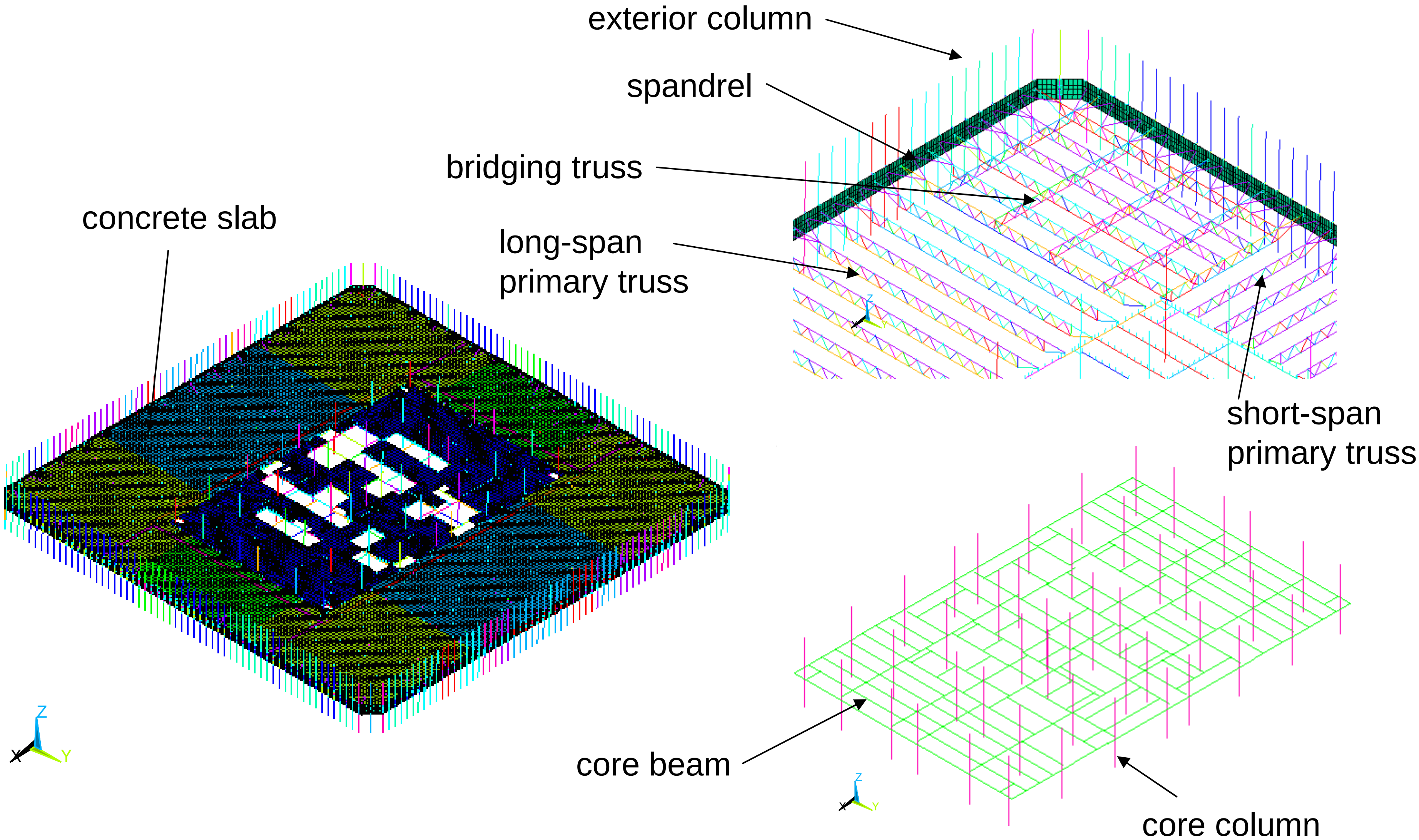

WTC 1 Floor 98 - Temperatures at 50 min

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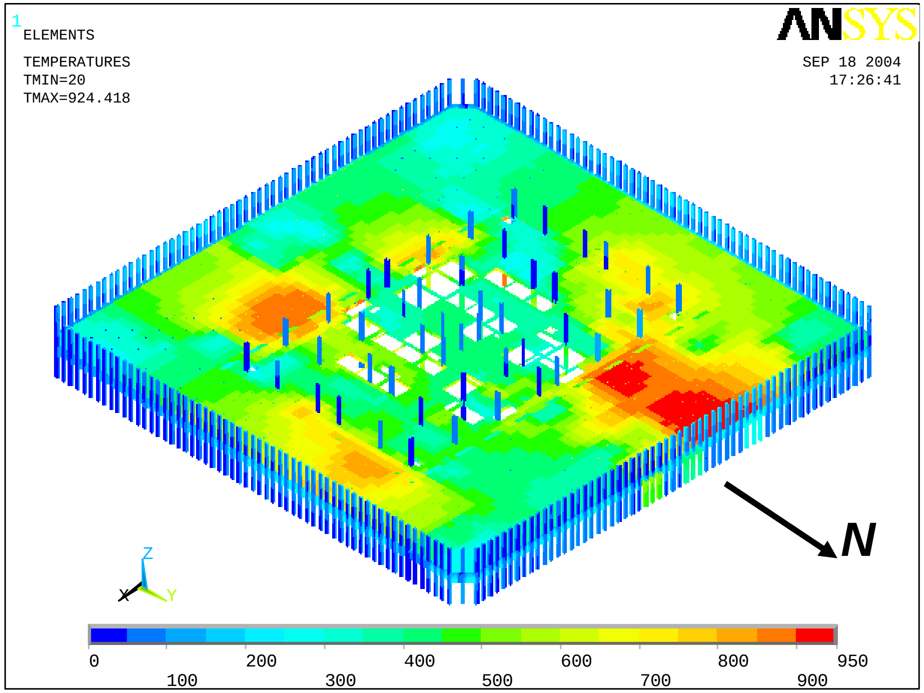

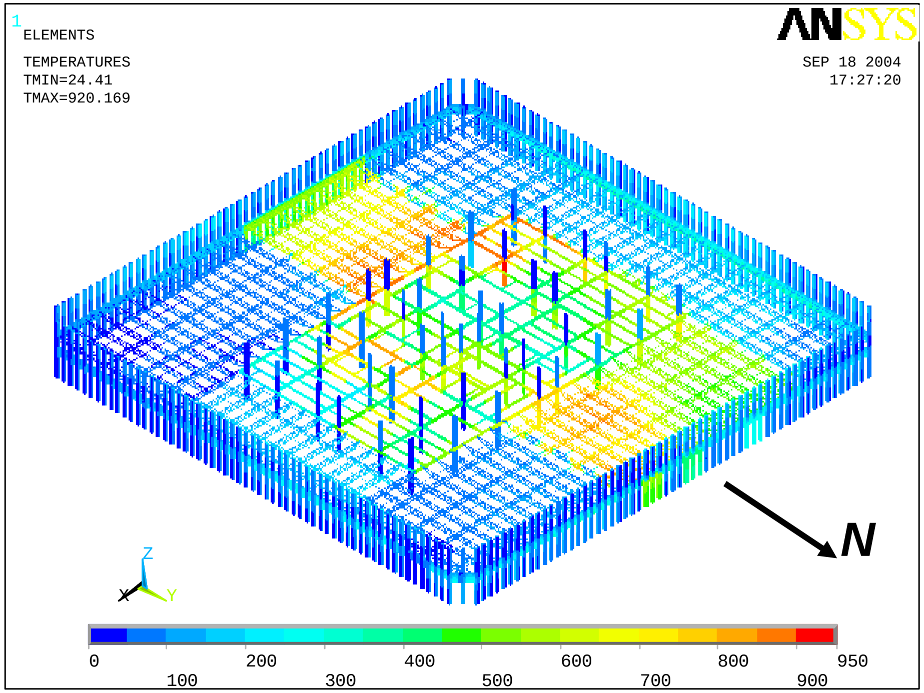

Concrete Slab Temperatures

Steel Temperatures

Break Elements in Full Floor Models

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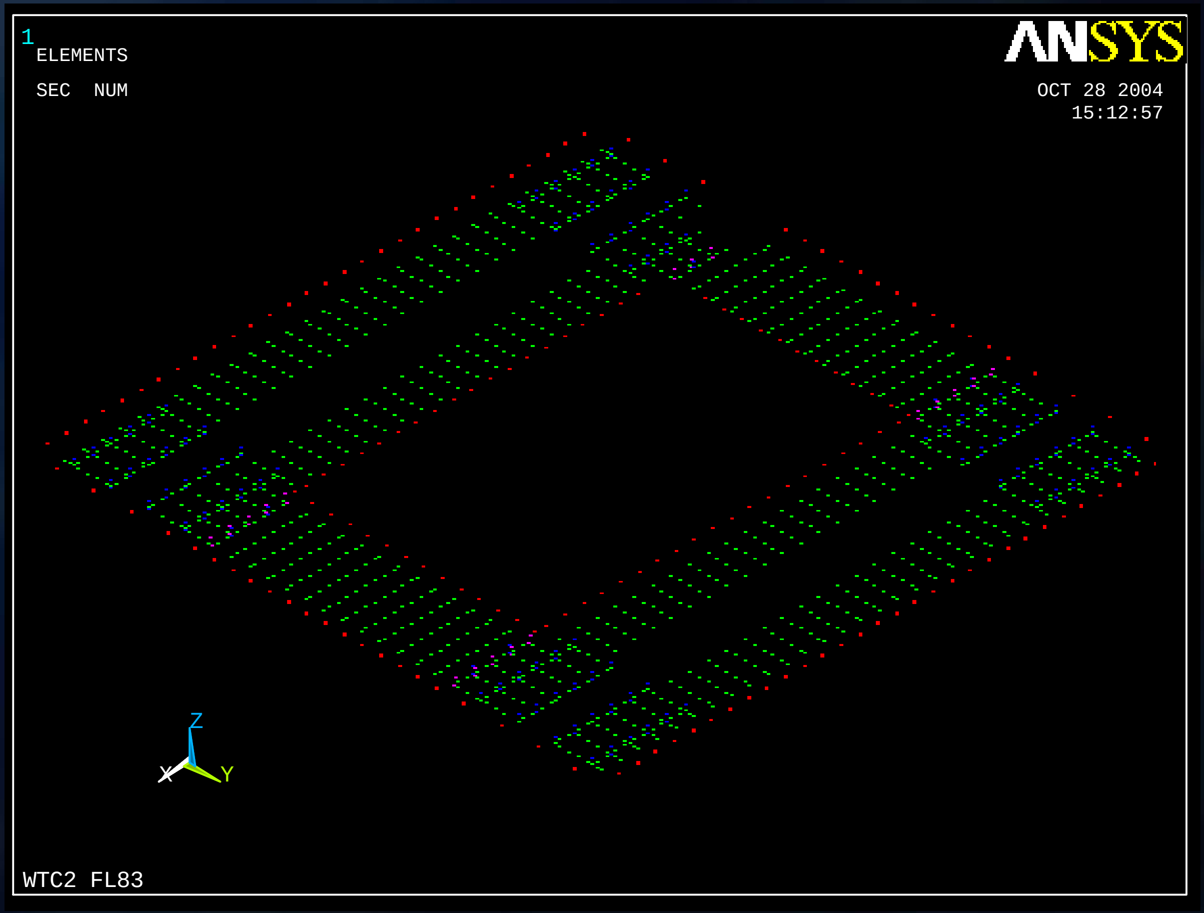
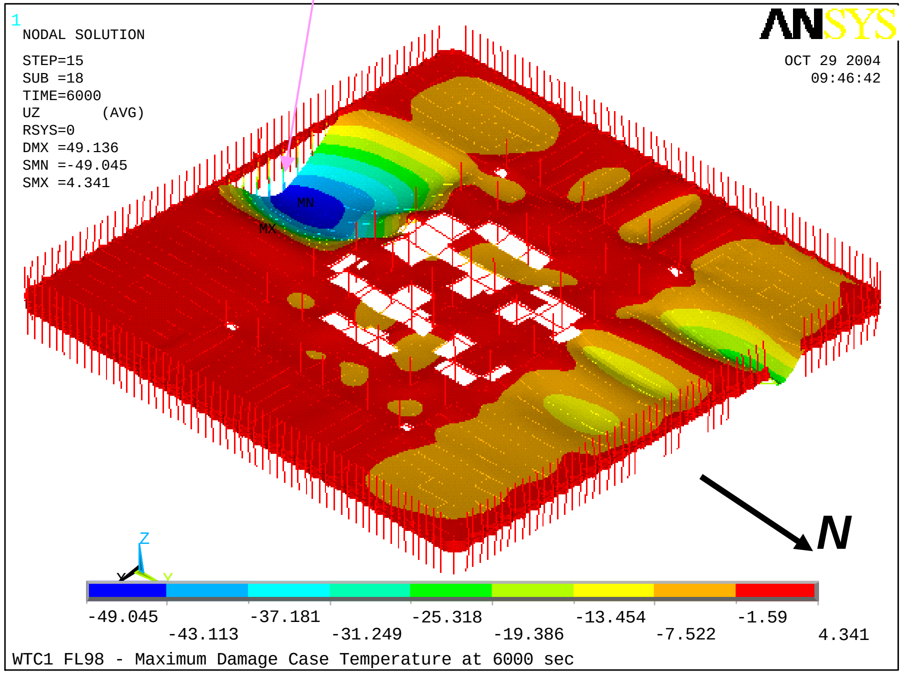
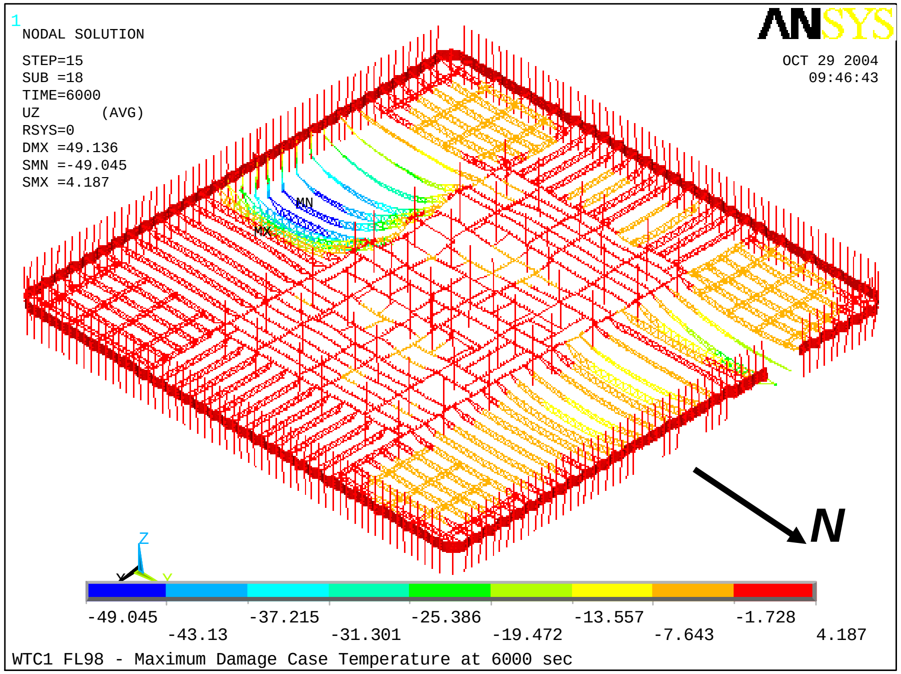
- Truss web diagonals – buckling and weld failure
- Gusset plates - fracture
- Truss seat bolt - shear off
- Truss seat - tension, shear, and walk-off failures
- Primary/bridging truss connection - failure
- Primary long-span/transfer truss connection - failure
- Studs at slab-spandrel connections – failure Strap anchors - weld failure



WTC 1 Floor 98 - Vertical Displacement at 100 min

Floor/wall disconnection





Max displacement = 49.0 in.

5x displacement magnification

WTC 1 Floor 96 – Effect of Fireproofing

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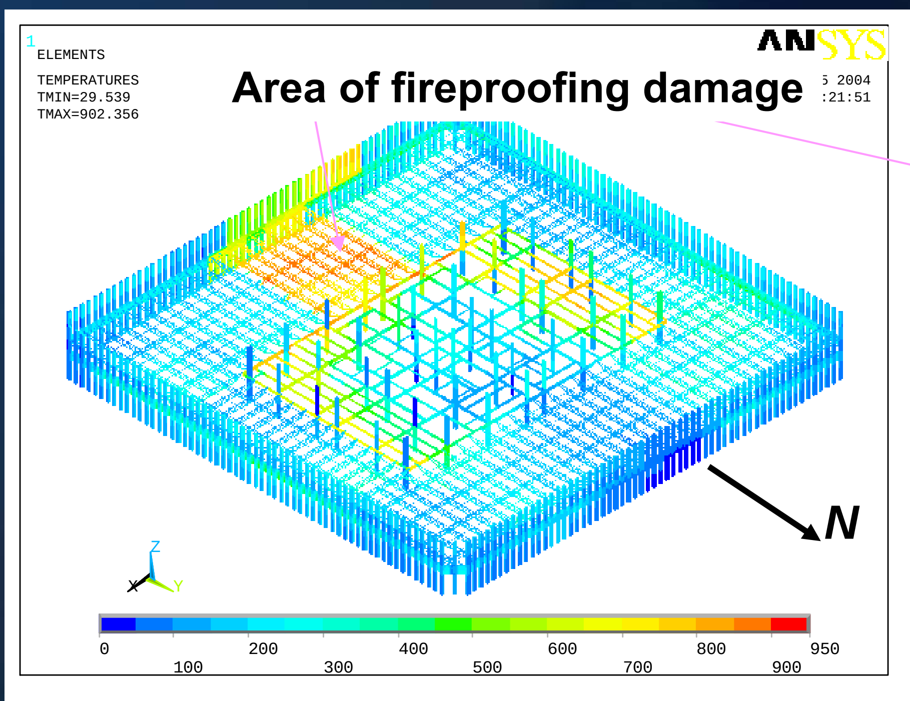
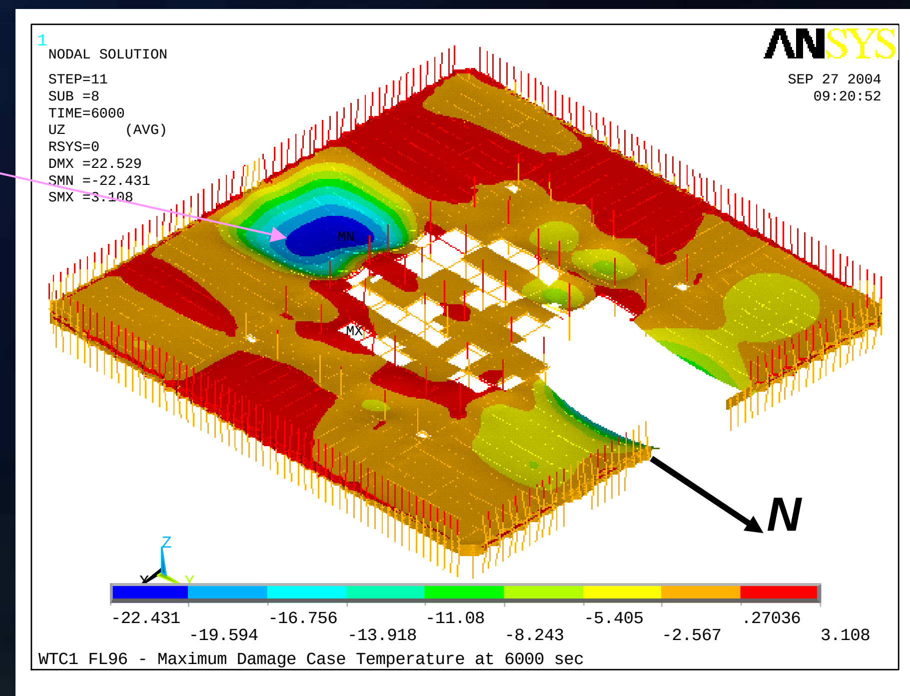
- Maximum temperature of steel members with fireproofing reached approximately 400 ˚C.
- Maximum temperature of steel members without fireproofing exceeded 600 ˚C and often reached 800 ˚C.



Temperature of steel members at 100 min



Vertical displacement (5x displacement magnification)

Exterior Walls

One-Story Exterior Column Model

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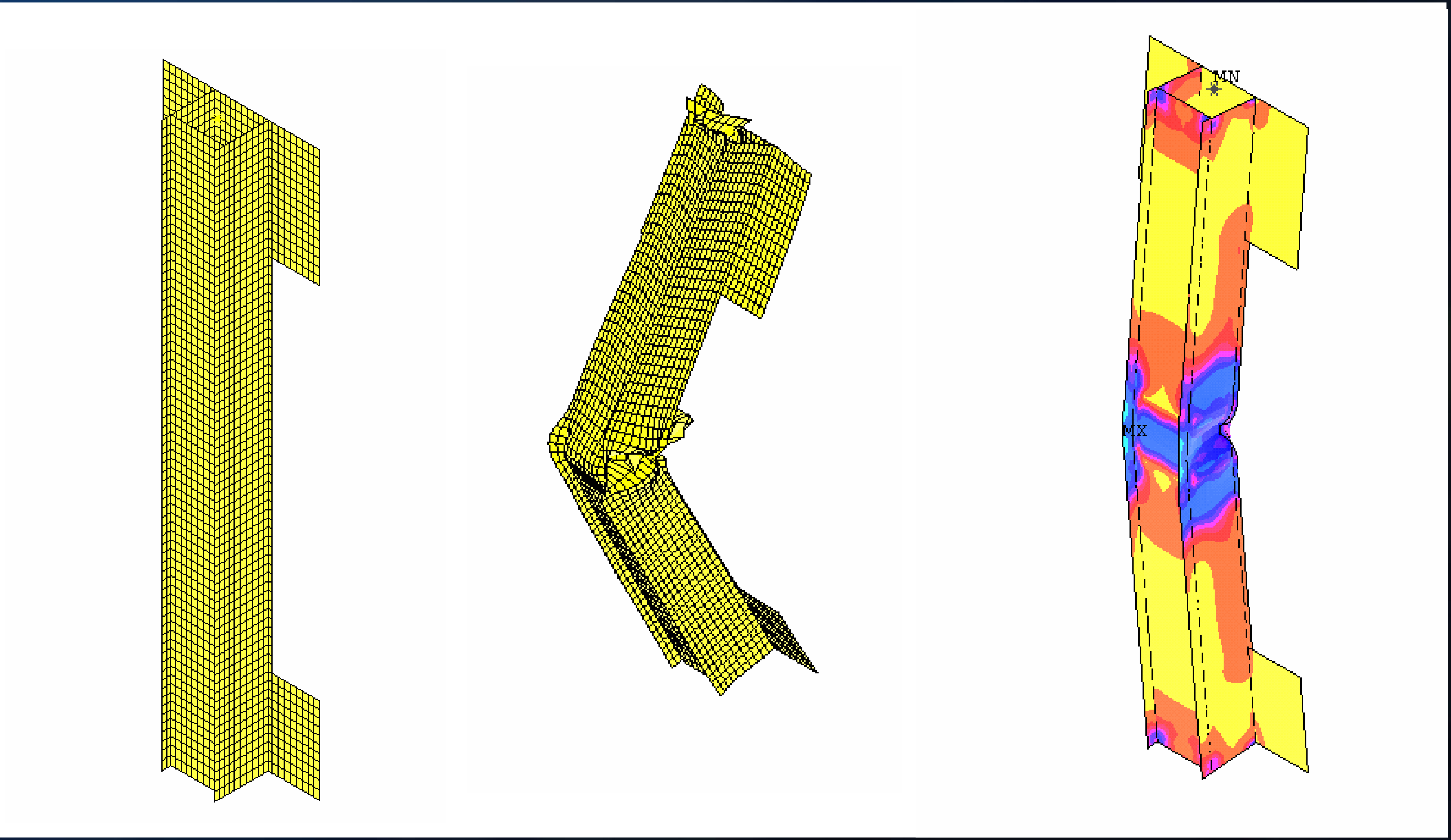
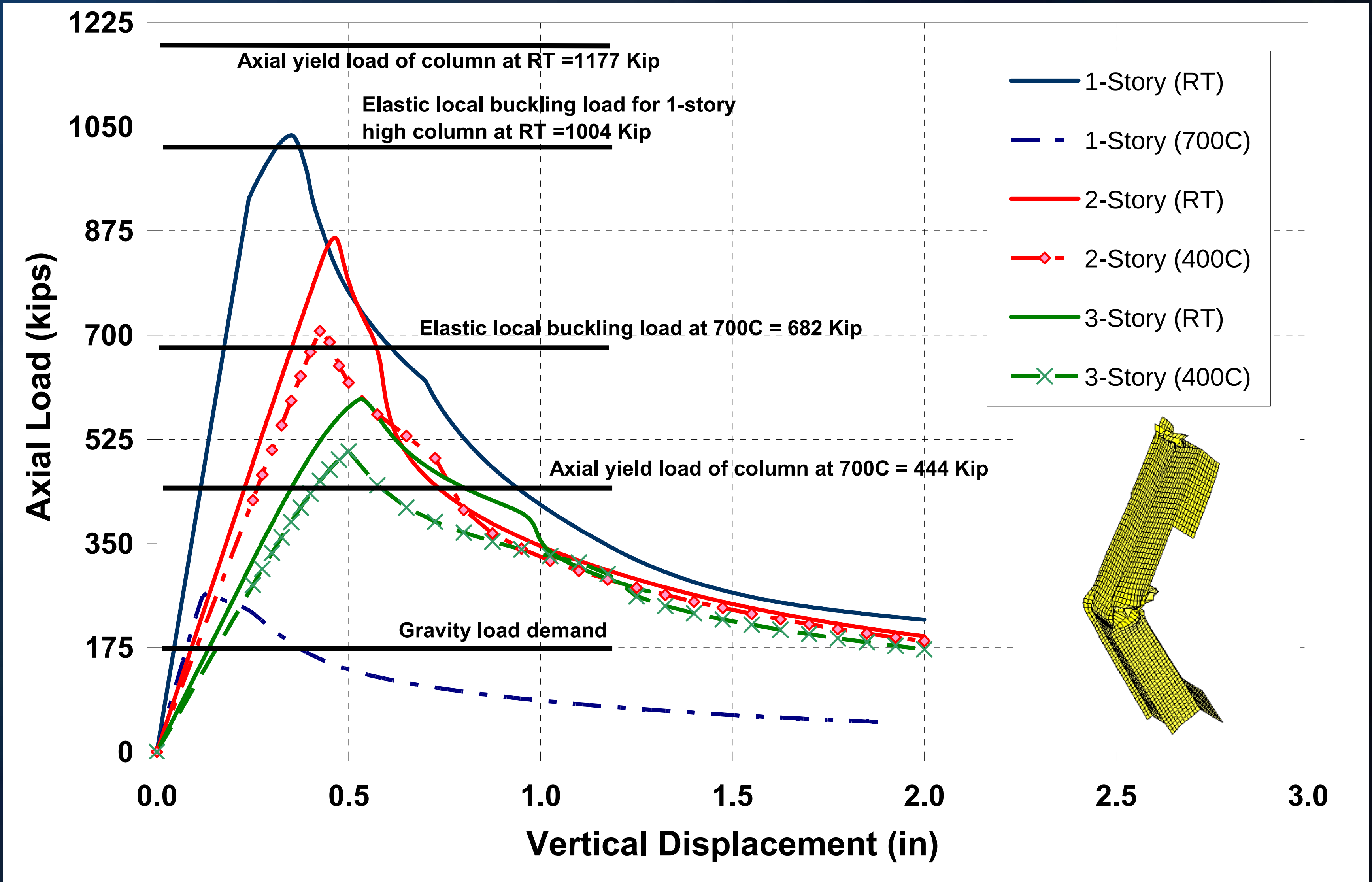
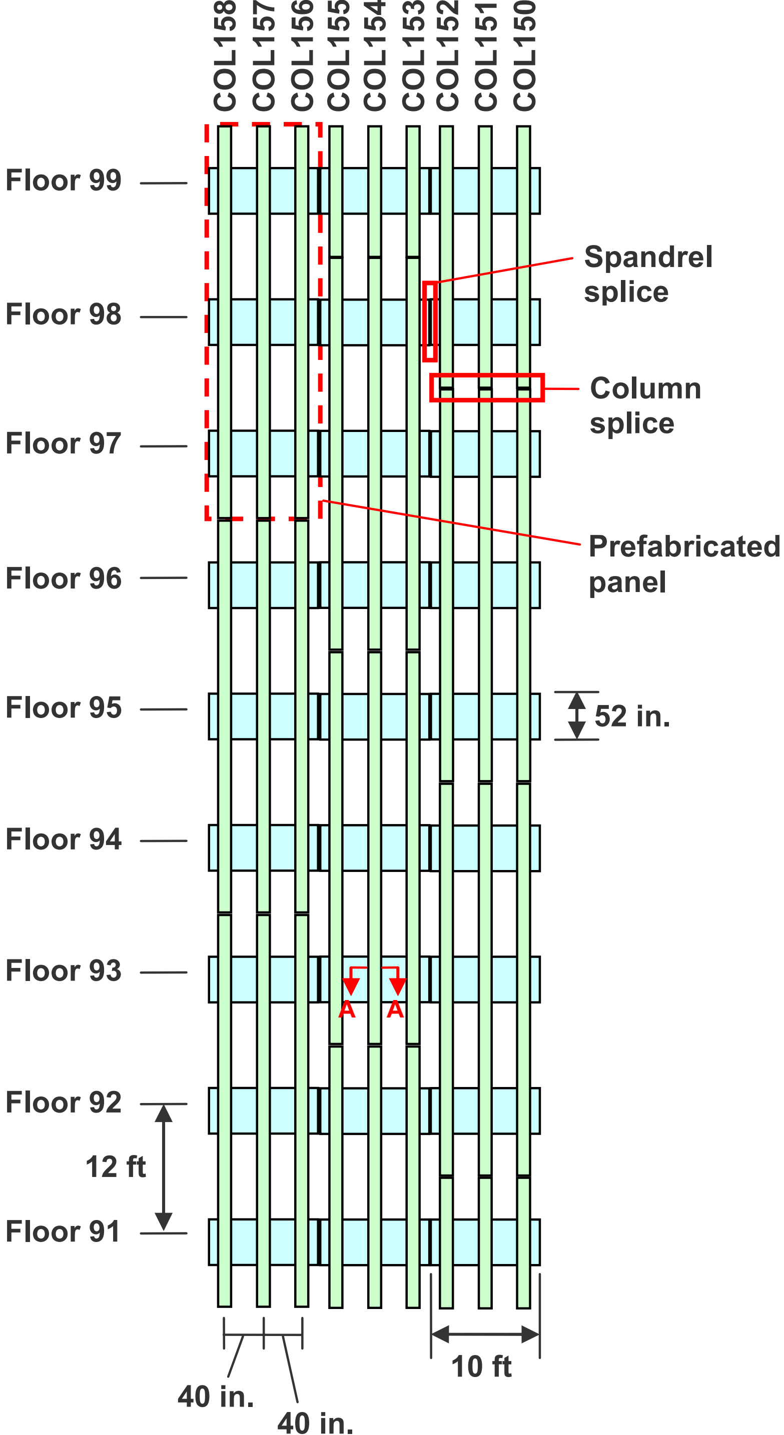


2 in. pushdown at room temperature

2 in. pushdown at 700 °C

Axial Load Deflection of Exterior Column





Exterior Wall Model

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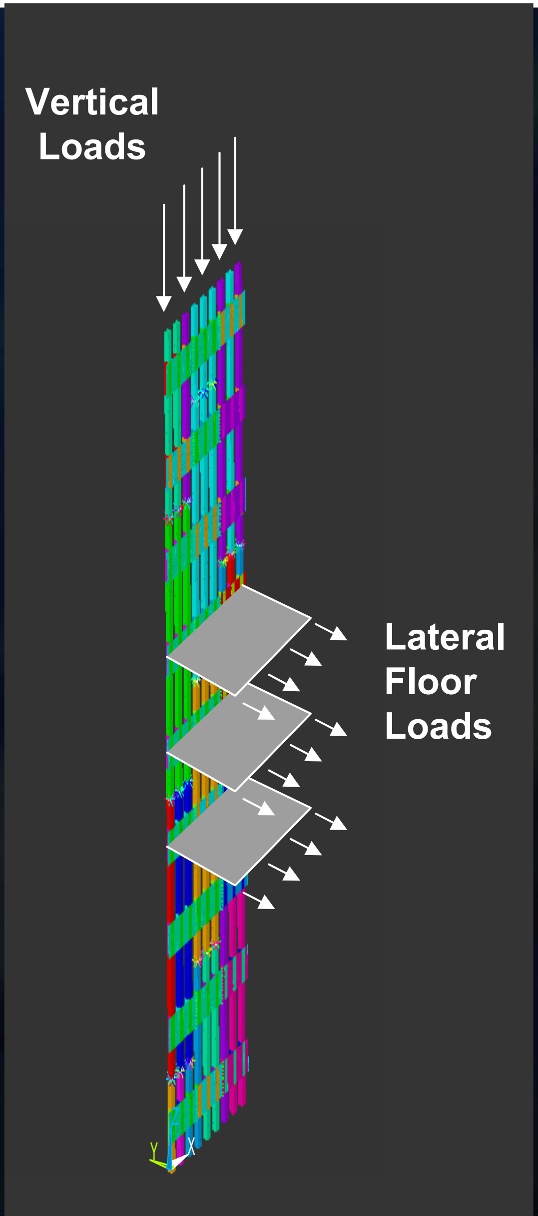
Subsystem Model: 9x9 wall section

- Columns
- Spandrels
- Column splices
- Spandrel splices

Exterior Wall Load Cases

- All floors connected
- Two floors disconnected
- Three floors disconnected
- Three floors disconnected with pull-in forces
- Three floors disconnected with push down forces.



Large Inelastic Buckling of Spandrel and Partial Separation at Connections

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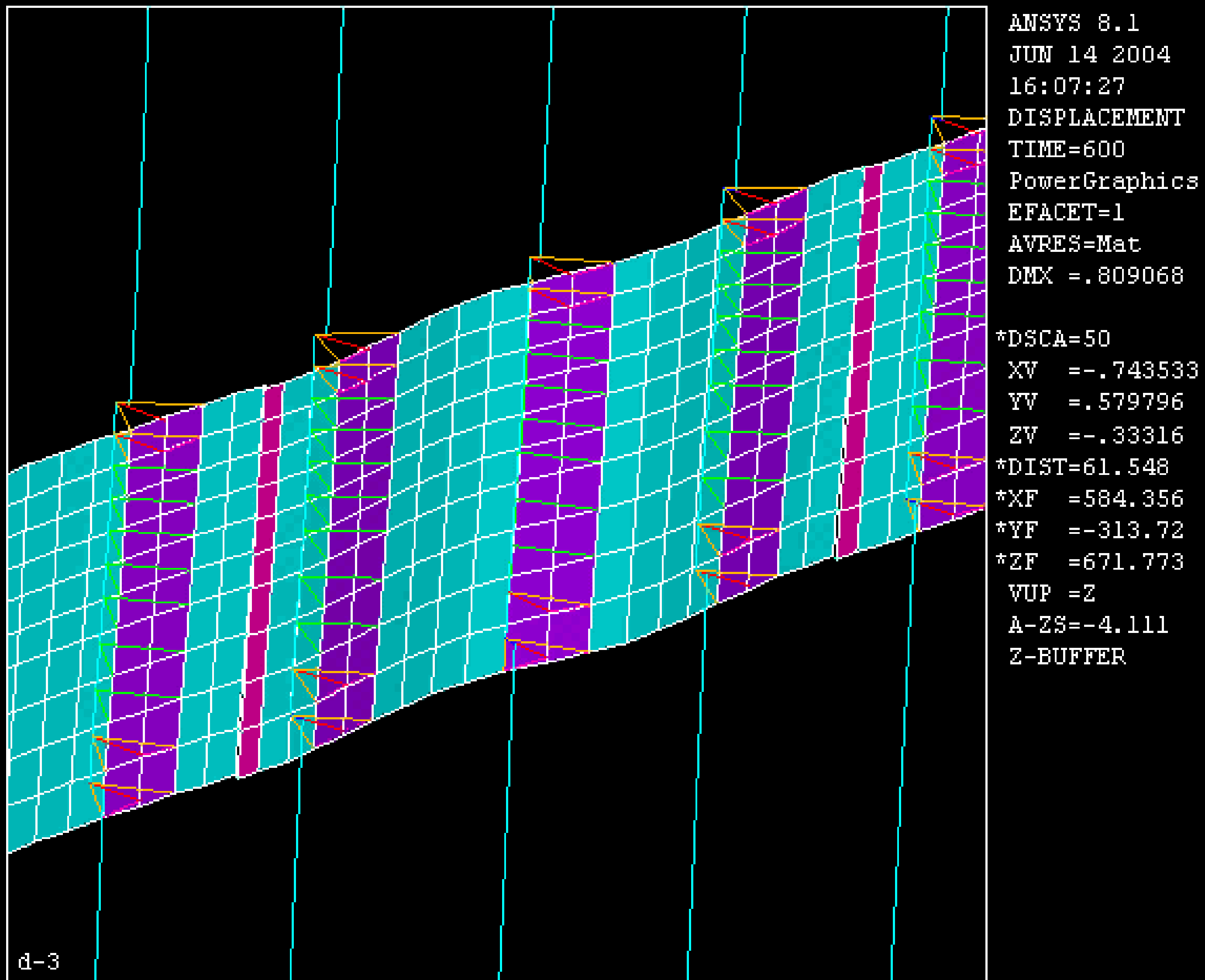

50x displacement magnification

Instability of Exterior Wall subjected to Horizontal Pull-in Forces at Three Floors

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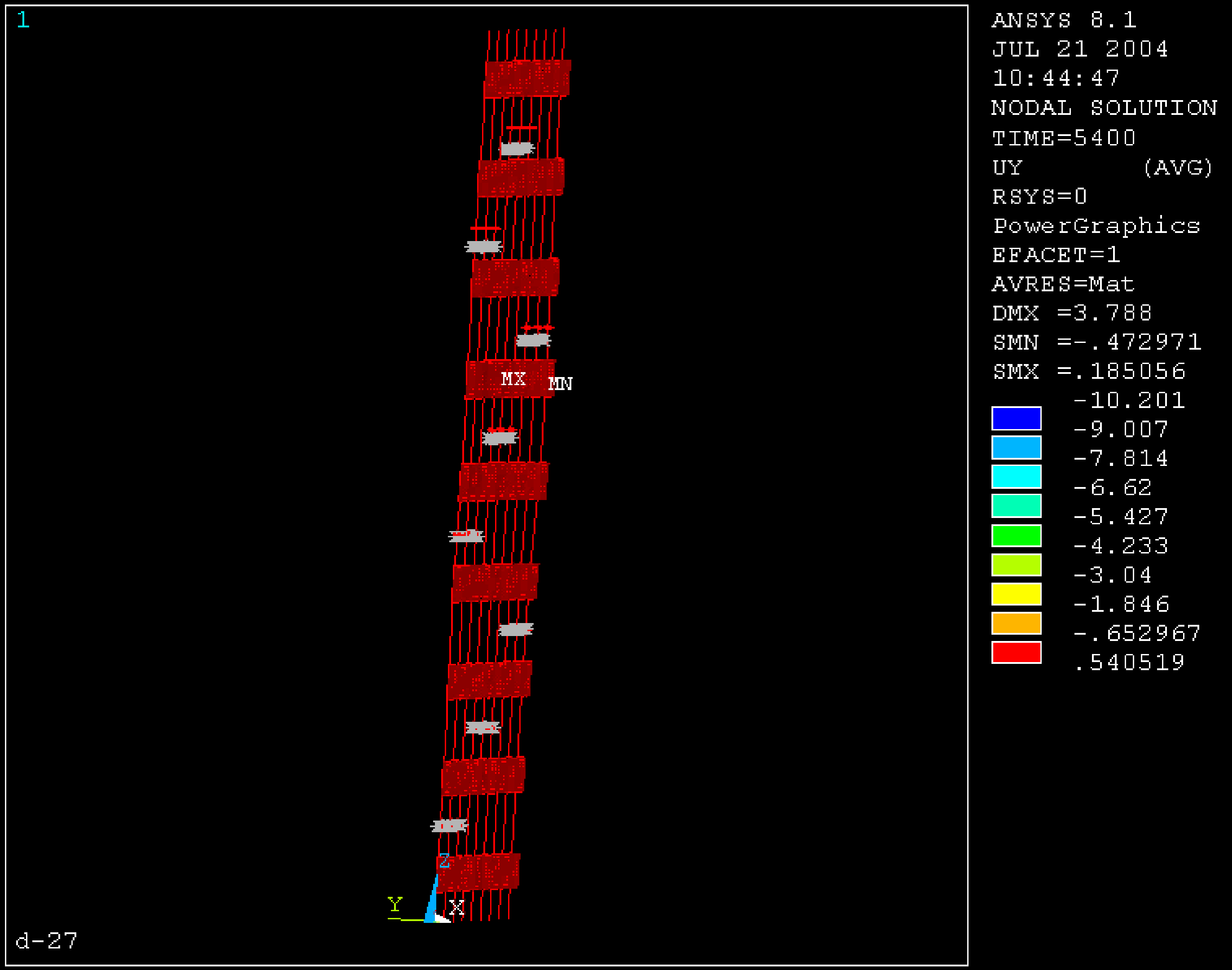

10X displacement magnification

Global Analysis of WTC 1 and WTC 2

Global Models

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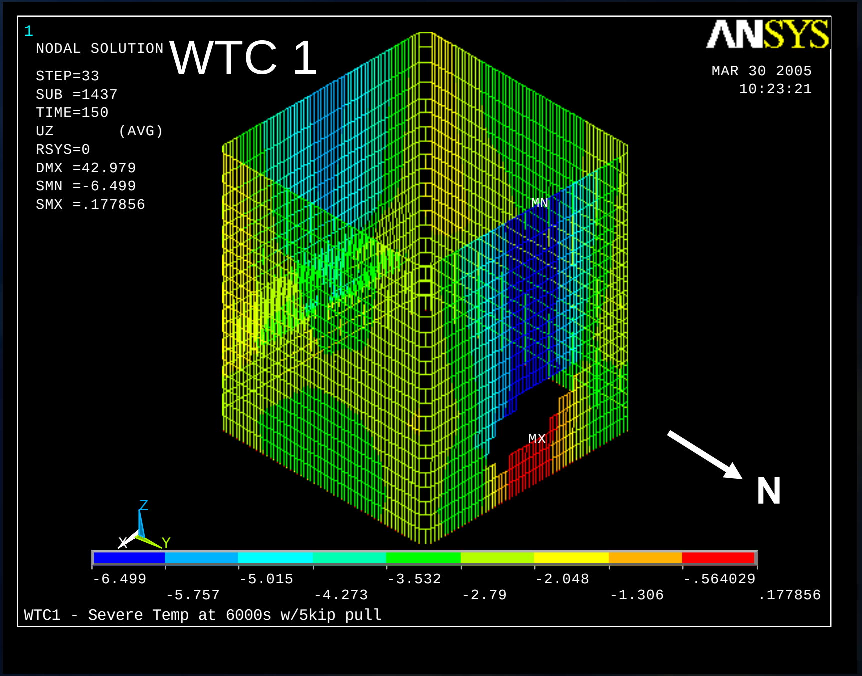
- ANSYS models were developed for nonlinear large deflection analysis of the towers.
- WTC 1: Truncated below Floor 91 with vertical springs for stiffness of floors below.
- WTC 2: Truncated below Floor 77 with vertical springs for stiffness of floors below and superelement above Floor 86.



- Tower Model Features
  - Columns included creep and inelastic buckling.
  - Spandrels were axially released to prevent local plate buckling, without loss of bending and shear stiffness.
  - Office floors modeled as a membrane capable of transferring in-plane loads between core and exterior wall.
  - Core slab and beams with moment connection were modeled simulating both membrane and bending stiffness for load transfer between columns.
  - Core beams without moment connections were not modeled. Core slab above these beams was modeled to match the in-plane stiffness of the composite floor.

Global Models

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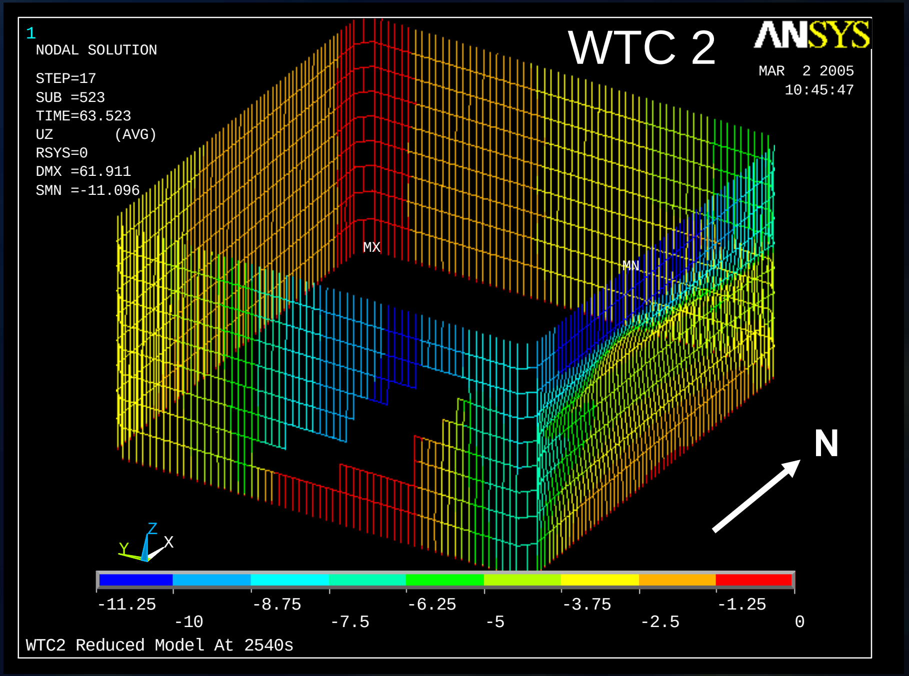
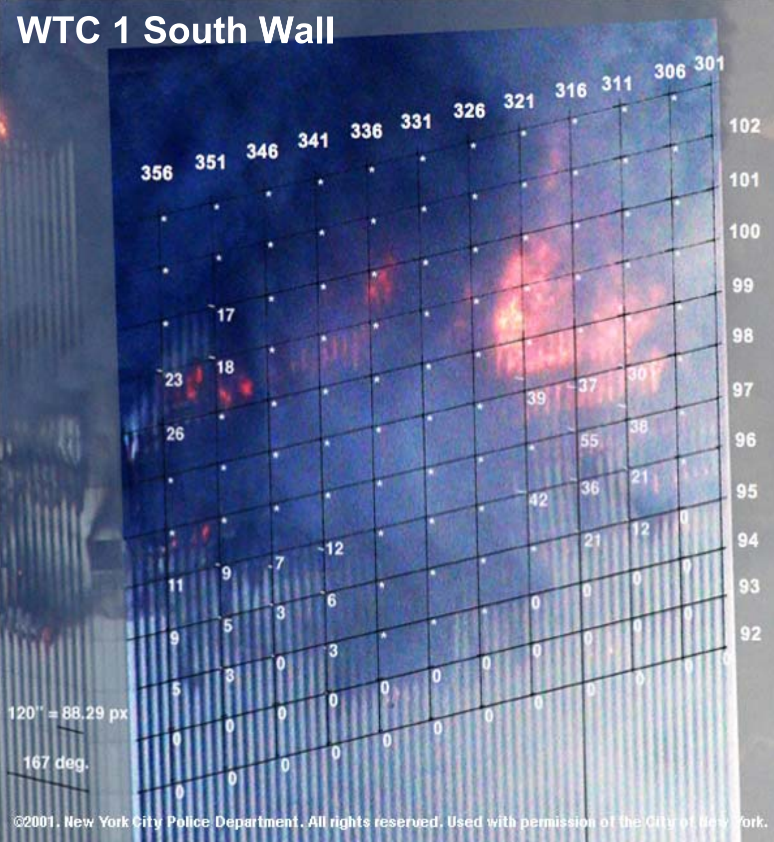
- Core and exterior columns had temperature-dependent properties
  - Thermal expansion
  - Plasticity
  - Creep
- Gravity Loads
  - Self-weight plus 8 psf superimposed dead
  - Live (25% of design live load)
  - Weight of antenna (750 kip) at the top of WTC 1
- Thermal Loads
  - Temperatures at 10 min intervals
- Floors
  - Full floor models were not included in global models due to computational limitations
  - Effects of the floor disconnections and inward pull forces due to floor sagging were included





Fire-Induced Damage

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- Disconnection of floor to exterior wall at truss seat connections
- Pull-in forces at truss seat connections due to sagging floors caused inward bowing of exterior walls

	Analysis	Observations
Locations of disconnections between the sagging floors and exterior walls	x	x
Bow-in areas of exterior wall system	x	x
Magnitude of inward bow	-	x
Magnitude of horizontal pull-in force	x	-

Estimation of Magnitude of Pull-in Forces in Global Model

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- Analyze structural response of global model with thermal effects.
- Impose floor disconnections and inward pull forces estimated from isolated wall models (South face of WTC 1; East face of WTC 2).
- Compare results with observed inward bowing.
- Adjust magnitude of inward bowing forces to match observations.

WTC 1 (South Face of Floors 95 to 99)	
Time Interval (s)	Inward Pull (kip)
0 – 4,800	0
4,800 – 6,000	5

WTC 2 (East Face of Floors 79 to 83)	
Time Interval (s)	Inward Pull* (kip)
0 – 1,800	1, 4
1,800 – 2,540	1.5, 3.0

* Pull forces applied to each of two regions

Important Factors in Global Analysis

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- Aircraft damage → Load redistribution
- Thermal expansion → Load redistribution
- Creep of steel in high temperature → Displacement increase, column axial shortening, and load redistribution
- Thermal weakening/softening of steel and concrete in high temperature
  - Loss of strength → Component failure and load redistribution
  - Loss of stiffness → Buckling and load redistribution

Results from Global Analysis of WTC 2

Vertical Displacement of Exterior Wall of WTC 2 (Floor 77 to Floor 86)

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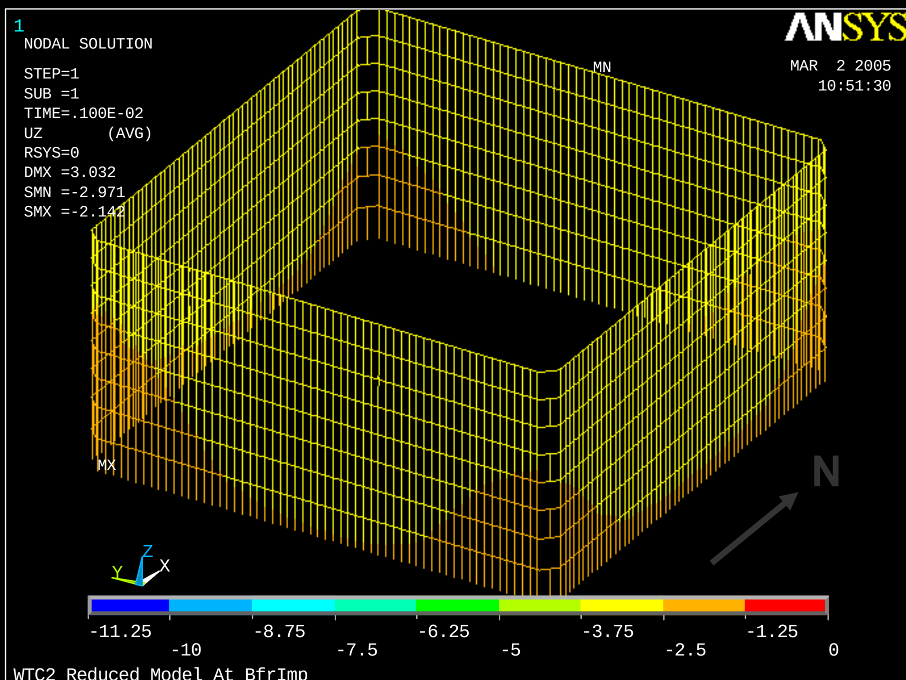
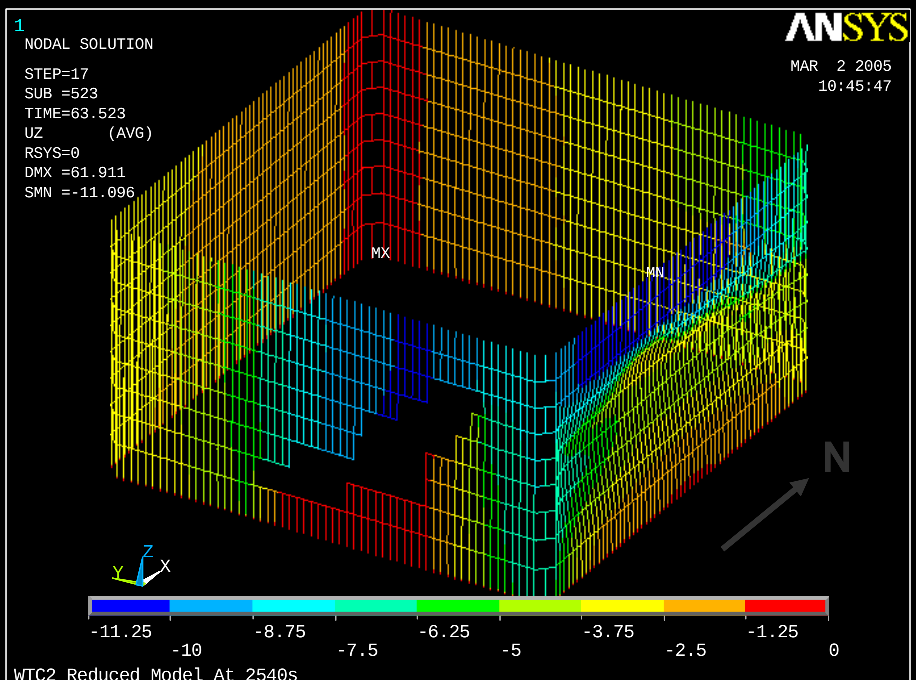
Before Aircraft Impact | **At 43 min**





Min = -3.0 in   Max = -2.1 in   Min = -11 in   Max = 0.0 in

(Downward displacement is negative)

Vertical Displacement of Core of WTC 2 (Floor 77 to Floor 86)

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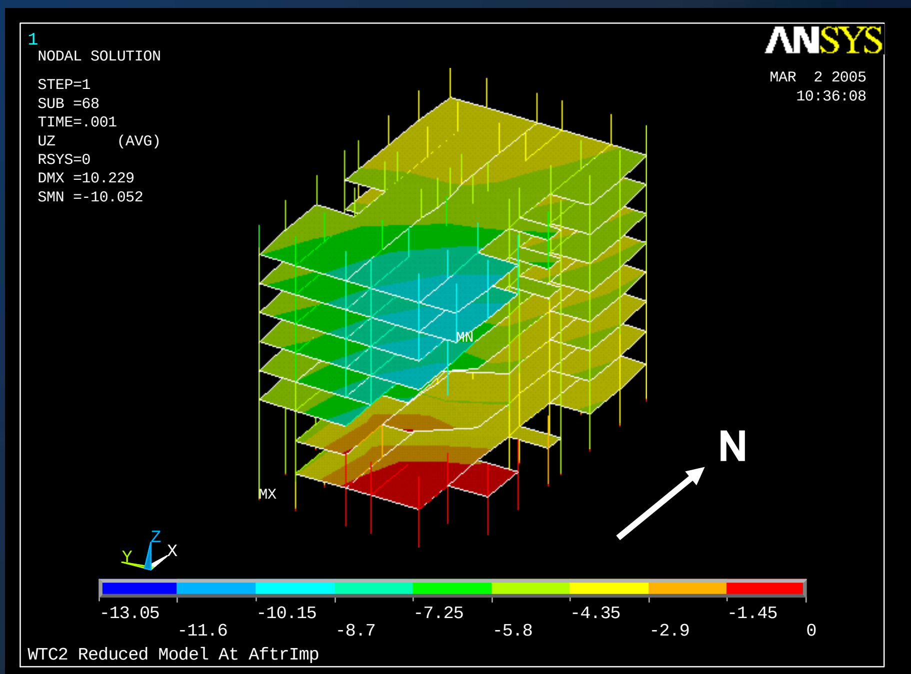
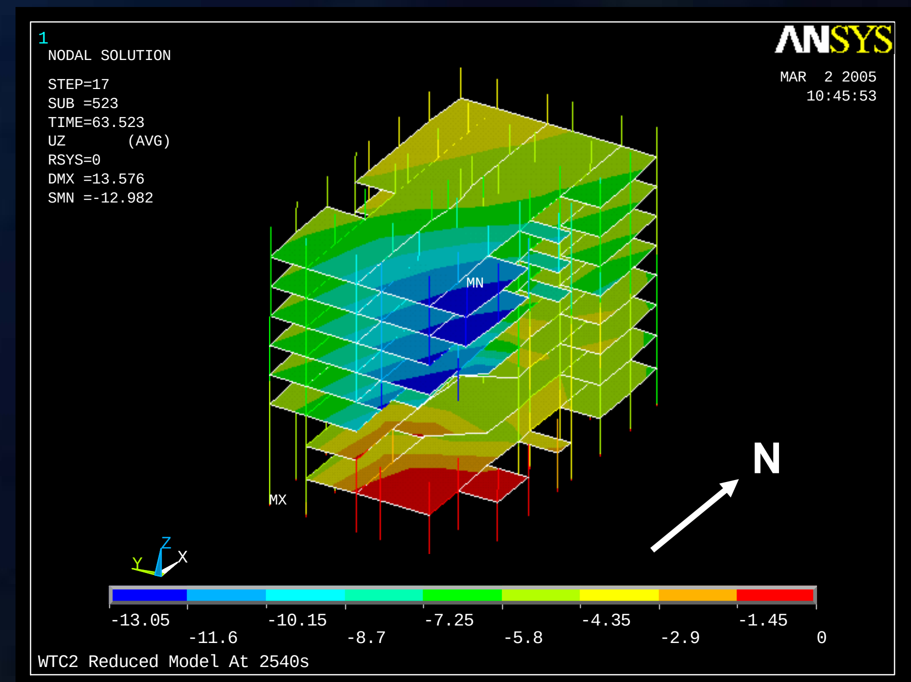
Before Aircraft Impact



Min = -10 in

Max = 0.0 in

43 min

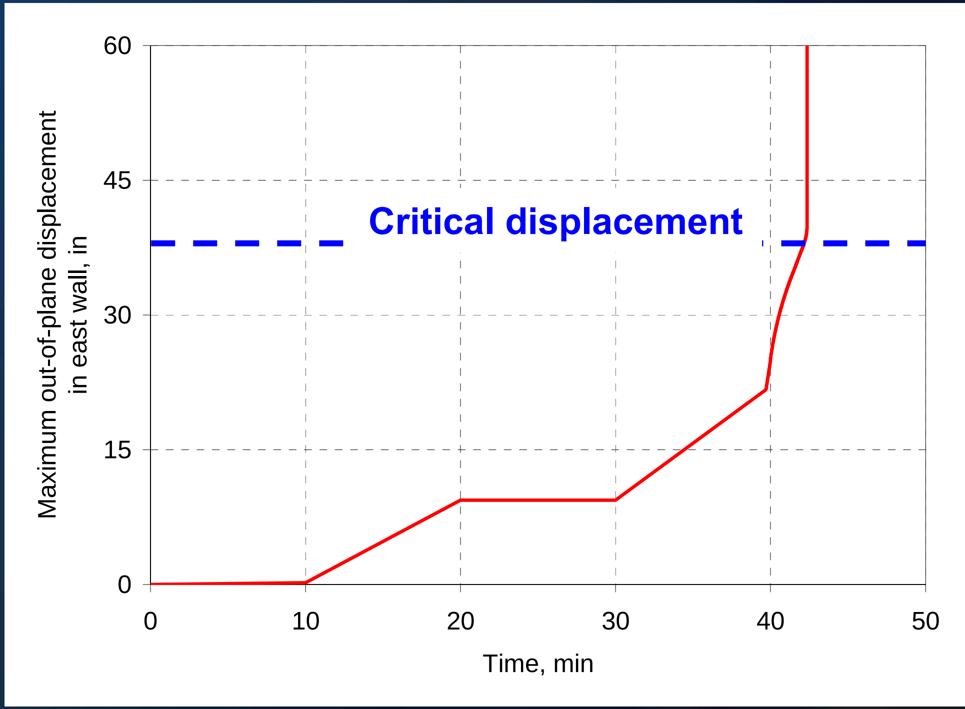


Min = -13 in

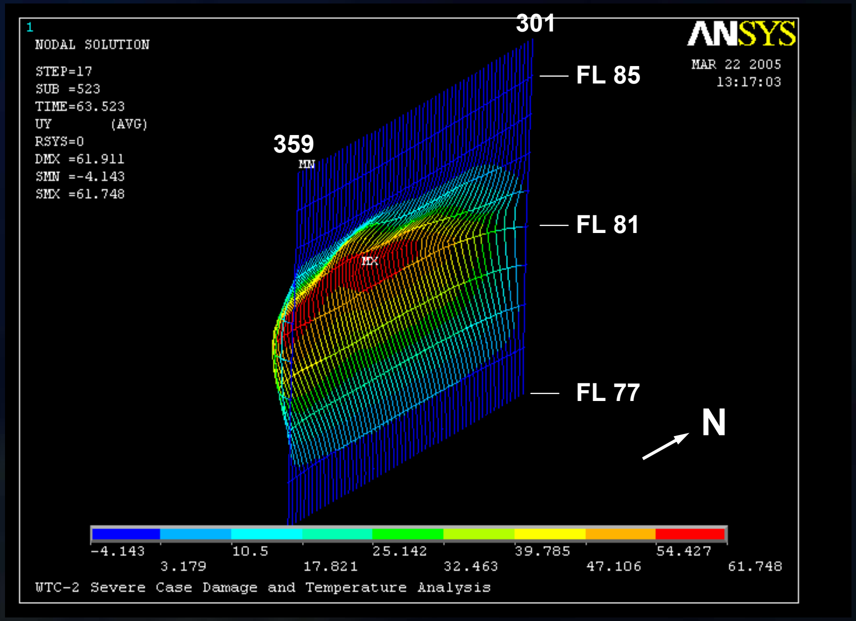
Max = 0.0 in

(Downward displacement is negative)

Out-of-Plane Displacement of East Wall of WTC 2



View from southeast at 43 min.



Min = -4.0 in

Max = 61.7 in

Variation of Vertical Displacements at Floor 86 of WTC 2

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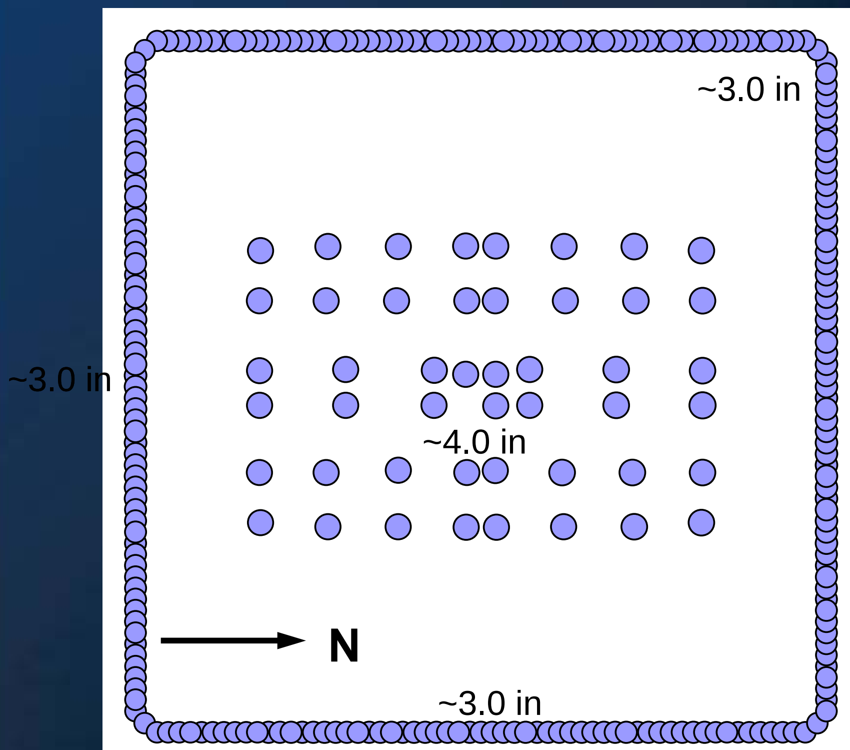
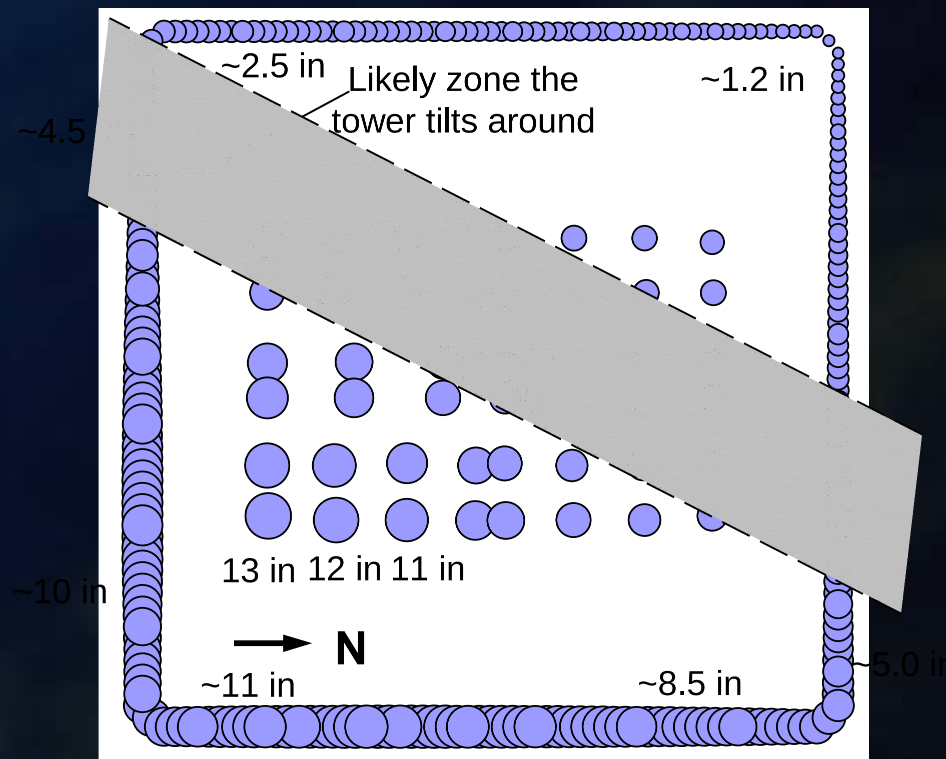
Before Impact



At 43 min



(Downward displacement is positive)

Tilt Above Floor 86 of WTC 2 at 43 min (Total Displacements)

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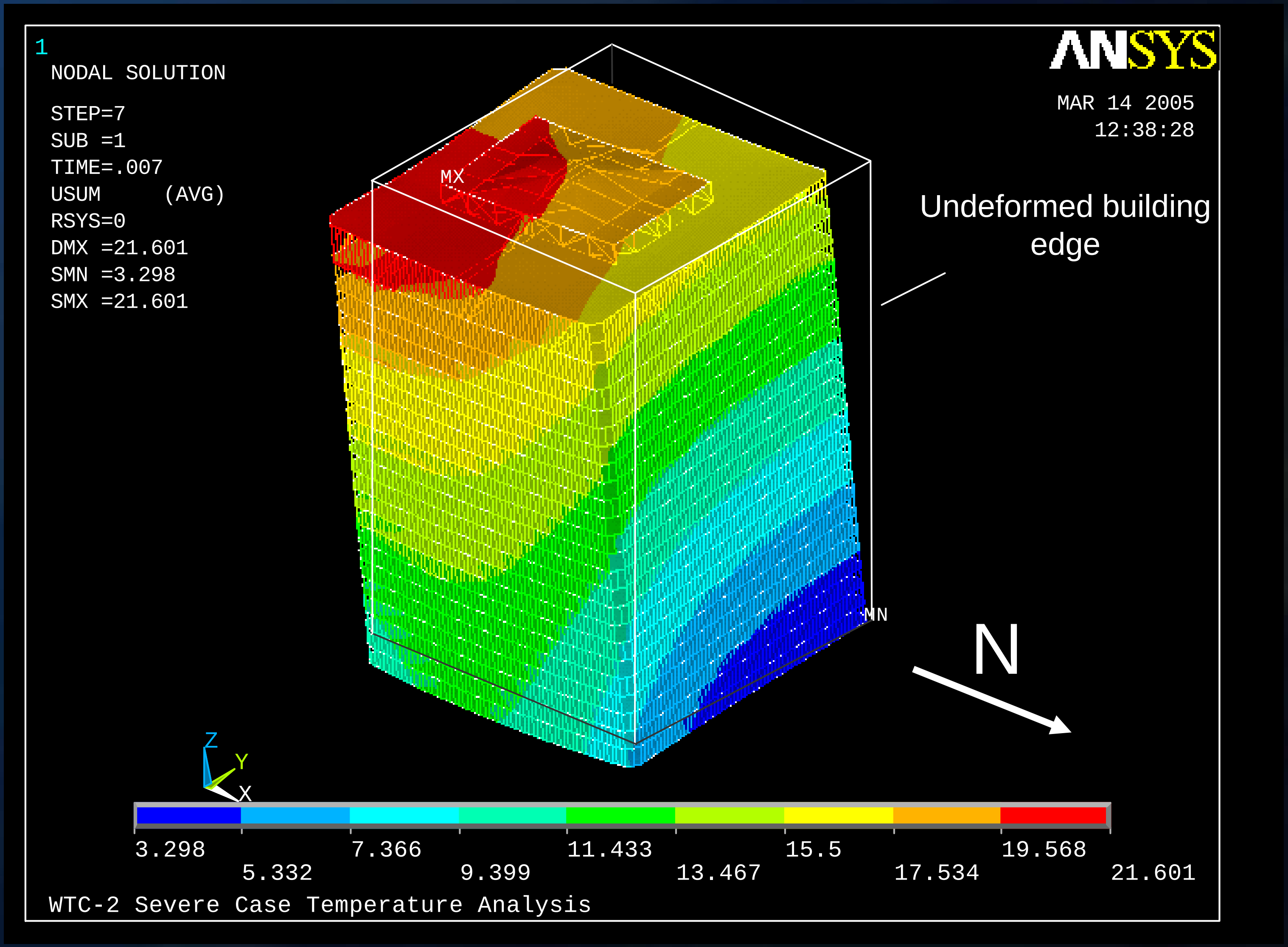

20X Magnification

Elastic + Plastic Strain in Columns – Maximum between Floor 78 and Floor 84 of WTC 2

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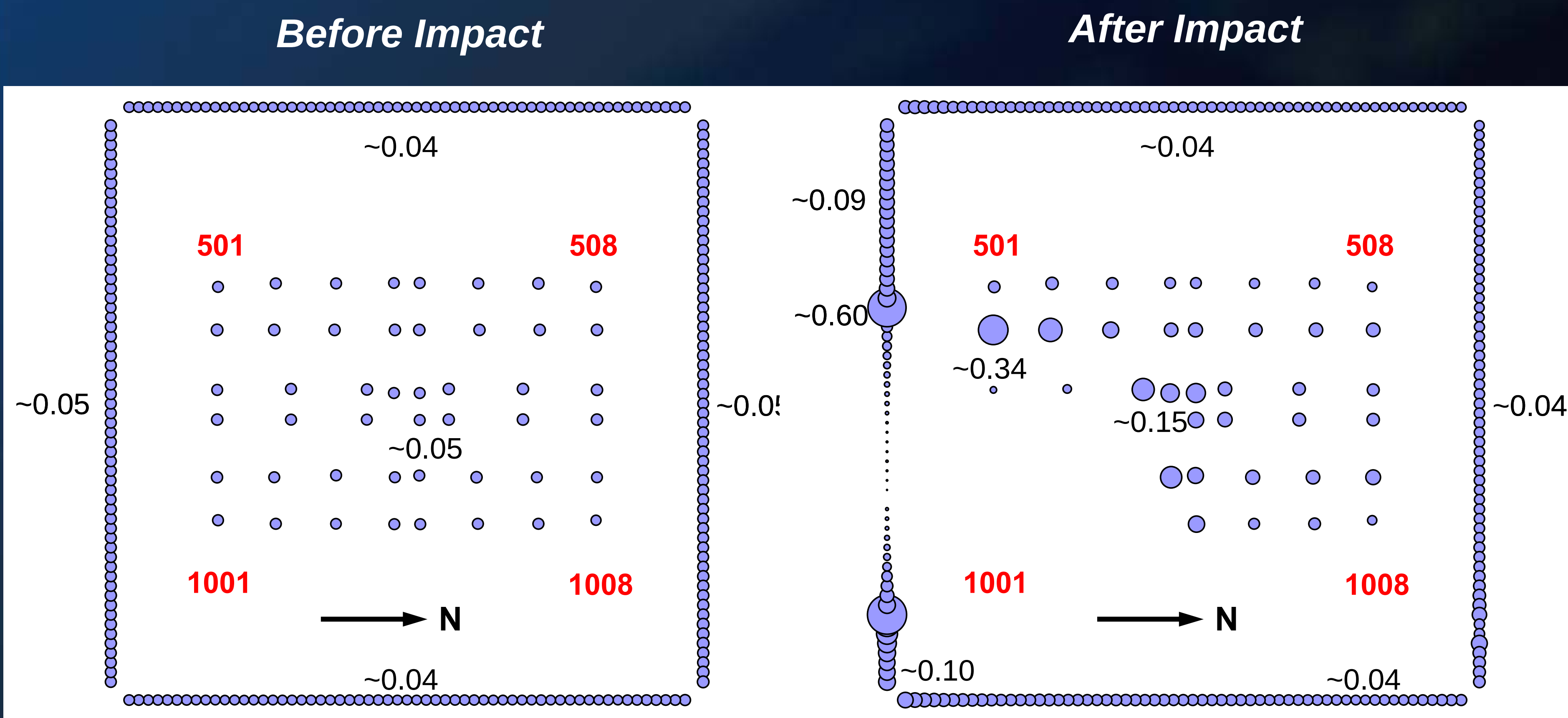

Compression is taken as positive.
Strain values are in %.

Elastic + Plastic Strain in Columns
Maximum between Floor 78 and Floor 84 of WTC 2

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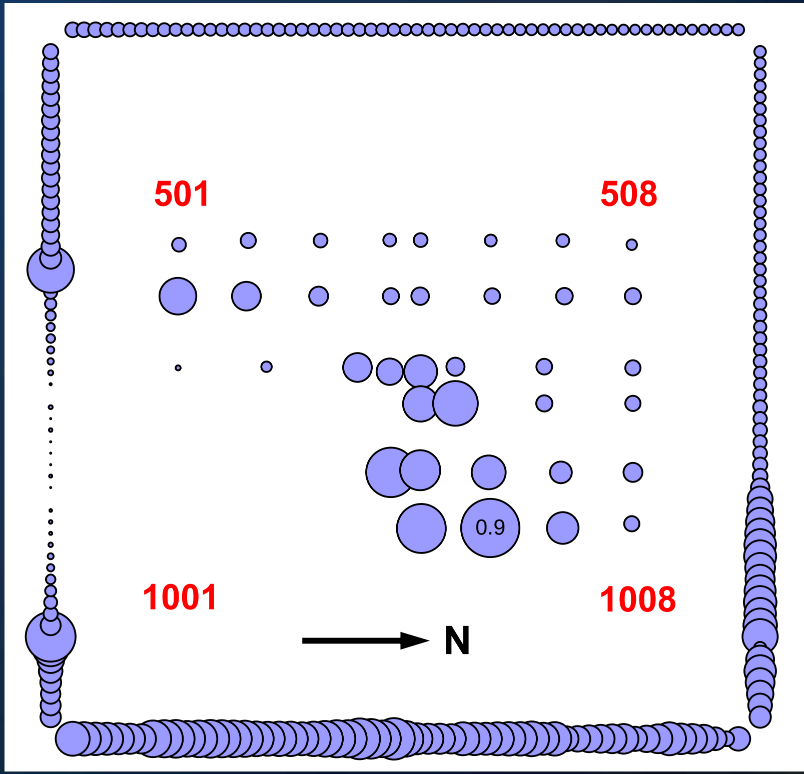
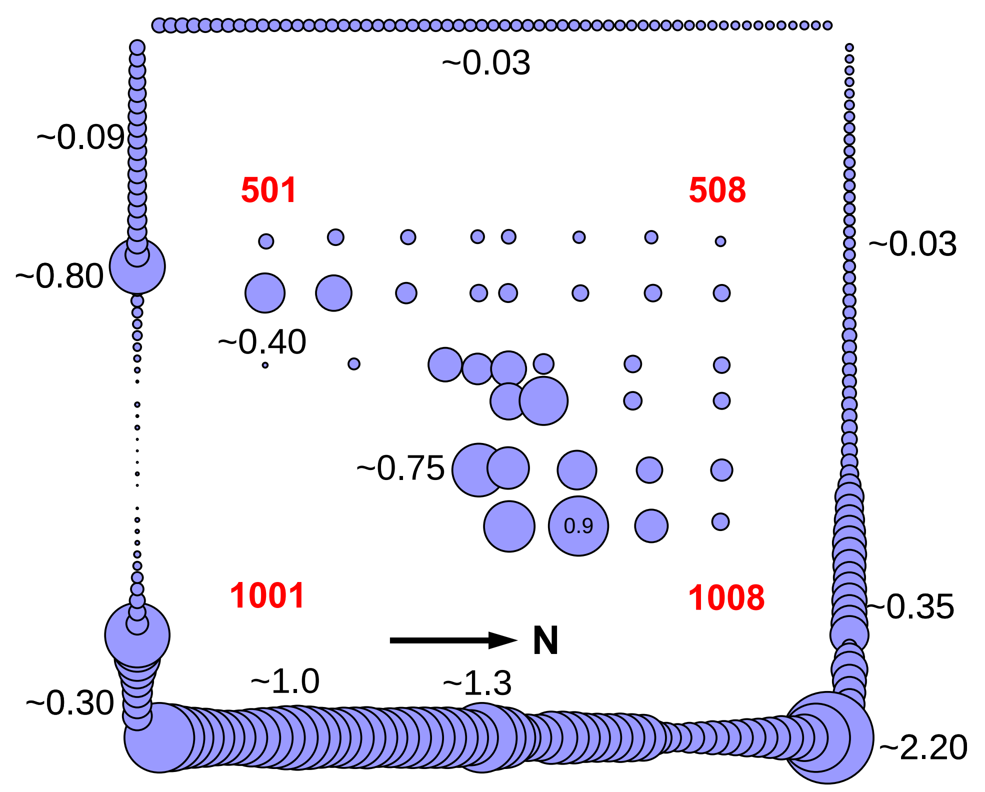
At 40 min



At 43 min



Compression is taken as positive.
Strain values are in %.

Elastic + Plastic + Creep Strain in Columns Maximum between Floor 78 and Floor 84 of WTC 2

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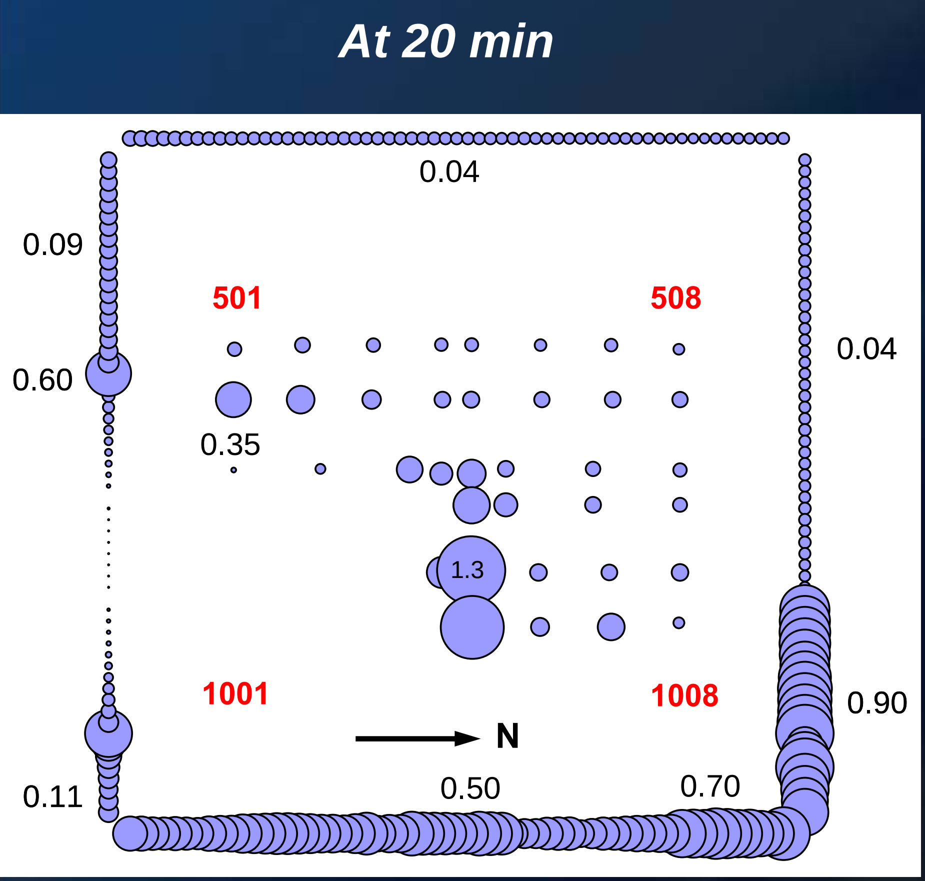

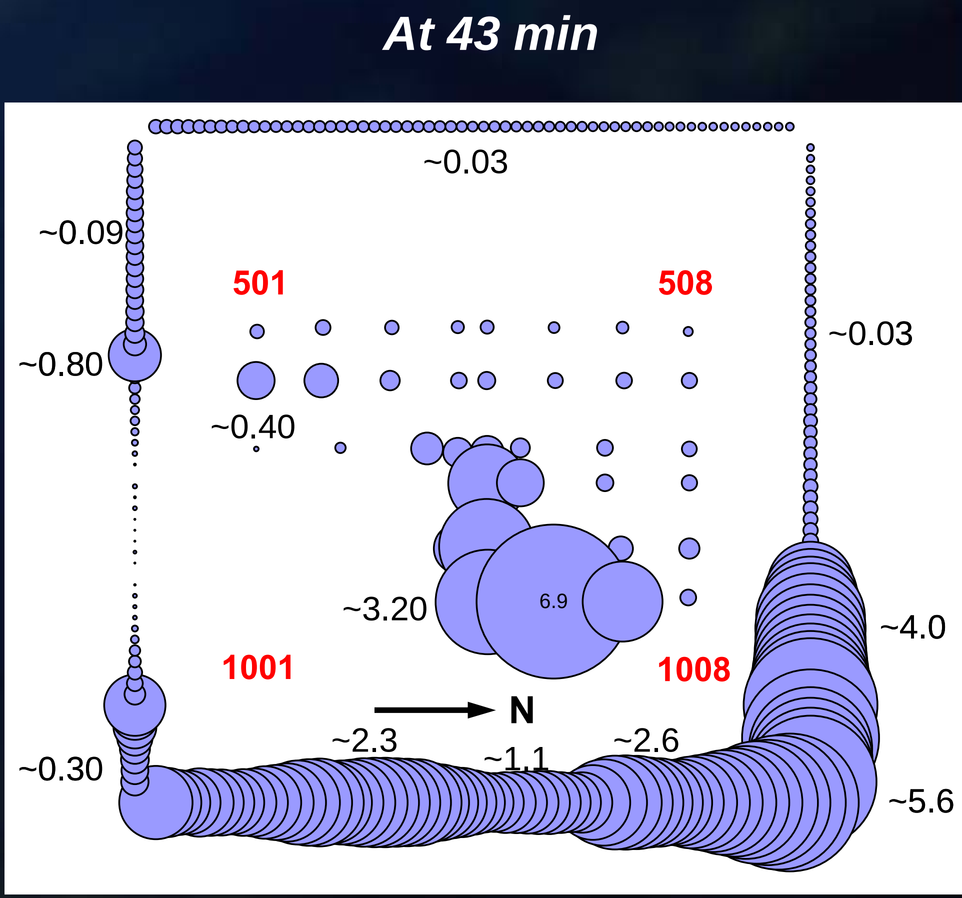

Compression is taken as positive.
Strain values are in %.

WTC 2 Hat Truss

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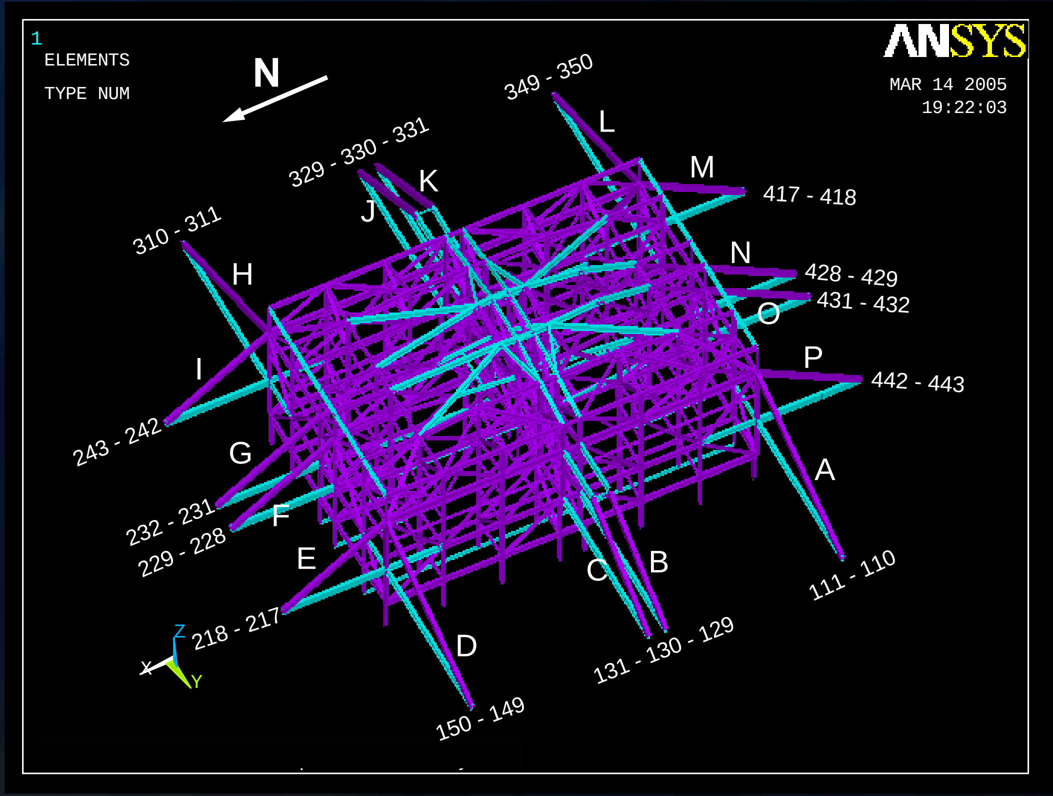
- Hat truss was part of the superelement
- Hat truss members and connections were checked for failure
- Analysis found that:
  - Failure of several column splices in the southeast corner of the core occurred due to impact
  - Additional column splices failed and an outrigger buckled due to subsequent fires
  - Such failures did not propagate and reduce the load on the overstressed outrigger.



WTC 2 Global Analysis Results

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After Aircraft Impact

- WTC 2 was stable after impact and had considerable reserve capacity.
- Severed columns in the southeast corner of the core caused the core to lean to the southeast. The tendency of the core to lean was resisted by floors and exterior walls.
- After impact, core loads decreased by 6%, east wall loads increased by 24%, and the north wall loads decreased by 10%.

Effects of Fires and Damaged Fireproofing

- Thermal expansion of the core columns caused core loads to increase until plastic and creep strains exceeded thermal strains and the columns shortened and unloaded.
- Loads were transferred between the exterior wall and the core primarily through the hat truss.
- The floors sagged and pulled inward on the east wall shortly after impact. The sag continued to increase due to the persistence of the fires on the east side of the tower.
- The east wall bowed inward 10 in. approximately 20 min after impact. The bowing increased until collapse.
- Loads were transferred between exterior walls through the spandrels.

Collapse Initiation

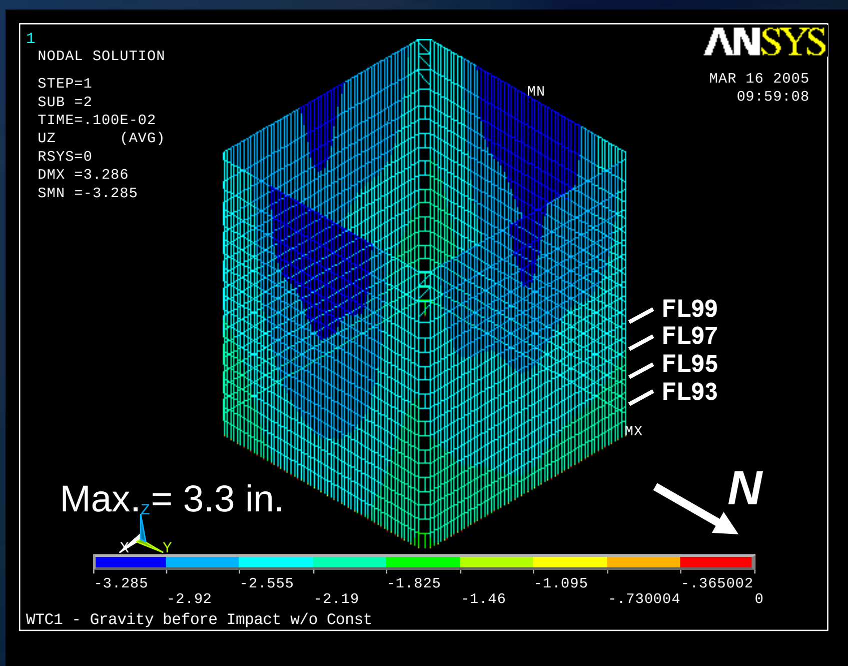
- When the east wall buckled, the loads were transferred to the weakened core and adjacent exterior walls.
- The building section above the impact area tilted to the southeast.

Results from Global Analysis of WTC 1

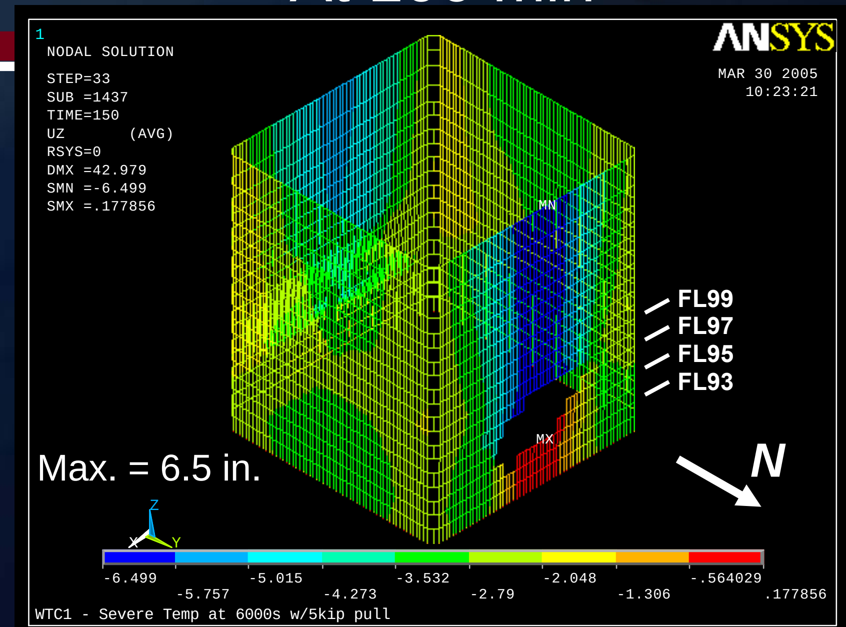
Vertical Displacement of Exterior Walls of WTC 1

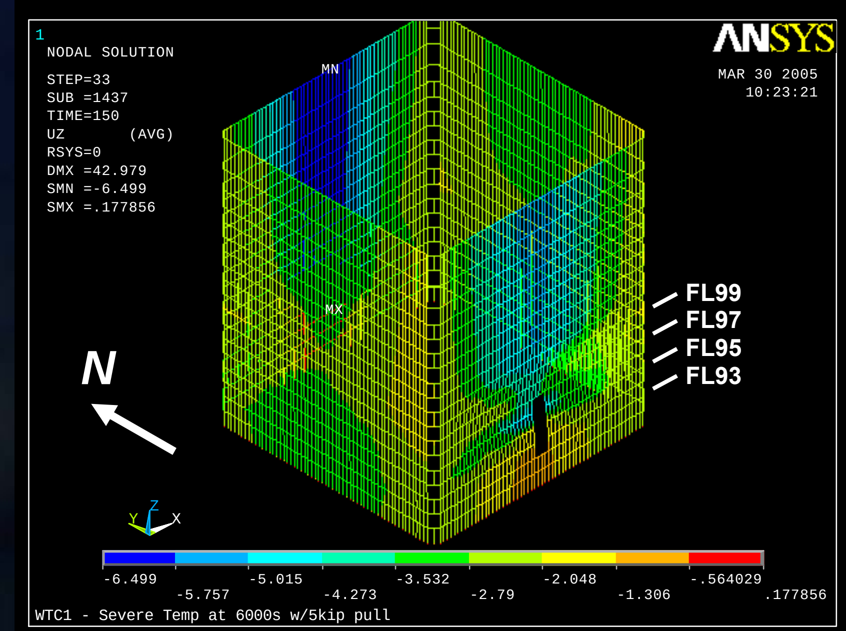
SGH Consulting Engineers

Before Impact



At 100 min



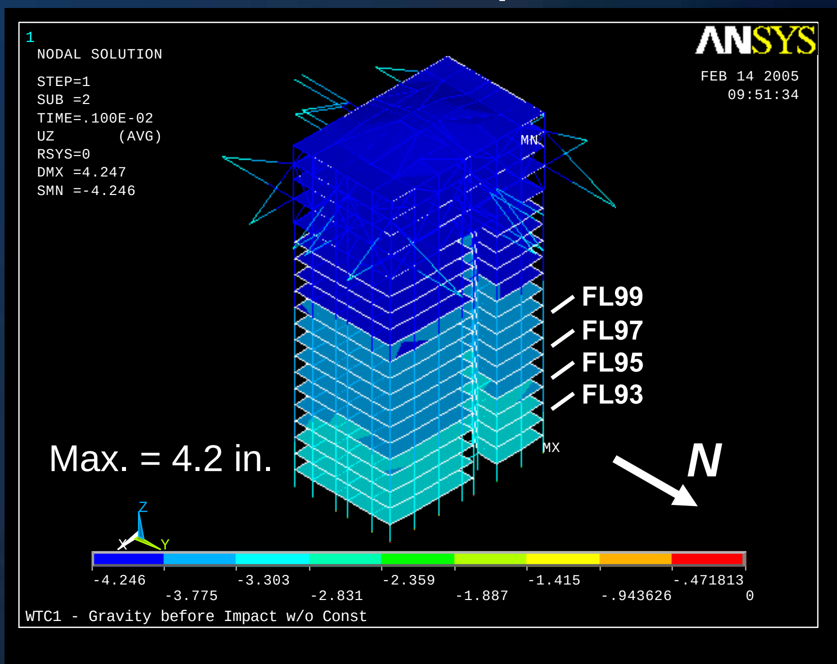


(Downward displacement is negative)

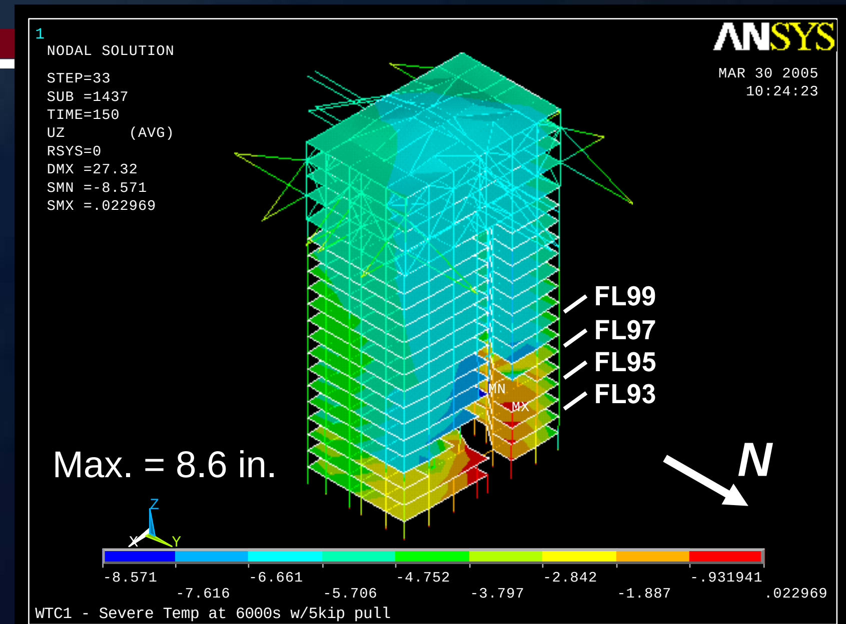
Vertical Displacement of Core of WTC 1

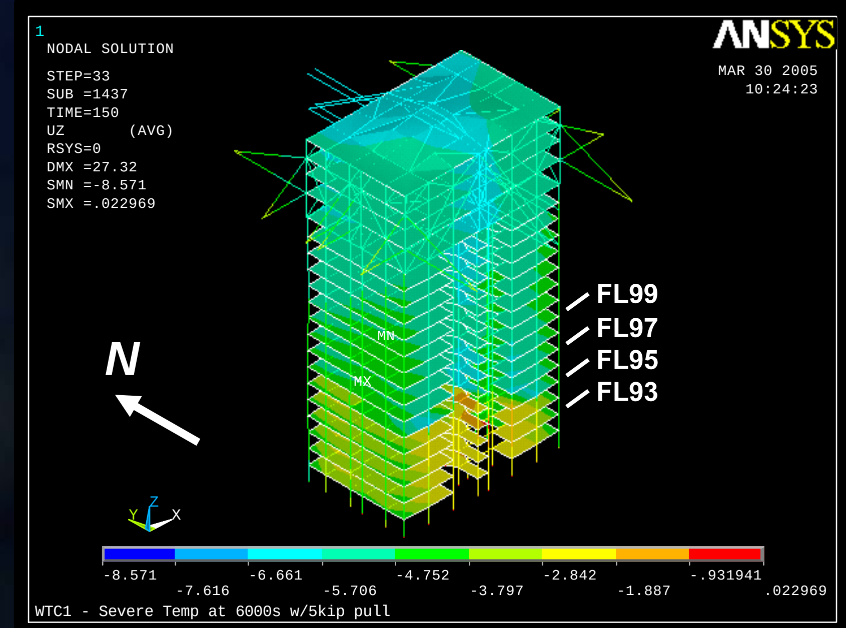
SGH Consulting Engineers

Before Impact



At 100 min



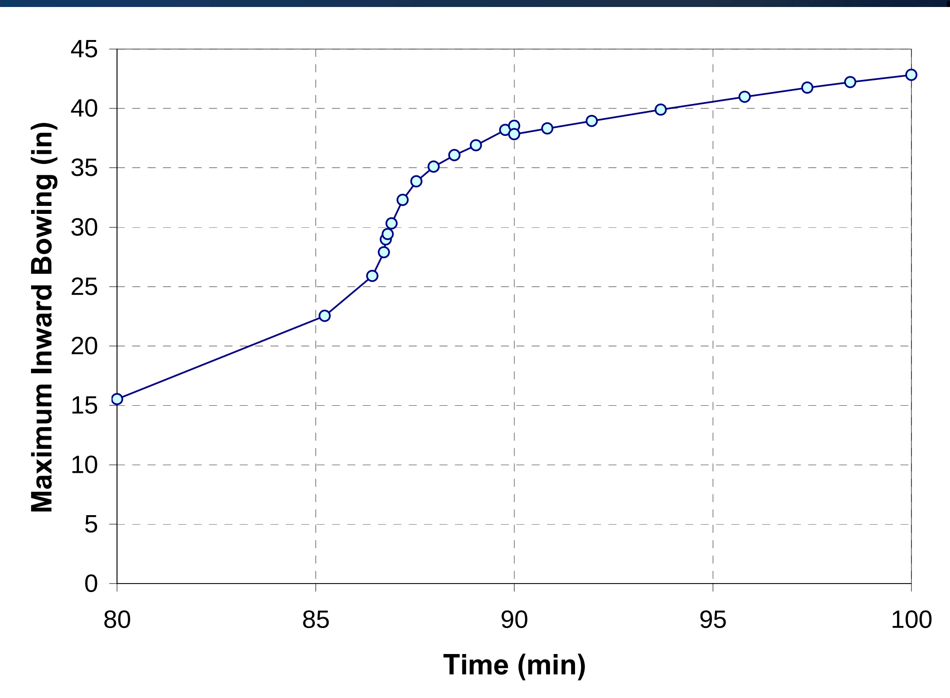


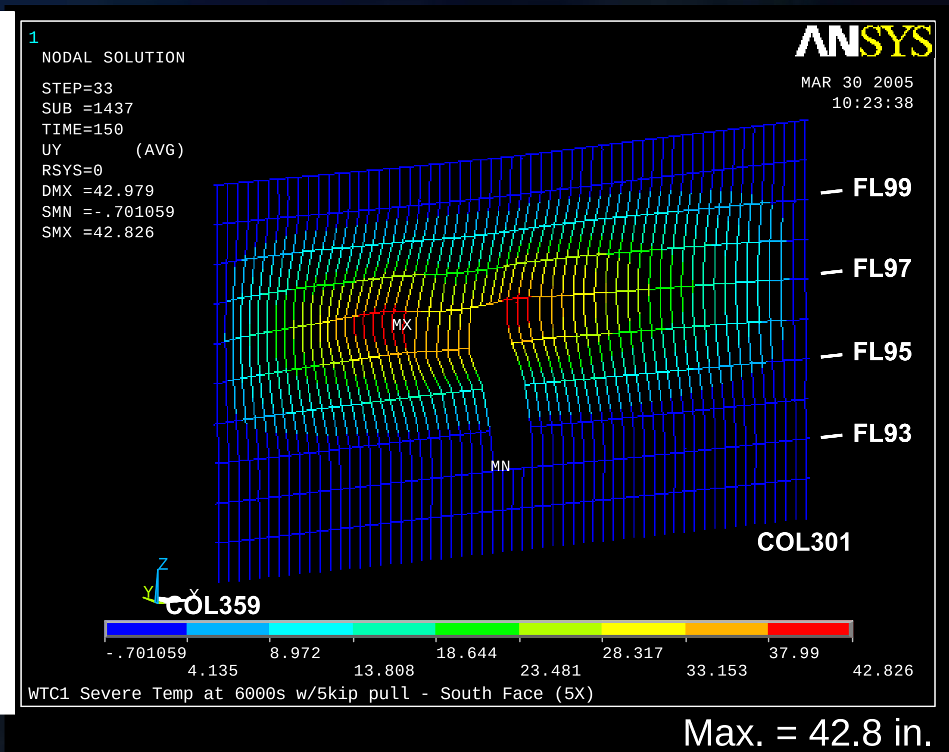
(Downward displacement is negative)

WTC 1 South Wall Out-of-Plane Displacement

SGH Consulting Engineers

At 100 min





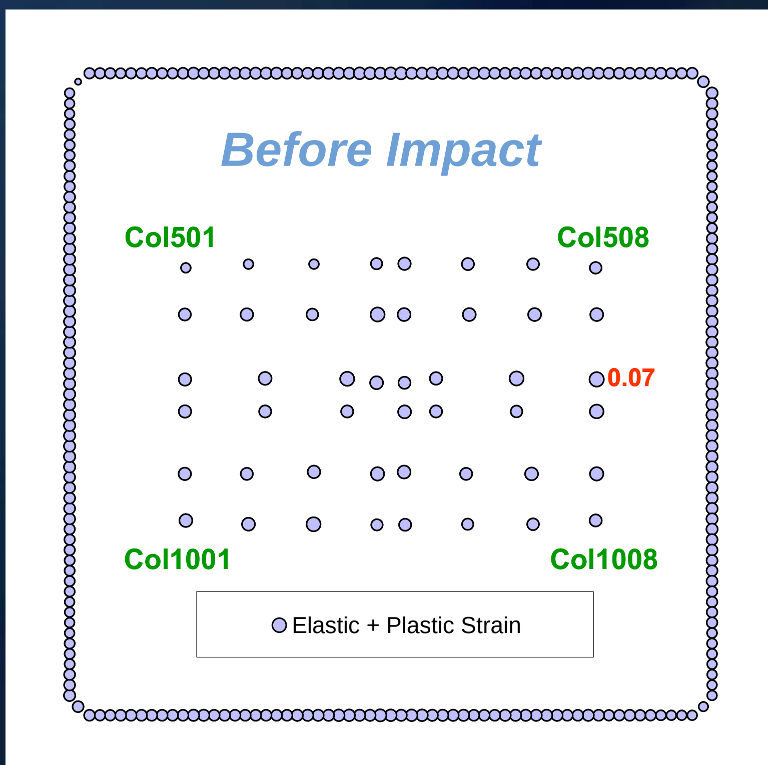
Looking from the outside of the building

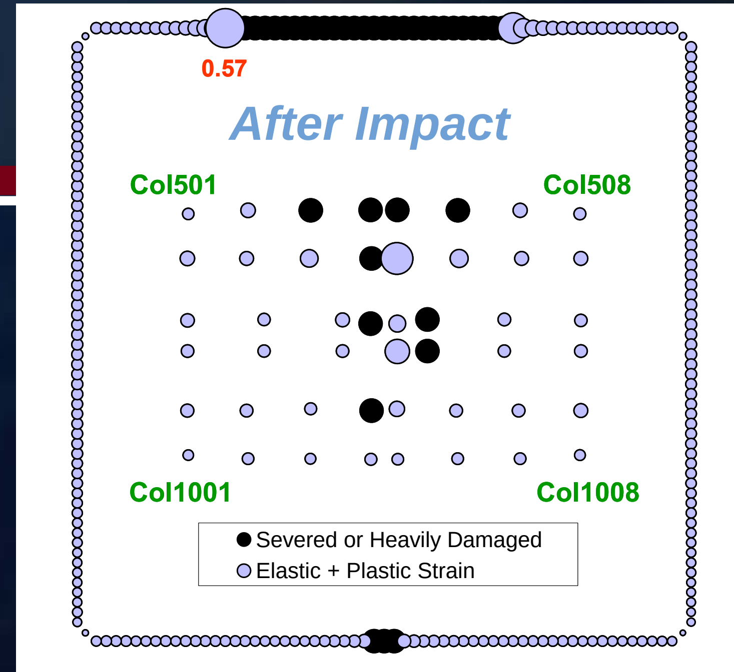
Inward displacement is shown as positive displacement

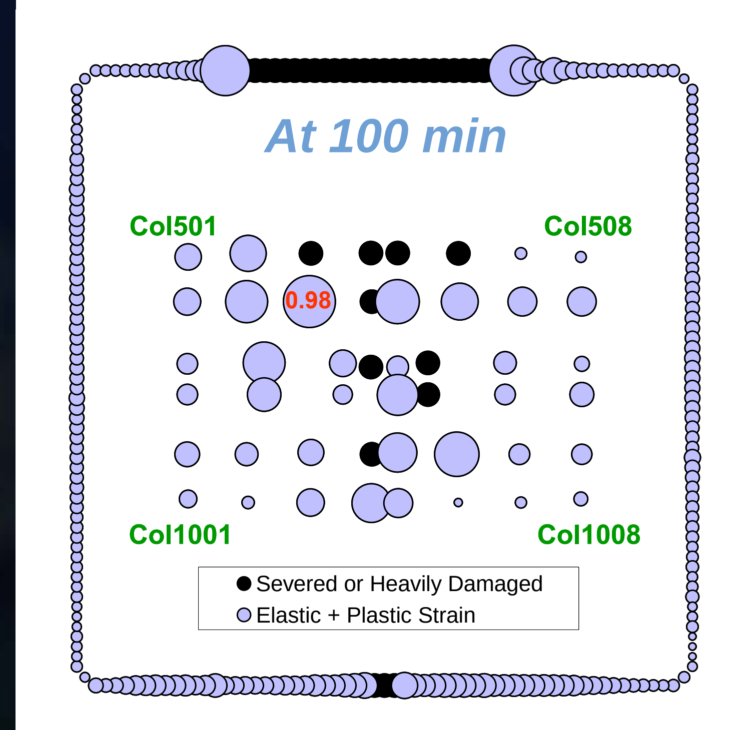
Elastic + Plastic Strain in Columns Maximum between Floor 93 and Floor 99

N

Maximum strain is given in %.
Compression is taken as positive.



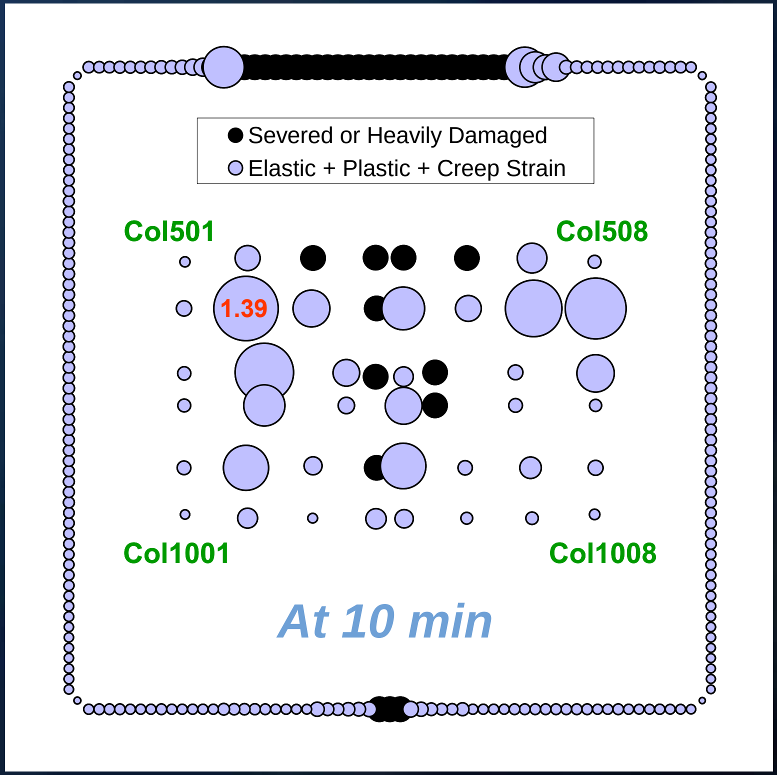


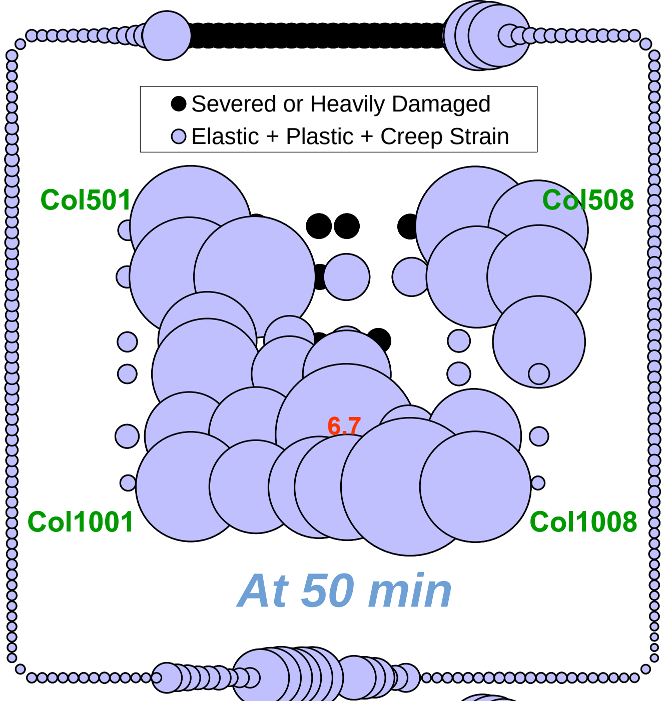


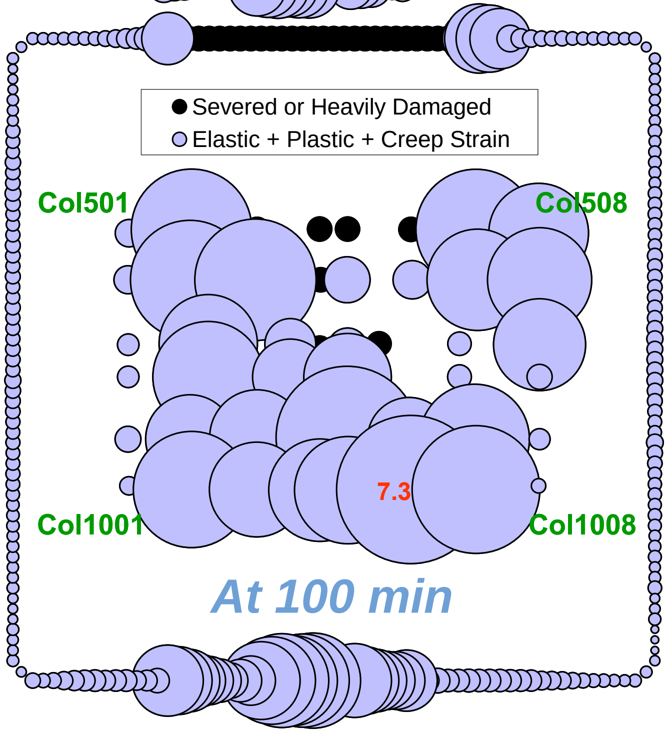
Elastic + Plastic + Creep Strain in Columns Maximum between Floor 93 and Floor 99

N

Maximum strain is given in %.
Compression is taken as positive.



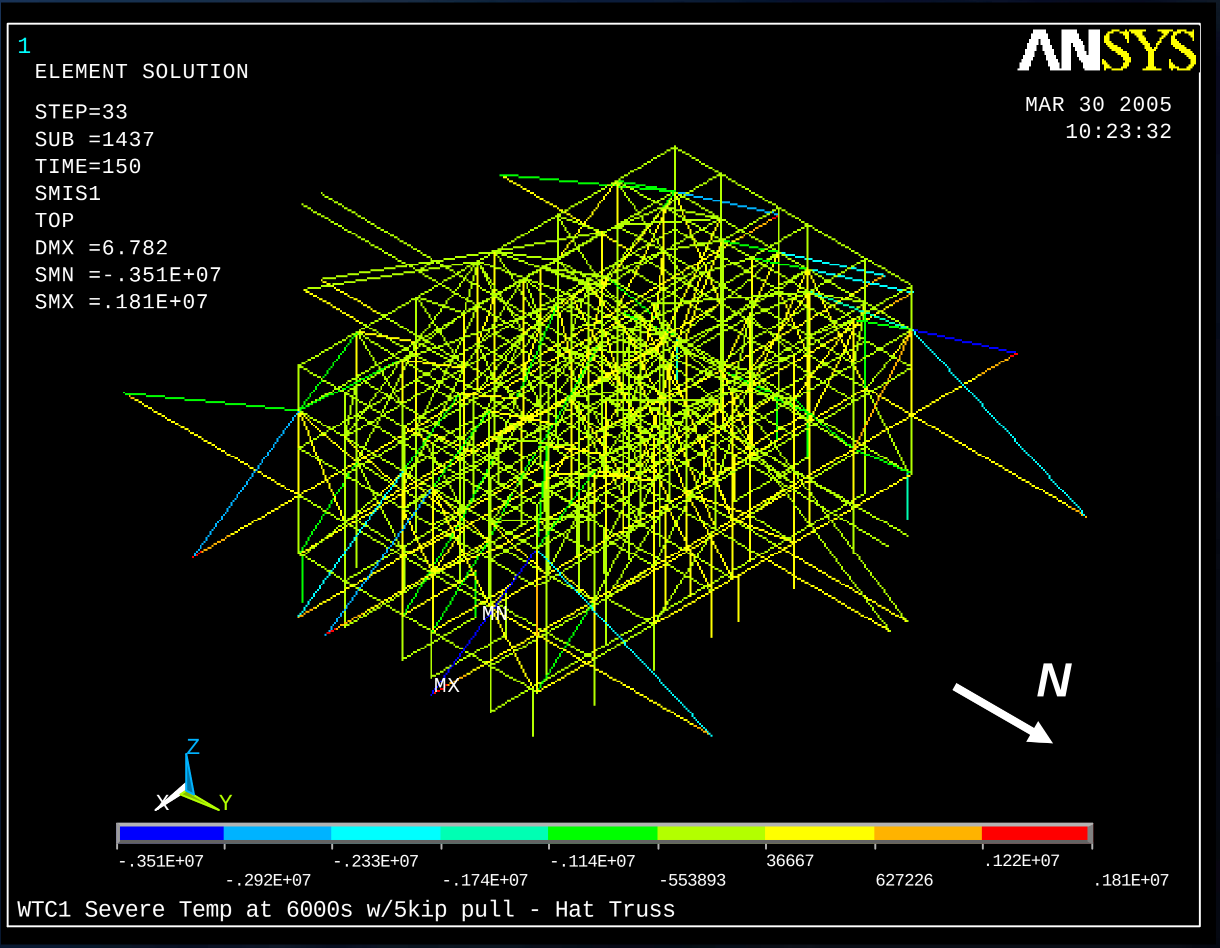




WTC 1 Hat Truss

SGH Consulting Engineers

- Analysis found no failure of hat truss members or supporting core columns.



Axial force in hat truss at 100 min

WTC 1 Global Analysis Results

SGH Consulting Engineers

After Aircraft Impact

- WTC 1 was stable after impact and had considerable reserve capacity.
- Severed core columns in the north side of the core caused it to lean slightly to the north.
- After impact, core loads increased by 1%, east and wall loads increased by 7%, and the north and south walls decreased by 7%.

Effects of Fires and Damaged Fireproofing

- Thermal expansion of the core columns caused core loads to increase until plastic and creep strains exceeded thermal strains and the columns shortened and unloaded.
- Loads were transferred between the exterior wall and the core primarily through the hat truss.
- Fires progressing from the north to the south side of the tower caused the floors to sag and pull inward on the south wall approximately 80 min after impact.
- The south wall bowed inward, reaching approximately 55 in. of inward displacement just before collapse.
- Loads were transferred between exterior walls through the spandrels.

Collapse Initiation

- When the south wall buckled, the loads were transferred to the weakened core and adjacent exterior walls.
- The building section above the impact area tilted to the south.