EXPANDING THE REALM OF POSSIBILITY

Aircraft Impact Analysis of the WTC Towers

NIST Symposium
September 14, 2005

APPLIED RESEARCH ASSOCIATES, INC.
An Employee-Owned Company

Aircraft Impact Analyses

Introduction

Very Fine (~0.01 in)	Very Fine (~1 inch)
Mesh Refinement	Model Size
Coarse (~1-10 in.)	Coarse (~100 feet)

Material Testing

Material Constitutive Modeling

↓

Component Analyses

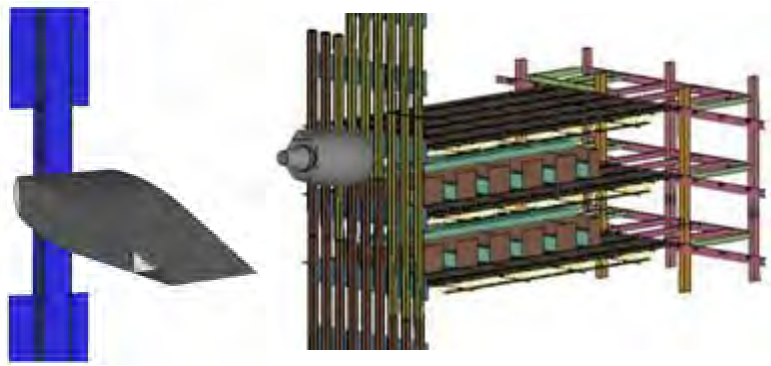
↓

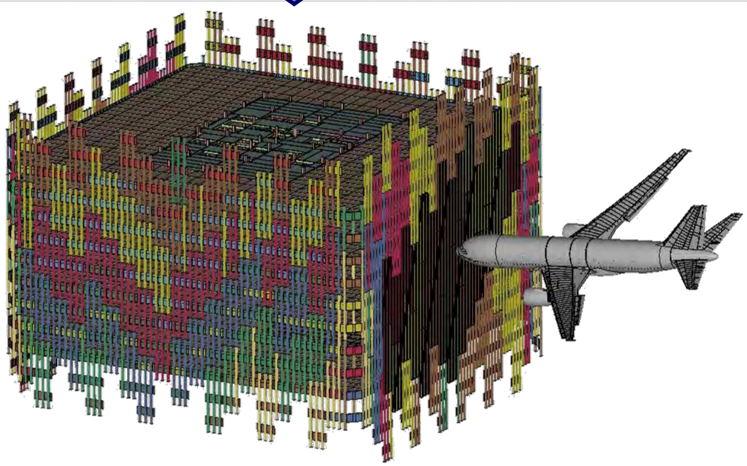
Subassembly Analyses

↓

Global Analyses

Observables





Aircraft Impact Analyses

Objectives

- **Perform aircraft impact analyses to obtain:**
  1. **Structural damage to the WTC towers produced by aircraft impacts.**
  2. **Estimates of jet fuel distribution.**
  3. **Estimates of debris distribution.**
  4. **Environment for fireproofing removal.**
  5. **Analysis of uncertainties in results.**

Aircraft Impact Analyses

Outline

- **Part 1** Material Constitutive and Failure Modeling
- **Part 2** WTC Tower Model Development
- **Part 3** Aircraft Data Collection & Model Development
- **Part 4** Component Impact Analyses
- **Part 5** Subassembly Impact Analysis
- **Part 6** Analysis of Aircraft Impact Conditions
- **Part 7** Component/Subassembly Uncertainty Analyses
- **Part 8** Global Impact Analyses

Part 1

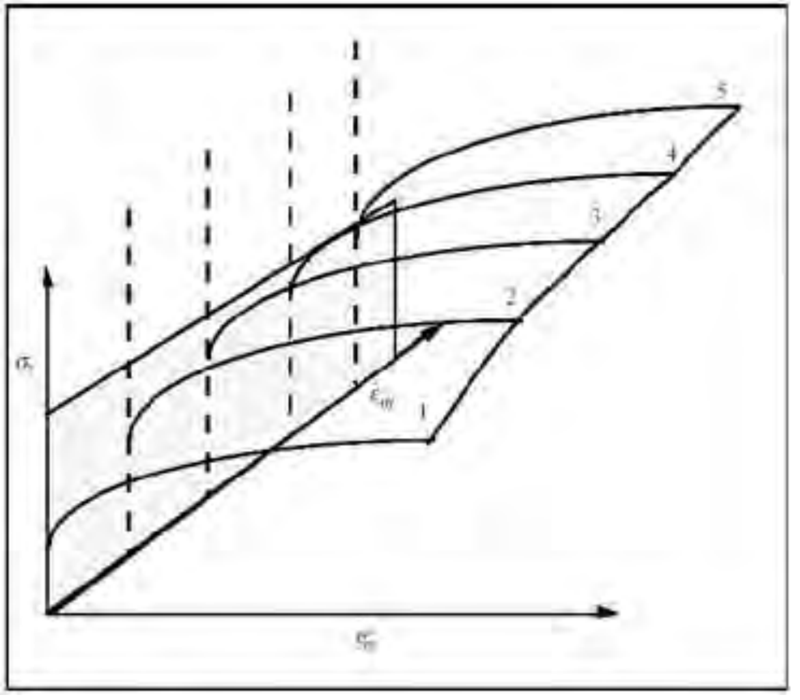
Material Modeling

- Tower steel constitutive modeling
- Aircraft material models
- Concrete material models
- Weld and connection failure models

Steel Constitutive Model

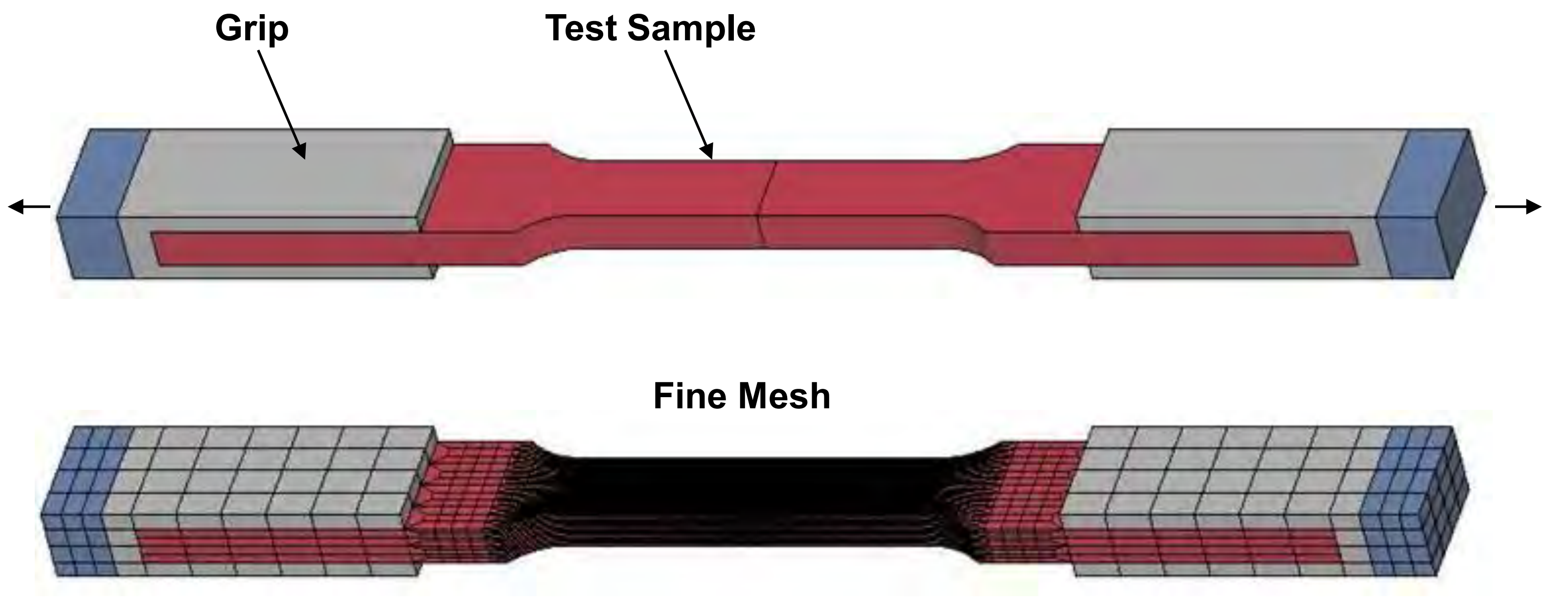
- **Piecewise Linear Plasticity Model**
  - **Yield stress dependence:**
    - **strain rate**
    - **plastic strain**
  - **Strain rate effects**
    - **Cowper & Symonds rate effects model used.**
    - **High-rate data provided by NIST.**
- **Models validated against NIST material test data.**

Yield Stress Variation with Effective Plastic Strain



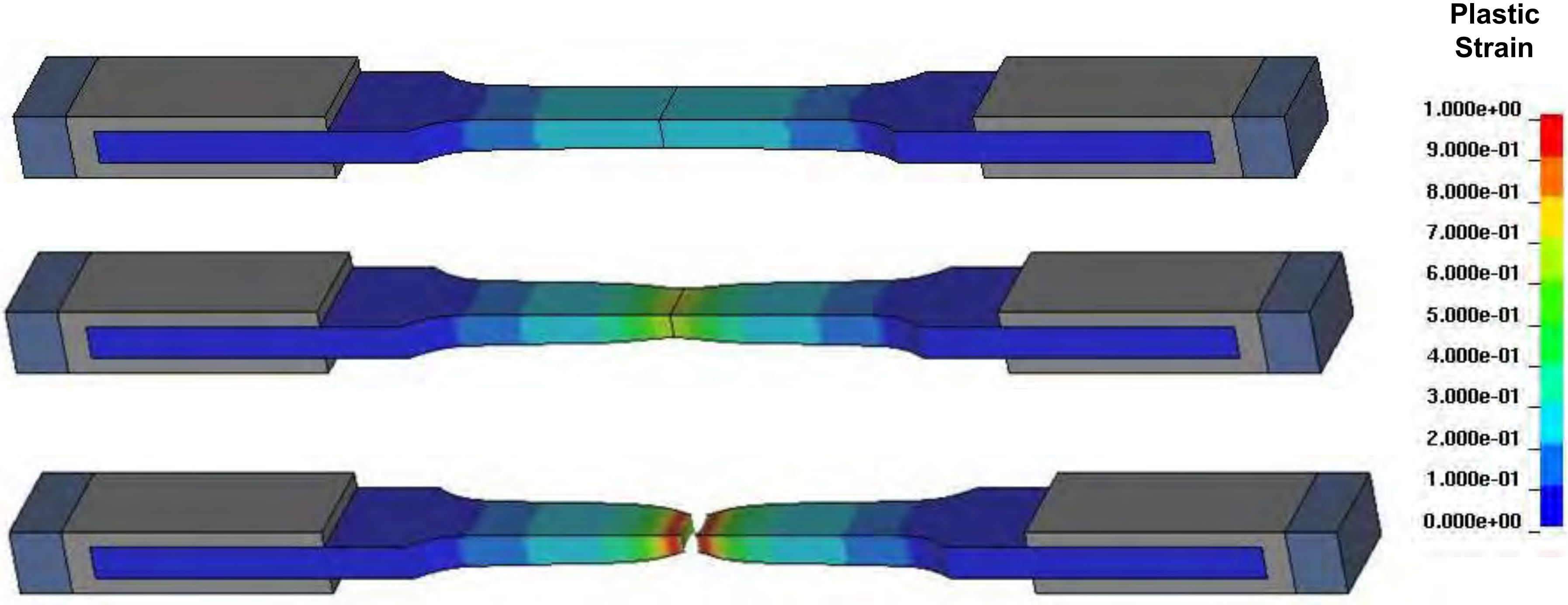
Material Model Validation

ASTM-A370 Tensile Specimen Model



Analysis of Material Testing Used to Validate the Constitutive Models

ASTM-370 Tensile Test Analysis
Fine Mesh: 0.3 mm spacing



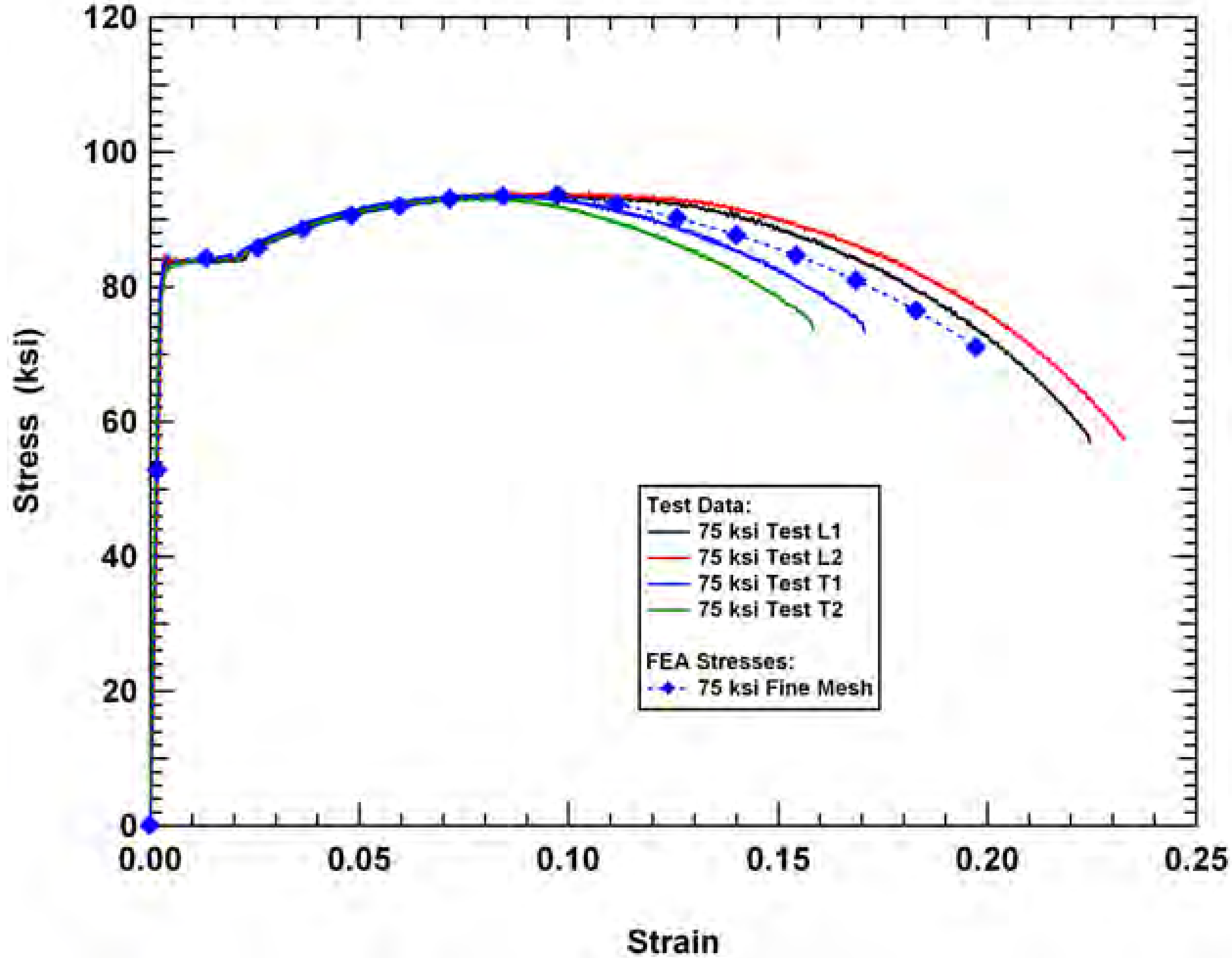
Analysis of a Material Test Including Necking and Failure

Material Model Validation

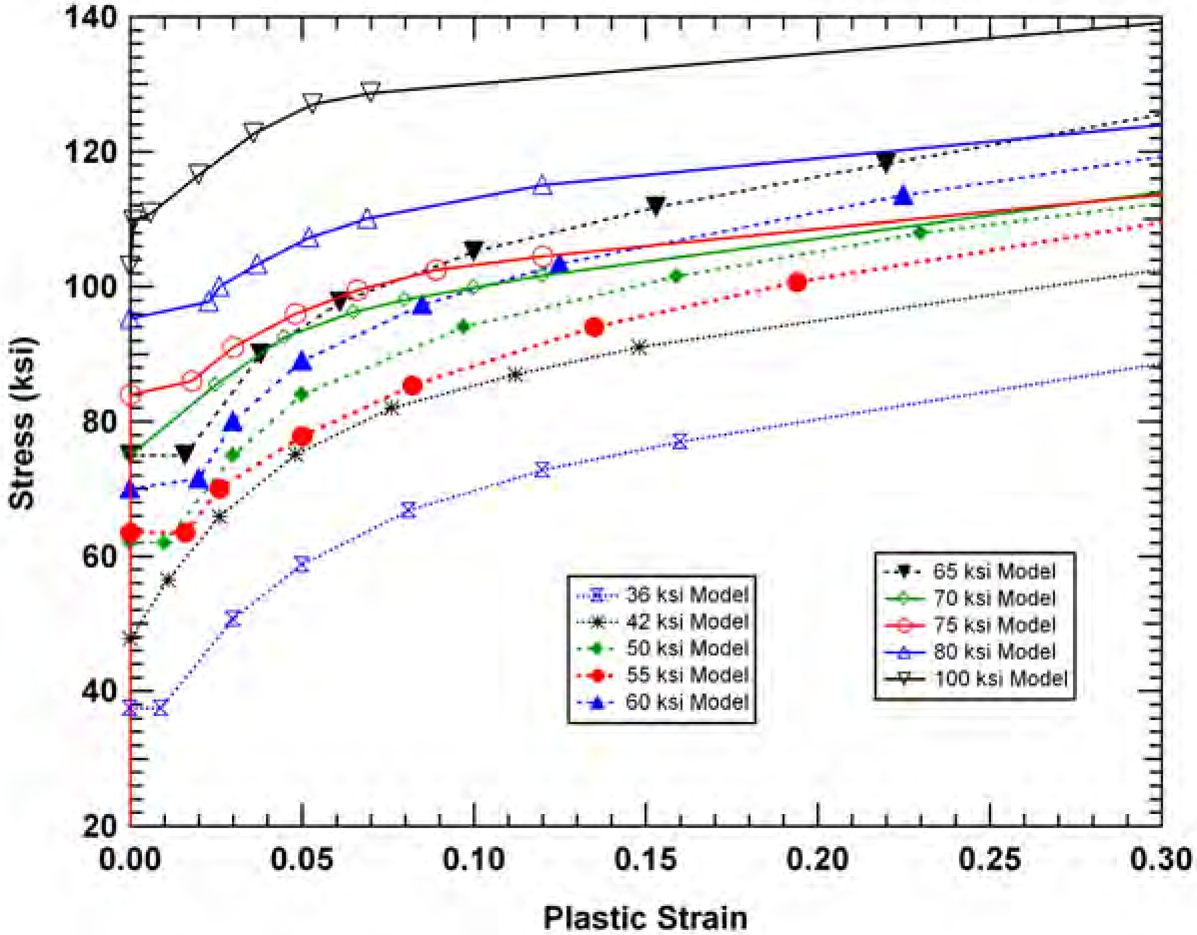
ASTM-A370 75 ksi Tensile Test Comparison

Procedure:

- Develop true stress-strain curve.
- Simulate material testing.
- Validate the model against engineering test data.



Validated True Stress-Strain Curves

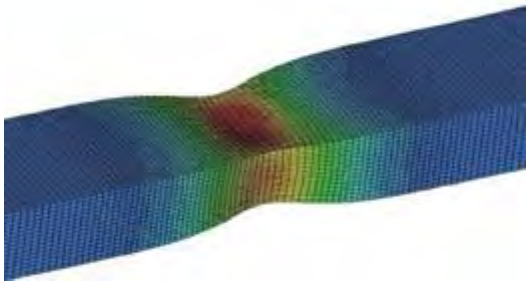


Constitutive Model Input for Mechanical Behavior

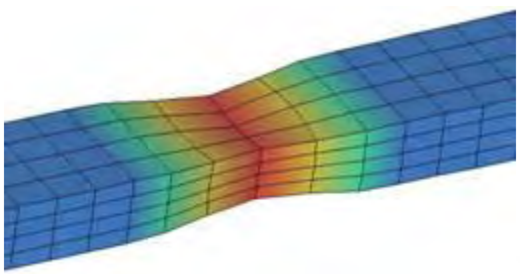
Mesh Refinement Effects

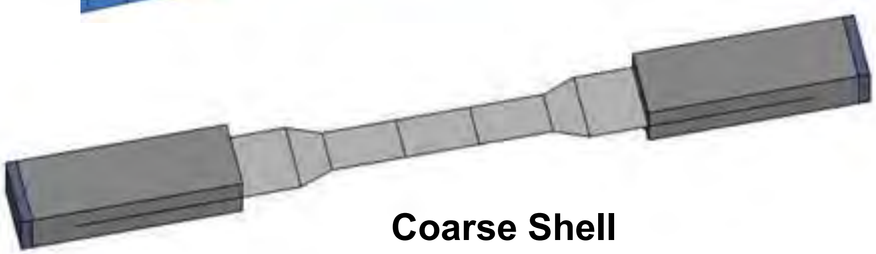
Tensile Test for 75ksi Steel

Fine Mesh Necking Behavior

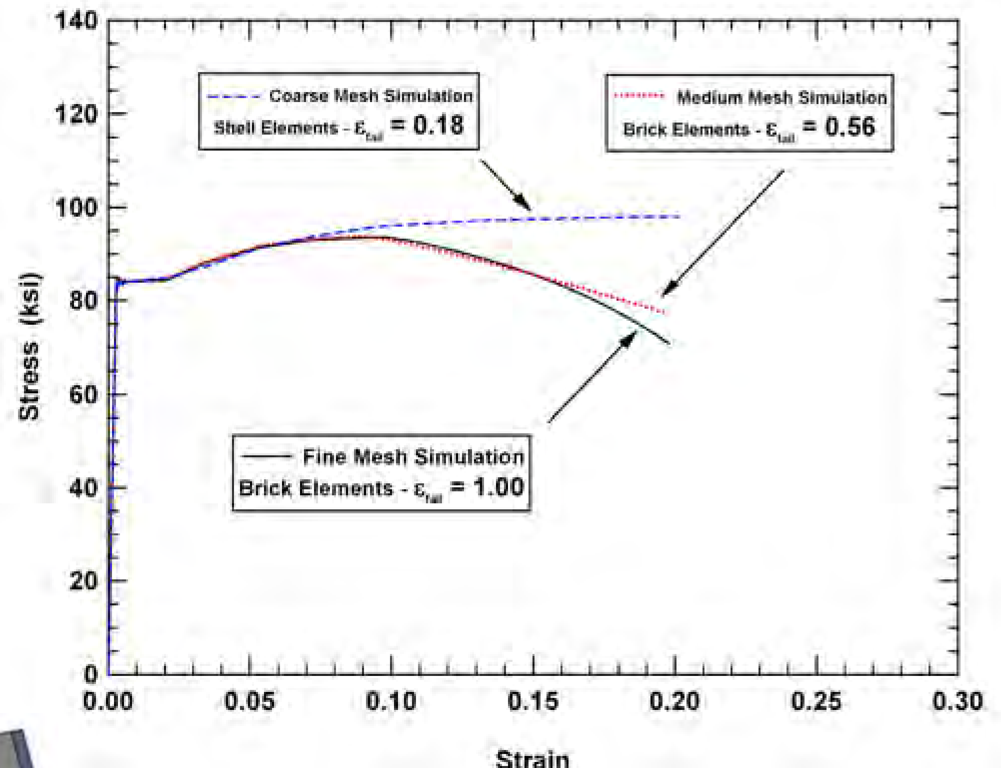


Coarse Mesh Necking Behavior





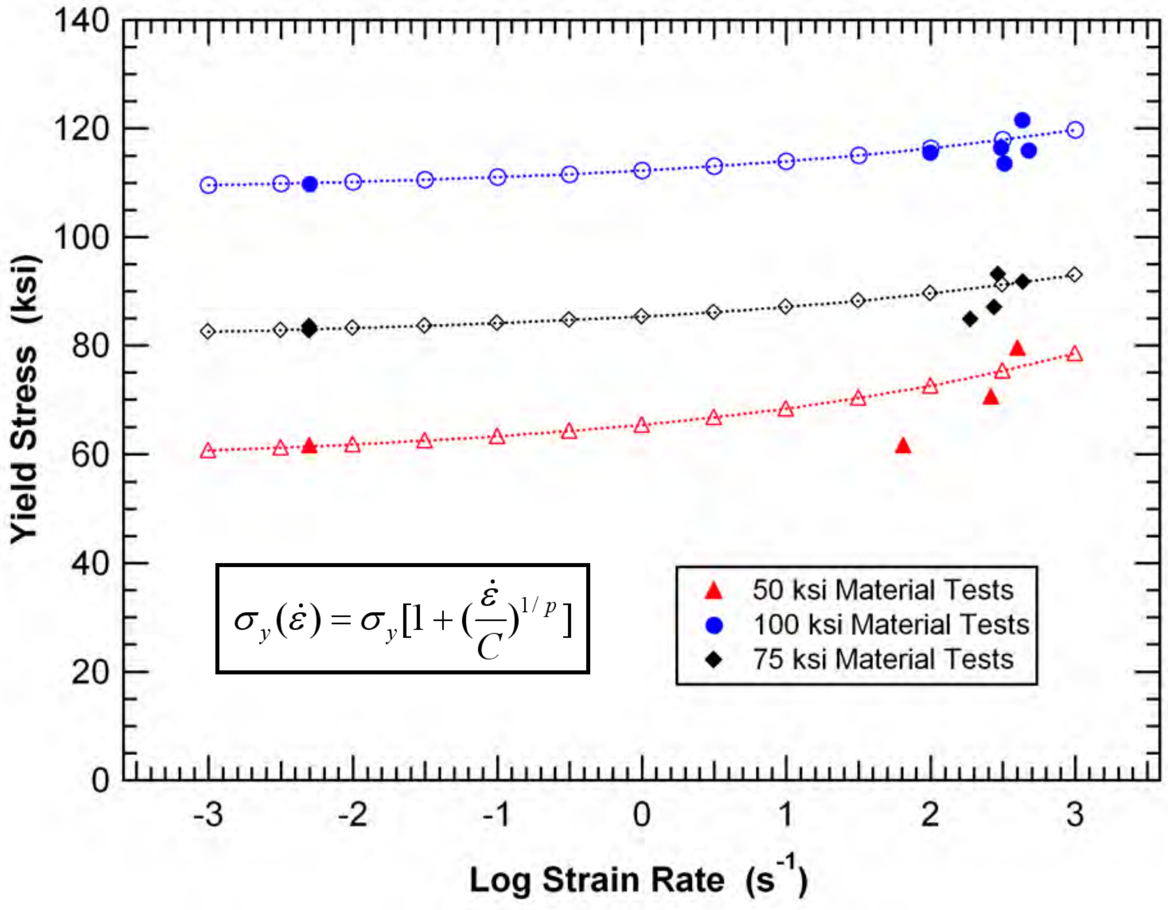
Coarse Shell Element Mesh



Mesh Effects on the Failure Strain

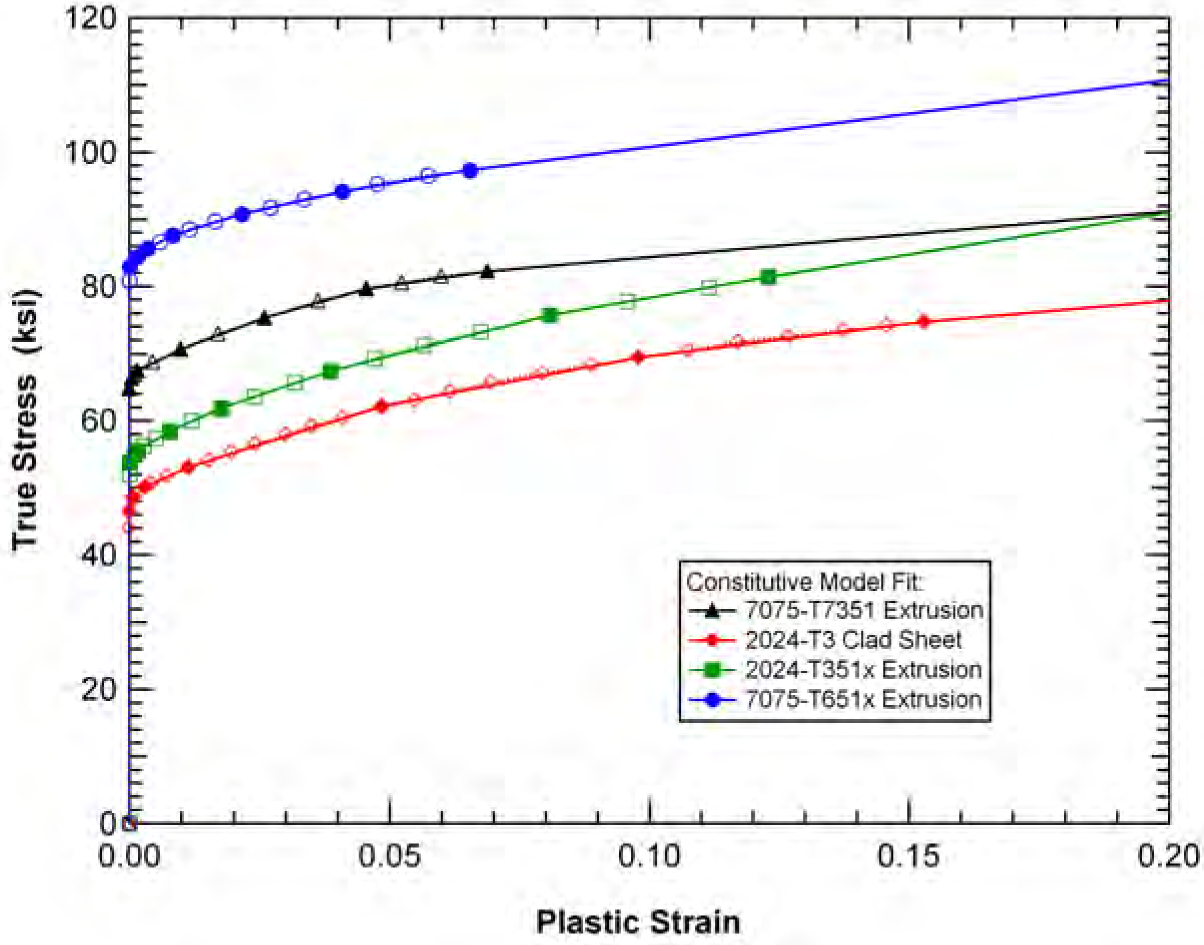
Strain Rate Effects

Cowper and Symonds Model



True Stress-Strain Curves

Aircraft Aluminum Alloys

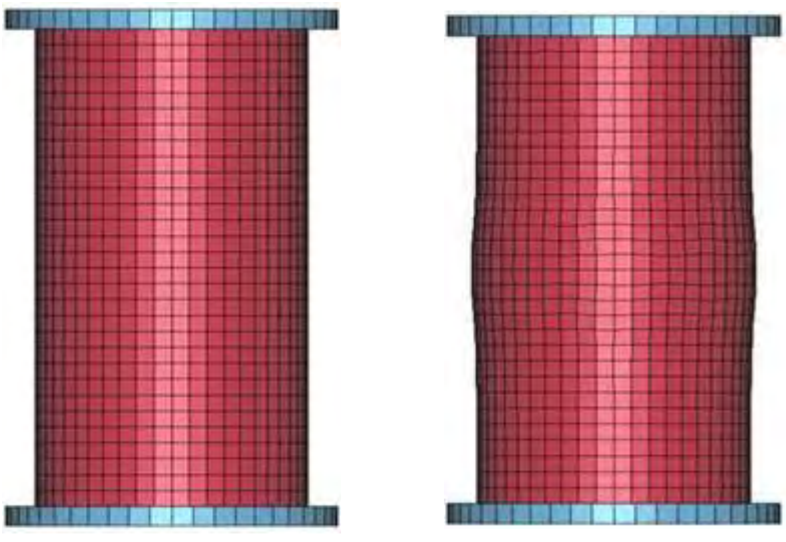


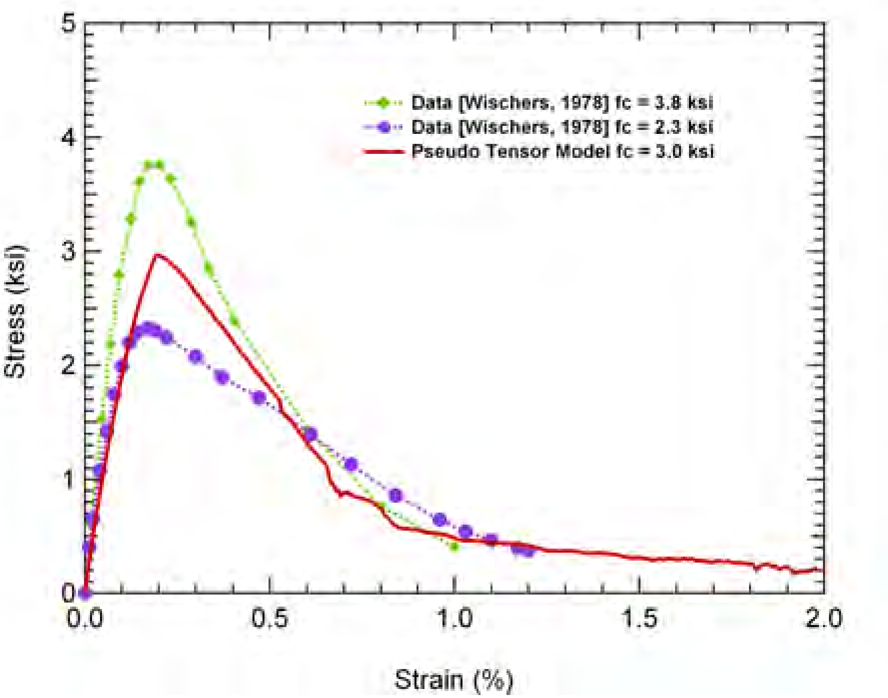
Developed From Open Source Data

Lightweight Concrete Model

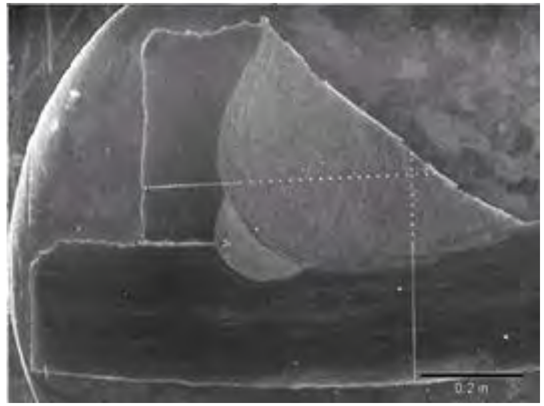
- **Pseudo-tensor model selected for this program:**
  - **Good for low-confinement modeling.**
  - **Tabular rate effects modeling - fit to data in literature sources.**
  - **Damage with softening and various failure/erosion options.**
- **Pseudo-tensor model was calibrated using a simulation of an unconfined compression specimen.**

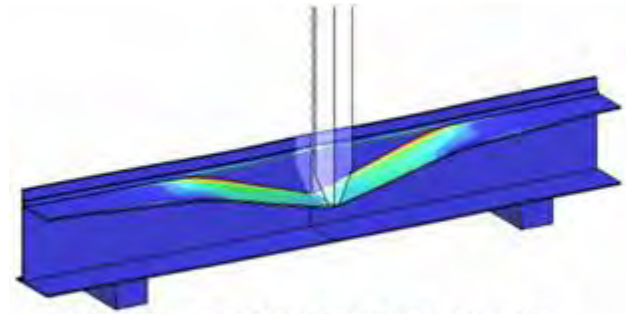
Unloaded **2% Displacement**



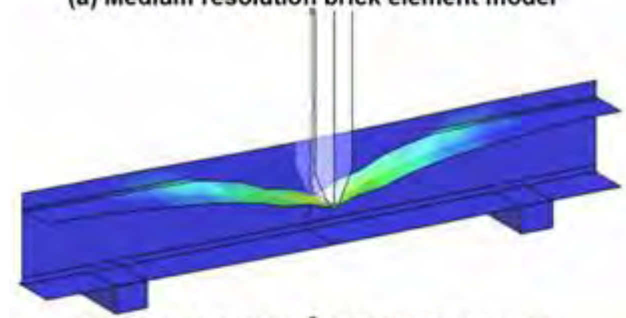


Weld Zone Modeling

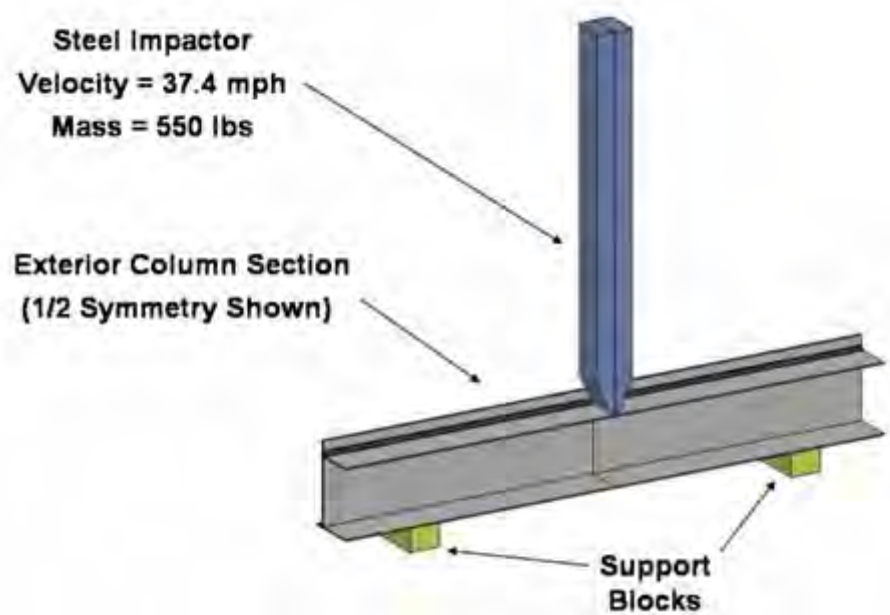


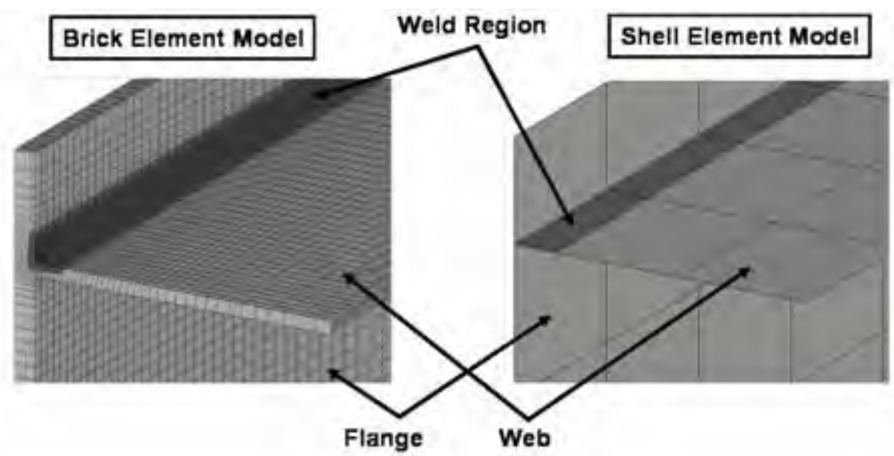


(a) Medium resolution brick element model



(b) Coarse resolution shell element model

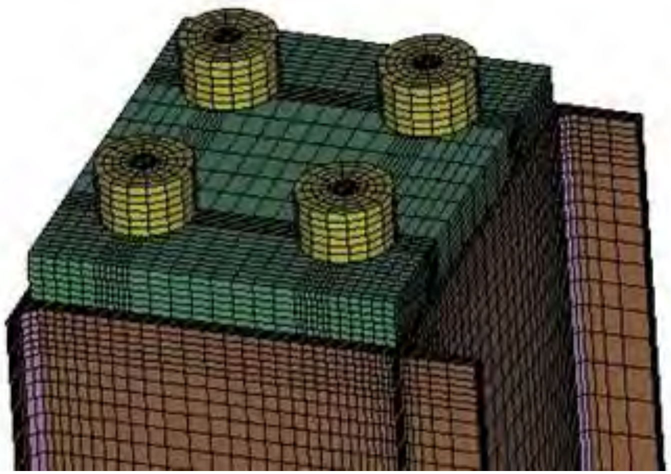


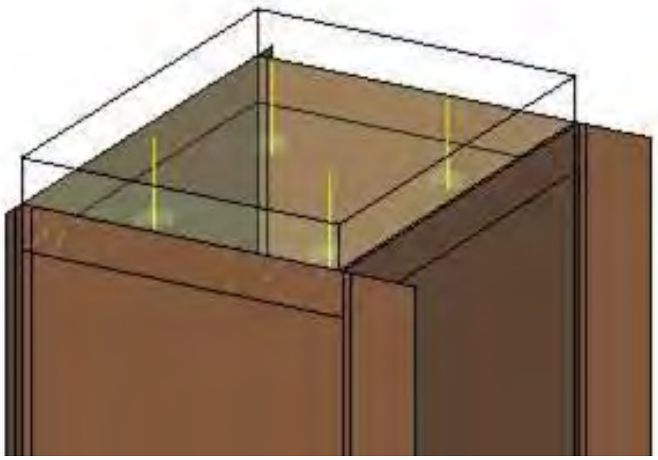


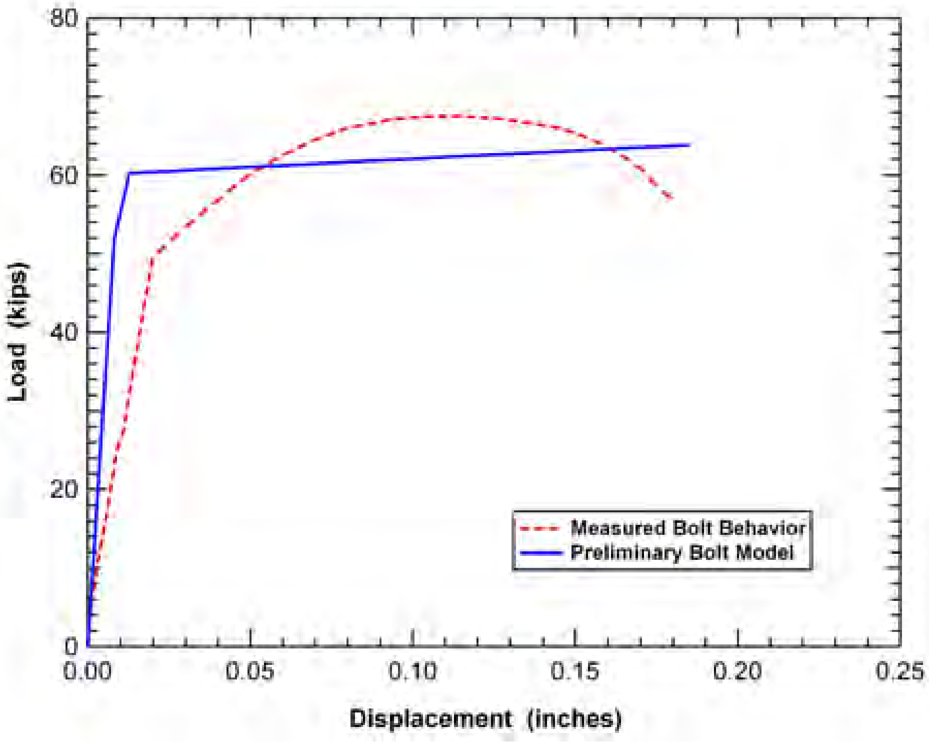
Exterior Column Bolt Modeling

- Strength of the bolted connections is important for damage analyses.
- Detailed models of the bolts not feasible beyond component level analyses

Exterior Column Bolt Modeling





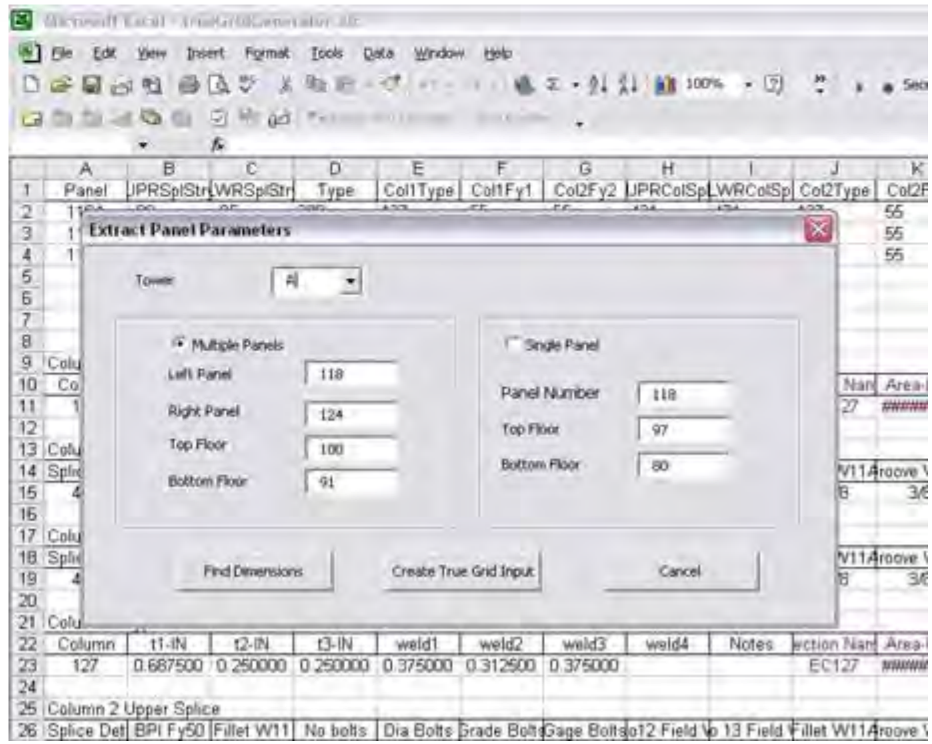


Part 2

WTC Tower Model Development

Automatic Model Generation

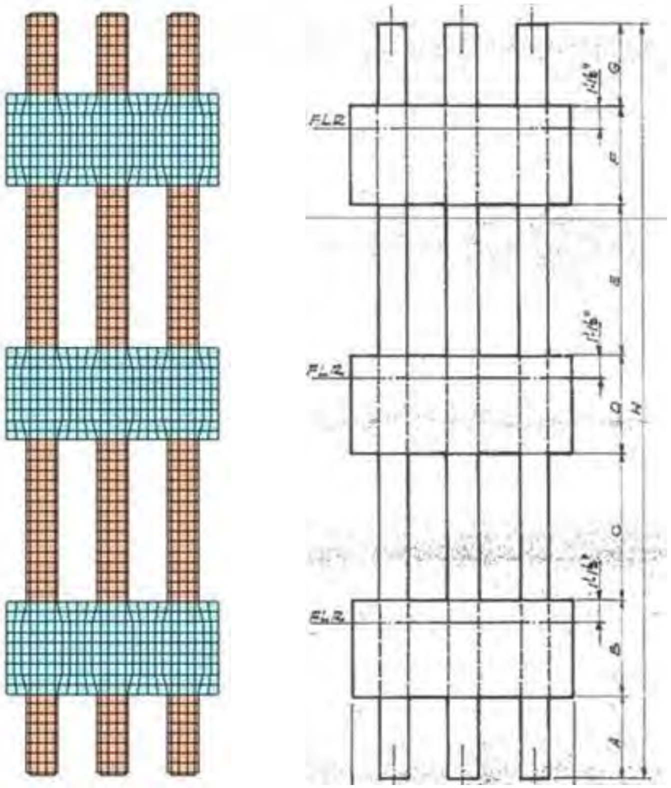
- Excel Visual Basic Tool
- Reads LERA database for dimensions
- Capabilities:
  - Exterior wall generation.
    - single panel
    - subassembly
    - global
  - Core Column Generation
  - Automatically inserts bolts and boundary butt plates.
  - Controls mesh refinement for different regions



- Approach selected to reduce the potential for model errors.

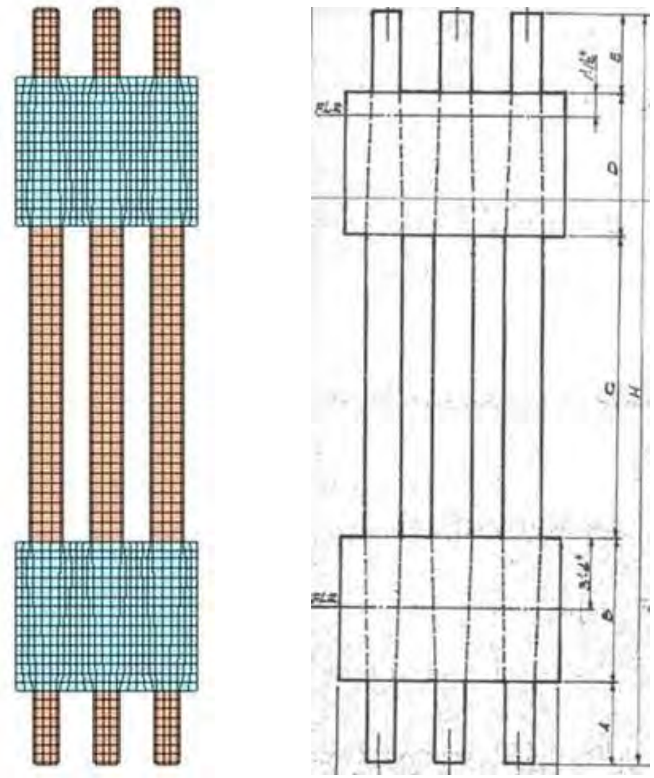
Exterior Panel Auto Generation

Panel Type 300-307



300 panel model shown

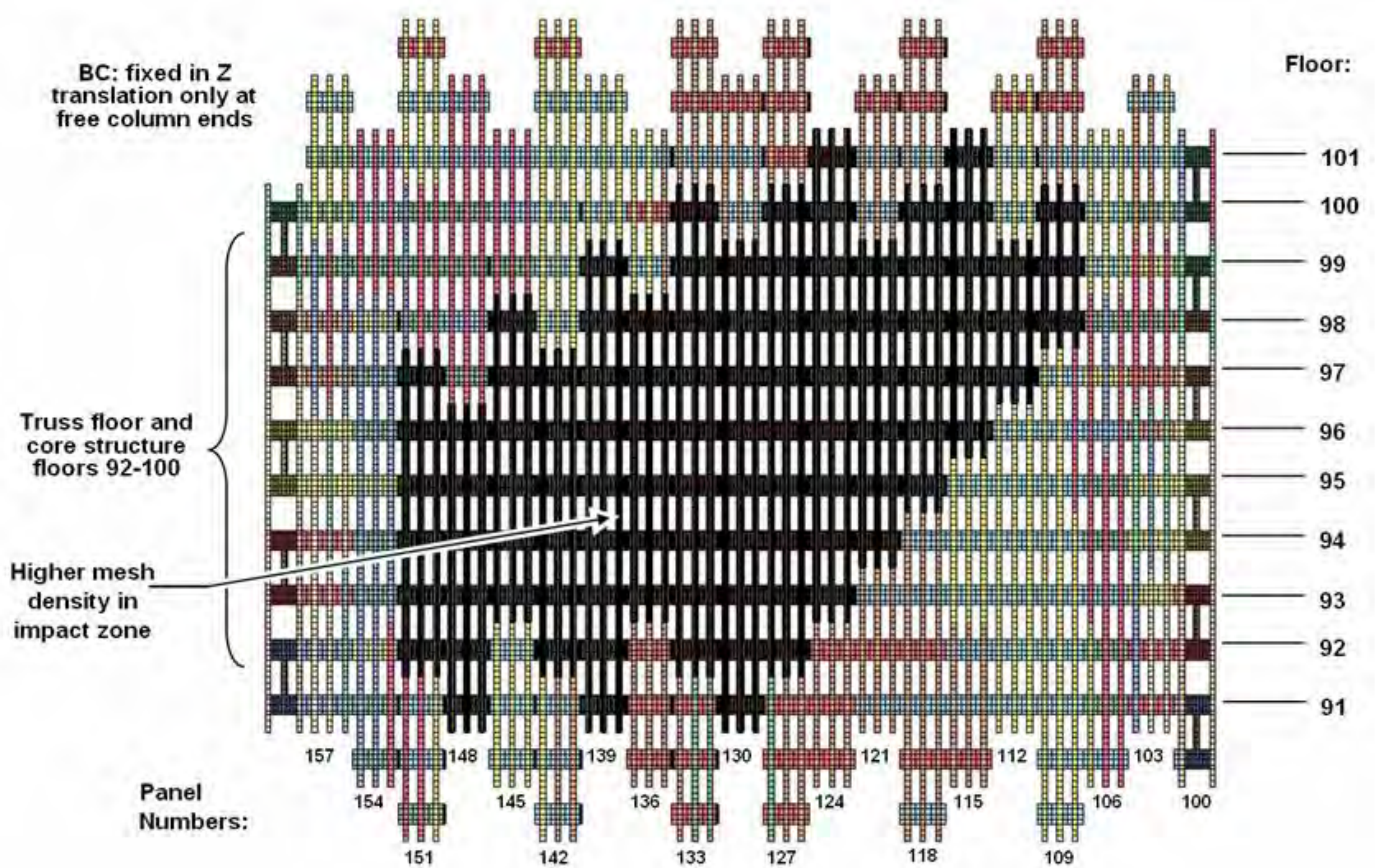
Panel Type 400-401



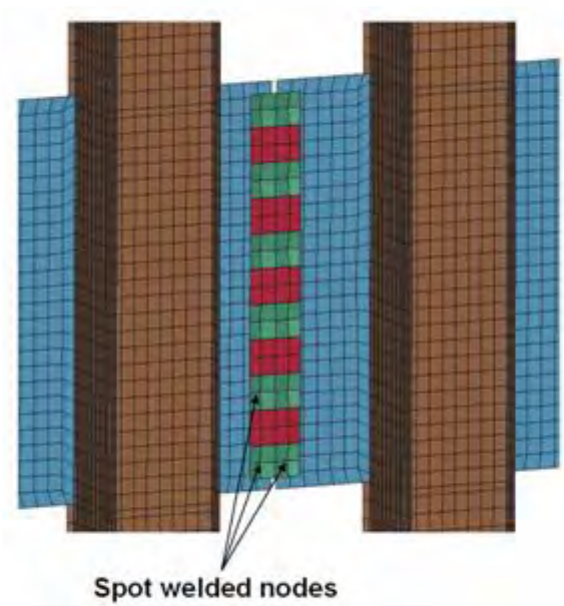
400 panel model shown

- Parameterized models developed for panel types.
- Parameters automatically extracted from database.

WTC 1 Impact Face Model

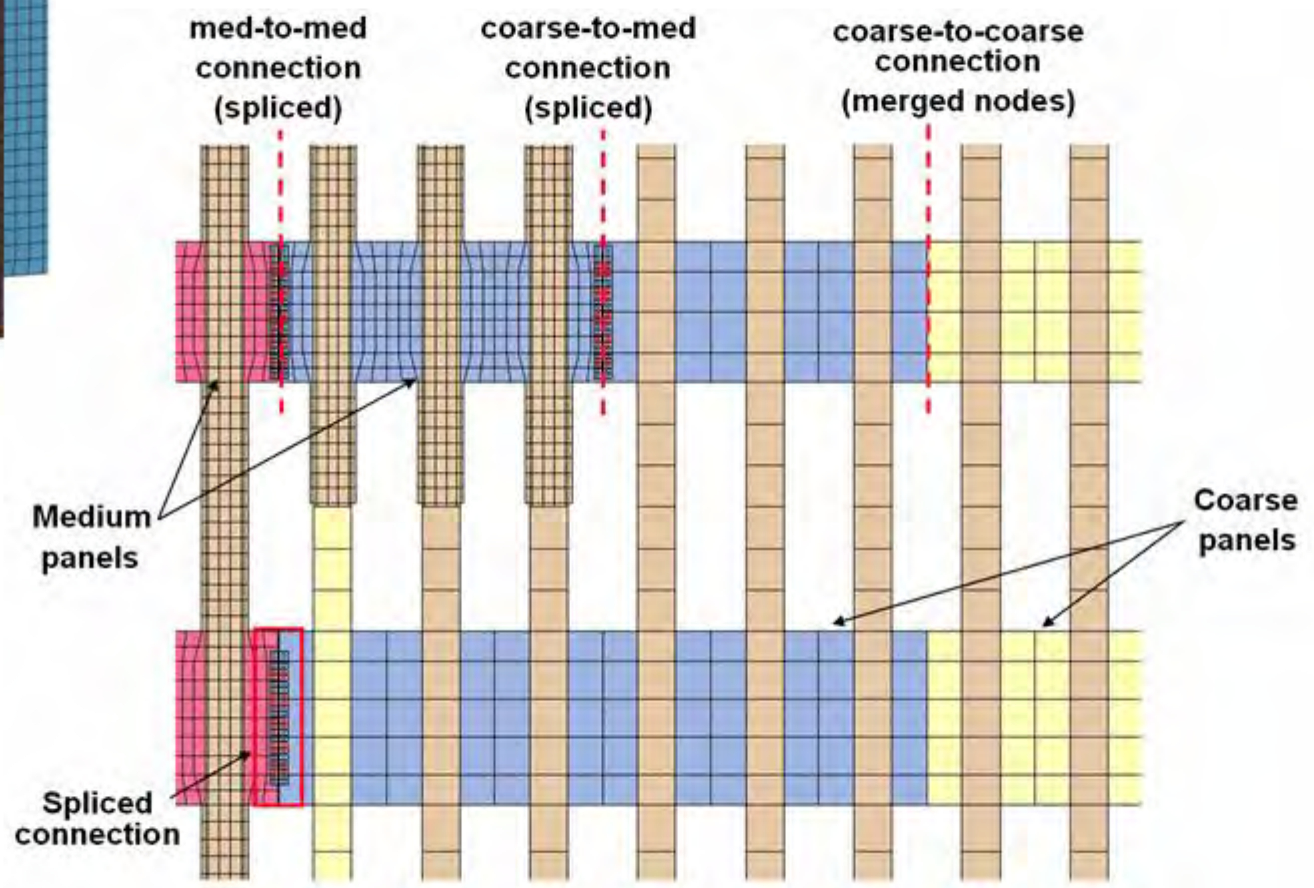


Spandrel Splice Connections



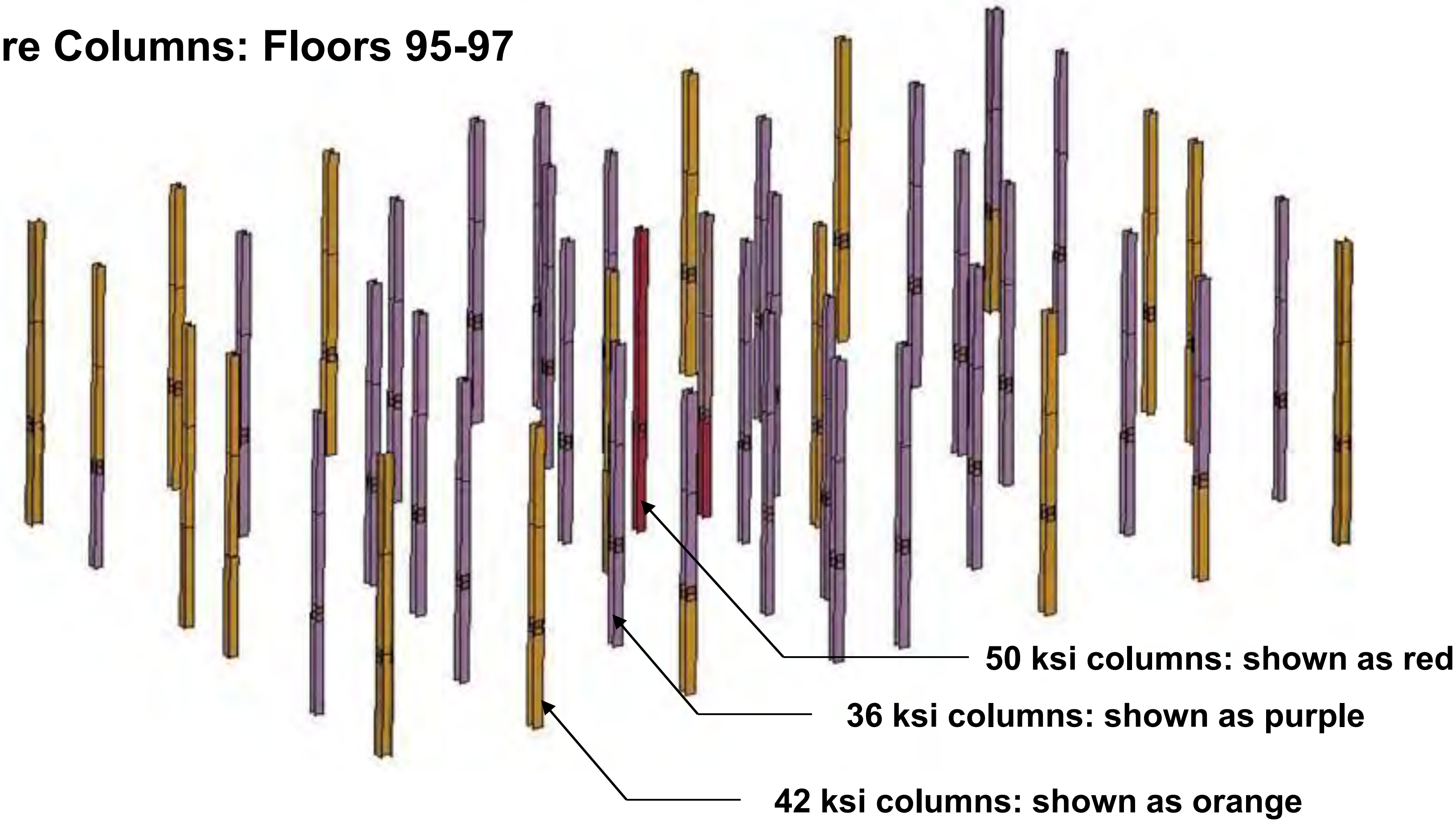
Connection Details

Placement of Splice Connections



Tower Model Development

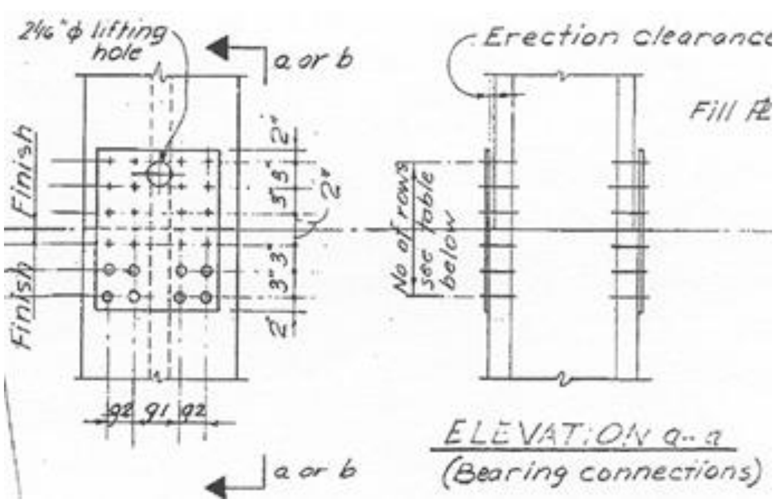
Core Columns: Floors 95-97

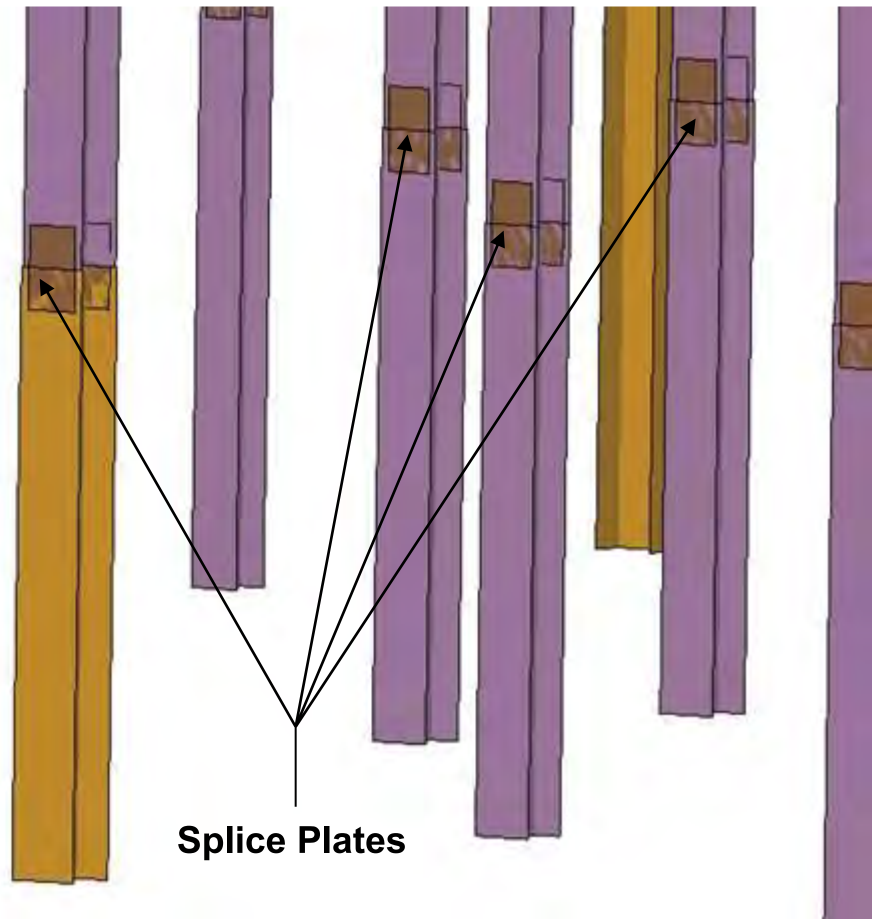


Dimensions and Materials Extracted from the Database

Tower Model Development

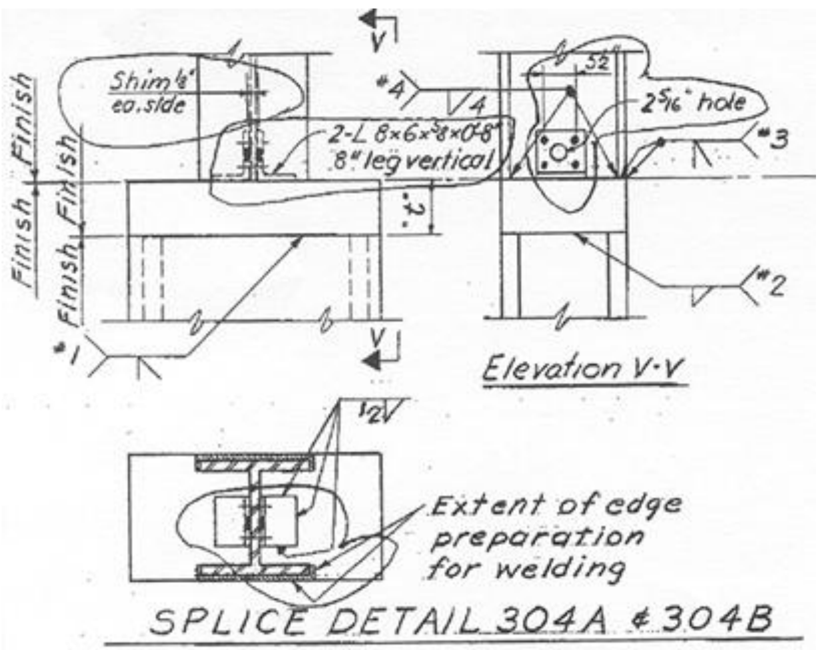
- Connections are weak points for lateral impacts.
- Wide Flange to Wide Flange Splice.
  - Connection made with tied interface between splice plates and column ends.

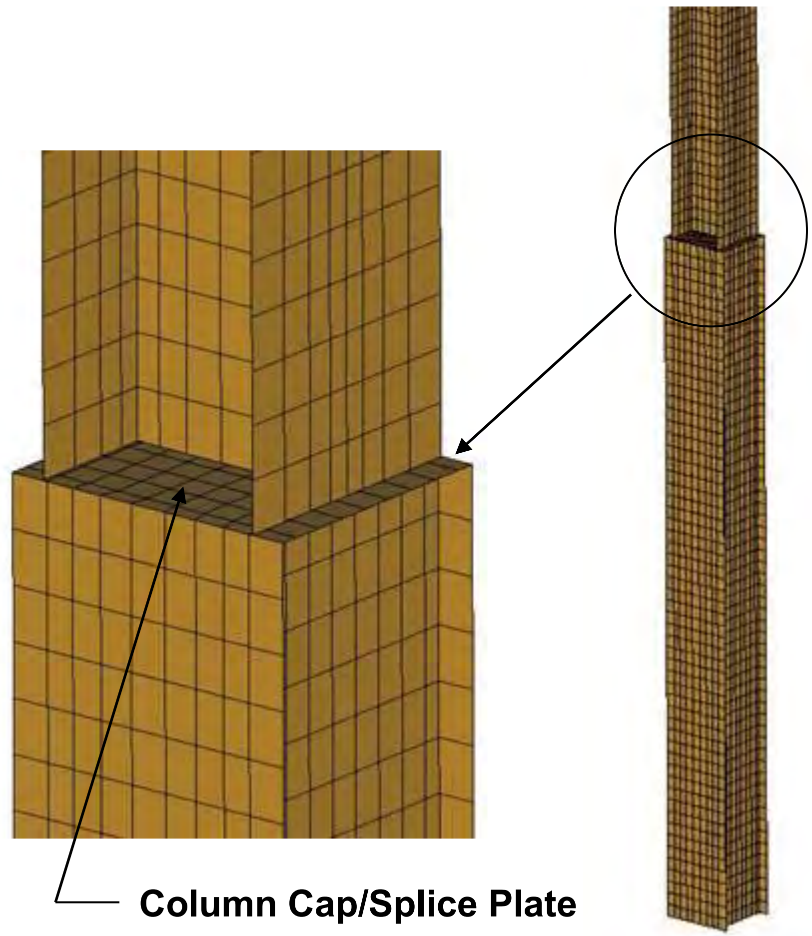




Tower Model Development

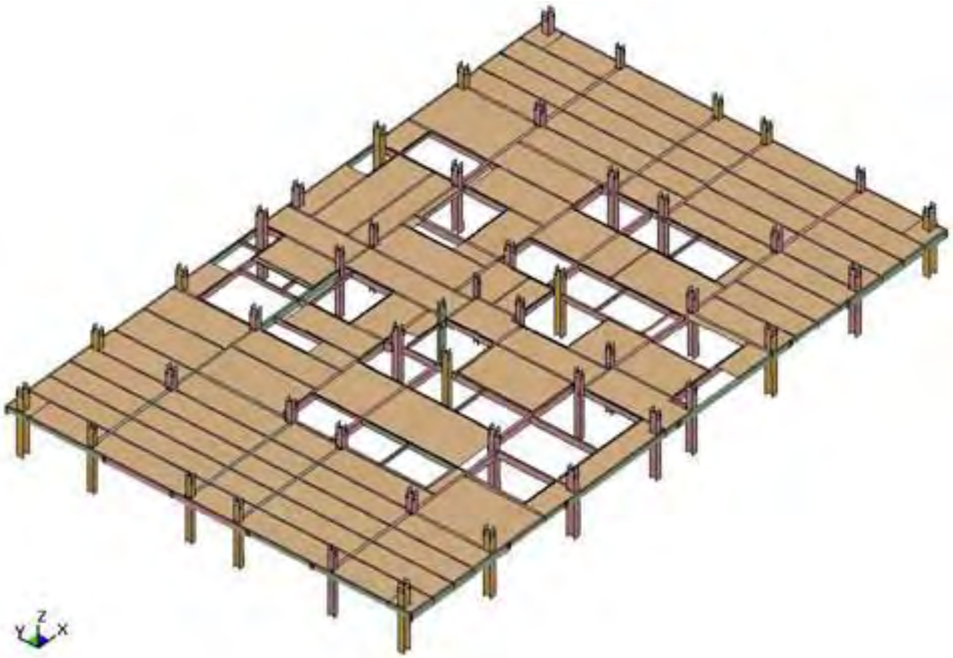
- **Box Column to Wide Flange Splice**
  - **Connection made with tied interface between column cap on BC and column end of WF**



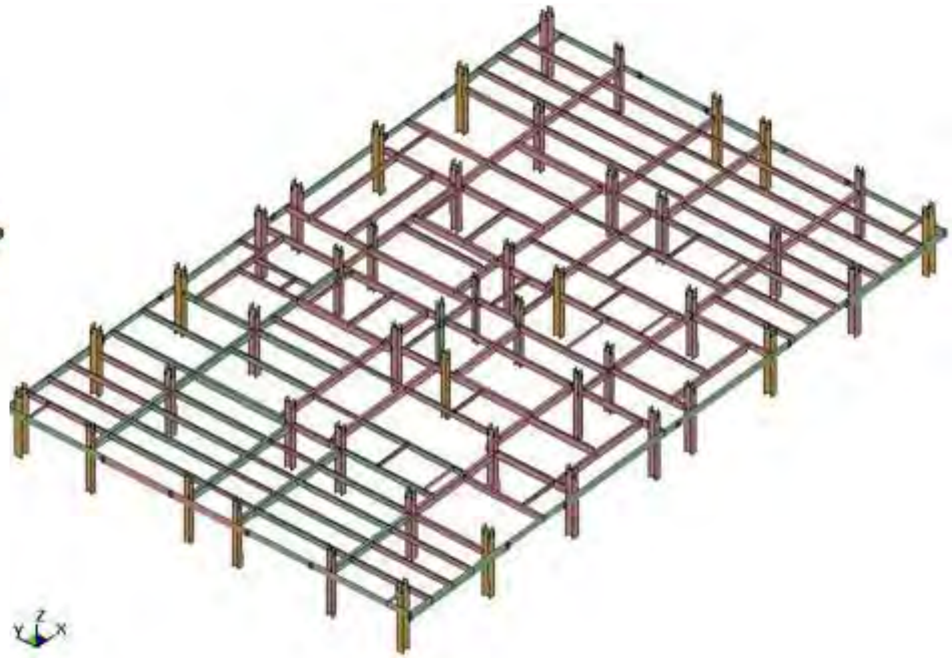


Tower Model Development

Core Floor Structure for 96th Floor



With Floor Slab



Without Floor Slab

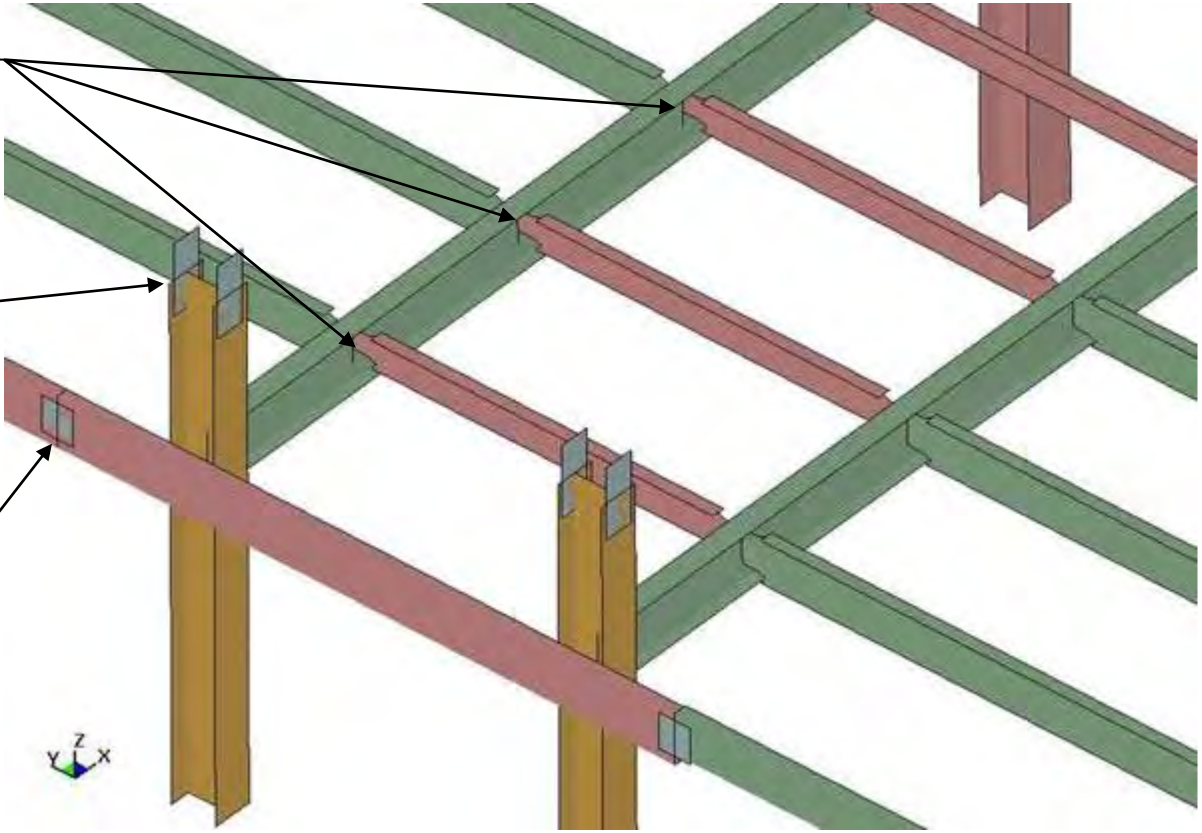
Tower Model Development: Core

Connection Details

Node-to-Surface Tied Interface at Floor Beam Connections

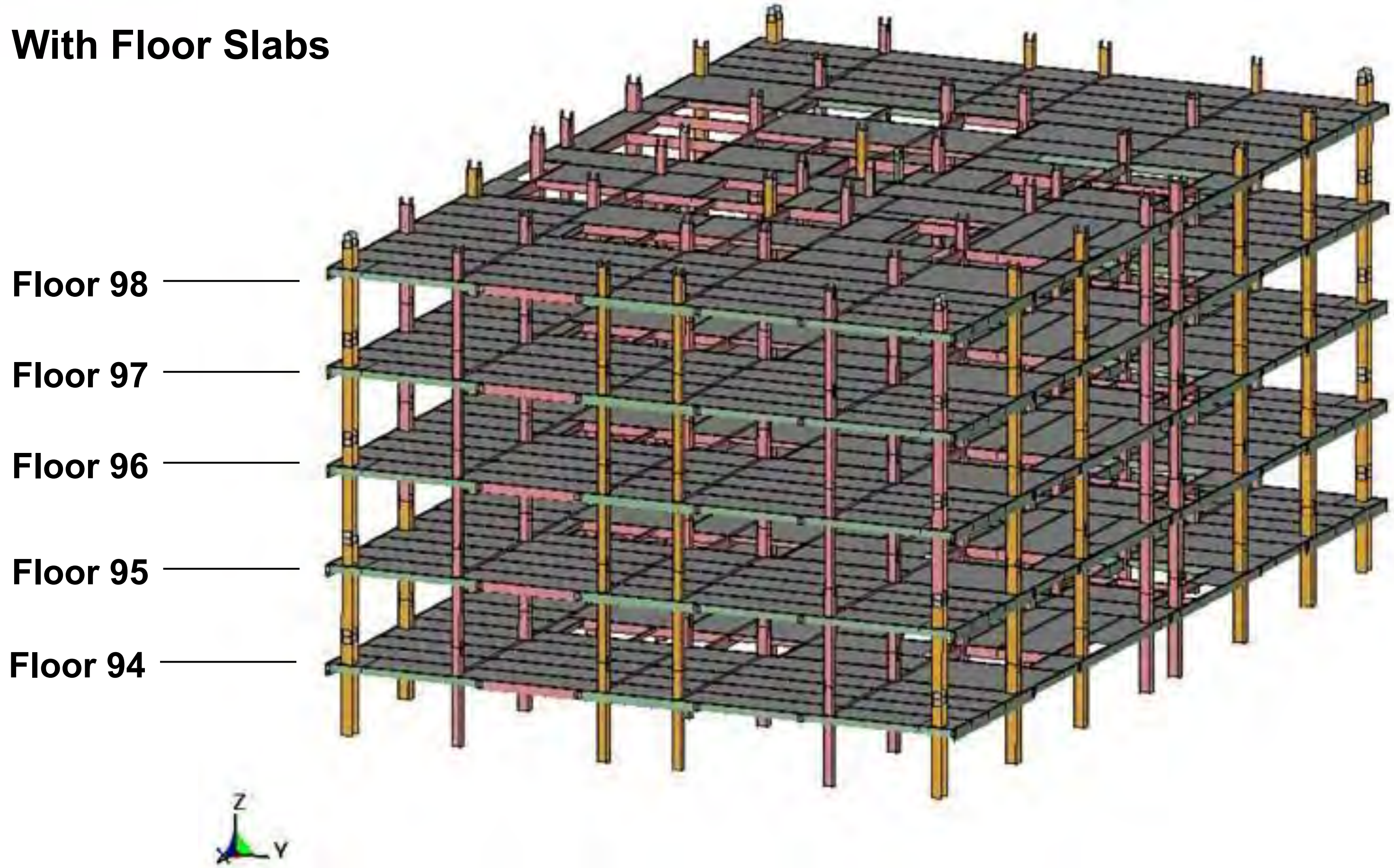
Splice Plates at Column Connections

Perimeter Beams Connected with Splice Plates



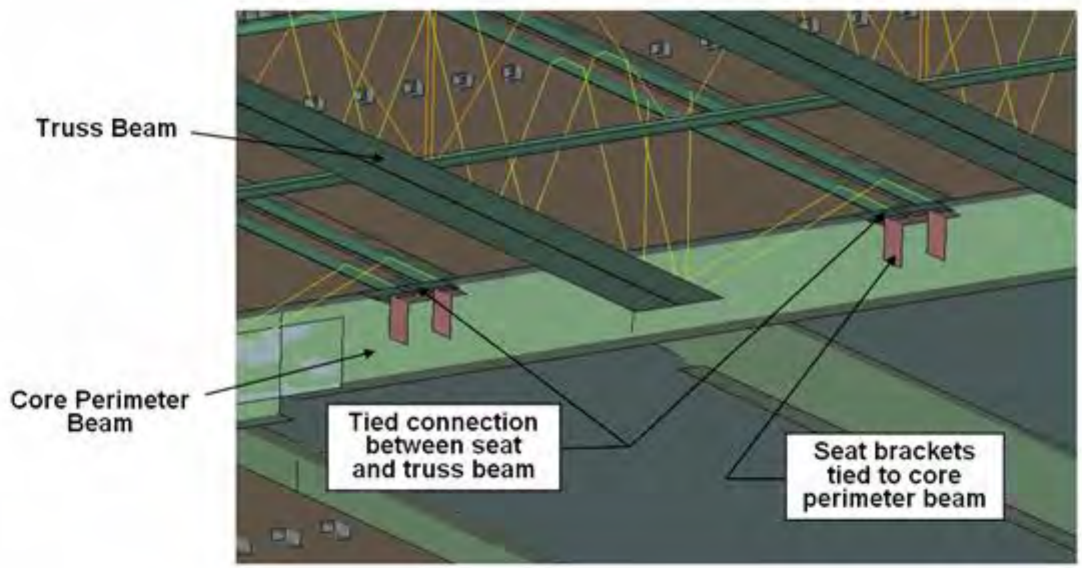
Tower Model Development: Core

With Floor Slabs

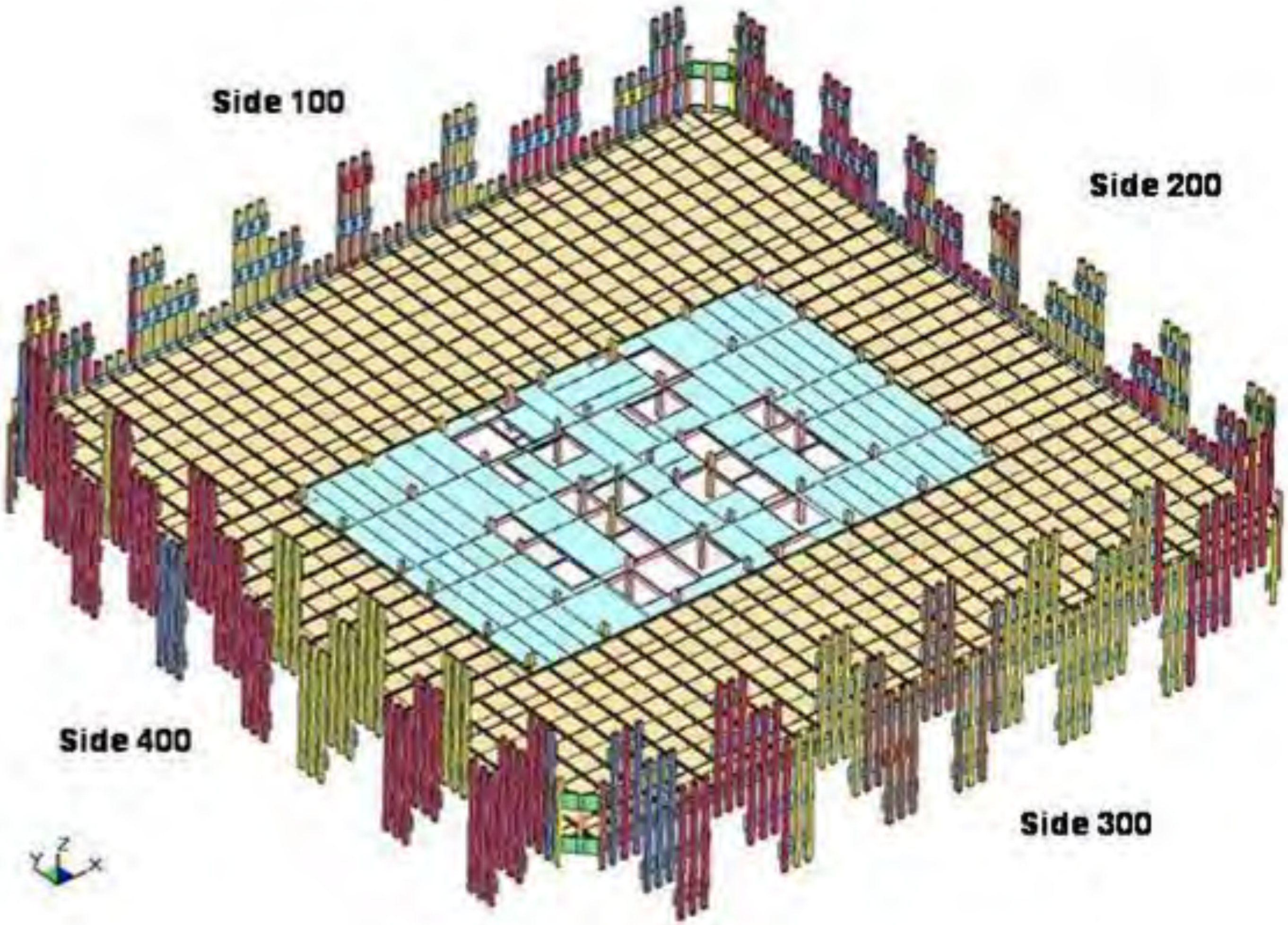


Note: Different Colors Correspond to Different Material Assignments

Tower Model Development: Truss Floor

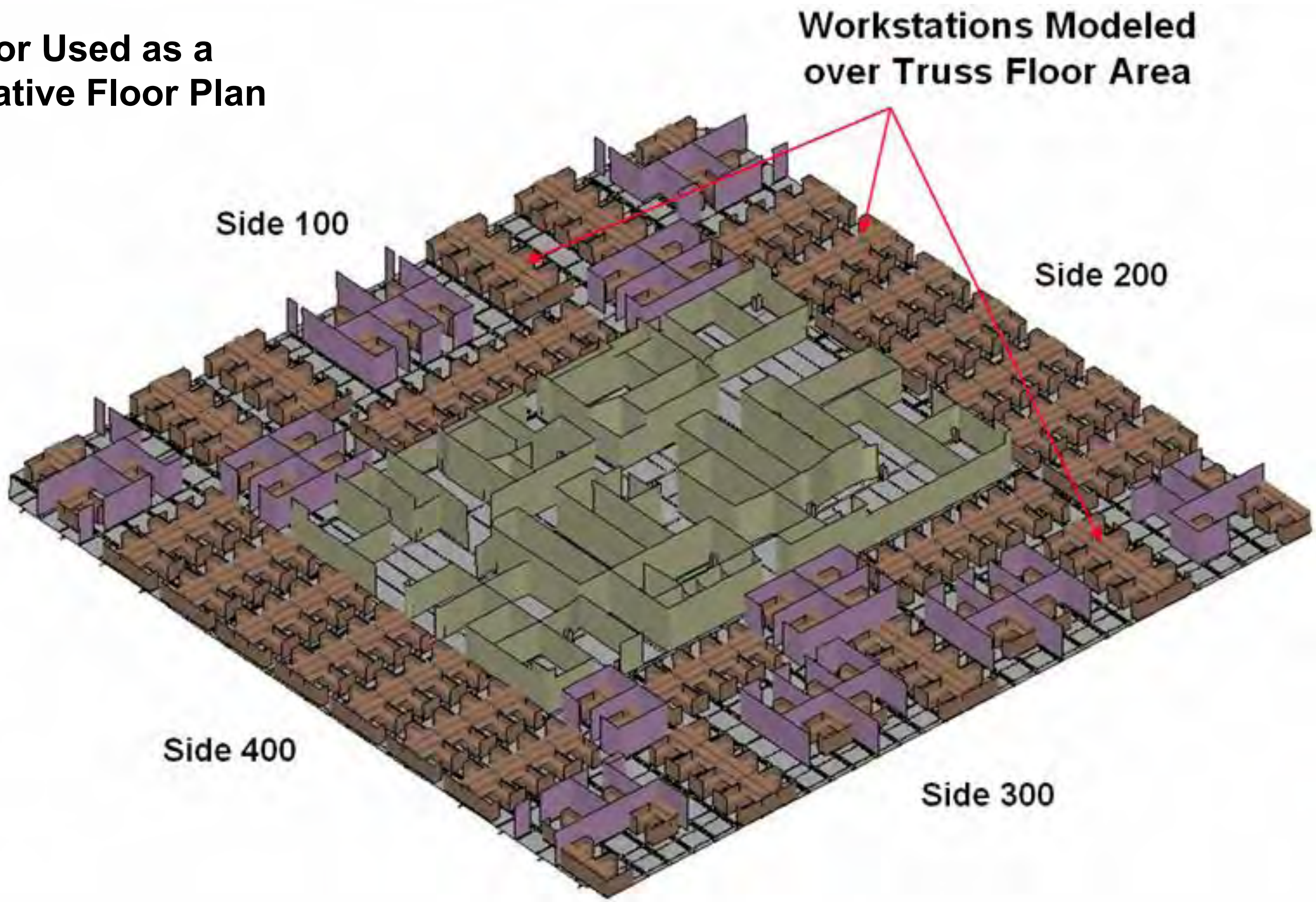


Tower Model Development:
96th floor of WTC 1

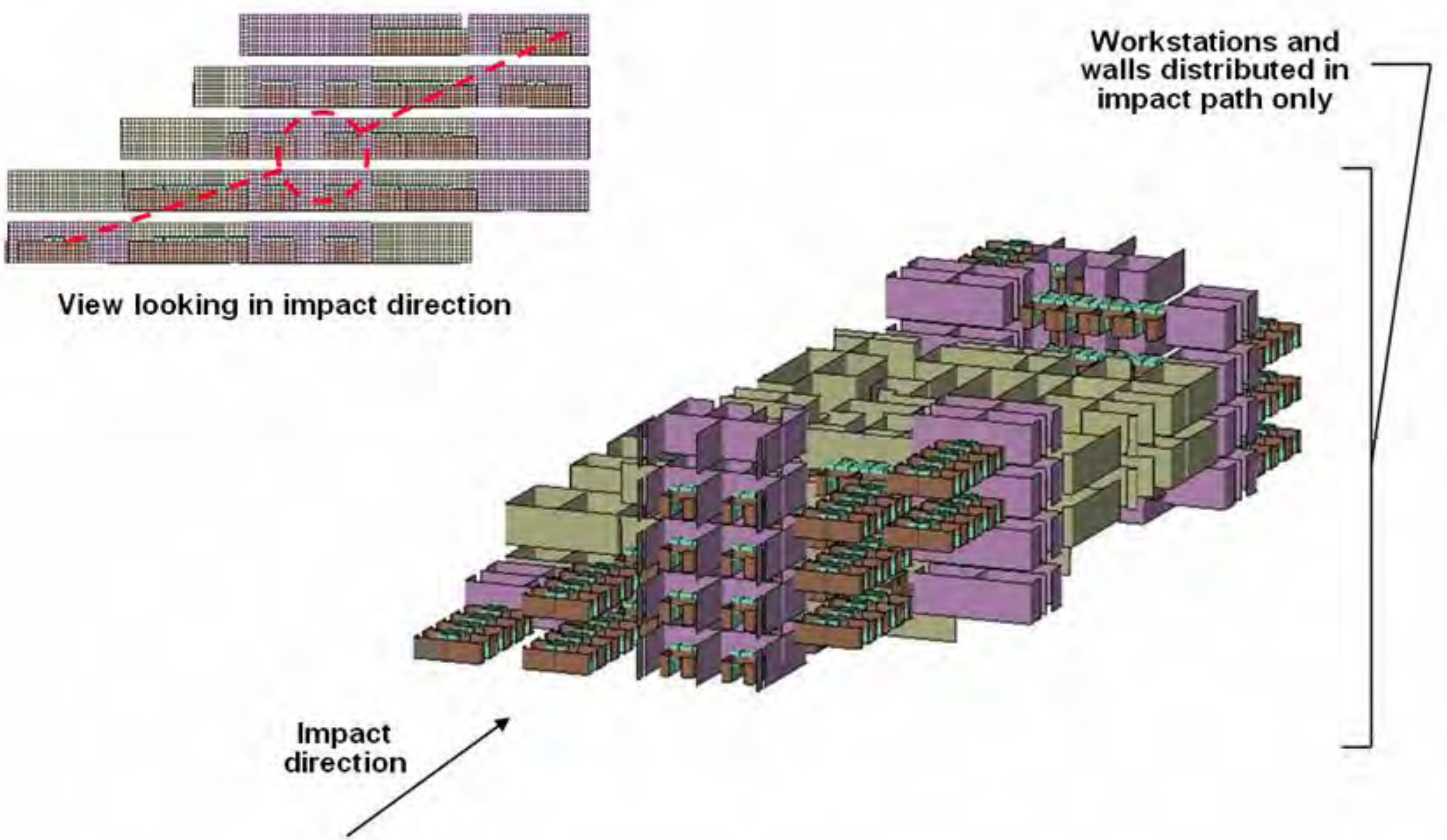


Tower Model Development:
96th floor of WTC 1 including interior contents

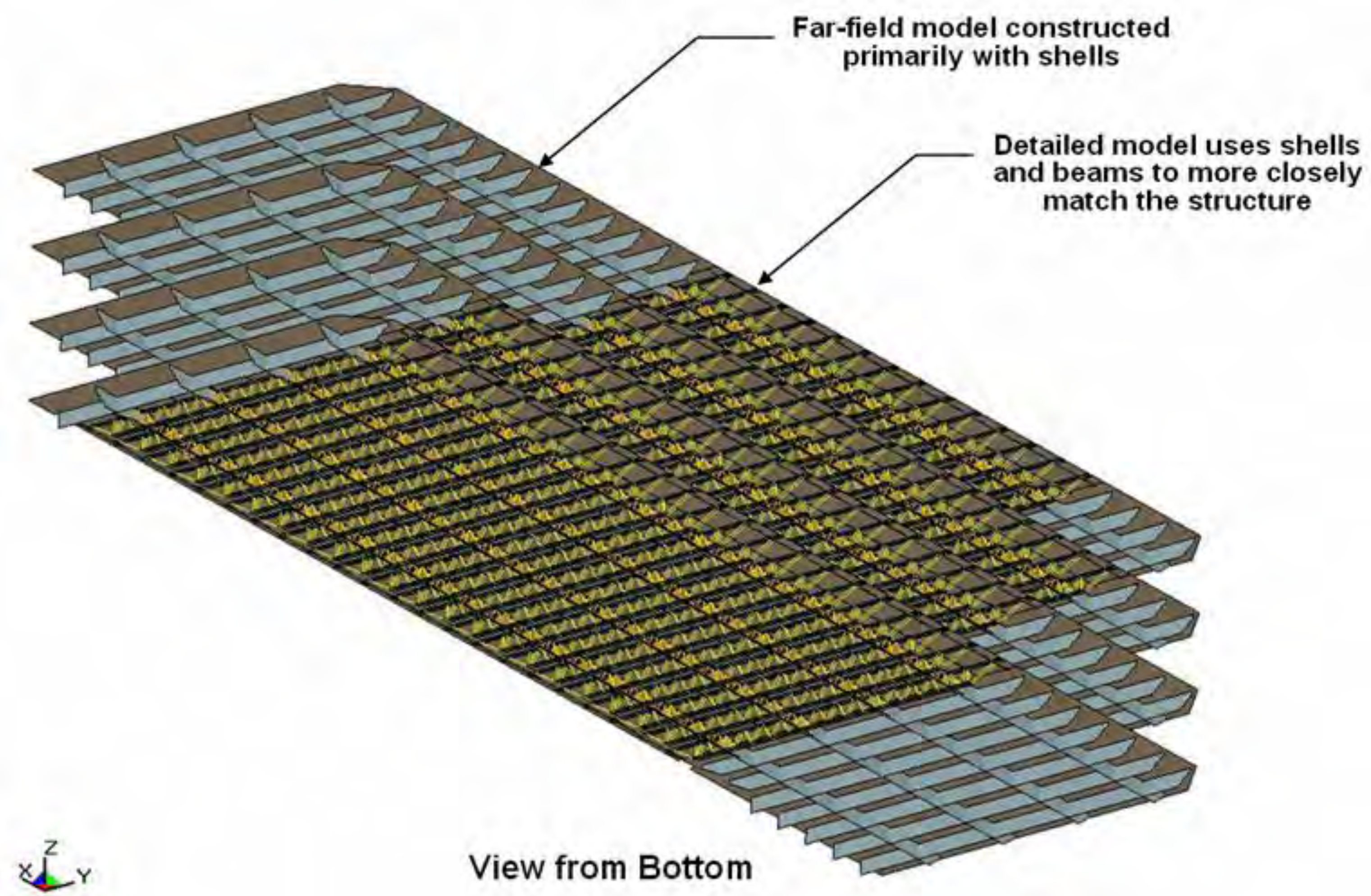
96th Floor Used as a Representative Floor Plan



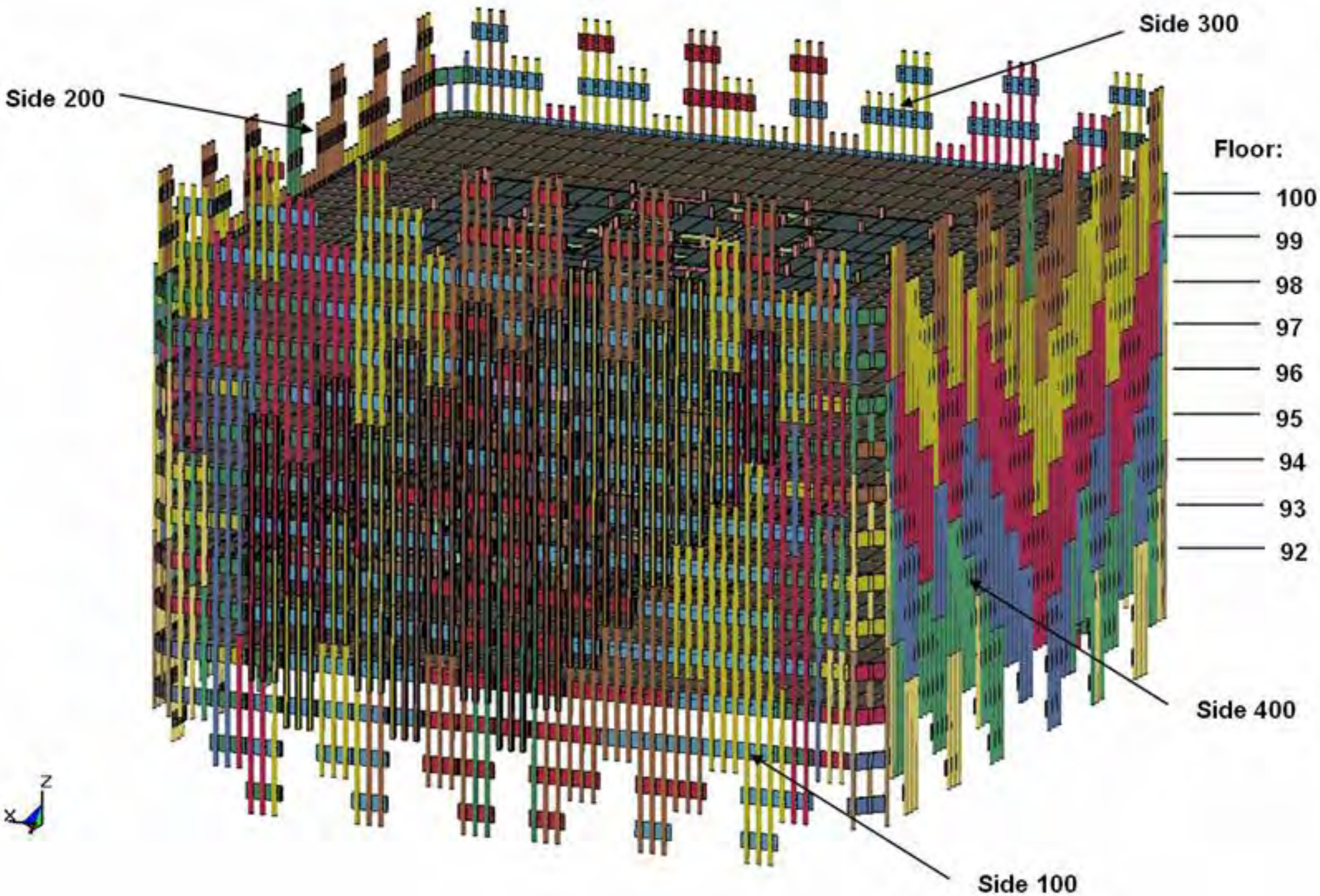
Tower Model Development:
96th floor of WTC 1 including interior contents



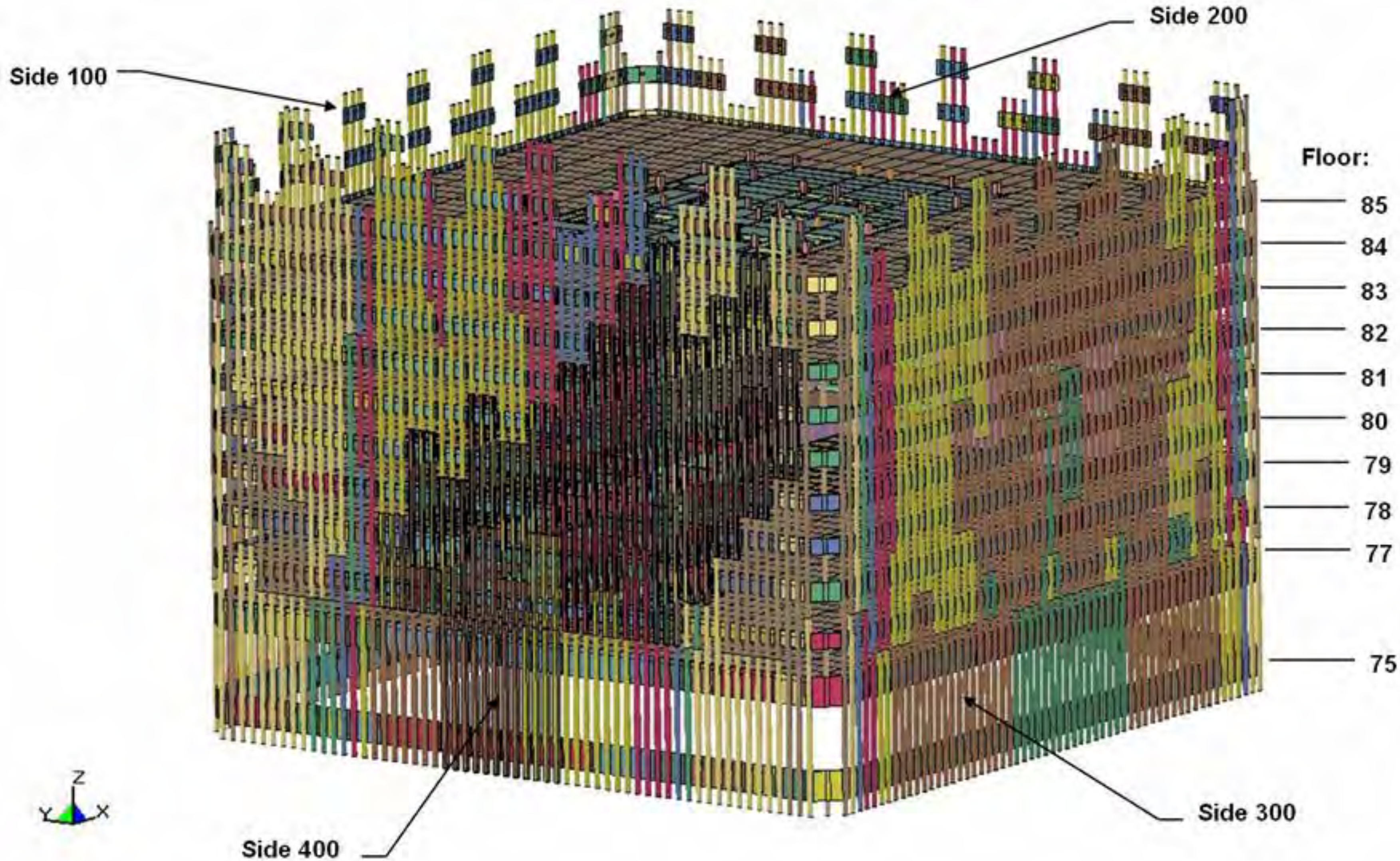
Tower Model Development:
96th floor of WTC 1 including interior contents



WTC 1 Global Tower Model

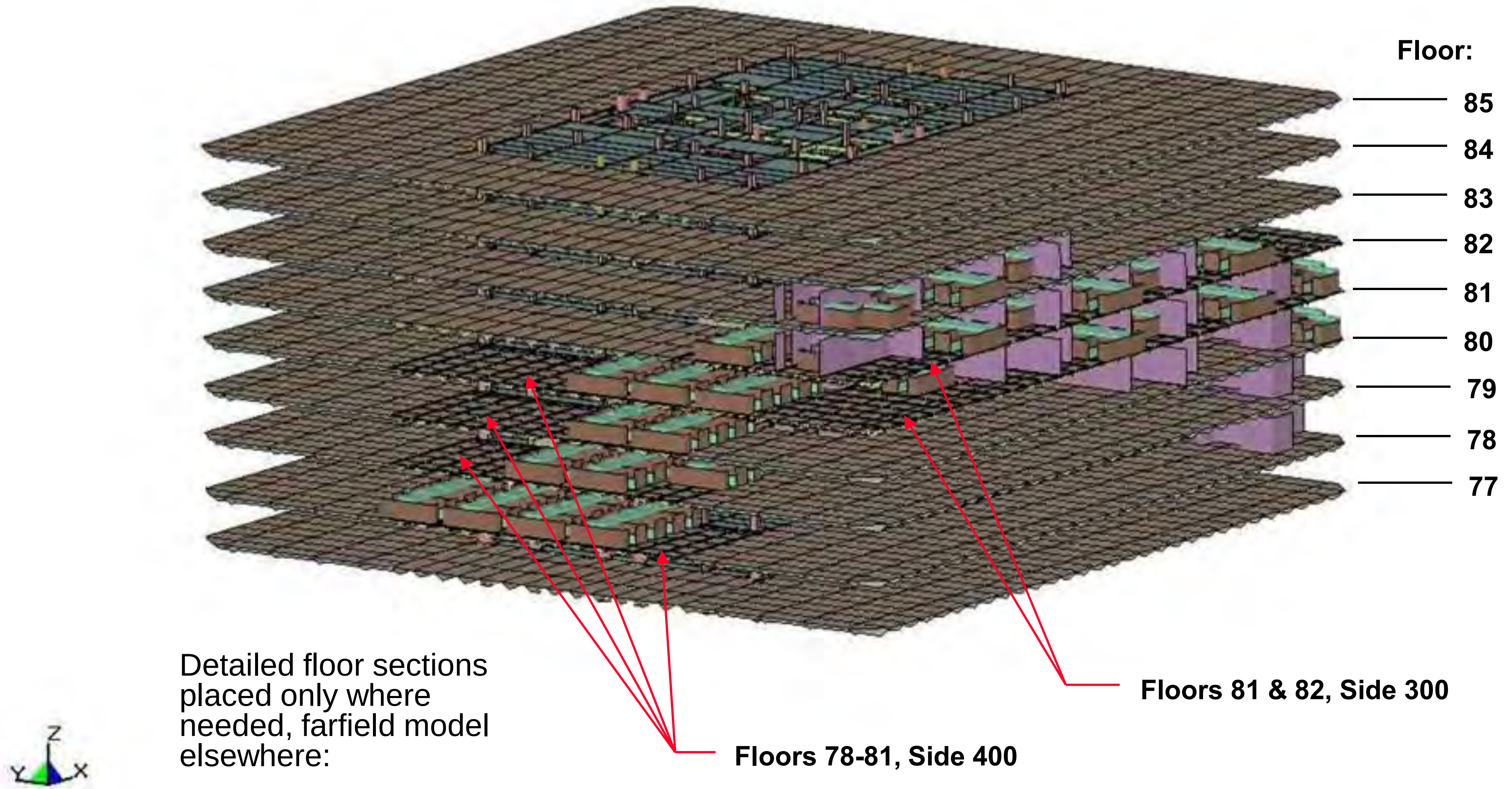


WTC 2 Global Tower Model



WTC 2 Global Tower Model

Exterior Removed



Detailed floor sections placed only where needed, farfield model elsewhere:

WTC Tower Model Parameters

Summary of the global impact models for the WTC towers.

	WTC 1 Tower Model	WTC 2 Tower Model
Number of Nodes	1,300,537	1,312,092
Hughes-Liu Beam Elements	47,952	53,488
Belytschko-Tsay Shell Elements	1,156,947	1,155,815
Constant Stress Solid Elements	2,805	2,498

Part 3
767 Model Development

- Data collection for the 767-200ER
- Development of aircraft model
- Fuel Distribution Analysis

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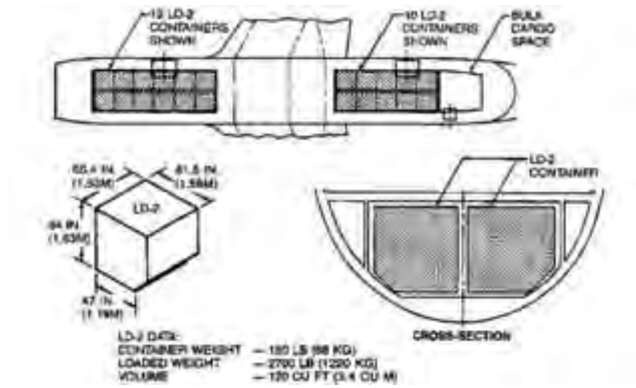
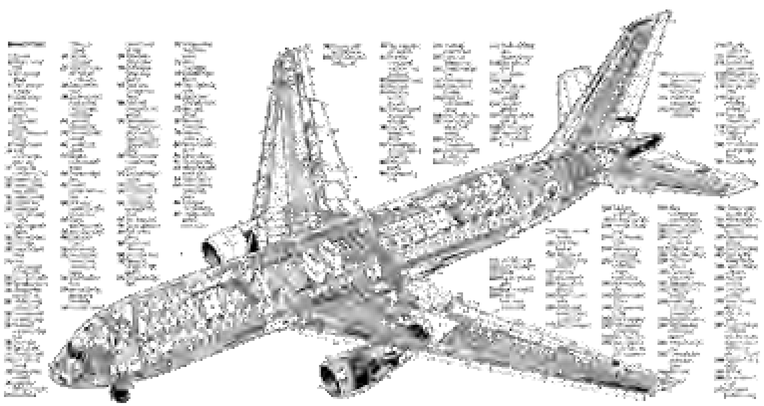
Aircraft Model Development:
Boeing 767-200ER

- Aircraft structural information collected from various sources.
- Remaining data was obtained from measurements on 767.



Airline Data



Open Literature Data Sources

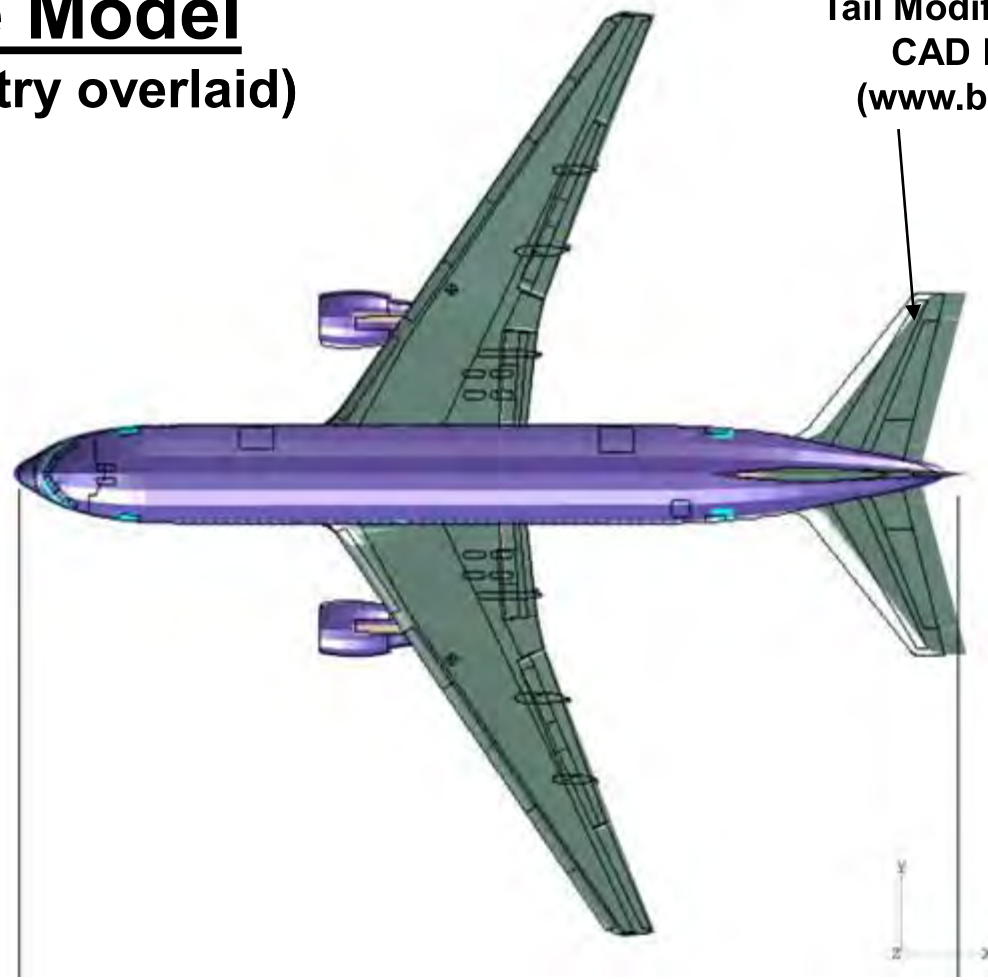
Commercially Available Geometry Models

Digimation Surface Model

Surface Model

(CAD geometry overlaid)

Tail Modified to match CAD Drawings (www.boeing.com)



Aircraft Inspection:
Main Landing Gear

Aircraft Inspection:

Ultrasonic thickness measurement of landing gear components

Nose gear measurement

Main landing gear beam measurement locations

Aircraft Inspection:
Control Surfaces and Control Linkage

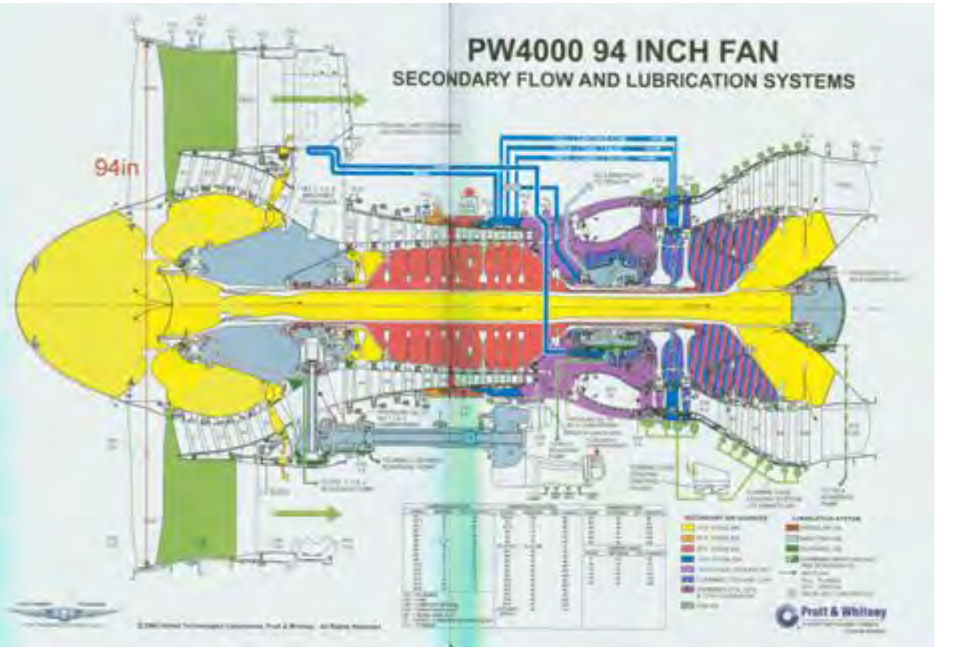
Passenger and Cargo Data

From United and American Airlines

	AA 11	UAL 175
Passengers and Crew	14,720 lbs	9,410 lbs
Freight	7,972 lbs	16,970 lbs
Luggage: Cargo hold	1,150 lbs	1,390 lbs
Luggage: Carry on	1,620 lbs	1,010 lbs
Catering	5,234 lbs	-
Total	**30,696 lbs**	**28,780 lbs**

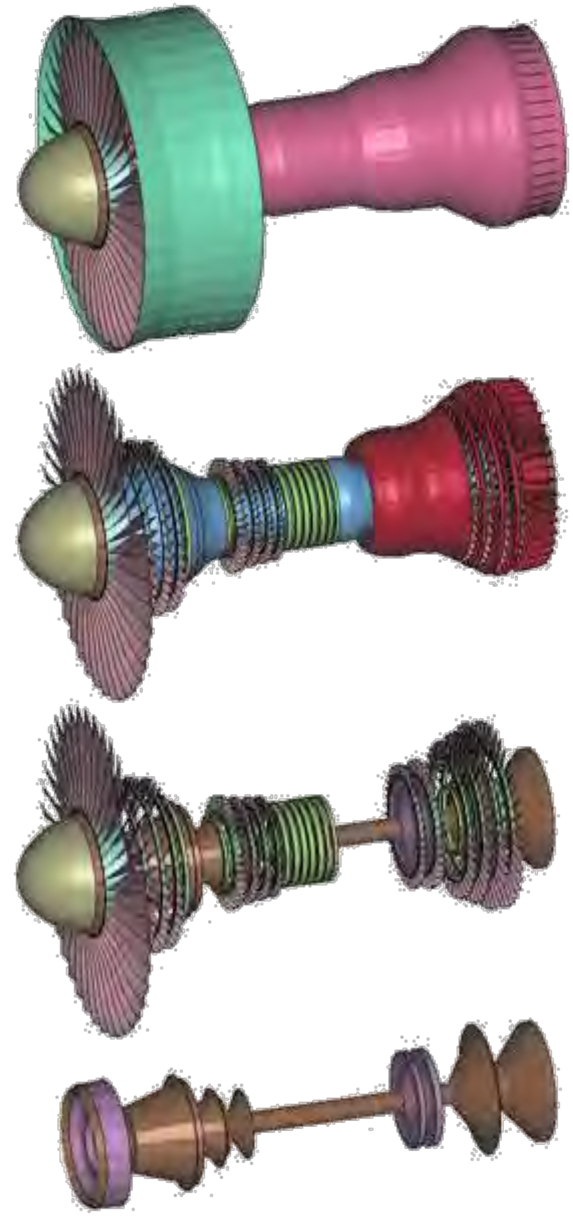
Engine Modeling: PW4000

- **Materials Received from Pratt & Whitney:**
  - PW4000 94 Inch Fan Secondary Flow and Lubrication Systems (CTC29748.20001020)
  - The Jet Engine (S14345)
  - PW4000/B747/767/ External Components Left Side (J38249)
  - PW4000/B747/767/ External Components Right Side (J38249)
  - PW4000 Engine Build Groups (ref. W058)
  - PW4000 94-Inch Fan Engine (S12049)

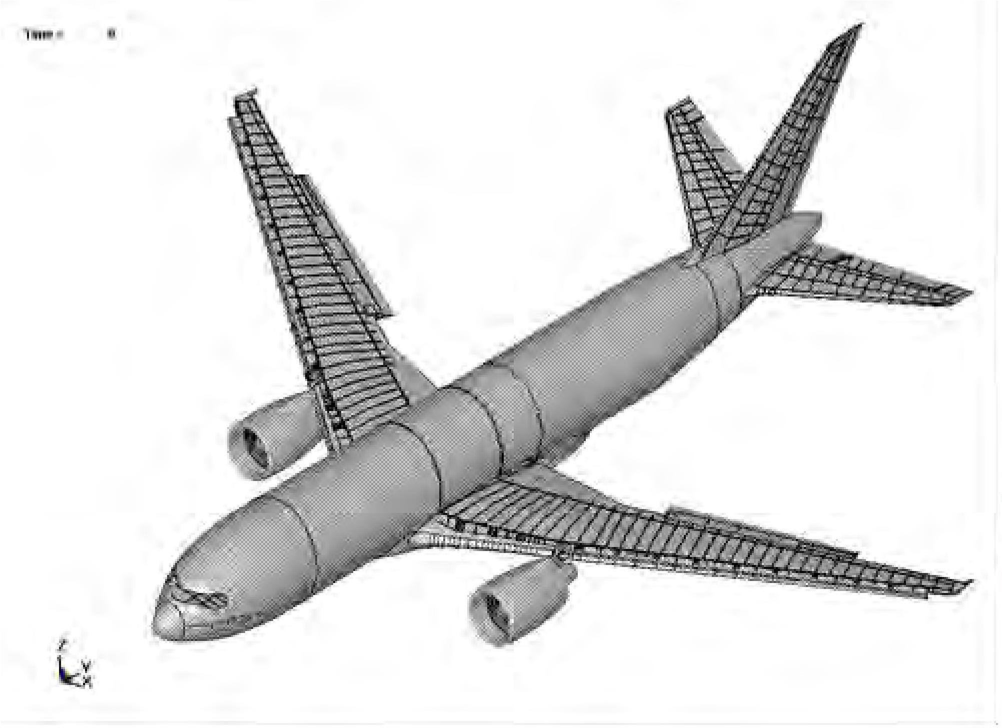


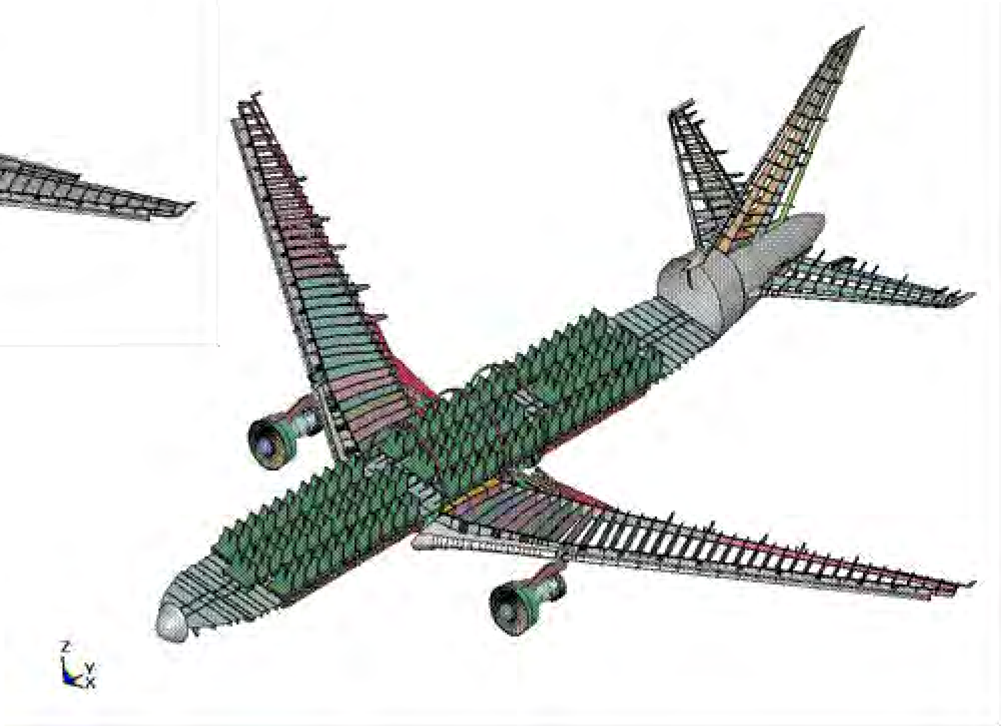
Engine Model

	PW4000 Engine Model
No. Brick Elements	9,560
No. Shell Elements	54,788
Total Nodes	101,822
Preliminary Engine Model Mass	7,873 lbs
Adjusted Engine Model Mass	9,447 lbs



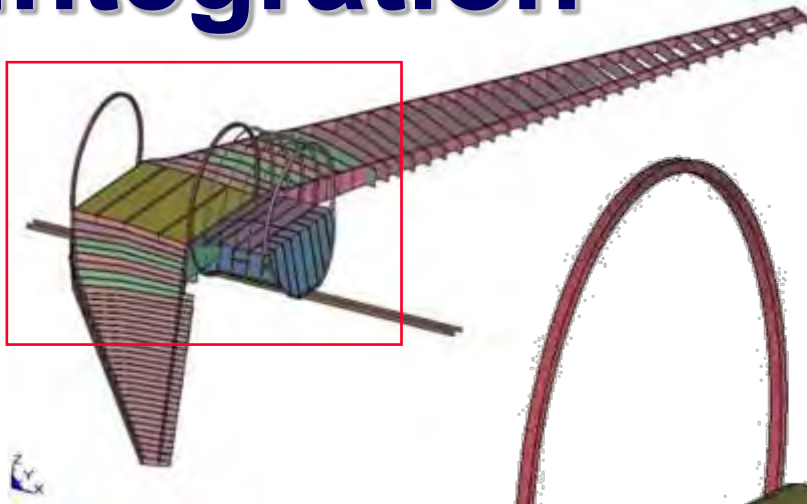
Boeing 767-200ER Aircraft Model

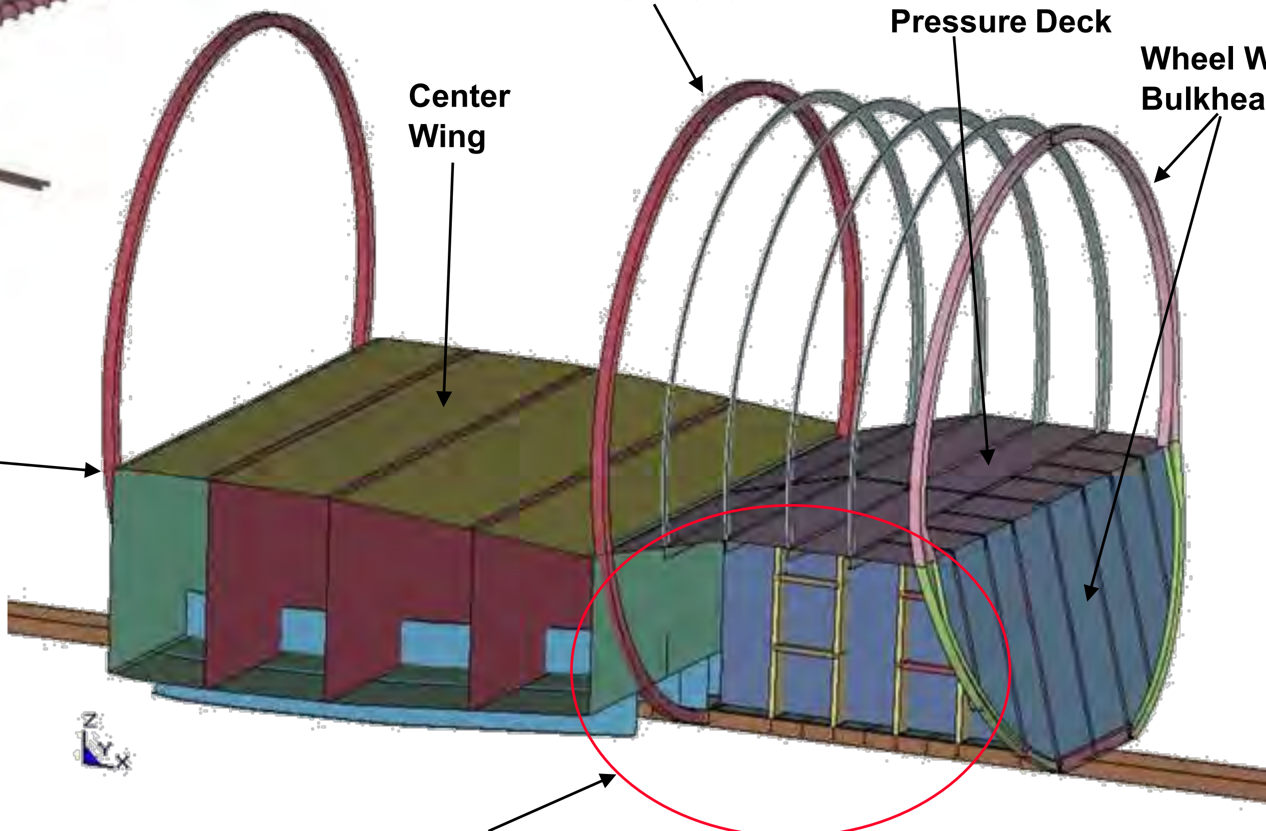




Finite Element Model of the Boeing 767-200ER.

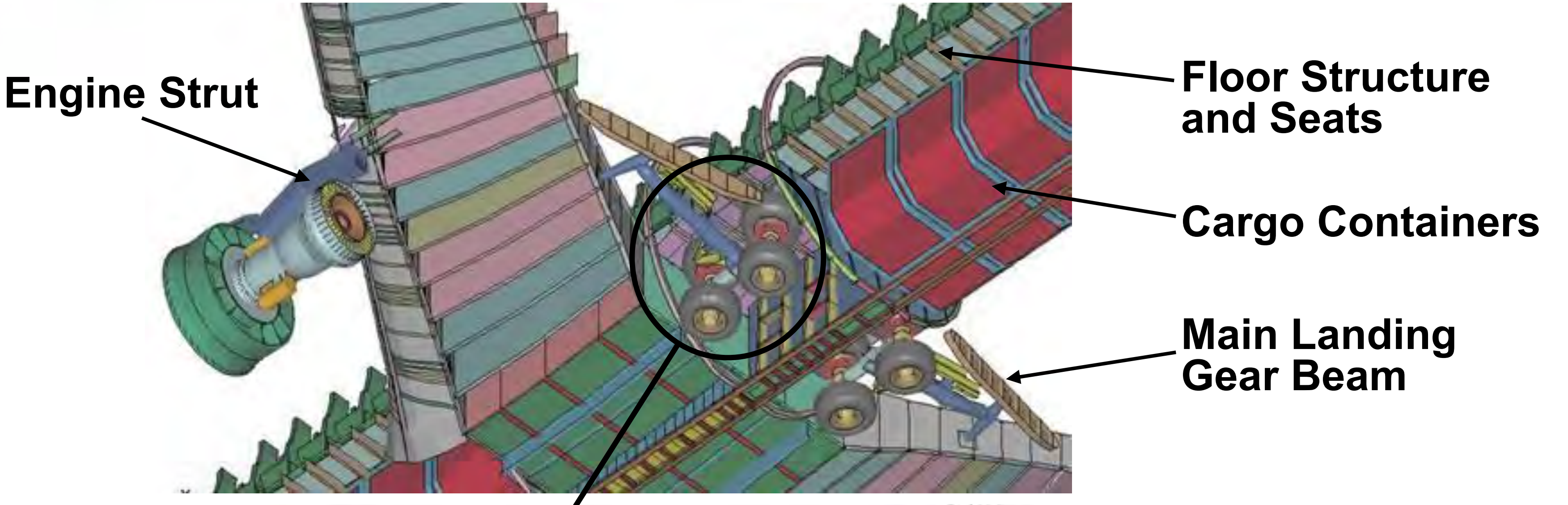
Fuselage Structure and Wing Integration

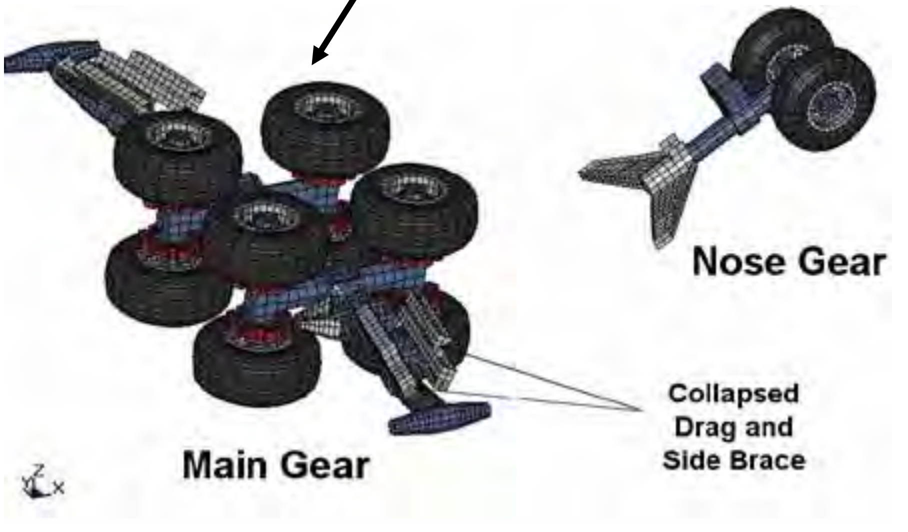




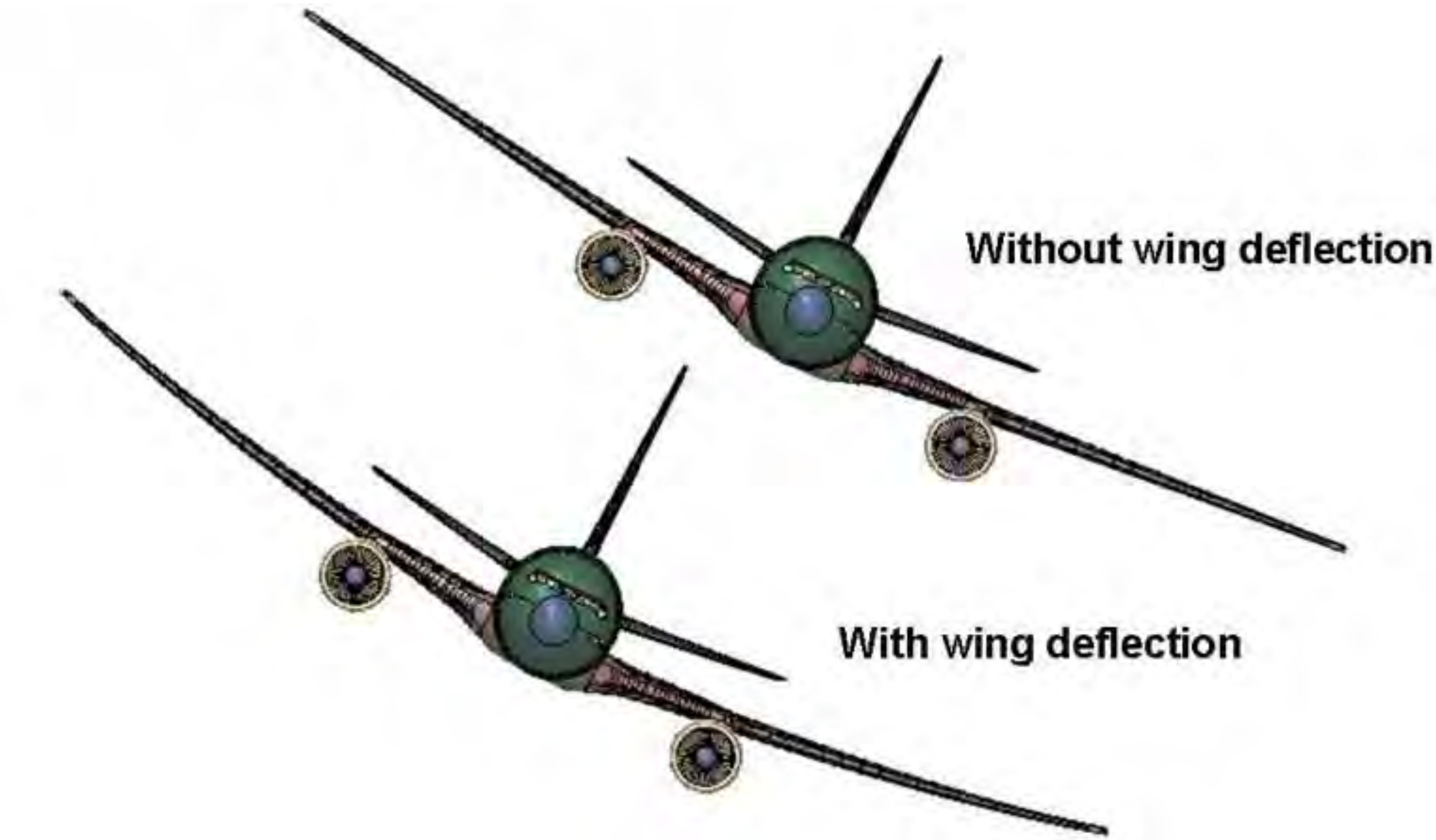
Aircraft Model

Internal Structure and Non-Structural Components

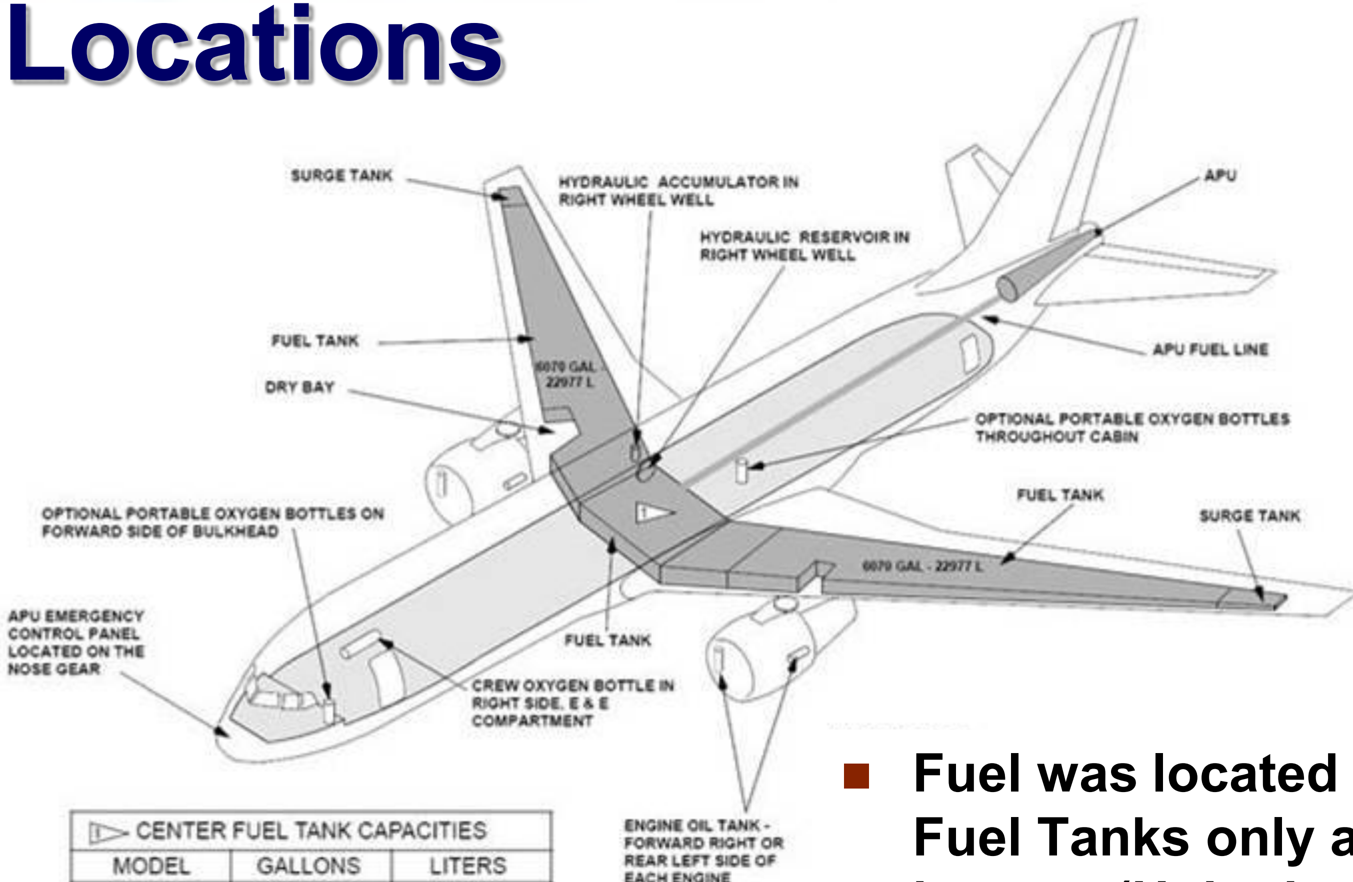




Boeing 767-200ER with Estimated Wing Deflection at Time of Impact



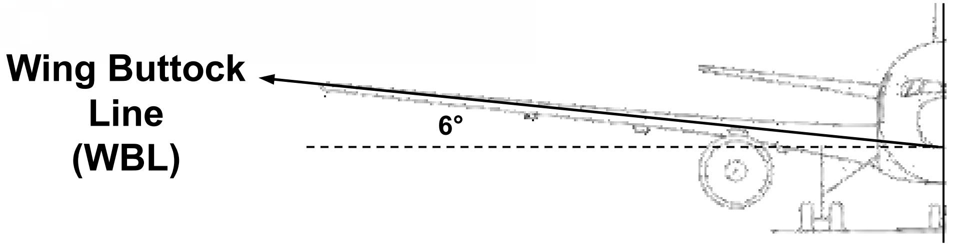
Fuel Tank Capacities and Locations

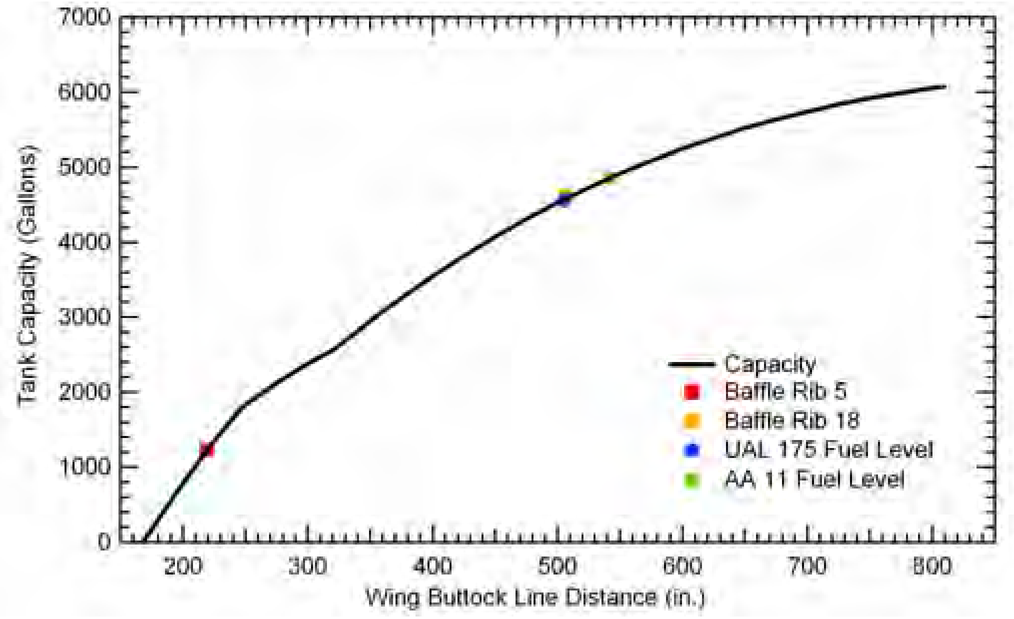


CENTER FUEL TANK CAPACITIES		
MODEL	GALLONS	LITERS
STANDARD	4,560	17,261
-200 ER	8,310	31,457
-300 ER	12,000	45,425
-400 ER	12,000	45,425

- Fuel was located in the Main Fuel Tanks only at the time of impact. (United and American Airlines Correspondence)

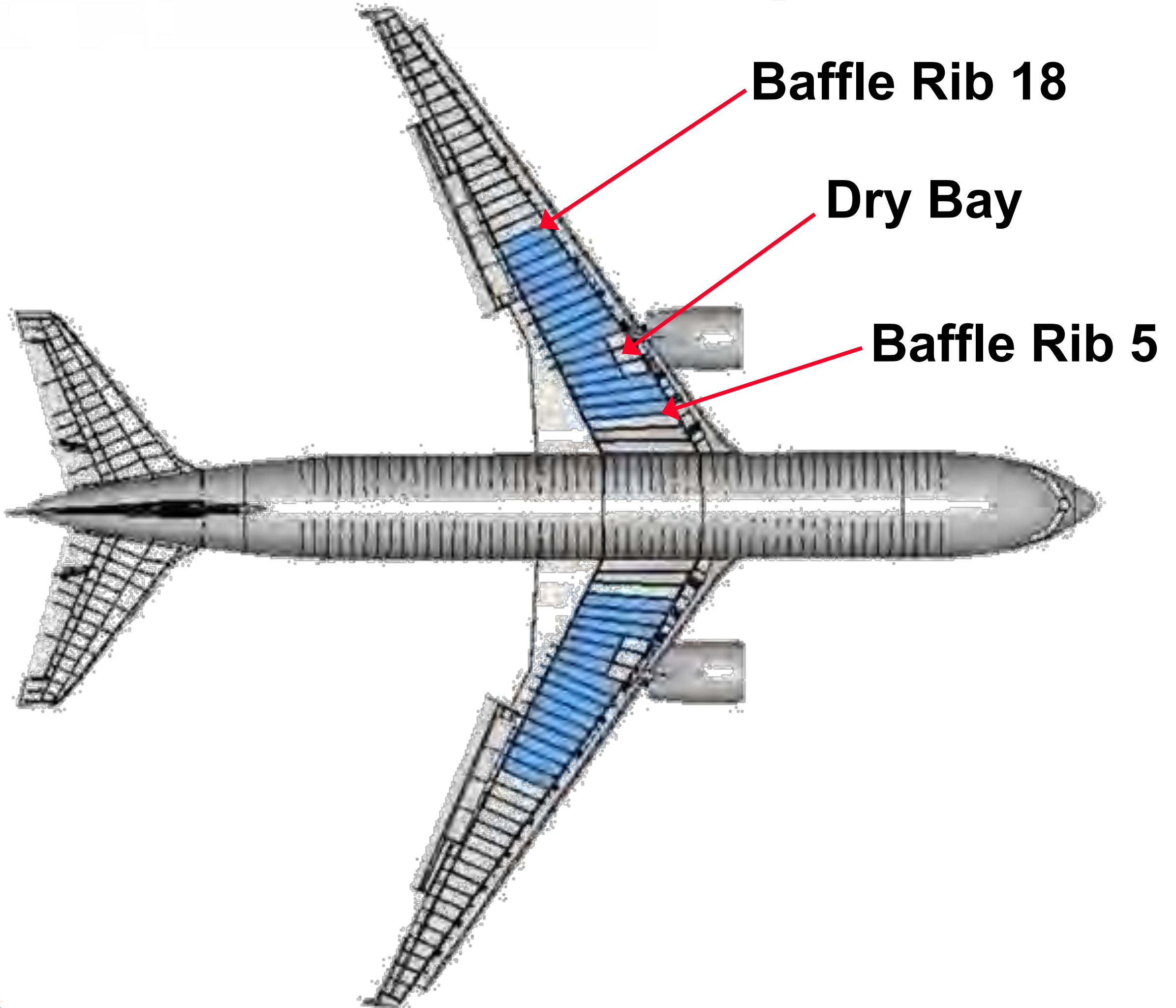
Fuel Tank Capacity and Fuel Distribution





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

Boeing 767-200ER with Fuel Load at Time of Impact



Boeing 767-200ER
Aircraft Model Parameters

	AA 11	UAL 175
No. Brick Elements	70,000	70,000
No. Shell Elements	562,000	562,000
No. SPH Fuel Particles	60,672	60,672
Total Nodes	740,000	740,000
Total Weight (Empty)	183,500 lbs	183,500 lbs
ULD/Cargo Weight	12,420 lbs	21,660 lbs
Cabin Contents Weight	21,580 lbs	10,420 lbs
Fuel Weight	66,100 lbs	62,000 lbs
Total Weight (Loaded)	**283,600 lbs**	**277,580 lbs**

Part 4
Component Impact Analyses

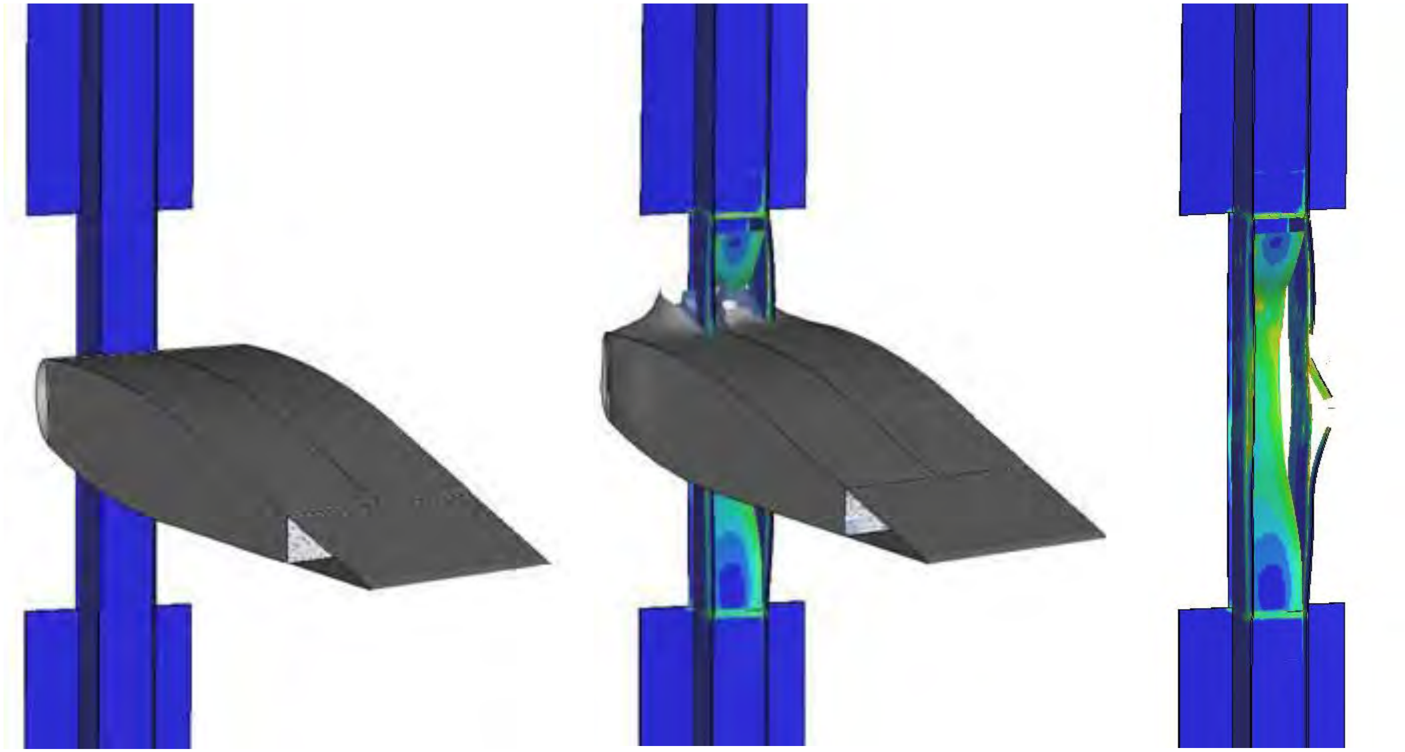
- **Exterior columns, core columns, and floor assembly components.**
- **Engine and wing section impactors.**

Component Level Analyses

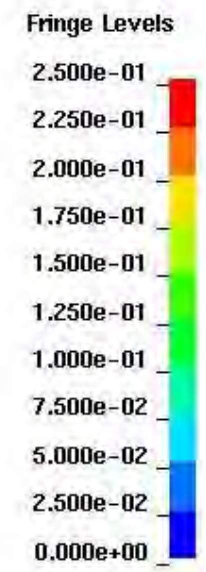
- **Primary objective is to develop the simulation techniques required for the global analysis of the aircraft impacts into the WTC towers.**
  - **Develop reduced FE models appropriate for high fidelity global impact analyses.**
- **Primary Component Simulations:**
  - **An exterior column impacted by an aircraft engine.**
  - **An interior column impacted by an aircraft engine.**
  - **An exterior column impacted by an aircraft wing segment.**
  - **An exterior column impacted by an aircraft wing filled with fuel.**
- **Additional Component Simulations:**
  - **Floor system with concrete slab obliquely impacted by an engine.**
  - **Bolted column and spandrel connections.**

Preliminary Component Analyses

- Detailed brick element column model.
- Shell elements for wing and fuel tank section.
- Fuel effects included.
  - Lagrangian fuel model.
- Failure modes of column analyzed.
- Model uses first estimate of material properties
  - 60 ksi yield Bilinear E-P column
  - 42 ksi yield Bilinear E-P spandrel
  - 30% failure strain

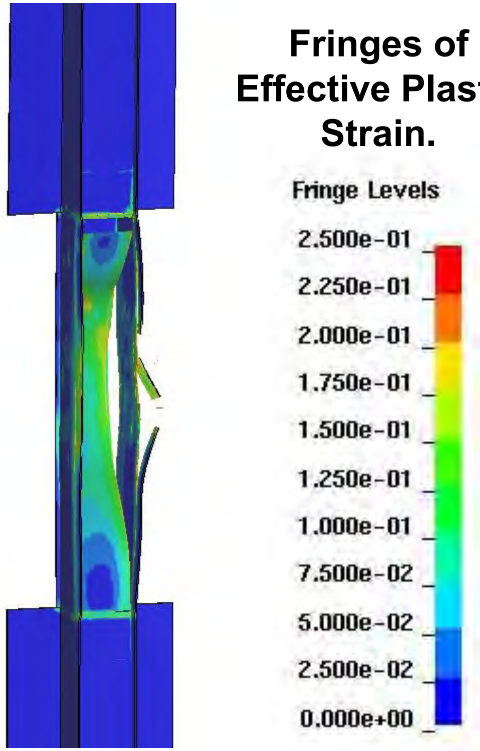


Fringes of Effective Plastic Strain.



Preliminary Component Analysis

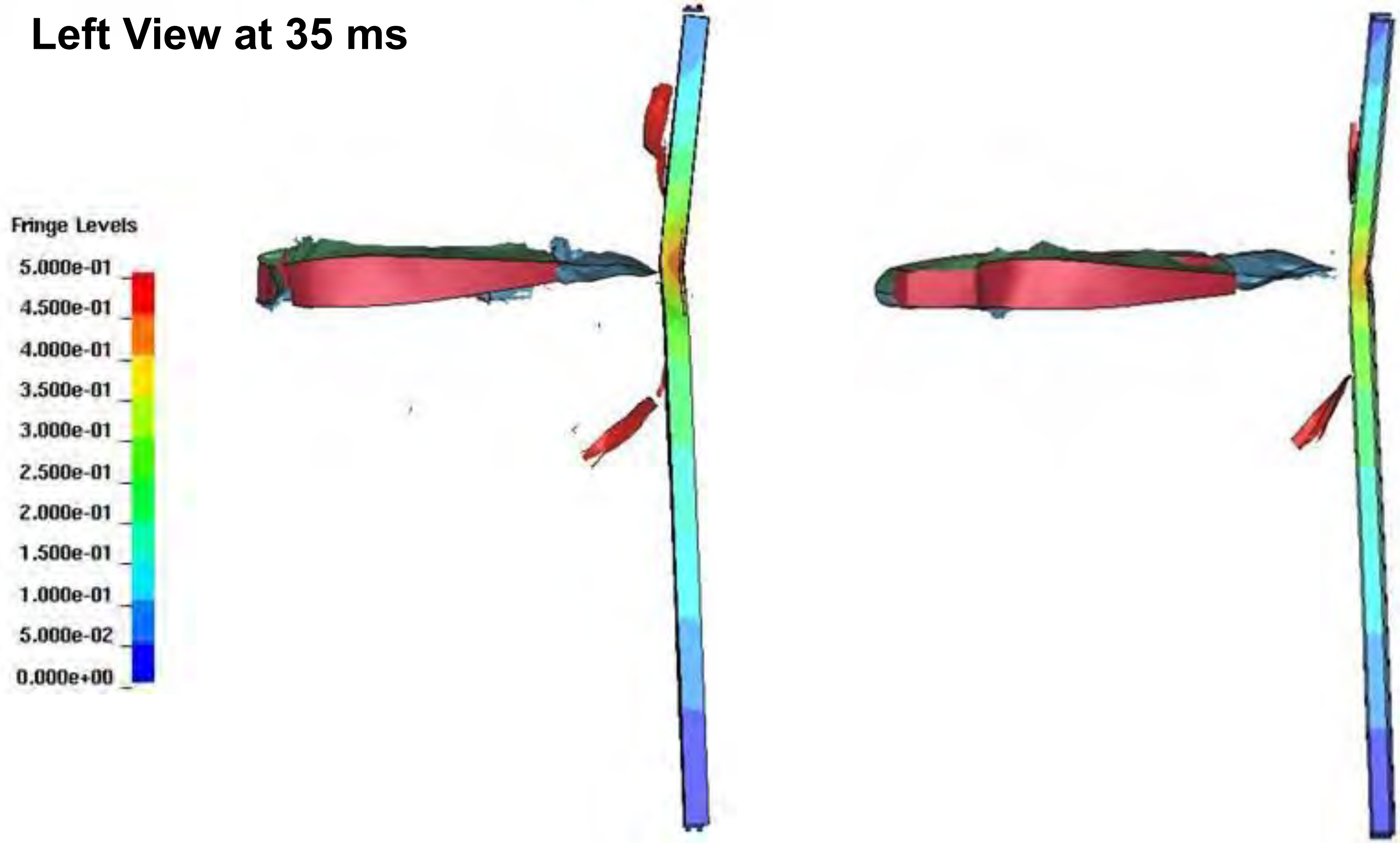
- Failure modes of column analyzed.
  - Shear failures of front plate.
  - Subsequent shear failure of back plate.
- Fuel overloads column welds
  - Subsequent analyses have no fuel for more subtle column response.



Component: External Column

Response Comparison [Displaying Contours of Resultant Displacement (m)]

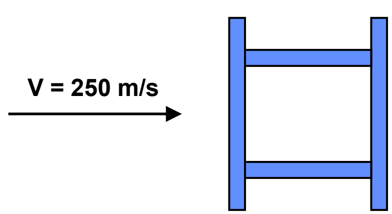
Left View at 35 ms



Fine Brick Element Model **Coarse Shell Element Model**

Core Box Column Impact

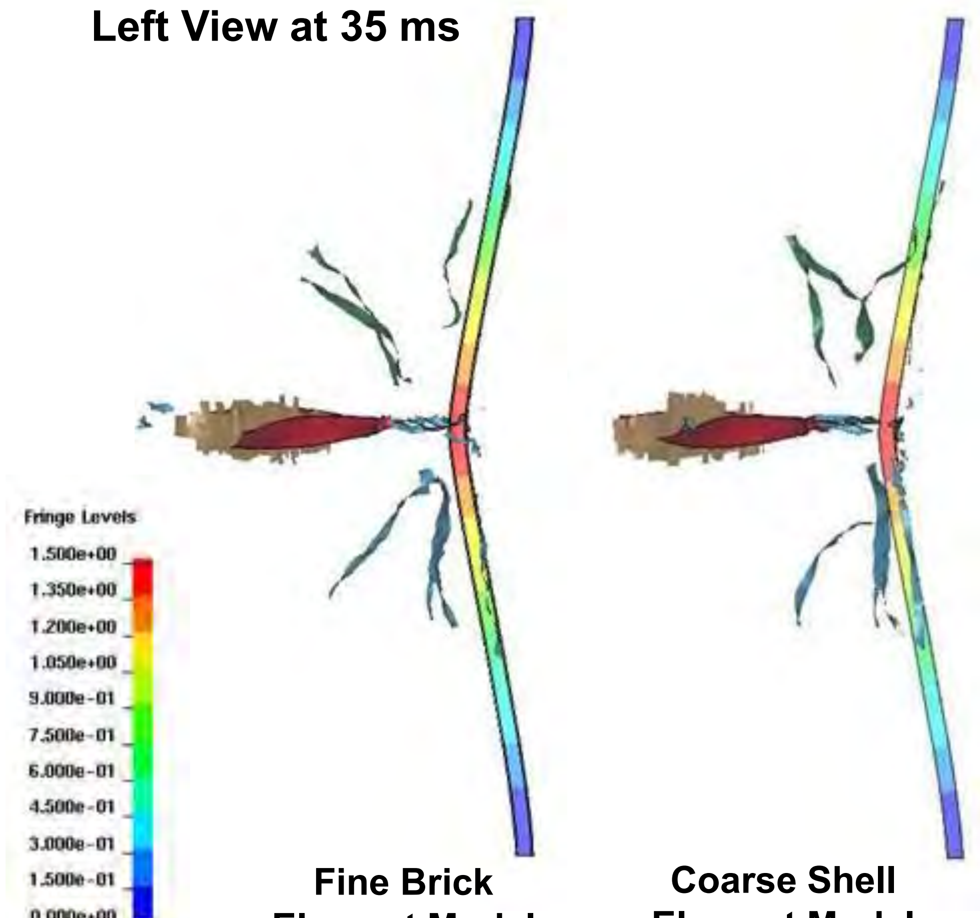
- Modeling Considerations
  - Column 801B, 77-80 Modeled
  - Impactor: Wing section with fuel
    - Standard Fuel density
    - 250 m/s impact
      (est. WTC 2 impact speed)
    - Impact on flange side
      - WTC-B impact scenario for 801B
  - BC treated by fixing ends of long column



Model Comparison

[Displaying Contours of Resultant Displacement (m)]

Left View at 35 ms



Fine Brick Element Model

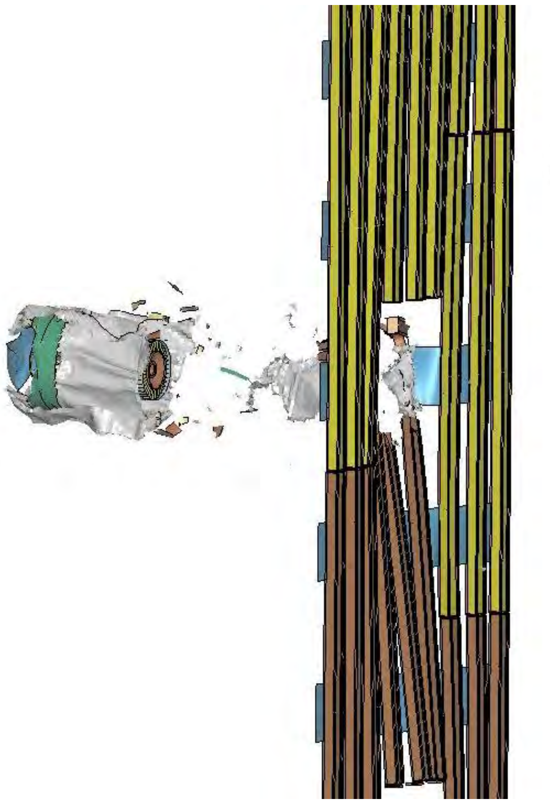
Coarse Shell Element Model

Engine & Exterior Wall

- Three Panels Wide
- Spandrel Centered Impact

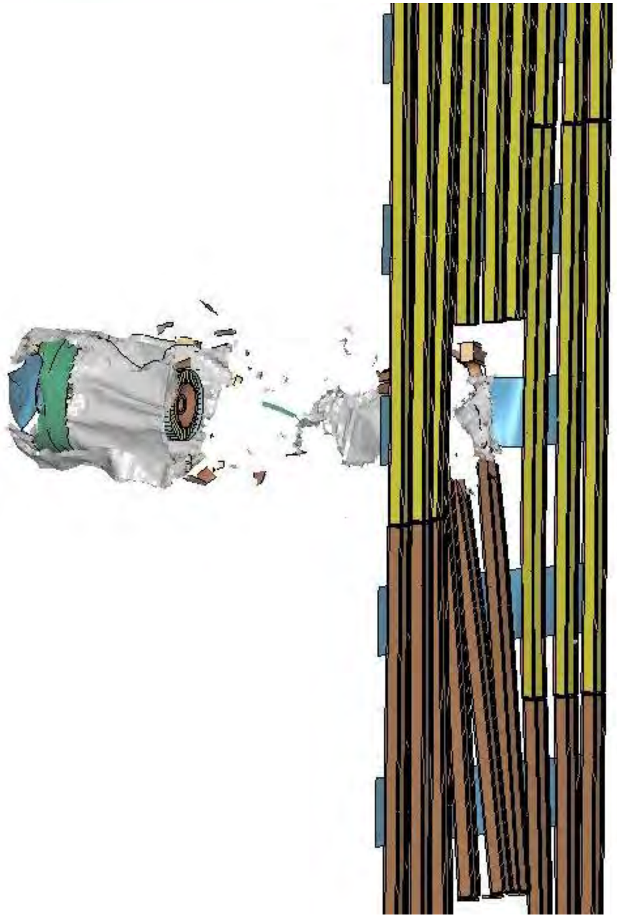
Initial Configuration

Impact Response at 40 ms



Impact Response at 80 ms

Engine & Exterior Wall



Spandrel Centered Impact

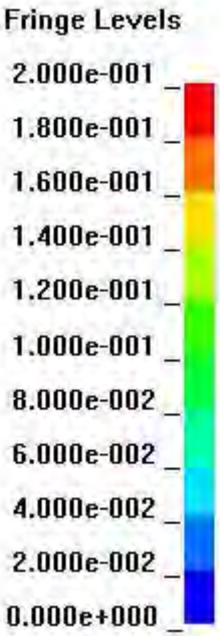
Between Spandrel Impact

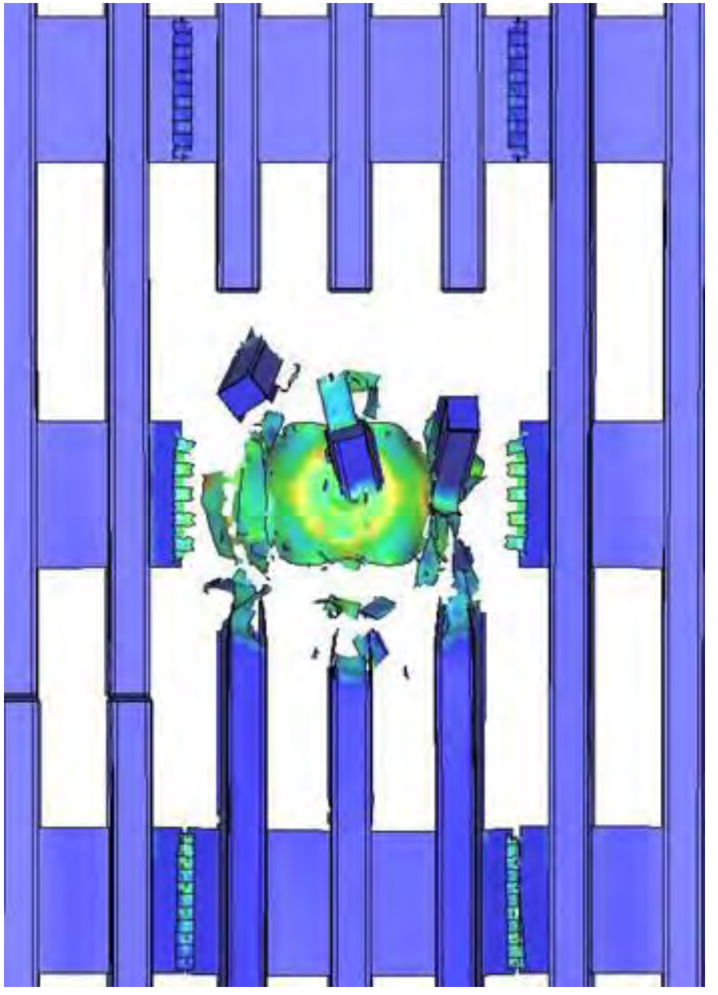
Impact Response at 80 ms

Spandrel Splice Plate Model

Connection: **Merged Spandrels** **Spandrels Plates**

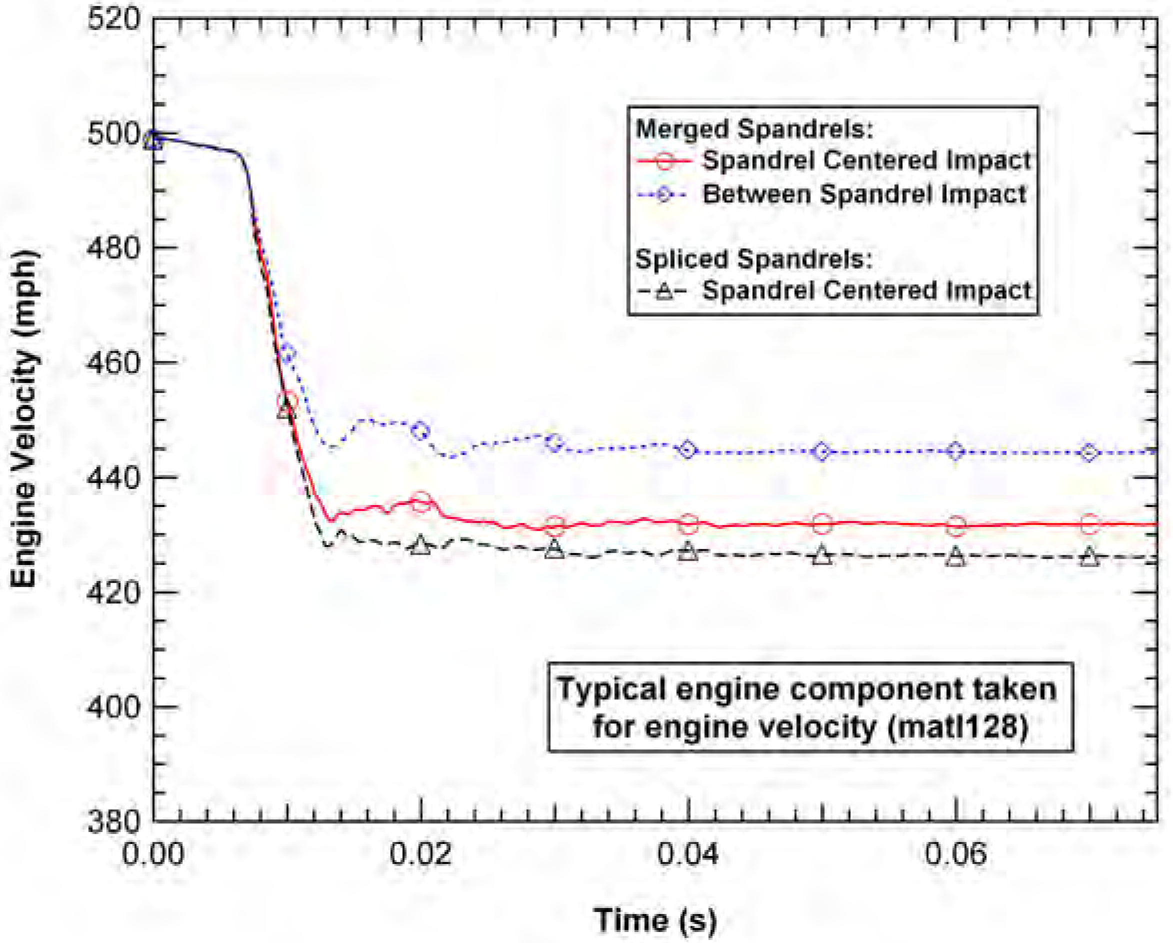
Plastic Strain





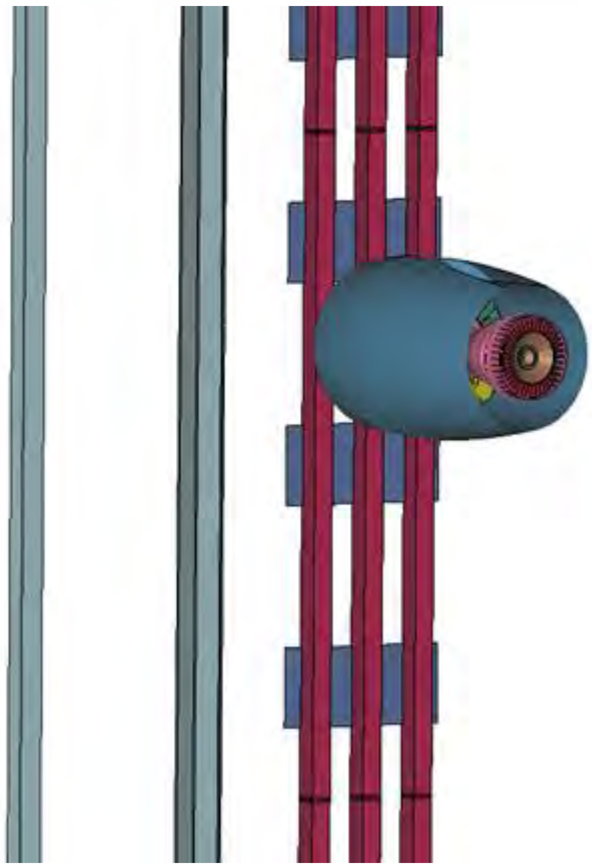
t = 75 ms

Engine & Exterior Wall

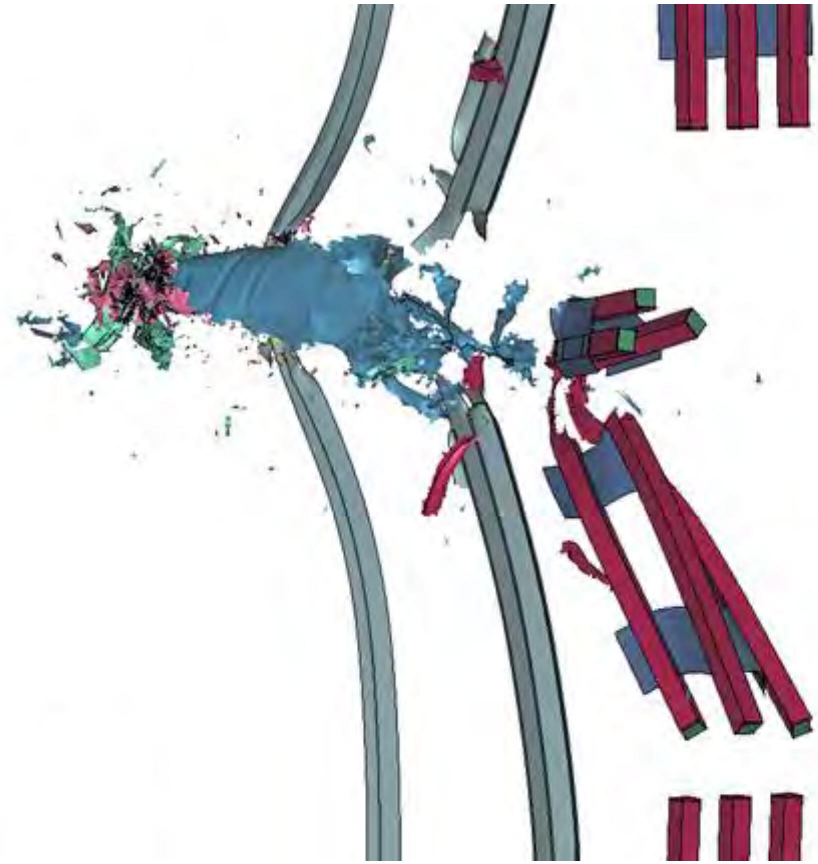


Comparison of Various Engine Impact Conditions

Engine Impact Analysis



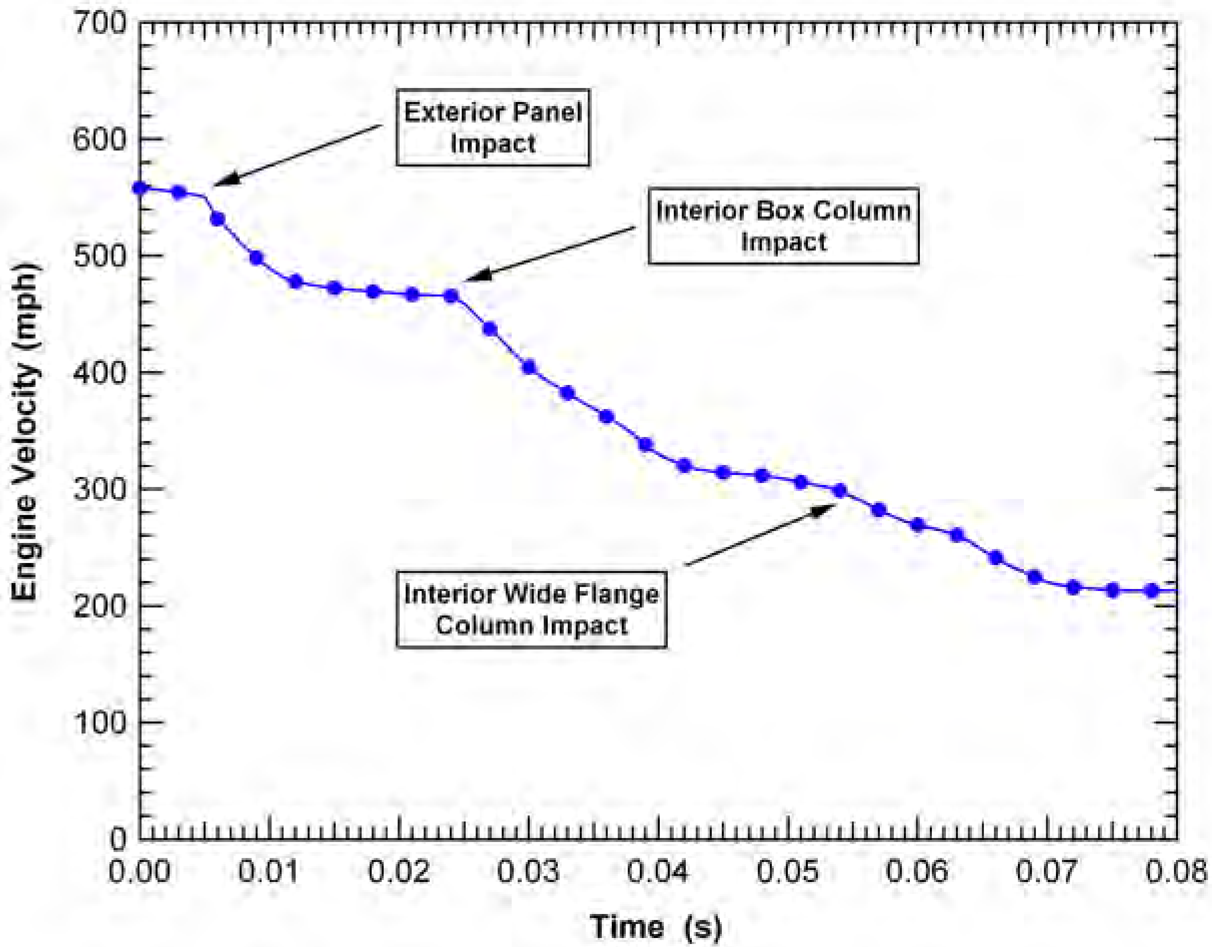
Initial Configuration



Impact Response at 90 ms

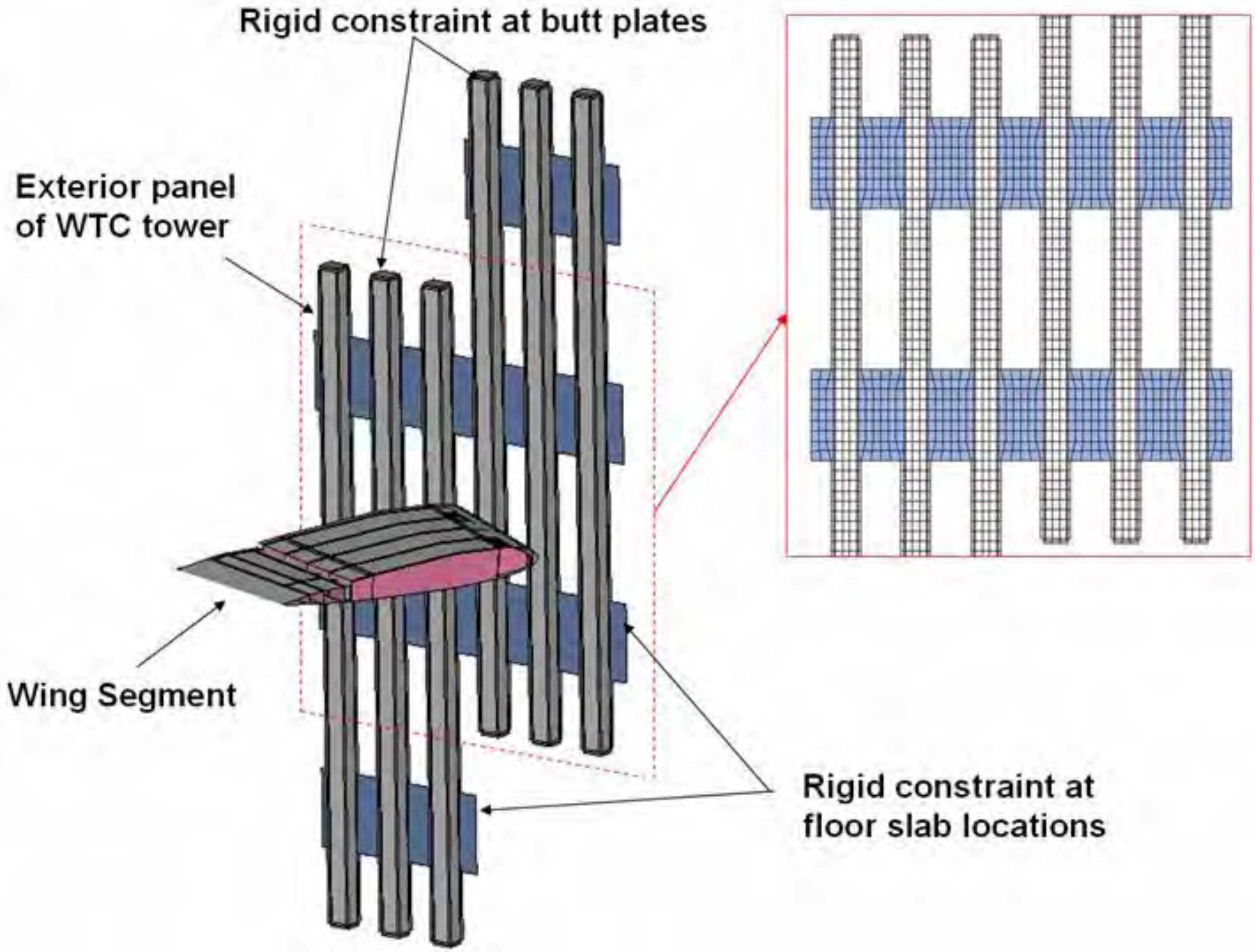
Combined Engine Impact Analysis – Exterior and Core Columns

Engine Impact Analysis

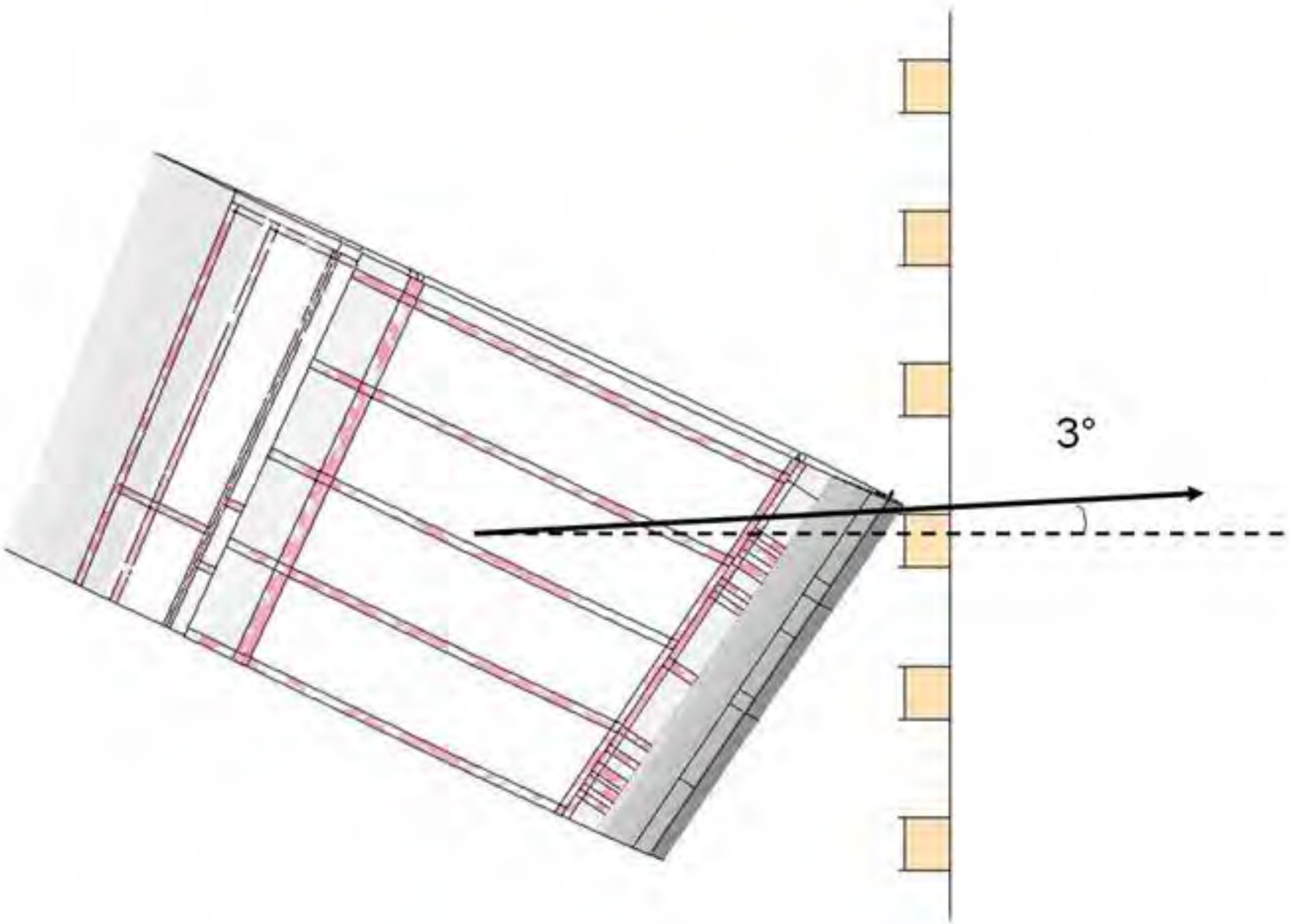


Combined Engine Impact Analysis – Exterior and Core Columns

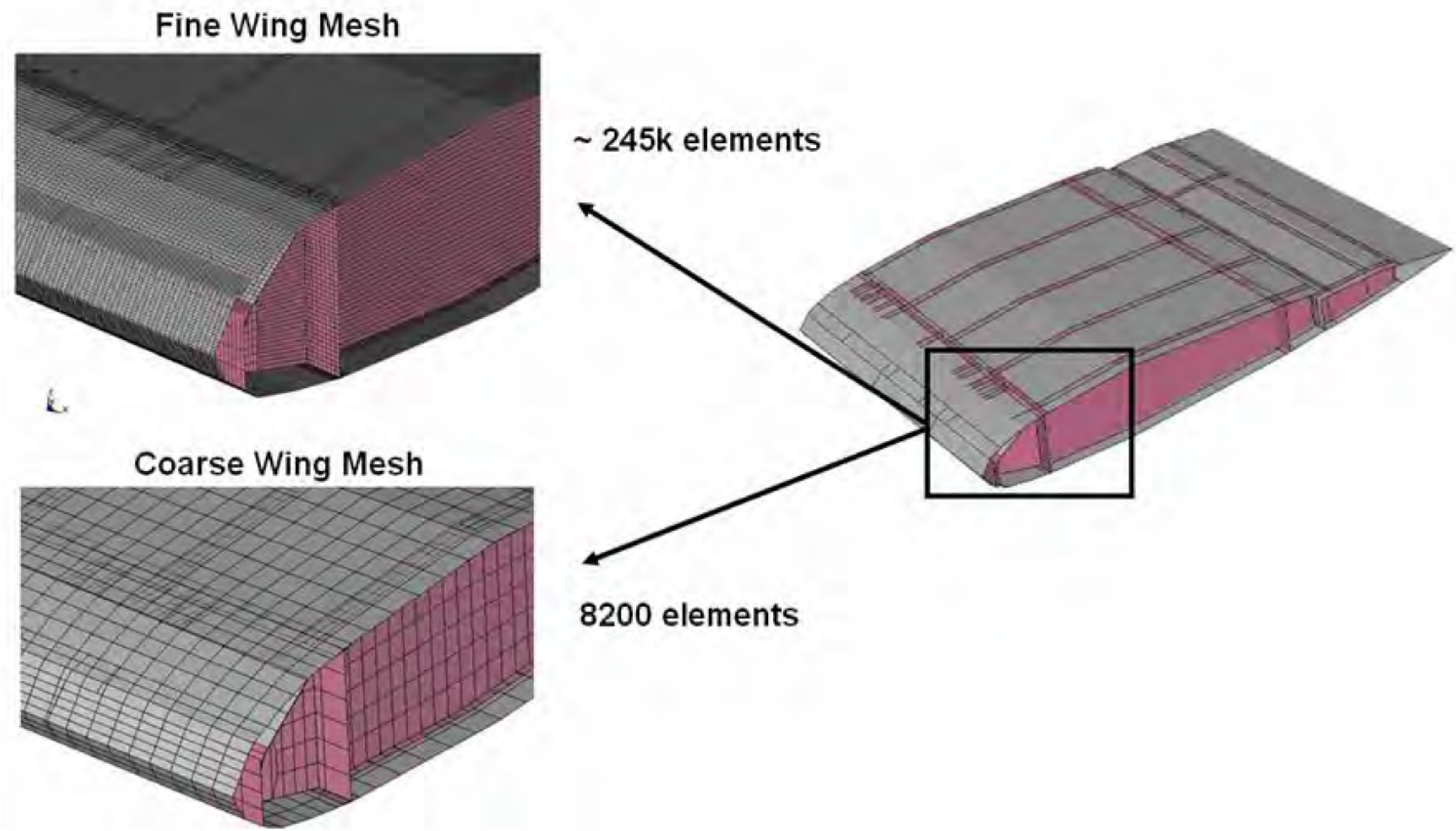
Wing Segment Component Analysis
Two Exterior Panels



Wing Segment Component Analysis
Two Exterior Panels

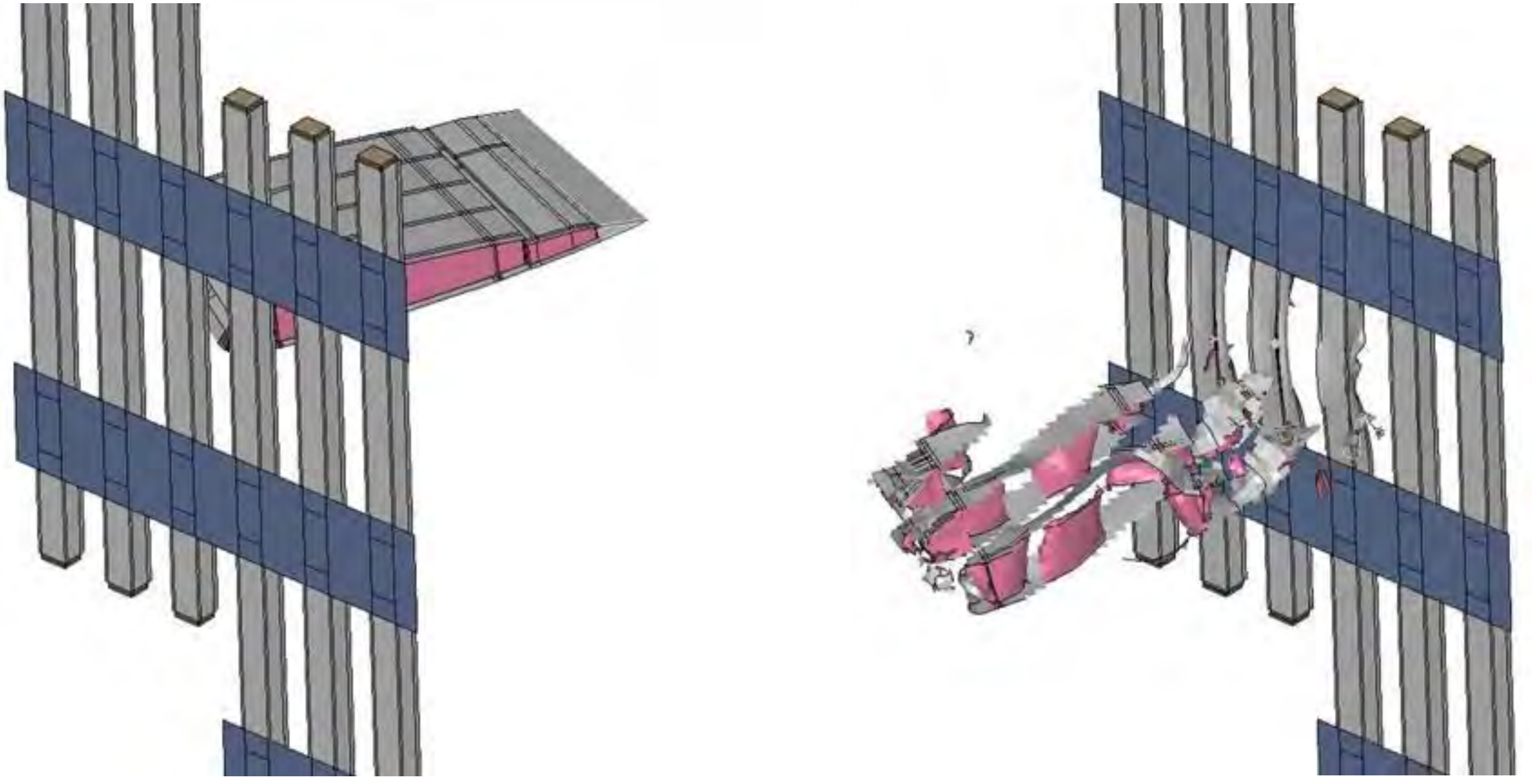


Wing Segment Component Analysis



Empty Wing Section Impact

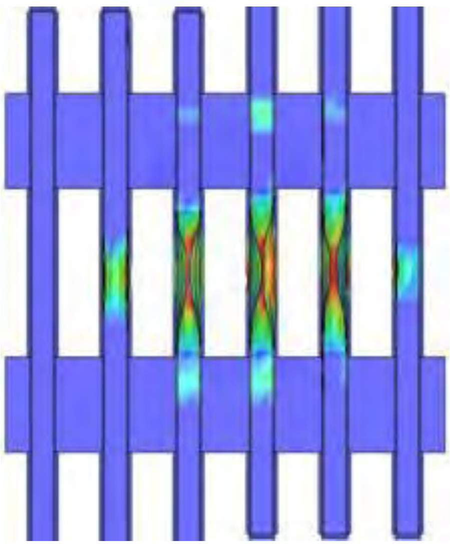
442 mph



Initial Configuration Impact Response at 40 ms

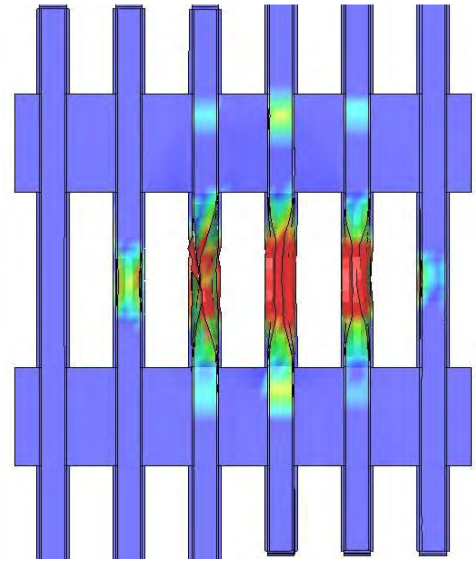
Coarse Shell Element Wing Section Model

Wing Segment Component Analysis

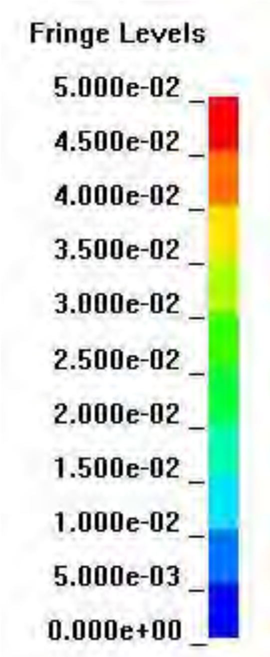


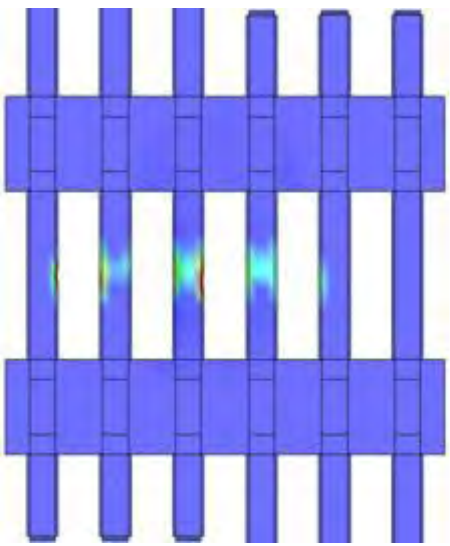
Fine Mesh (Front)

Coarse Mesh (Front)



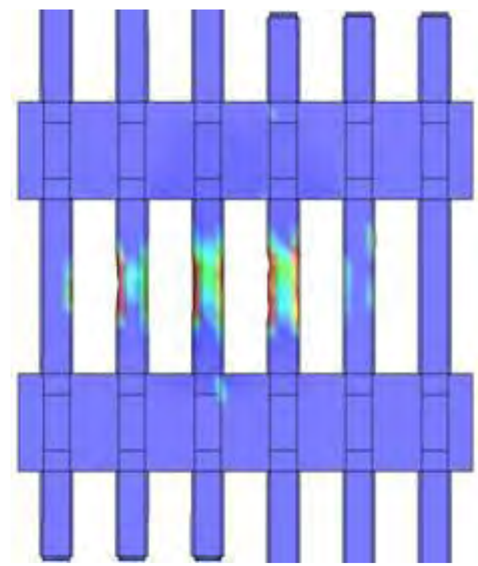
Effective Plastic Strain





Fine Mesh (Back)

Coarse Mesh (Back)



Treatment of Aircraft Fuel

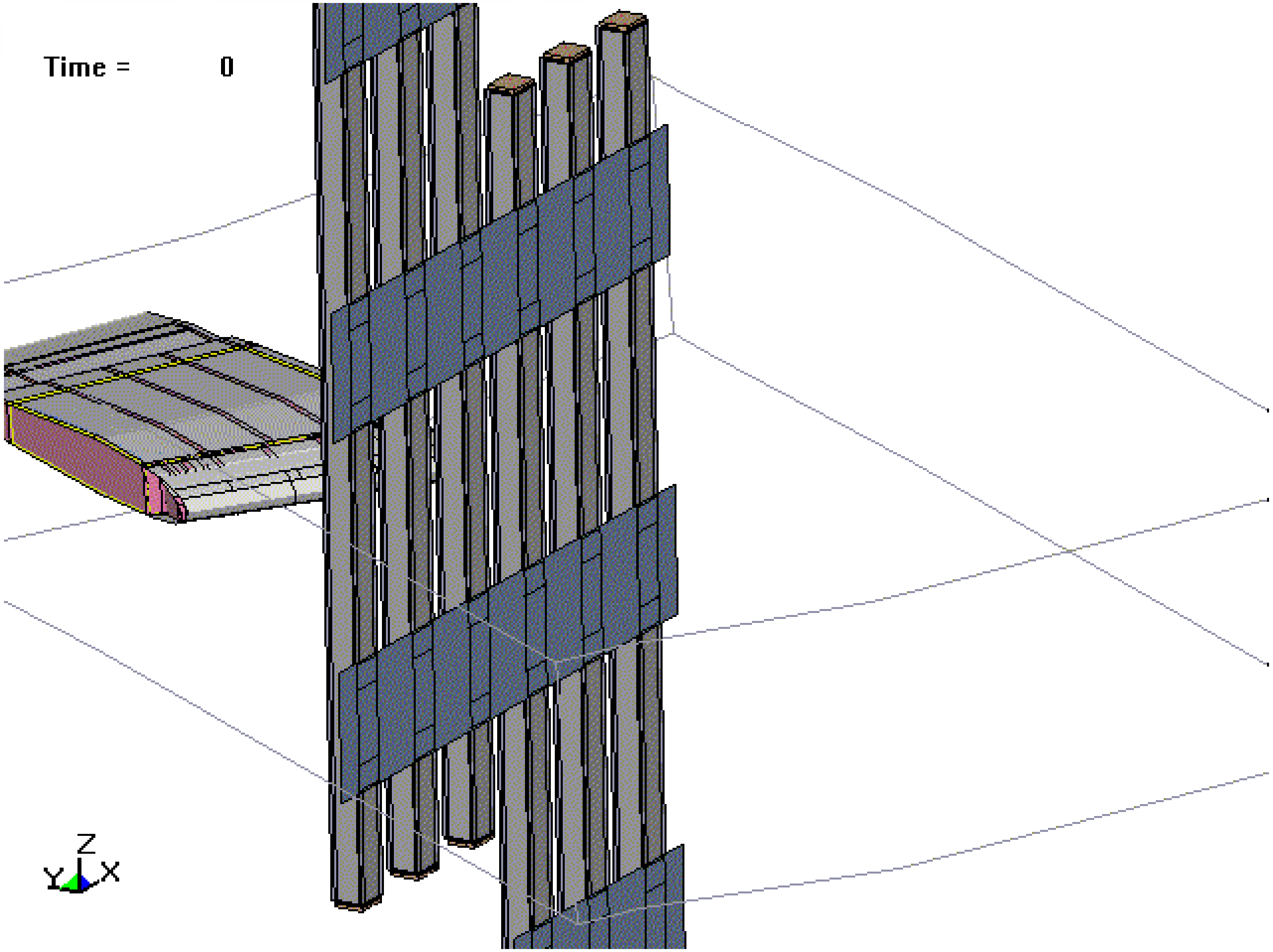
- Fluid Structure Interaction (FSI) is difficult to model with traditional computational methods and requires special analysis techniques.
- FSI approach needs to capture:
  - Primary inertial affects of fuel impacting structural members.
  - Secondary fuel dispersion.
- 3 Options for this program:
  - 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).
    - Appropriate methodology for analysis of continuous fluid dynamics.
  - 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.
- Neither methodology includes physics of droplet formation, wetting of structures, or fuel combustion.

Wing Segment with ALE Fuel

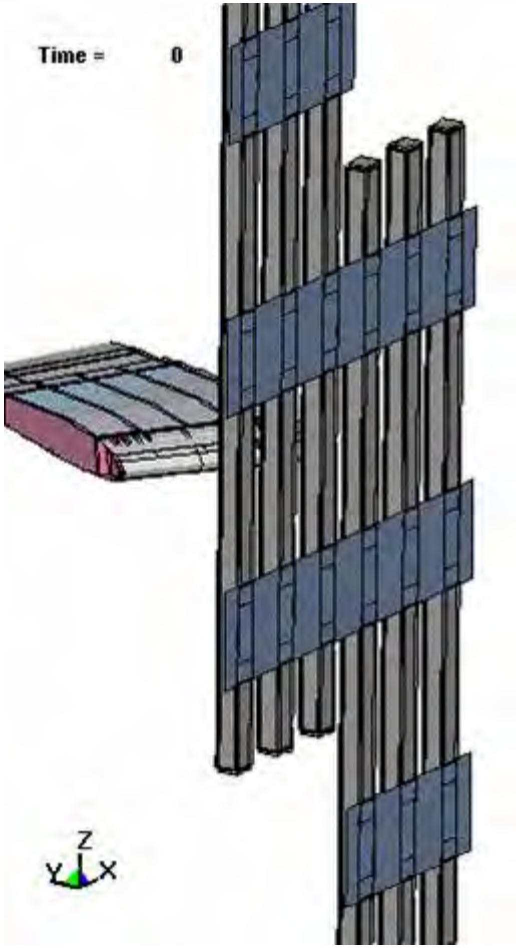
V = 500 mph



AVI

Wing Segment with SPH Fuel

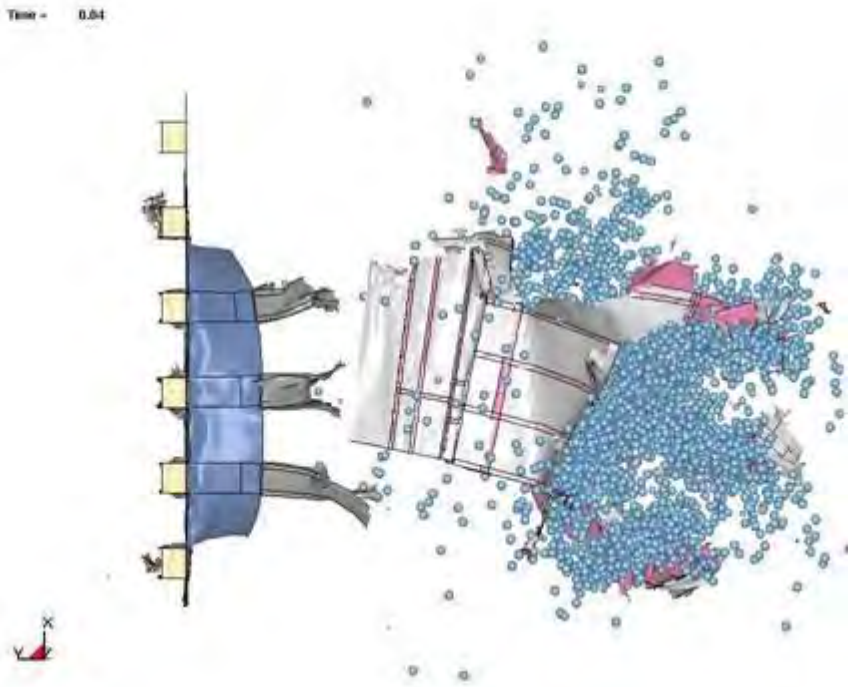
V = 500 mph



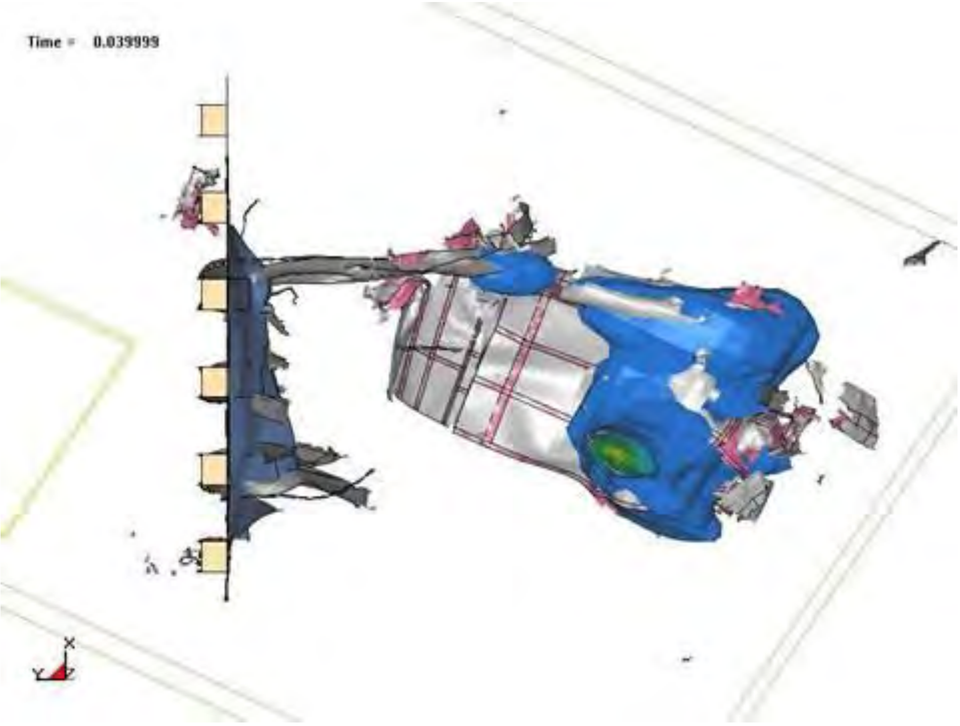
AVI

Wing Segment with Fuel Comparison
V = 500 mph

SPH

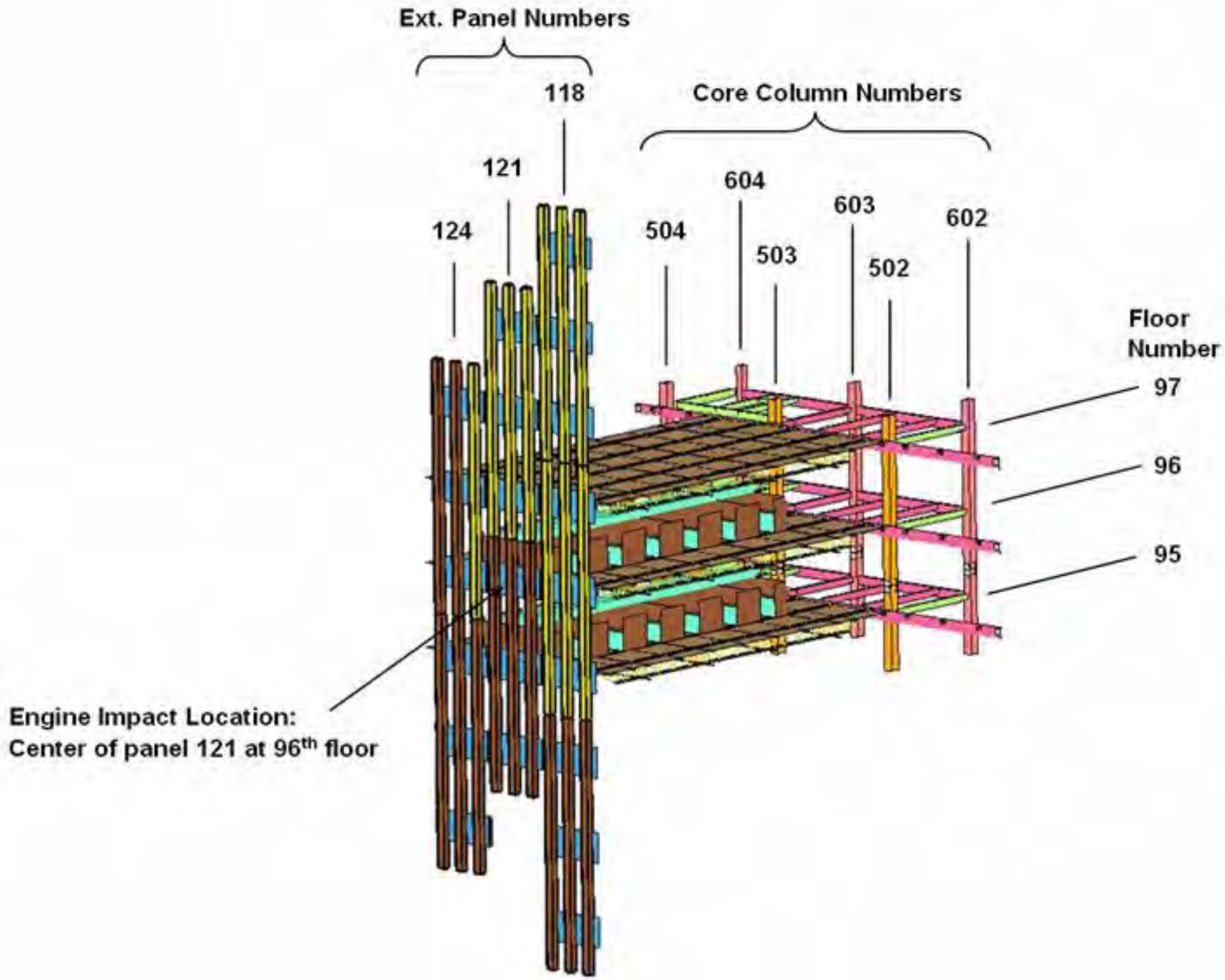


ALE



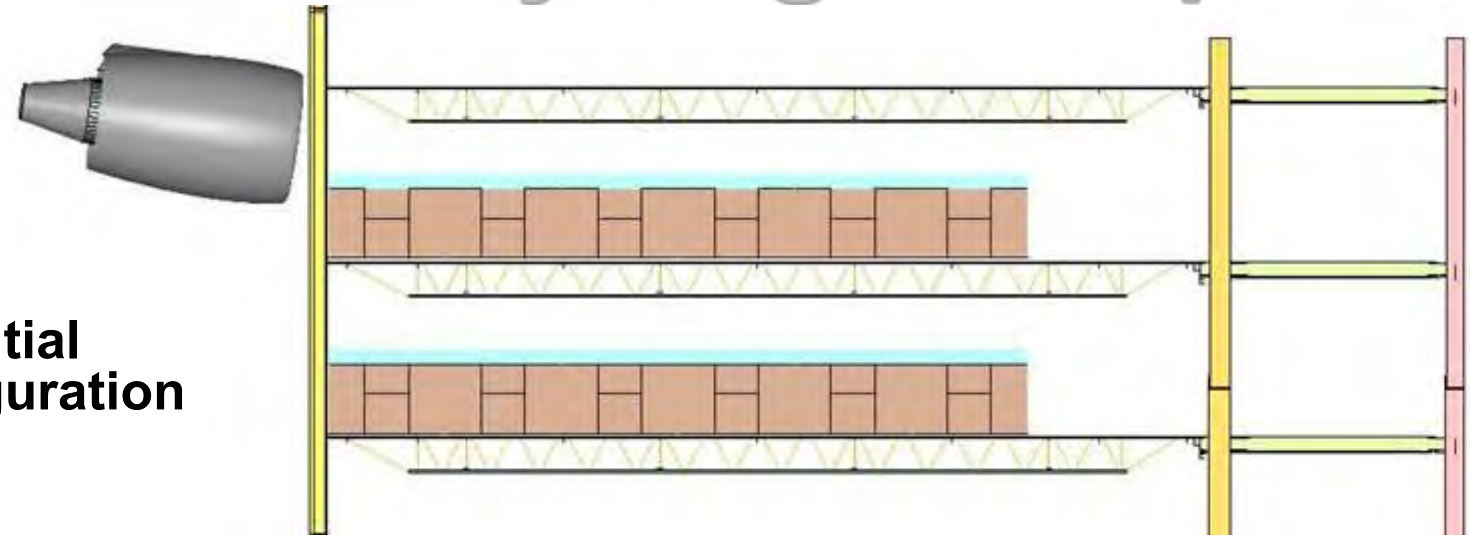
Part 5
Subassembly Impact Analyses

Tower Subassembly Model

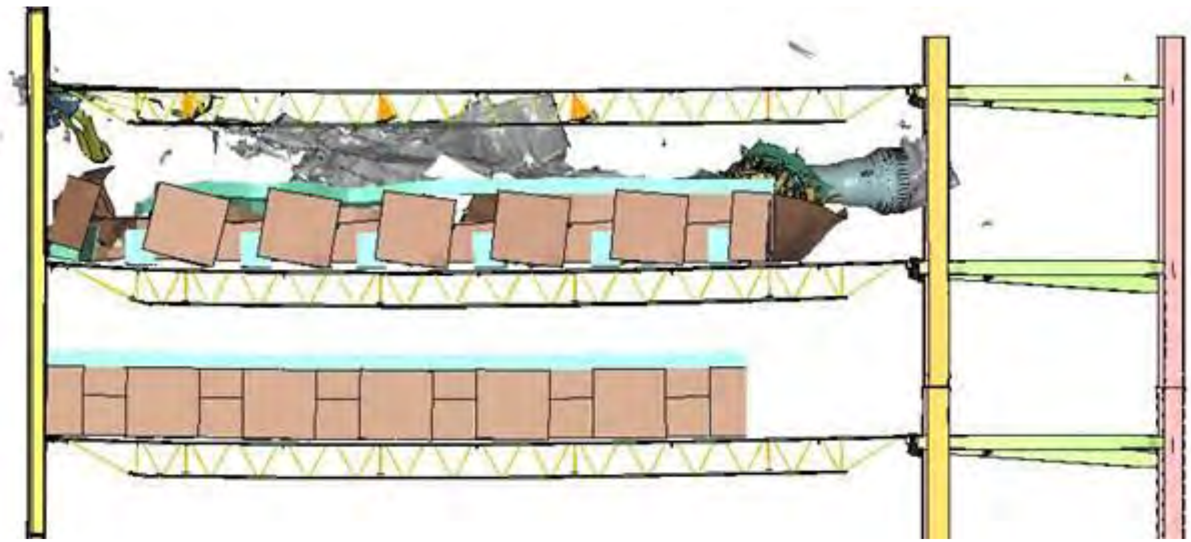


Subassembly Engine Impact

Initial
Configuration

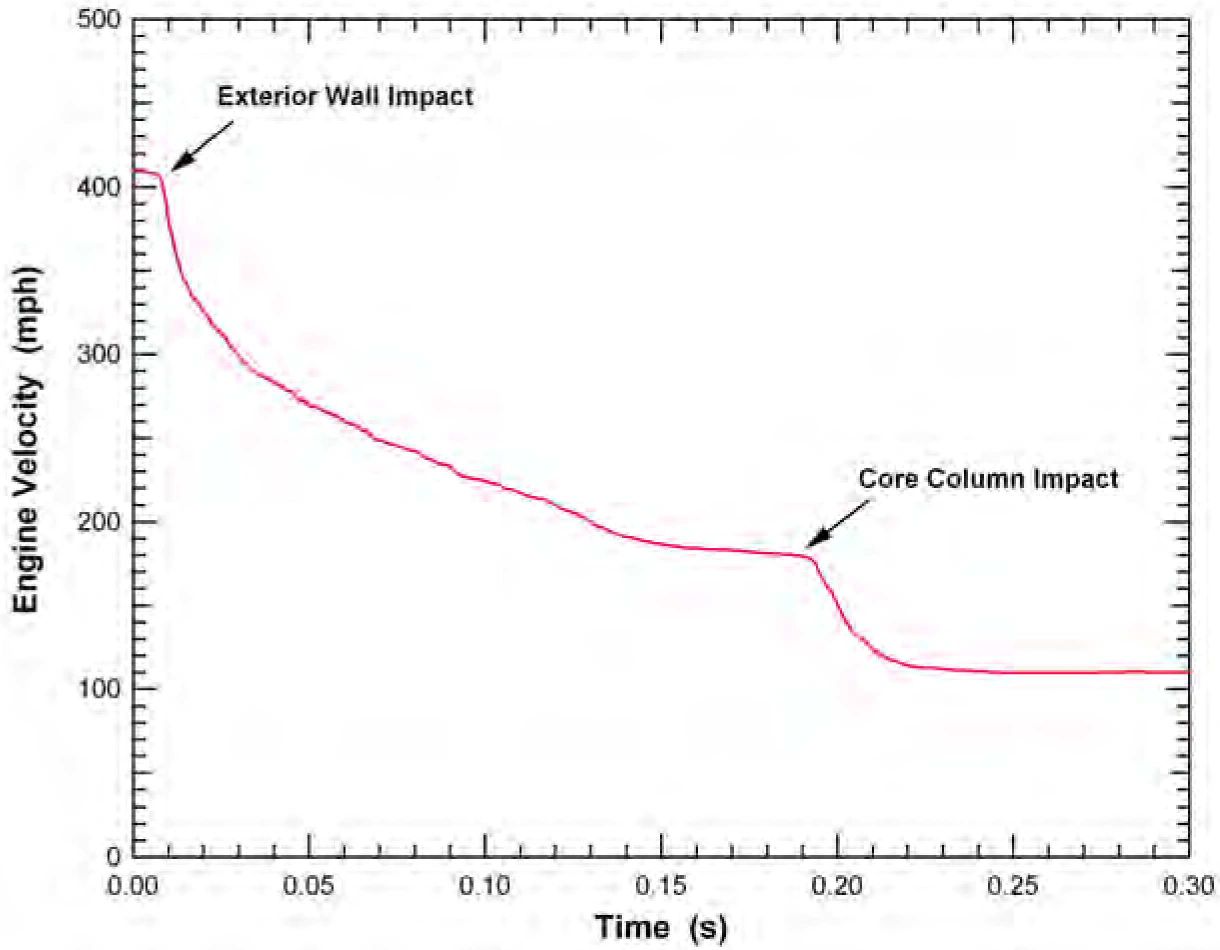


Impact
Response
at 0.25 s

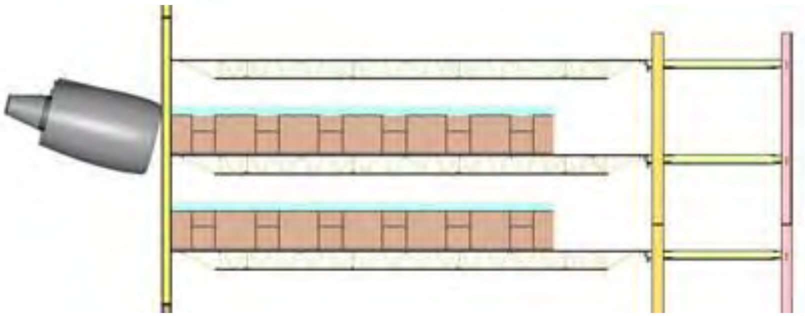


Subassembly Engine Impact

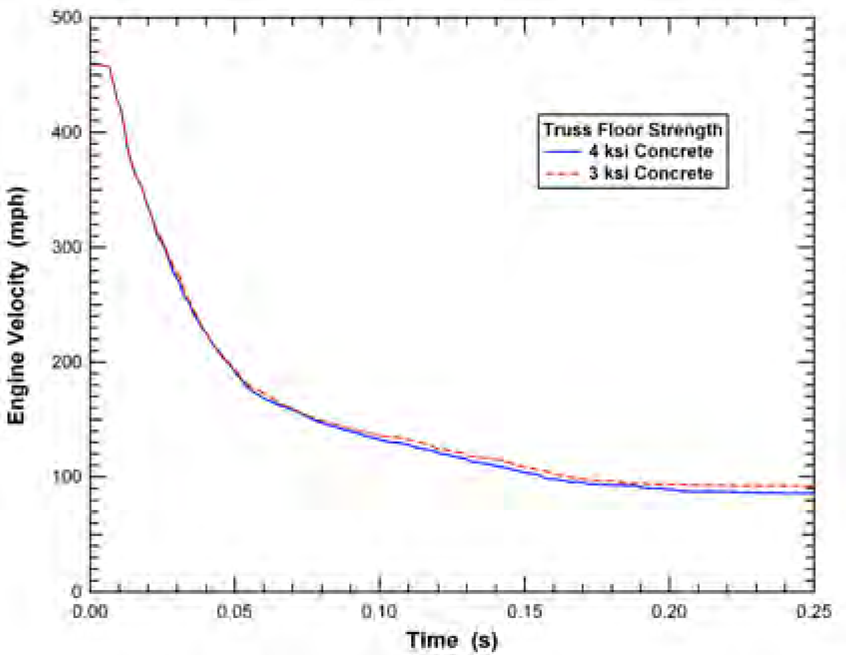
- Engine deceleration produced by the interaction with:
  - Exterior wall
  - Truss floor
  - Internal contents
  - Core Column



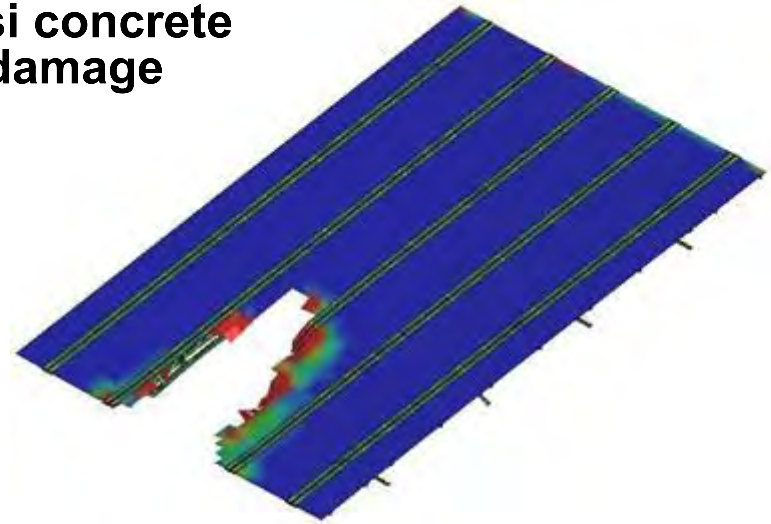
Subassembly Engine Impact



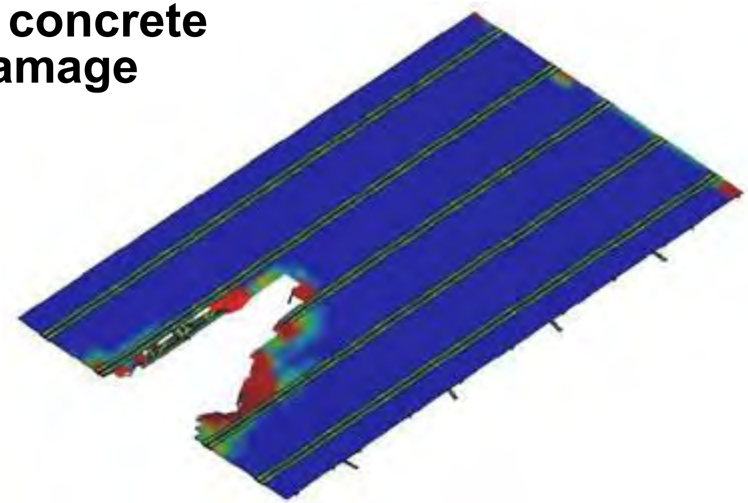
Impact Configuration



4 ksi concrete damage

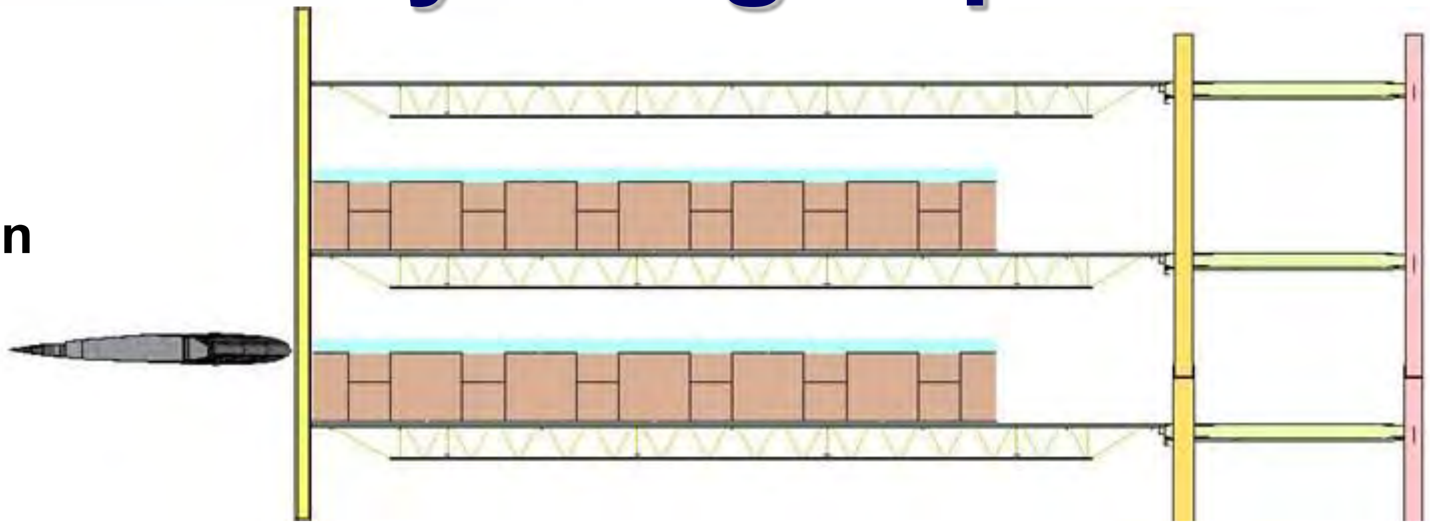


3 ksi concrete damage

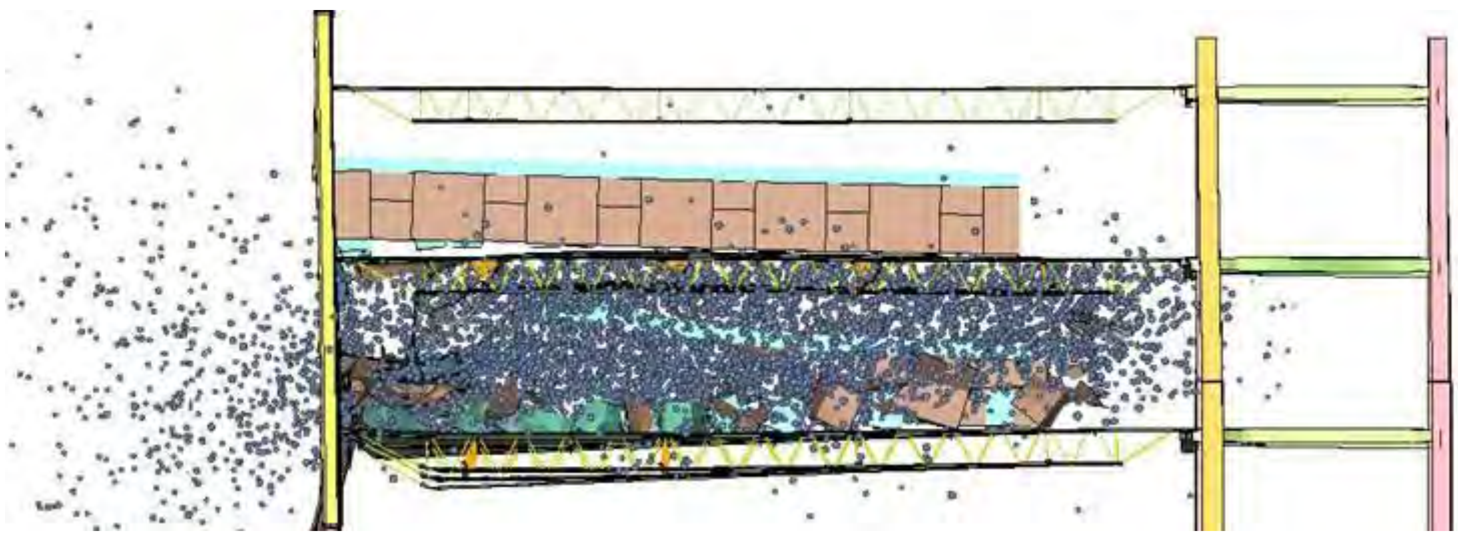


Subassembly Wing Impact

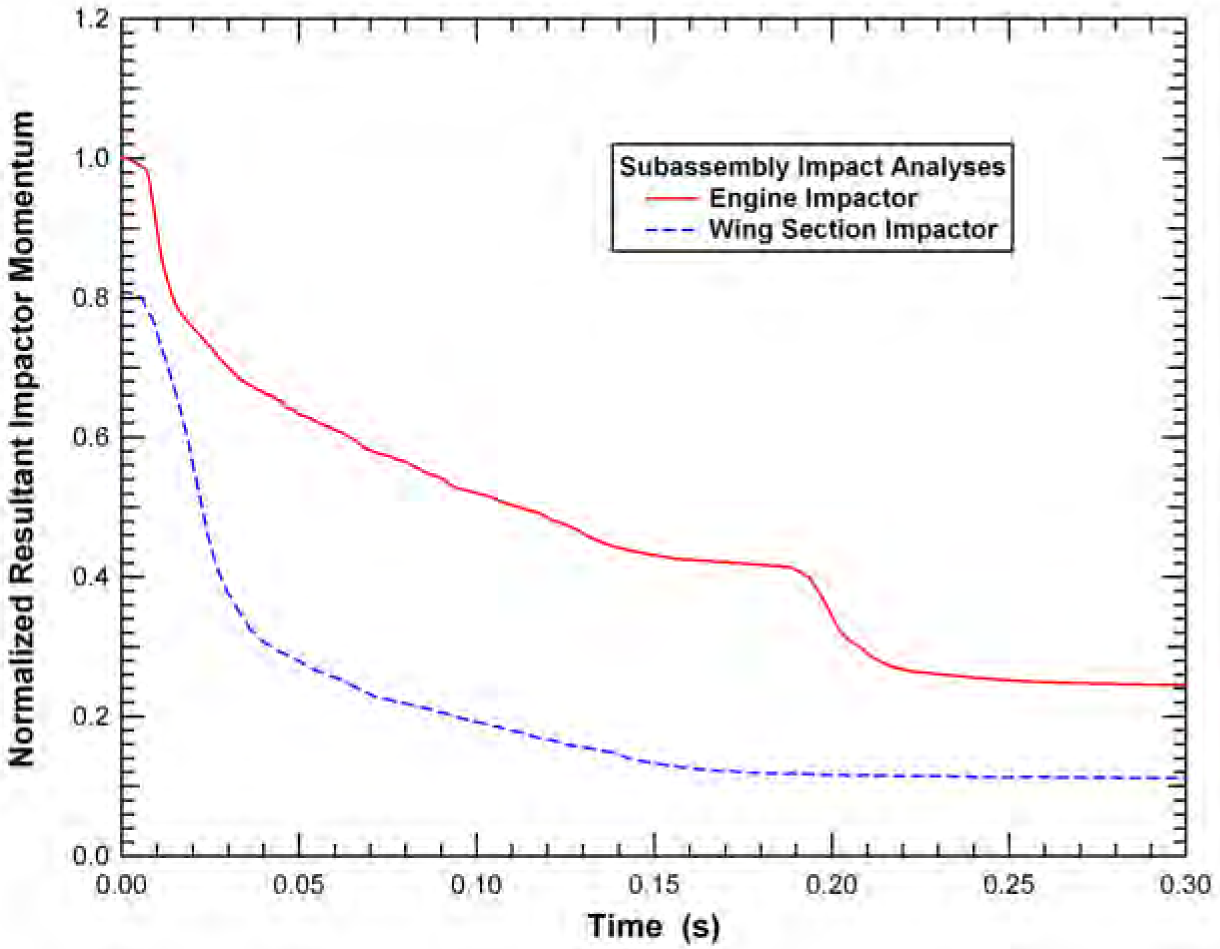
Initial Configuration



Impact Response at 0.10 s



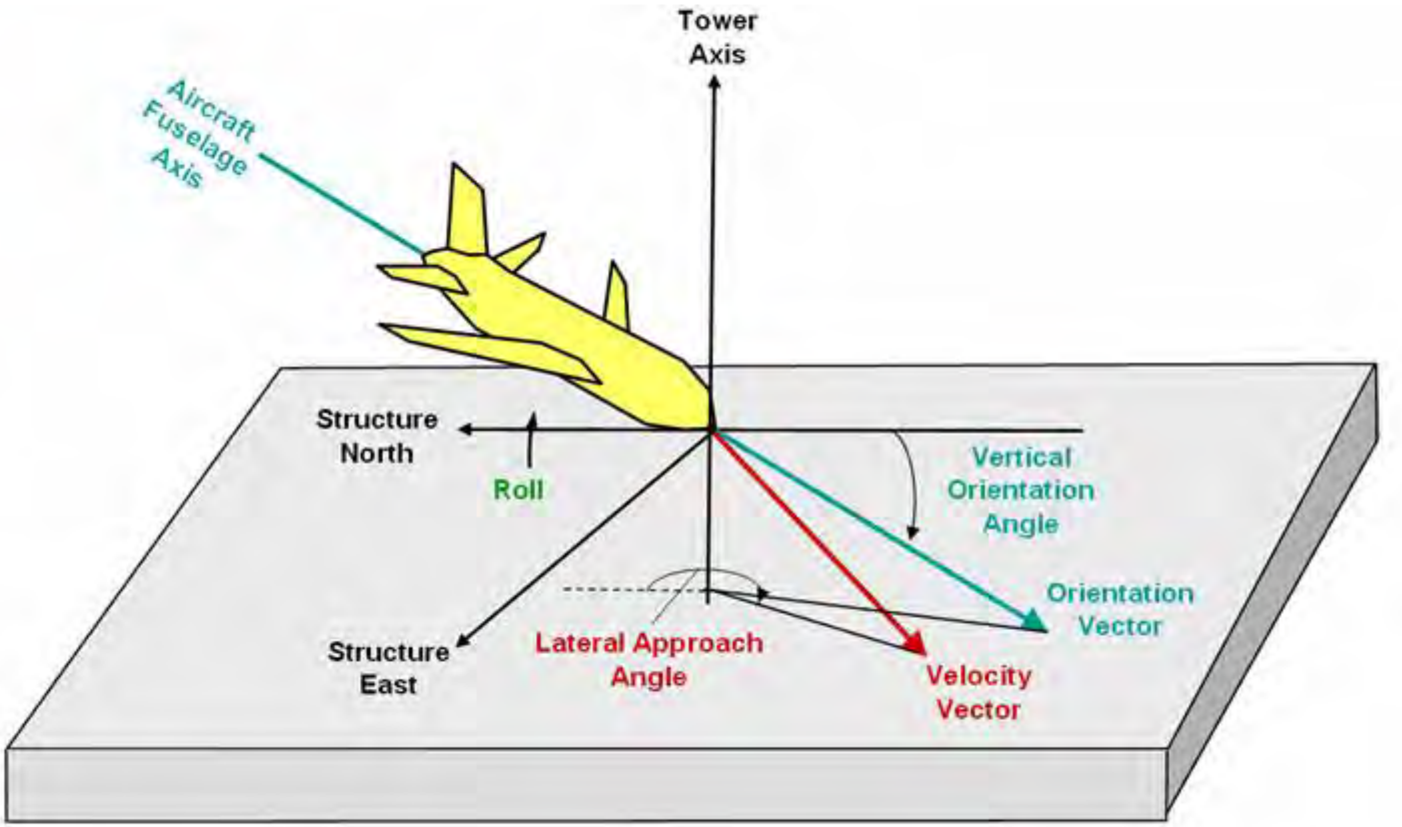
Subassembly Impact Analyses



Comparison of Engine and Fuel Momentum Transfer

Part 6
Analysis of Aircraft Impact Conditions

Definitions of the Aircraft Impact Parameters



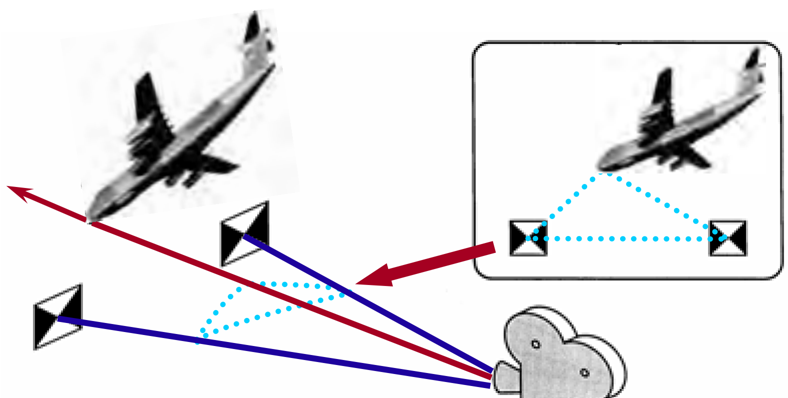
Analysis of Aircraft Impact Conditions

- Video footage of the aircraft impacts were first used to assess the impact conditions
  - Two videos of WTC 1
  - Seven videos of WTC 2.
- A complex video analysis technique was first applied to generate initial estimates of orientation and location.
- Estimates from the video analysis were refined using the visible damage on the impact face of the towers.
- Aircraft speed was determined using a simplified video analysis.

Analysis of Aircraft Impact Conditions

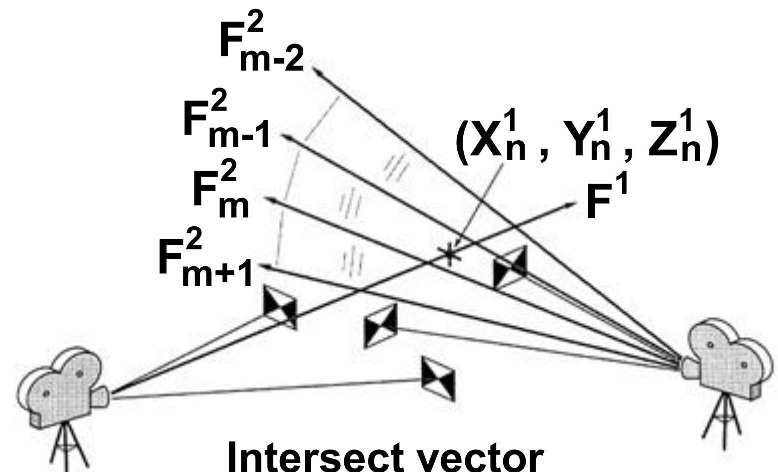
Complex Motion Analysis Methodology:

Step 1:



Location of the object along the vector not known.

Step 2:



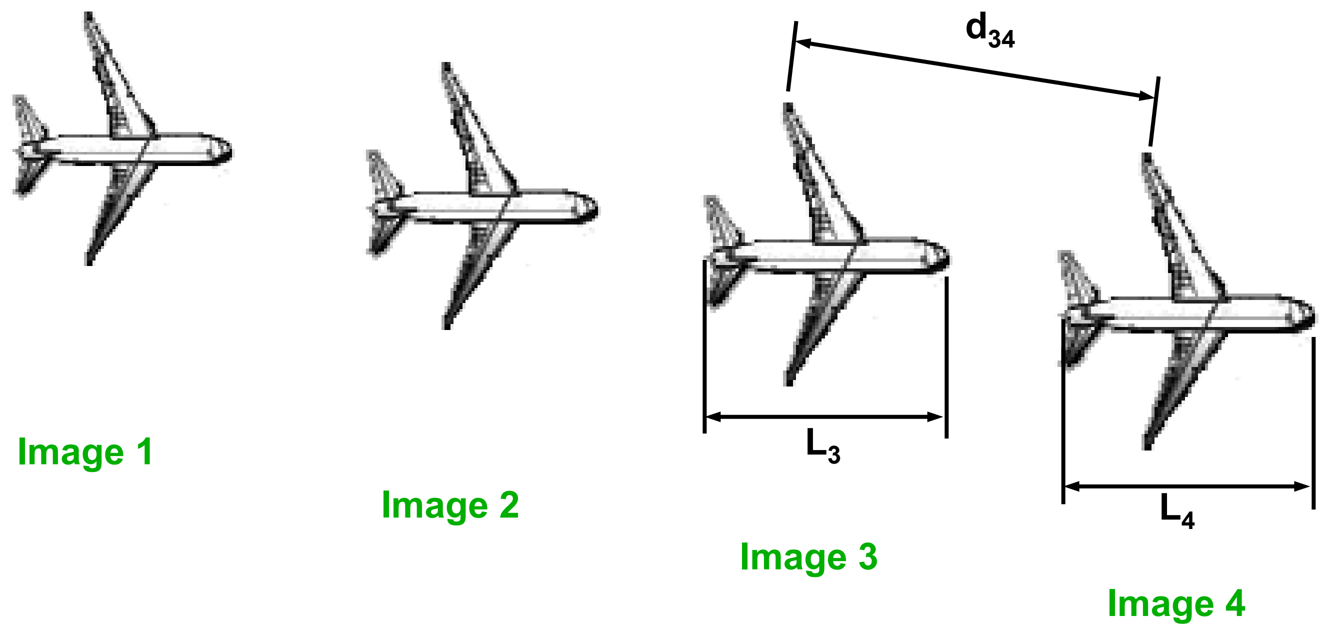
Camera No. 1

Intersect vector from one camera with data from a second camera.

Camera No. 2

Analysis of Aircraft Impact Conditions

Simplified Motion Analysis Methodology:

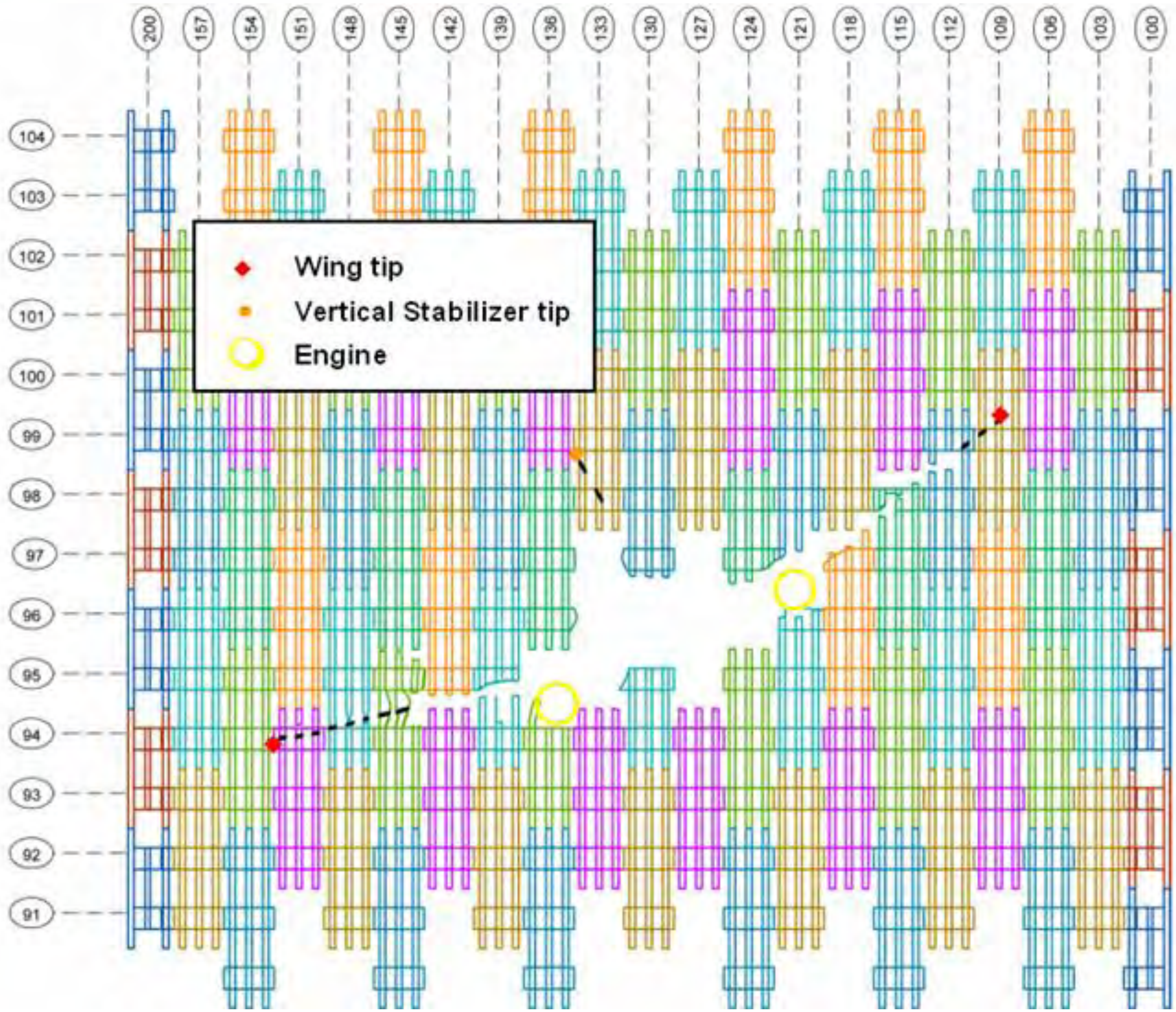


$$\text{Speed} = \frac{(d_{34})}{(L_3+L_4)/2}\ \text{(Actual plane length)(Image Rate)}$$

Refinement of the Aircraft Impact Orientation and Location

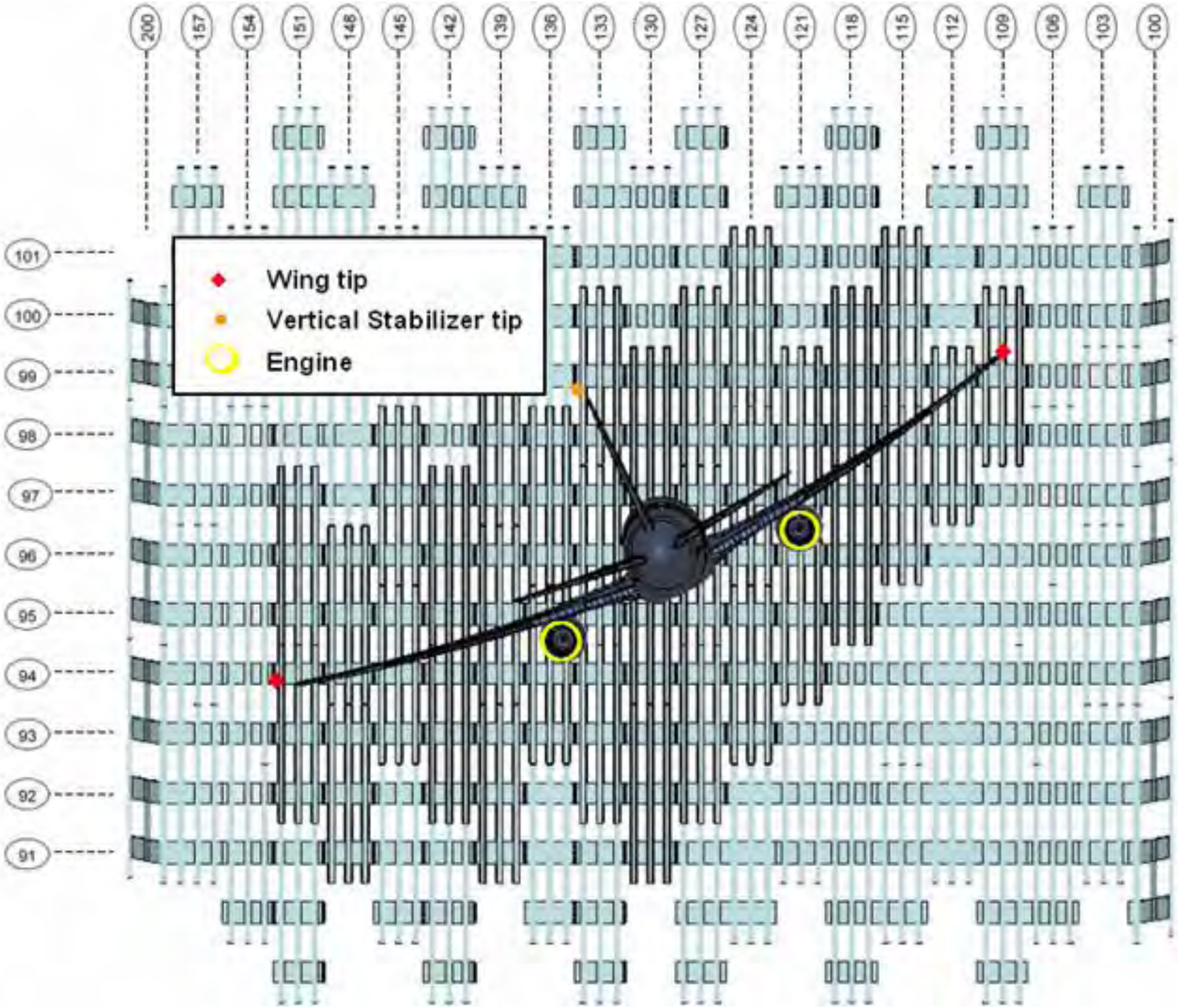
- Damage pattern on the external panels was used to determine the impact location, orientation and trajectory within the bounds of the video analysis.
- Impact locations for the engines, wing tips and and tip of the vertical stabilizer is most clearly seen in the impact damage.
- Relative locations of wing, engine, and tail strike place constraints on possible combinations of orientation and trajectory.

Schematic of Impact Damage – WTC 1

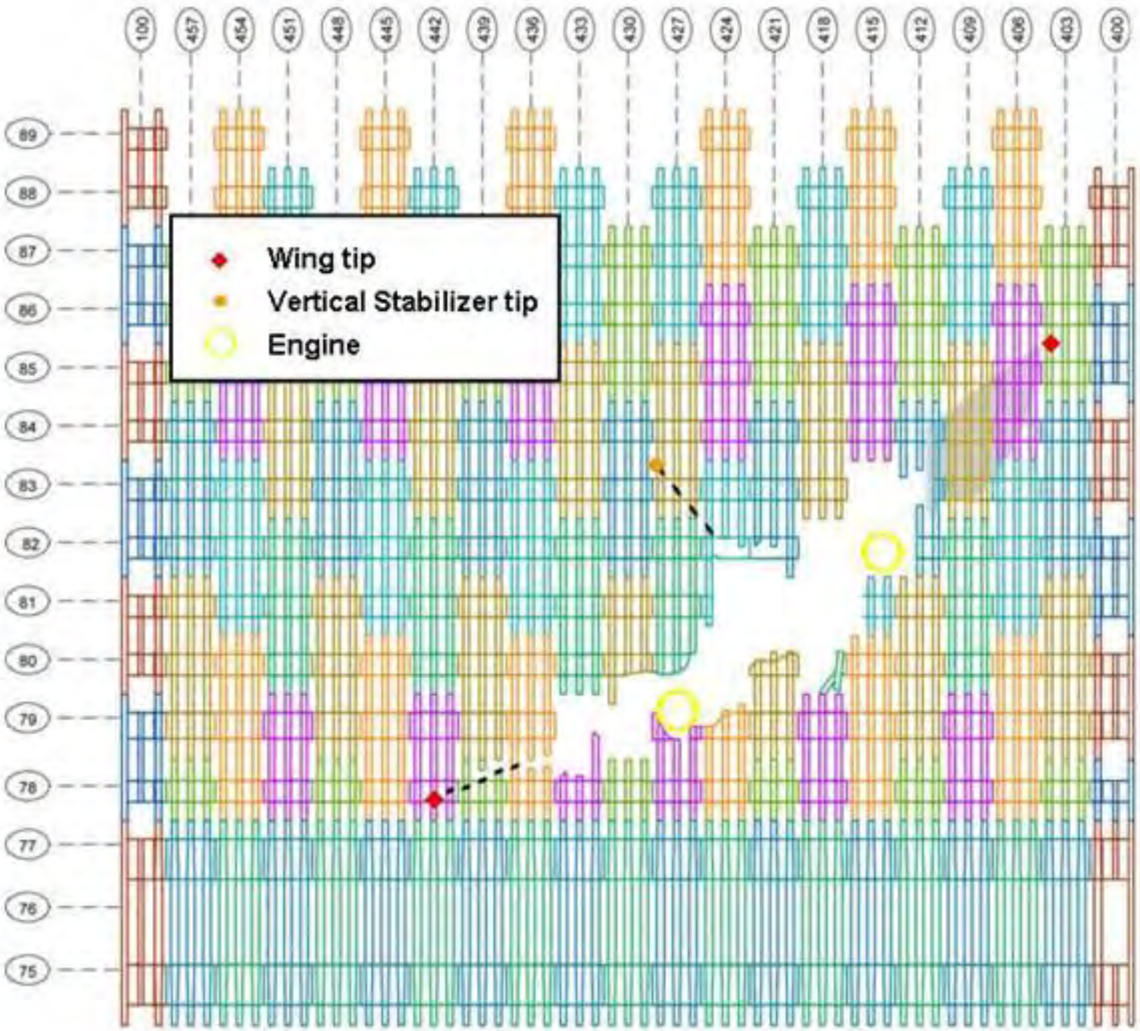


WTC 1 – Baseline Impact conditions

vertical angle = 10.6°, lateral angle = 0°



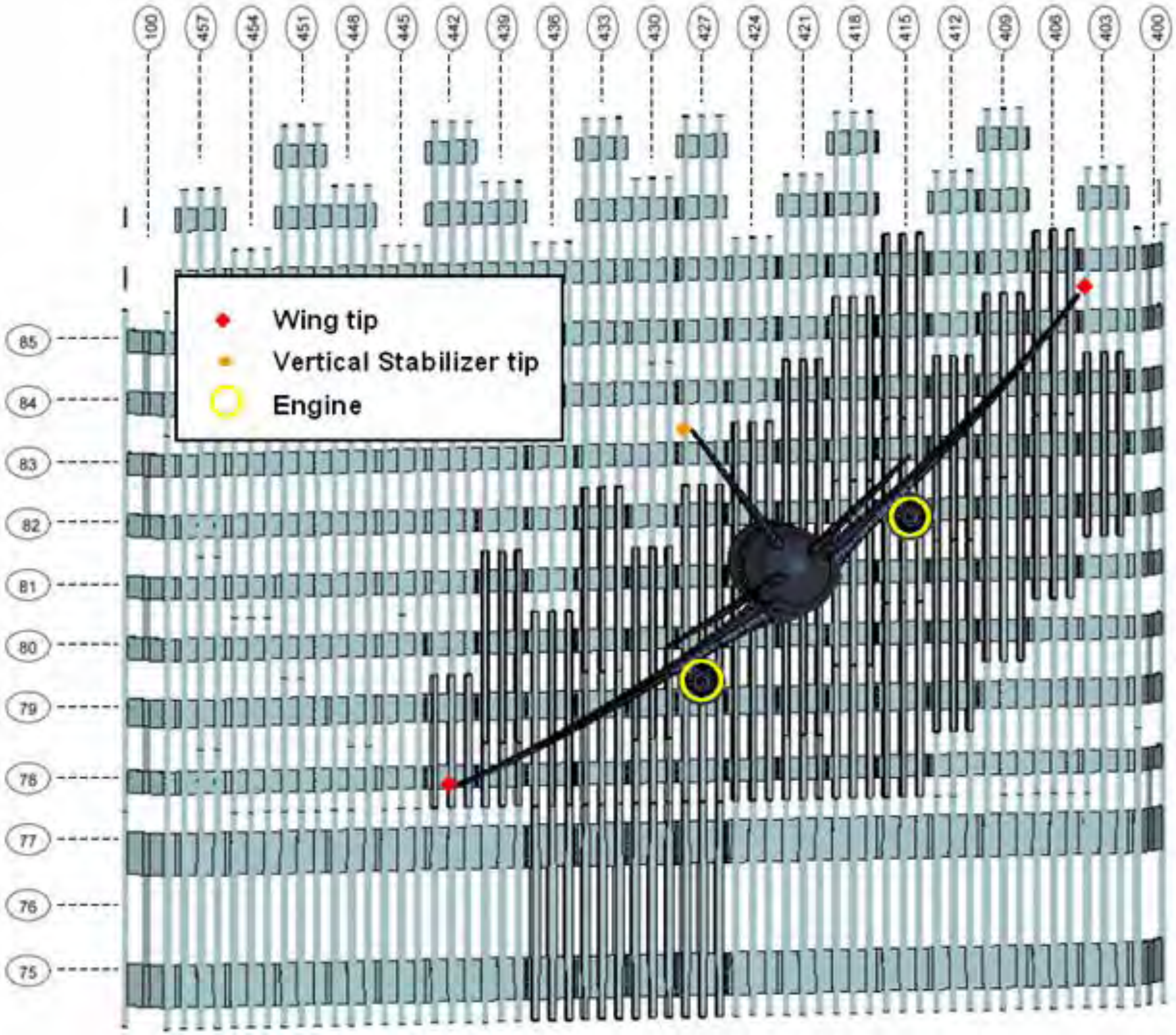
Schematic of Impact Damage – WTC 2



Damage in shaded area cannot be accurately determined.

WTC 2 Impact Conditions

vertical angle = 6°, lateral angle = 13°



Aircraft Impact Conditions

	Horizontal Location	Vertical Location
AA 11 (WTC 1)	2.0 ± 3 ft. west of centerline	1.6. ± 4 ft. above 96th floor
UAL 175 (WTC 2)	23.1 ± 3 ft. east of centerline	0.6. ± 4 ft. above 81st floor

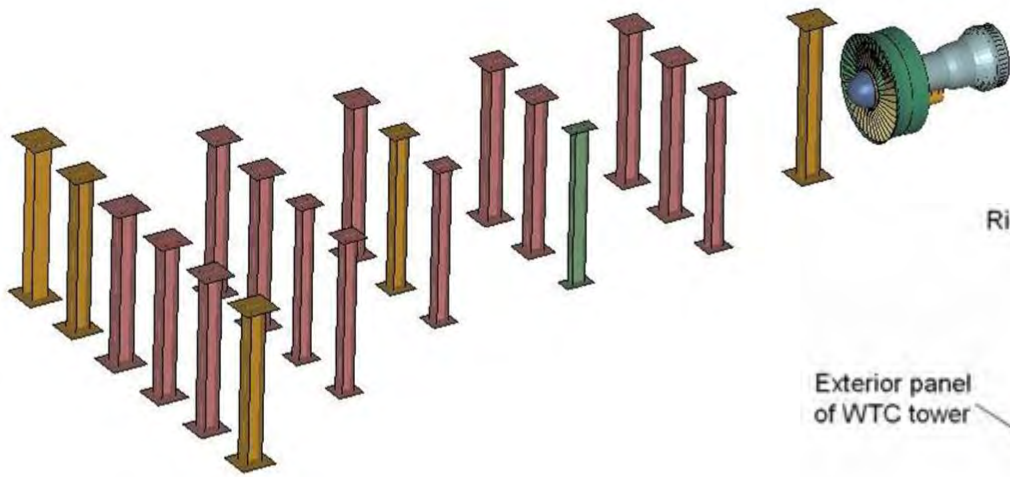
	AA 11 (WTC 1)	UAL 175 (WTC 2)
Impact Speed (mph)	443 ± 30	542 ± 24
Vertical Approach Angle (Velocity vector)	10.6° ± 3° below horizontal (heading downward)	6° ± 2° below horizontal (heading downward)
Lateral Approach Angle (Velocity vector)	180.3° ± 4° clockwise from Structure North[1]	15° ± 2° clockwise from Structure North[1]
Vertical Fuselage Orientation Relative to Trajectory	2° nose-up from the vertical approach angle	1° nose-up from the vertical approach angle
Lateral Fuselage Orientation Relative to Trajectory	0° clockwise from lateral approach angle	-3° clockwise from lateral approach angle
Roll Angle (left wing downward)	25° ± 2°	38° ± 2°

1. Structure north is approximately 29 degrees clockwise from True North.

Part 6
Uncertainty Analyses

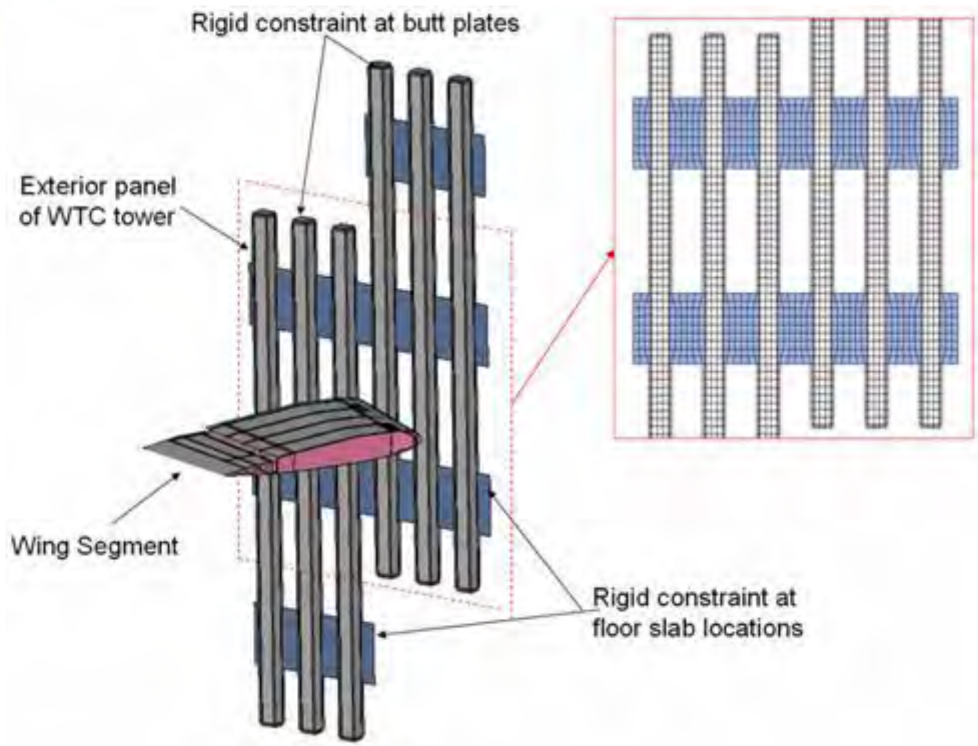
- Component Uncertainty Analyses
- Subassembly Uncertainty Analyses

Component-Level Uncertainty Analyses



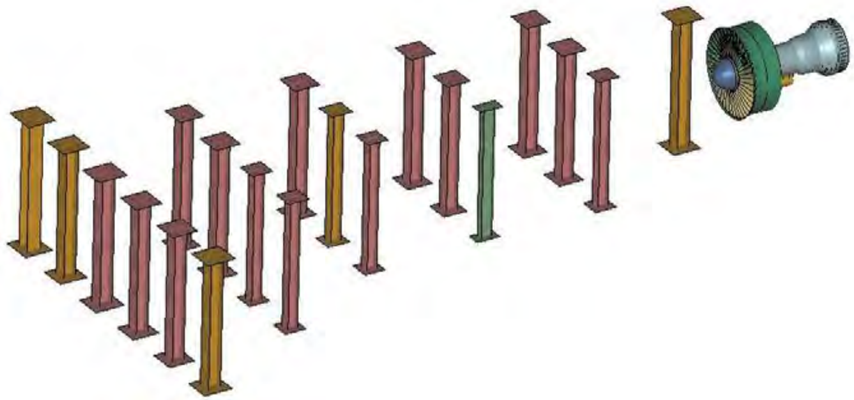
Engine-Core Column

Wing Segment – Exterior Panel



Parameter Variation

Engine – Core Column



Uncertainty Parameters		Parameter ID	Minimum Value	Baseline Value	Maximum Value
Flight Parameters	Speed	1	392 mph	485 mph	579 mph
	Vertical Impact Location	2	0.00 ft	0.00 ft	2.03 ft
	Horizontal Impact Location	3	0.00 ft	0.00 ft	3.00 ft
Engine Parameters	Material Assignment Set[1]	4	1	1	2
	Material Strength	5	65%	100%	135%
	Failure Strain	6	50%	100%	150%
	Strain Rate Effects	7	10%	100%	1000%
Tower Parameters	Material Strength	8	85%	100%	115%
	Failure Strain	9	50%	100%	150%
	Strain Rate Effects	10	10%	100%	1000%
Model Parameters	Erosion Parameter[1]	11	1	1	2
	Contact Parameter[1]	12	1	1	2
	Friction Coefficient	13	0.0	0.3	0.6

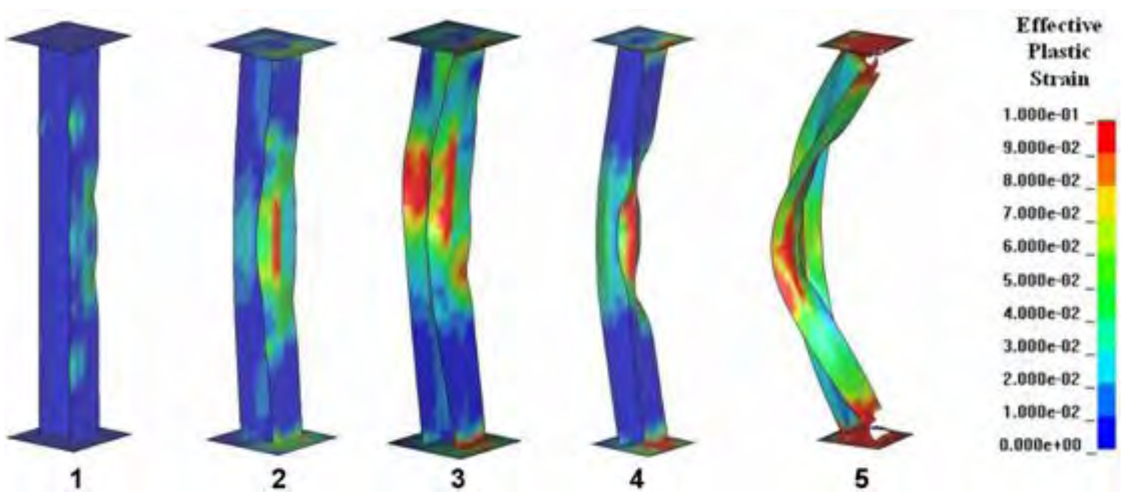
Experimental Design

Engine – Core Column

Fractional Factorial 2^{13-9} Experimental Design

Runs ID-->	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	-1	1	1	-1	-1	1	1	-1	-1	-1	1
2	1	1	-1	-1	-1	1	1	-1	-1	1	1	-1	1
3	1	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1
4	1	-1	-1	-1	1	-1	1	-1	1	-1	1	1	-1
5	-1	1	1	1	1	1	-1	-1	-1	-1	1	-1	-1
6	-1	1	1	-1	-1	-1	1	1	1	1	-1	-1	-1
7	-1	-1	1	1	-1	-1	-1	-1	1	1	1	1	1
8	-1	-1	1	-1	1	1	1	1	-1	-1	-1	1	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	1	1	1	-1	1	1	-1	1	-1	-1	1	-1
11	1	1	1	-1	1	-1	-1	1	-1	1	1	1	-1
12	1	-1	1	1	1	-1	1	-1	-1	1	-1	-1	1
13	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	1
14	-1	1	-1	1	-1	-1	1	1	-1	-1	1	1	1
15	-1	1	-1	-1	1	1	-1	-1	1	1	-1	1	1
16	-1	-1	-1	1	1	1	1	1	1	1	1	-1	-1
17	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

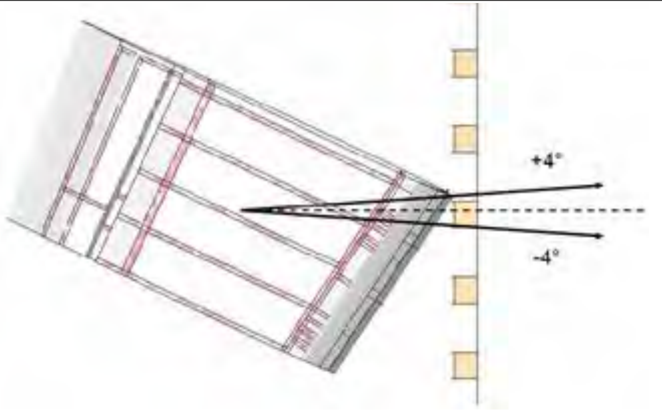
Measures of Core Column Damage



Parameter Variation

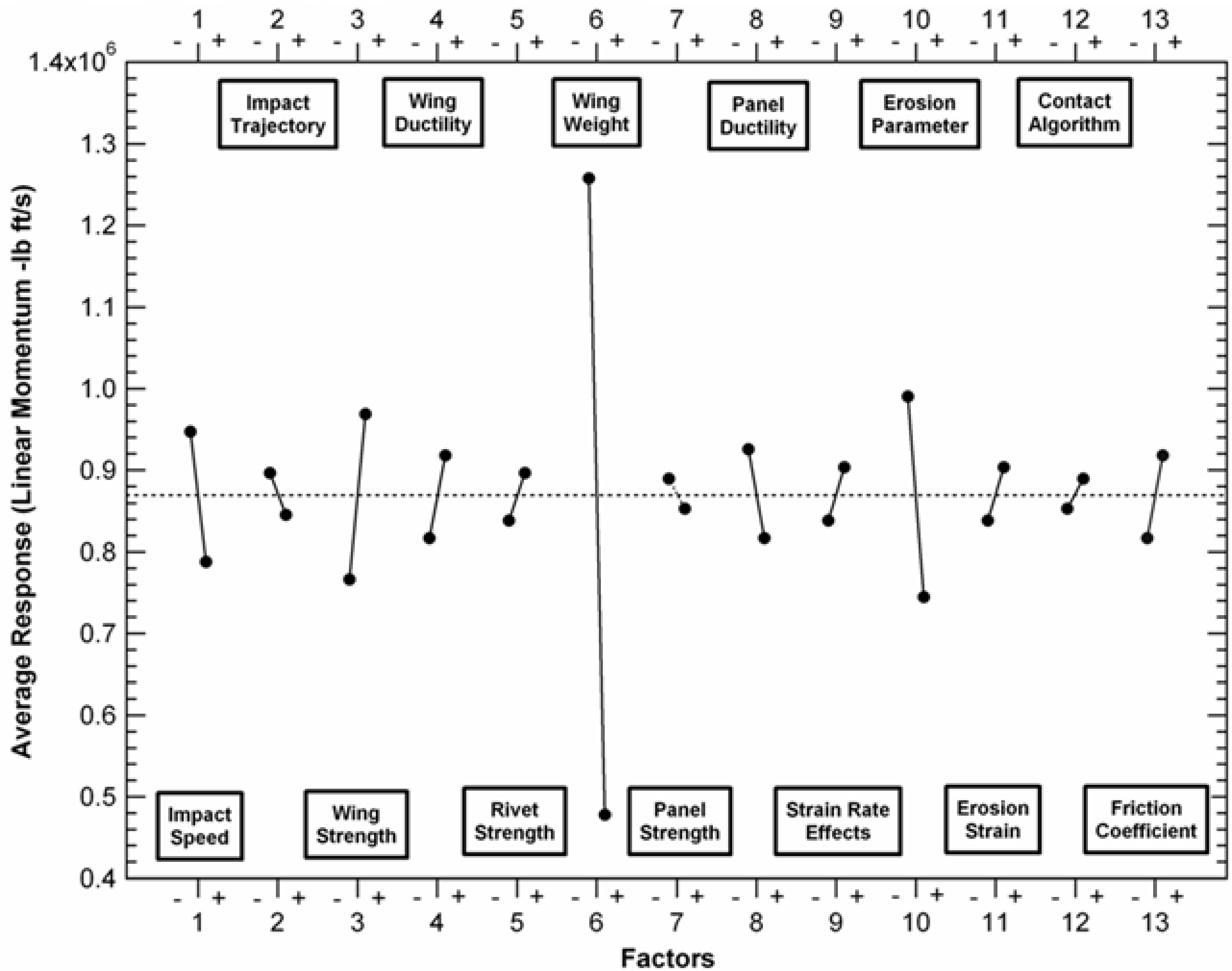
Wing Segment – Exterior Panel

Uncertainty Parameters		Parameter ID	Minimum Value	Baseline Value	Maximum Value
Flight Parameters	Speed	1	413 mph	443 mph	521 mph
	Lateral Approach Angle	2	-4.0°	0.0°	4.0°
Wing Parameters	Material Strength	3	65%	100%	135%
	Failure Strain	4	50%	100%	150%
	Rivet Strength	5	50%	100%	150%
	Weight Factor	6	1.5	2.0	3.0
Tower Parameters	Material Strength	7	85%	100%	115%
	Failure Strain	8	50%	100%	150%
	Strain Rate Effects	9	10%	100%	200%
Model Parameters	Erosion Parameter[1]	10	1	1	2
	Erosion Strain	11	0.2	0.3	0.4
	Contact Parameter[1]	12	1	1	0
	Friction Coefficient	13	0.0	0.3	0.6

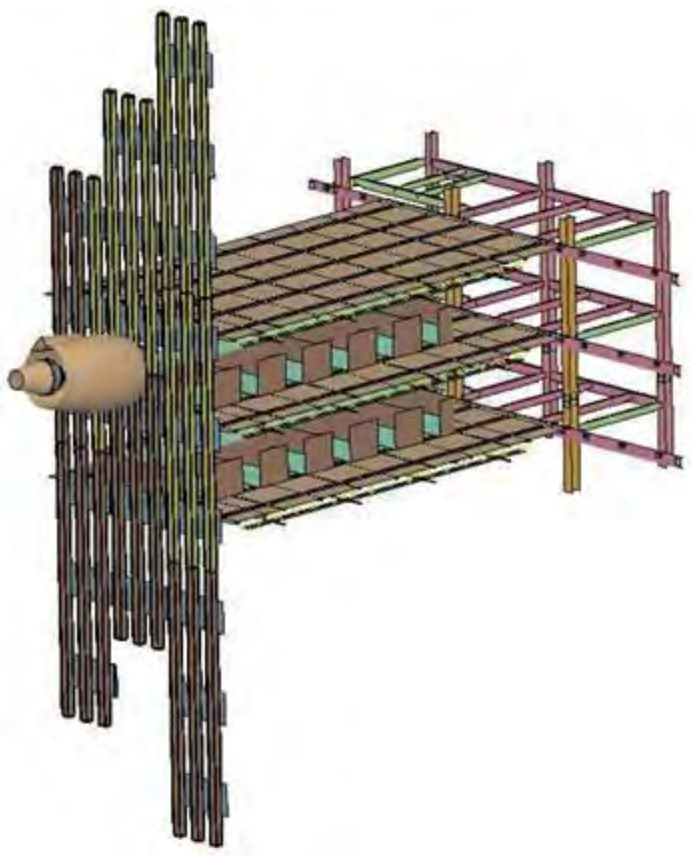


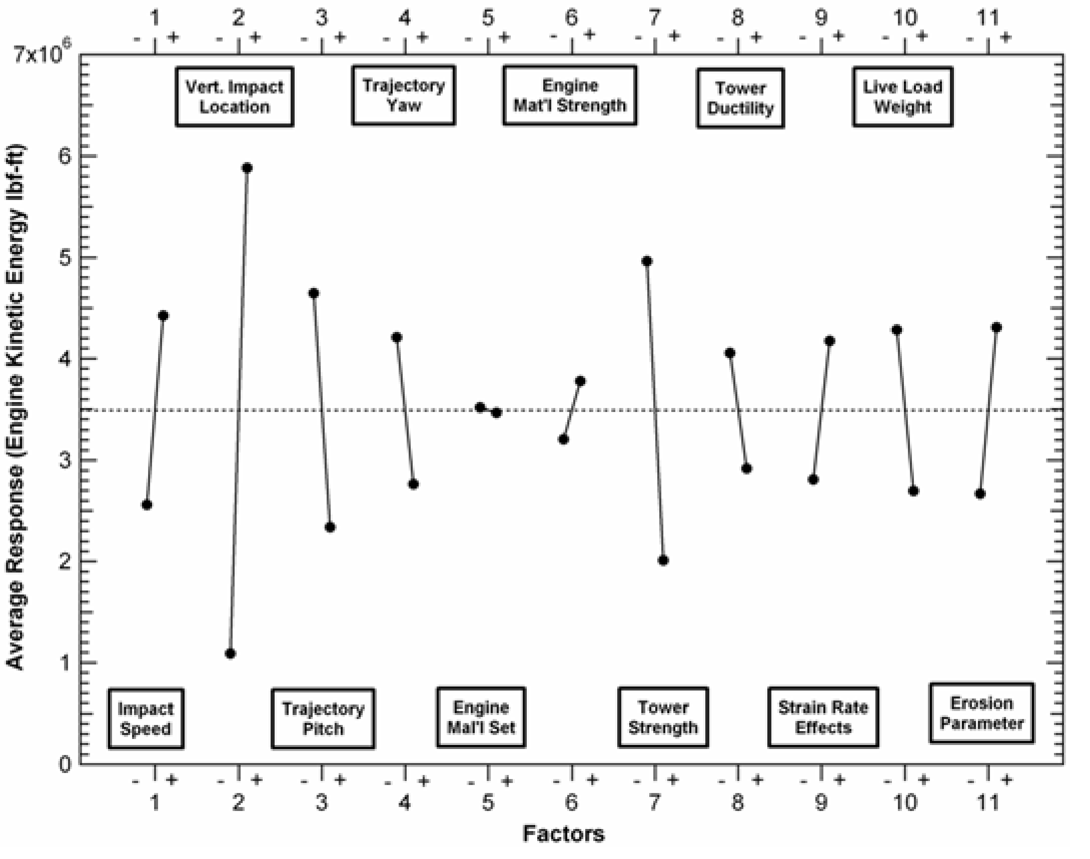
Main Effects Plot

Wing Segment – Exterior Panel



Engine-Subassembly Uncertainty Analysis





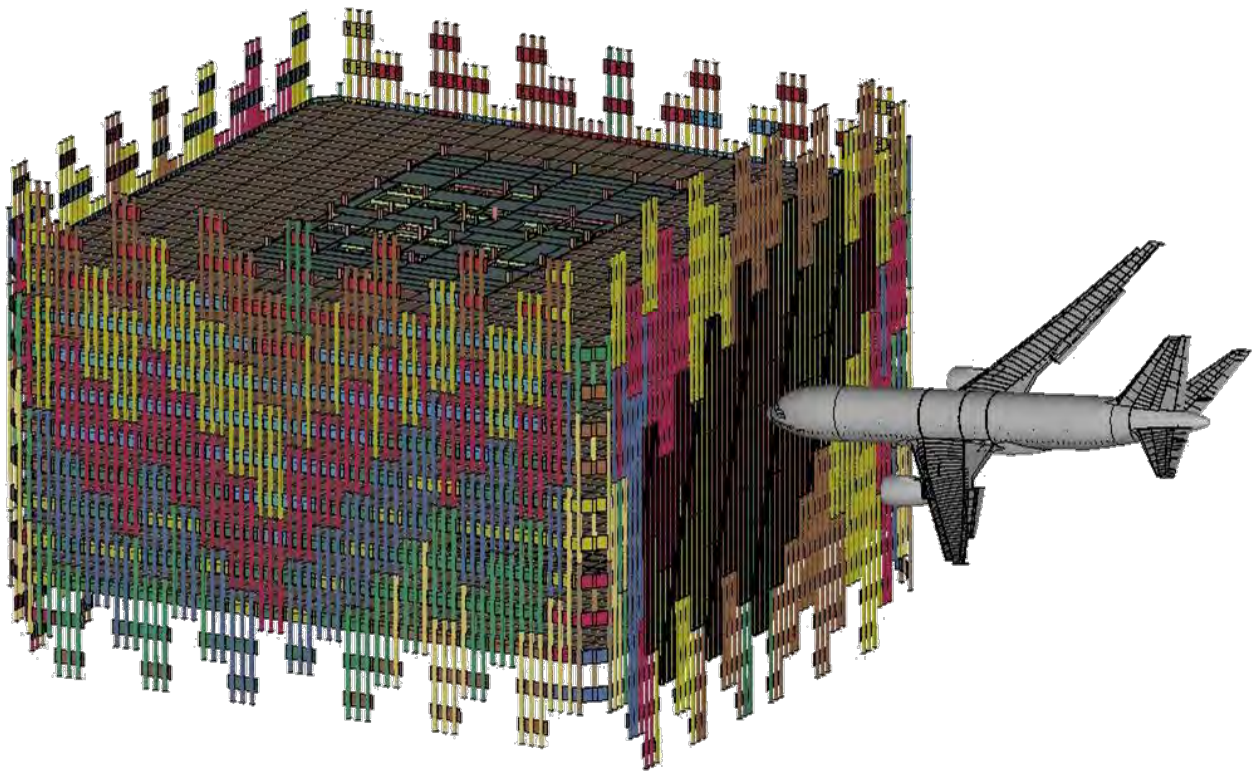
Significant Modeling Parameters for the Global Impact Analysis

		Engine – Core Column Component	Wing Section – Exterior Panel Component	Engine – Subassembly Impact
	Impact velocity		✓	✓-
Flight	Vertical impact location			✓
Parameters	Vertical Approach Angle			✓
	Lateral Approach Angle			✓-
	Aircraft materials strength	✓	✓	
Aircraft	Aircraft materials failure strain		✓-	
Parameters	Wing section weight		✓	
	Engine materials set	✓-		
	Tower materials strength			✓
Tower	Tower materials failure strain	✓	✓-	✓-
Parameters	Tower materials strain rate effects	✓		✓-
	Live load weight			✓-
Model	Friction coefficient		✓-	
	Erosion Parameter		✓	

Part 7
Global Impact Analyses

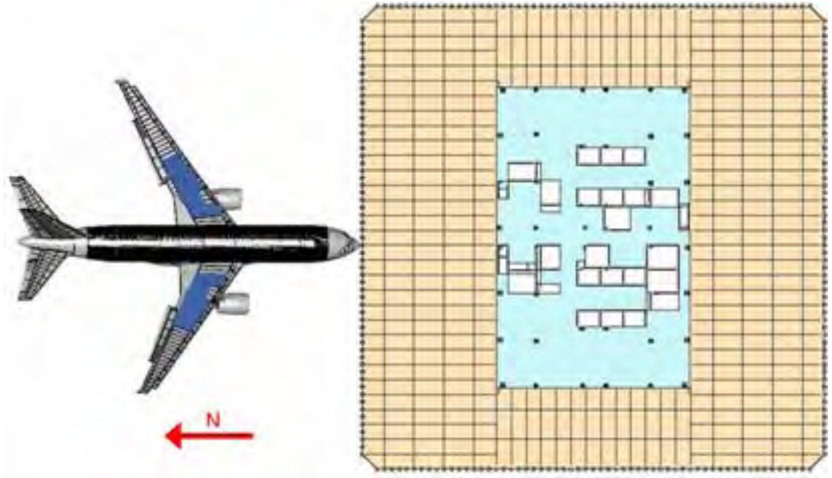
Global Impact Analyses

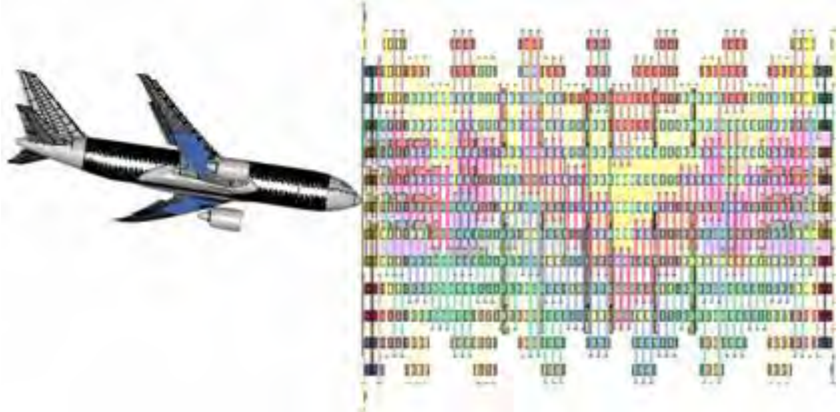
	WTC 1 Tower Model	WTC 2 Tower Model
Number of Nodes	2,068,736	2,110,970
Belytschko-Tsay Shell Elements	1,682,615	1,716,249
Constant Stress Solid Elements	73,189	72,906
Hughes-Liu Beam Elements	47,952	53,488
SPH Fuel Particles	60,672	60,672



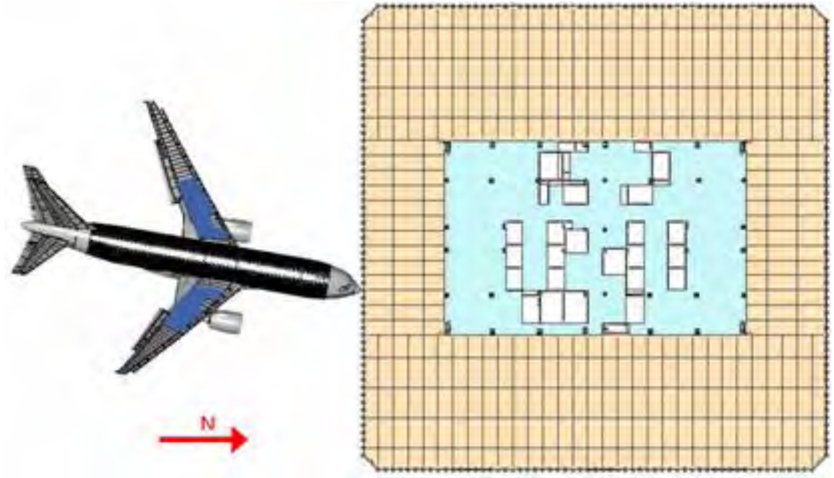
Global Impact Analyses

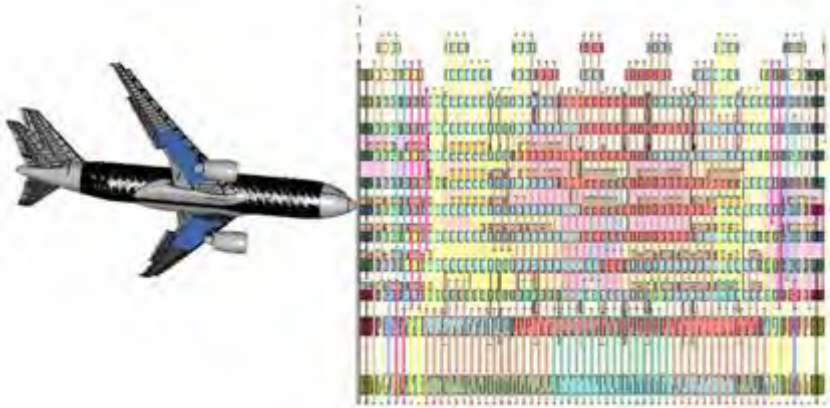
WTC 1



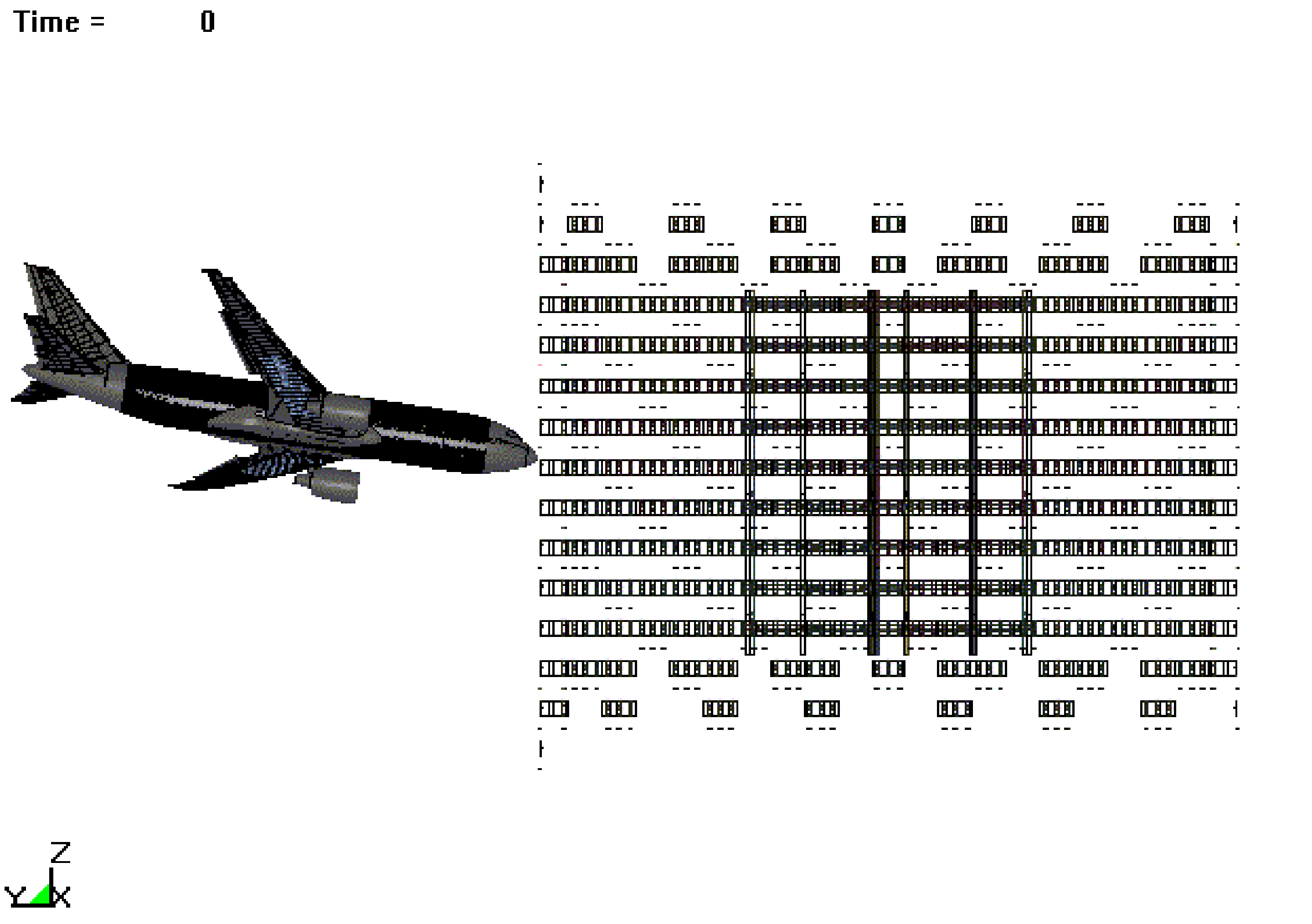


WTC 2

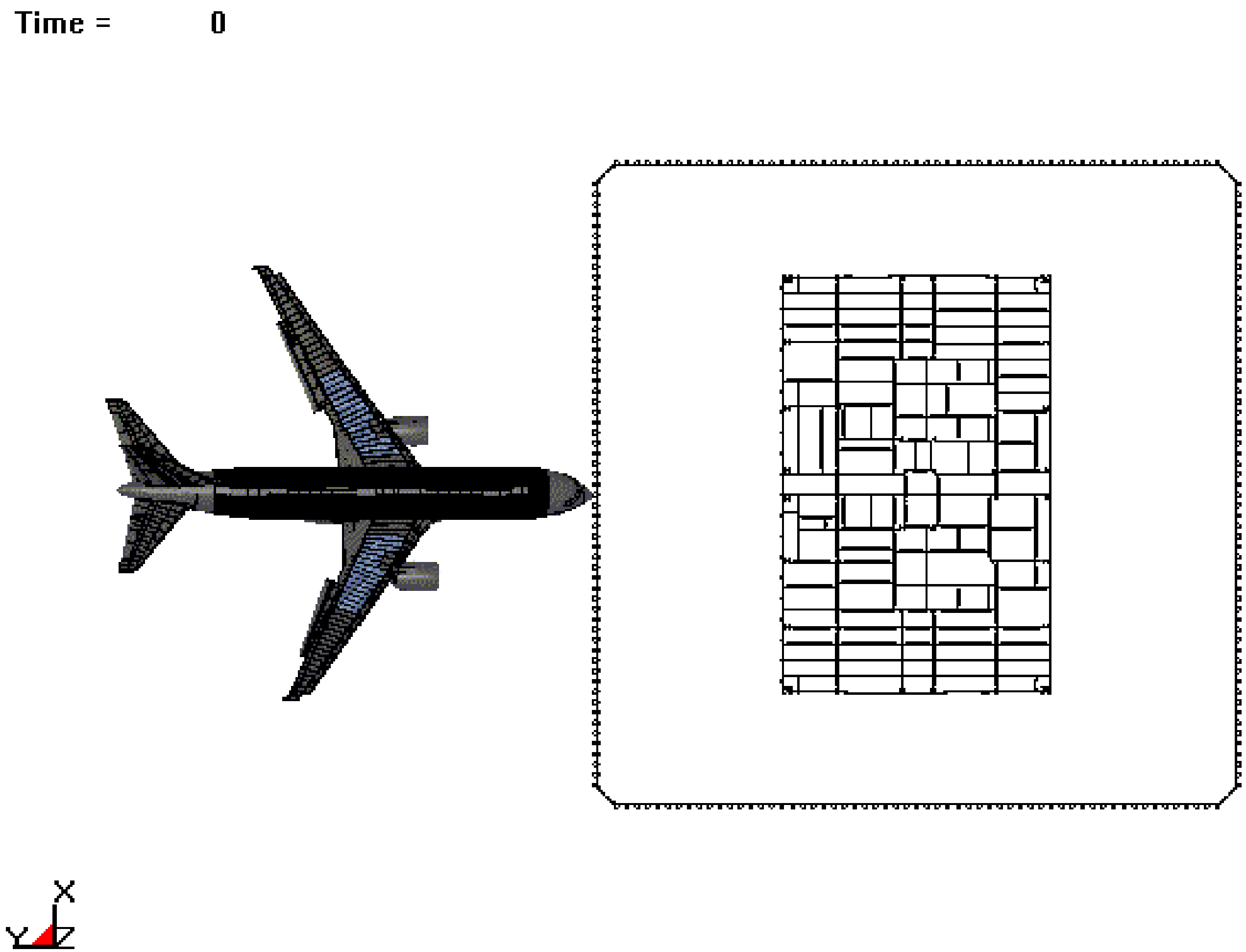




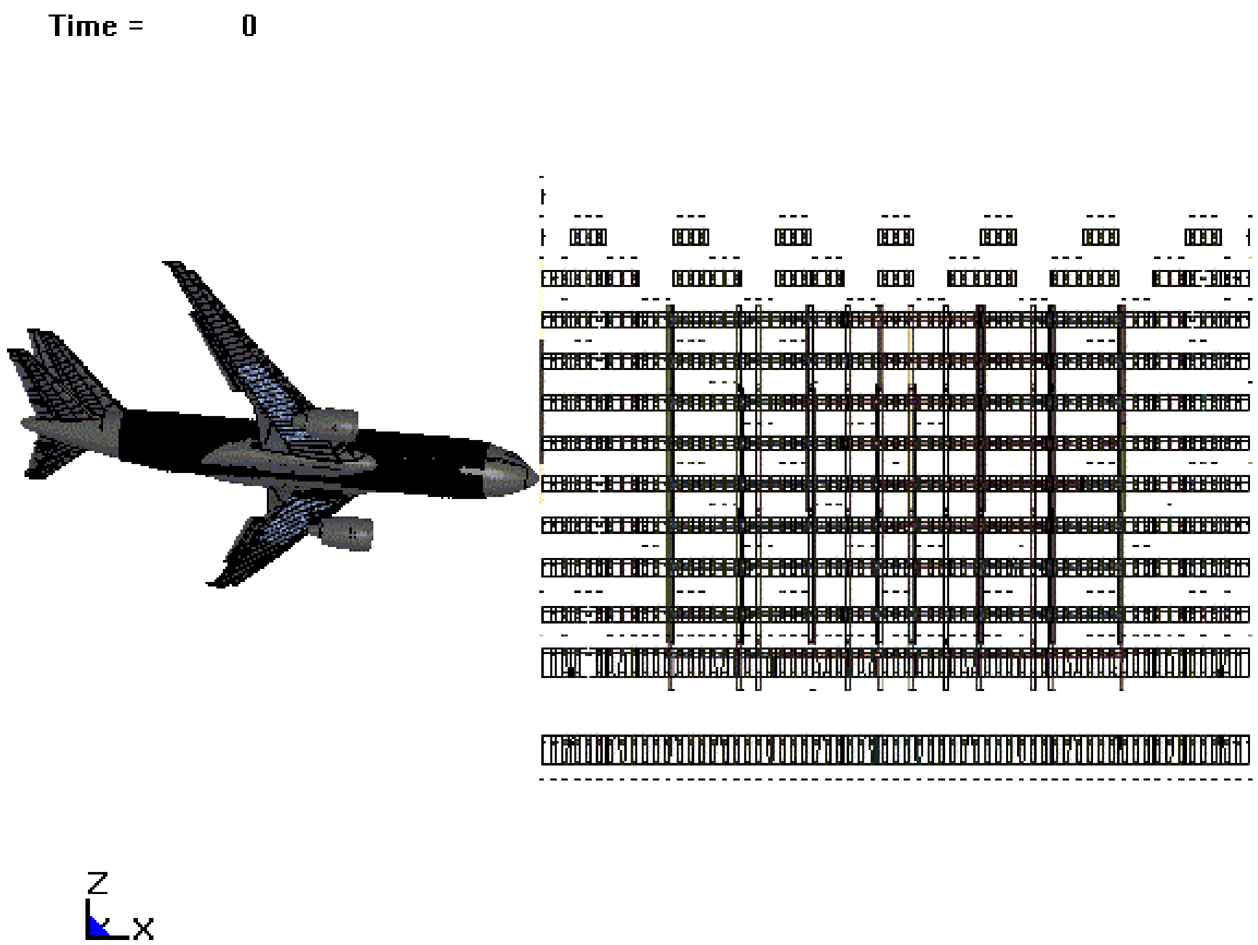
Global Impact – WTC 1



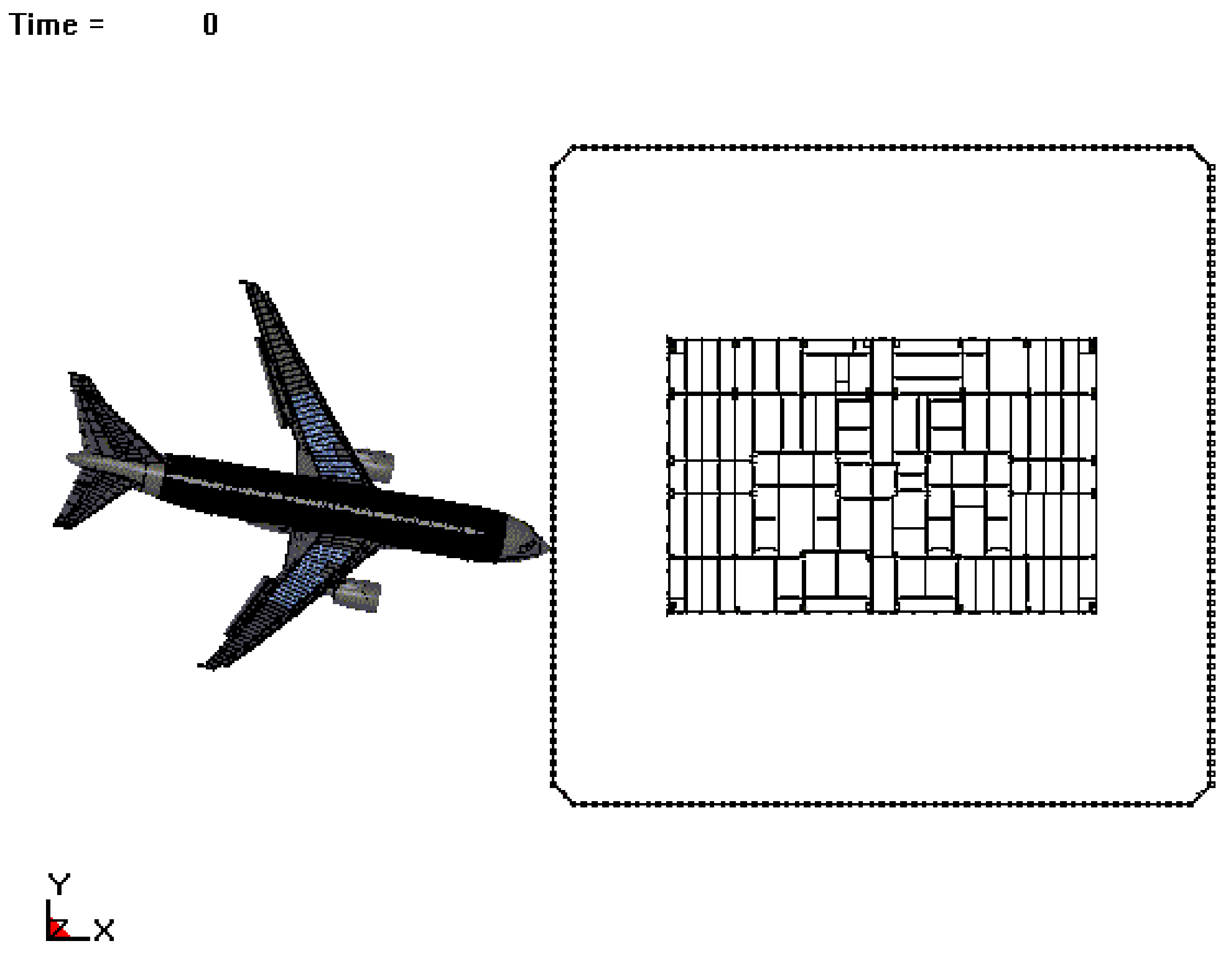
Global Impact – WTC 1



Global Impact – WTC 2



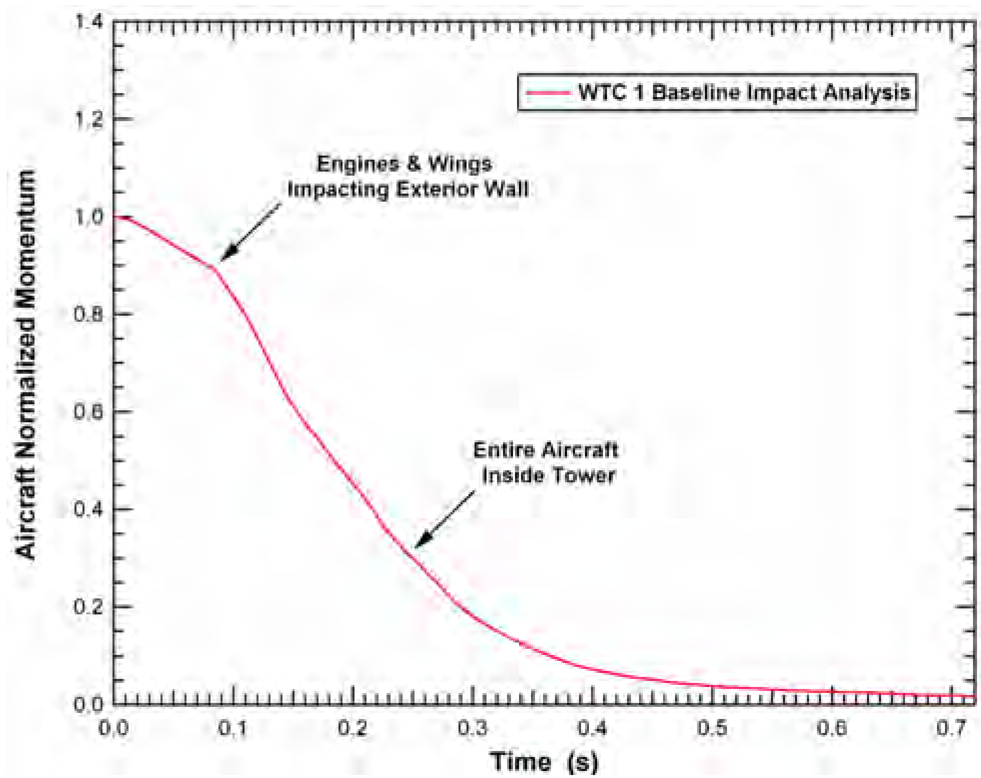
Global Impact – WTC 1



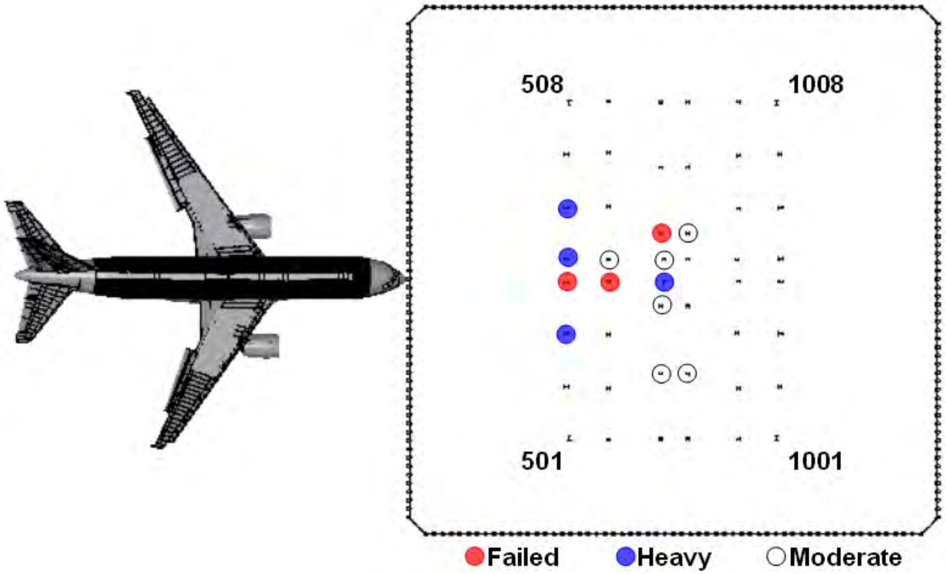
Aircraft Breakup and Momentum Loss – WTC 1

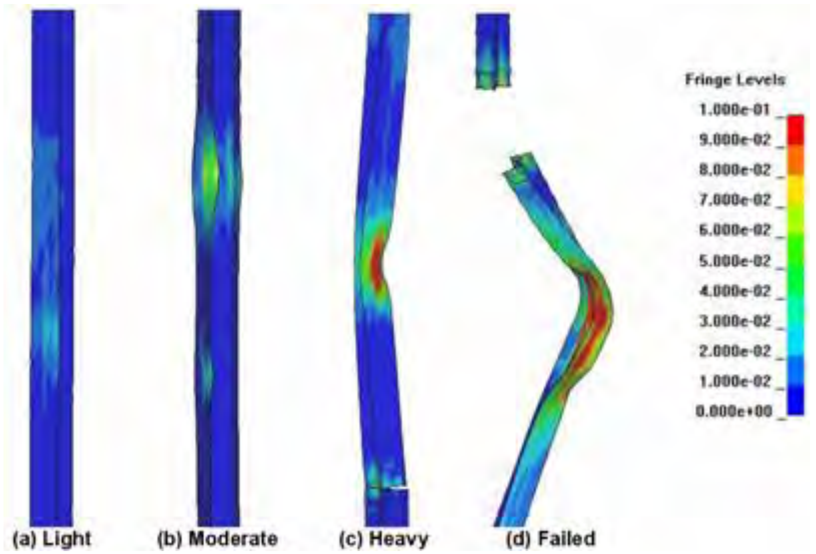

(a) Aircraft structure (time=0.00 s)

(b) Aircraft debris field (time=0.715 s)

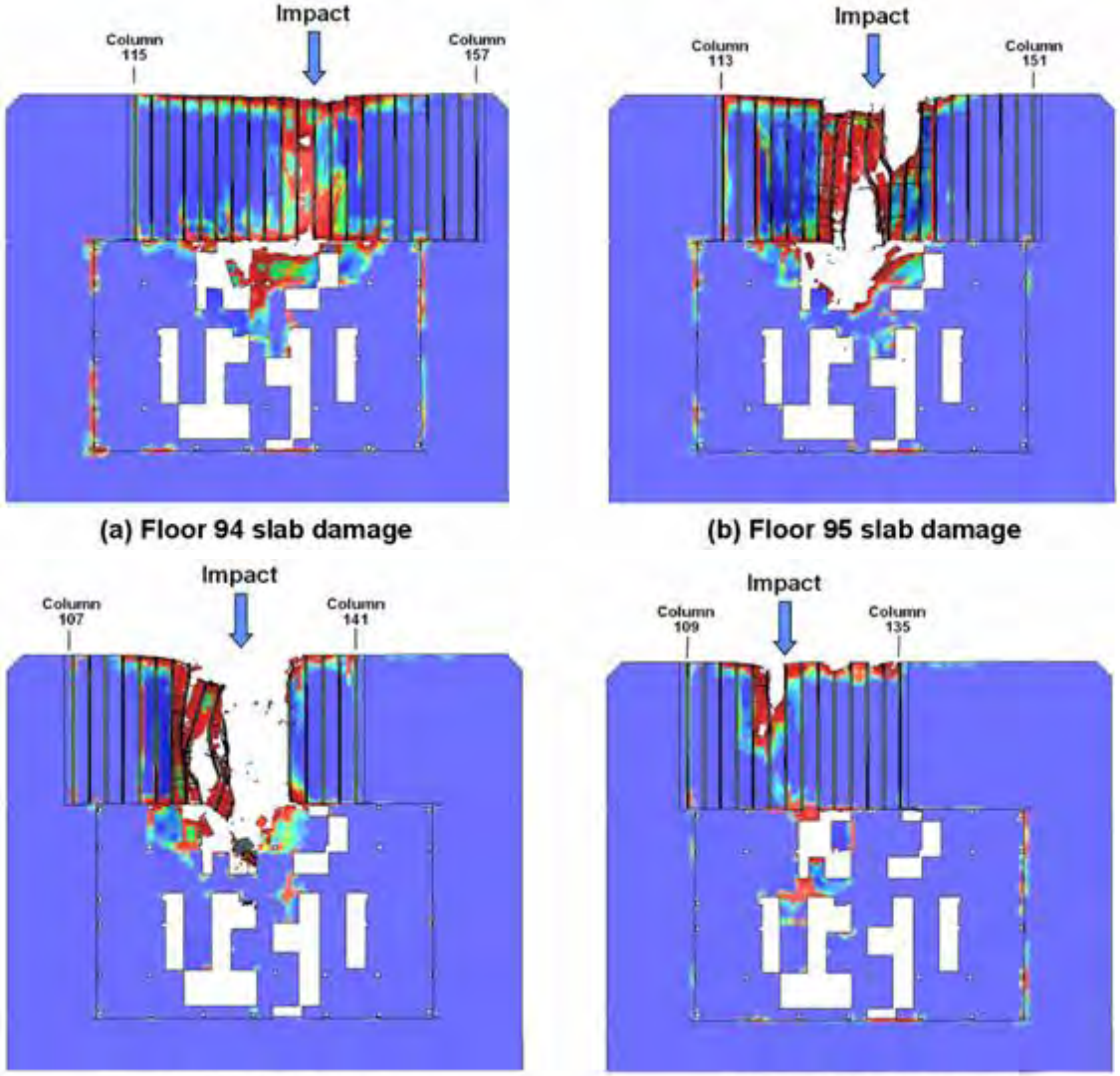


WTC 1 Core Column Damage





WTC 1 Floor Slab Damage



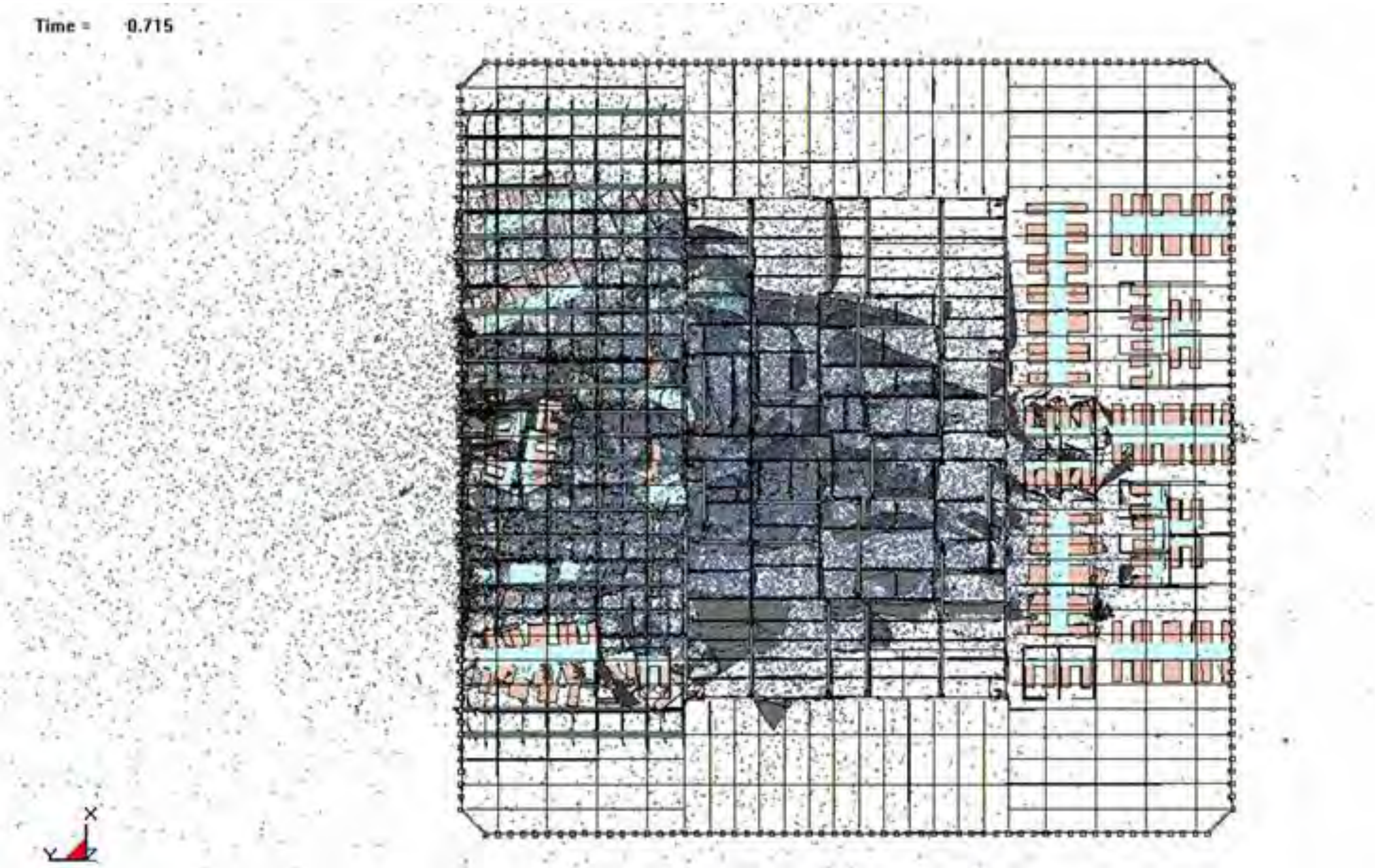
(a) Floor 94 slab damage

(b) Floor 95 slab damage

(c) Floor 96 slab damage

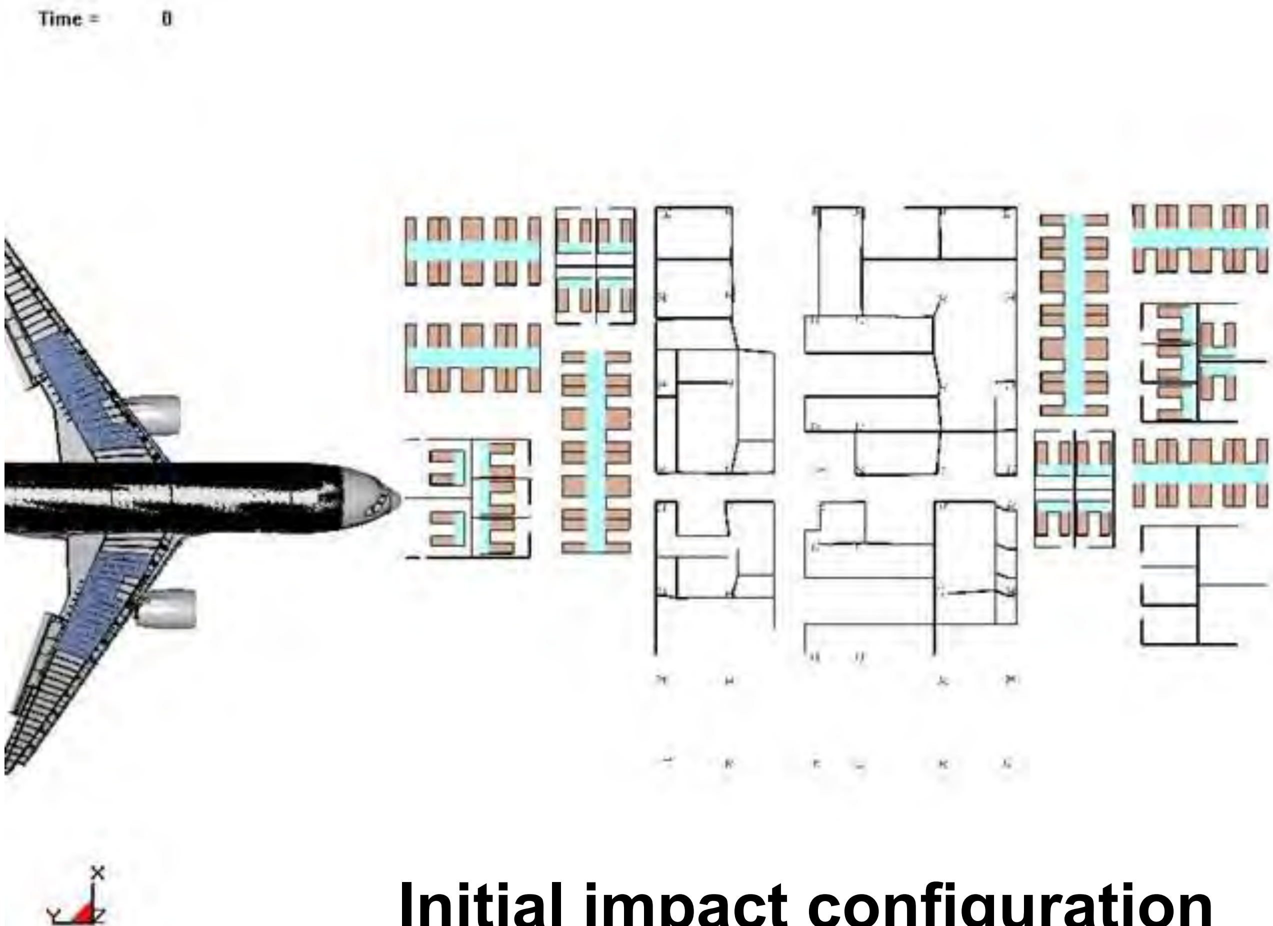
(d) Floor 97 slab damage

WTC 1 Fuel/Debris Distribution



(Floor slab removed from view)

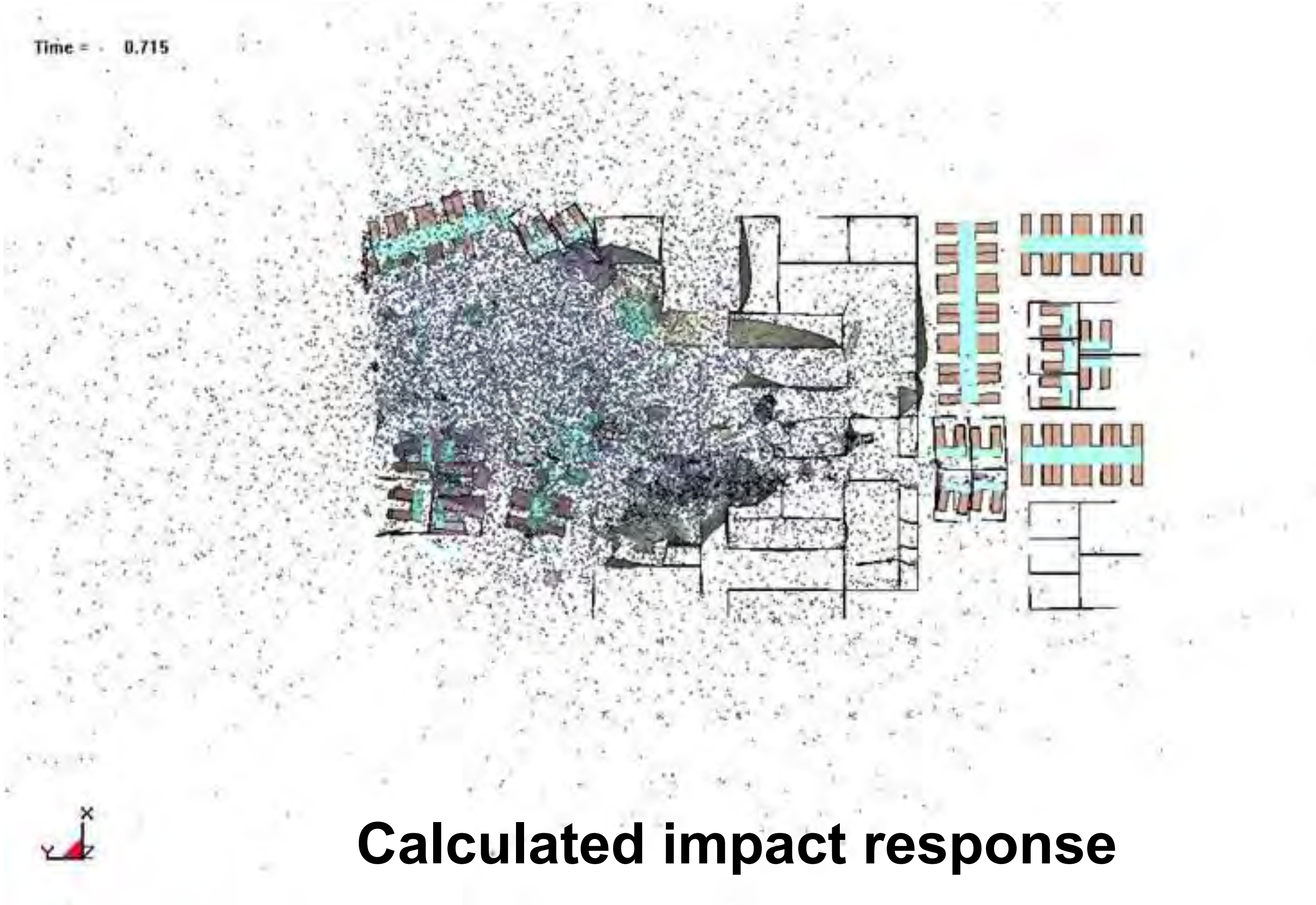
WTC 1 Fuel/Debris Distribution
Floor 94



Initial impact configuration

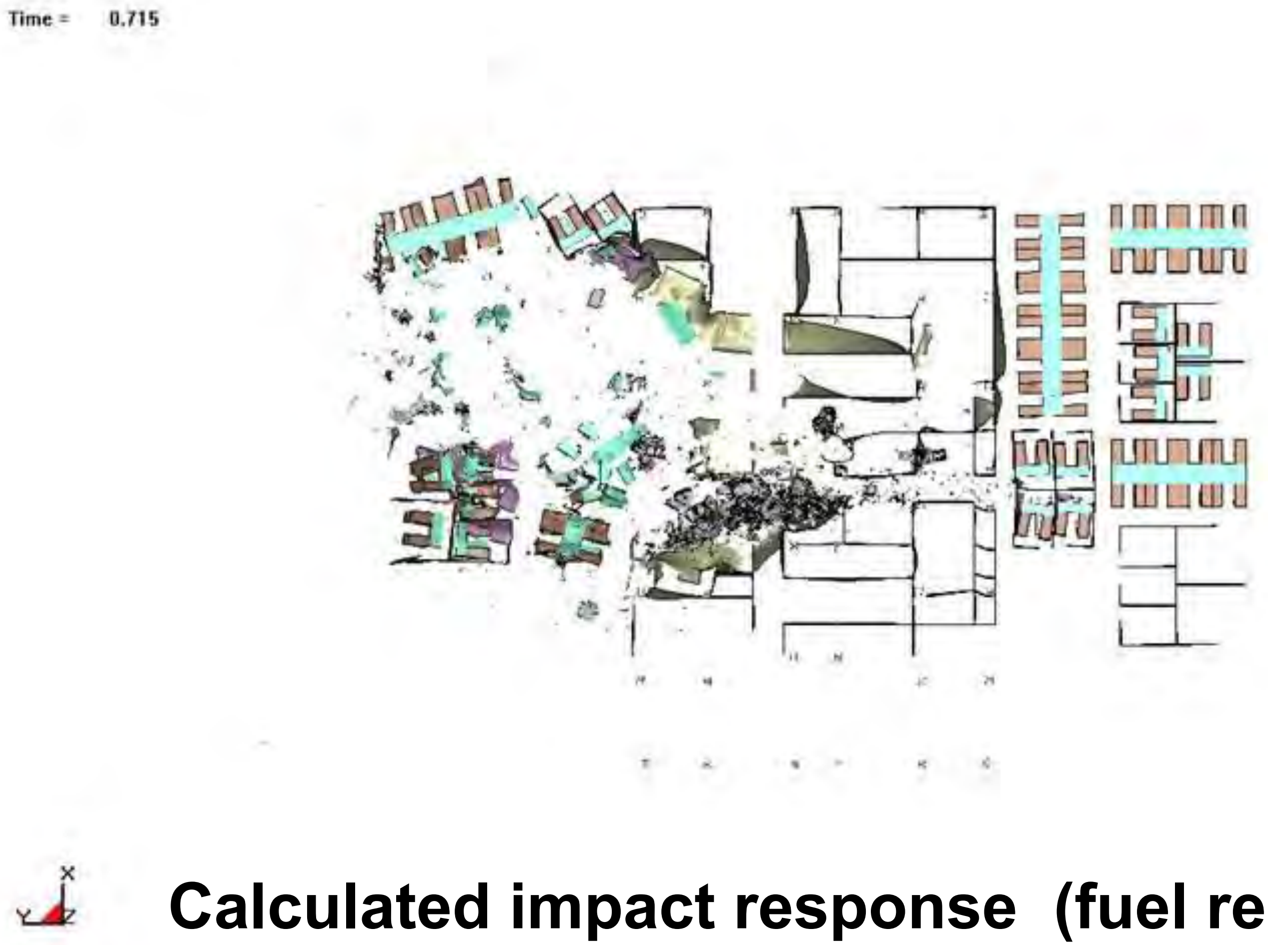
WTC 1 Fuel/Debris Distribution

Floor 94



Calculated impact response

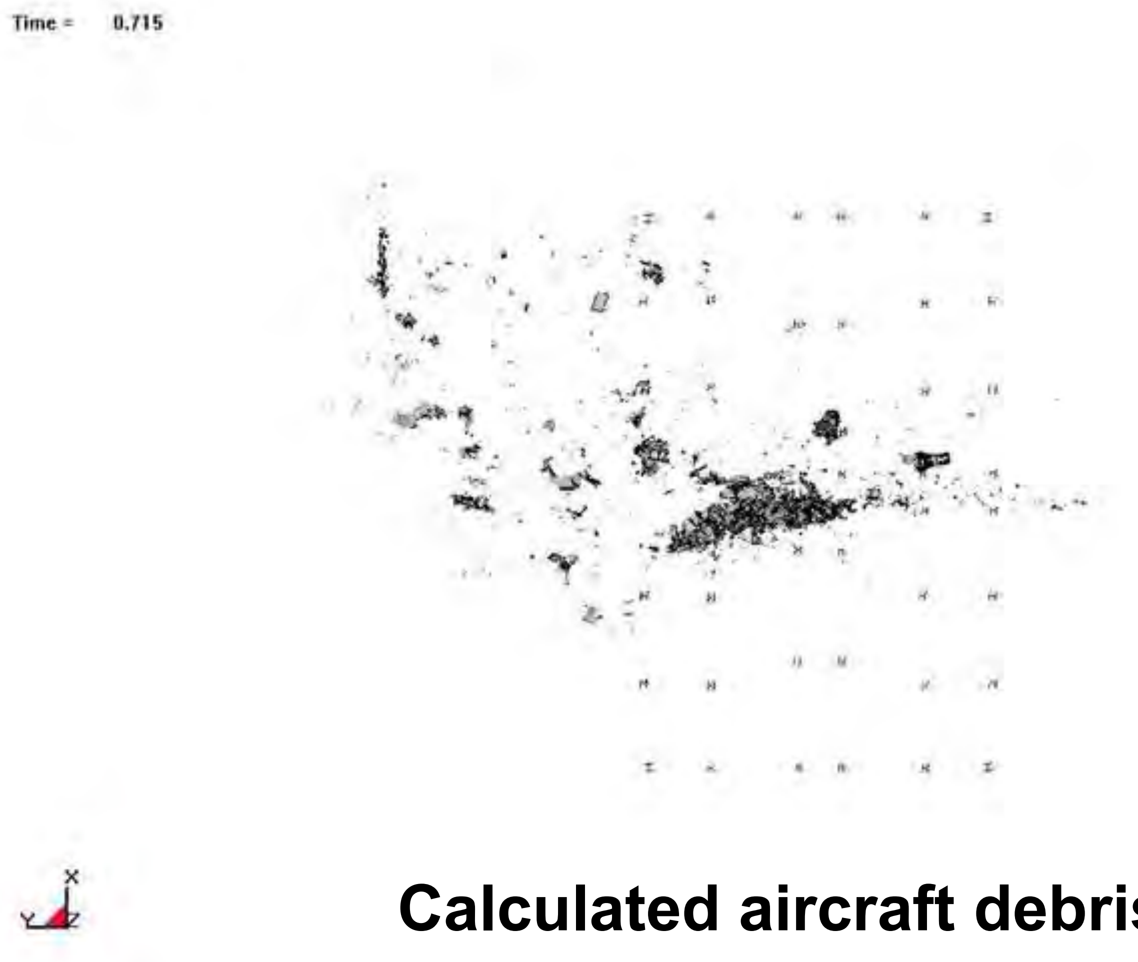
WTC 1 Fuel/Debris Distribution
Floor 94



Calculated impact response (fuel removed)

WTC 1 Fuel/Debris Distribution

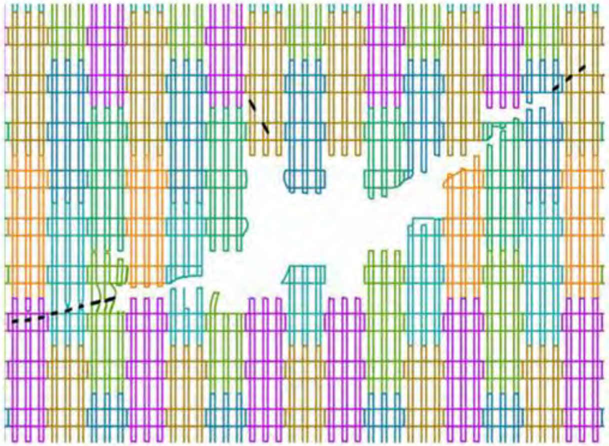
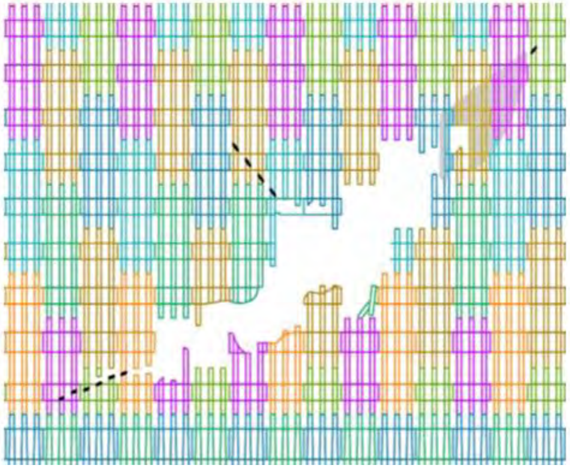
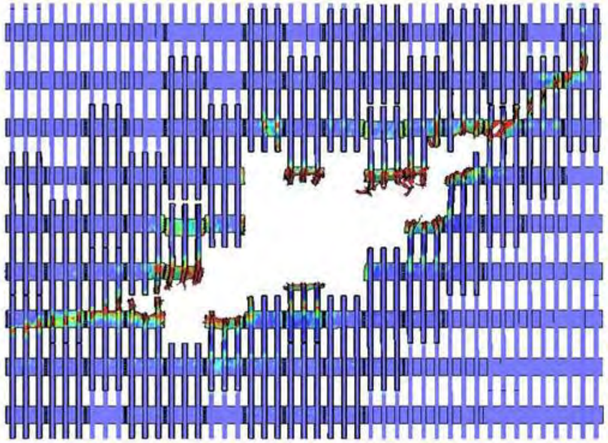
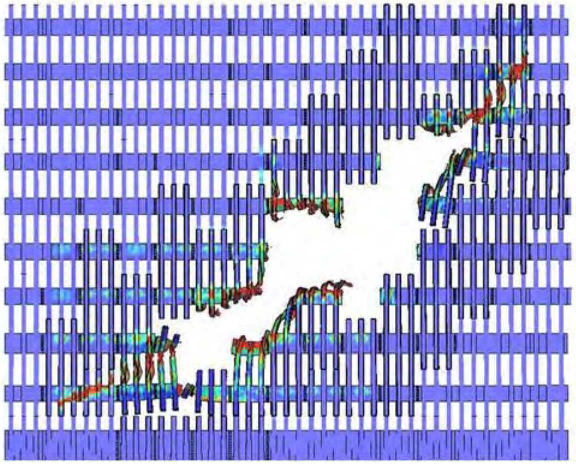
Floor 94



Calculated aircraft debris

Impact Damage on the Tower Exterior

Impact Face

WTC 1	WTC 2
 Schematic of actual damage	 Schematic of actual damage
 Calculated damage	 Calculated damage

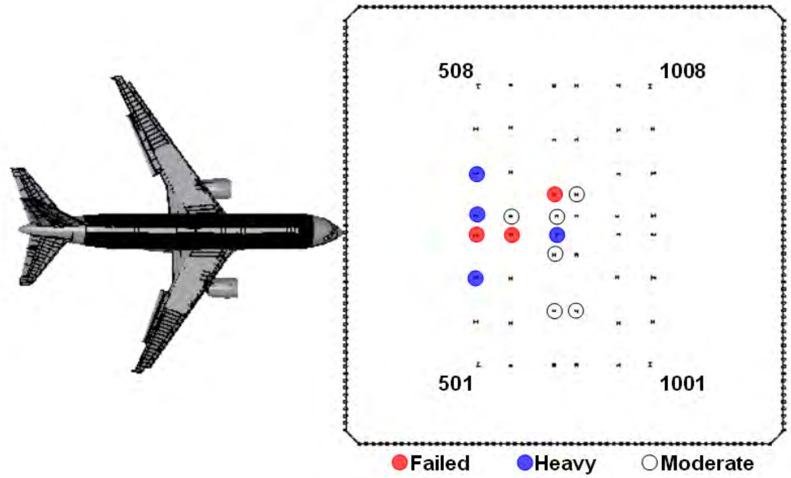
Input Parameters for Additional WTC 1 Global Impact Analyses

Analysis Parameters		Base case	More Severe	Less Severe
Flight Parameters	Impact Velocity	443 mph	472 mph	414 mph
	Trajectory - pitch	10.6°	7.6°	13.6°
	Trajectory - yaw	0.0°	0.0°	0.0°
	Orientation - pitch	8.6°	5.6°	11.6°
	Orientation - yaw	0.0°	0.0°	0.0°
Aircraft Parameters	Weight	100 percent	105 percent	95 percent
	Failure Strain	100 percent	125 percent	75 percent
Tower Parameters	Failure Strain	100 percent	80 percent	120 percent
	Live Load Weight[1]	25 percent	20 percent	25 percent

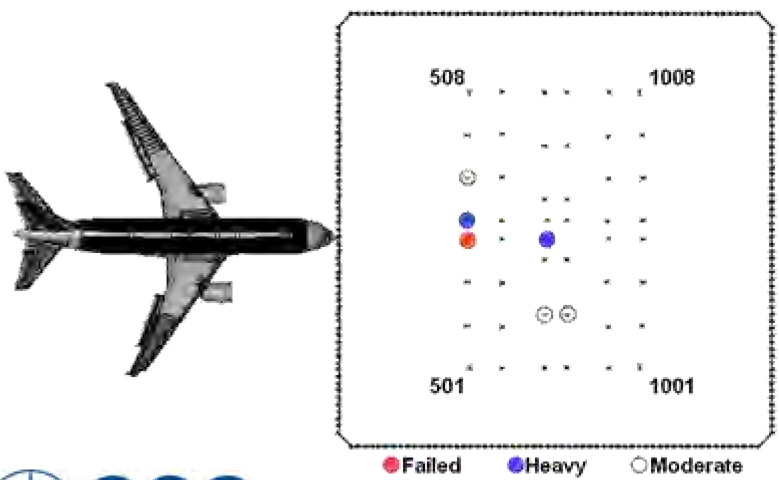
1. Live load weight expressed as a percentage if the design live load.

Calculated WTC 1 Core Damage

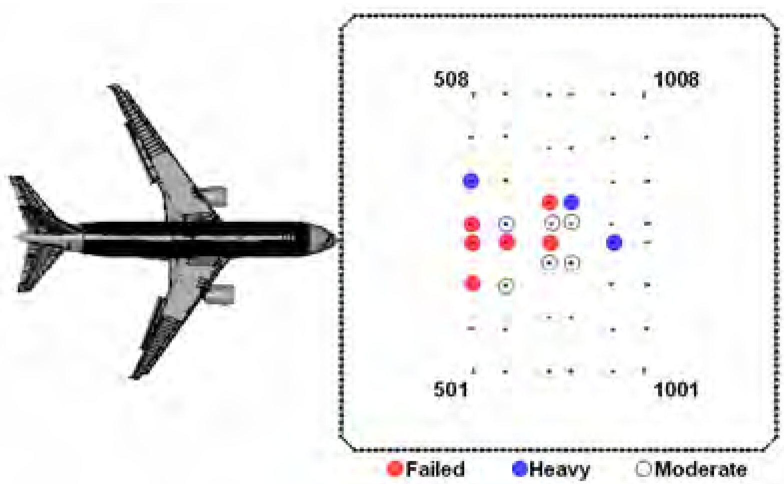
Calculated base case impact damage



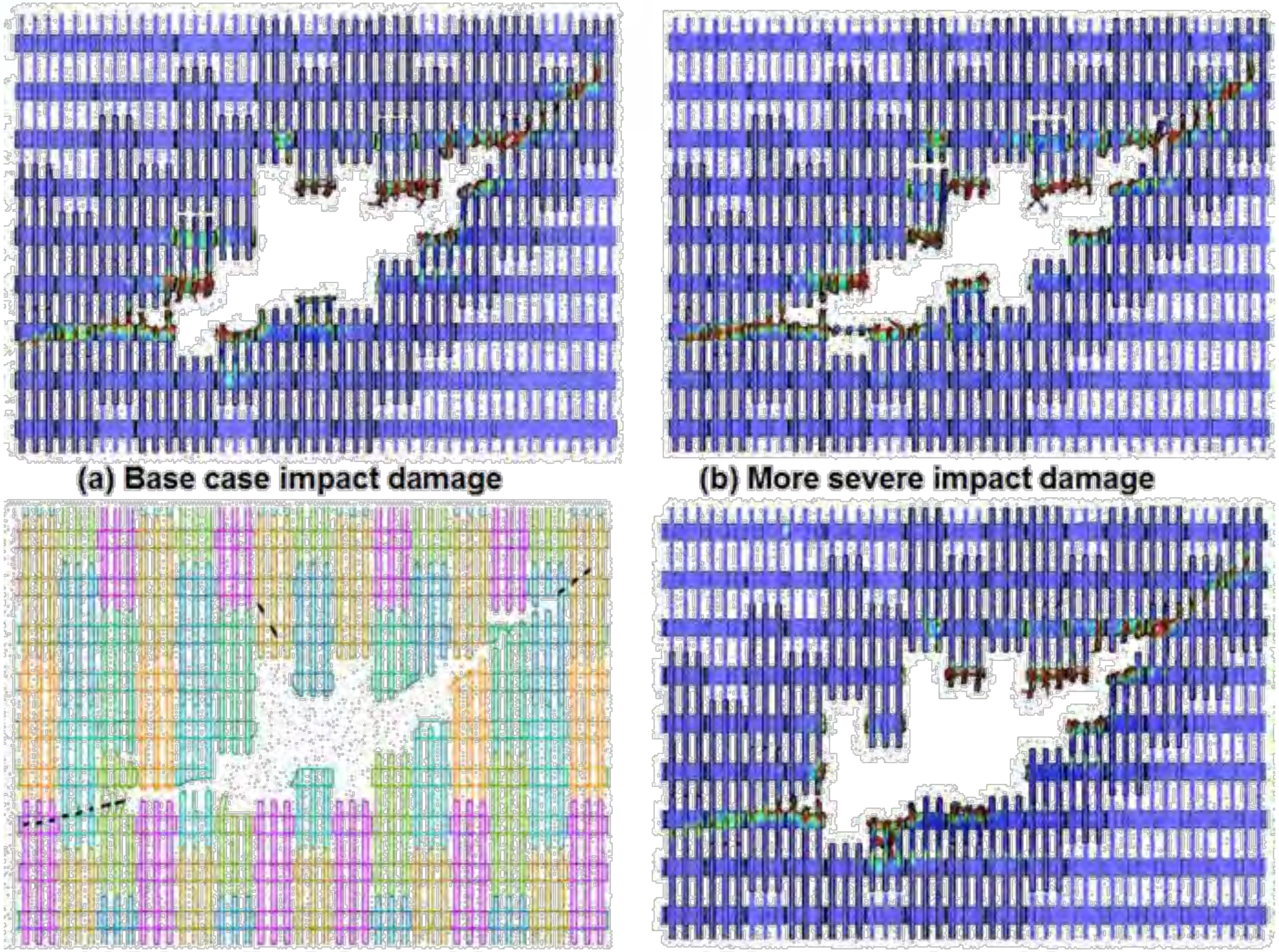
Calculated less severe impact damage



Calculated more severe impact damage



WTC 1 Exterior Damage Comparison



(a) Base case impact damage

(b) More severe impact damage

(c) Schematic of observed damage

(d) Less severe impact damage

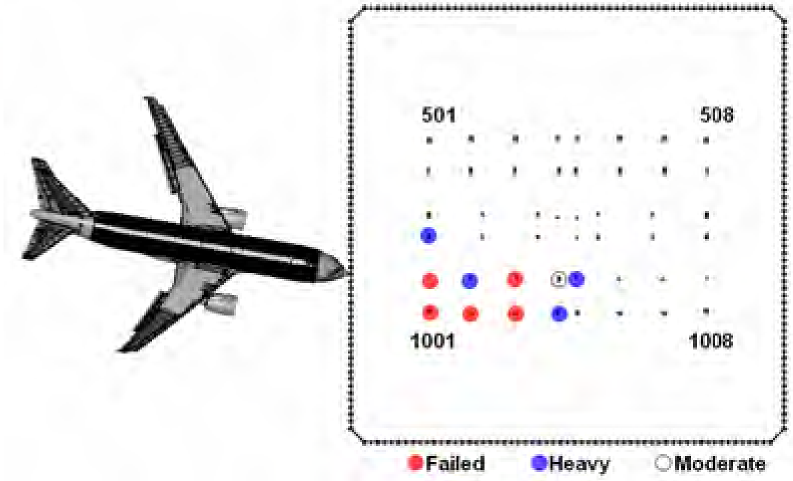
Input Parameters for Additional WTC 2 Global Impact Analyses

Analysis Parameters		Base Case	More Severe	Less Severe
Flight Parameters	Impact Velocity	546 mph	570 mph	521 mph
	Trajectory - pitch	6.0°	5.0°	8.0°
	Trajectory - yaw	13.0°	13.0°	13.0°
	Orientation - pitch	5.0°	4.0°	7.0°
	Orientation - yaw	10.0°	10.0°	10.0°
Aircraft Parameters	Weight	100 percent	105 percent	95 percent
	Failure Strain	100 percent	115 percent	75 percent
Tower Parameters	Contents Strength	100 percent	80 percent	100 percent
	Failure Strain	100 percent	90 percent	120 percent
	Live Load Weight[1]	25 percent	20 percent	25 percent

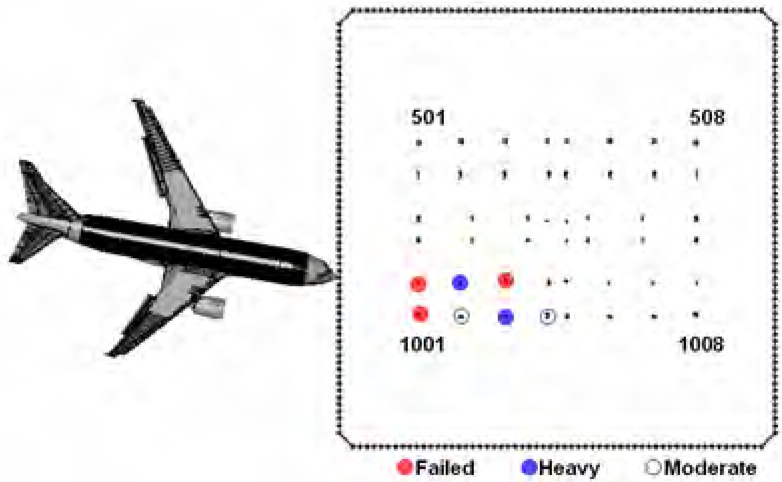
1. Live load weight expressed as a percentage of the design live load.

Calculated Core Impact Damage to WTC 2

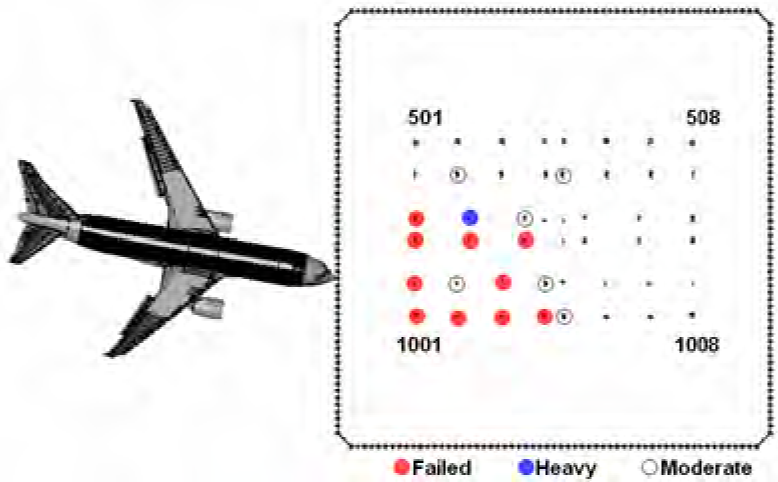
Calculated base case impact damage



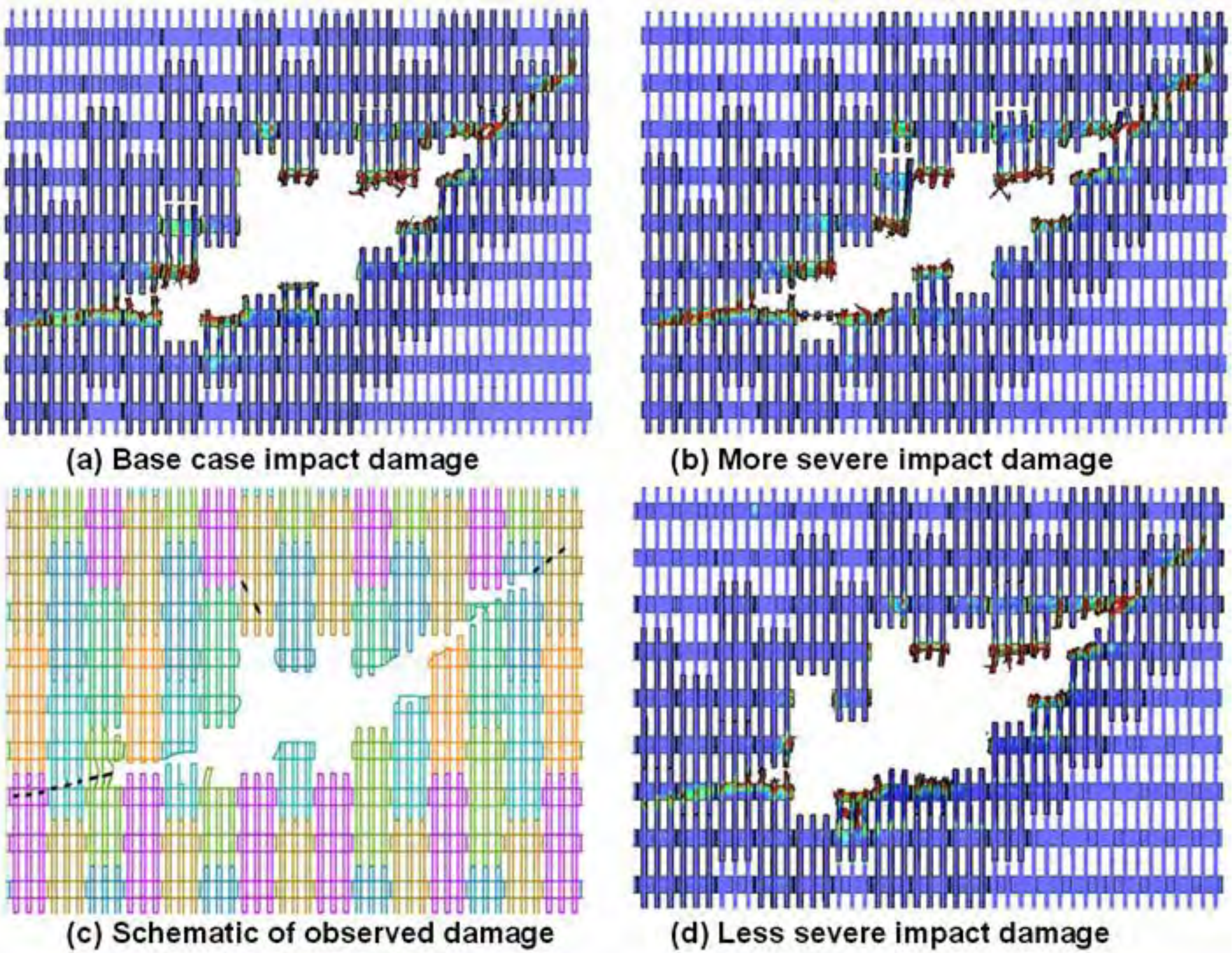
Calculated less severe impact damage



Calculated more severe impact damage



Exterior Wall Damage Comparison for WTC 2



(a) Base case impact damage

(b) More severe impact damage

(c) Schematic of observed damage

(d) Less severe impact damage

Summary

- Component, subassembly and global aircraft impact analyses were performed on WTC 1 and WTC 2.
- Global impact damage comparisons with available observable evidence was good.
- Predictions of damage to the tower core columns:

WTC Impact Investigation	WTC 1 Core Column Damage	WTC 2 Core Column Damage
NIST Base Case Impact Analysis	3 Failed Plus 4 Heavily Damaged	5 Failed Plus 4 Heavily Damaged
NIST More Severe Impact Analysis	6 Failed Plus 3 Heavily Damaged	10 Failed Plus 1 Heavily Damaged
NIST Less Severe Impact Analysis	1 Failed Plus 2 Heavily Damaged	3 Failed Plus 2 Heavily Damaged