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

Baseline Structural Performance and Aircraft Impact Damage Analysis

June 22, 2004

Fahim Sadek, Michael A. Riley, Emil Simiu, William Fritz, and H.S. Lew

Building and Fire Research Laboratory

National Institute of Standards and Technology

U.S. Department of Commerce

fahim.sadek@nist.gov

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Scope of Project

- Baseline Performance
  - ❑ Develop reference structural models of the WTC towers
  - ❑ Establish baseline performance under design loading conditions (gravity + wind)
- Aircraft Impact Damage
  - ❑ Simulate aircraft impacts into the towers to estimate probable damage to structural, mechanical, and architectural systems
  - ❑ Determine the response of towers immediately after impact (How close to collapse were the buildings immediately after aircraft impact?)

Summary (December 2, 2003)

- Completed the development of structural databases of the WTC towers. Final approval shortly.
- Completed the development of reference structural models of the WTC towers. Models are under review.
- Baseline performance analysis will start upon approval of the reference models. Progress made in defining wind loading on towers.
- Aircraft impact analysis: Progress made in development of aircraft model, component level analysis, and towers models.
- Simplified stability analysis of the towers is ongoing.

Summary (June 22, 2004)

- Completed the development and review of structural databases of the WTC towers. Databases have been approved by NIST.
- Completed the development and review of reference structural models of the WTC towers. Models have been approved by NIST.
- Estimates of wind loading on the towers completed by NIST, reviewed by Skidmore, Owings & Merrill (SOM), a NIST contractor. Baseline performance analysis is nearing completion, review to start shortly.
- Aircraft impact analysis: development of aircraft model, material constitutive modeling, and component level analysis completed. Subassembly analysis and global towers models are nearing completion. Global analysis and sensitivity analyses are ongoing.
- Preliminary stability analysis of the towers nearing completion.

Overview of Presentation

- Results of the review of the reference structural models of the towers
- NIST estimates of wind loading on the towers and third-party review by SOM
- Status of baseline performance analysis
- Status of aircraft impact analysis
- Preliminary stability analysis of the towers: methodology and results

Review of Reference Structural Models

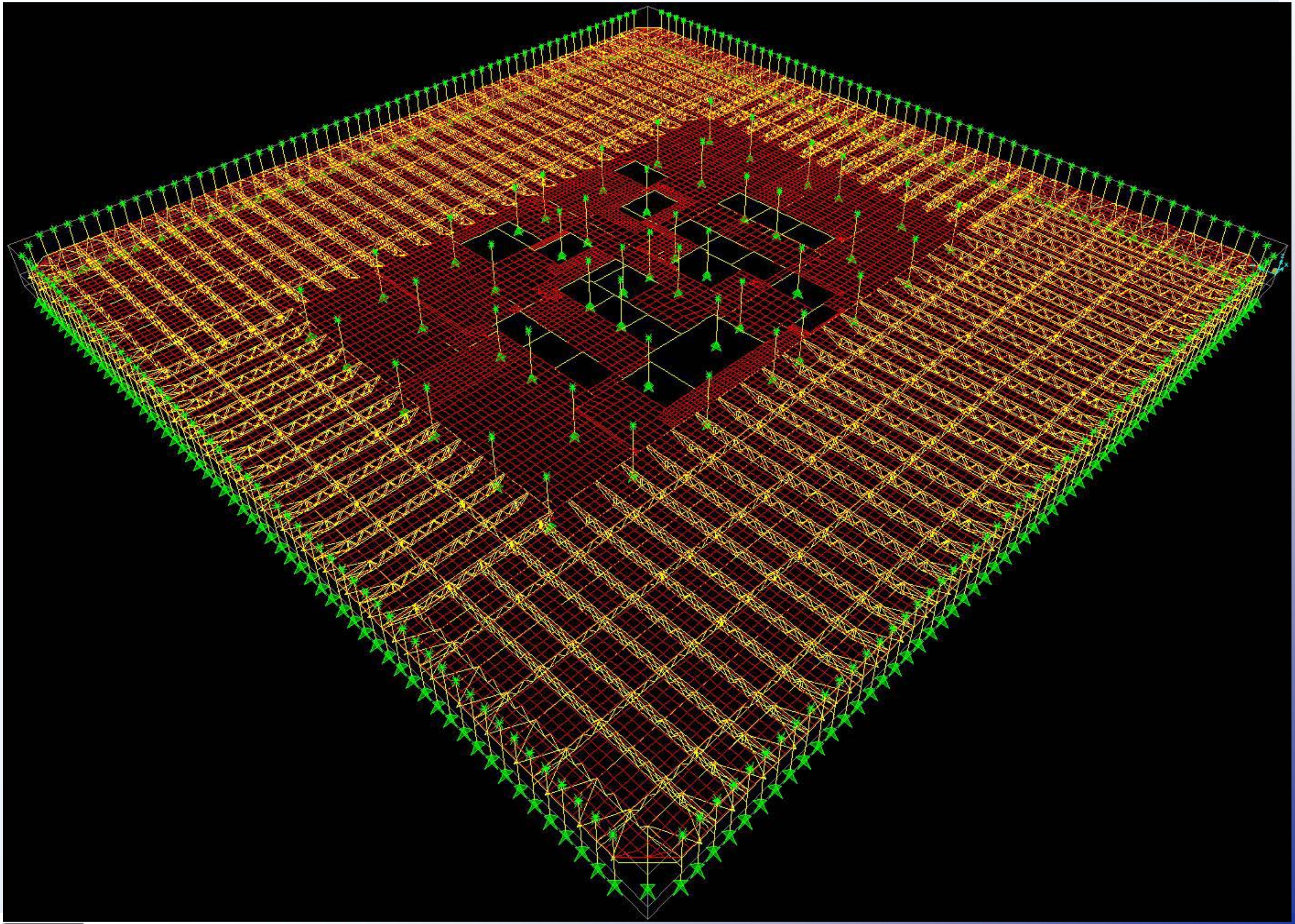
SOM Third-party Review

- Consistency with original design
  - Random checks
- Verification/validation of models
  - Review assumptions and level of detail
  - Perform analyses using various loading conditions to test the accuracy of the models

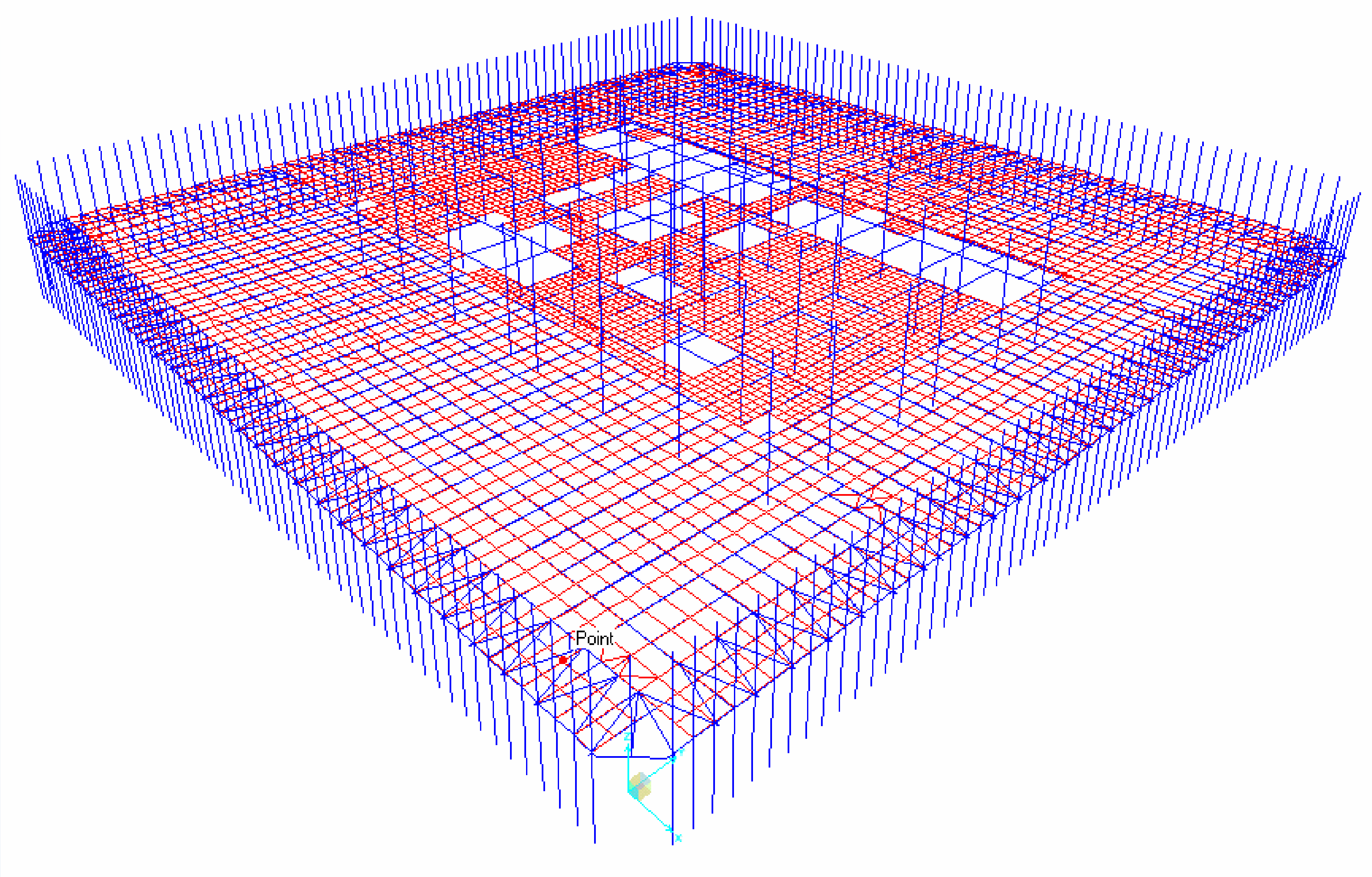
NIST In-House Review

- Consistency with original design
  - Models geometry / cross section properties
  - Material properties
- Verification/validation of models
  - Review assumptions and level of detail
  - Perform analyses using various loading conditions to test the accuracy of the models

Floor Systems: *Floor 96-A Model*



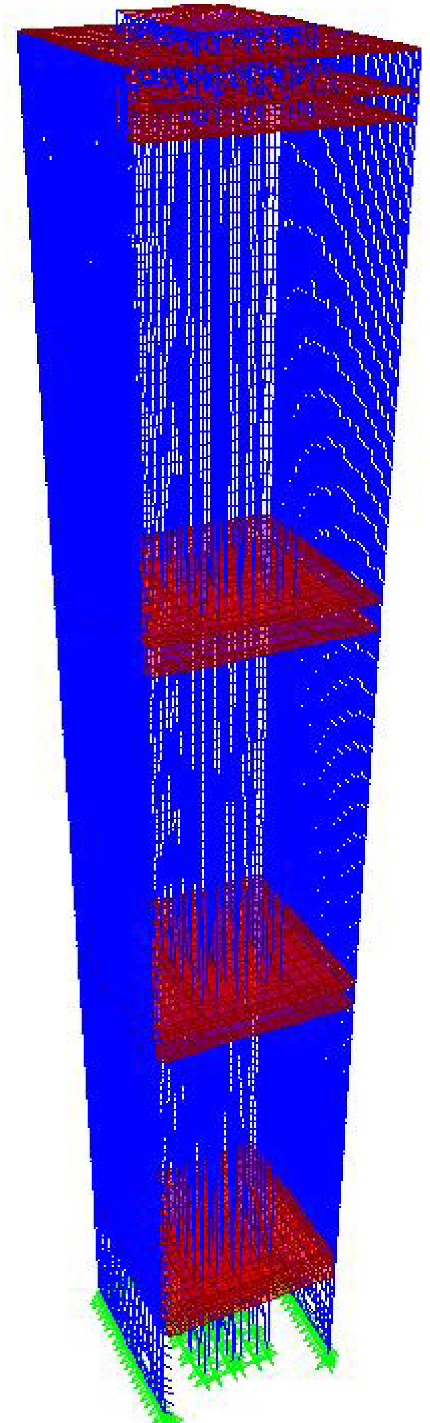
Floor Systems: *Floor 75-B Model*



Tower Structural System FE Models (Global Model)

Models include:

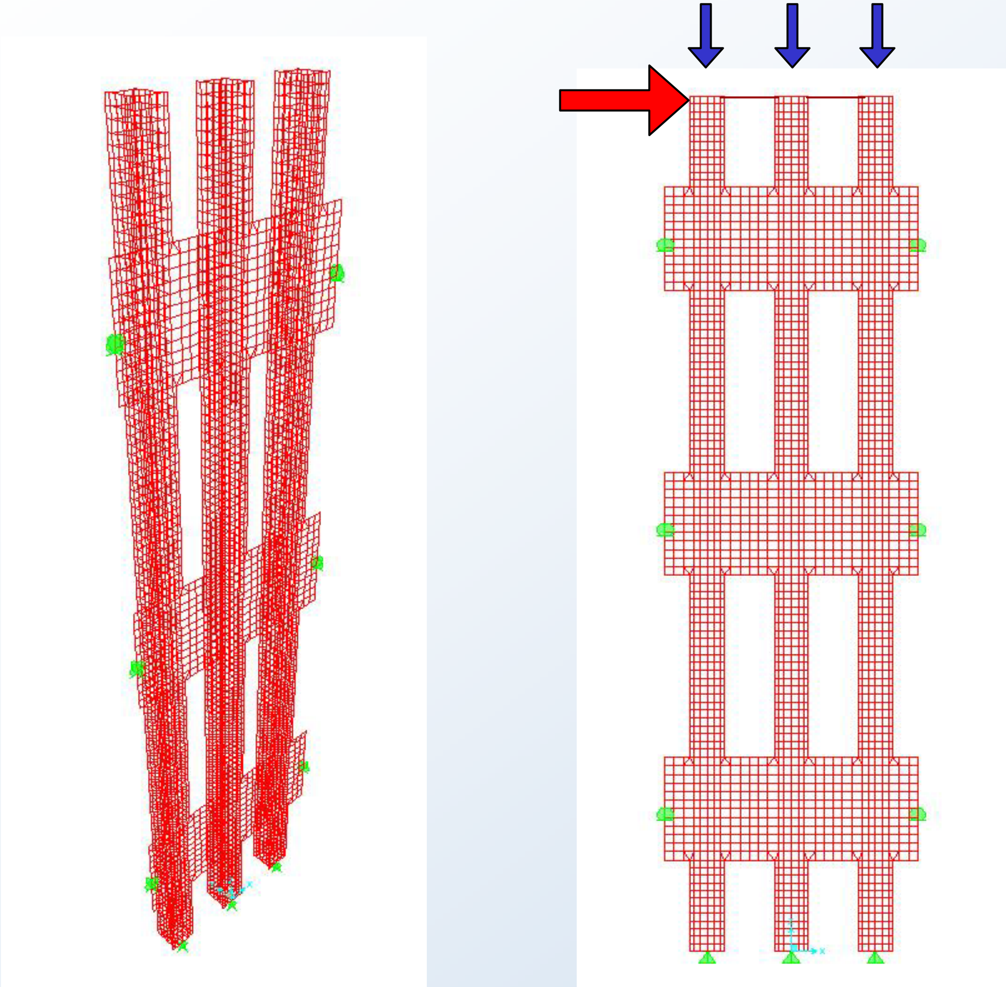
- Core columns
- Exterior panels
  - Foundation to floor 7
  - Trees (transition from 3’-4 to 10’-0 col. spacing)
  - Floor 9 to 106
  - Floor 107 to roof
- Hat truss
- Rigid floor diaphragms
- Flexible floor diaphragms



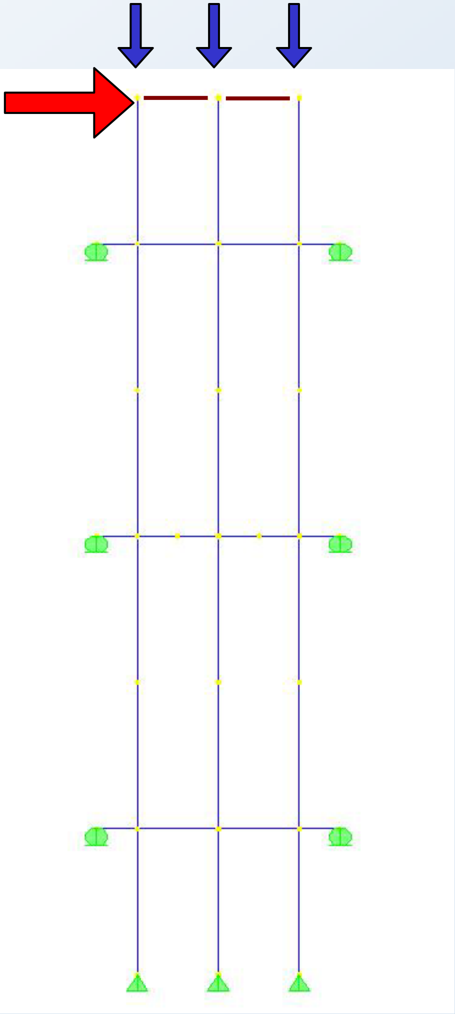
Review of Reference Structural Models

- Reviews indicated minor discrepancies between the developed reference models and the original design documents.
- Modeling assumptions and level of detail in the models are, in general, accurate and suitable for the purpose of the project.
- Identified two areas where the models need to be modified:
  - The effect of additional vertical stiffness of the exterior wall panels due to the presence of the spandrel beams
  - Modeling of the connections of the floor slab to the exterior columns of the typical beam-framed floor model, where this connection appeared to be fixed while the connection should be modeled as pinned
- The minor discrepancies and the areas identified for modification were reported to Leslie E. Robertson Associates (LERA), a NIST contractor, who implemented the changes and modified the models accordingly.
- The reference structural models have been approved by NIST and have been made available for other phases of the NIST investigation.

Modeling of Exterior Panels



Detailed shell model of exterior panel



Equivalent beam model of exterior panel

NIST Estimates of Wind Loads on the Towers

- Objective: to provide estimates of wind-induced forces and moments on WTC 1 and WTC 2 towers, based on the state of the art in wind engineering.
- NIST estimates are based on assessment of results of wind tunnel tests and extreme wind climatological estimates conducted by Rowan Williams Davis and Irwin, Inc. (RWDI) and by Cermak Peterka Peterson, Inc. (CPP). NIST performed independent extreme wind climatological estimates, based on airport wind speed data obtained from the National Climatic Data Center, NOAA, and the NIST hurricane wind speed database.
- NIST estimates of wind-induced forces and moments must rely primarily on RWDI results, since no results for WTC 1 are available from CPP. However, the estimates take into account a comparison between RWDI and CPP results for WTC 2.

NIST

NIST Estimates of Wind Loads on the Towers

- Summary Comparison by Weidlinger Associates, Inc., of CPP and RWDI Estimates

Approximate maximum base moments induced by ASCE 7-98 Standard wind loads

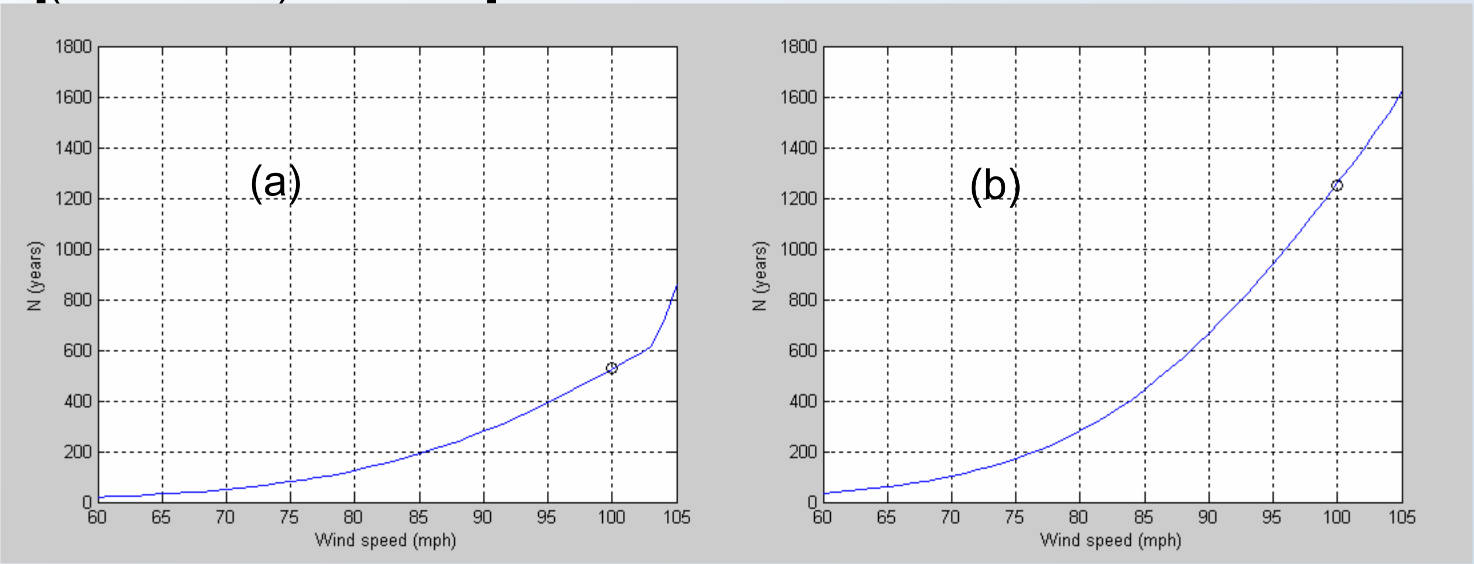
	$\lvert M_y \rvert$ (lb-ft)	$\lvert M_x \rvert$ (lb-ft)
RWDI 2 (Table 2a)	10.1e+9	11.1e+9
CPP (Upper Table, p. 21)	14.0e+9	15.5e+9

- Both RWDI and CPP results indicate that the critical base moments occur for an angle of about 210 degrees.

NIST

NIST Estimates of Wind Loads on the Towers

- Review of CPP Estimates:
  - NIST estimated a 720-yr, 3-s peak gust speed of 99.8 mph for 210° (via interpolation between speeds for 202.5° and 225°).
  - CPP estimated a 720-yr, 3-s peak gust speed of 117.5 mph for 210°.
  - CPP results overestimated wind loads by about 39% [$(99.8/117.5)^2=1/1.386$].



Estimates of wind speeds with various MRIs for: (a) 202.5°, and (b) 225° directions

NIST Estimates of Wind Loads on the Towers

- Review of CPP Estimates:
  - CPP results should be modified to account for their use of the sector-by-sector approach to integrate aerodynamic and extreme wind climatological data. This approach is not fully realistic from a physical point of view.
  - Using a rigorous probabilistic approach, NIST showed that CPP's sector-by-sector approach underestimates wind effects with a specified mean recurrence interval.
  - NIST preliminary estimates, that would need to be confirmed by research, indicate that the underestimation is about 15%.
  - Therefore, the overall reduction factor applied to the estimated CPP effects to account for overestimated wind speed and underestimation resulting from the sector-by-sector approach should be approximately 20% ($1.15/1.386 \approx 1/1.205$).

NIST

NIST Estimates of Wind Loads on the Towers

❑ Review of RWDI Estimates:

- A comparison of RWDI results with the corrected CPP estimates indicates that the RWDI results underestimate the moments by about 15%.
- The underestimation is due largely to the incorrectly supported assumption that wind profiles in hurricanes are flatter than in non-hurricane winds. RWDI, therefore, estimated the ratio between responses to 88 mph (ASCE 7-98) and 80 mph (NYBC) wind speeds to be about 1.1, rather than about $(88/80)^2=1.21$.
- Also, it is not clear that RWDI's use of the up-crossing method (with hurricane wind speeds weighted in proportion to their squares) leads to unbiased estimates. (No justification or references were provided for the weighting procedure.)

NIST Estimates of Wind Loads on the Towers

- Summary

  - Wind loads consistent with ASCE 7-02 Standard design wind speeds can be estimated for both towers from RWDI results via multiplication by 1.15. This factor is recommended for baseline analysis. However, it may be that the actual number is anywhere between, 1.10 and 1.20.

  - More elaborate calculations and/or tests would be desirable. They should be reported in a transparent manner that can readily be scrutinized and might lead to more comprehensive and precise results. However, in the absence of sufficiently detailed information, obtaining such results is not practicable now.

NIST Estimates of Wind Loads on the Towers

- Third-party Review by SOM under contract from NIST:
  - "NIST recommends a wind load that is between the RWDI and CPP estimates. The NIST recommended values are approximately 83% of the CPP estimates and 115% of the RWDI estimates. SOM appreciates the need for NIST to reconcile the disparate wind tunnel results. It is often that engineering estimates must be done with less than the desired level of information. In the absence of wind tunnel testing and wind engineering done to NIST specifications, **NIST has taken a reasonable approach to estimate appropriate values to be used in the WTC study.** However, SOM is not able to independently confirm the precise values developed by NIST."

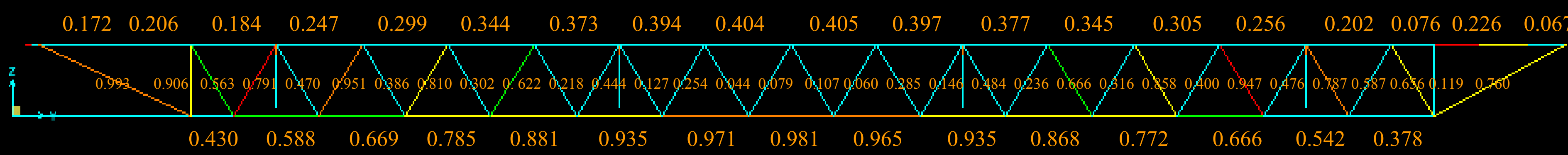
Status of Baseline Performance Analysis

- Conduct linear static, structural analyses of each of the two towers to establish their baseline performance under the following loads:
  - ❑ Load combination 1:
    - Dead loads
    - Live loads used in the original design of the towers
    - Wind loads used in the original design of the towers
  - ❑ Load combination 2:
    - Dead loads
    - Live loads according to ASCE 7-02 Standard
    - Wind loads estimated by NIST based on the state of the art in wind engineering
- Analyses are nearing completion. In-house and third-party review to start shortly.

NIST

Floor 96-A: Long Span Trusses

D/C Ratios, AISC-ASD89



Average Truss Diagonal D/C Ratio = 0.475

Maximum Deflection:

CDL= 0.75”

SDL = 0.12”

LL = 1.09”

Total = 1.96”

NIST

Aircraft Impact Analysis: Outline

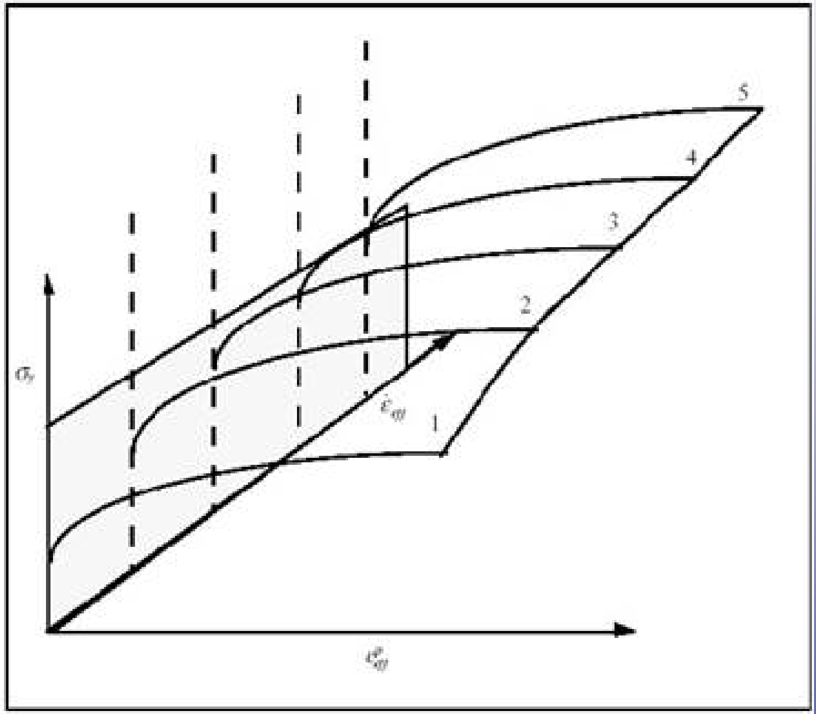
- Material Constitutive and Failure Modeling
- Aircraft Data Collection and Model Development
- WTC Towers Model Development
- Component Impact Analyses
- Subassembly and Global Impact Analysis

Material Constitutive and Failure Modeling

- Develop constitutive and failure models from test data of recovered steel (Project 3)
  - Detailed finite element analysis (FEA) of material tests (validation)
    - Very fine to fine mesh resolution
  - Analysis of local structural response
    - Fine to medium mesh resolution
  - Apply to analysis of tower structural components
    - Medium to coarse mesh resolution

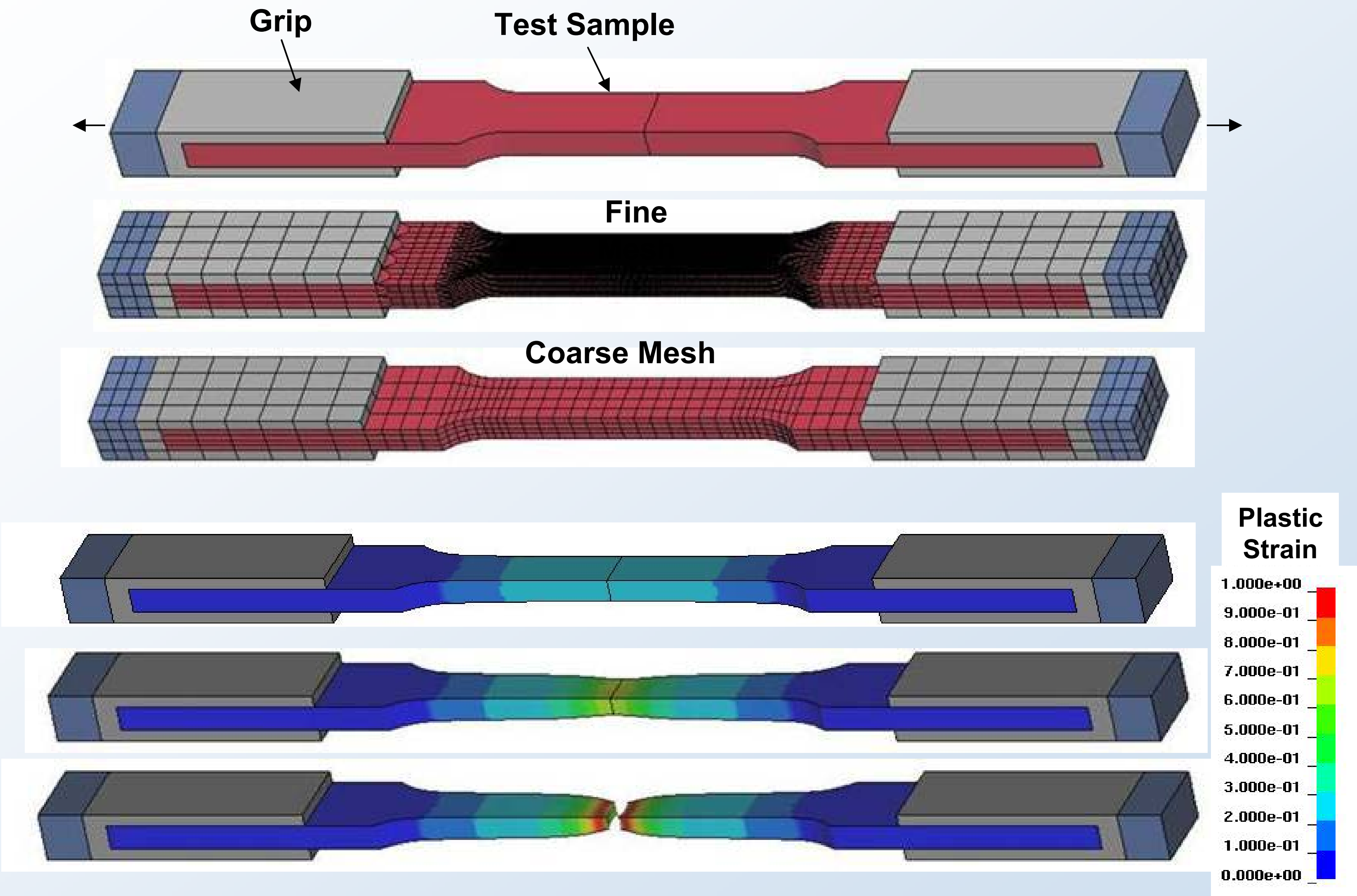
Steel Constitutive Modeling

- Piecewise Linear Plasticity Model.
  - Yield Stress Dependence:
    - Plastic Strain
    - Strain rate
  - Strain rate effects:
    - Cowper and Symonds rate effects model based on test results from Project 3



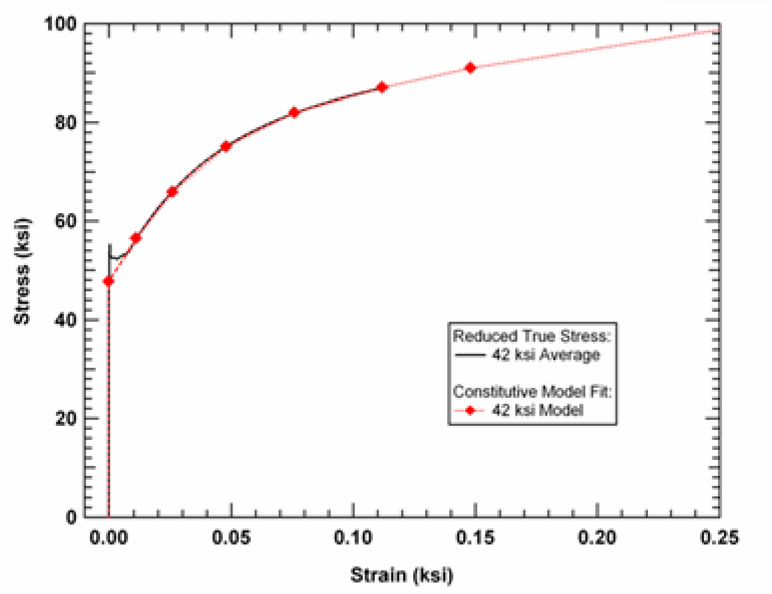
Yield Stress Variation with Effective Plastic Strain

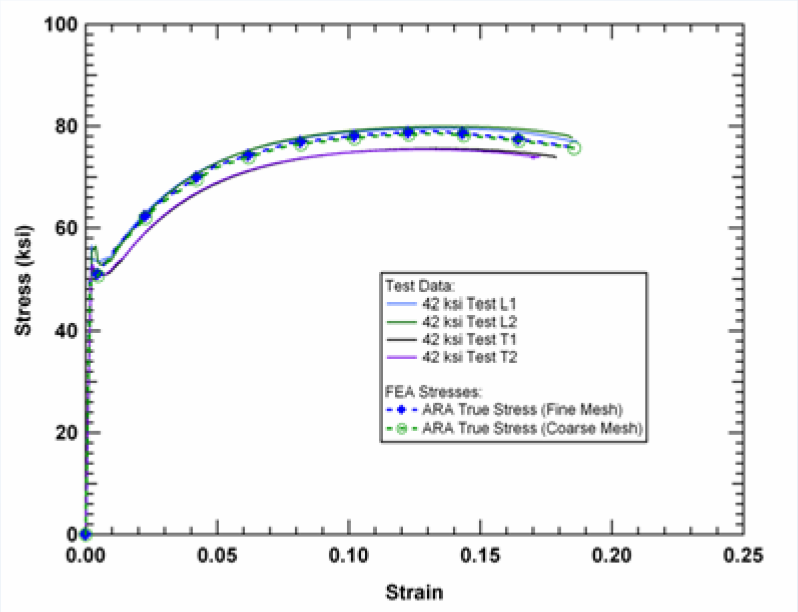
ASTM-A370 Tensile Specimen Model



Stress-Strain Behavior

Constitutive Model True Stress (42 ksi WF Core Steel)





Core wide flange yield strength:

- 42 ksi nominal
- 50 ksi actual

Development of the true stress-strain behavior.

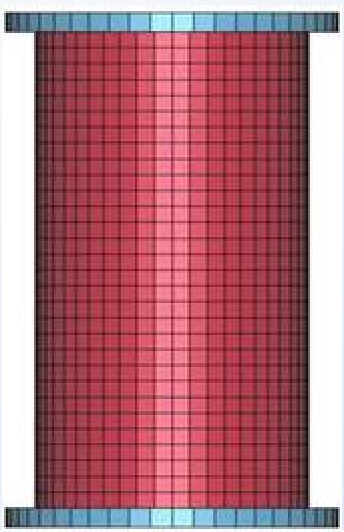
Comparison of the measured and calculated (FEA) stress-strain behavior.

Updated model agrees well with the test data.

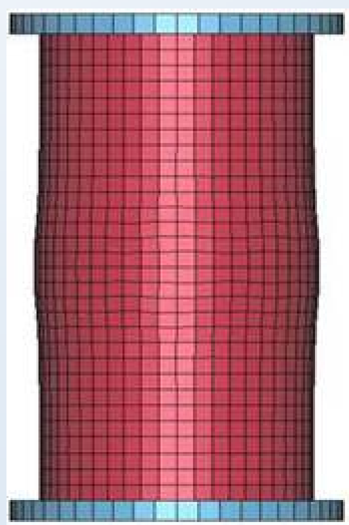
Reinforced Concrete Modeling

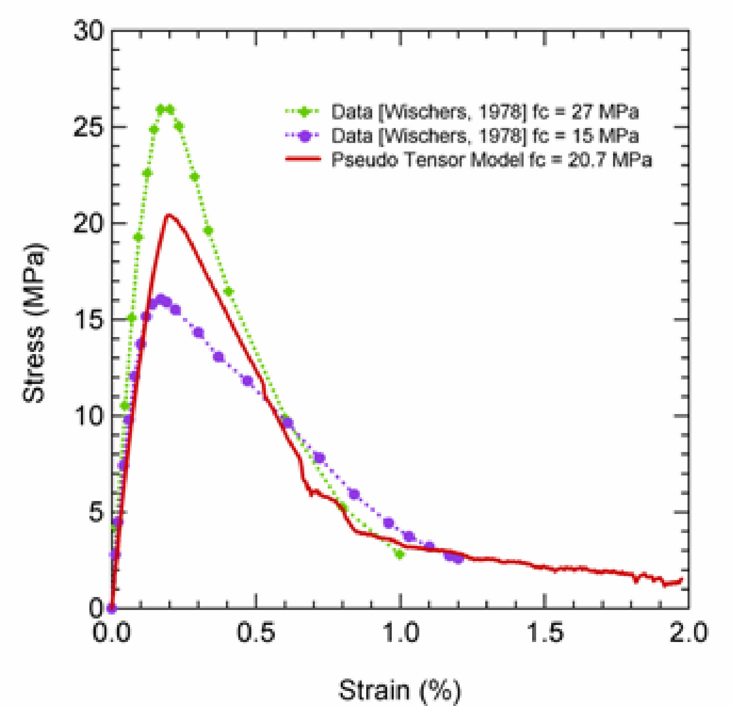
- Pseudo-Tensor Model:
  - Appropriate for low-confinement modeling
  - Tabular rate effects modeling
  - Damage with softening and various failure/erosion options
- Pseudo-tensor model was calibrated using a simulation of an unconfined compression specimen.

Unloaded



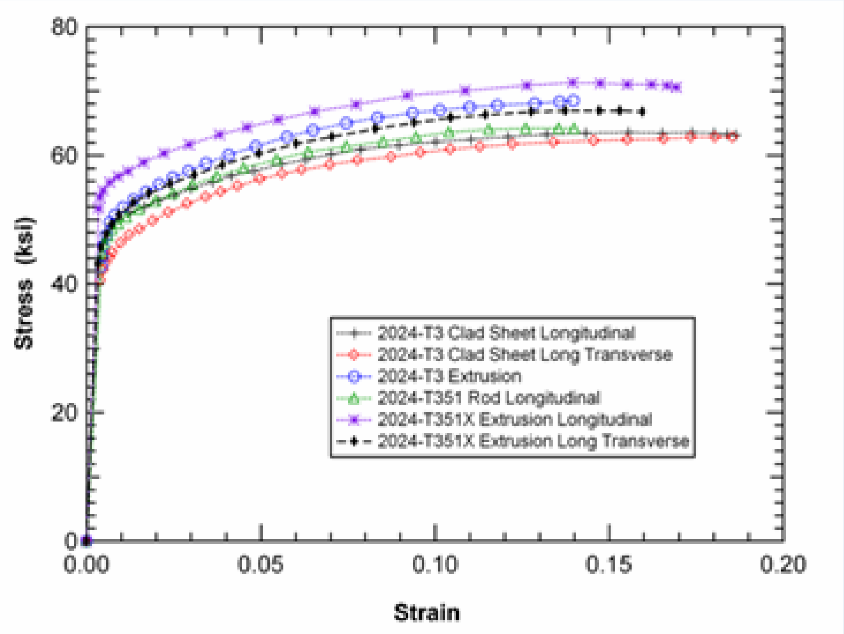
2% Displacement

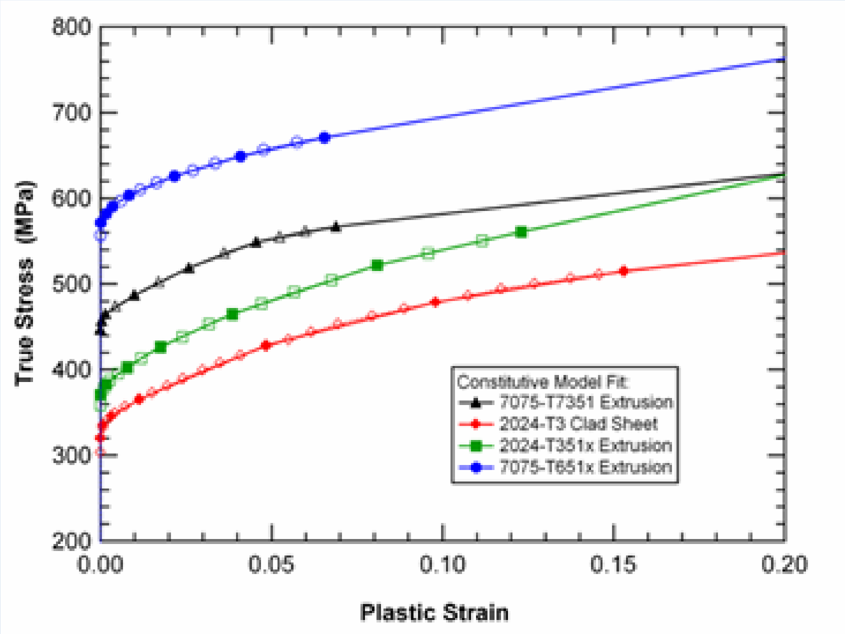




Aircraft Materials Modeling

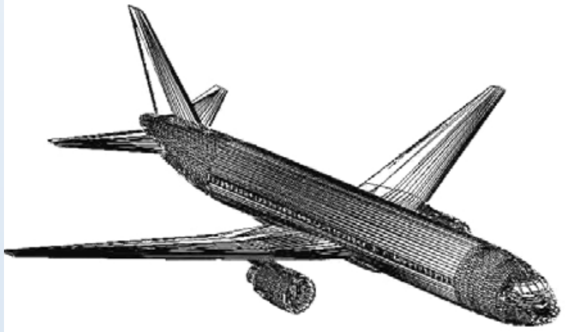
- Open literature sources used to obtain material data for significant aircraft materials
  - Aerospace Structural Metals Handbook
  - MIL-HNBK-5F: Metallic Materials and Elements for Aerospace Vehicle Structures

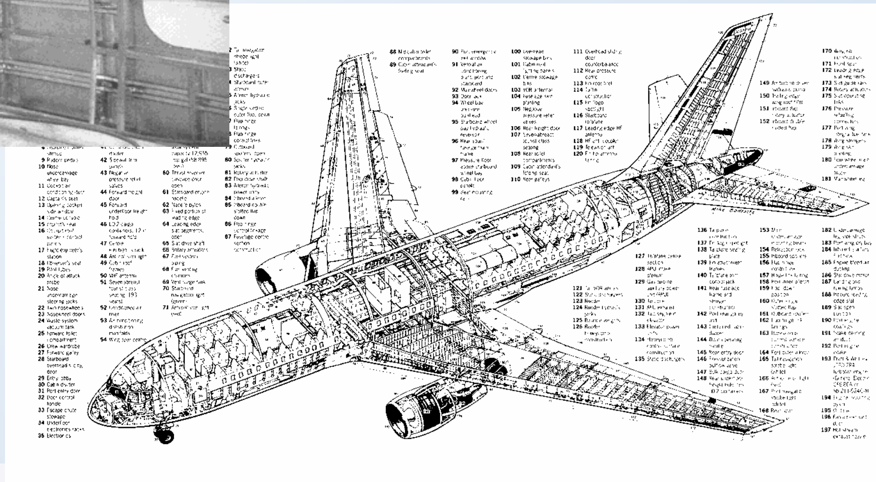




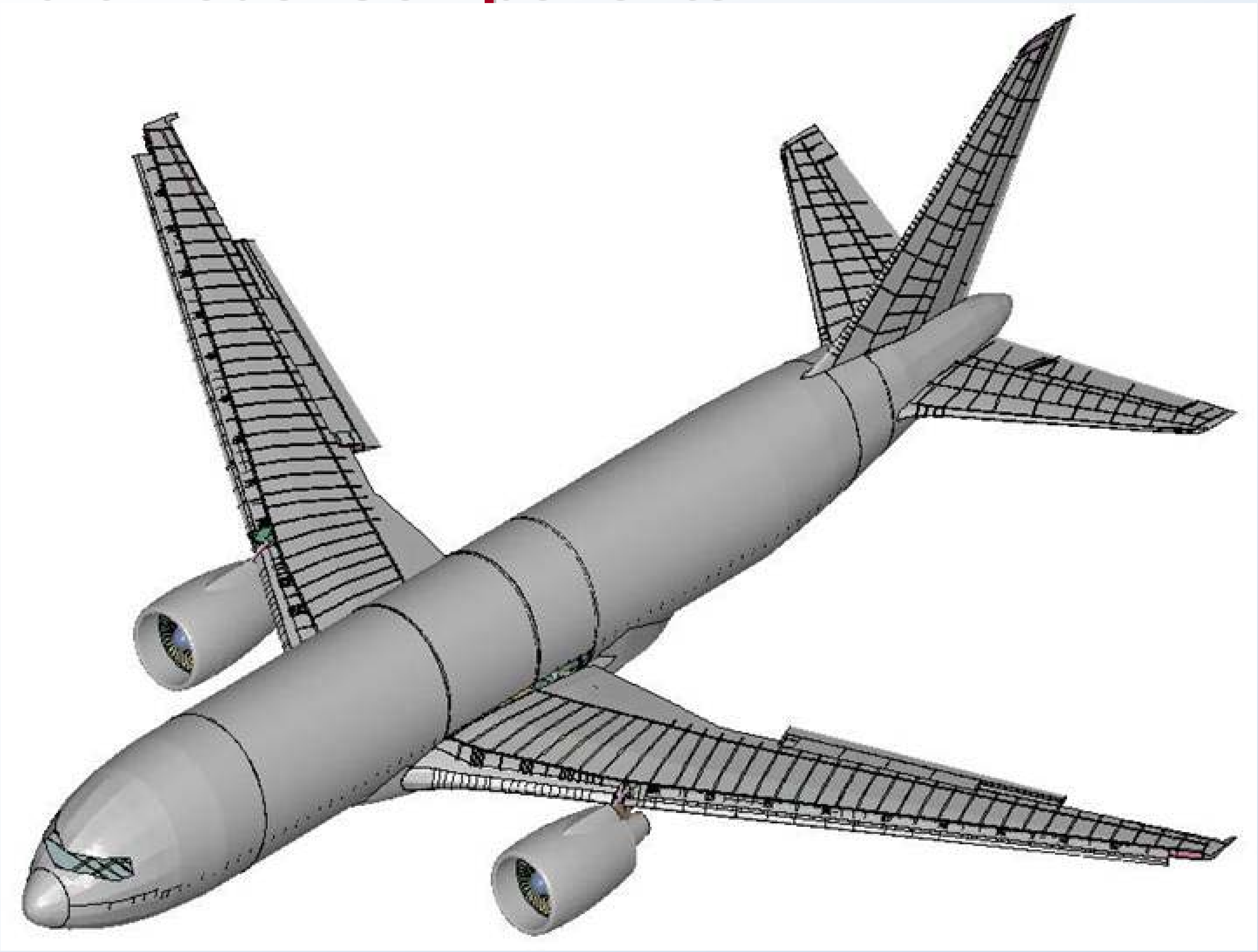
Aircraft Data Collection and Model Development

- Aircraft Model Development: Boeing 767-200ER
  - ❑ Documentary aircraft structural information
  - ❑ Data from measurements on 767 aircraft

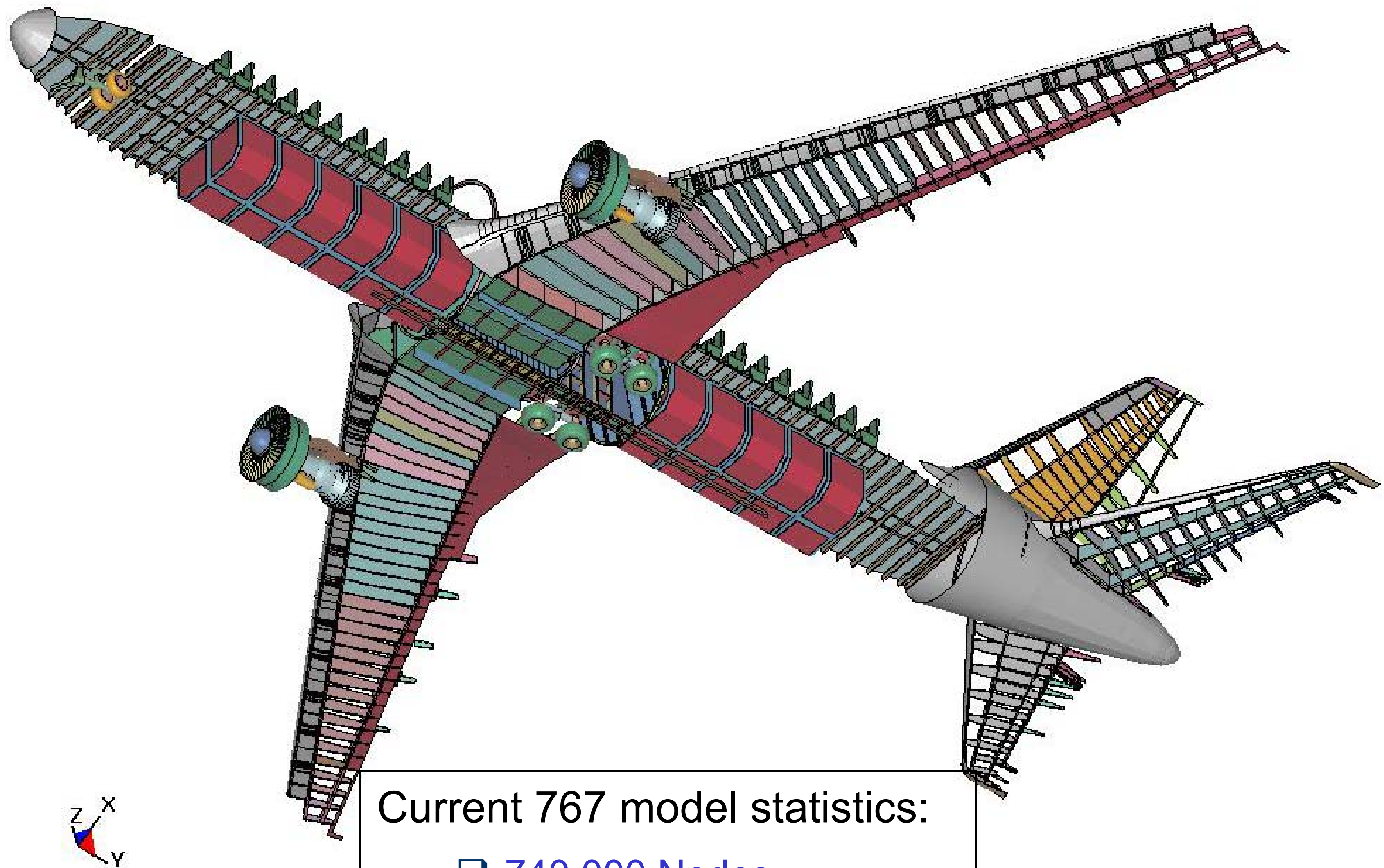




Aircraft Model Components



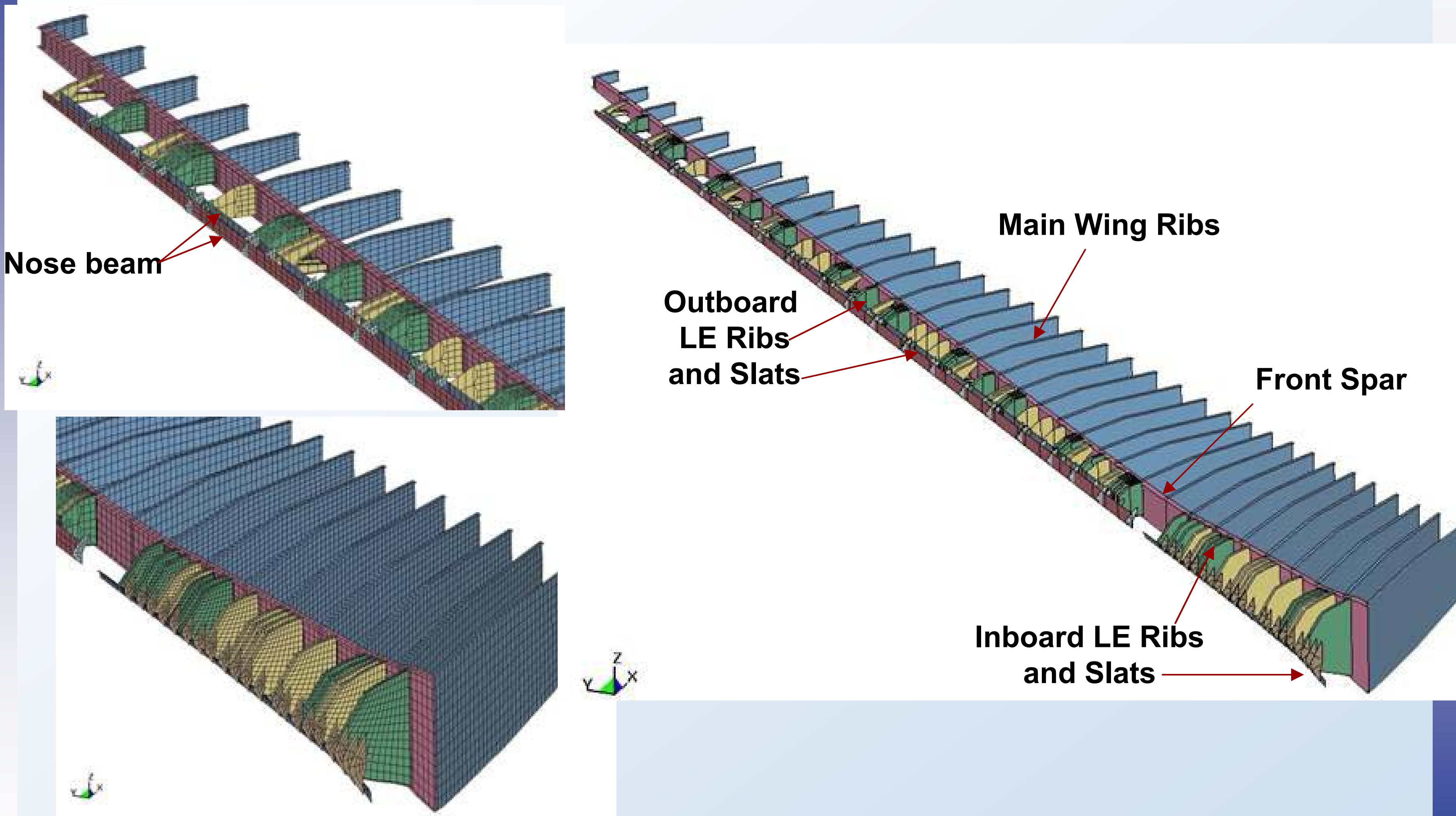
Aircraft Model Components



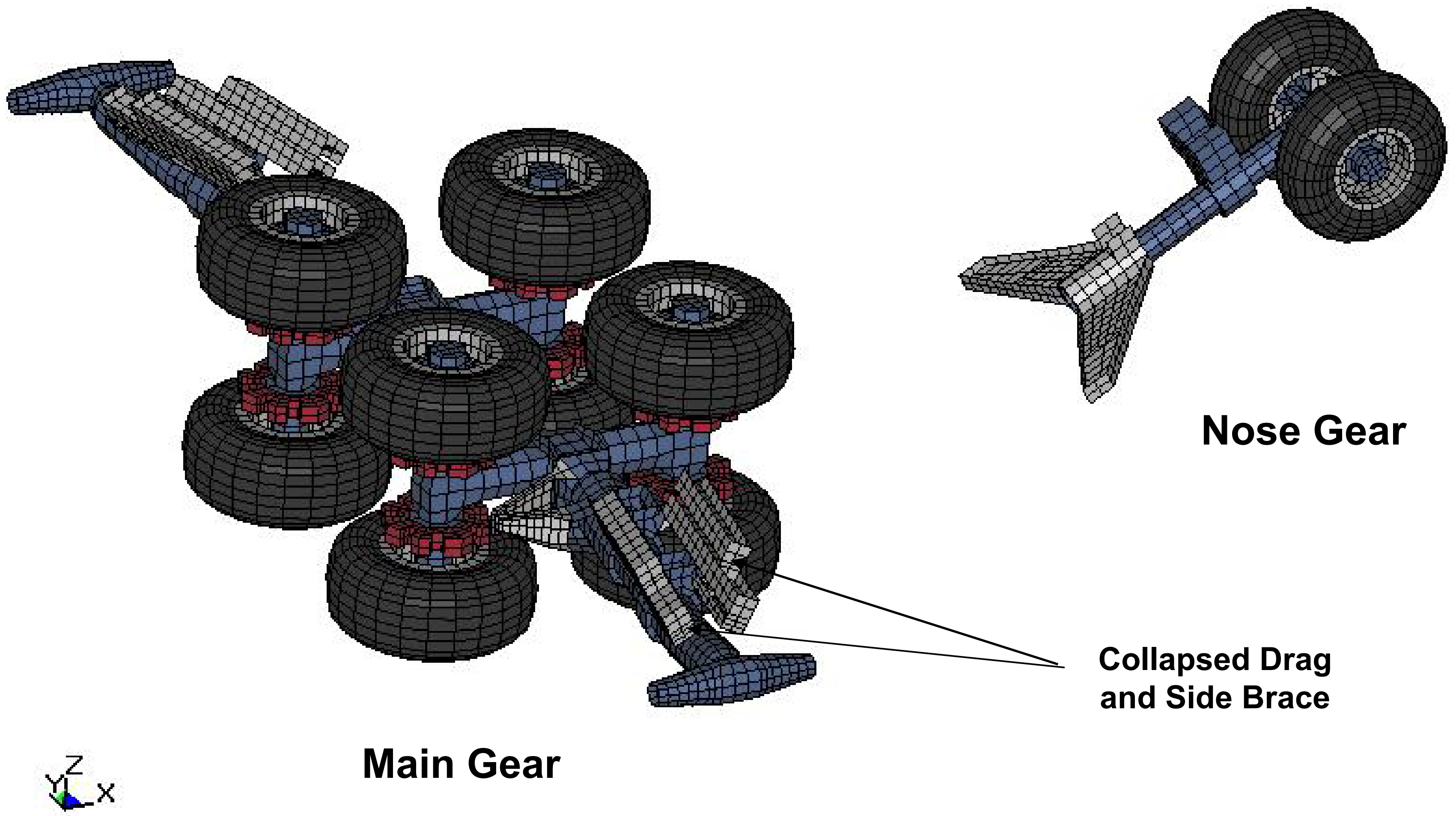
Current 767 model statistics:

- ❑ 740,000 Nodes
- ❑ 562,000 shell elements
- ❑ 70,000 brick elements

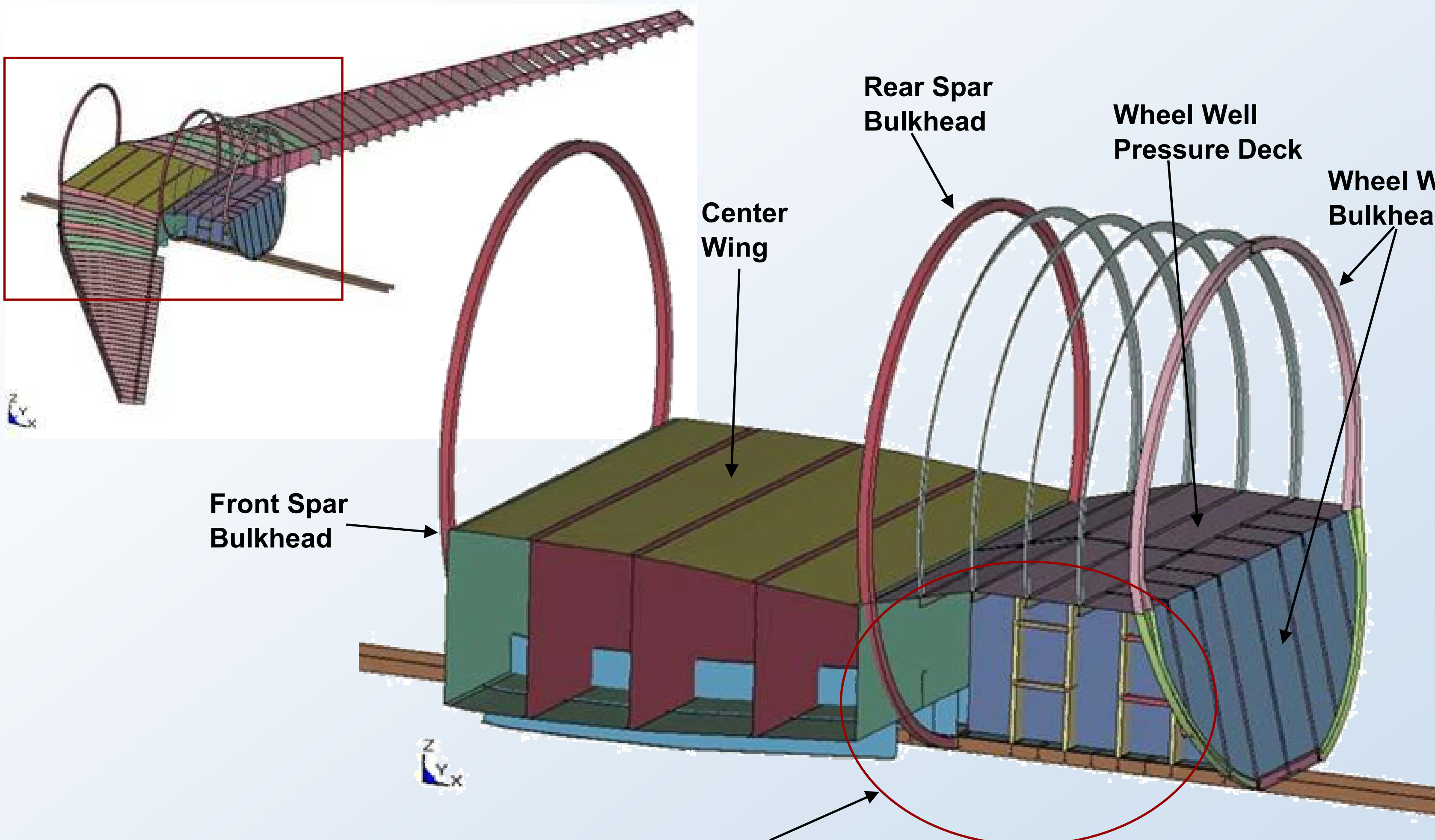
Wing - Leading Edge Structures



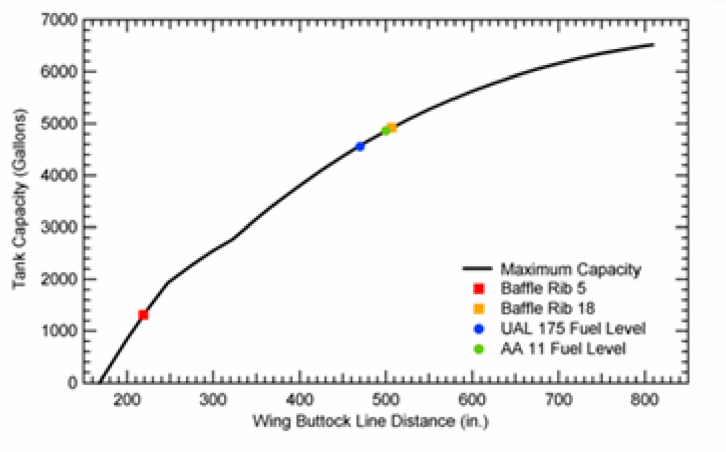
Landing Gear Model

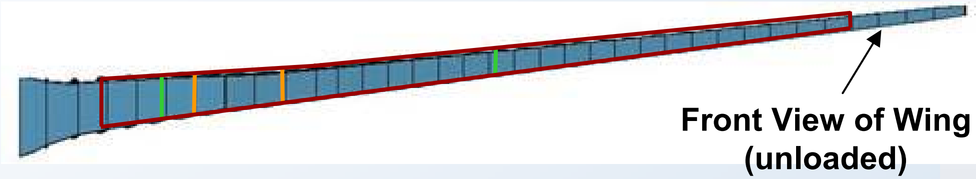


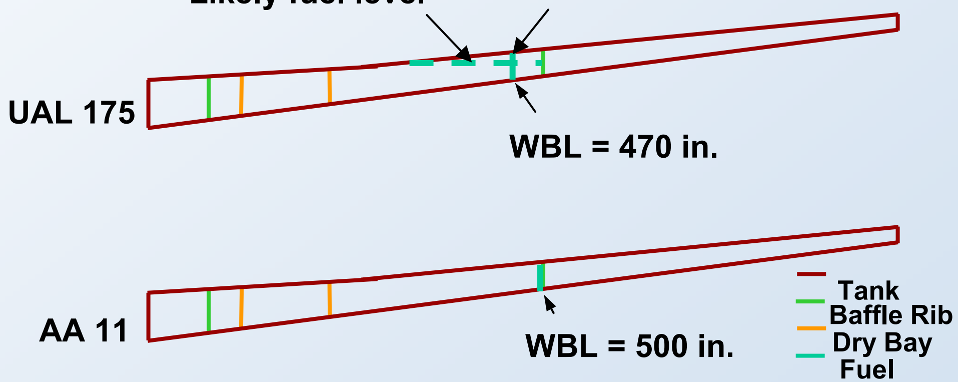
Fuselage Structure and Wing Integration



Fuel Distribution Analysis



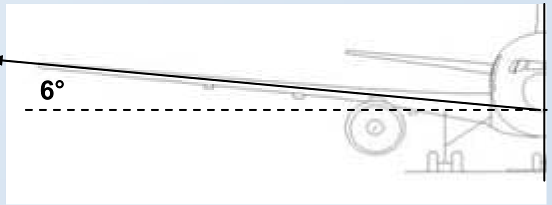




First Estimate:

- Assume all fuel has flowed inboard of outboard baffle rib (18)
- Assume an undeformed wing shape.
- Use tank capacity for fuel location.

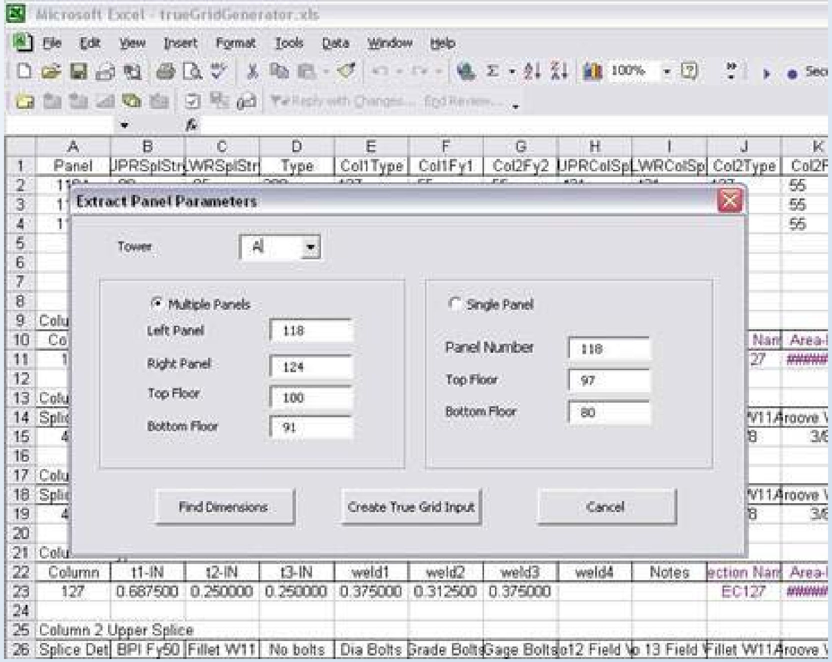
Wing Buttock Line (WBL)



Tank capacity to Baffle Rib 18 is approximately the same volume as the fuel onboard at the time of impact.

WTC Tower Model Development

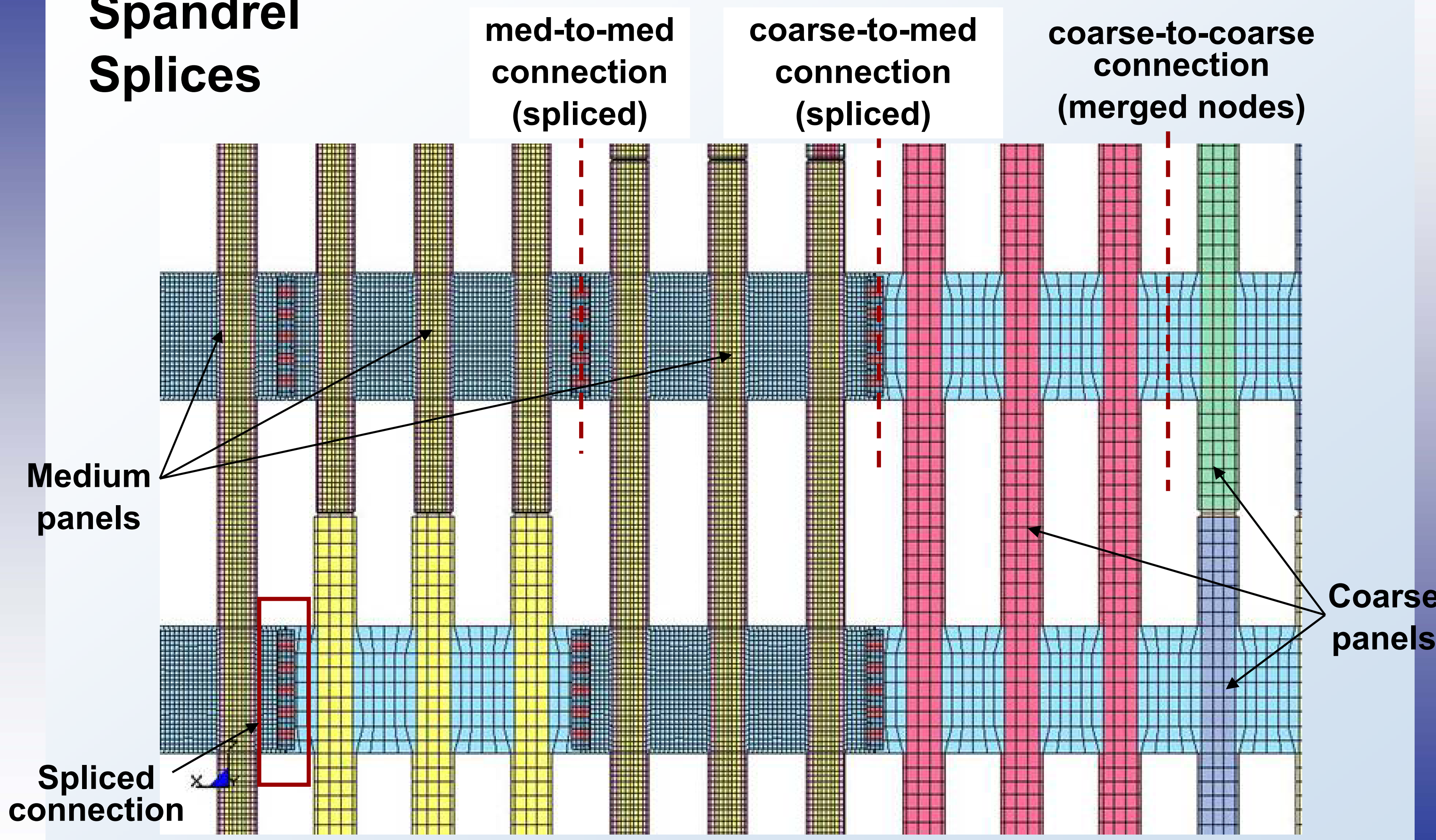
- Automated mesh generation developed for structural systems using the electronic structural database.
  - ❑ Automated mesh generation for exterior walls and core structures
  - ❑ Automatically inserts bolts, butt plates, and splices
  - ❑ Controls mesh refinement for different regions



NIST

Exterior Panel Auto Generation

Spandrel Splices



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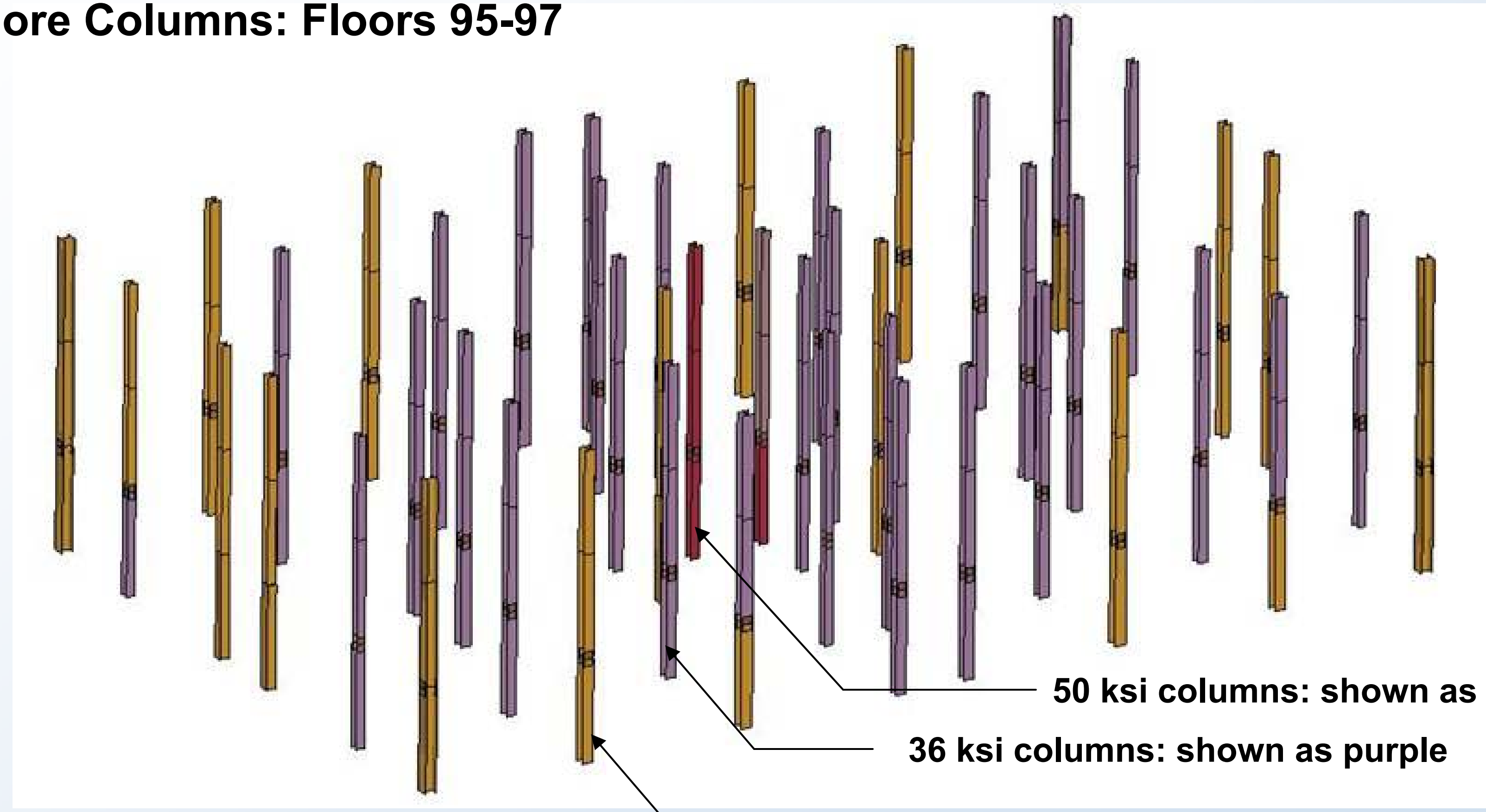
Global Model Development

Core Columns: Floors 95-97



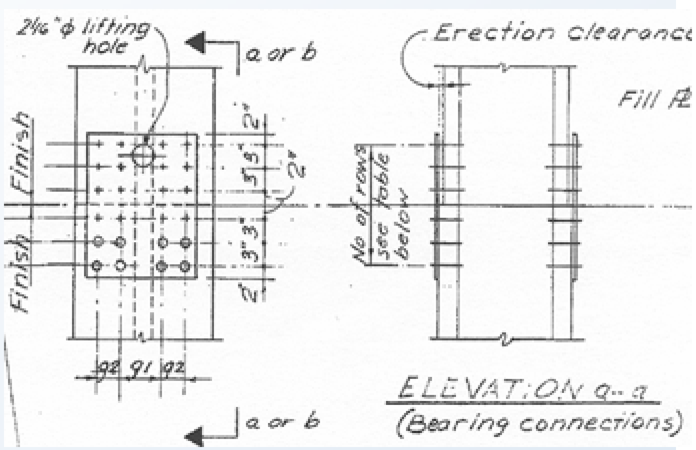
50 ksi columns: shown as red

36 ksi columns: shown as purple

42 ksi columns: shown as orange

Global Model Development

- Wide Flange to Wide Flange Splice
  - Connection modeled with tied interface between splice plates and column ends



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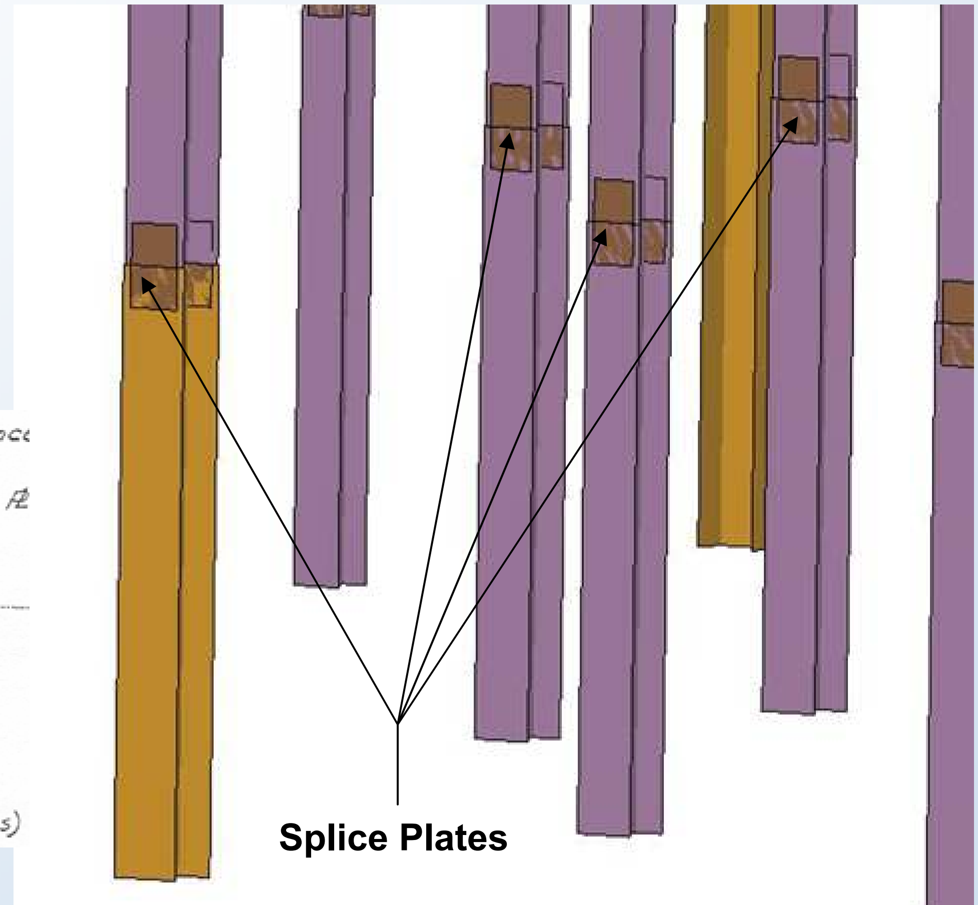
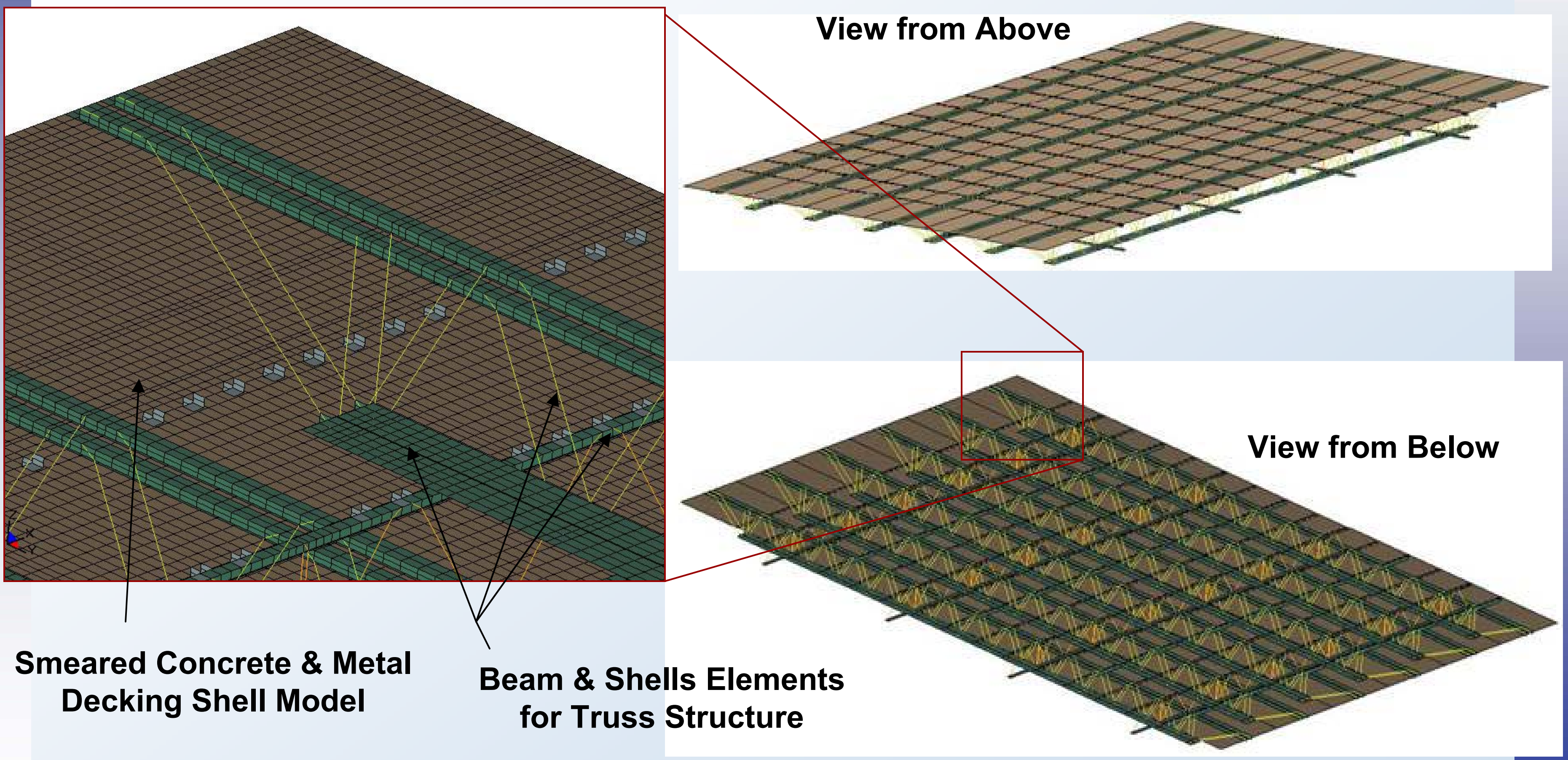


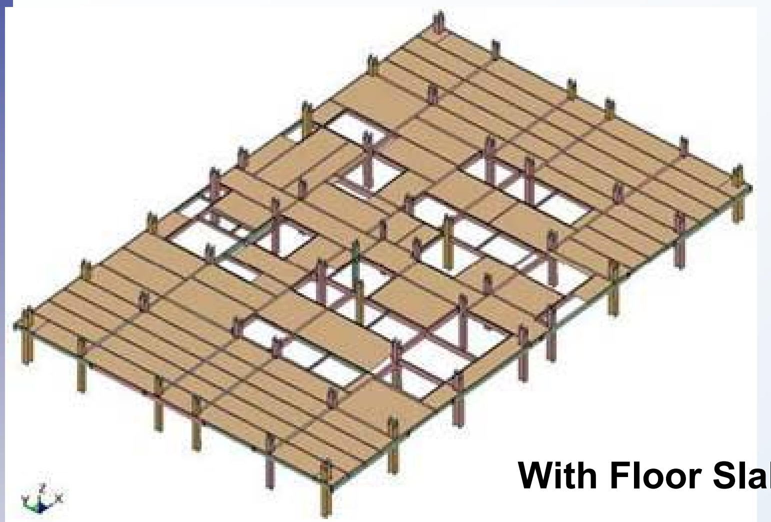
Global Tower Model: Truss Floor

Moderate Resolution Shell Based Model

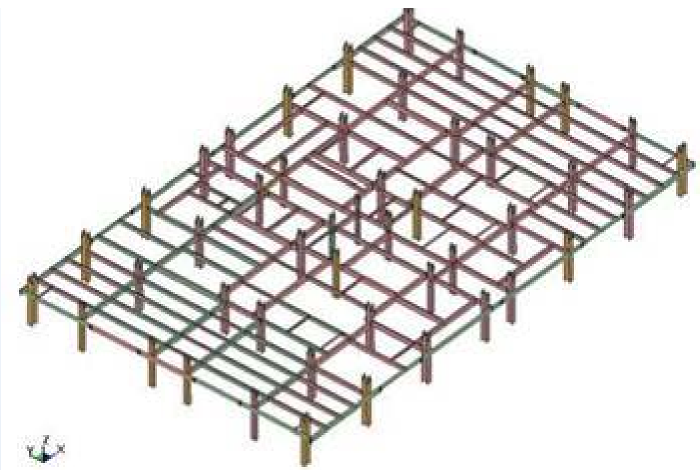


Global Tower Model: Core

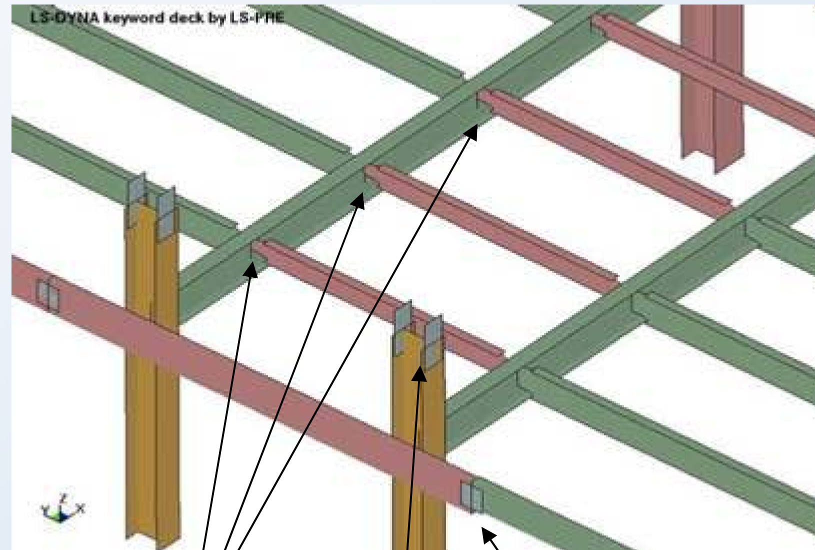
Core Floor Structure for 96th Floor



With Floor Slab



Without Floor Slab

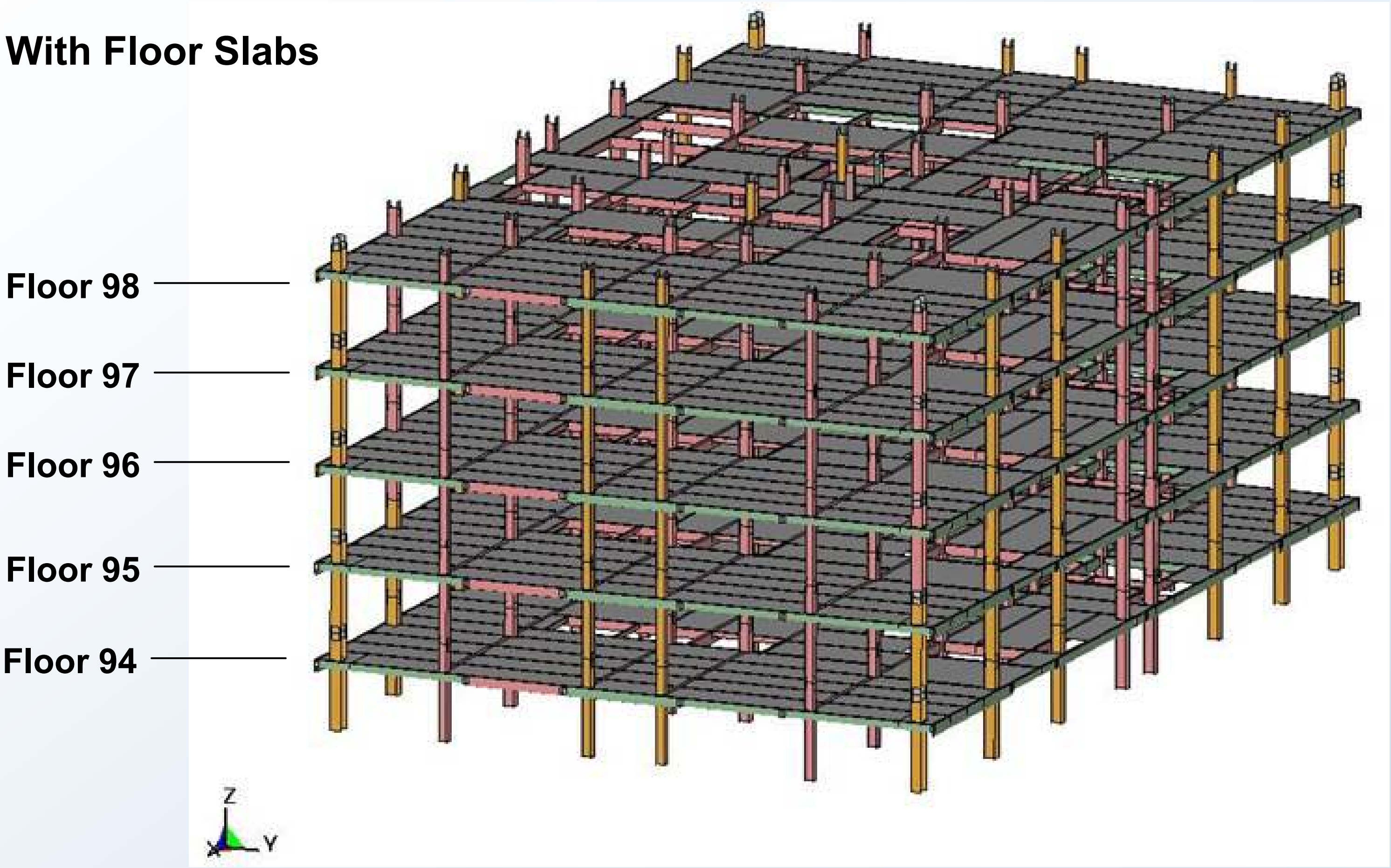


Node-to-Surface Tied Interface at Floor Beam Connections

Splice Plates at Column Connections

Perimeter Beams Connected with Splice Plates

Global Tower Model: Core



Note: Different Colors Correspond to Different Material Assignments

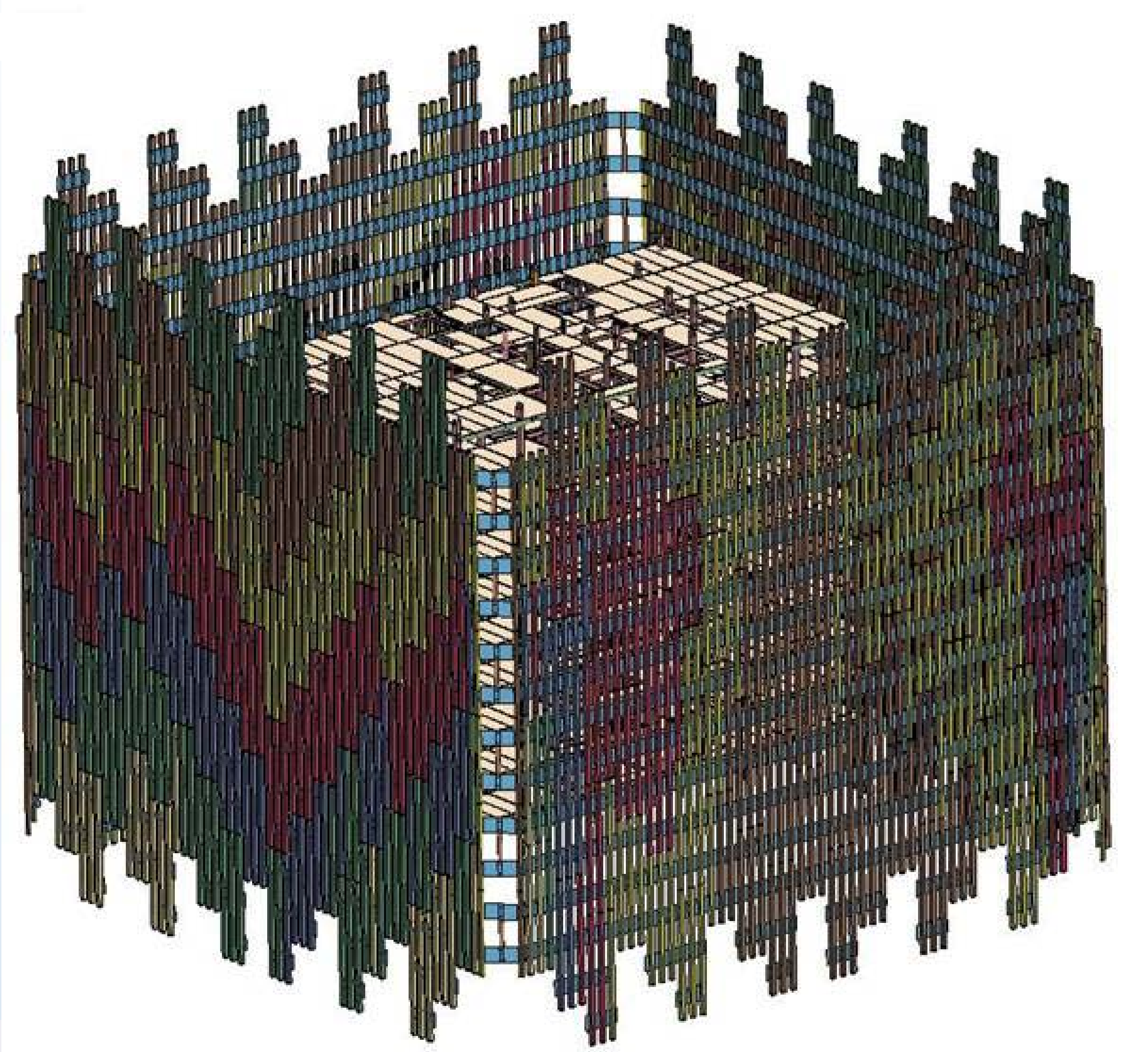
Global Tower Model

WTC 1 Tower Model

- Core & Exterior Assembled

Floors 90-101

- Impact zone plus extra floors above and below

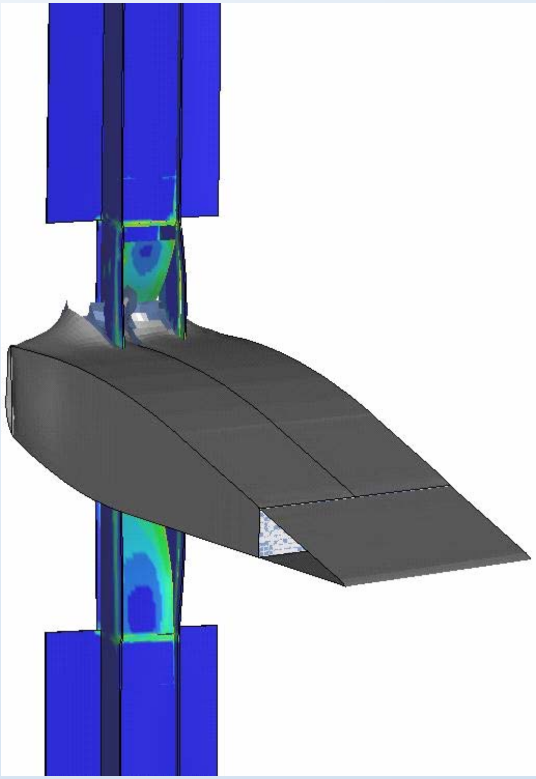


Note: Different Colors Correspond to Different Material Assignments

NIST

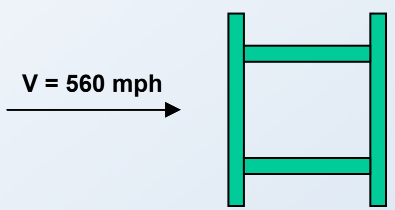
Component Level Analysis

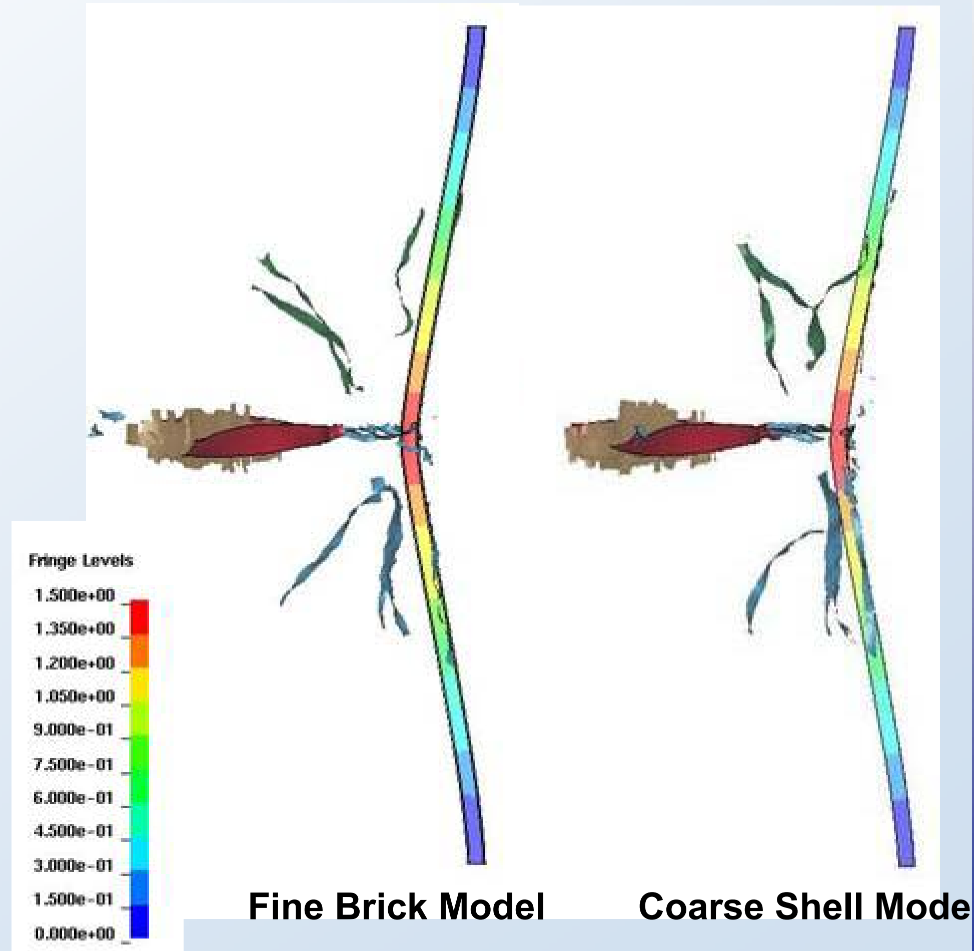
- Exterior and interior column impacted by aircraft engine
- Exterior column impacted separately by:
  - Segment of an aircraft wing
  - Model of aircraft fuel tanks filled with fuel
- Analyses include
  - Highly-detailed finite element models considering possible dynamic plastic fracture criteria of materials
  - Coarser finite element models similar to those used in the global analyses



Box Core Column Impact

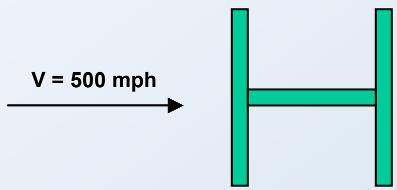
- Modeling Considerations
  - Column 801B, floors 77-80 modeled
  - Impactor: wing section with fuel
    - Standard fuel density
    - 560 mph impact
    - Impact on flange side
  - Boundary conditions: fixing ends of long column

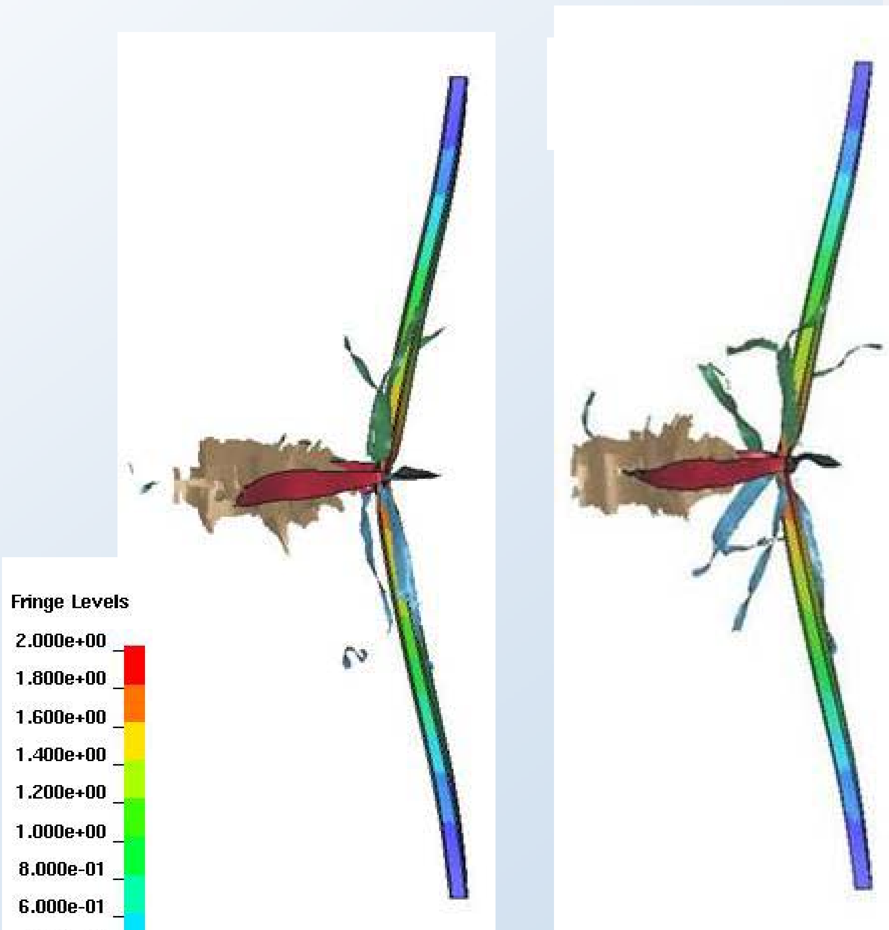




Wide Flange Core Column

- Modeling Considerations
  - Column 503A, floors 95-98 modeled
  - Impactor: Wing section with fuel
    - Double the fuel density to promote more damage
    - 500 mph impact
    - Impact on flange side
  - Boundary conditions: fixing ends of long column

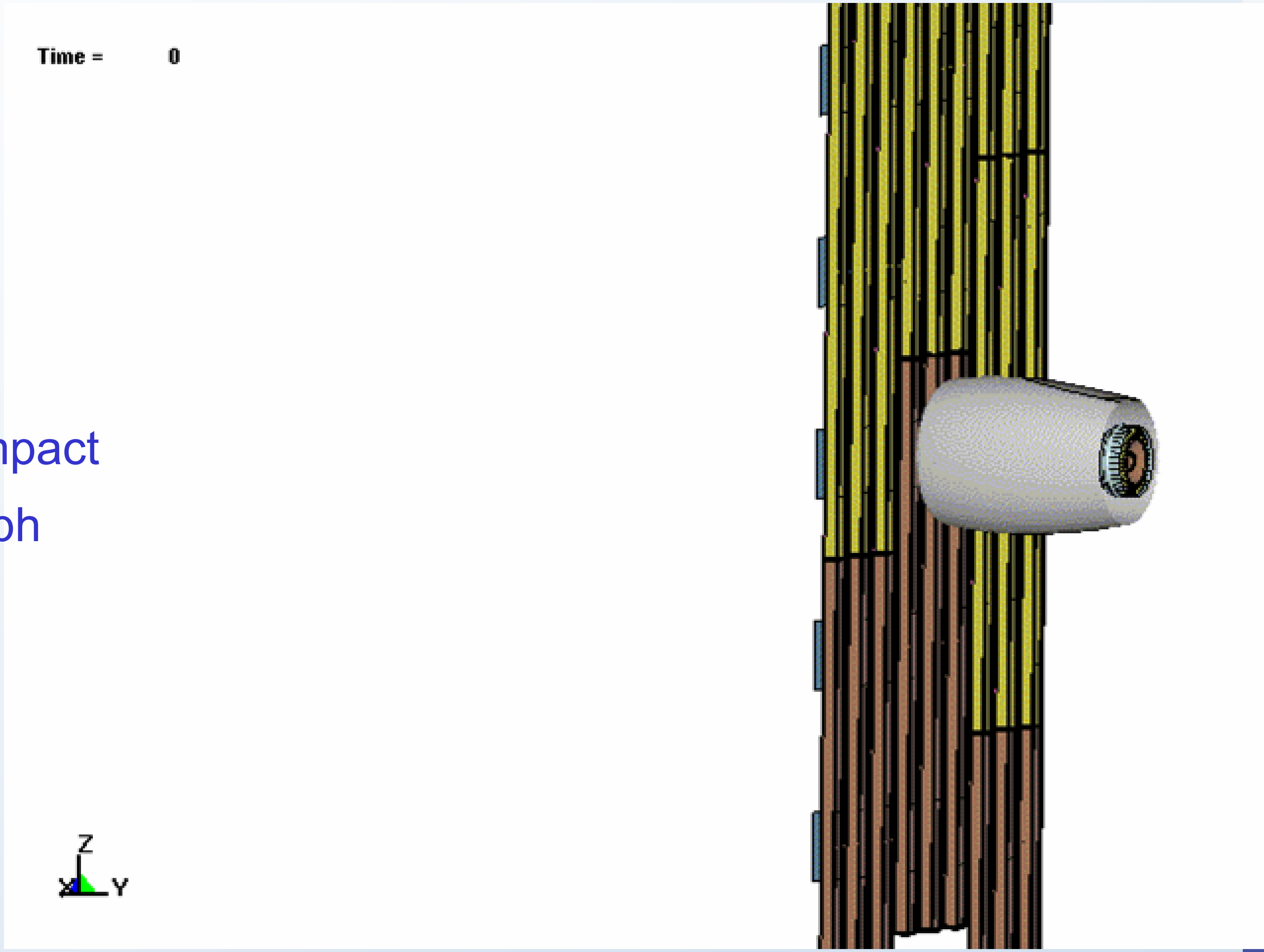




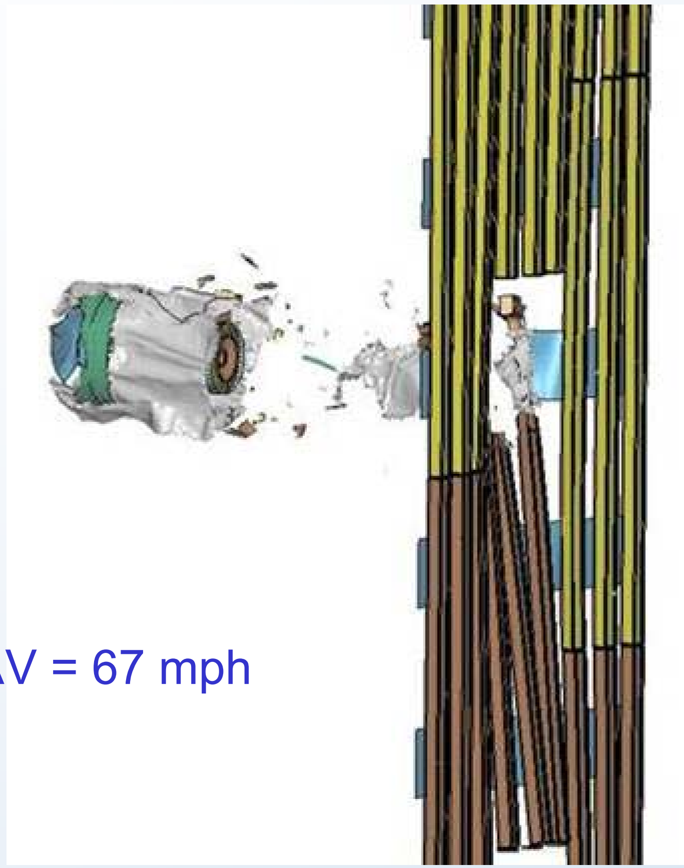
Fine Brick Model Coarse Shell Model

Engine Impact on an Exterior Wall

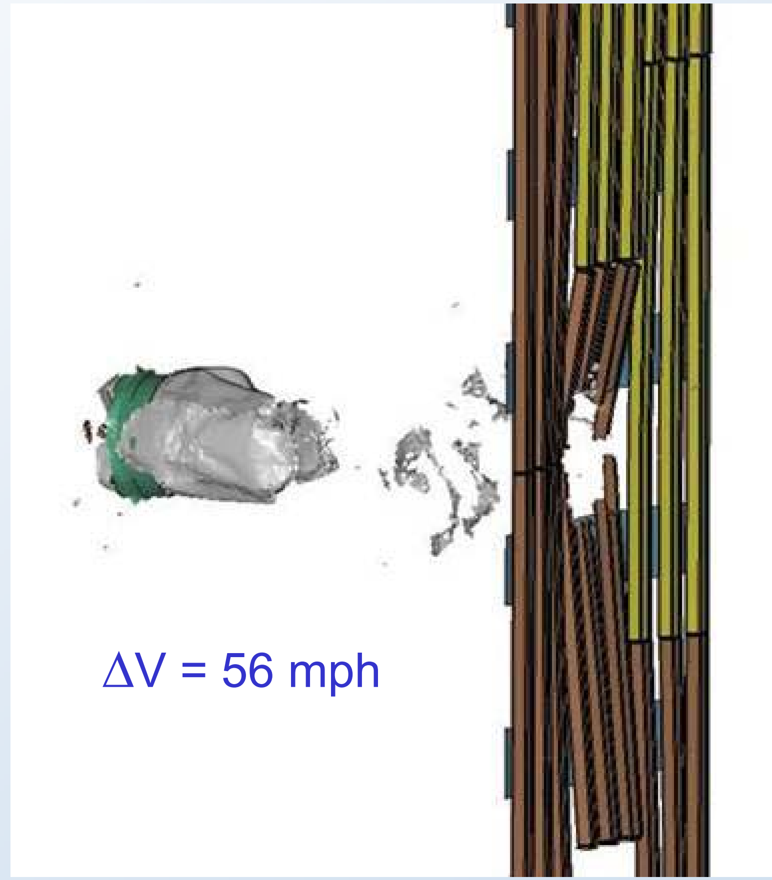
- Three panels wide
- Spandrel centered impact
- Impact speed 500 mph



Engine Impact on an Exterior Wall



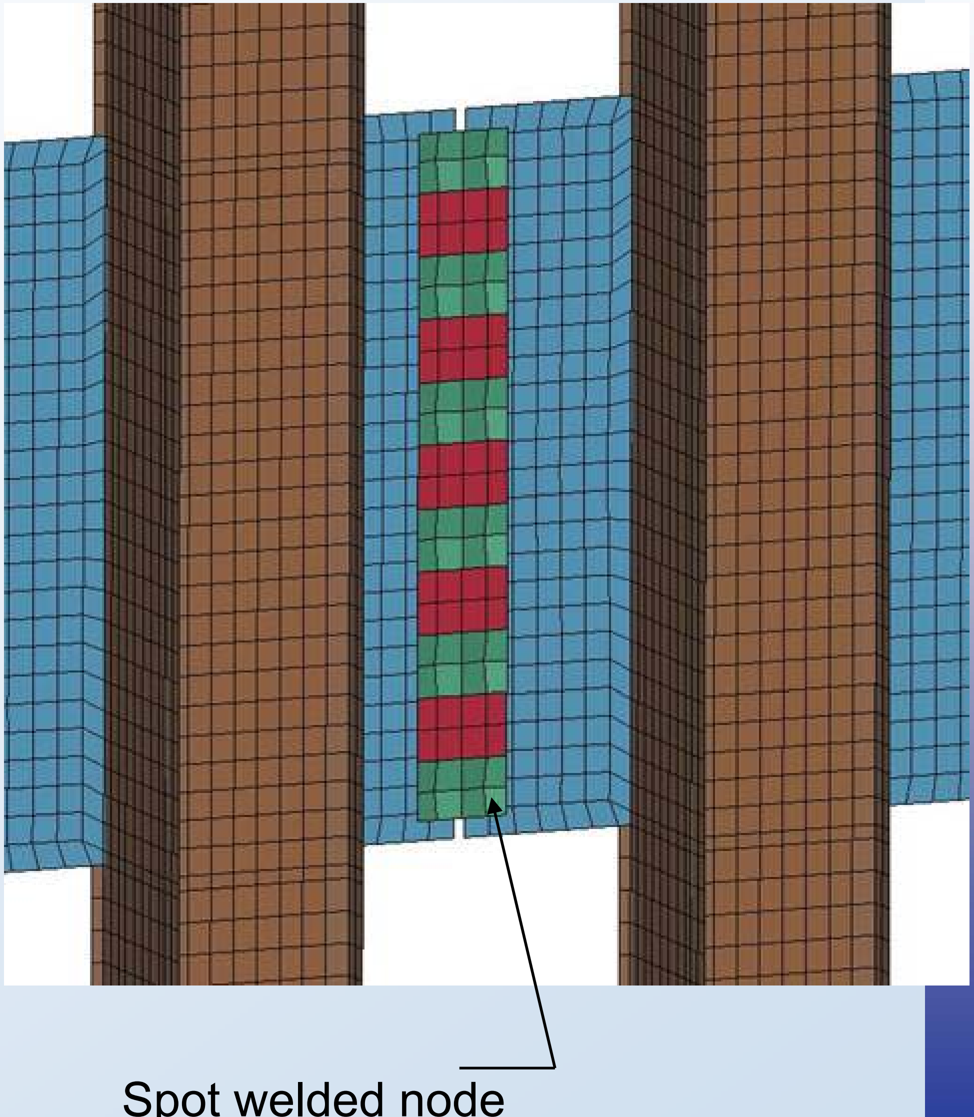
Spandrel Centered Impact



Between Spandrel Impact

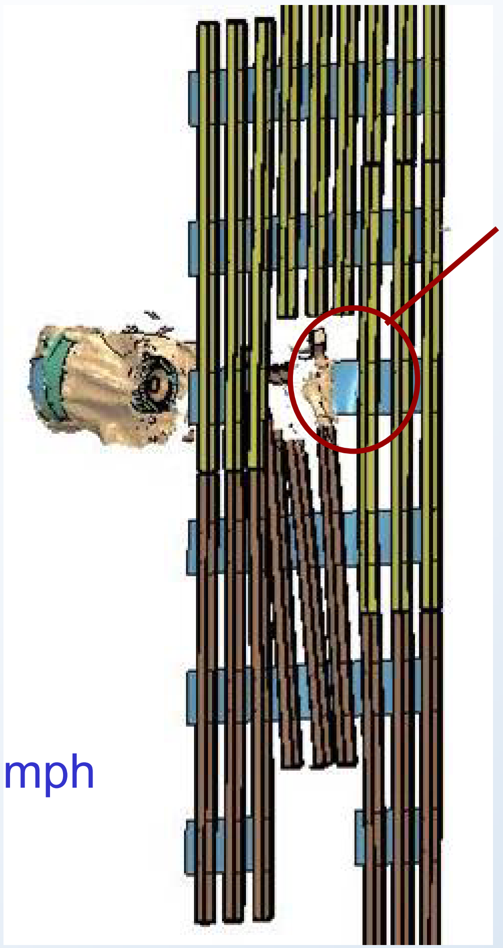
Spandrel Splice Plate Model

- Plates are connected to spandrels with spot weld tied nodes
  - ❑ LS-DYNA tied interface type 7
  - ❑ Spot weld approximates bolted connection
    - Material failure severs joint, not interface failure
- Two materials make up the plate (red & green)
  - ❑ Identical material specification but different material #
    - Done for contact stability



Spandrel Splice Plate Model

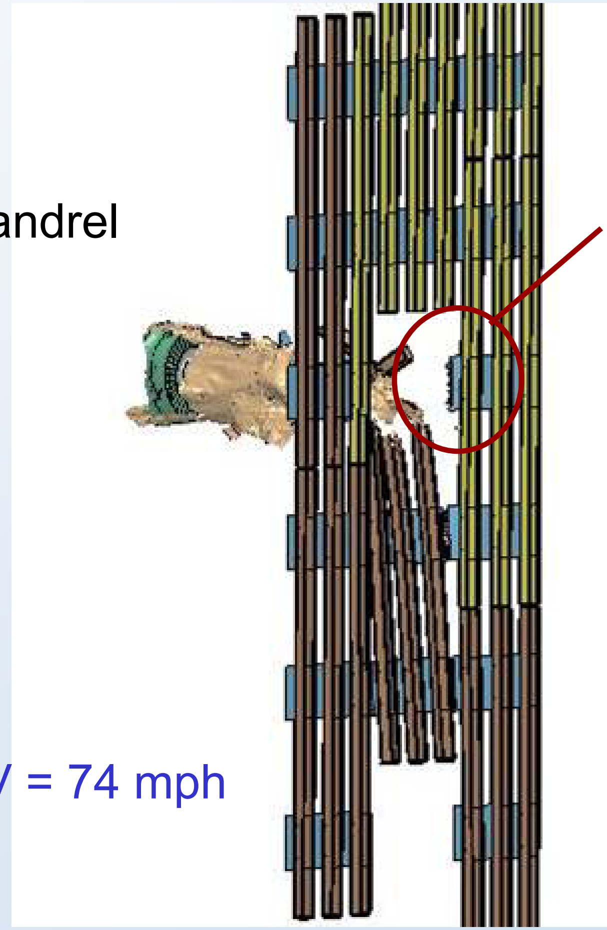
Connection: Merged Spandrels



No Spandrel failure

ΔV = 67 mph

Spandrels Plates

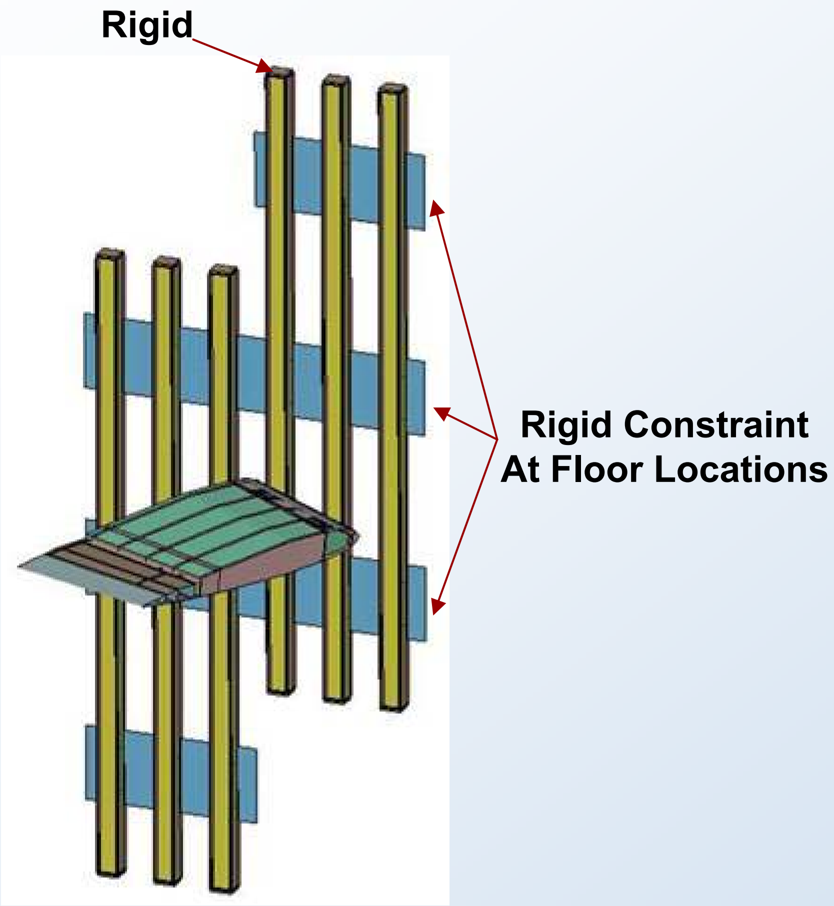


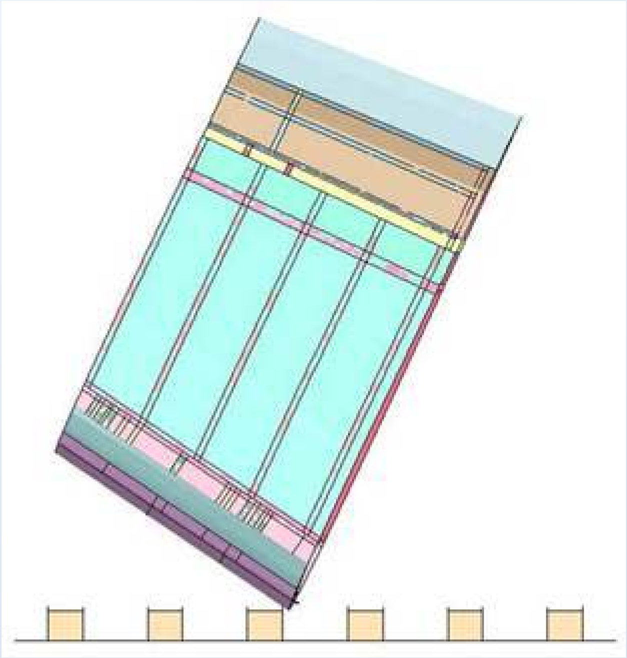
Spandrel plate failure

ΔV = 74 mph

t = 50 ms

Wing Segment Component Analysis





Top View

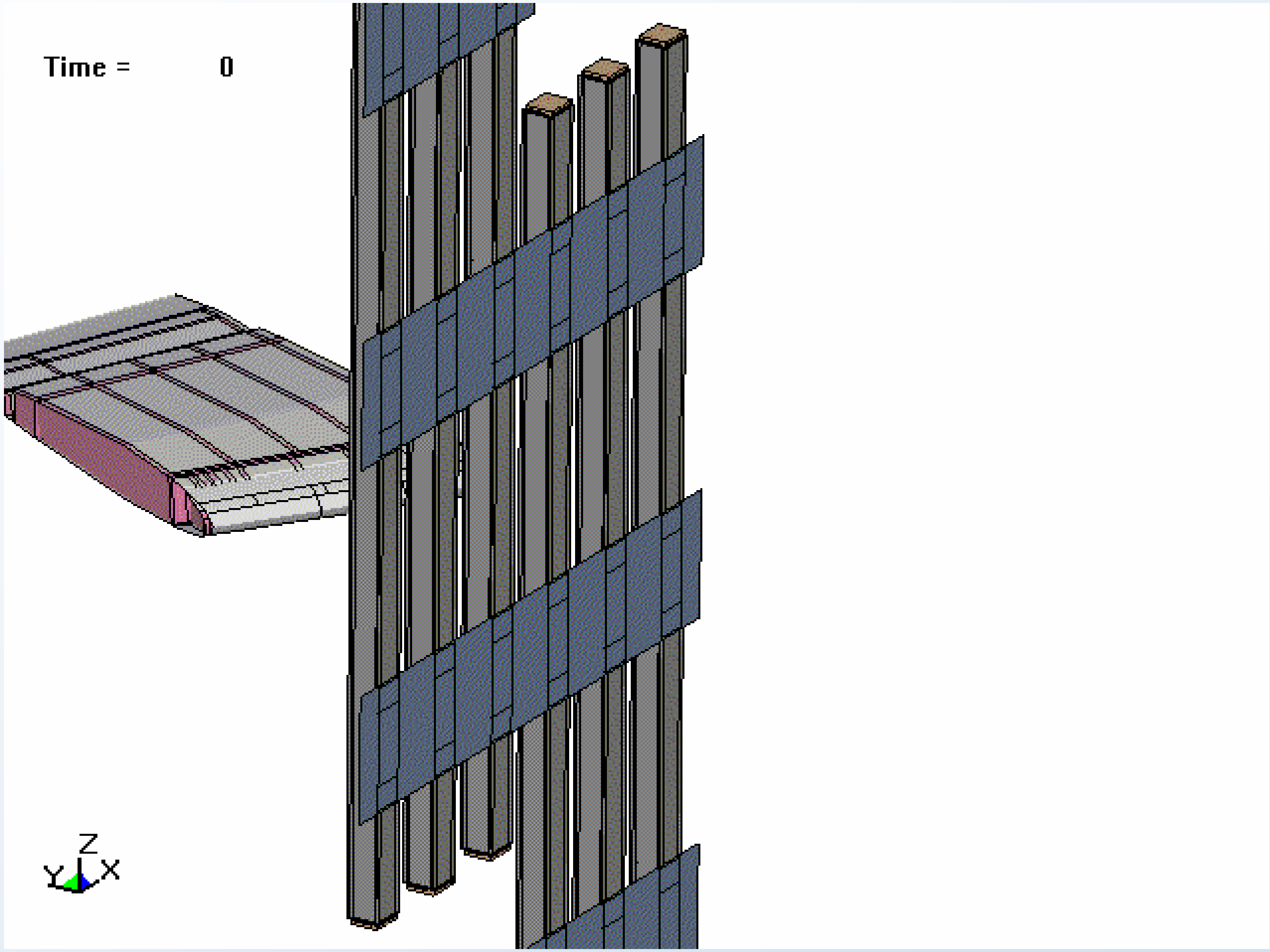
Treatment of Aircraft Fuel

- Fluid Structure Interaction (FSI) is difficult to model with traditional computational methods and requires special analysis techniques.
- FSI approach needs to capture:
  - ❑ Primary inertial effects of fuel impacting structural members
  - ❑ Secondary fuel dispersion
- 3 options for this analysis:
  - ❑ Arbitrary Lagrangian-Eularian (ALE)
  - ❑ Smoothed Particle Hydrodynamics (SPH)
  - ❑ Lagrangian analysis with erosion (traditional approach)
    - Cannot solve fuel motions after initial impact.

Fuel Analysis Methodologies

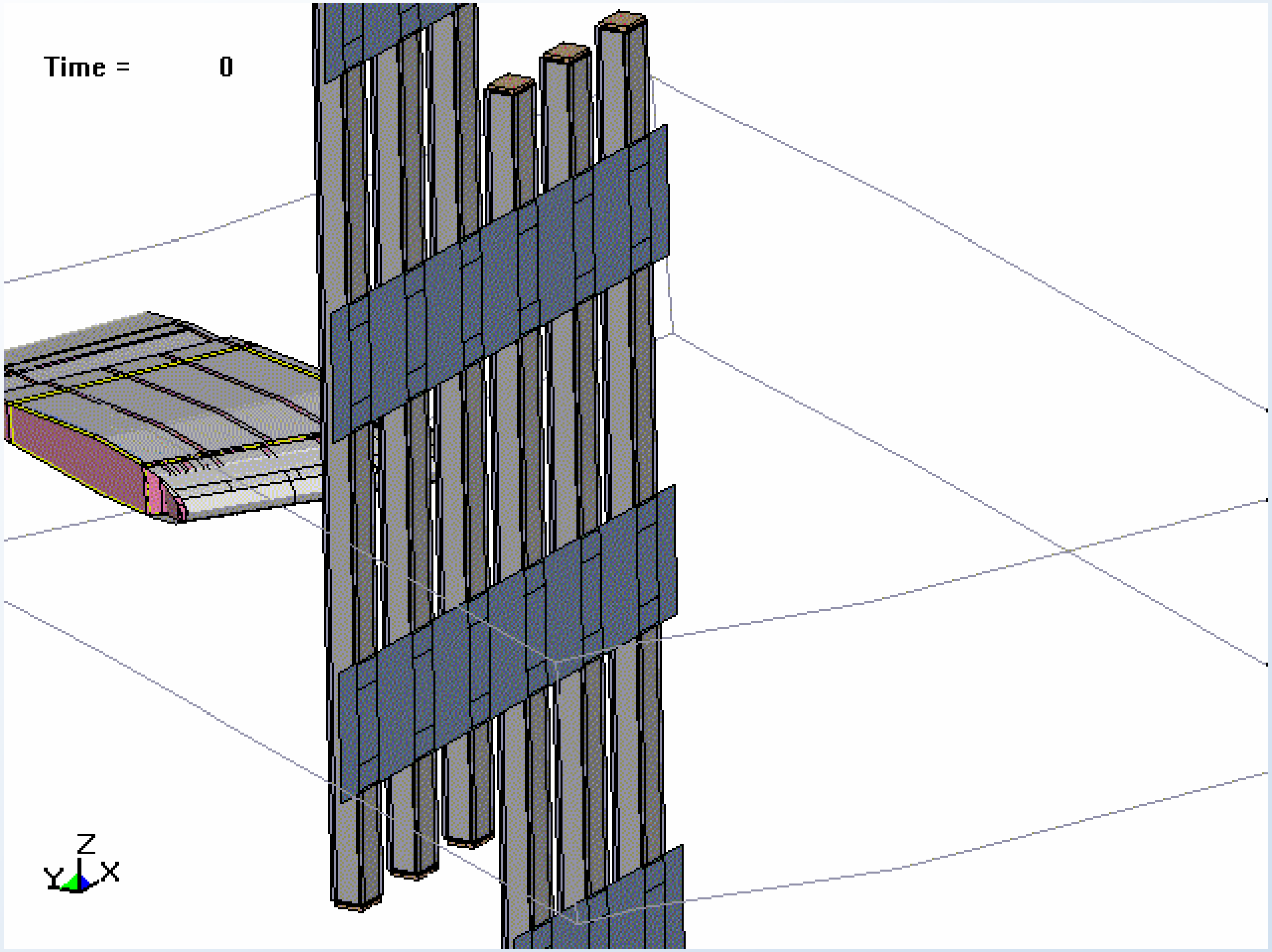
- ALE - Eulerian treatment of fuel with Lagrangian structural components.
  - ❑ Fluid motion represented with Euler equations (inviscid Navier-Stokes).
    - Potential for very accurate analysis.
  - ❑ Large meshes are required for ALE fuel modeling.
    - Longer run times are required.
- SPH - Mesh-Free model of fuel with Lagrangian structural components.
  - ❑ Smaller mesh is required: shorter run time.
  - ❑ SPH well suited for debris cloud calculations.
    - Less accurate fluid flow analysis.

Wing Segment without Fuel
V = 500 mph



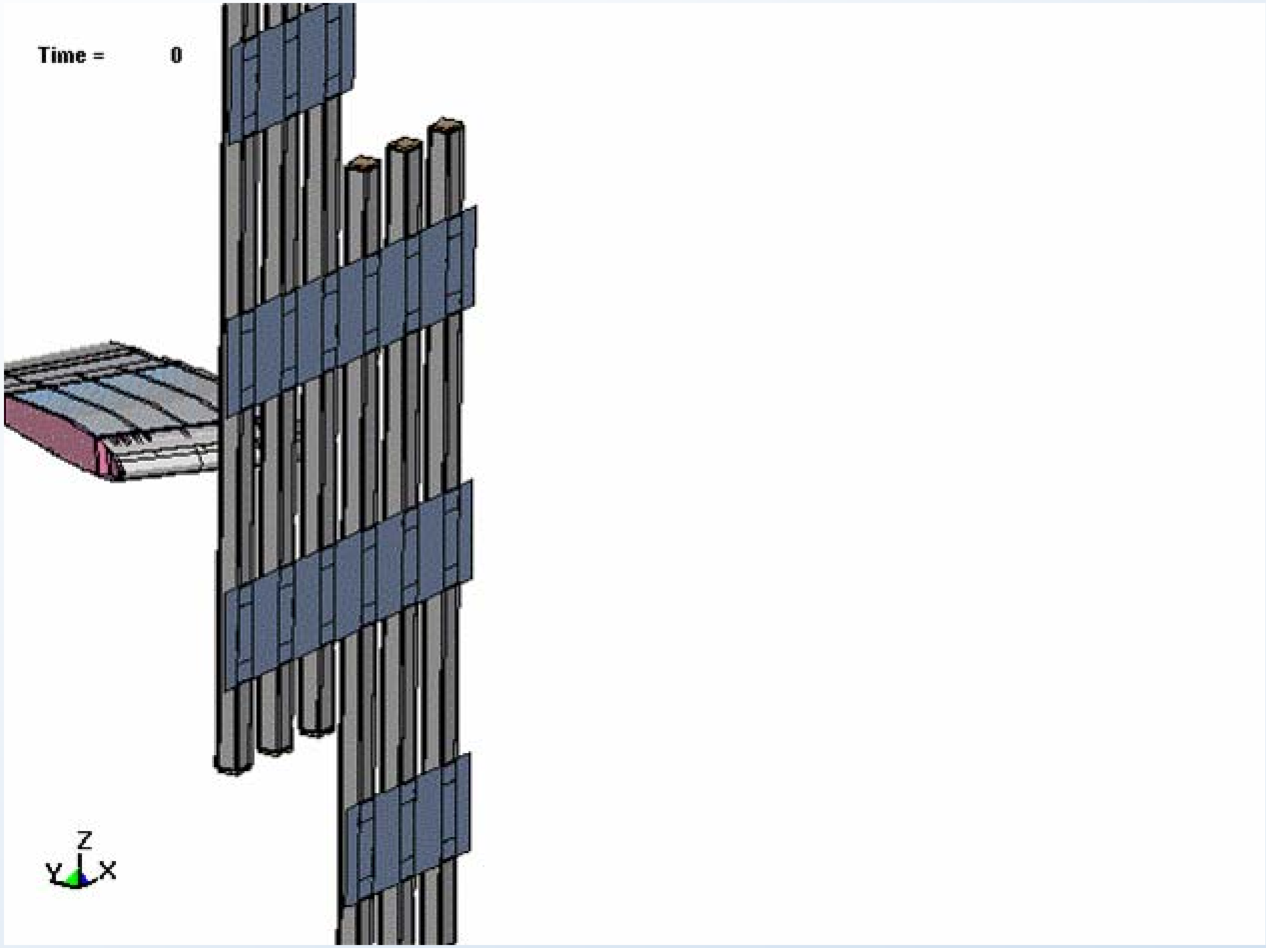
Wing Segment with Fuel (ALE)

V = 500 mph

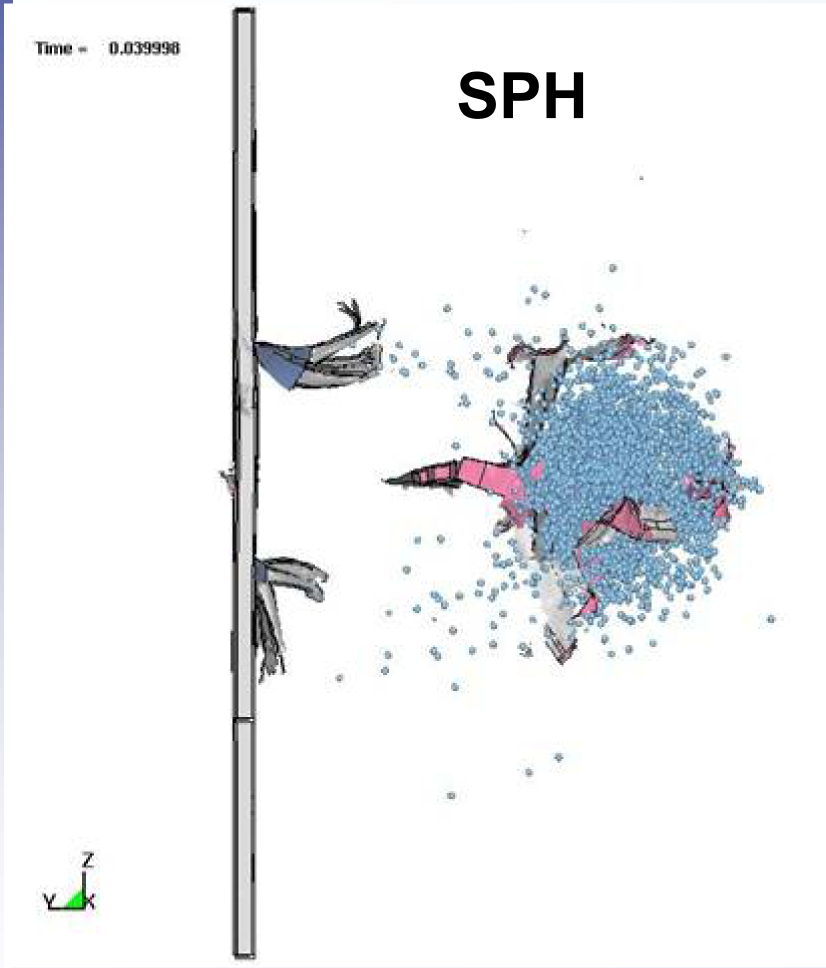


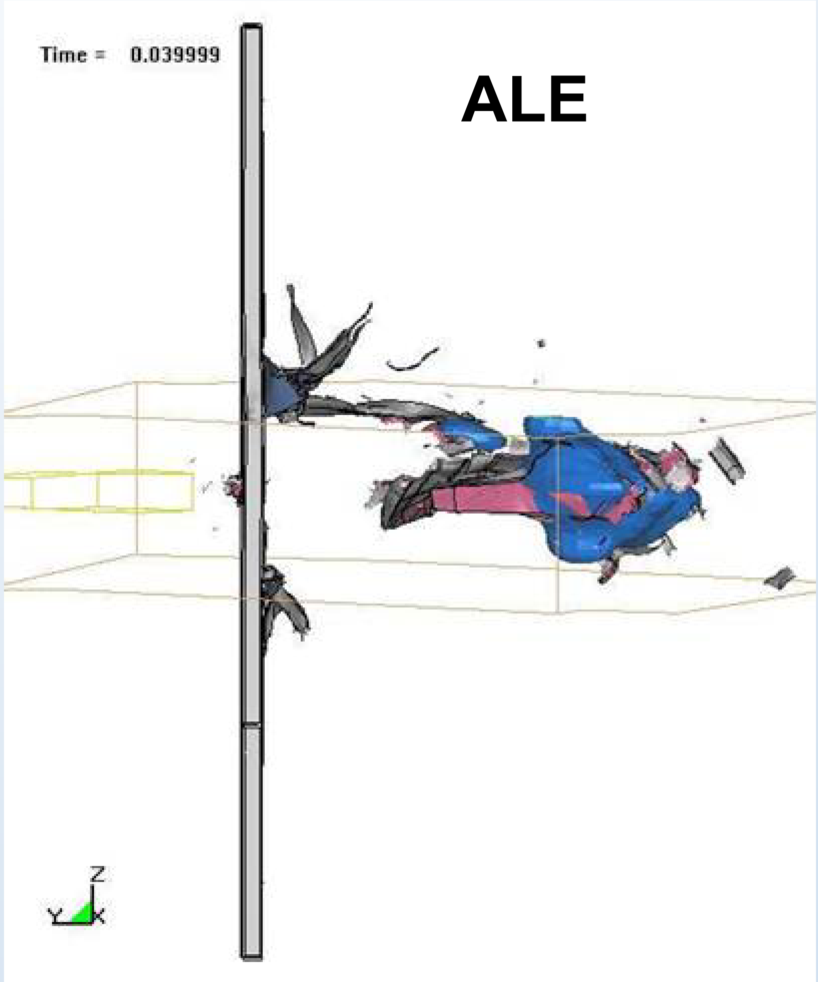
Wing Segment with SPH Fuel

V = 500 mph

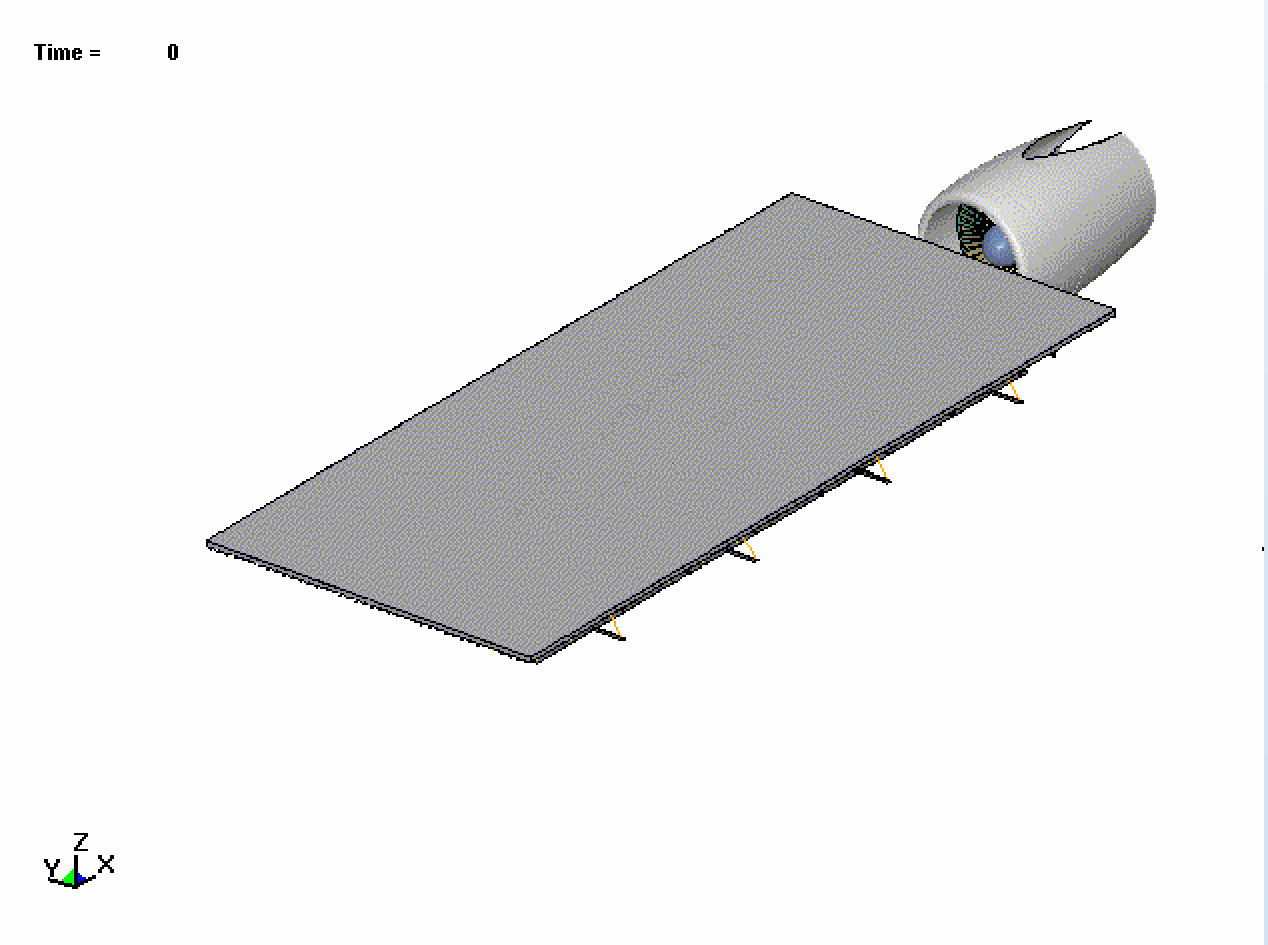


Wing Segment with Fuel Comparison
V = 500 mph



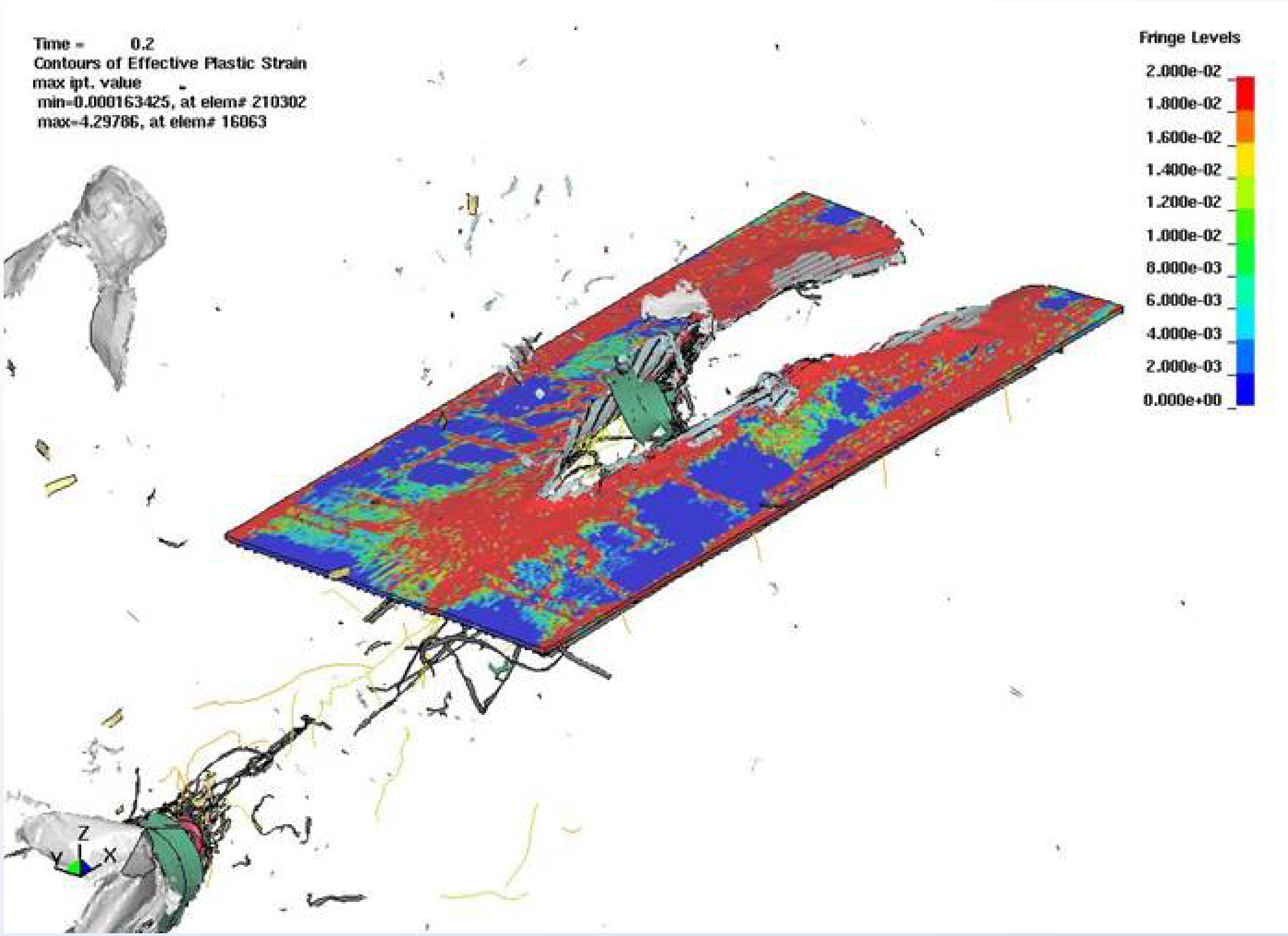


Floor Section Analysis



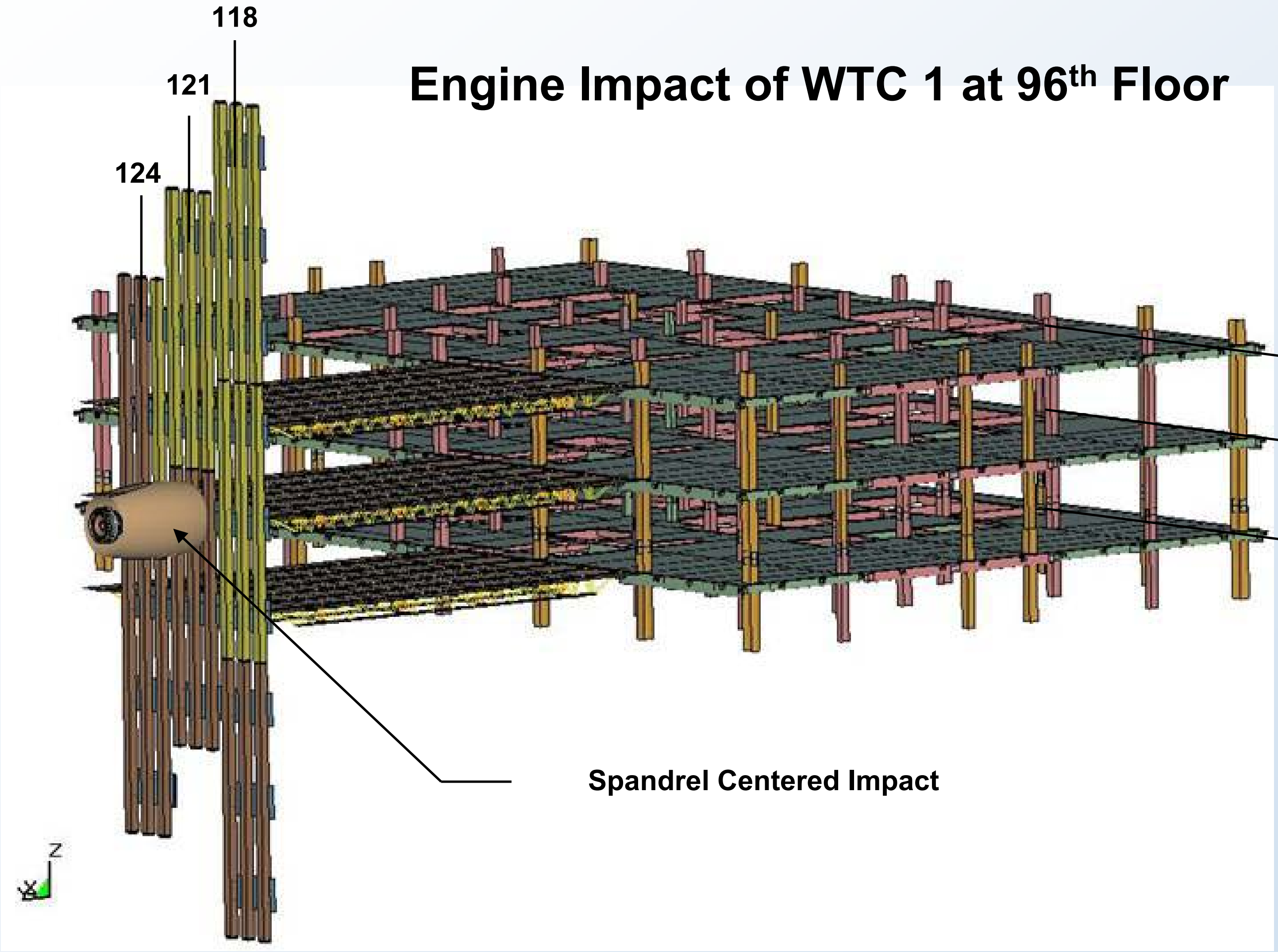
Fine Brick Element Floor Section Model

Floor Section Analysis



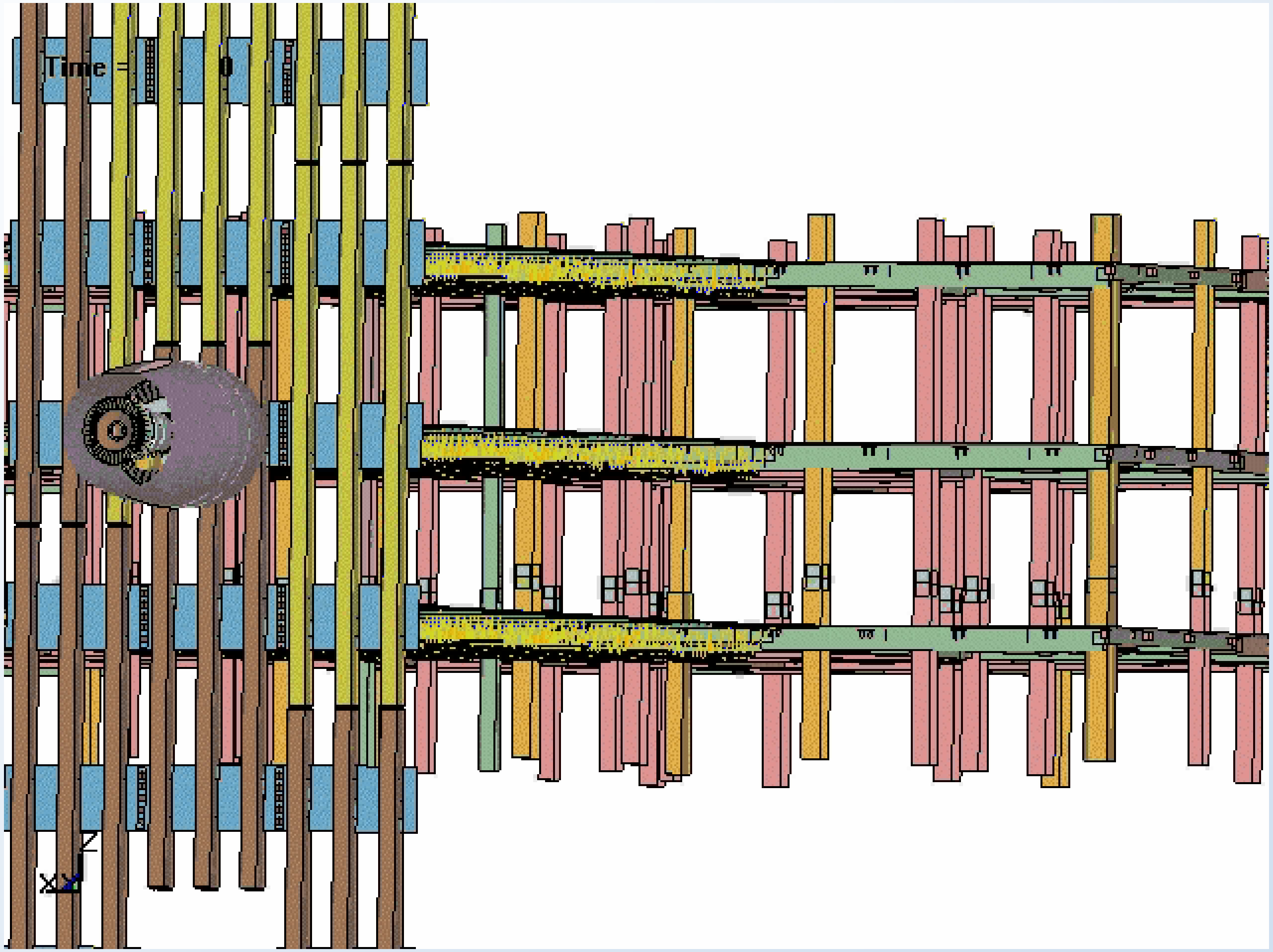
Fine Brick Element Floor Section Model

Subassembly Modeling



Subassembly Modeling

Animation View 1: perspective from outside and to side



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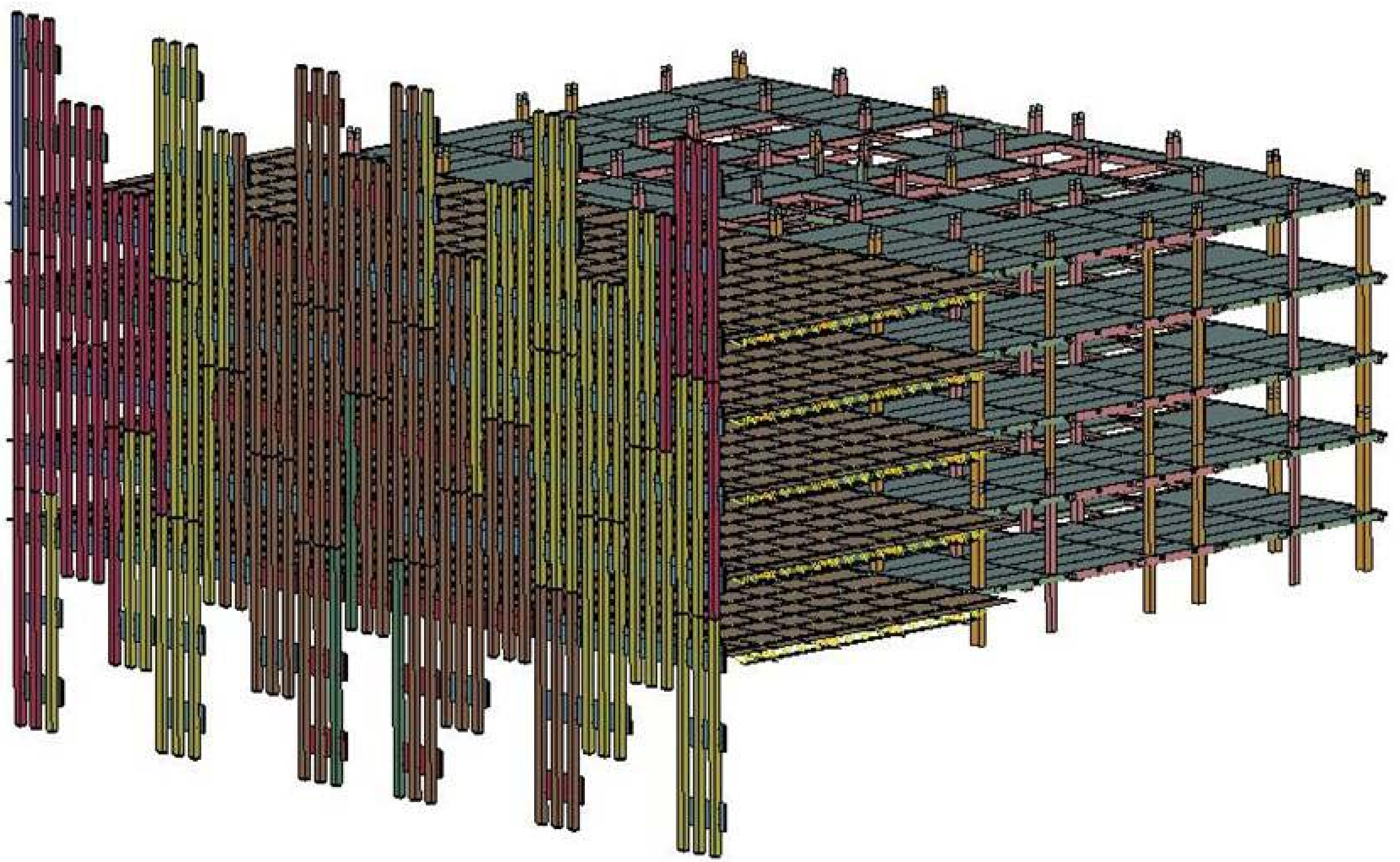
Global Analysis



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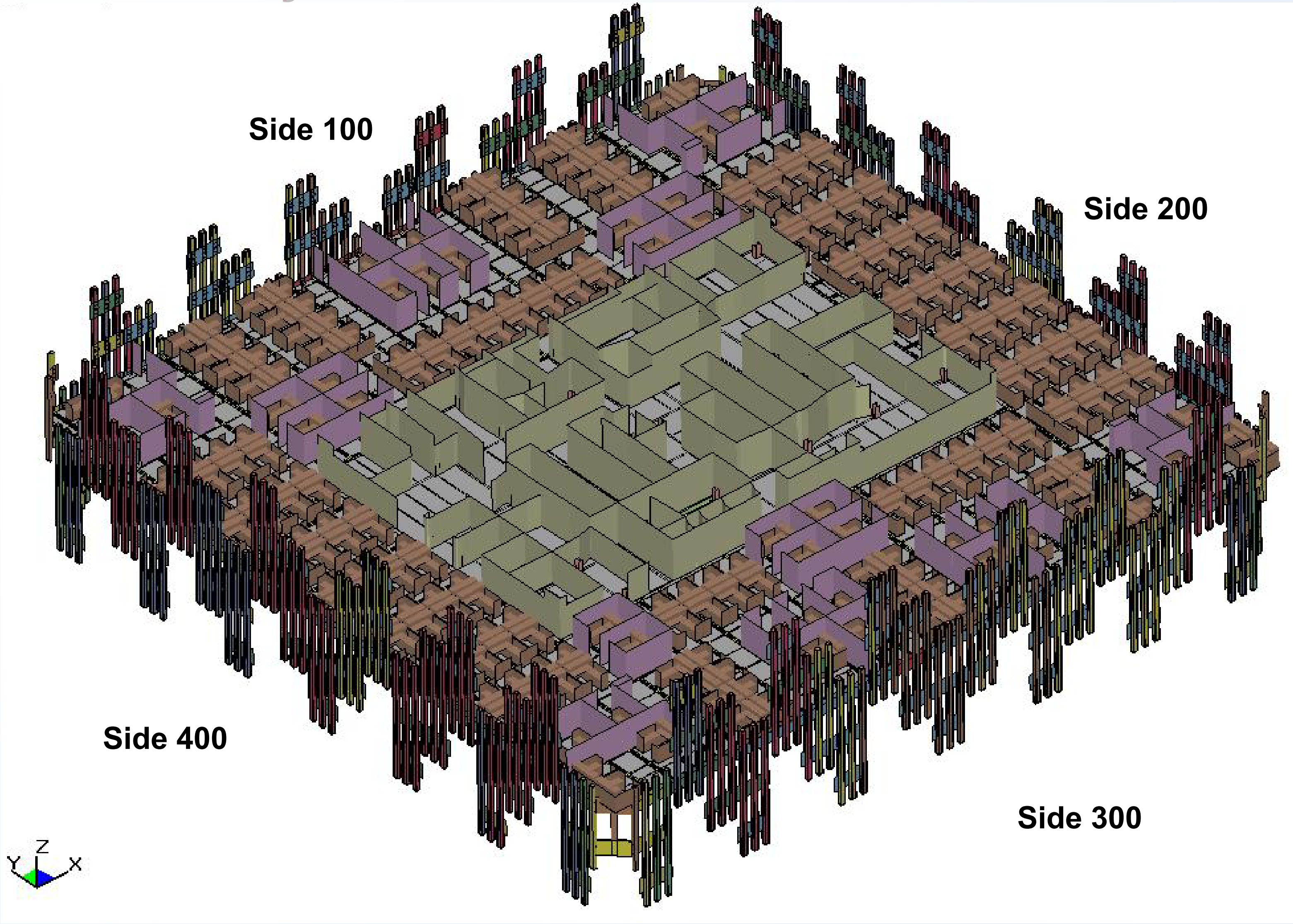
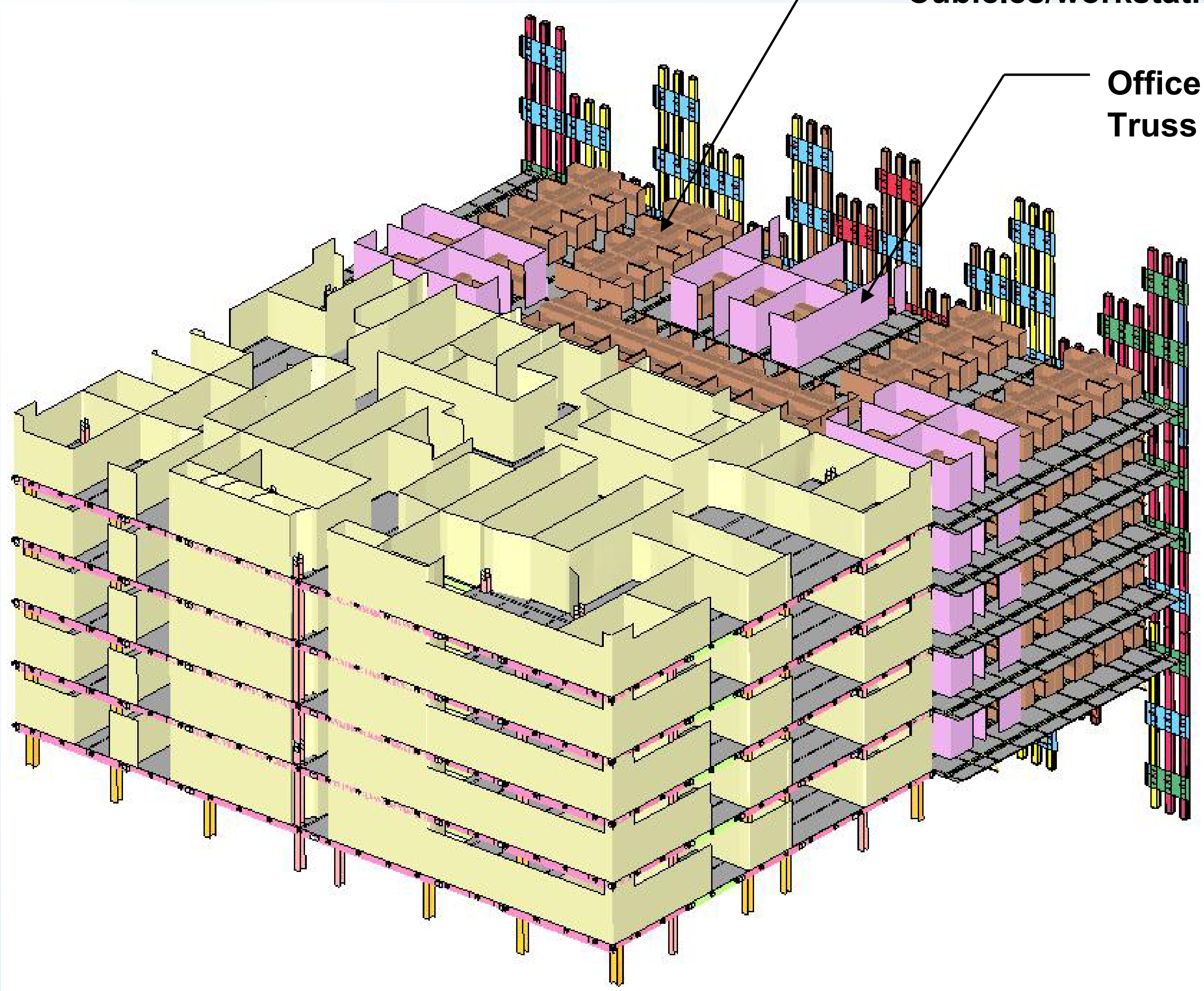
Global Analysis

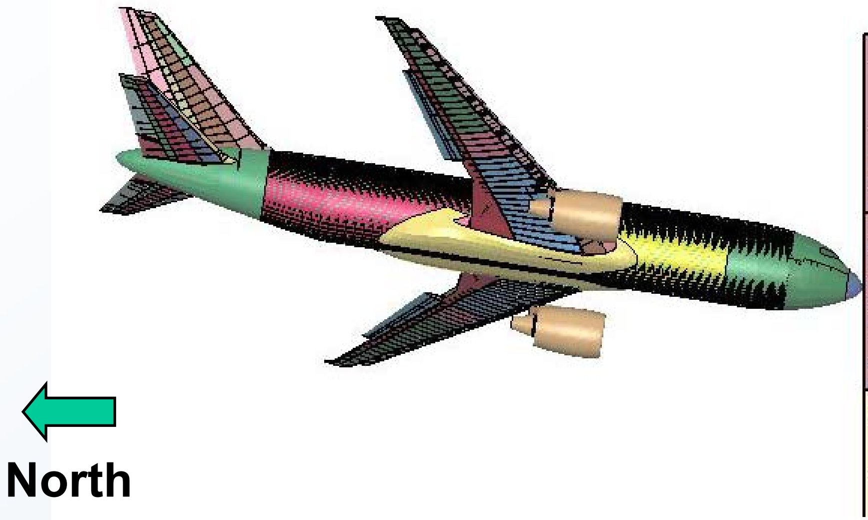


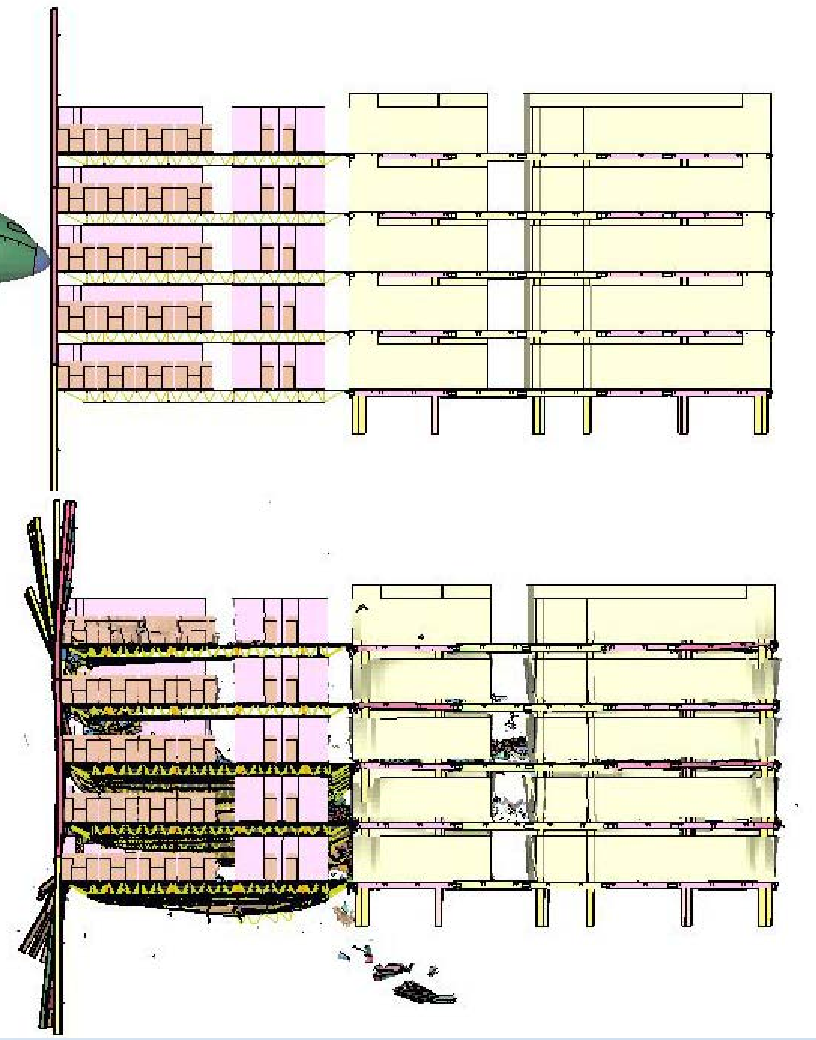
Partitions, workstations, and cubicles added throughout floor area

Global Analysis



Aircraft Impact into WTC 1





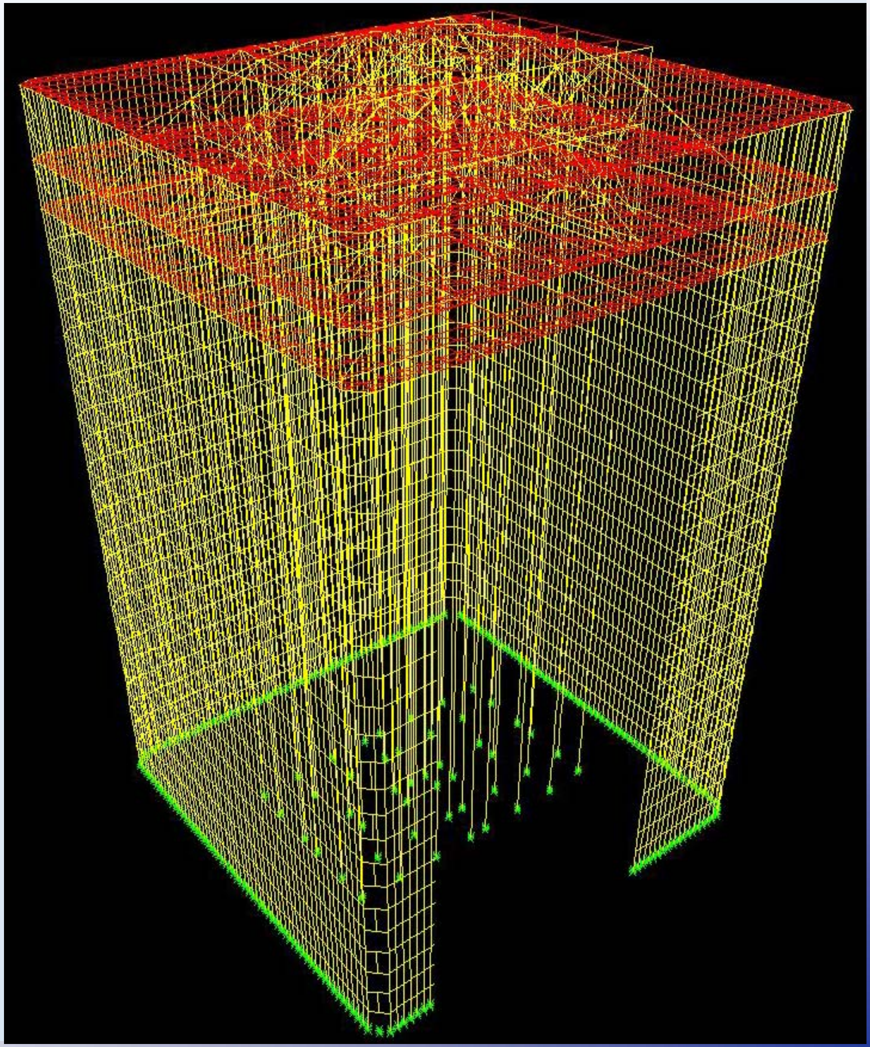
Global impact analysis of WTC 1 and 2 is ongoing

Preliminary Stability Analysis of the Towers

- Objectives
  - ❑ Examine the overall stability of the towers when floors are removed
  - ❑ Study the load redistribution mechanisms when core columns are destroyed by aircraft impact
  - ❑ Study the response of WTC 1 when columns and spandrels in the exterior walls and columns in the core are destroyed by aircraft impact, and columns in the exterior are damaged due to the subsequent fires, as observed in photographs and videos.

Reduced Global Model of WTC 1

- Steel yield and ultimate strengths adjusted based on Project 3 results.
- Structure below the 84th floor of WTC 1 removed and represented by equivalent vertical springs.
- Gravity loads represent service conditions and are estimated from detailed floor models.



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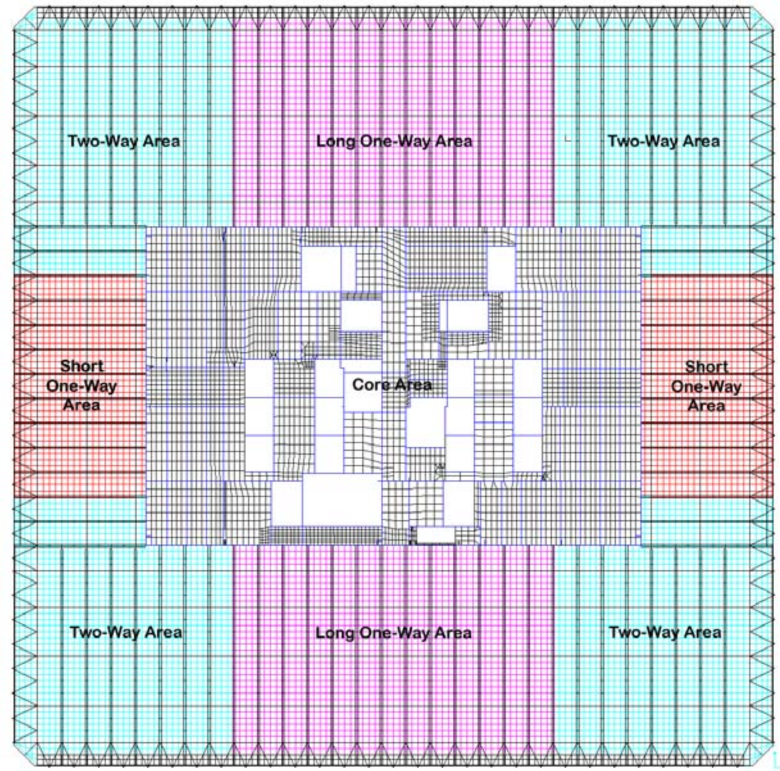
WTC Tower Model Loads



- Applied Loads:
  - ❑ Full dead load, superimposed dead load (SDL), and antenna load.
  - ❑ 25% of design live load.
- Loads varied with location.
  - ❑ Large variation in core area.
- Loads based on reactions from detailed SAP2000 floor models:
  - ❑ Typical floors (85 to 106) from model of WTC 1, floor 96.
  - ❑ Other floors (107 to 110 and roof) from tabulated design loads applied to model of WTC 1 floor 96.

Staged Construction

- Used to eliminate unrealistic loads in hat truss region due to stiffness differences between core and exterior wall.
  - Approximates the method used during construction to limit differential vertical deformations.
- Three construction stages:
  1. Floors below hat truss
     - Floors up to 106
     - Dead load and SDL applied
  2. Hat truss
     - Floors 107 through roof
     - Dead load and SDL applied to new members
  3. Remaining loads applied
     - Live load on all members
     - Antenna load on roof

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Eigenvalue Buckling Analysis

- The linear stability analysis examines the stability of the undamaged tower under **service loads** through floor removal (increased unbraced column lengths) in the absence of material nonlinearities.
- Results for intact WTC 1 (no damage, no reduction in stiffness):
  - The tower was stable when **2 floors** were removed.
  - Two core columns buckled (704, 705) when **3 floors** were removed, but the tower maintained its overall stability.
  - Two additional core columns buckled (601, 608) when **4 floors** were removed, but the tower maintained its overall stability.
  - Global instability of the tower occurred when **5 floors** were removed.
- Assuming that all columns at the region of removed floors reached a temperature of 600ºC (0.74E), the analysis indicated that removal of four floors would induce global instability.

Redistribution of Forces within the Core

- When columns are severed in the core, the possible load redistribution mechanisms include:
  - load redistribution to neighboring core columns through the floor,
  - load redistribution to the hat truss through tensile loads on affected core columns, or
  - a combination of both.
- A two-step approach was used:
  - The 96th floor model was analyzed with severed core columns replaced by equivalent vertical springs, representing the combined stiffness of the columns above, and hat truss. The analysis estimated what portion of the load would be redistributed as forces in the springs to the hat truss, and what portion would be redistributed to neighboring columns through the floor system.
  - The tensile capacities of the core column splices between the affected floors and the hat trusses were estimated to determine if the columns could carry the calculated tensile loads.

Redistribution of Forces within the Core

- If 15 columns are assumed severed in the core:

Column Number	Floor 98 Column Load kips (kN)	Floor 98 Load to Capacity Ratio	Floor 101 Column Load kips (kN)	Floor 101 Load to Capacity Ratio	Floor 104 Column Load kips (kN)	Floor 104 Load to Capacity Ratio	Floor 106 Column Load kips (kN)	Floor 106 Load to Capacity Ratio
503	109.3 (486)	0.21	273.2 (1215)	0.72	437.1 (1944)	***1.15***	546.3 (2430)	***1.58***
504	82.8 (368)	0.22	207.0 (921)	0.54	331.2 (1473)	***1.30***	414.0 (1841)	***1.20***
505	92.7 (412)	0.24	231.8 (1031)	0.61	370.9 (1650)	***1.46***	463.6 (2062)	***1.34***
506	214.7 (955)	0.41	375.7 (1671)	0.98	536.7 (2387)	***1.41***	644.0 (2865)	***1.86***
603	64.6 (287)	0.25	161.5 (718)	0.63	258.4 (1149)	***1.02***	323.0 (1437)	0.93
604	57.5 (256)	0.23	143.8 (640)	0.57	230.1 (1024)	0.90	287.7 (1280)	0.83
605	72.3 (321)	0.28	180.7 (804)	0.71	289.1 (1286)	***1.14***	361.3 (1607)	***1.04***
606	138.7 (617)	0.55	242.8 (1080)	0.95	346.9 (1543)	***1.36***	416.2 (1851)	***1.20***
703	39.1 (174)	0.15	97.8 (435)	0.38	156.5 (696)	0.61	195.6 (870)	0.56
704	20.1 (90)	0.08	50.4 (224)	0.20	80.6 (358)	0.32	100.7 (448)	0.29
705	27.3 (121)	0.11	68.2 (303)	0.27	109.1 (485)	0.43	136.3 (606)	0.39
706	27.2 (121)	0.11	68.0 (303)	0.27	108.9 (484)	0.43	136.1 (605)	0.39
803	24.8 (110)	0.10	62.0 (276)	0.24	99.2 (441)	0.39	124.0 (552)	0.36
804	36.2 (161)	0.14	90.4 (402)	0.36	144.7 (644)	0.57	180.9 (805)	0.52
805	18.9 (84)	0.07	47.1 (210)	0.19	75.4 (335)	0.30	94.3 (419)	0.27

Redistribution of Forces within the Core

- If 8 columns are assumed severed in the core:

	Floor 98		Floor 101		Floor 104		Floor 106	
Column Number	Column Load kips (kN)	L/C Ratio	Column Load kips (kN)	L/C Ratio	Column Load kips (kN)	L/C Ratio	Column Load kips (kN)	L/C Ratio
Loads with all column splices intact								
504	34.7 (154)	0.09	138.9 (618)	0.36	243.1 (1081)	0.96	312.5 (1390)	0.90
505	79.5 (354)	0.21	198.8 (884)	0.52	***318.1 (1415)***	***1.25***	***397.6 (1769)***	***1.15***
604	21.3 (95)	0.08	85.2 (379)	0.33	149.1 (663)	0.59	191.7 (853)	0.55
605	77.0 (343)	0.30	154.0 (685)	0.61	231.0 (1028)	0.91	282.4 (1256)	0.82
703	45.0 (200)	0.18	90.0 (400)	0.35	134.9 (600)	0.53	164.9 (734)	0.48
704	3.6 (16)	0.01	14.3 (64)	0.06	25.1 (112)	0.10	32.2 (143)	0.09
706	21.0 (93)	0.08	36.7 (163)	0.14	52.4 (233)	0.21	62.9 (280)	0.18
903	36.2 (161)	0.09	90.6 (403)	0.36	145.0 (645)	0.57	181.2 (806)	0.52

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Redistribution of Forces within the Core

- If 15 core columns are assumed severed, the floor immediately above the failed columns induces tension in these columns. The tension force increases as more floor loads are picked by the columns. At a certain floor level, the splice fails and all floors below the failed splices must redistribute their loads directly to neighboring undamaged columns.

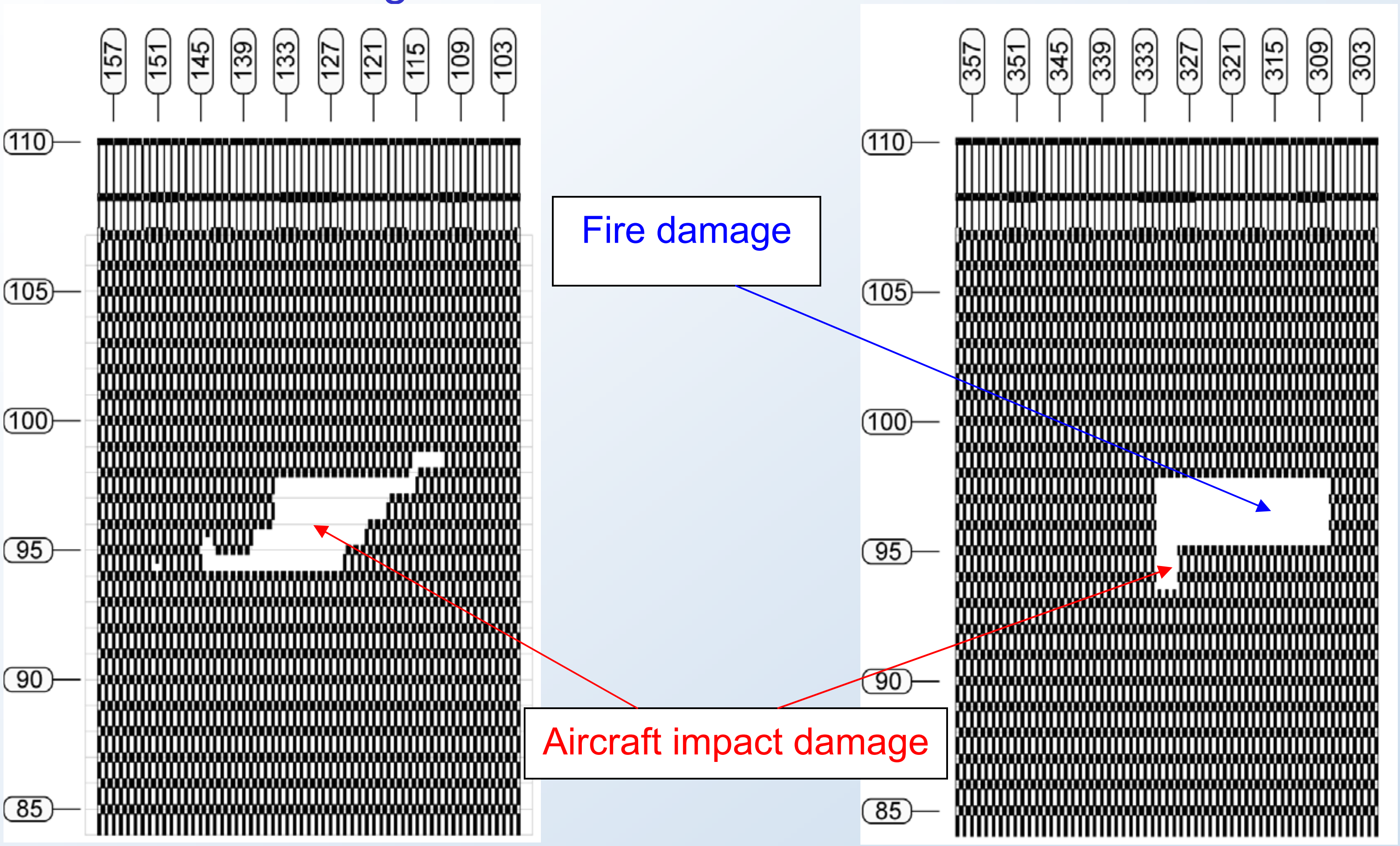
- If only 8 core columns are assumed severed, the tension forces in the columns are smaller, due to the relatively larger stiffness of the floor. These forces may still fail the columns at the splices. The extent to which severed core columns assist in transferring loads via the hat truss without failing the splices is sensitive to the relative magnitudes of the floor loads and splice capacity.

Nonlinear Analysis

- Nonlinear response when an estimated pattern of damage (loss of columns and spandrels in the exterior wall, and columns in the core) has occurred.
- A series of nonlinear, plastic hinges added to the heavily loaded members to capture their post-yield behavior.
- Representative aircraft impact damage stage:
  - members in the north wall of WTC 1 that were visibly severed or missing
  - an exterior panel in the south face
  - 8 columns in the core were assumed severed
- Representative fire damage stage:
  - 24 columns on the south wall of WTC 1 between floors 96 and 98 were assumed to have buckled and lost all load carrying capacity based on video evidence that indicates that columns in this area were visibly deformed inward a few minutes before the tower collapsed.

Nonlinear Analysis

- Exterior damage



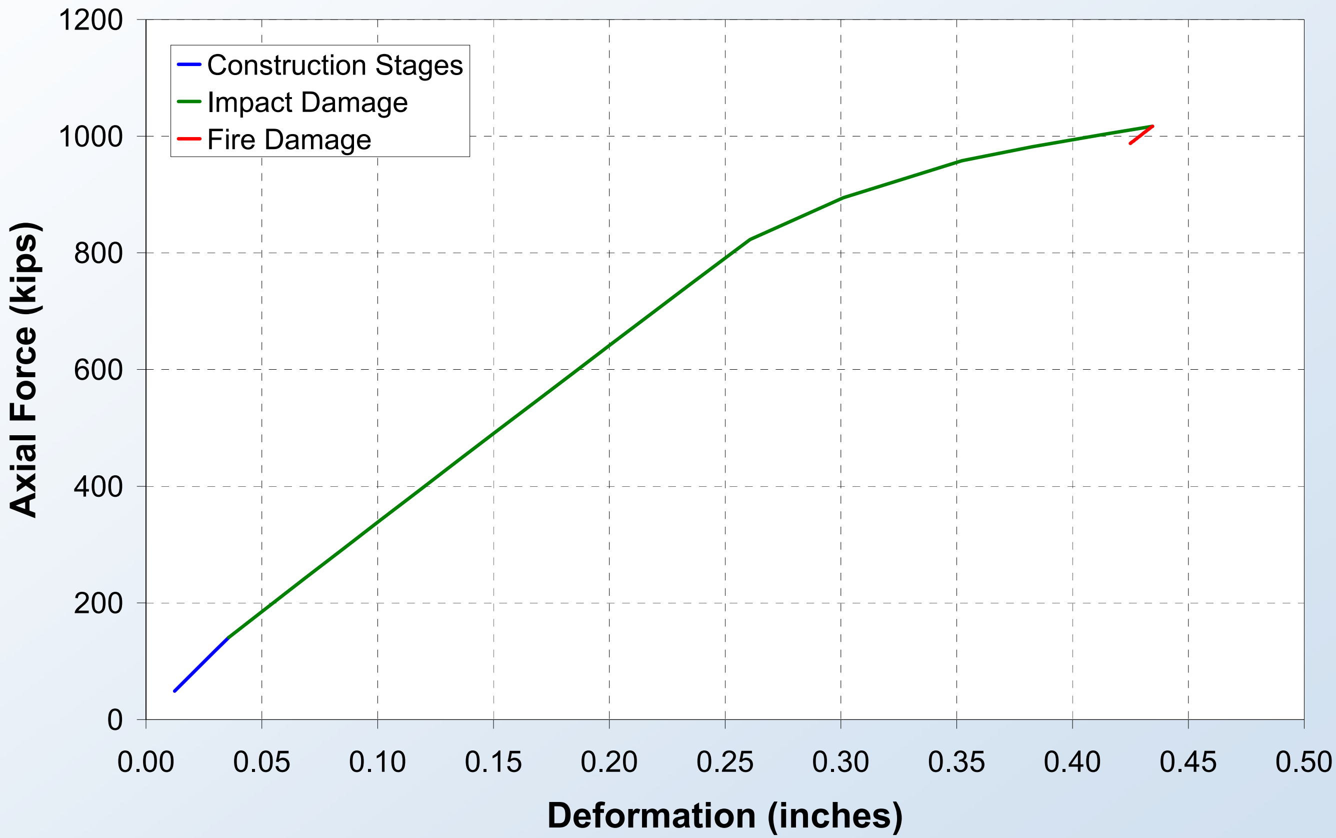
North Wall **South Wall**

Nonlinear Analysis: Results

- After aircraft impact, the tower maintained its stability, where the highest stressed elements were the exterior columns next to the damaged area on the north face of the tower.
- The tower also maintained its stability after losing columns in the south wall due to fire effects with some reserve capacity left, indicating that additional loss or weakening of columns in the core, weakening of additional columns in the exterior, or additional loss of floors is needed to collapse the tower.
- More detailed models will account for local buckling of columns, and the failure and role of the floor system in redistributing the loads; factors that are not considered in this analysis.

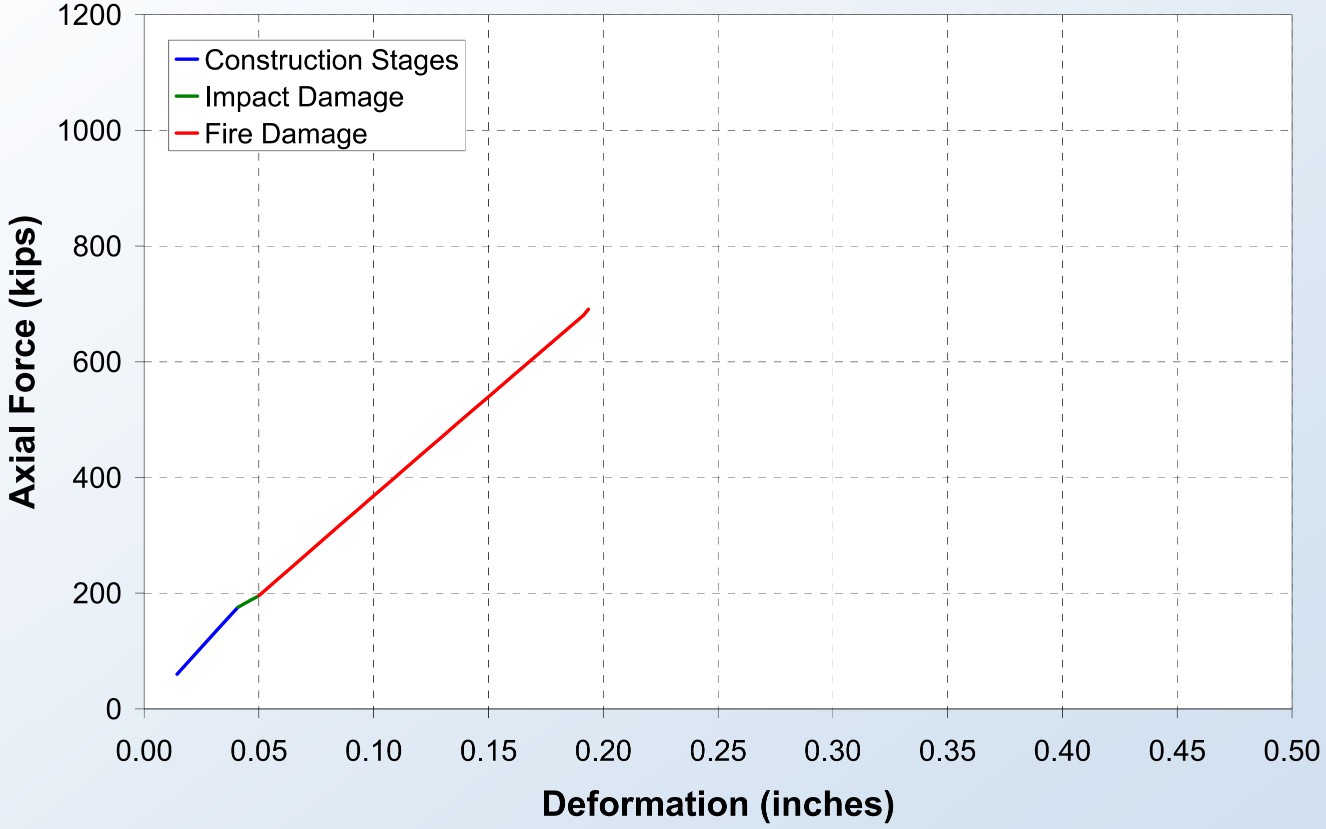
Nonlinear Analysis: Results

- Load vs. deformation in column 111 at floor 98 (north face, west side of damage)



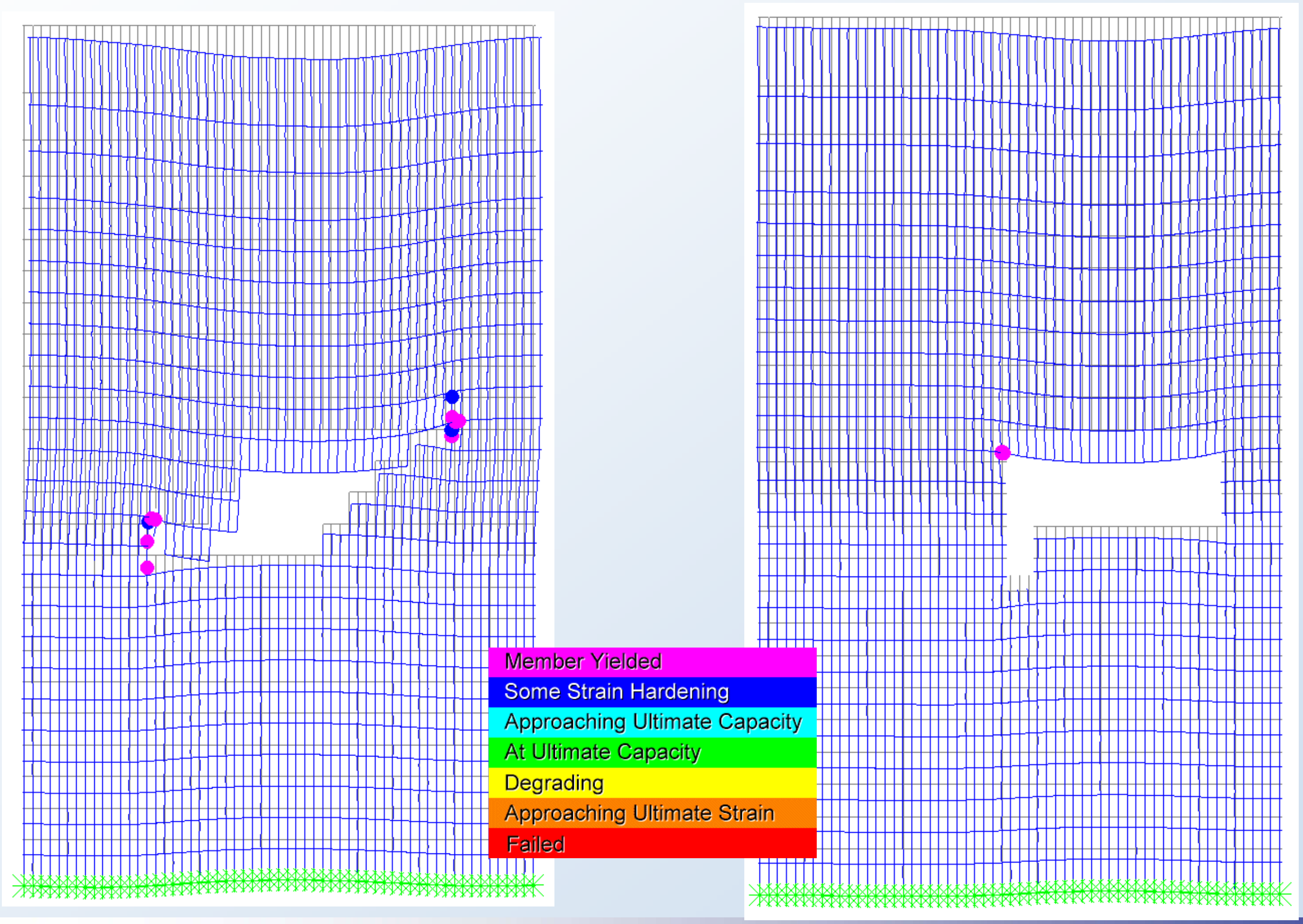
Nonlinear Analysis: Results

- Load vs. deformation in column 332 at floor 97 (south face, west side of damage)



Nonlinear Analysis: Results

- Displacements and locations of plastic hinges in the north and south exterior walls of WTC 1 after impact and fire damage



Preliminary Findings

- A 500 mph engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of perimeter columns. If the engine does not impact a floor slab, the majority of the engine core remains intact through the exterior wall penetration with a reduction in velocity of about 10% and 20%. The residual velocity and mass of the engine after penetration of the exterior wall are sufficient to fail a core column in a direct impact condition. Interaction with additional interior building contents, or a misaligned impact against the core column, could change this result .

- A normal impact of the exterior wall by an empty wing segment produces significant damage to the exterior columns but not necessarily complete failure. A fuel-filled wing section impact results in extensive damage to the exterior wall, including complete failure of the exterior columns. This is consistent with photographs showing the exterior damage to the towers due to impact.

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Preliminary Findings, cont.

- At room temperature, global instability of the intact tower occurs when five floors are removed from the tower model. At column temperatures of 600ºC, the removal of four floors induces global instability.
- When 15 core columns are assumed severed, it is likely that column splices below the hat truss will fail due to the large tensile loads in the columns. When only 8 core columns are assumed severed, the splices may fail; however, the results are not conclusive.
- The tower maintained its stability with the removal of columns in the exterior walls and core columns representative of aircraft impact and also after losing columns in the south wall due to fire effects with some reserve capacity left, indicating that additional weakening or loss of other structural members is needed to collapse the tower.