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

Baseline Structural Performance and Aircraft Impact Damage Analysis

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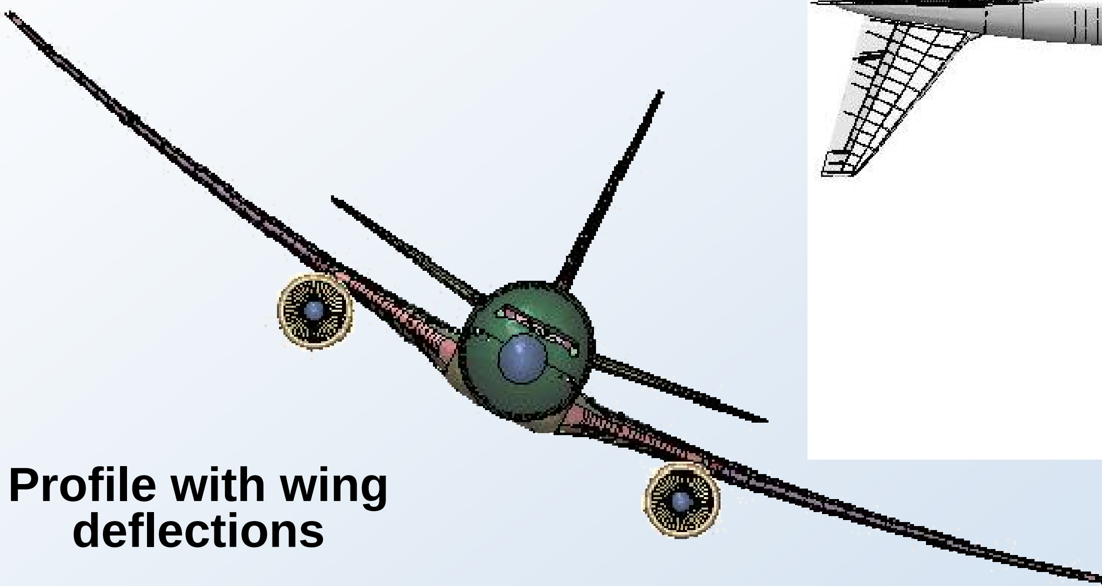
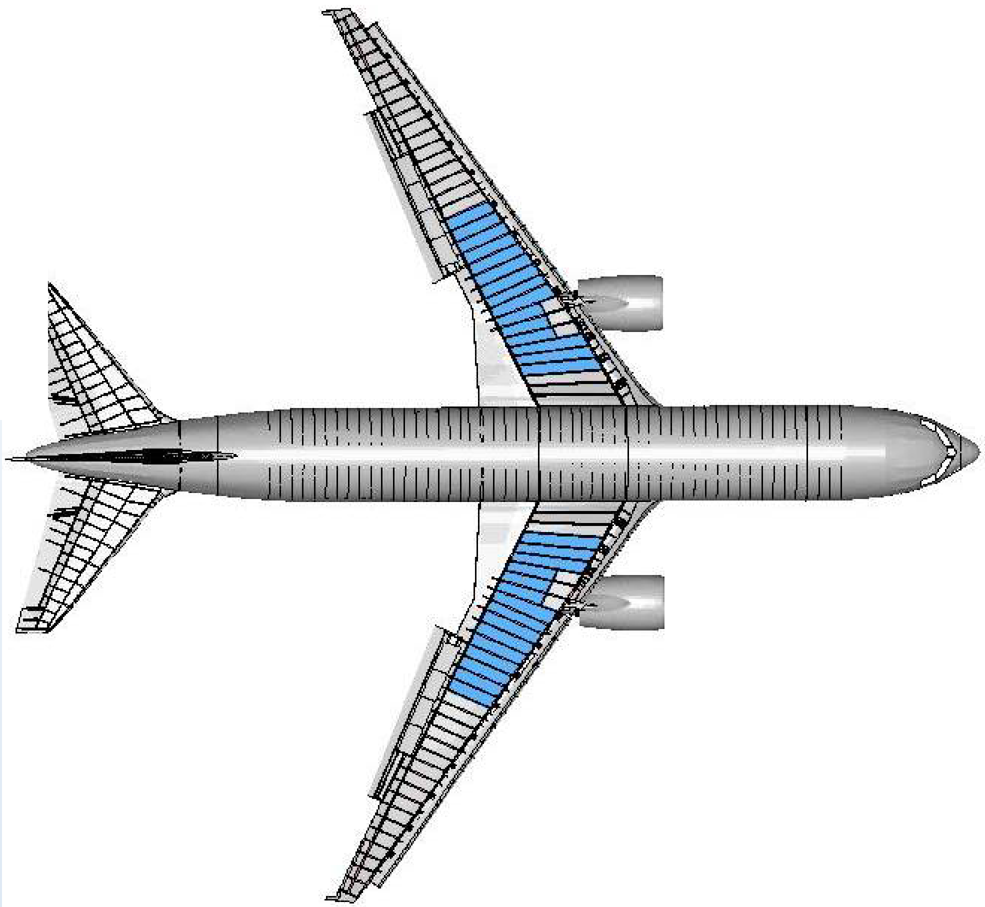
Boeing 767-200 Aircraft Model

Impact Conditions:

- Speed = 443 mph (198 m/s)
- Roll Angle = 25°
- Pitch Angle = 8.6°
- Descent Angle = 10.6°



Profile with wing deflections



Global Aircraft Model with SPH Model of Fuel Included

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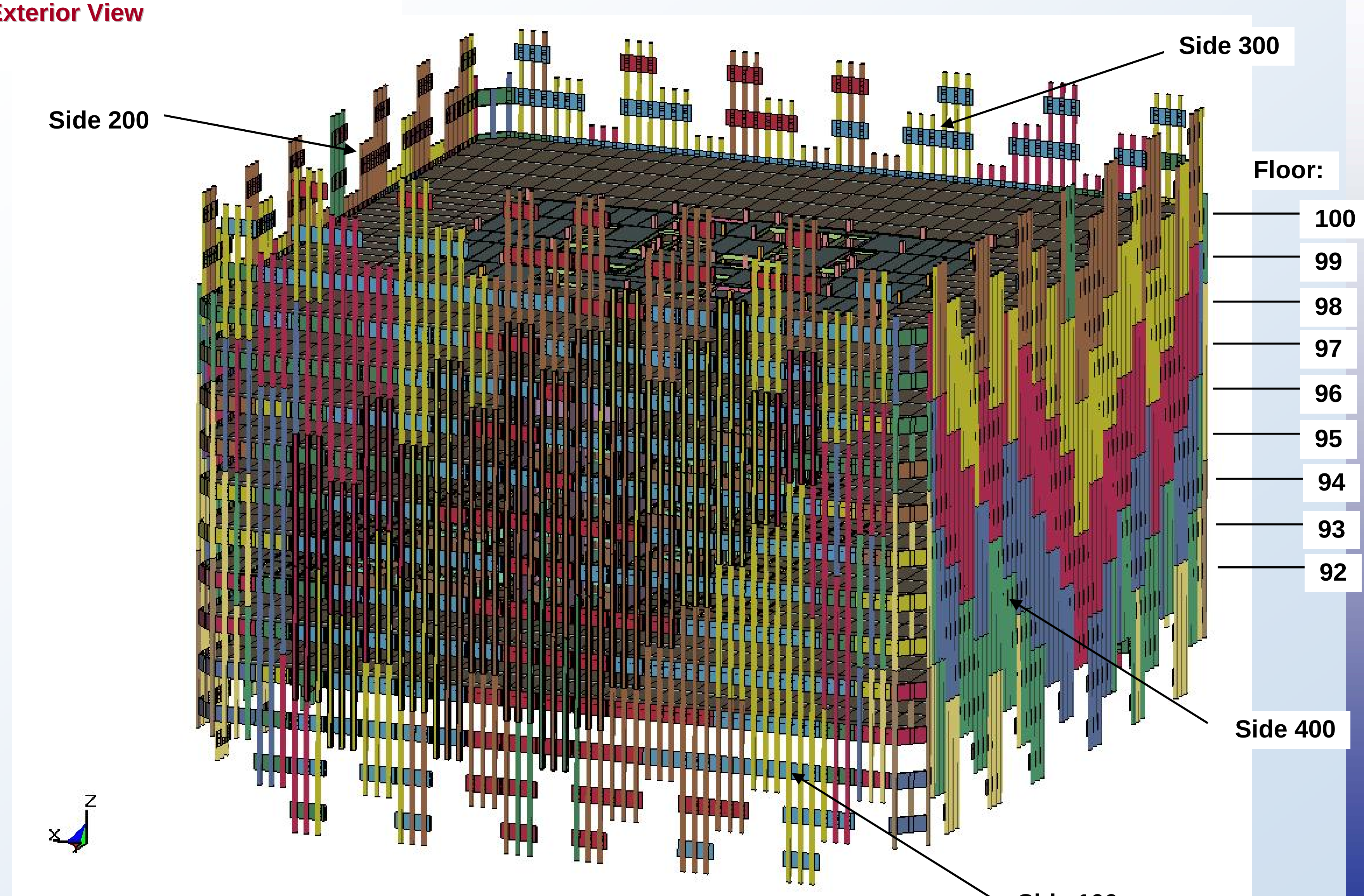
WTC 1 Global Tower Model

Exterior View



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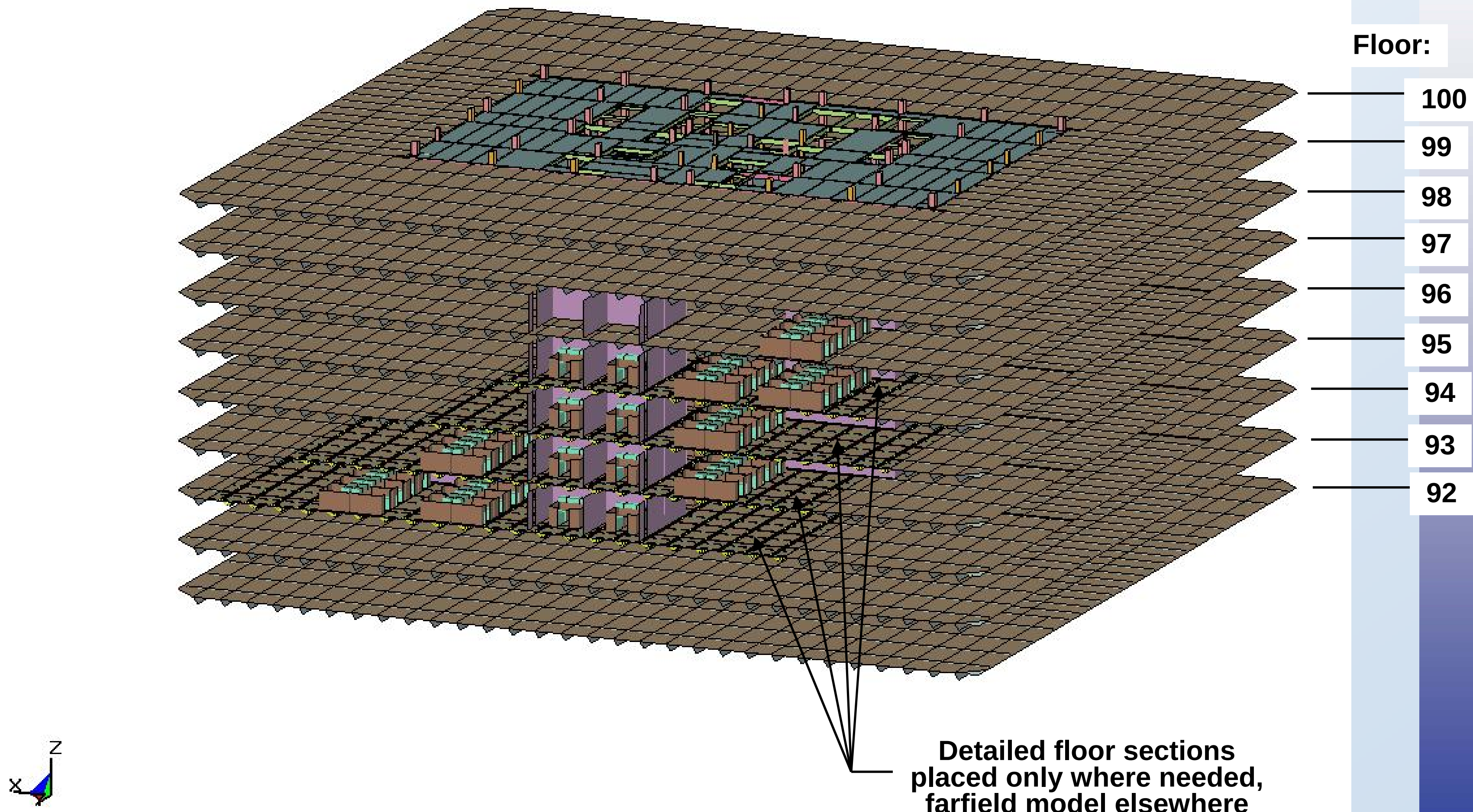
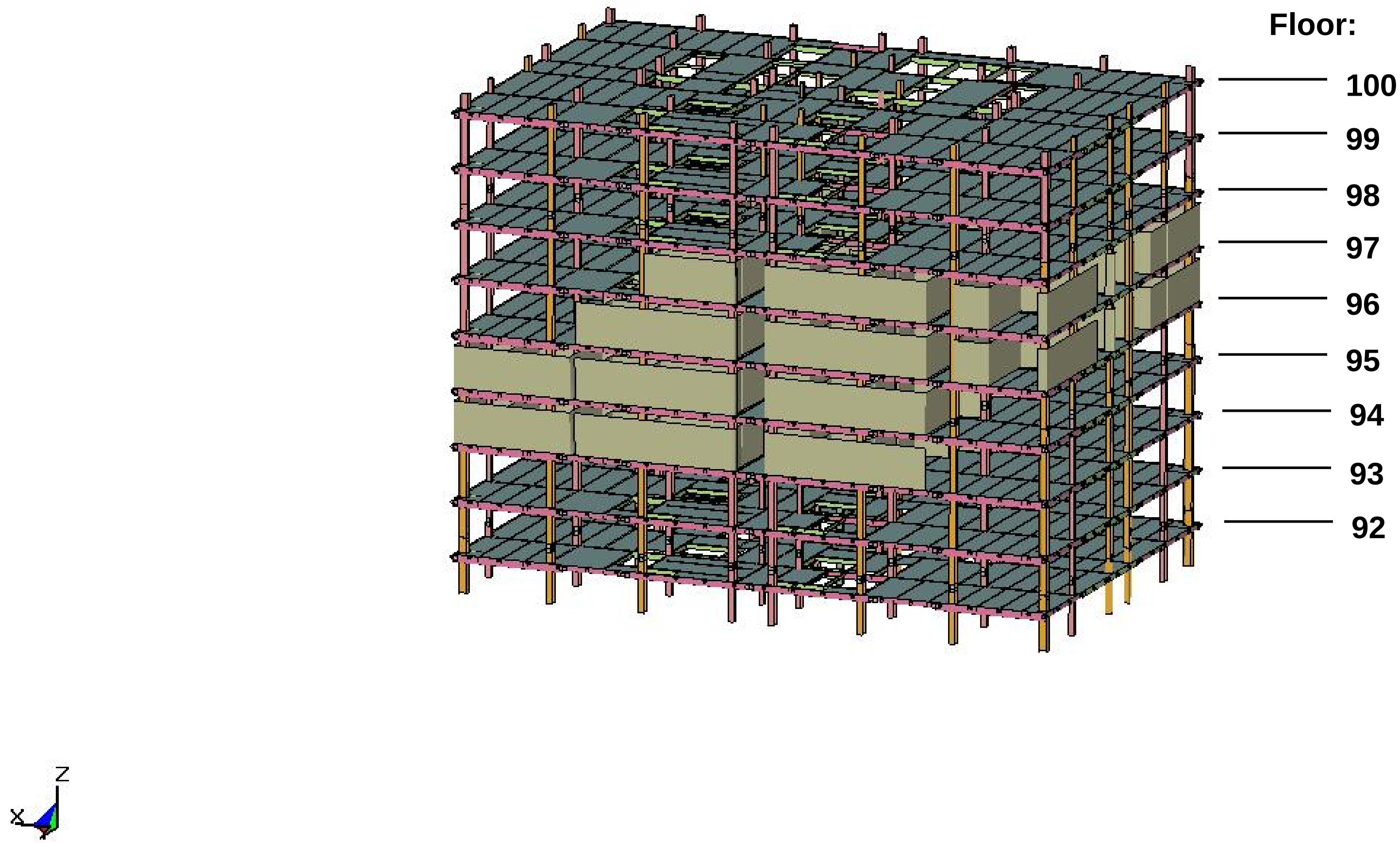
WTC 1 Global Tower Model

Exterior Removed



WTC 1 Global Tower Model

Core Structure



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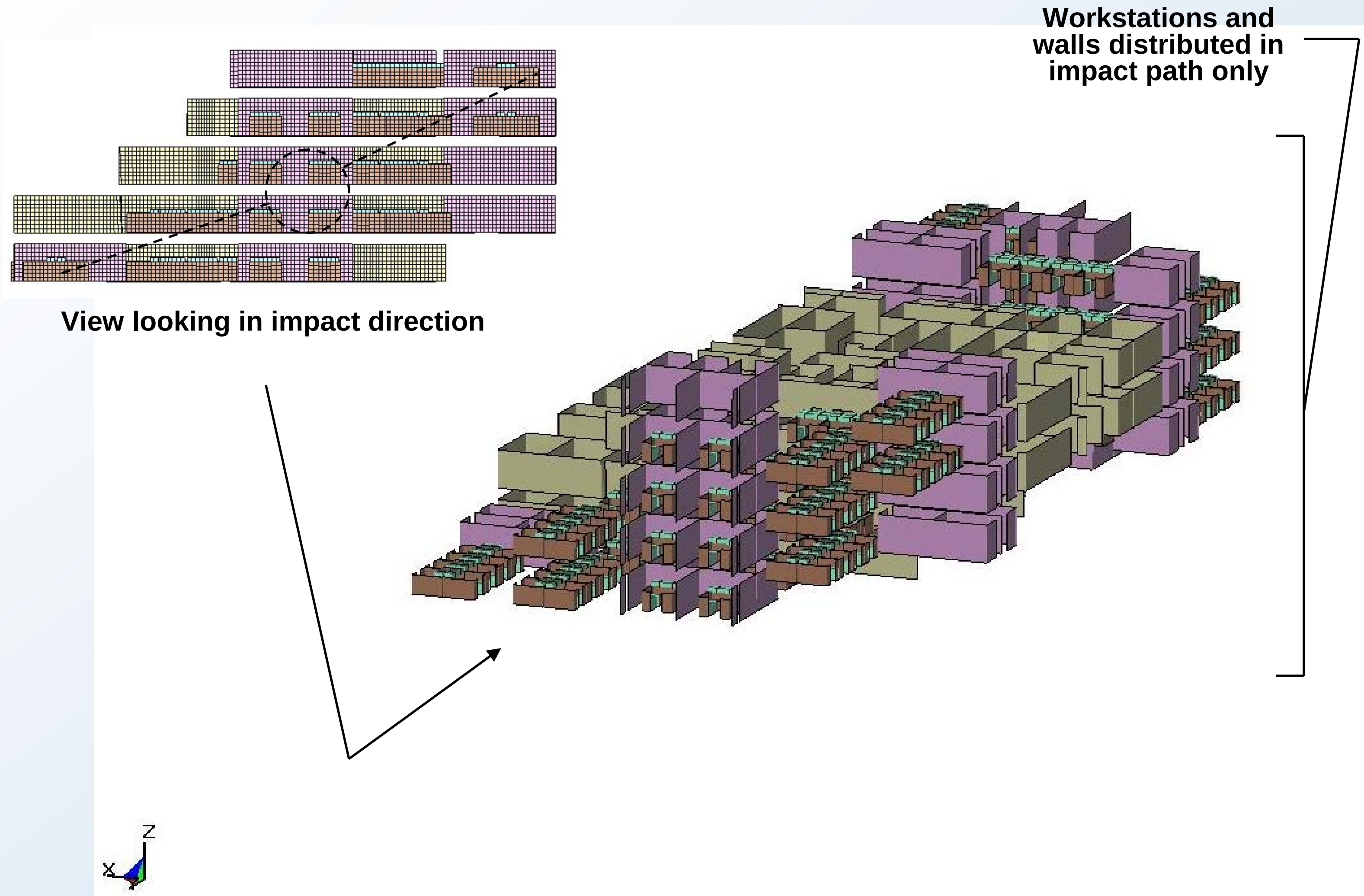
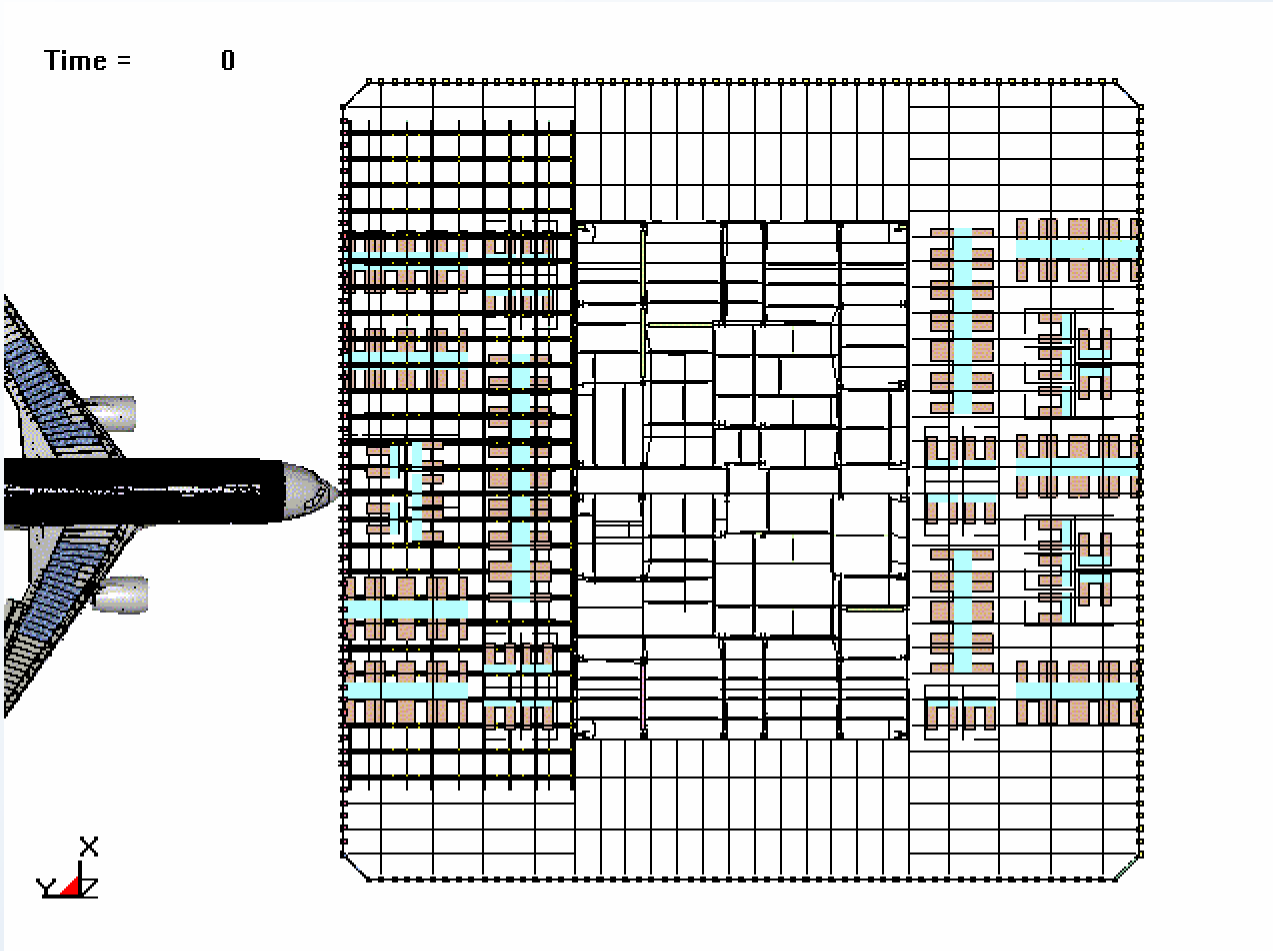
WTC 1 Global Tower Model

Interior Walls and Workstations

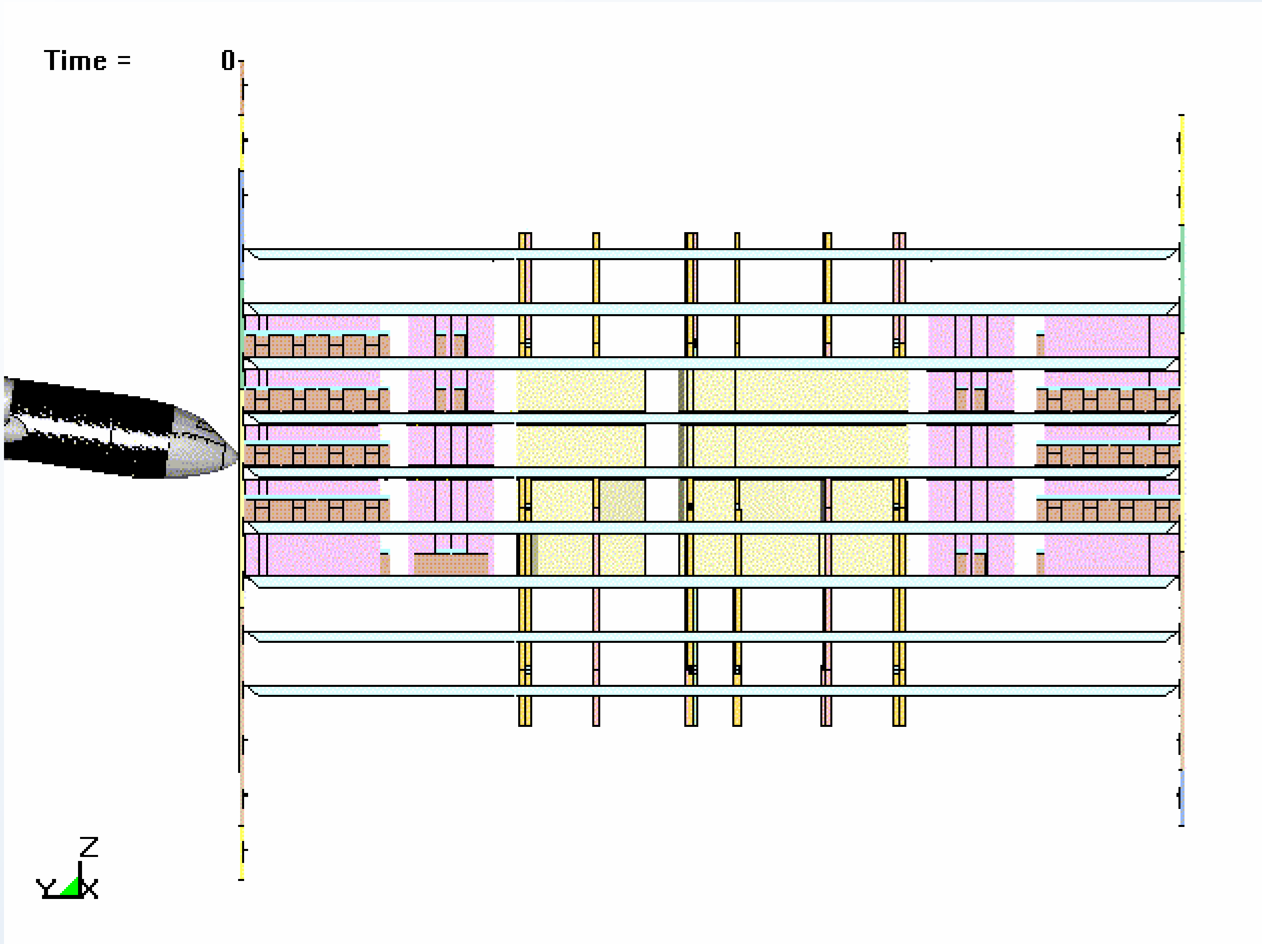


WTC 1 Global Impact Analysis



View from Top

WTC 1 Global Impact Analysis



Oblique View

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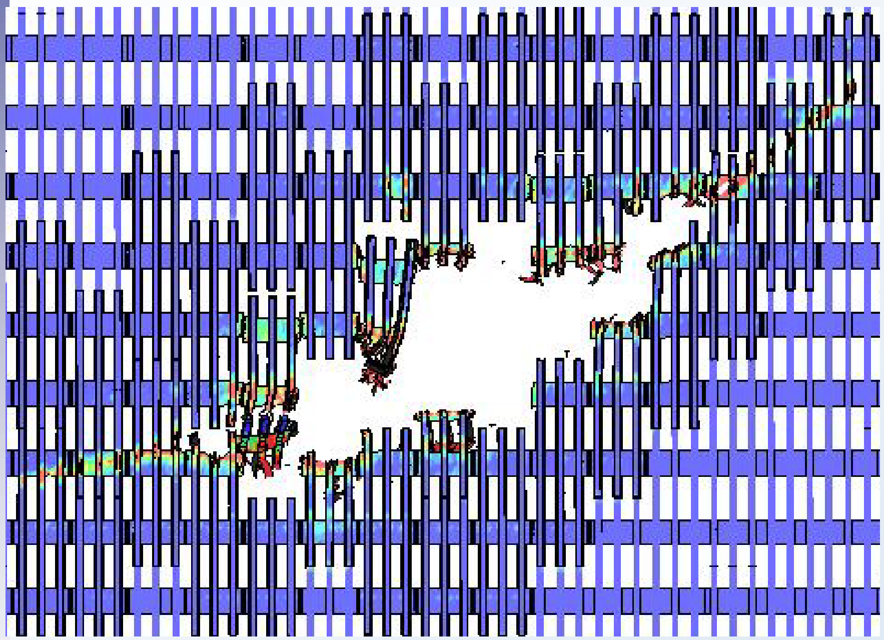
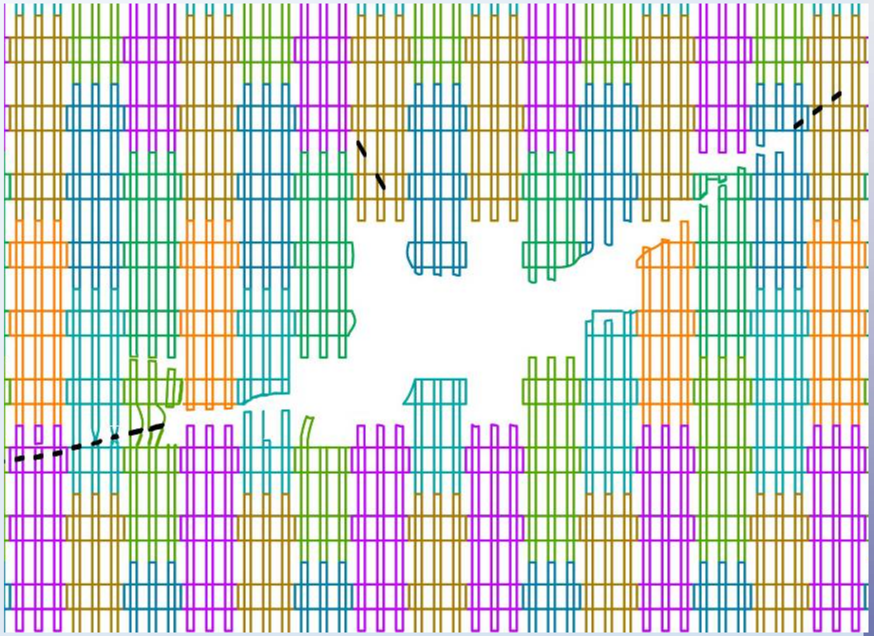
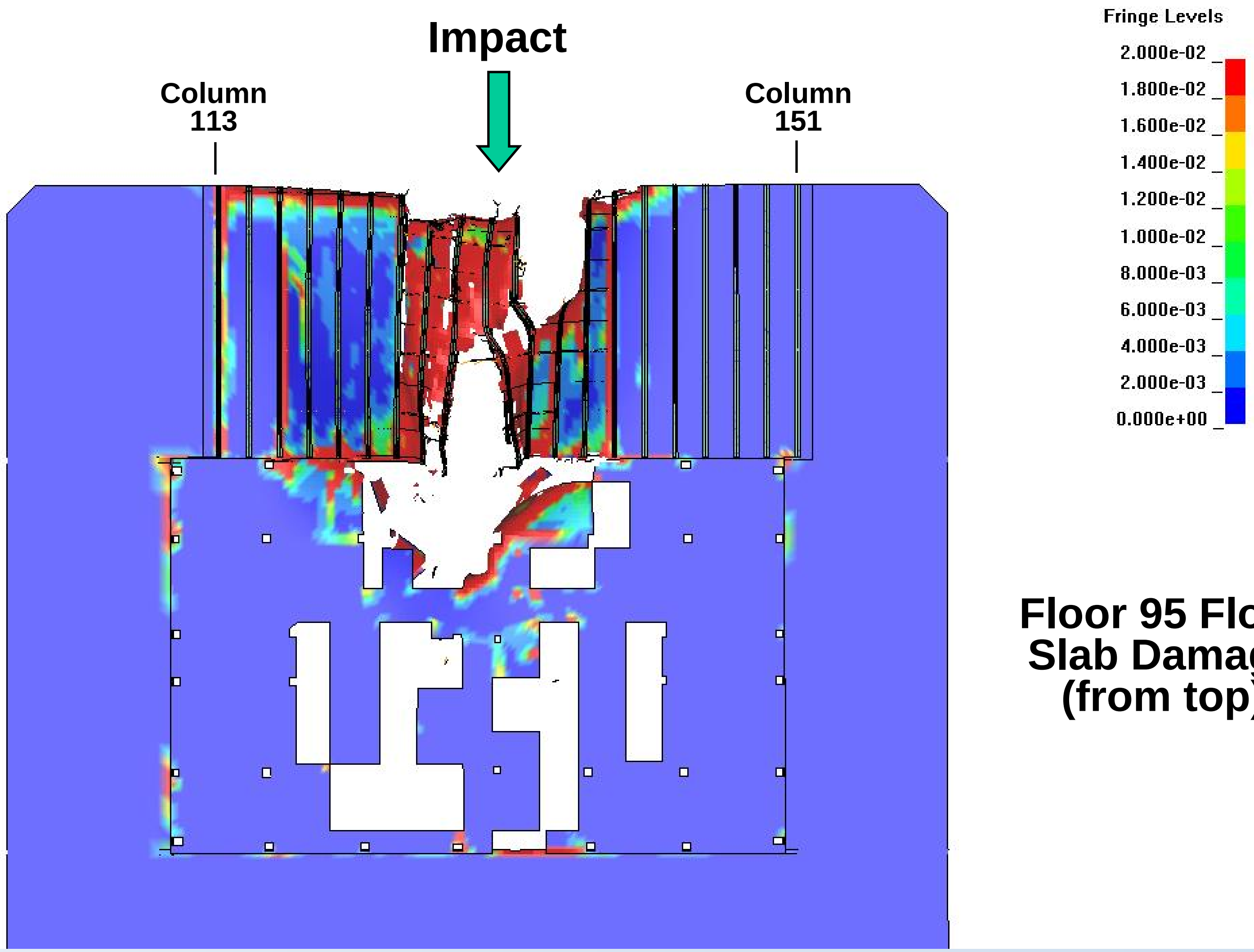
Aircraft Impact into WTC 1
Exterior Damage





t = 0.715 s

Aircraft Impact into WTC 1
Floor Slab Damage



Floor 95 Floor Slab Damage (from top)

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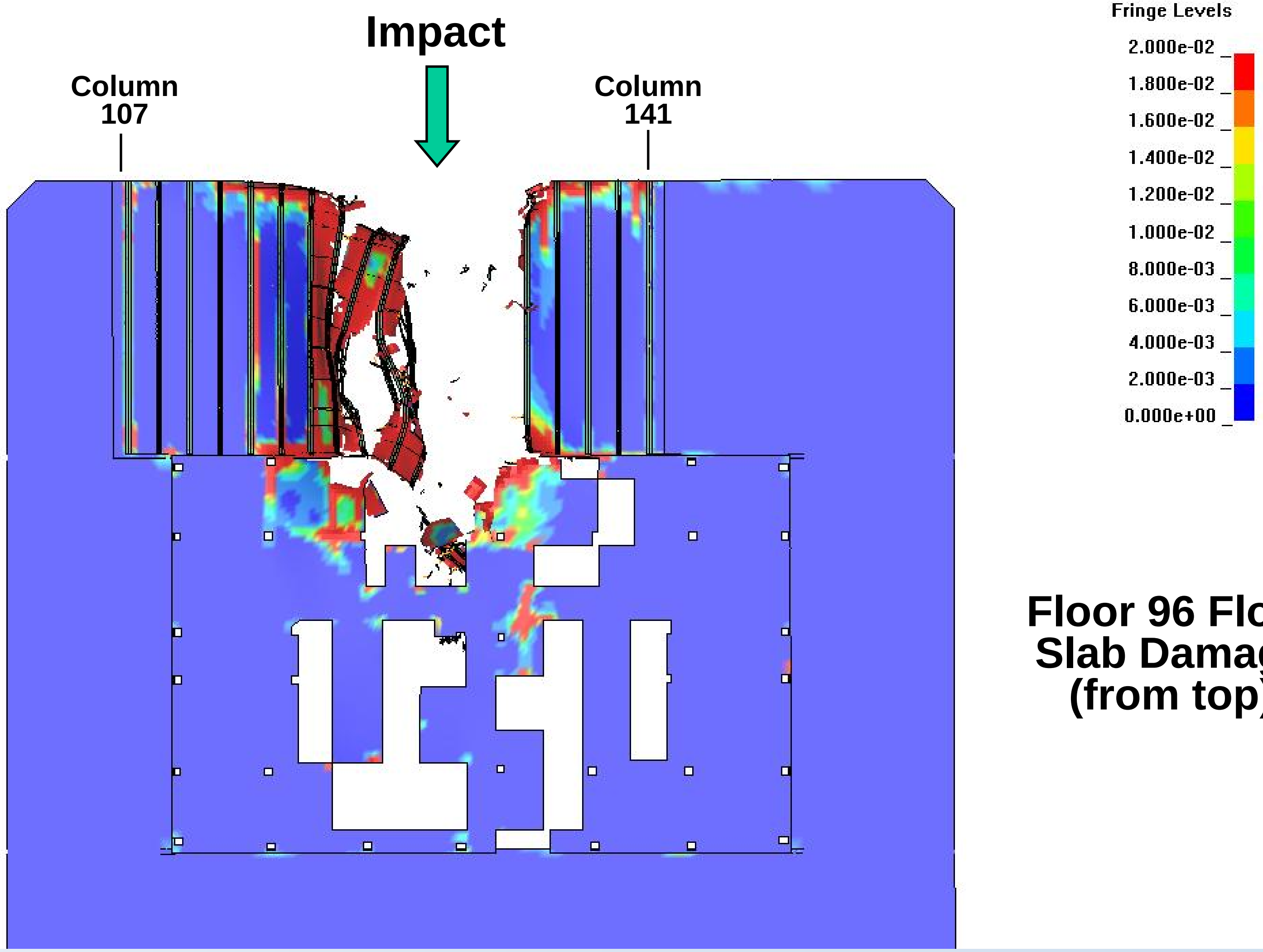
Aircraft Impact into WTC 1
Floor Slab Damage

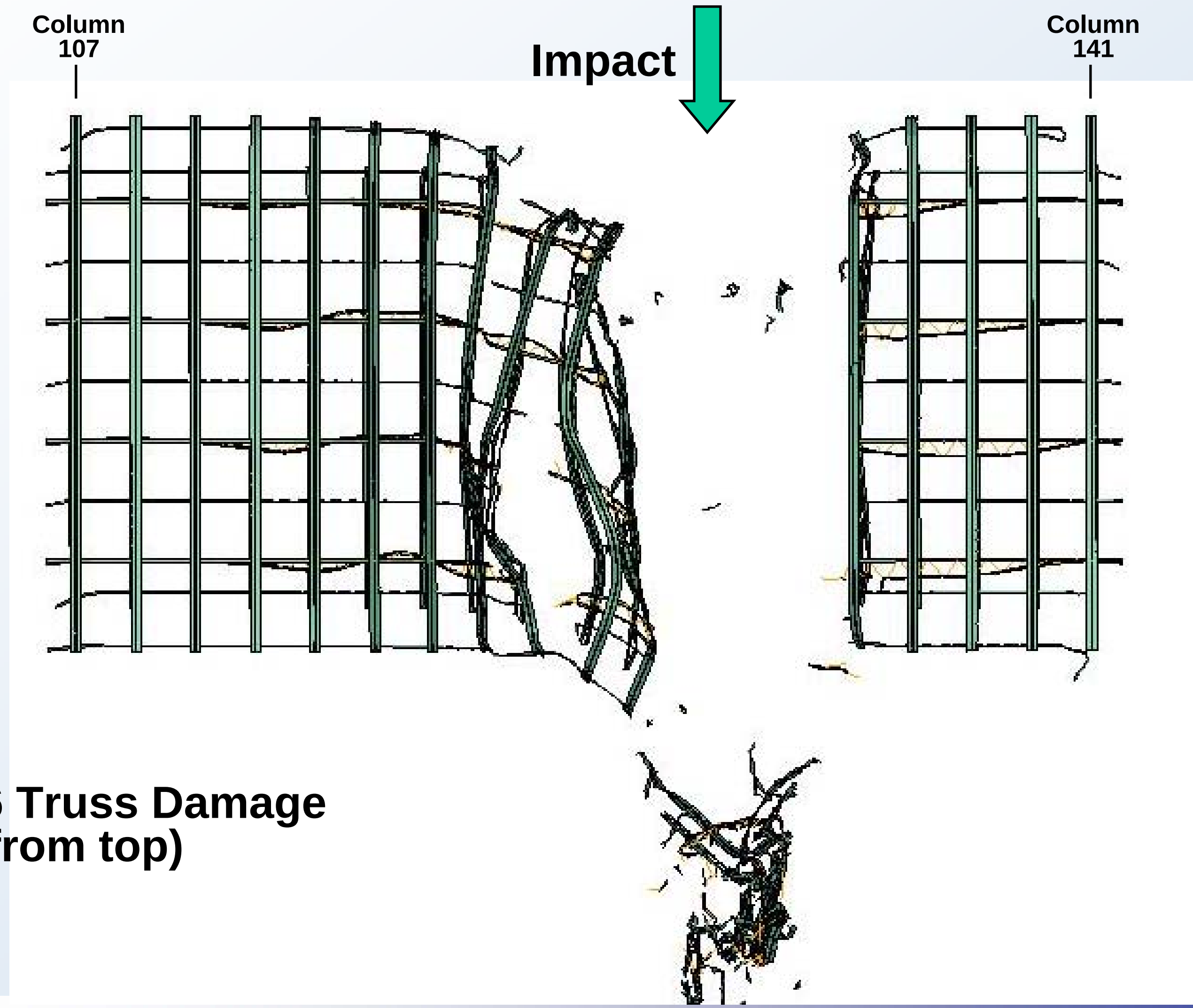


Floor 96 Floor Slab Damage (from top)

Aircraft Impact into WTC 1
Floor Truss Damage

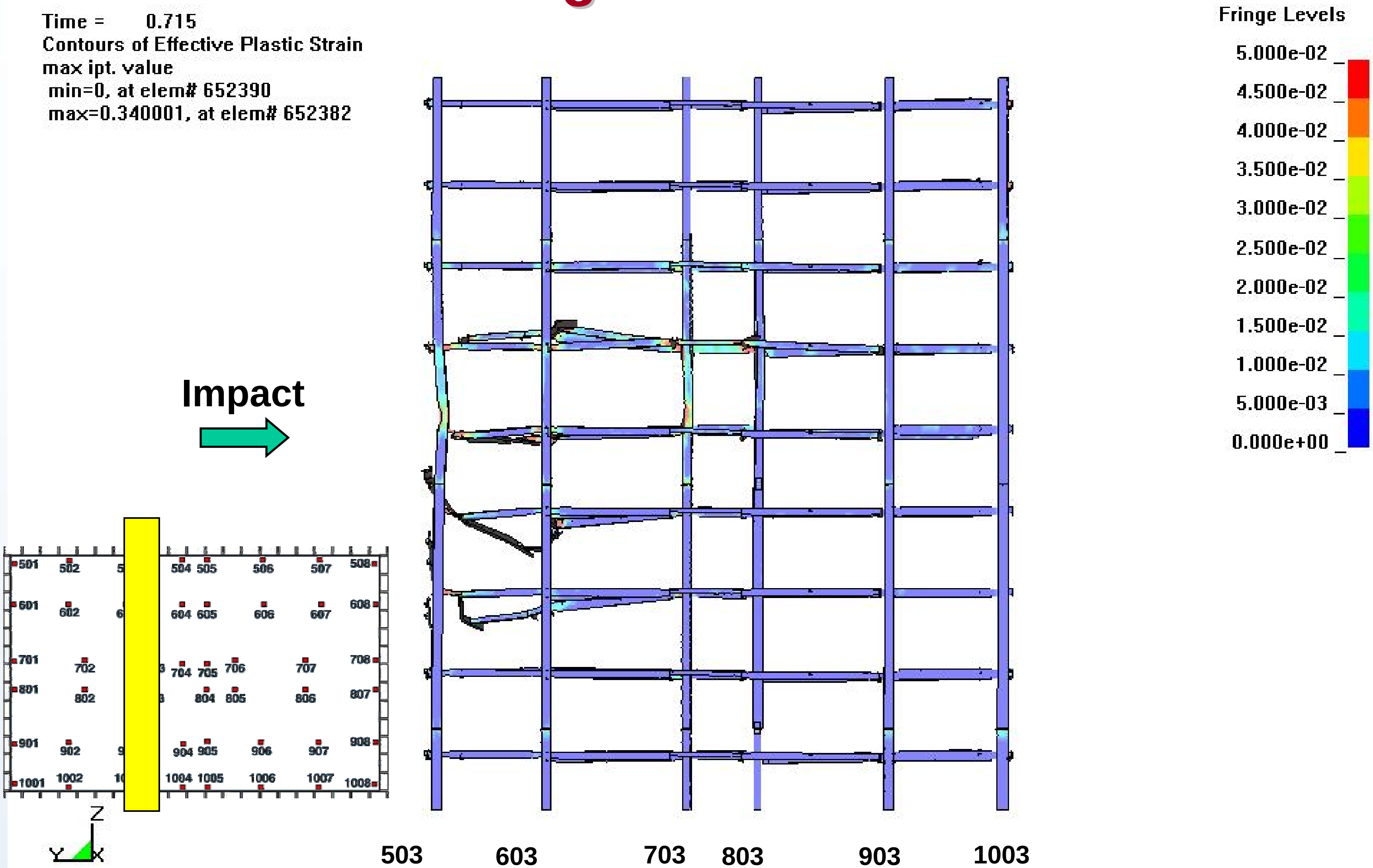
Floor 95 Truss Damage (from top)

Aircraft Impact into WTC 1
Floor Truss Damage



Floor 96 Truss Damage
(from top)

Aircraft Impact into WTC 1
Core Column Damage



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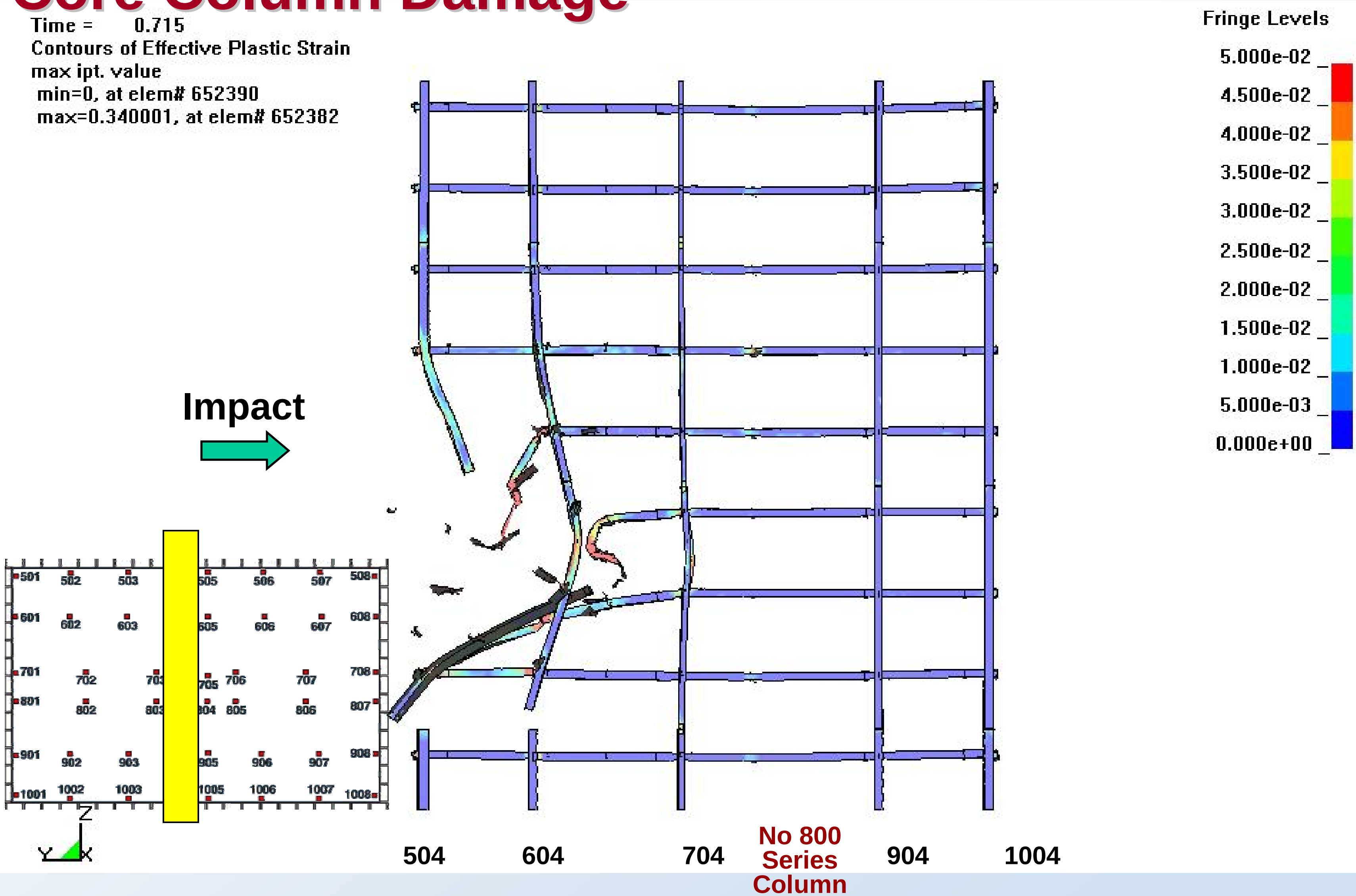
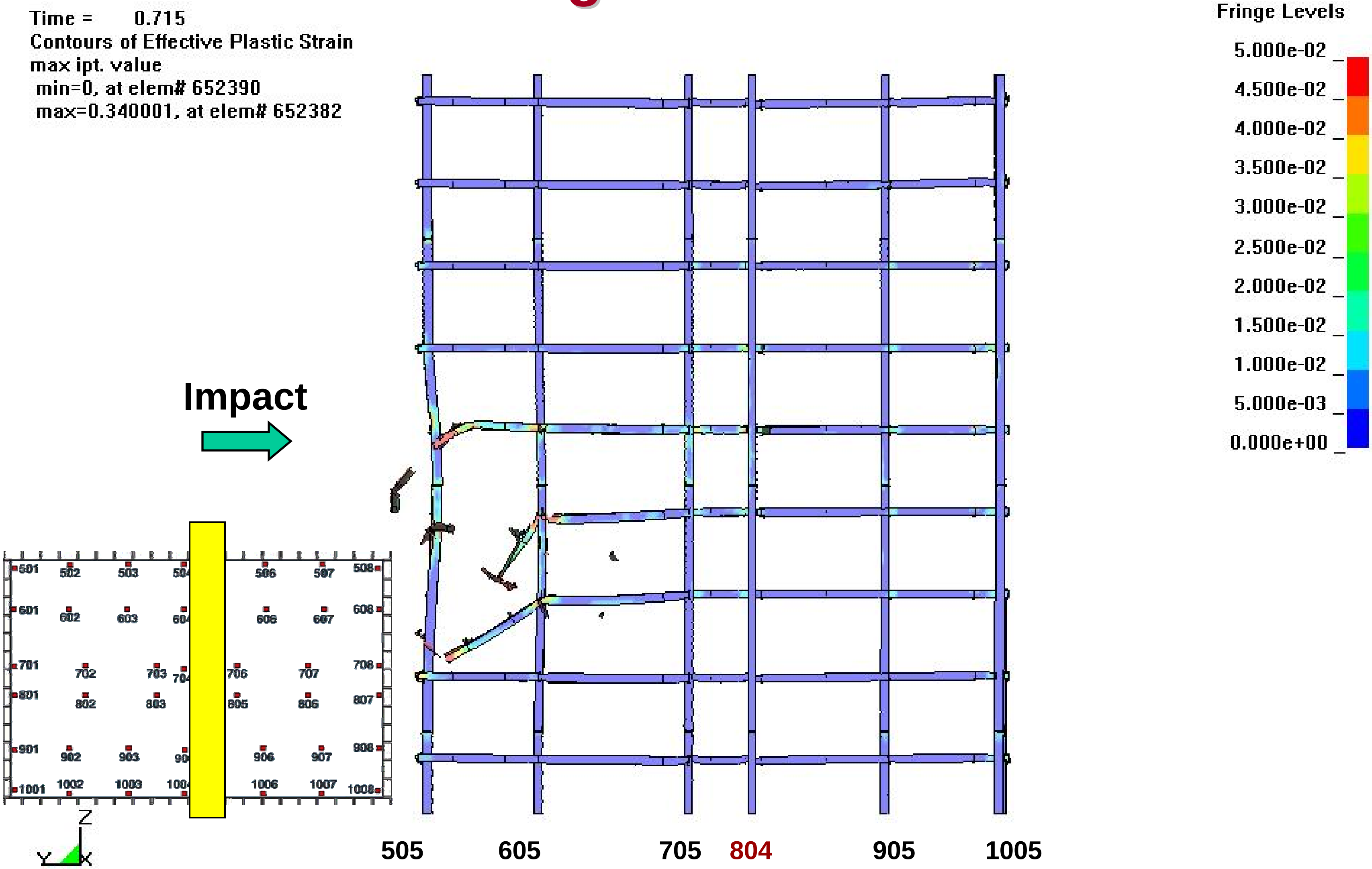
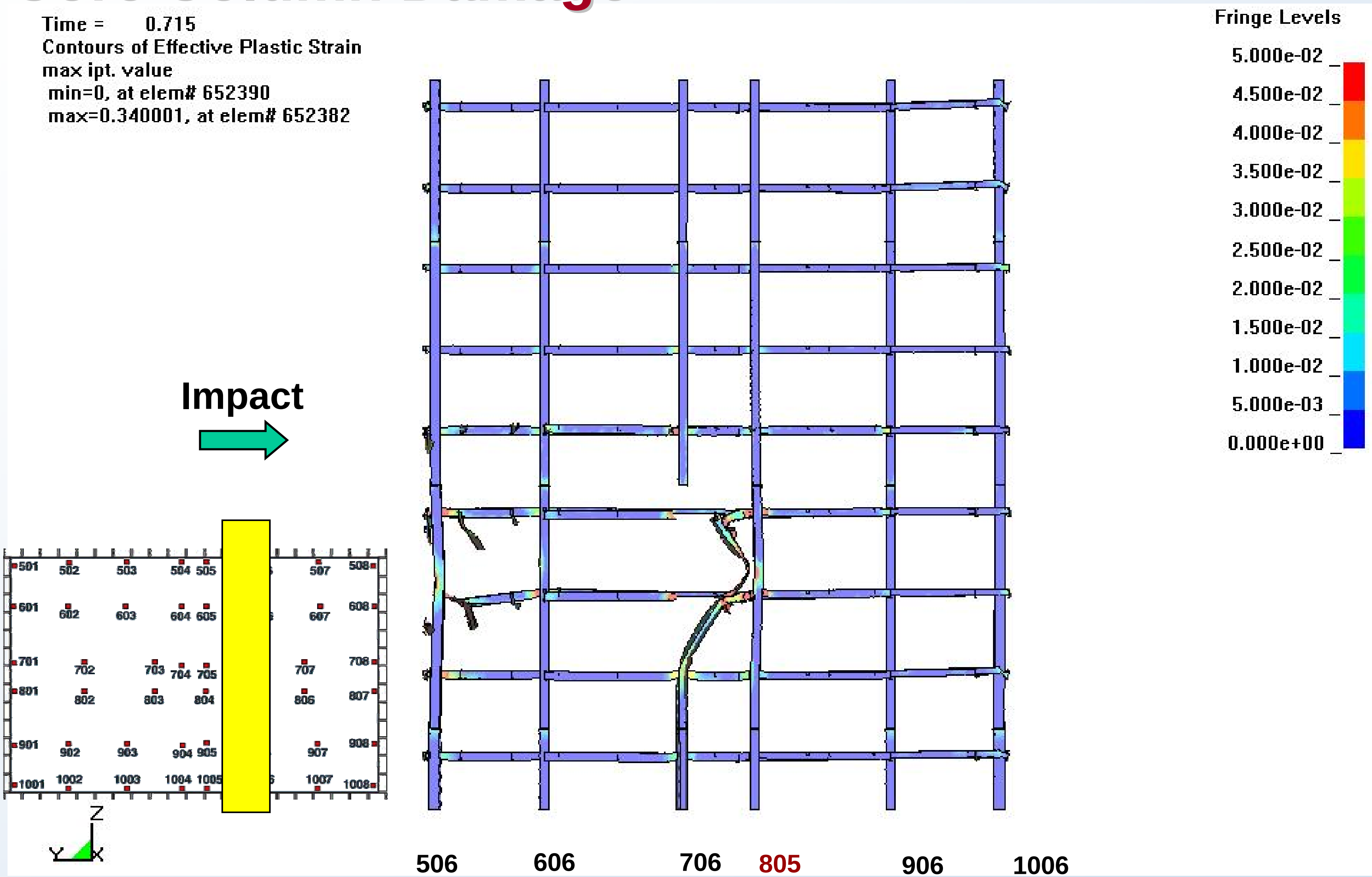
Aircraft Impact into WTC 1
Core Column Damage



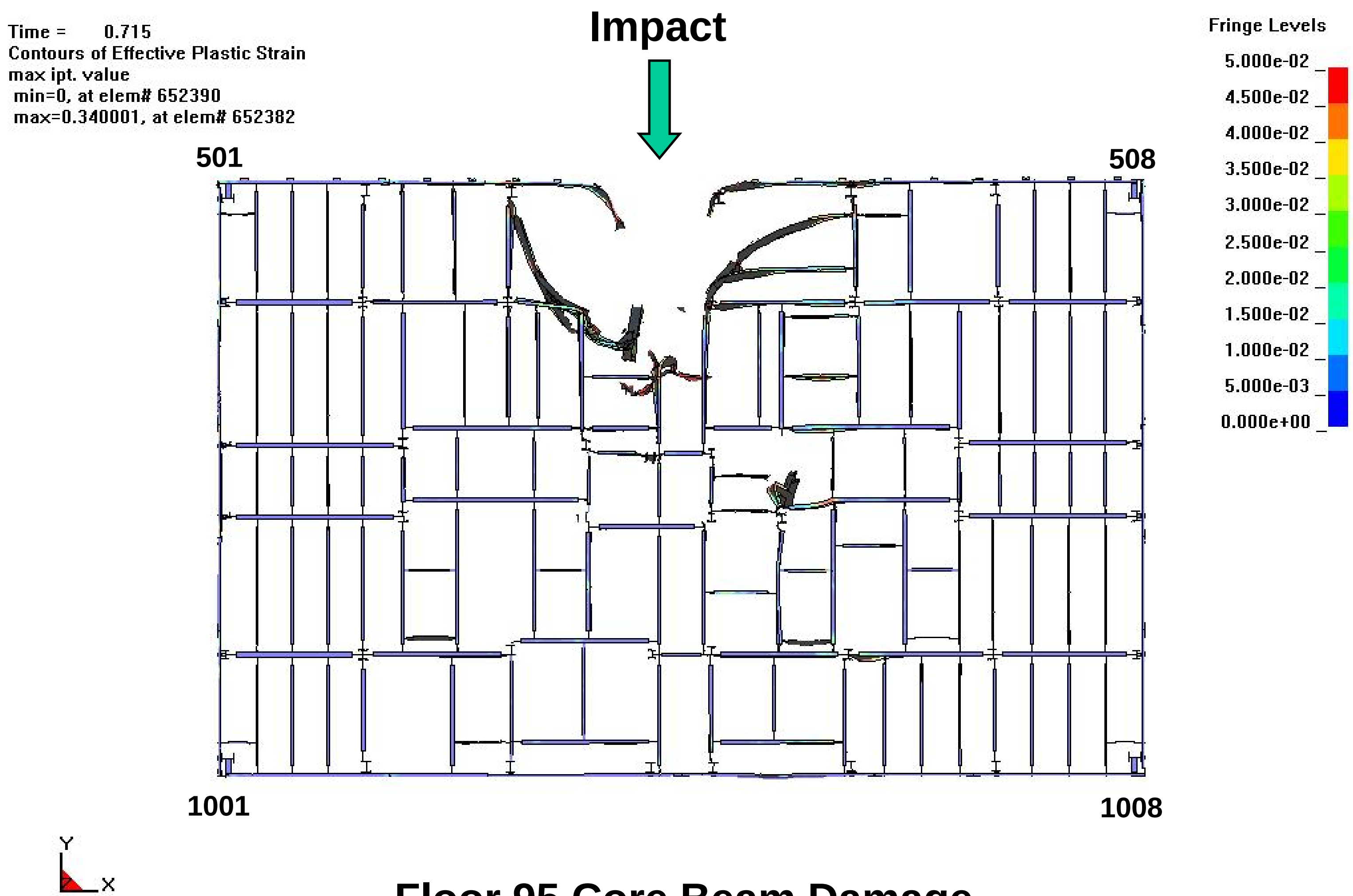
Aircraft Impact into WTC 1
Core Column Damage



Aircraft Impact into WTC 1
Core Column Damage

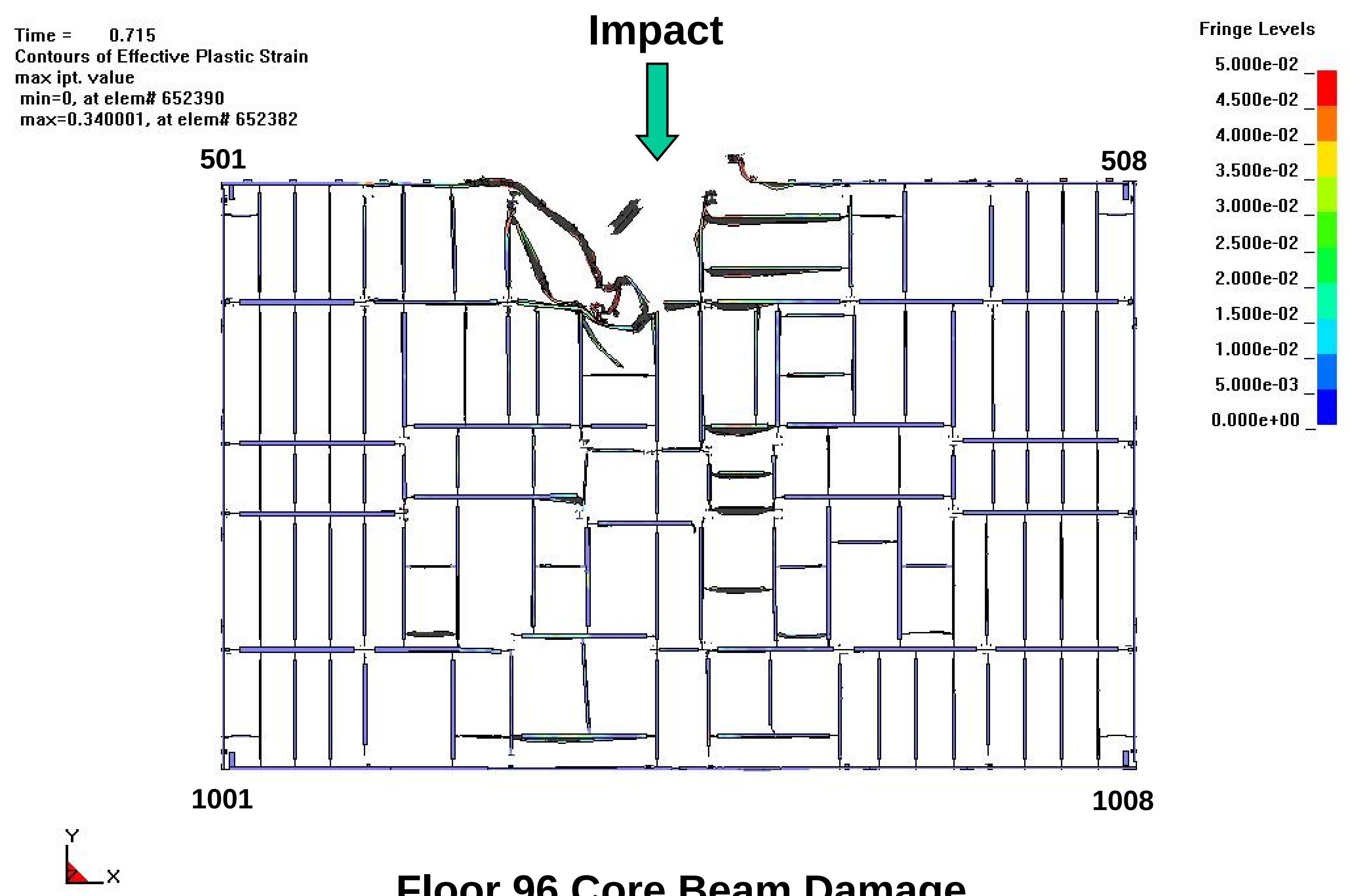


Aircraft Impact into WTC 1
Core Beam Damage



Floor 95 Core Beam Damage

Aircraft Impact into WTC 1
Core Beam Damage



Floor 96 Core Beam Damage

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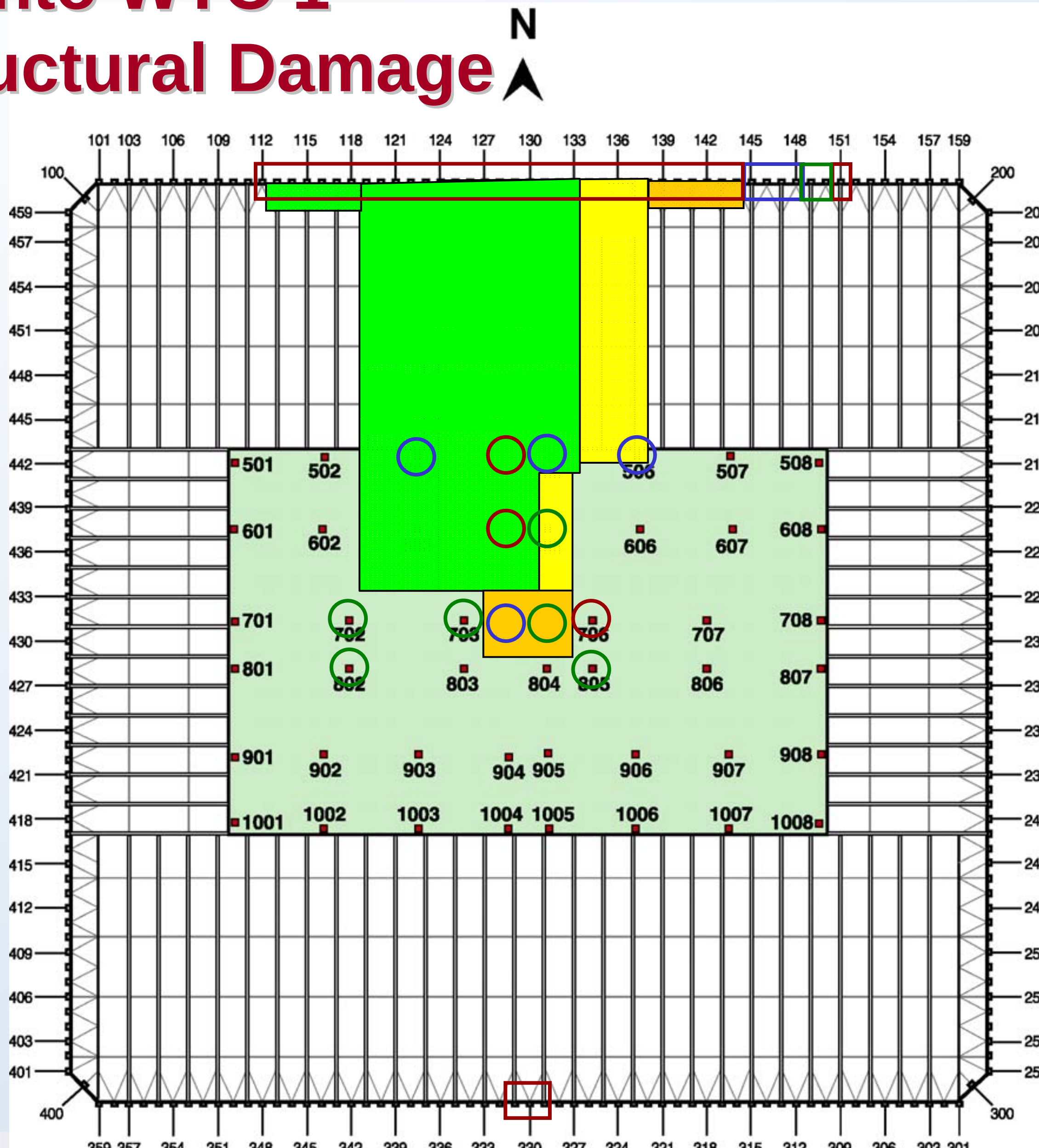
Aircraft Impact into WTC 1
Summary of Structural Damage

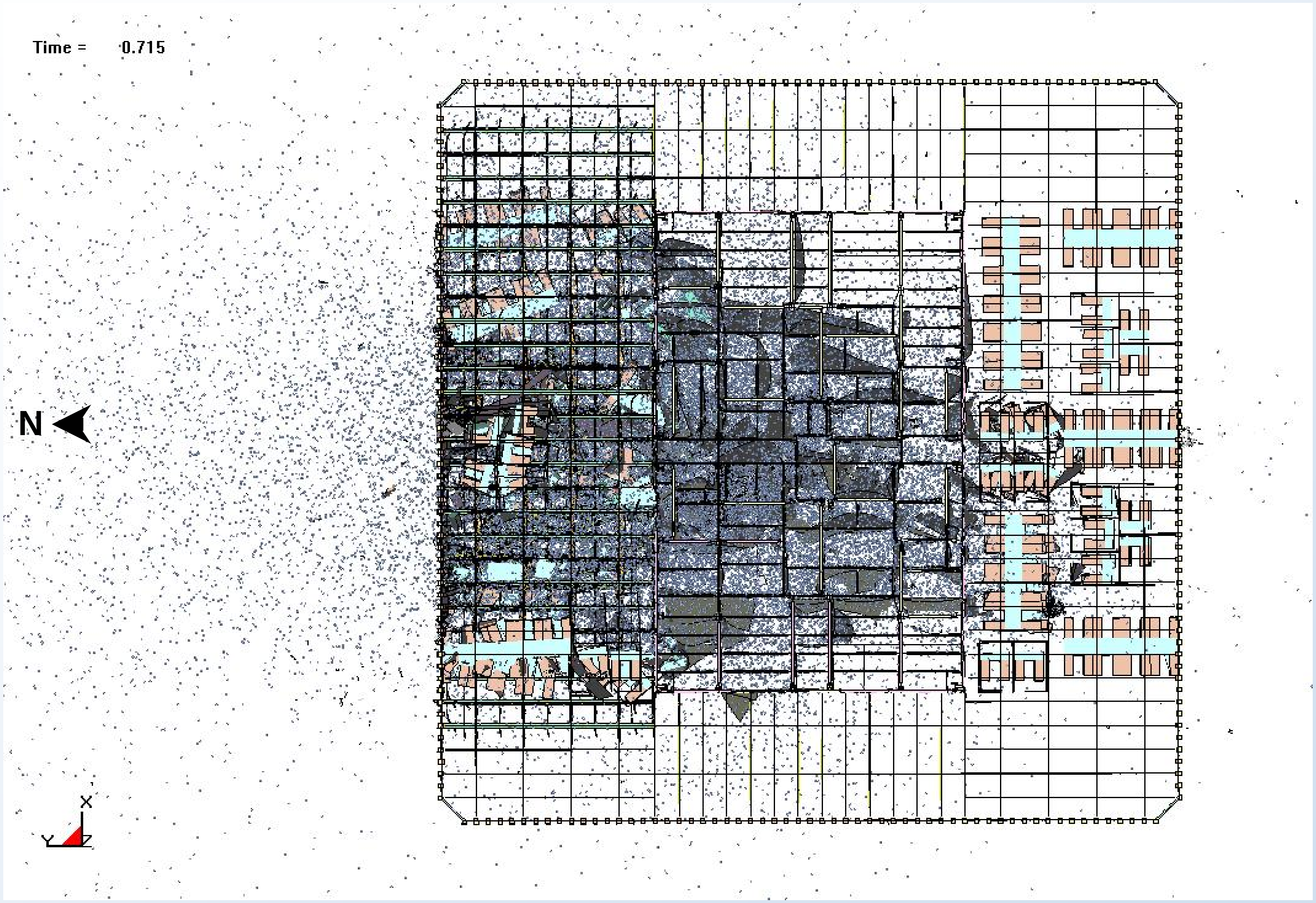


Severed

Heavy Damage

Moderate Damage

Aircraft Impact into WTC 1
Fuel and Debris Distributions



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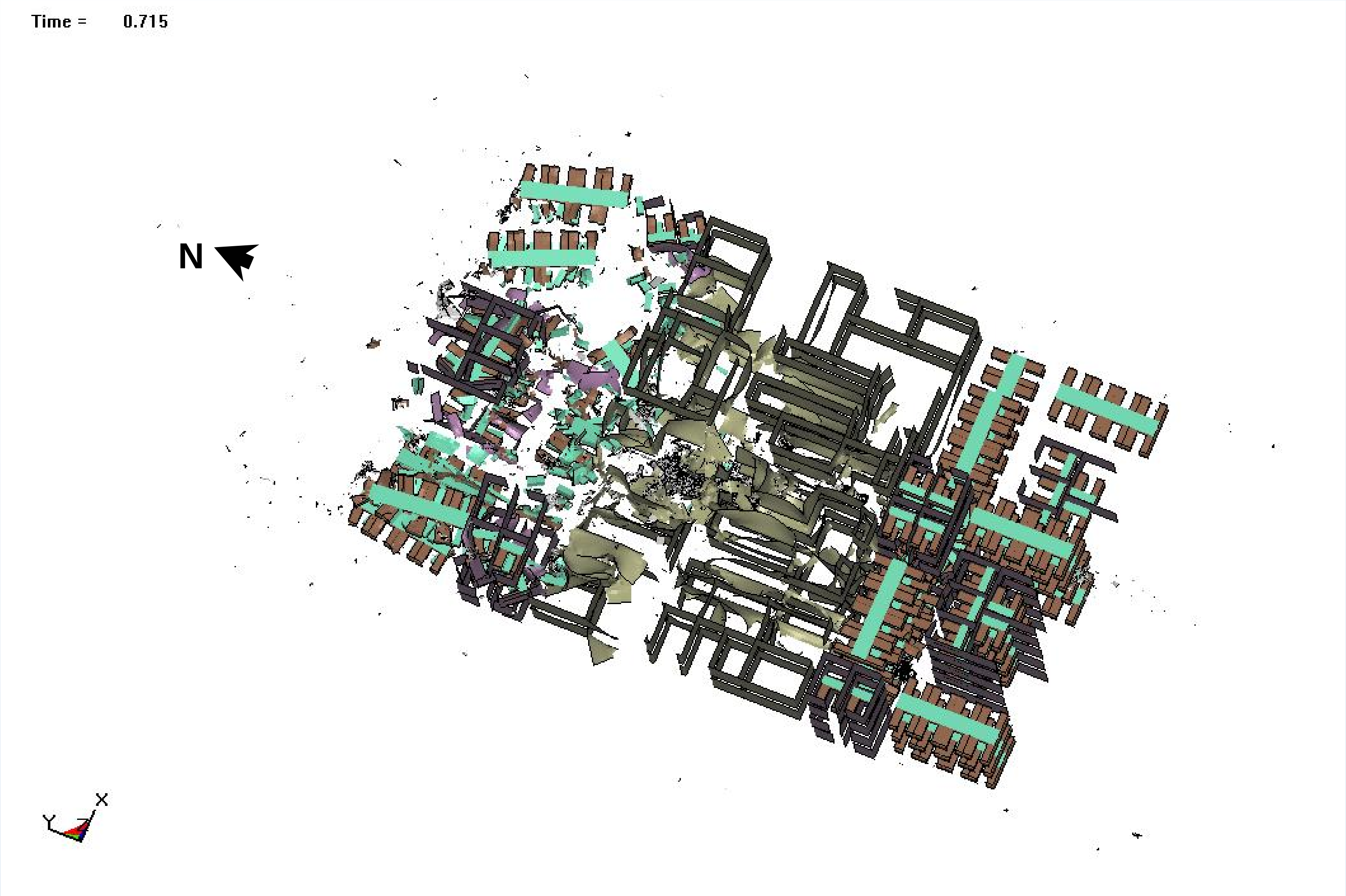
Aircraft Impact into WTC 1
Fuel and Debris Distributions



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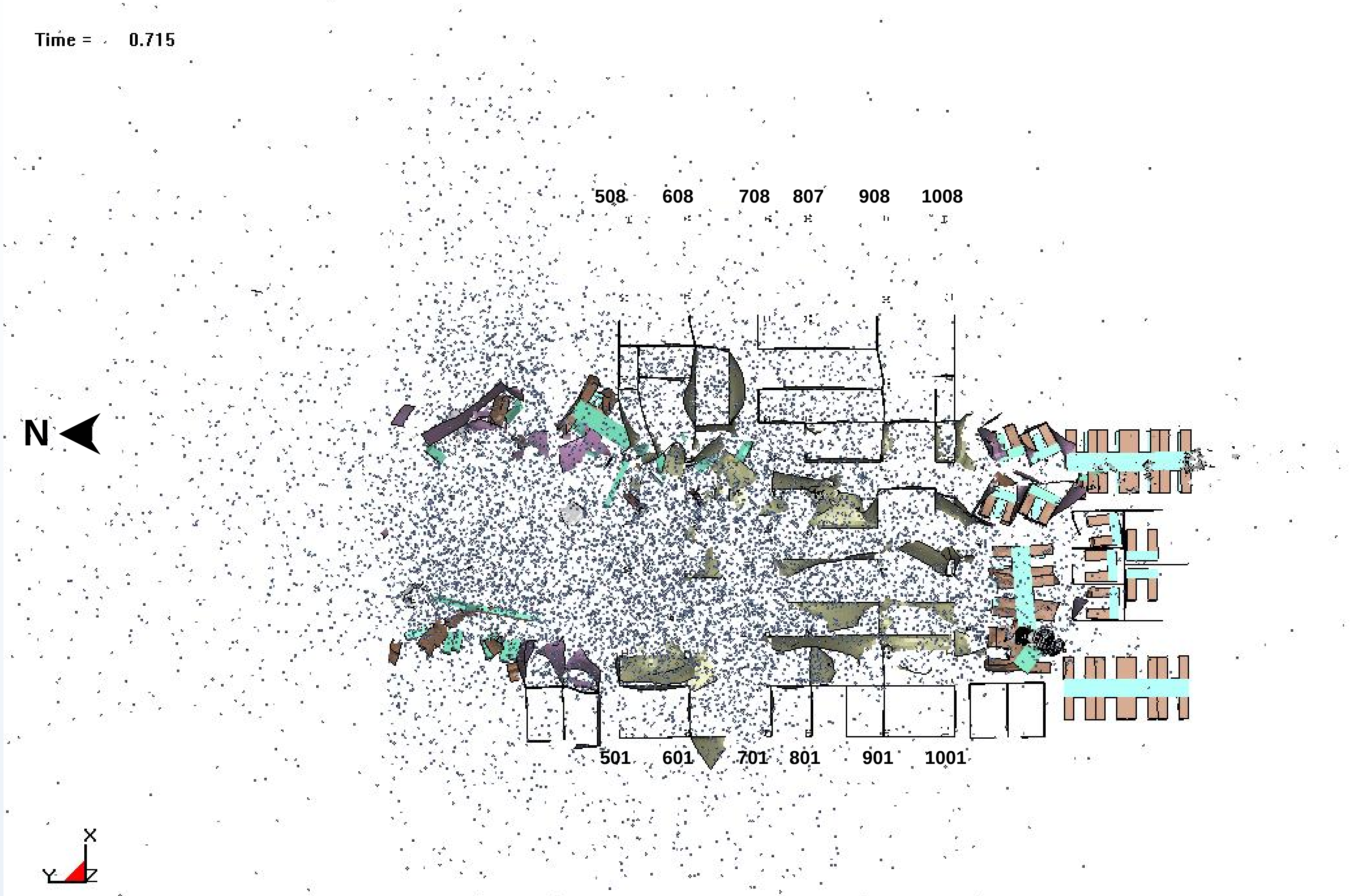
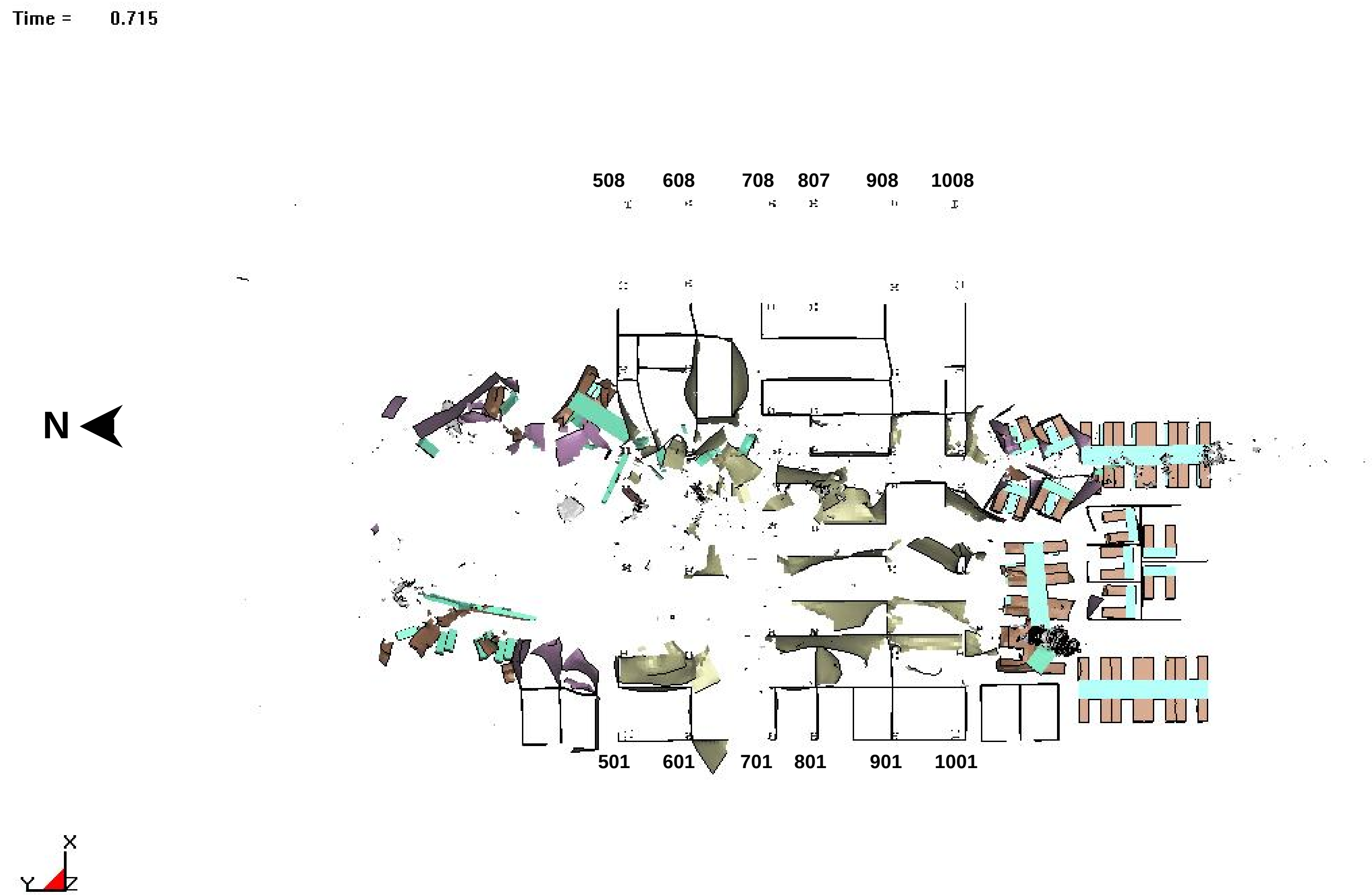
Aircraft Impact into WTC 1
Fuel and Debris Distributions



Floor 96

Aircraft Impact into WTC 1
Fuel and Debris Distributions



Floor 96

Aircraft Impact into WTC 2
Impact Conditions: Viewpoint along trajectory

Baseline Condition:

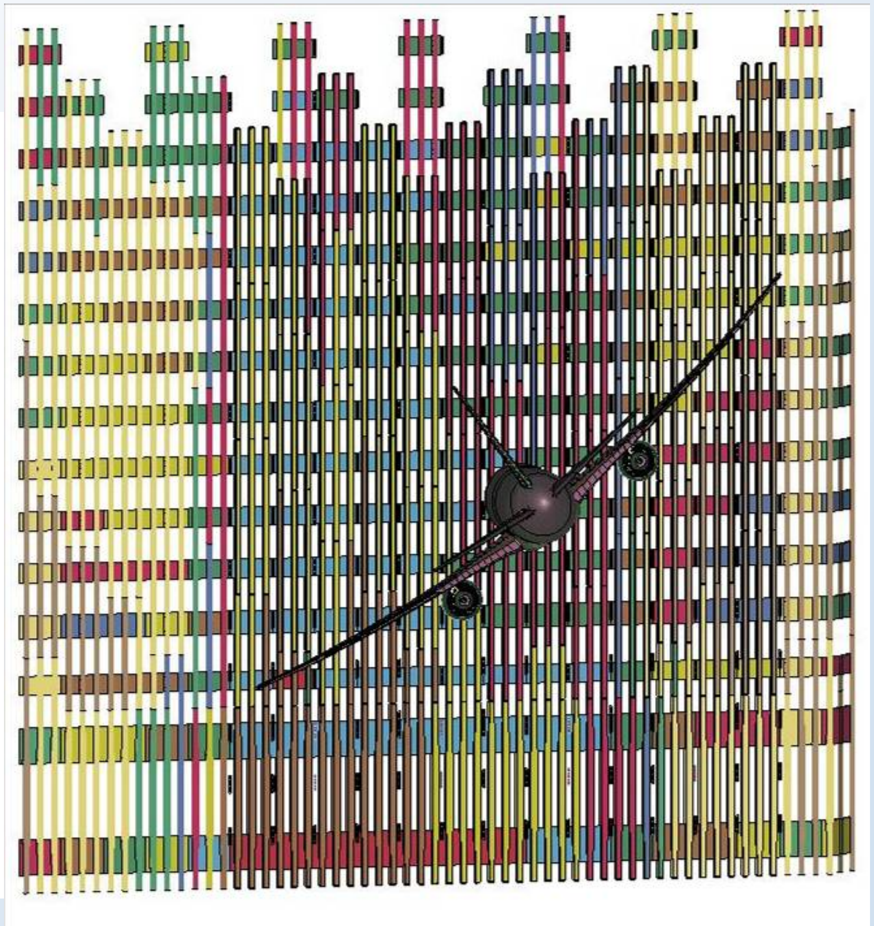
Aircraft Speed: 546 mph (244 m/s)

Orientation:

- Roll = 38°
- Pitch = 5°
- Yaw = 10°

Trajectory:

- Nose Down = 6°
- CW from N. = 13°



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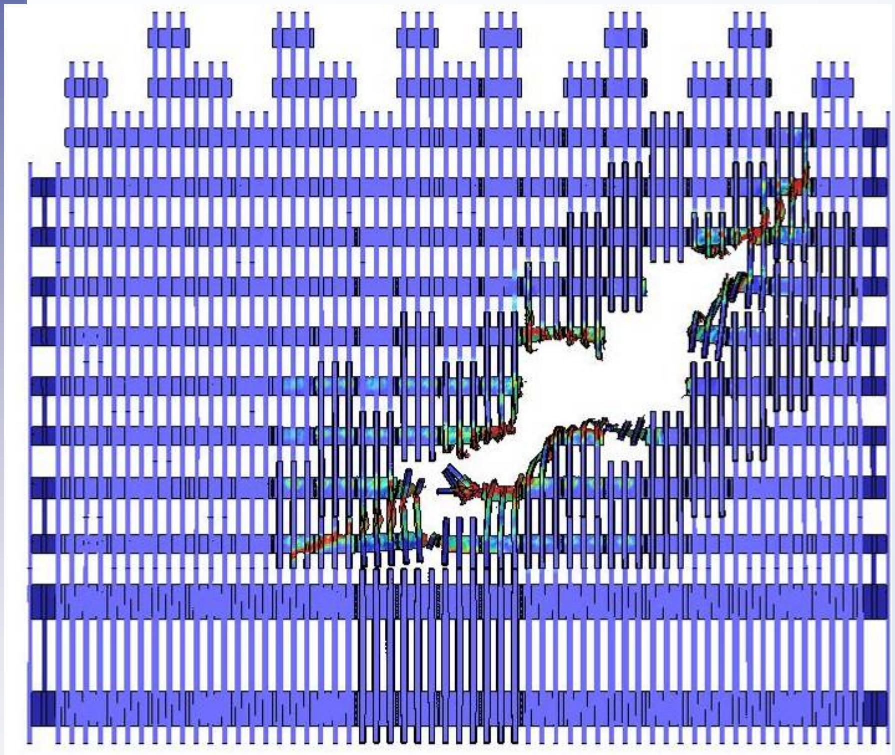
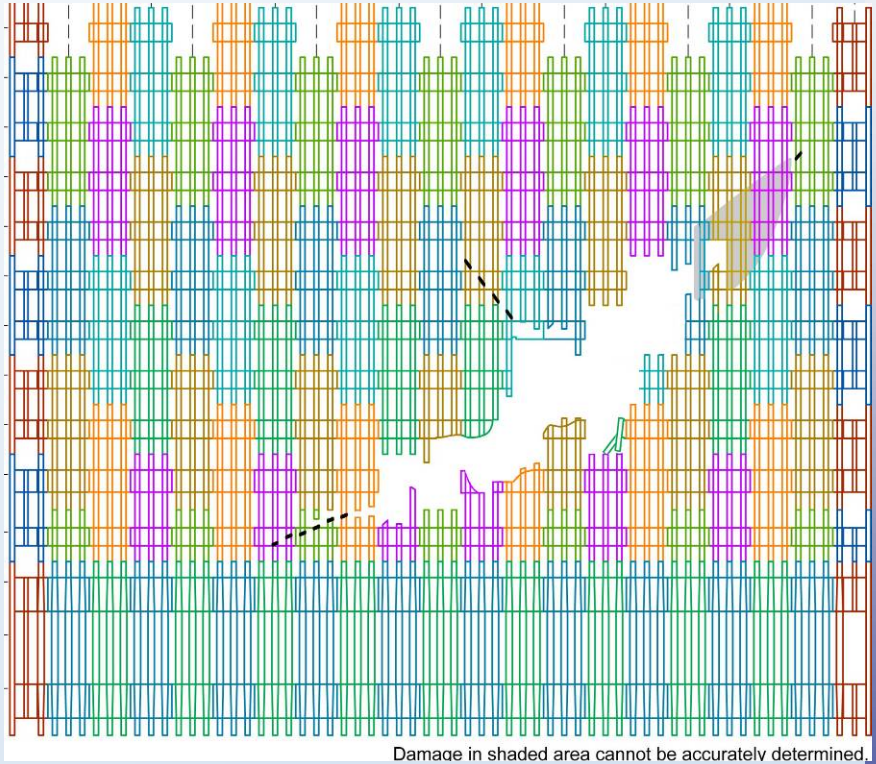
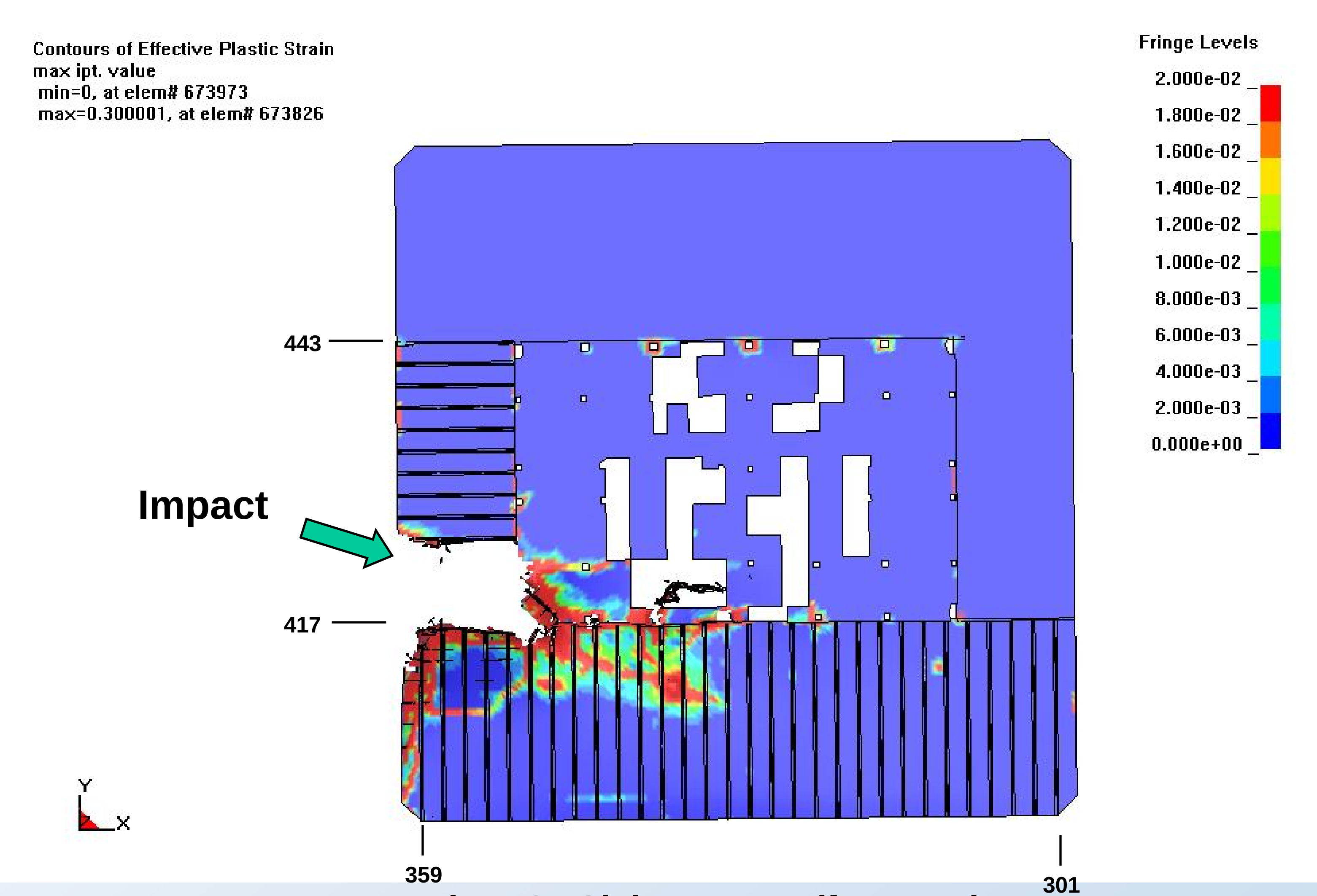
Aircraft Impact into WTC 2
Exterior Wall Damage



t = 0.62 s



Aircraft Impact into WTC 2
Floor Slab Damage



Floor 81 Slab Damage (from top)

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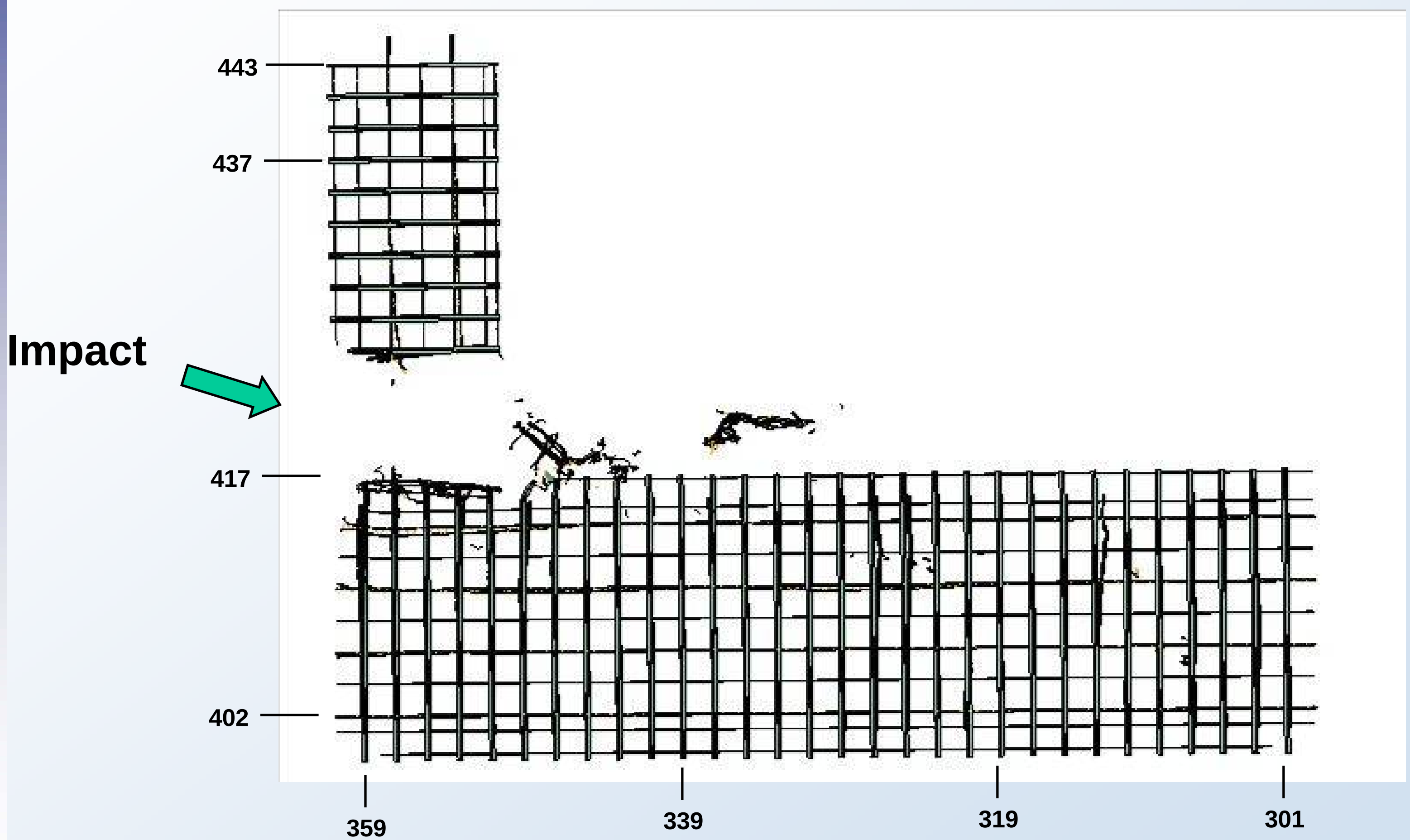
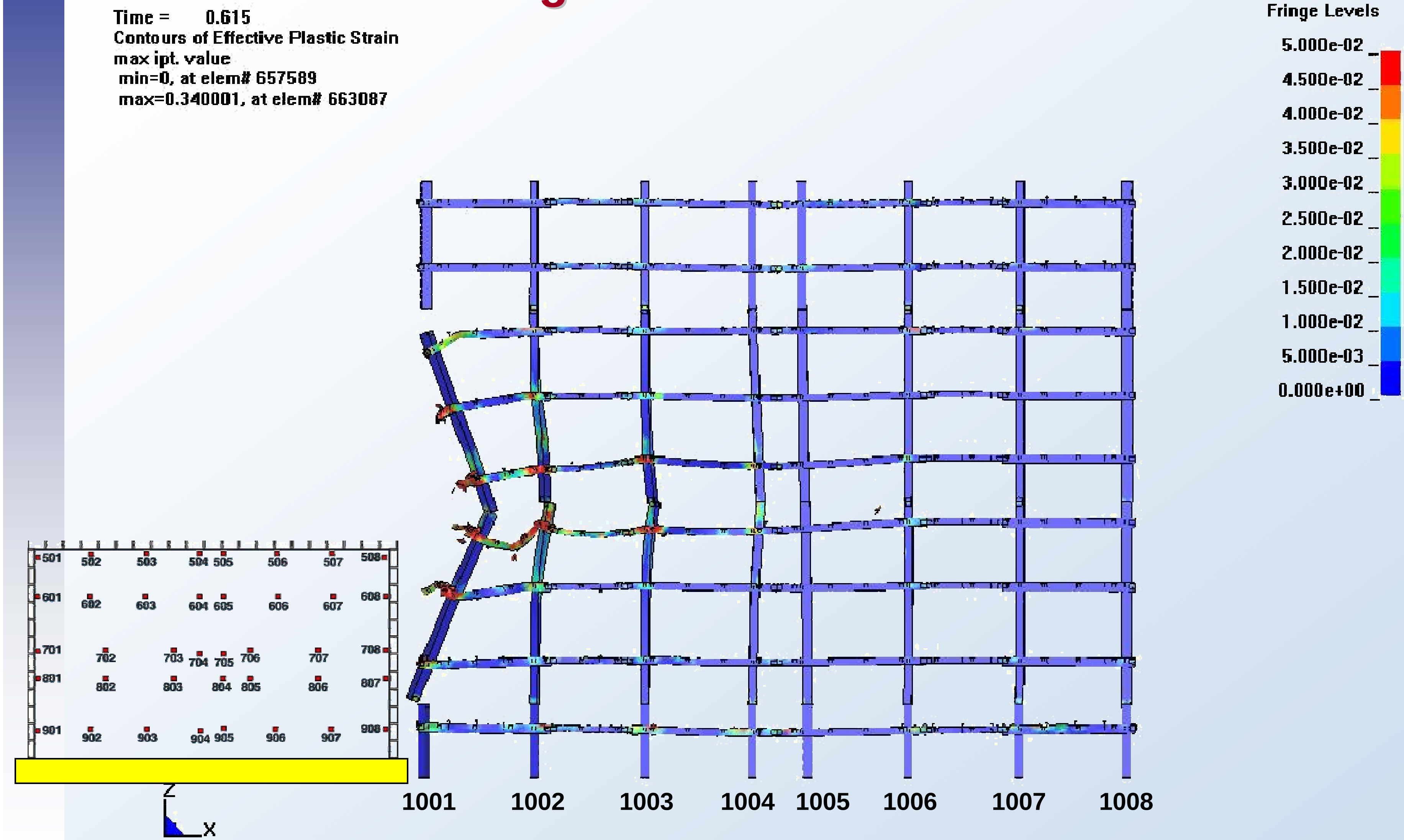
Aircraft Impact into WTC 2
Floor Truss Damage



Floor 81 Truss Damage (from top)

WTC 2 Global Impact Analysis
Core Column Damage



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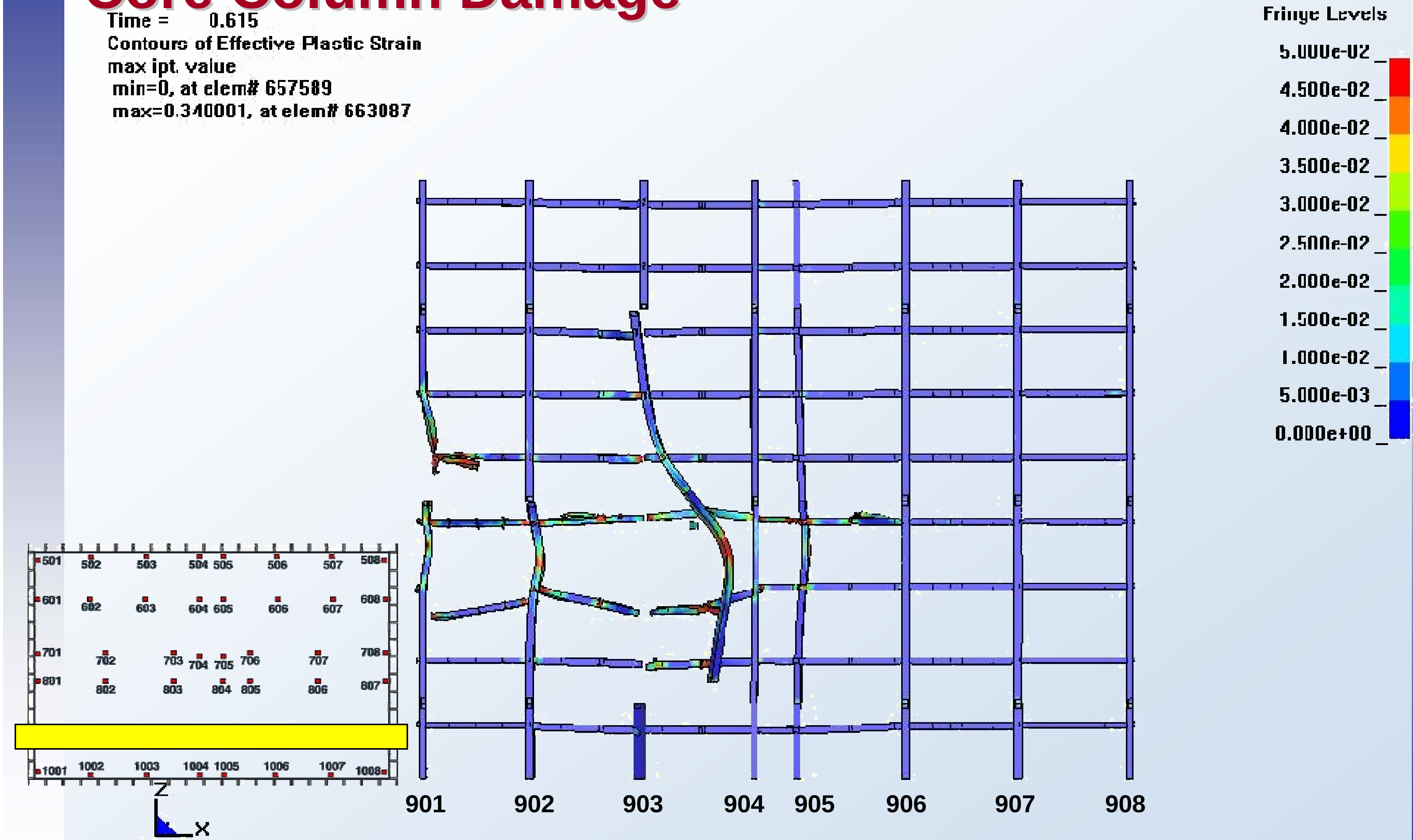
WTC 2 Global Impact Analysis
Core Column Damage



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WTC 2 Global Impact Analysis
Core Column Damage

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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?)

Reference Models and Baseline Analysis

Summary of Prior Work Performed

- ❑ Development and review of structural databases
- ❑ Development and review of reference structural models
  - Typical floor models
  - Global tower models
- ❑ Development and review of estimates of wind loading on the towers based on state-of-the-art considerations in wind engineering

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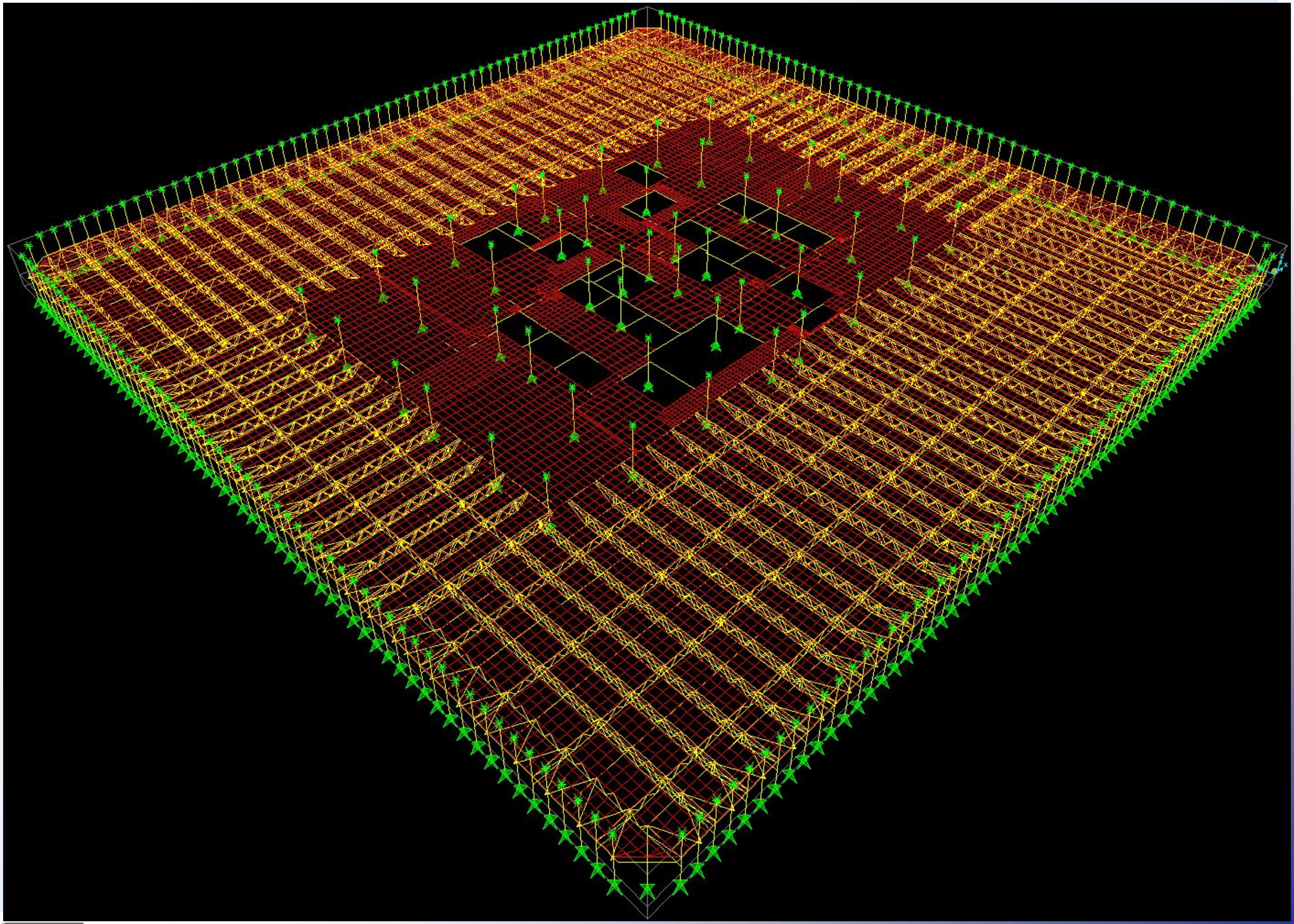
Floor Systems: *Floor 96-A Model*



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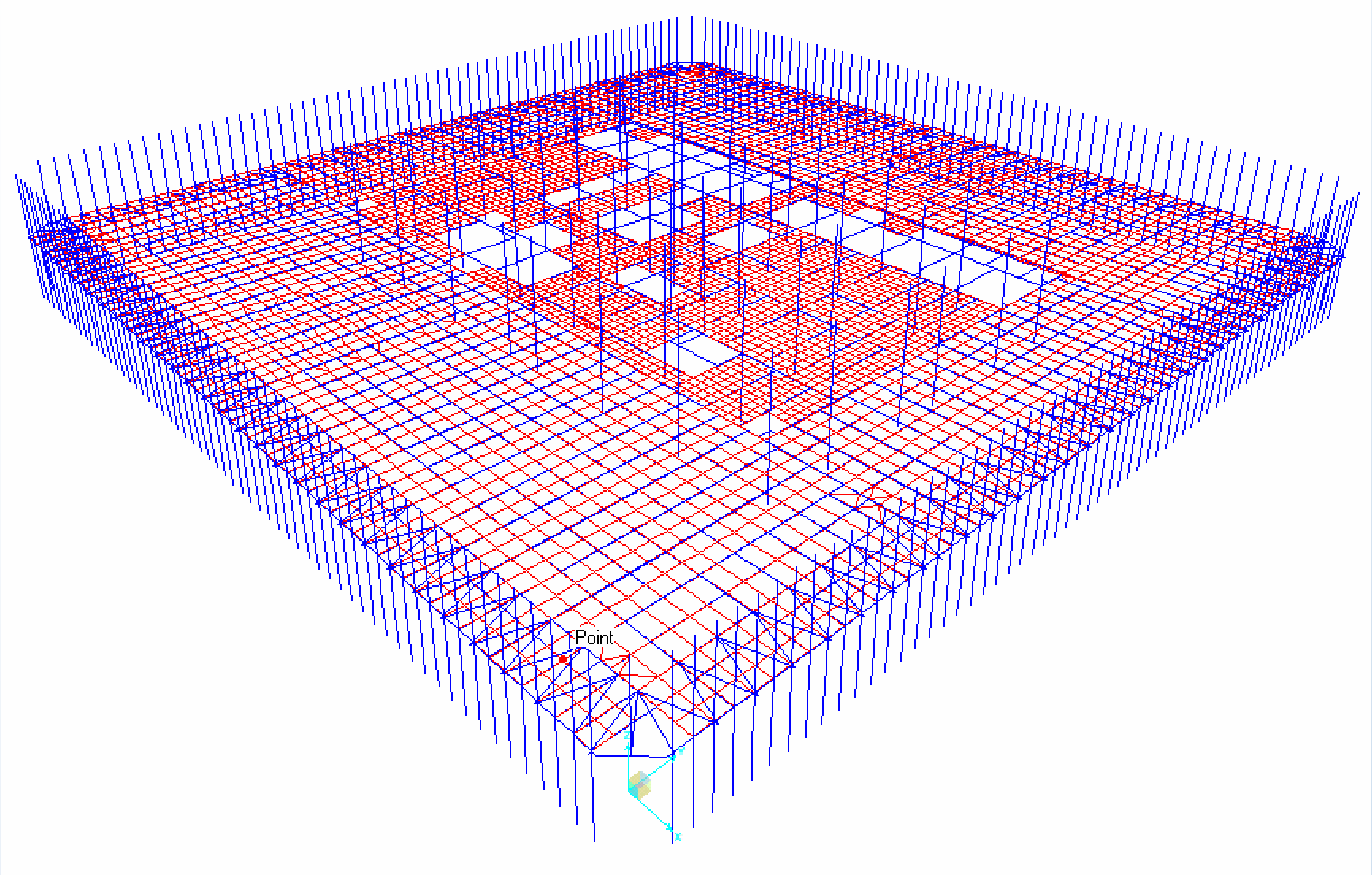
Floor Systems: *Floor 75-B Model*



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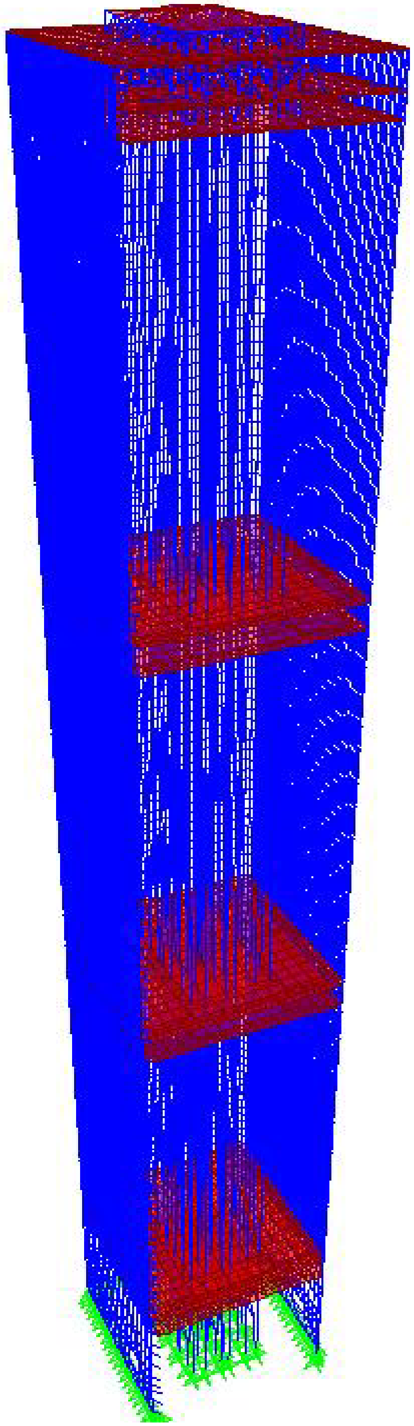
Tower Structural System FE Models (Global Model)

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



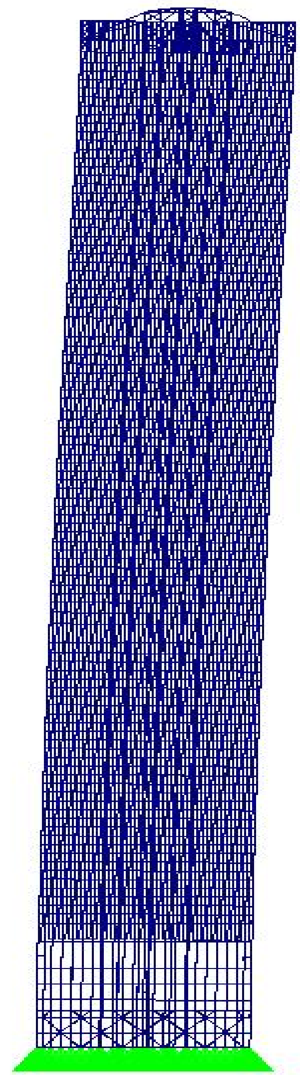
Natural Periods (s)

WTC 1 Analysis

	N-S	E-W
Average measured	11.4	10.6
Theoretical value (original design)	11.9	10.4
Reference global model	11.4	10.7

WTC 2 Analysis

	N-S	E-W
Average measured	--	--
Theoretical value (original design)	10.4	11.9
Reference global model	10.6	11.4



Wind Loading

Wind loads being considered include:

- Original WTC design wind loads, 1960’s
- Wind loads based on two recent wind tunnel studies conducted by CPP and RWDI for insurance litigation concerning the towers, 2002
- State-of-the-art wind load estimates developed by NIST and reviewed by SOM, 2004

Comparison of Wind Loads
Wind Load Estimates for WTC 1

Source	Year	Base Shear 10^3 kips			Base Moment 10^6 kips-ft		
		N-S	E-W	Most unfavorable combined peak	About N-S	About E-W	Most unfavorable combined peak
NYC Building Code	1938	5.3	5.3		4.2	4.2	
NYC Building Code	1968 to date	9.3	9.3		7.7	7.7	
RWDI / NYC Building Code	2002	11.4	10.5	13.0	10.1	10.5	12.2
RWDI / ASCE 7-98	2002	12.3	11.3	14.0	10.8	11.4	13.1
CPP / NYC Building Code	2002	NA	NA	NA	NA	NA	NA
CPP / ASCE 7-98	2002	NA	NA	NA	NA	NA	NA
NIST / third-party SOM review	2004	14.1	13.0	16.1	12.4	13.1	15.1
Original WTC Design	1960’s	9.8	10.6	14.0	10.3	9.1	13.7

Comparison of Wind Loads
Wind Load Estimates for WTC 2

Source	Year	Base Shear 10^3 kips			Base Moment 10^6 kips-ft		
		N-S	E-W	Most unfavorable combined peak	About N-S	About E-W	Most unfavorable combined peak
NYC Building Code	1938	5.3	5.3		4.2	4.2	
NYC Building Code	1968 to date	9.3	9.3		7.6	7.6	
RWDI / NYC Building Code	2002	9.7	11.1	12.3	10.1	9.2	11.3
RWDI / ASCE 7-98	2002	10.6	12.2	13.5	11.1	10.1	12.4
CPP / NYC Building Code	2002	NA	NA	NA	NA	NA	NA
CPP / ASCE 7-98*	2002	15.1	15.3	17.1	15.5	14.0	17.0
NIST / third-party SOM review	2004	12.2	14.0	15.6	12.8	11.6	14.3
Original WTC Design	1960's	13.1	10.1	16.5	8.8	12.6	15.2

* Using ASCE 7-98 sections 6.5.4.1 and 6.6

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Comparison of Wind Loads

Base Shears and Base Moments Due to Wind Loads from Different Building Codes

	1938 NYC Code	1968-2001 NYC Code	1964 NY State Code	1965 BOCA/BBC	1967 Chicago Municipal Code
Base Shear (10^3 kips)	5.3	9.3	9.5	9.8	8.7
Base Moment (10^6 kips-ft)	4.2	7.7	7.6	8.5	7.5

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State-of-the-Art 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 considerations related to the state of the art in wind engineering.
- NIST has performed SOA estimates of the wind effects on the WTC towers based on the limited information available at the time of the investigation. The information used included results of wind tunnel tests and extreme wind climatological estimates conducted by RWDI and CPP, wind speeds from the National Climatic Data Center, and the NIST hurricane wind speed database.
- More elaborate calculations and/or test results would be desirable. However, obtaining such results was not practicable.

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State-of-the-Art 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 for WTC 2

	$\|M_y\|$ (lb-ft)	$\|M_x\|$ (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 estimates of wind-induced forces and moments had to 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.

State-of-the-Art 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°, while CPP's estimate was 117.5 mph, i.e., CPP results overestimated wind loads by about 39% $[(99.8/117.5)^2 = 1/1.386]$.
  - 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 is not realistic physically and probabilistically.
  - 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% ($1.15/1.386 \approx 1/1.205$).

State-of-the-Art 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 assumption, inconsistent with published measurements, that wind profiles in hurricanes are flatter than in non-hurricane winds. Using this assumption, RWDI estimated the ratio between the responses to an 88 mph speed (ASCE 7-98) and an 80 mph speed (NYCBC) to be about 1.1, rather than about $(88/80)^2=1.21$.

  - Also, it is not clear that RWDI's use of the out-crossing method (with hurricane wind speeds weighted in proportion to their squares) leads to unbiased estimates. (No justification/references were provided for weighting procedure; parameters used in out-crossing procedure have enormous coefficients of variation – of up to 150!)

State-of-the-Art Estimates of Wind Loads on the Towers

- Summary
  - Wind loads consistent with ASCE 7-02 Standard design wind speeds were 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, say, 1.10 and 1.20.

Baseline Performance Analysis

- **Load Combinations**
  - Original WTC design loads case:
    - WTC design gravity (dead and live) loads
    - Original WTC design wind loads.
  - Lower-bound state-of-the-practice case:
    - Current New York City Building Code (NYCBC) live loads
    - RWDI wind loads with wind speed scaled to the current NYCBC wind speed (80 mph fastest mile).
  - State-of-the-art case:
    - Current ASCE 7 Standard (a national standard) live loads
    - Wind loads developed by NIST based on considerations related to the current state of the art in wind engineering.

Results of Baseline Analysis

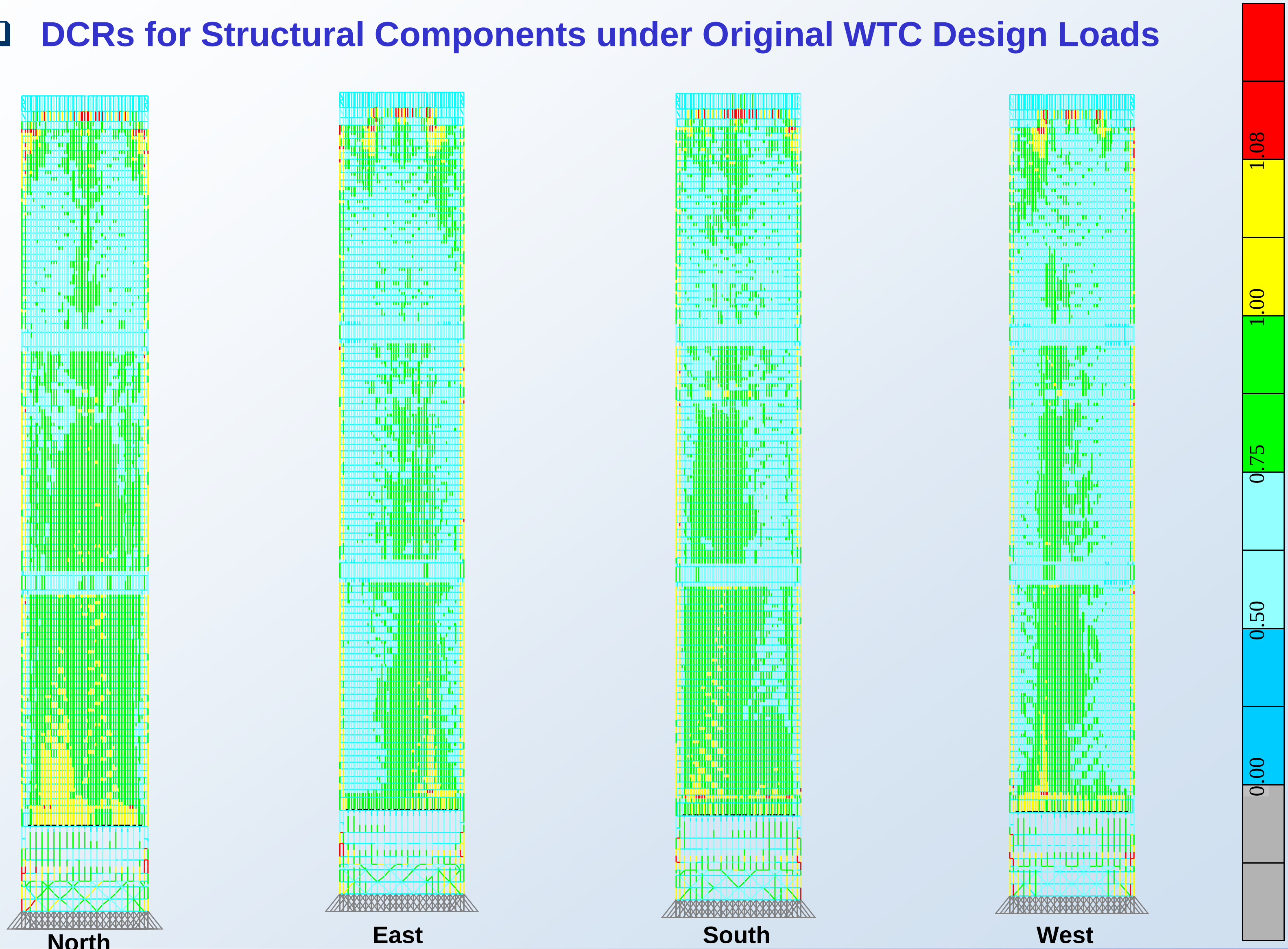
- Analysis completed by LERA (NIST contractor). Results presented reviewed by NIST and SOM (NIST contractor).

- Demand / Capacity ratios (DCRs) for structural components estimated using Allowable Stress Design (ASD) for the three loading cases.

- Calculated drift (maximum sway at roof) due to original design wind loads:
  - WTC 1: 4 ft – 8.6 in. (~ H/300)
  - WTC 2: 5 ft – 5.4 in. (~ H/260)

Results of Baseline Analysis for WTC 1

- DCRs for Structural Components under Original WTC Design Loads



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Results of Baseline Analysis for WTC 1

	Mean DCR	% members with DCR>1	% members with DCR>1.05	Approx. # of members with DCR>1.05	Max DCR
Exterior Columns (Floor 9-106)					
Original WTC Design Loads	0.76	1.1	0.4	120*	1.31
Lower Bound SOP Case	0.78	2	0.9	281*	1.44
SOA Case	1.10	72	60	18,572*	2.05
Spandrel Beams (Floor 9-106)					
Original WTC Design Loads	0.31	0	0	0	0.83
Lower Bound SOP Case	0.32	0	0	0	0.80
SOA Case	0.52	0.5	0.3	100	1.31
Core Columns					
Original WTC Design Loads	0.86	10	5.3	278	1.36
Lower Bound SOP Case	0.86	9.9	5.3	278	1.36
SOA Case	0.84	8.9	5.2	270	1.40
Hat Truss (Columns)					
Original WTC Design Loads	0.47	0.4	0.4	1	1.26
Lower Bound SOP Case	0.45	0.4	0.4	1	1.26
SOA Case	0.52	3.8	0.8	2	1.26

* Number of members includes columns with ½ floor height due to the presence of column splices.

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Results of Baseline Analysis for Typical Truss-Framed Floor (Floor 96)

- DCRs for Structural Components under Original WTC Design Loads

	Mean DCR	% members with DCR<1	Max DCR
One-Way Long Span Trusses			
Diagonals	0.44	96	1.14
Bottom chord members	0.74	100	0.99
One-Way Short Span Trusses			
Diagonals	0.33	100	0.92
Bottom chord members	0.37	100	0.55
Two-Way Trusses			
Diagonals	0.30	99	1.06
Bottom chord members	0.48	100	0.94
Core Beams	0.33	99	1.07

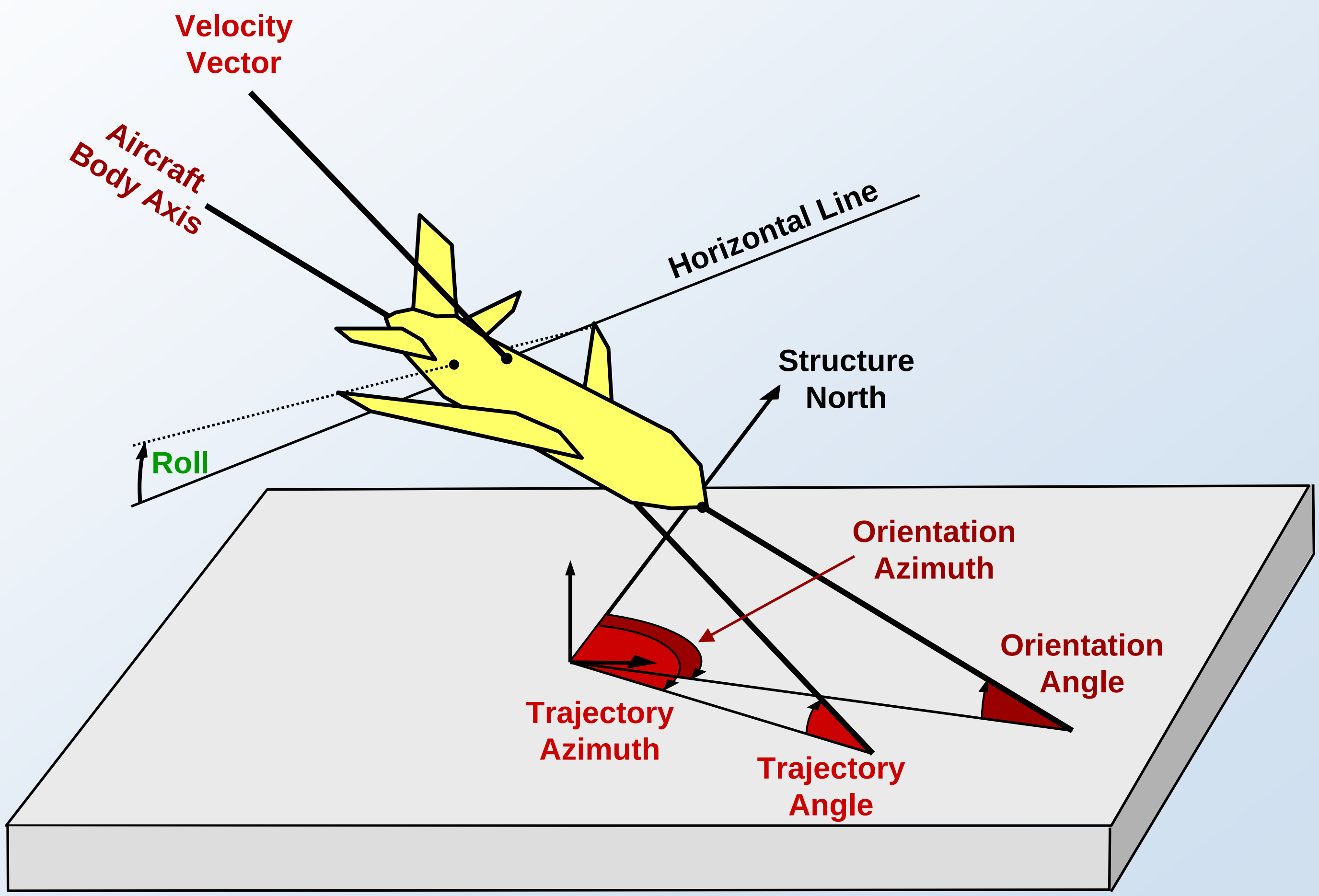
Aircraft Impact Analysis

Summary of Prior Work Performed

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

Aircraft Impact Initial Conditions

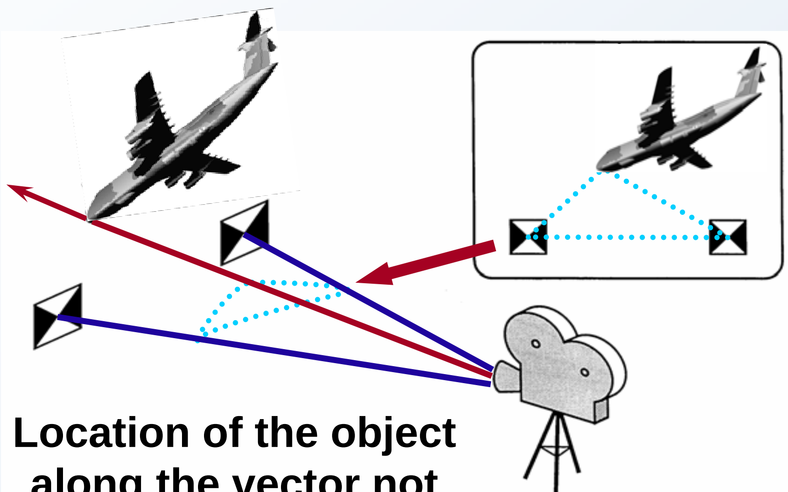
- Determine aircraft speed, orientation, and point of nose impact at time of impact



Aircraft Impact Initial Conditions

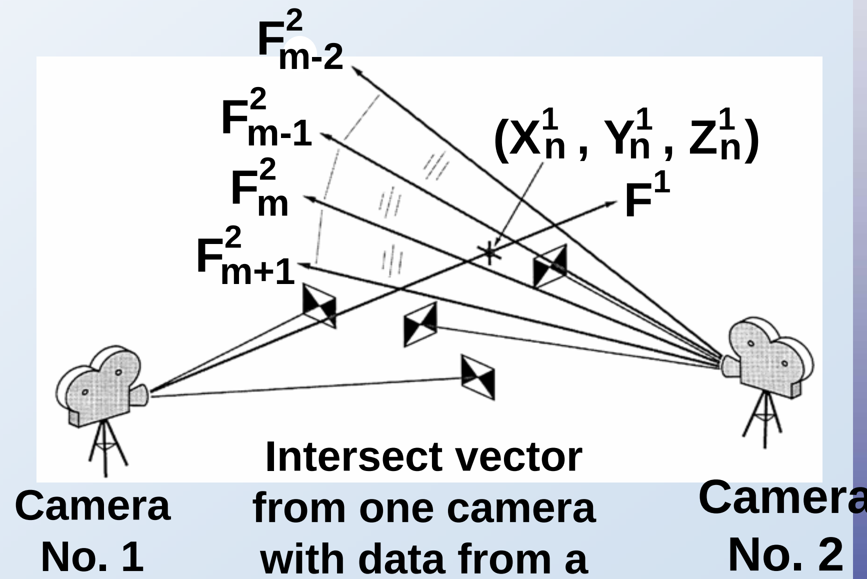
- Complex motion analysis methodology

Step 1:



Location of the object along the vector not known.

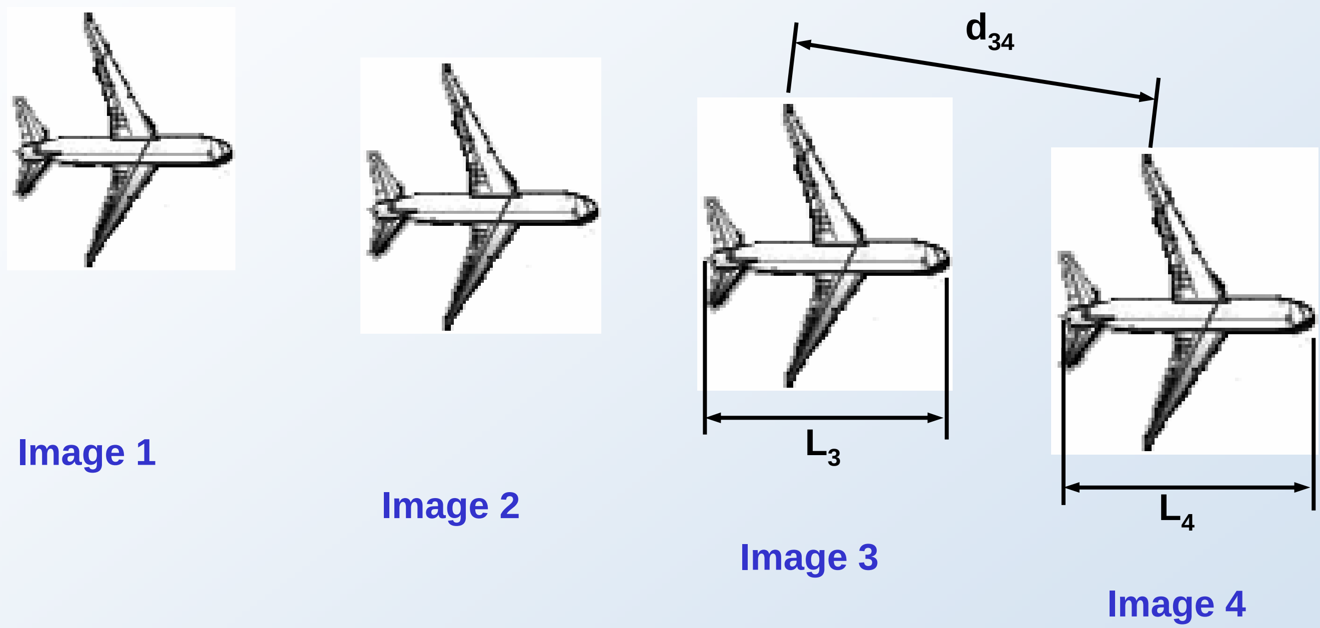
Step 2:



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

Aircraft Impact Initial Conditions

- Simplified motion analysis methodology



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

Aircraft Impact Initial Conditions

Summary of WTC aircraft impact conditions

	AA 11 (WTC 1)	UAL 175 (WTC 2)
Impact Speed (mph)	443 ± 30	546 ± 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	15° ± 2° clockwise from Structure North
Vertical Fuselage Orientation Relative to Trajectory	2° nose-up from vertical approach angle	1° nose-up from 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°

Aircraft Impact Initial Conditions

- 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 tip of the vertical stabilizer are clearly identified in the impact damage photographs.
- Relative locations of wing, engine, and tail strike place constraints on possible combinations of orientation and trajectory.

NIST

Global Aircraft Impact Analysis

- Nonlinear explicit dynamics solver
- Contact algorithm
- Failure criteria and element erosion
  - Effect of mesh size
- Modeling of fuel: ALE and SPH

NIST

Global Aircraft Impact Analysis: WTC 1

Global Tower WTC 1 Impact Zone Model:

- Full exterior model
  - floors 91 to 101 on 100 face, mixed coarse and farfield panels
  - floors 92 to 102 on 200-400 faces, all farfield panels
- Truss floor - exterior to core floors 92 to 100 all sides
- Core structure and floor slab for floors 92 to 100.
- Non Structural walls and workstations included in interior (only in impact path)

Tower Model Statistics:

- 1,299,241 nodes
- 47,952 beam elements
- 1,156,947 shell elements
- 2,805 solid elements

Boeing 767 model statistics:

- 740,000 Nodes
- 562,000 shell elements
- 70,000 brick elements
- 60,600 SPH particles

NIST

Aircraft Impact into WTC 2
Core Beam Damage

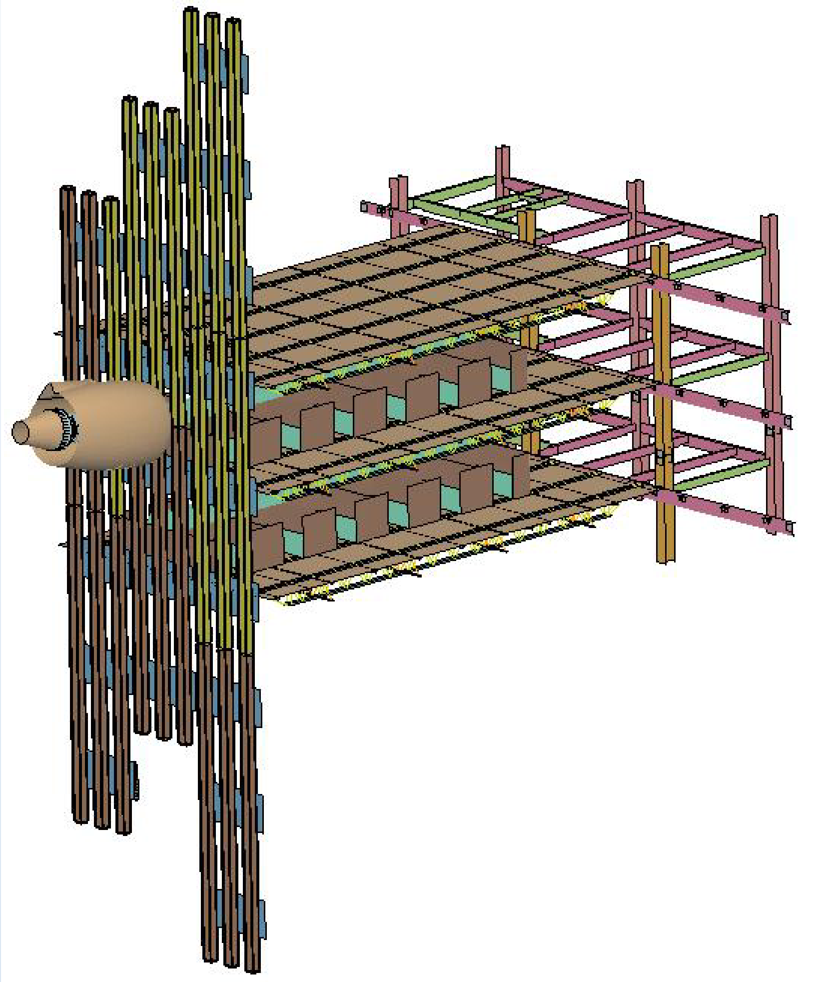
Floor 79 Core Beam Damage

Uncertainty Analysis

Engine Impact - Subassembly

Parameters

Parameter		ID	Min. -1	Base 0	Max. +1	Remark
Flight Param.	Velocity (m/s)	1	185	198	211	
	Imp. Loc. V	2	-1 m	0	+1 m	
	Trajectory - pitch	3	- 3°	10.6°	+ 3°	
	Trajectory - yaw	4	0°	2°	+4°	
Engine	Assignment Set #	5	1	1	2	discrete
	Strength	6	-35%		35%	
Tower	Strength	7	-15%		15%	
	Failure Strain	8	-50%		50%	
	Strain rate effects	9	0.1	1	2	
	Live Load Wgt. Scale Factor	10	15%	25%	40%	
Model	Erosion Param.	11	0	0	2	discrete



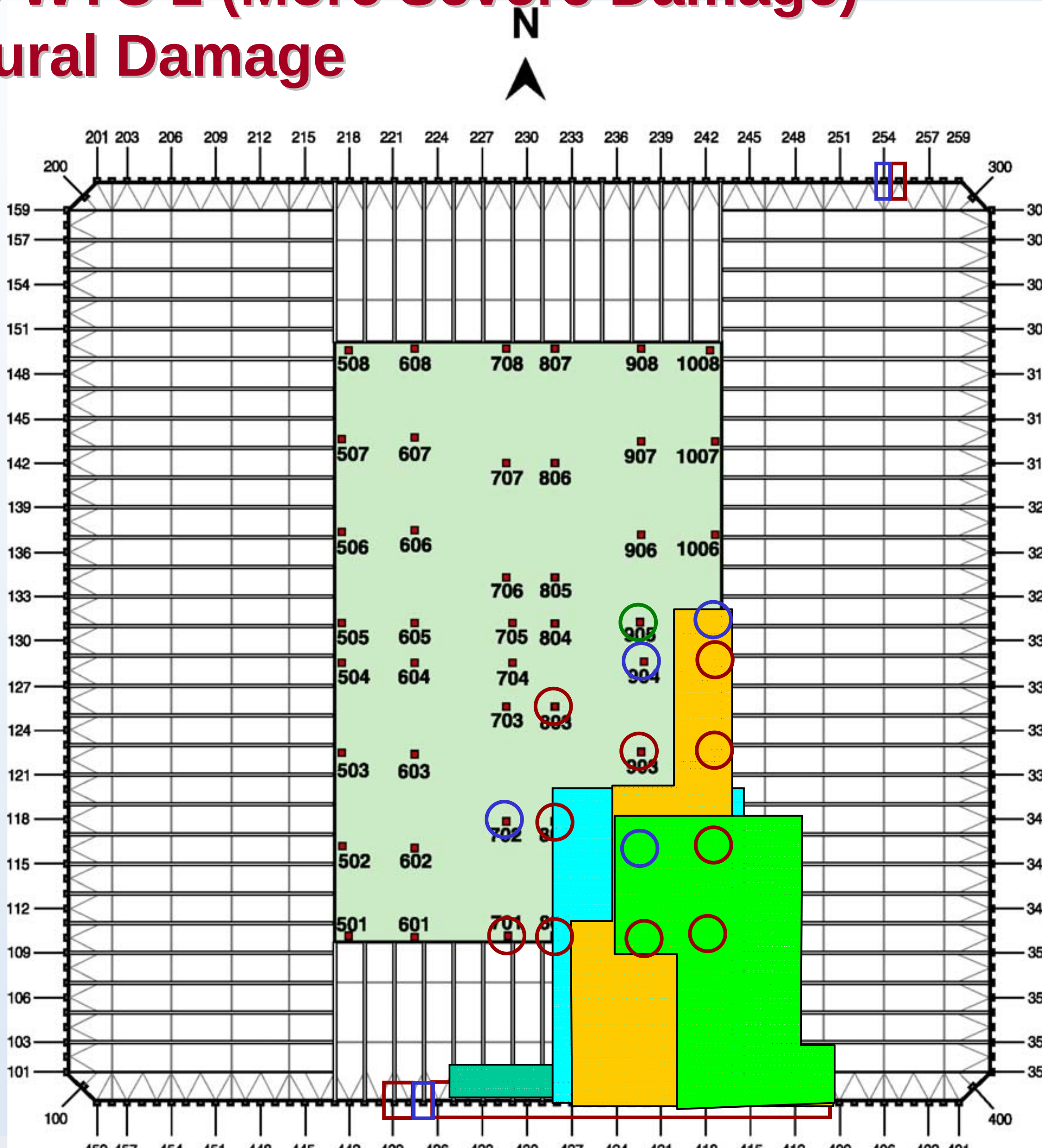
Residual engine KE used as the response parameter.

Aircraft Impact into WTC 2 (More Severe Damage)
Summary of Structural Damage

Severed

Heavy Damage

Moderate Damage



Comparison with Previous Studies

- MIT:

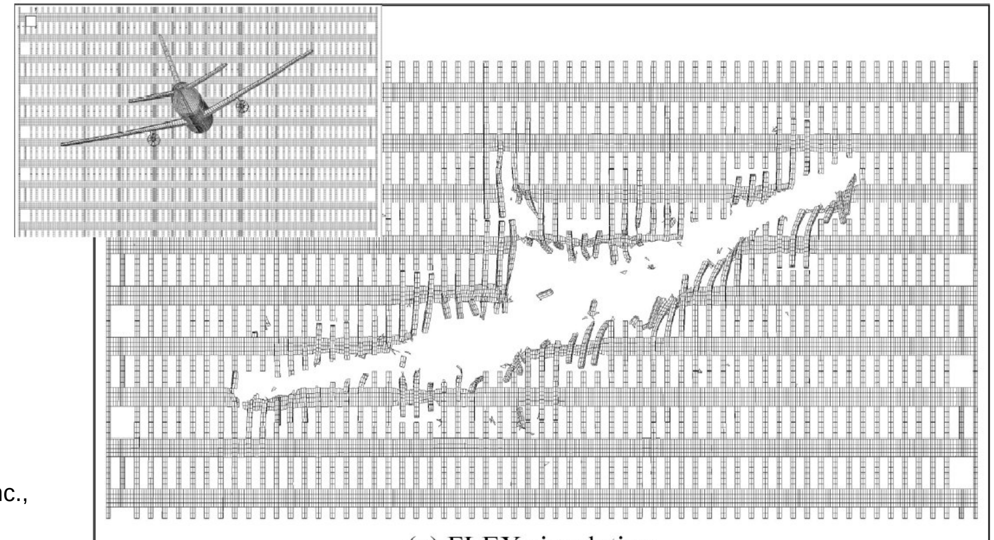
  Used an energy approach to estimate damage to core columns

$$E_{kinetic} = E_{plane} + E_{ext.\ Col.} + E_{floor} + E_{core}$$

- Weidlinger Associates, Inc.

  Used a finite element analysis to estimate damage to both towers

Source: Levy, M., and N. Abboud. *WTC Structural Engineering Investigation*. Weidlinger Associates, Inc., Hart-Weidlinger, August 2002.


(a) FLEX simulation

NIST

Comparison with Previous Studies

Summary Comparison of Damage to Core Columns from Various Studies

	WTC 1	WTC 2
MIT	4 - 12	7 – 20
Weidlinger	23 severed 5 damaged	14 severed 10 damaged
NIST – Realistic Damage	3 severed 10 damaged	5 severed 5 damaged
NIST – More severe Damage	6 severed 11 damaged	10 severed 5 damaged

Findings -- Wind Loads

- The original design wind loads on the towers exceeded those established by the New York City building code prior to 1968 (when the WTC towers were designed) and through 2001 (when the towers were destroyed). The design values also are higher than those required by other selected building codes of the era, including the relevant national model building code.
- State-of-the-art wind load estimates developed by NIST are higher by as much as about 15% than the most unfavorable original design wind loads for WTC 1, and lower by about 5% than the most unfavorable original design loads for WTC 2.
- The purpose of these comparisons is to better understand and assess the effects of successive changes in standards, codes and practices.

Findings -- Wind Loads, Cont.

- Estimated wind-induced loads on the towers vary by as much as 40% between two wind tunnel/climatological studies conducted in 2002 by CPP and RWDI as part of insurance litigation concerning the towers. These differences are mainly due to (1) the relatively high wind speed estimates in the CPP study, (2) the RWDI assumption that hurricane wind speed profiles are flatter than non-hurricane profiles, and (3) the methods used in both studies to integrate wind tunnel results with climatological data.

NIST

Findings -- Baseline Performance Analysis

- DCRs estimated from the original design case are in general close to those obtained from the lower bound state-of-the practice case. For both loading cases, a small fraction of structural components had DCRs larger than 1.0. These were observed around the corners of the exterior wall columns and spandrels as well as the core columns.
- Normal design practice is intended to achieve a DCR <= 1
- DCRs from the state-of-the-art case exceed those from the original design and state-of-the-practice cases due to the following reasons:
  - SOA wind loads are higher than those used in the lower bound SOP case by about 25 percent. Note that SOA wind loads are 20 percent smaller than those obtained by CPP (an upper bound SOP case).
  - The current national standard for loads (ASCE 7-02) does not allow the 1/3 increase of allowable stresses under wind loads.

NIST

Findings -- Baseline Performance Analysis, Cont.

- Allowable stress design has an inherent factor of safety for structural components. For example, the safety factor for yielding and buckling is:
  - 1.67 and 1.92 for core columns in the original design and SOP cases, and for all columns in SOA case.
  - 1.26 and 1.44 for perimeter columns in the original design and SOP case (discounting the 1/3 increase in allowable stress under wind loads).
- After reaching the yield strength, structural steel components continue to possess significant reserve capacity, thus allowing for load redistribution to other components that are still in the elastic range.
- On September 11, the towers were subjected to in-service live loads, which are considered to be approximately 25 % of the design live loads.
- On September 11, the wind loads were minimal, thus allowing significantly more reserve capacity for the exterior walls (exterior columns roughly at 1/3 of their capacity).
- The safety of the WTC towers on September 11 was most likely not affected by the small fraction of members with DCRs > 1.

Relevant Investigation Issues

- Availability of standards for conducting wind tunnel tests and for methods to estimate wind effects from test results for design purposes.
  - Tall buildings almost always rely on wind tunnel tests.
  - Load combinations, including material-specific (e.g., steel, concrete, and composites) response to peak loads.
  - Profile of hurricane and non-hurricane winds.
  - Estimation methods for combining directional wind loads, integrating climatological (wind) and aerodynamic (wind tunnel) data.

Relevant Investigation Issues, Cont.

- Availability of protocols for selection of site-specific wind speed and directionality.
  - Currently proprietary data are tabulated by zip code.
  - Estimates of hurricane wind speeds for all U.S. hurricane-prone regions similar to estimates currently performed for the State of Florida by NOAA Hurricane Research Division.
  - Protocols to allow the site-specific use of climatological databases.
  - Zoning analysis considering environmental impacts of potential future construction (impact of future construction on wind loads for existing buildings).
- Adequacy of prescriptive wind load standards for very tall buildings.

NIST

Findings -- Aircraft Impact

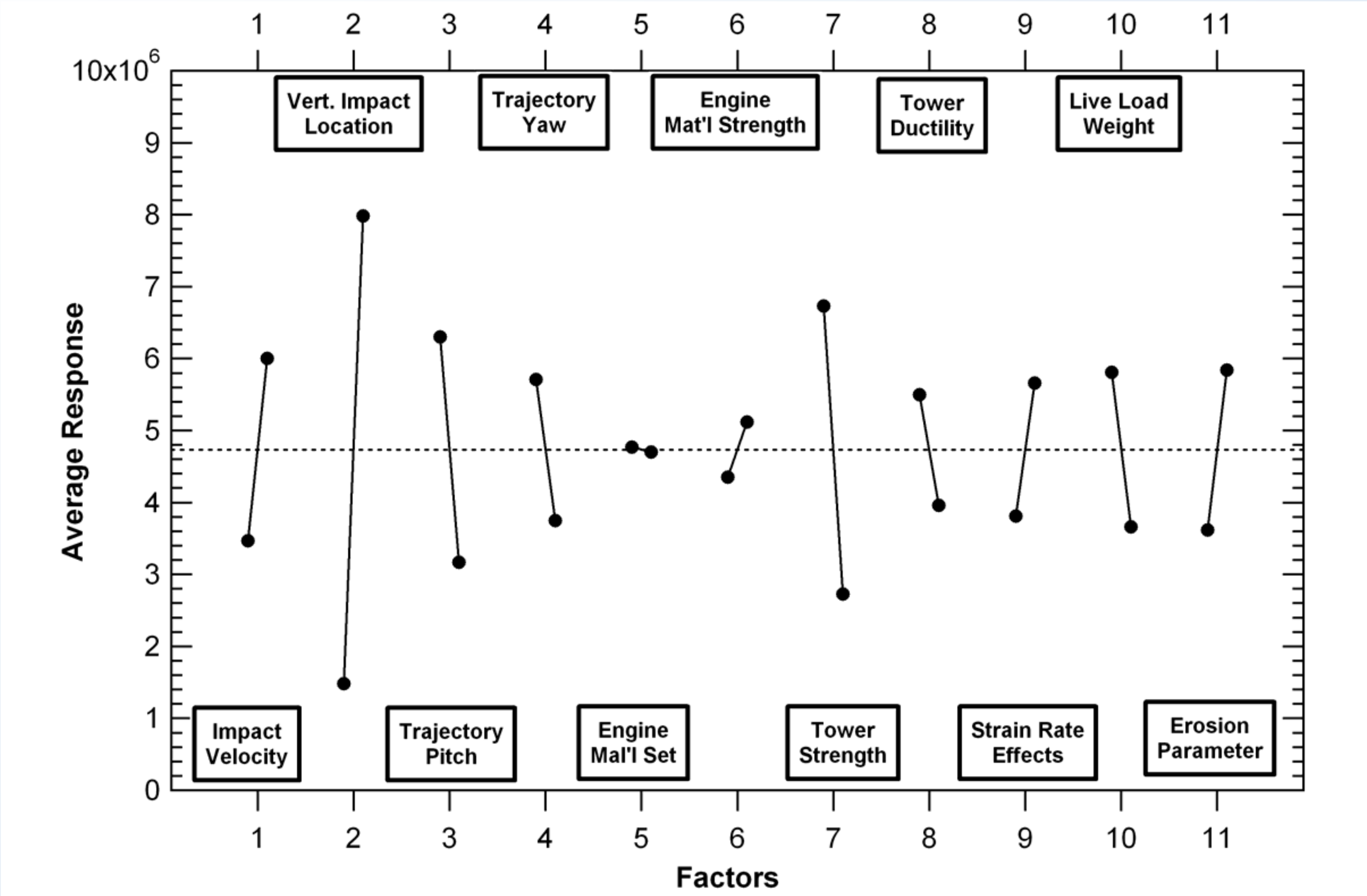
- WTC 1 Impact:
  - Speed of aircraft at time of impact was estimated at 443±30 mph.
  - Aircraft impact caused significant damage to the north wall with about 36 columns completely severed and 3 columns damaged. Good agreement is obtained between the calculated and observed damage to the north wall.
  - The north exterior wall completely failed in the regions of the fuselage, engine, and fuel-filled wing section impacts. Exterior columns were damaged but not completely severed in the outer wing and vertical stabilizer impact regions. Failure of exterior columns occurs both at the bolted connections between column ends and at various locations in the column depending on the local severity of the impact load and the proximity of the bolted connection to the impact.
  - The realistic damage analysis indicates significant damage to floor slabs, floor trusses, and core beams. Calculated impact response produces severe damage to floor trusses in the primary impact path of the fuselage between the exterior wall to the core. Truss floor systems on floors 94 to 96 were damaged and sagging downward due to impact loading.

Findings -- Aircraft Impact

- WTC 1 Impact:
  - The realistic damage analysis indicates 3 severed core columns over multiple floors in addition to 10 damaged core columns. Core columns in line with the aircraft fuselage were failed on the impact side. In general, affected core columns are mainly to the north center of the core.
  - The bulk of the fuel and aircraft debris were deposited in floors 93 through 97 with the greatest concentration on floor 94. About 17,400 lbs of debris and 6,700 lbs of the aircraft fuel were outside the tower at the end of the impact analysis, either rebounding from the impact face or passing through the tower. The analysis may have overestimated this amount since the exterior walls were not modeled with windows that could contain the fuel cloud and small debris inside the towers.

Uncertainty Analysis

Engine Impacting Tower Subassembly



Main Effects Plot

Parameters for Max/Min Runs

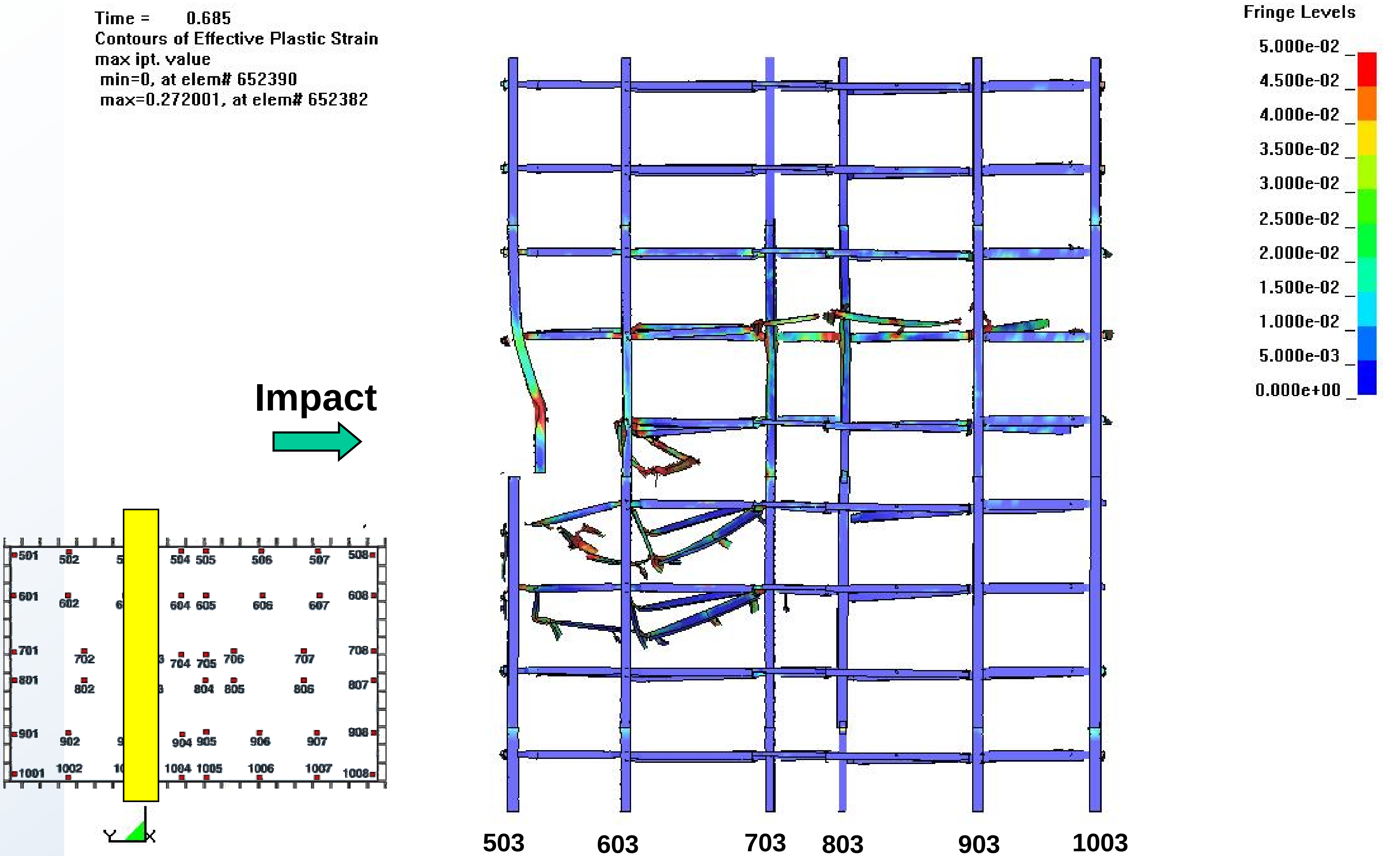
WTC 1

Parameter		Run 1 (Realistic Damage Estimate)	Run 2 (More Severe Damage)	Run 3 (Less Severe Damage)
Flight Param.	Velocity (m/s)	198	211	185
	Trajectory - pitch	10.6°	7.6°	13.6°
	Orientation - pitch	8.6°	5.6°	11.6°
Aircraft	Weight	100%	105%	95%
	Failure Strain	100%	115%	85%
Tower	Partition Strength	100%	80%	100%
	Failure Strain	100%	90%	110%
	Live Load Scale Factor	25%	20%	25%

WTC 2

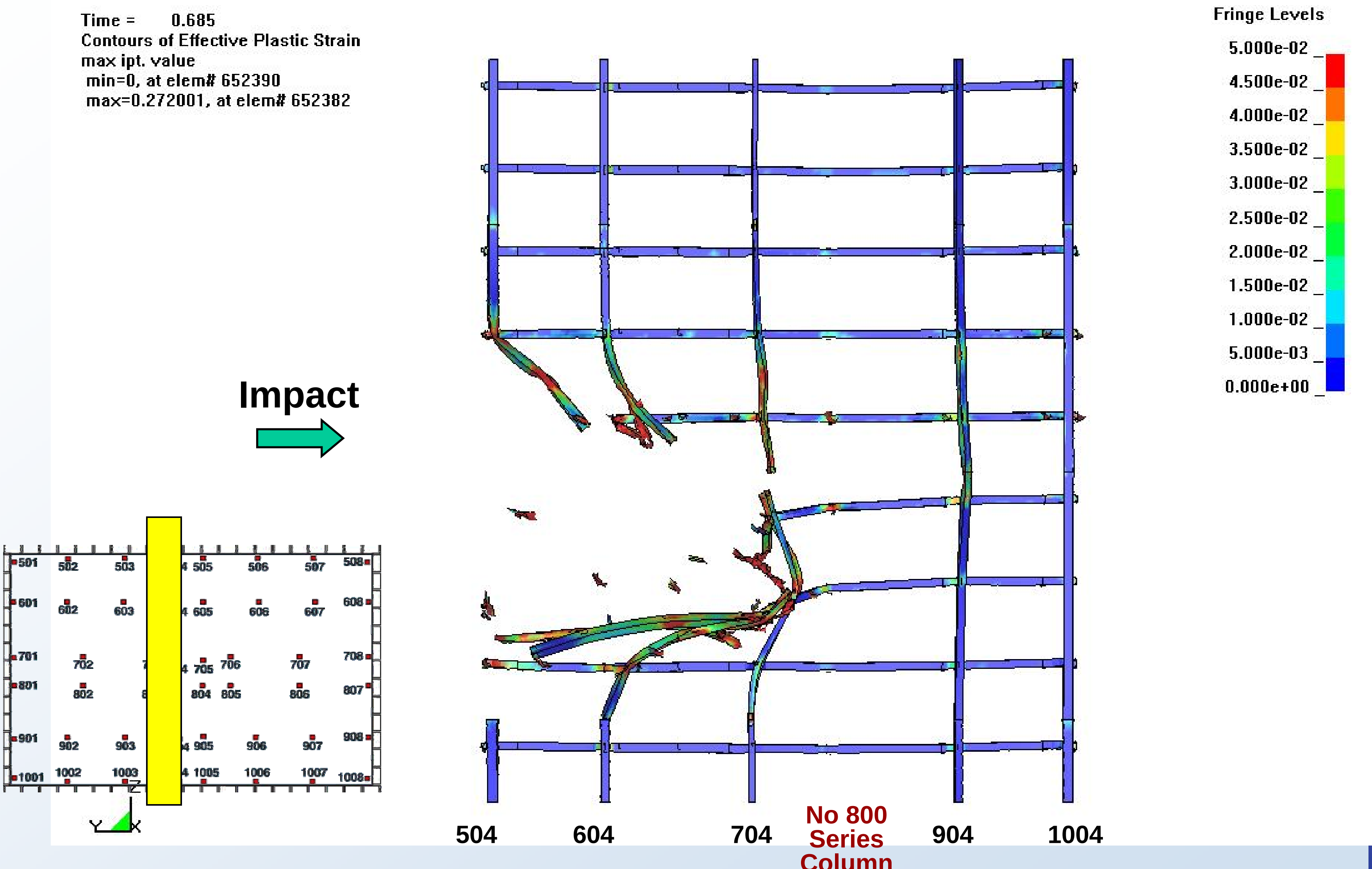
Parameter		Run 1 (Realistic Damage Estimate)	Run 2 (More Severe Damage)	Run 3 (Less Severe Damage)
Flight Param.	Velocity (m/s)	244	255	233
	Trajectory - pitch	6°	4°	8°
	Orientation - pitch	5°	3°	7°
Aircraft	Weight	100%	105%	95%
	Failure Strain	100%	115%	85%
Tower	Partition Strength	100%	80%	100%
	Failure Strain	100%	90%	110%
	Live Load Scale Factor	25%	20%	25%

Aircraft Impact into WTC 1 (More Severe Damage)
Damage to Core Columns

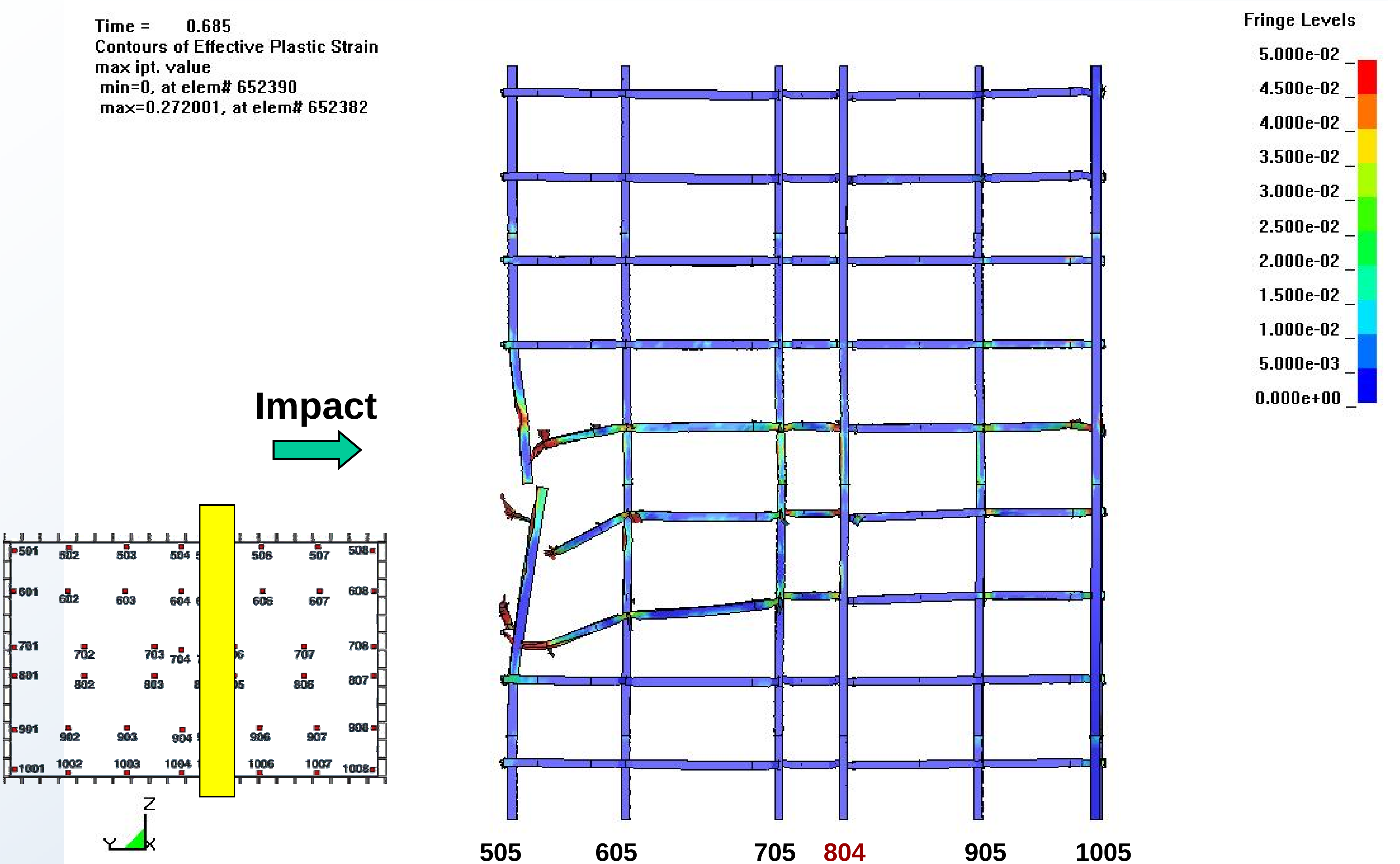


NIST

Aircraft Impact into WTC 1 (More Severe Damage)
Damage to Core Columns

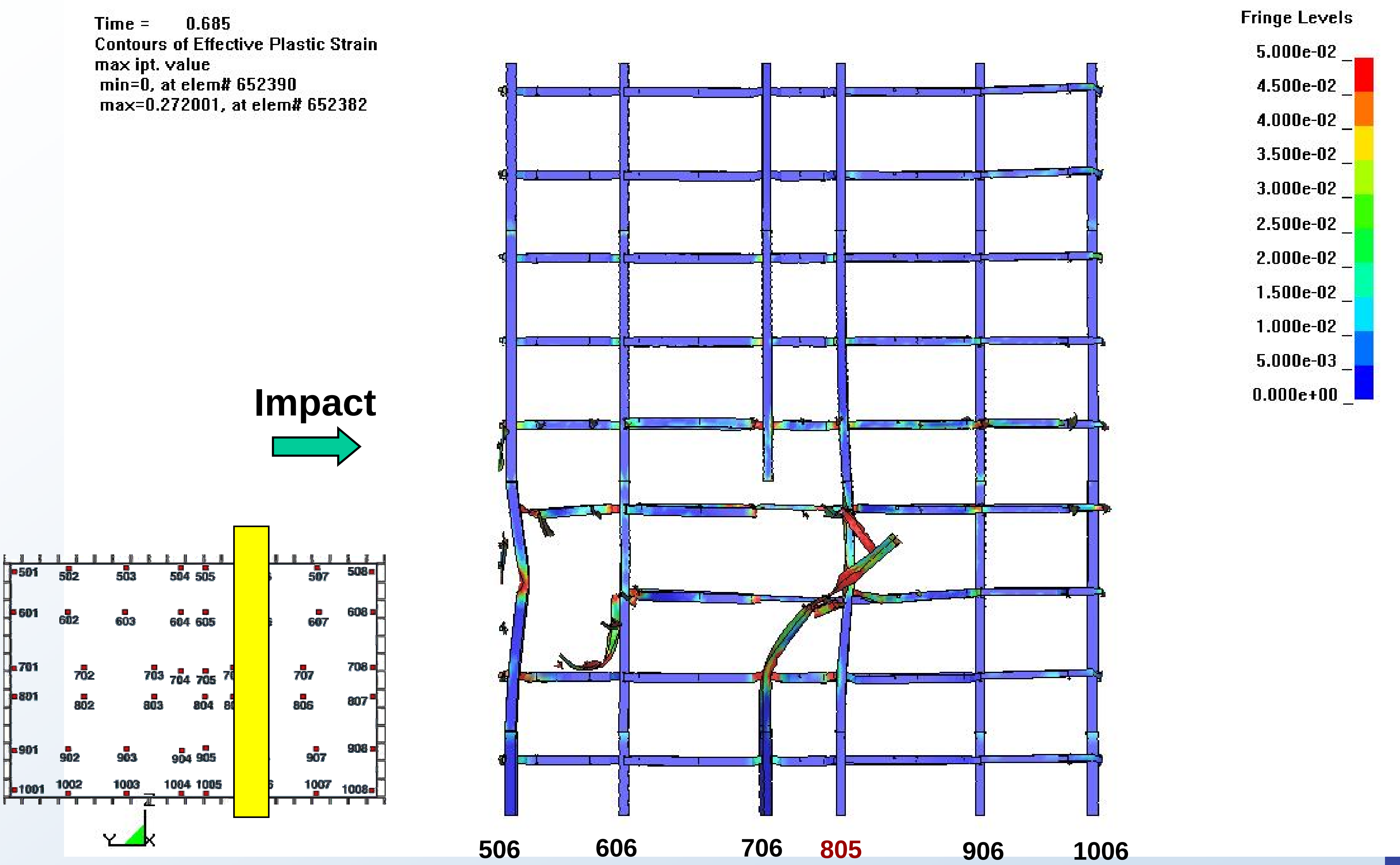


Aircraft Impact into WTC 1 (More Severe Damage)
Damage to Core Columns



NIST

Aircraft Impact into WTC 1 (More Severe Damage)
Damage to Core Columns

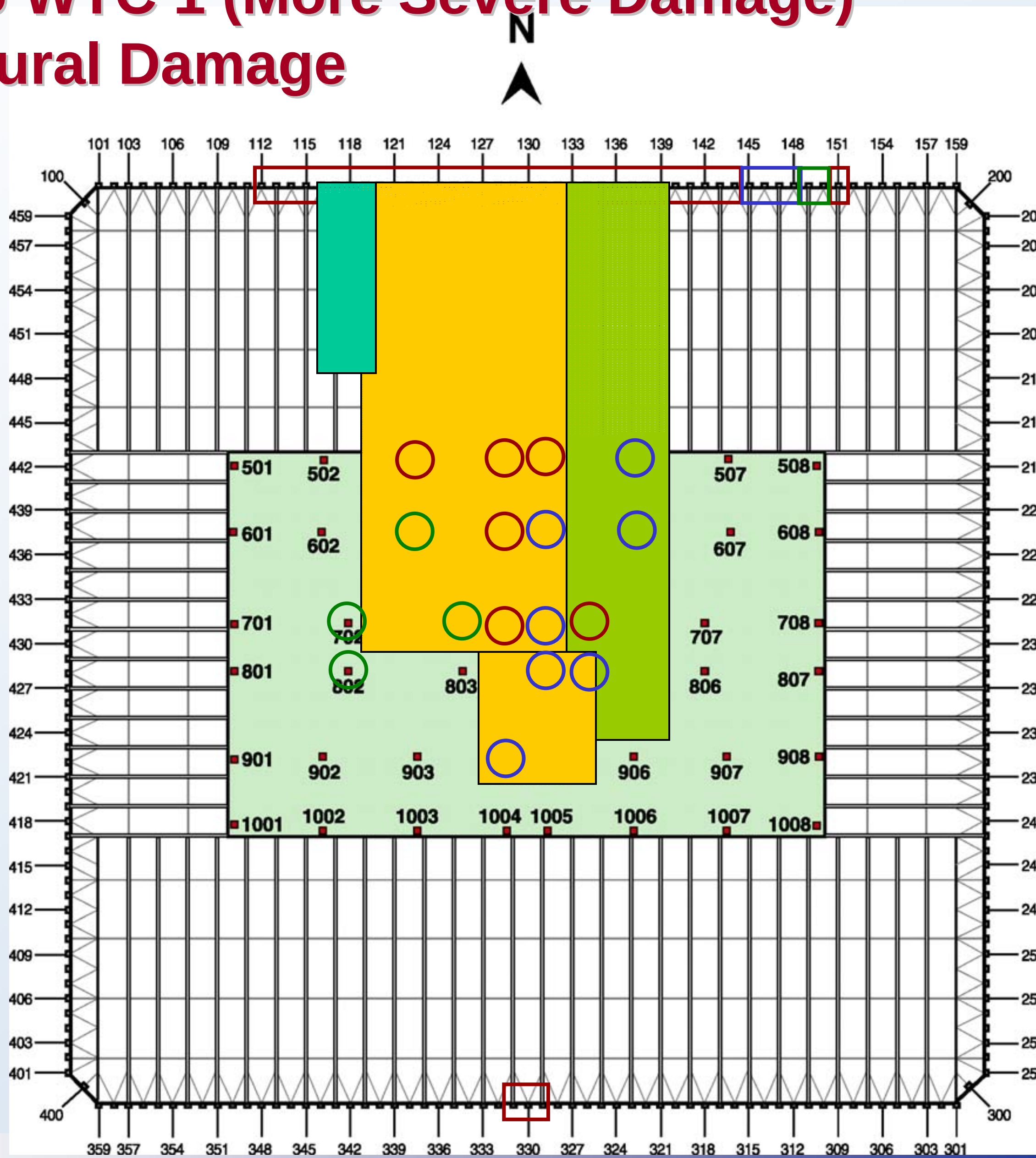


Aircraft Impact into WTC 1 (More Severe Damage) Summary of Structural Damage

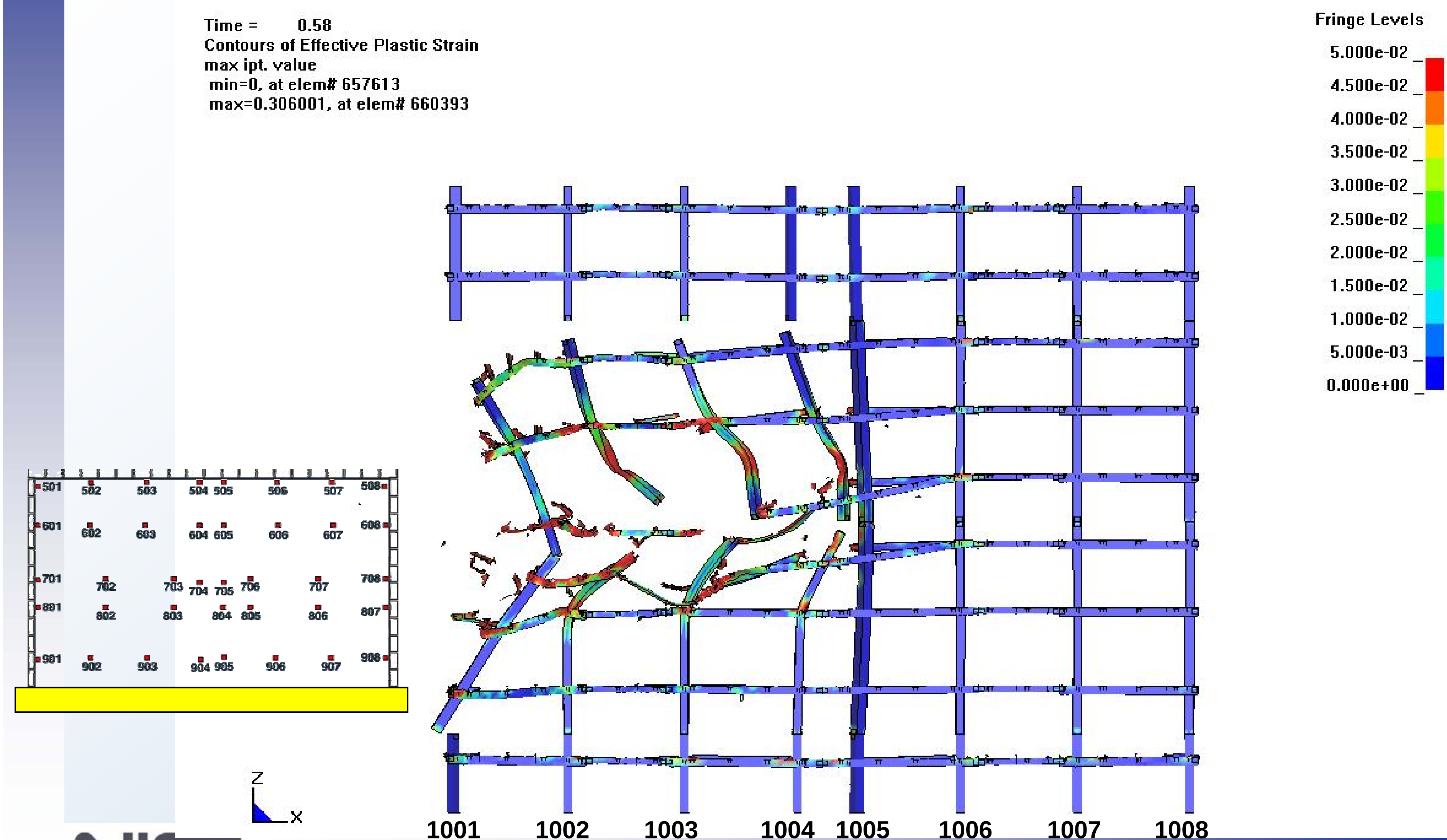
Severed

Heavy Damage

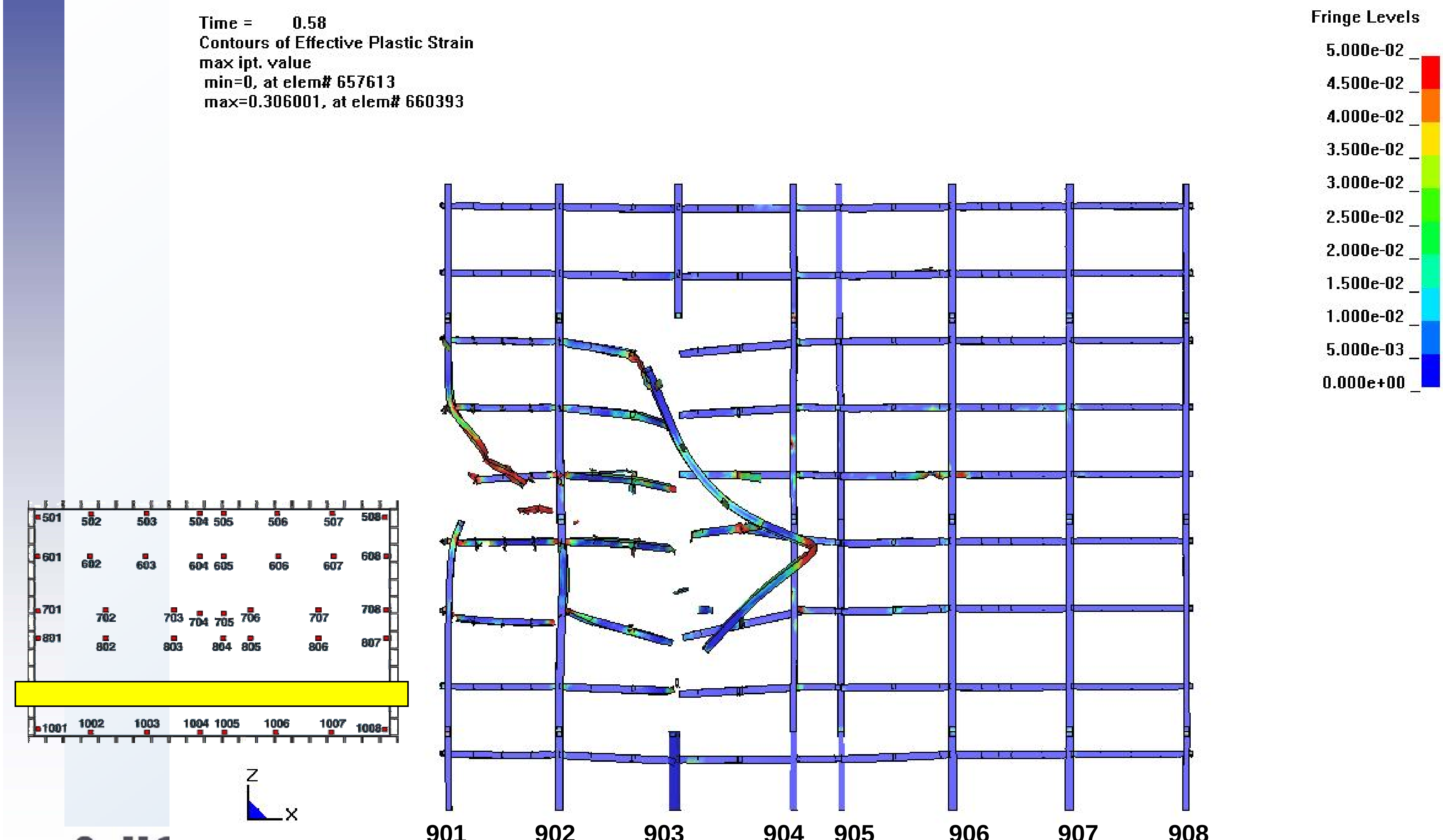
Moderate Damage



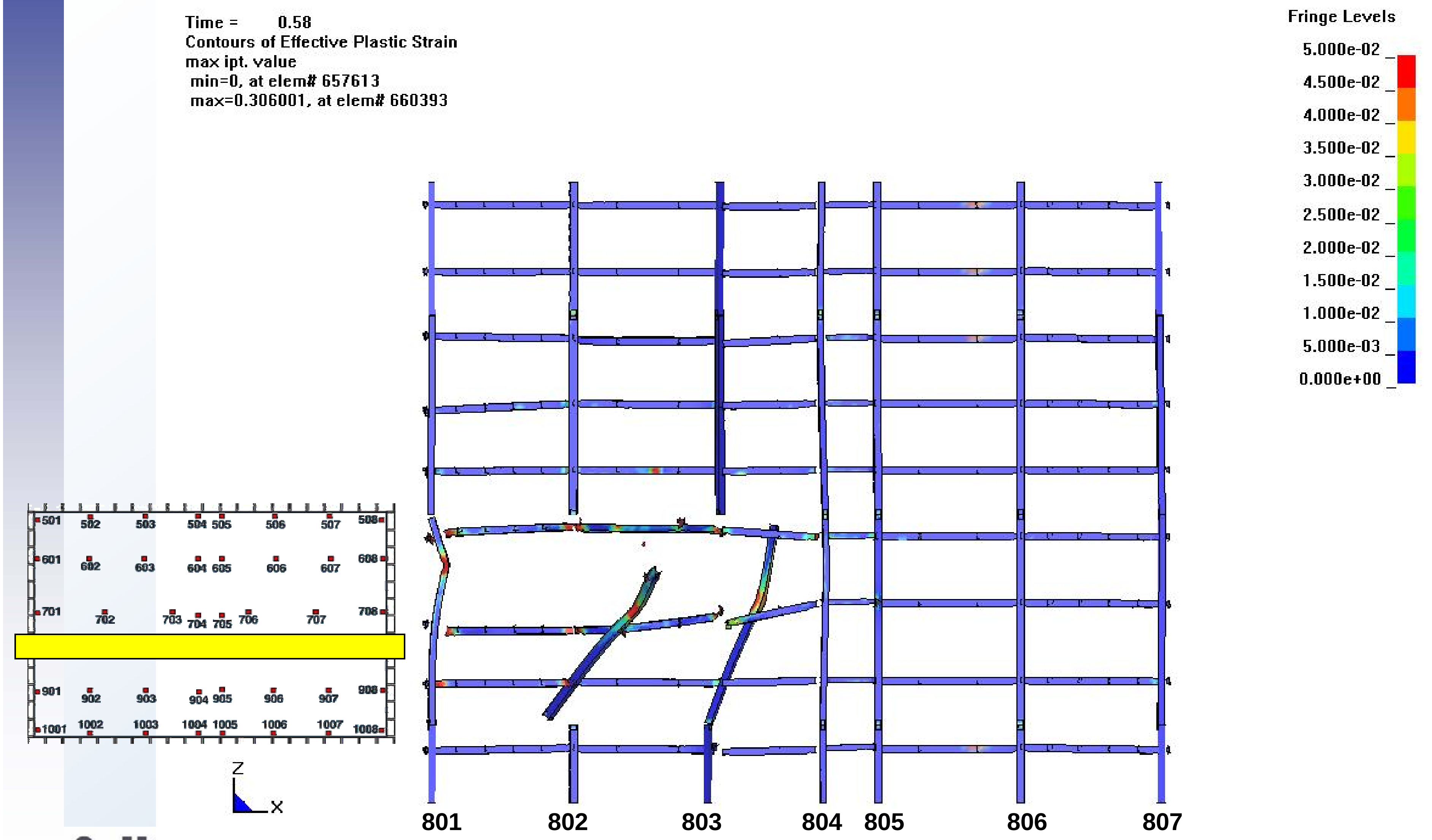
Aircraft Impact into WTC 2 (More Severe Damage)
Damage to Core Columns



Aircraft Impact into WTC 2 (More Severe Damage) Damage to Core Columns



Aircraft Impact into WTC 2 (More Severe Damage)
Damage to Core Columns

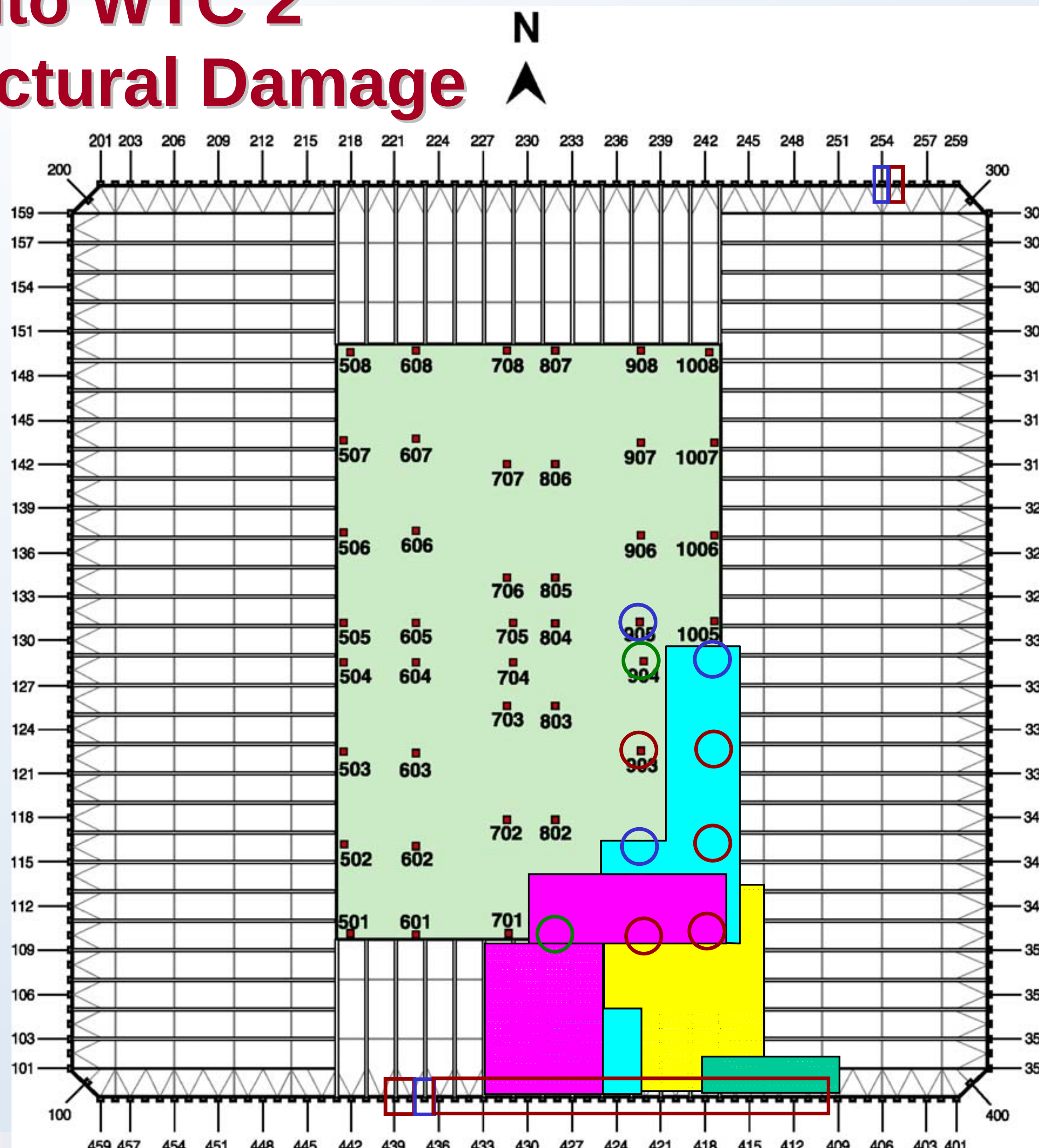


Aircraft Impact into WTC 2
Core Beam Damage

Floor 80 Core Beam Damage

NIST

Aircraft Impact into WTC 2
Summary of Structural Damage

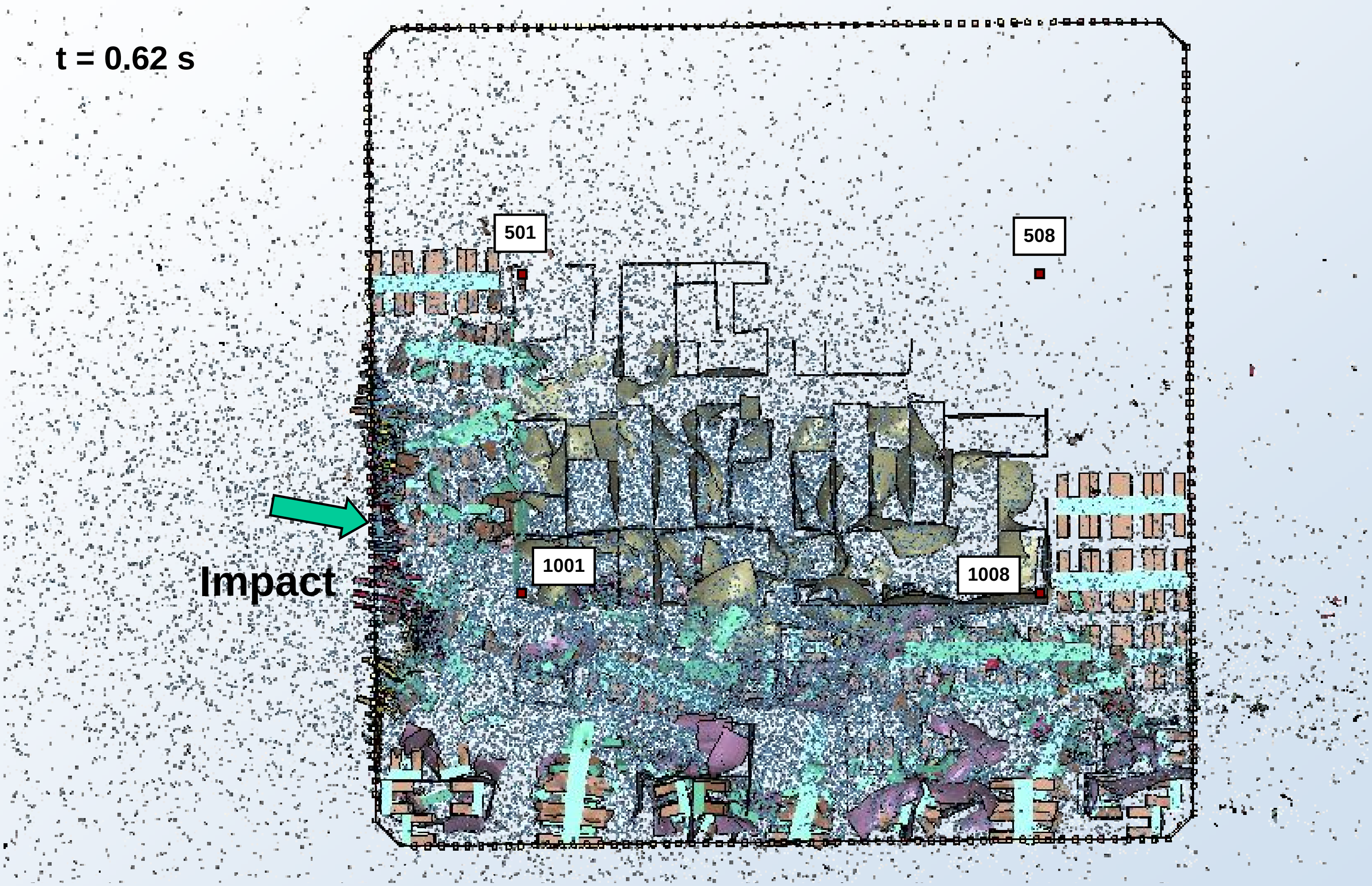


Severed

Heavy Damage

Moderate Damage

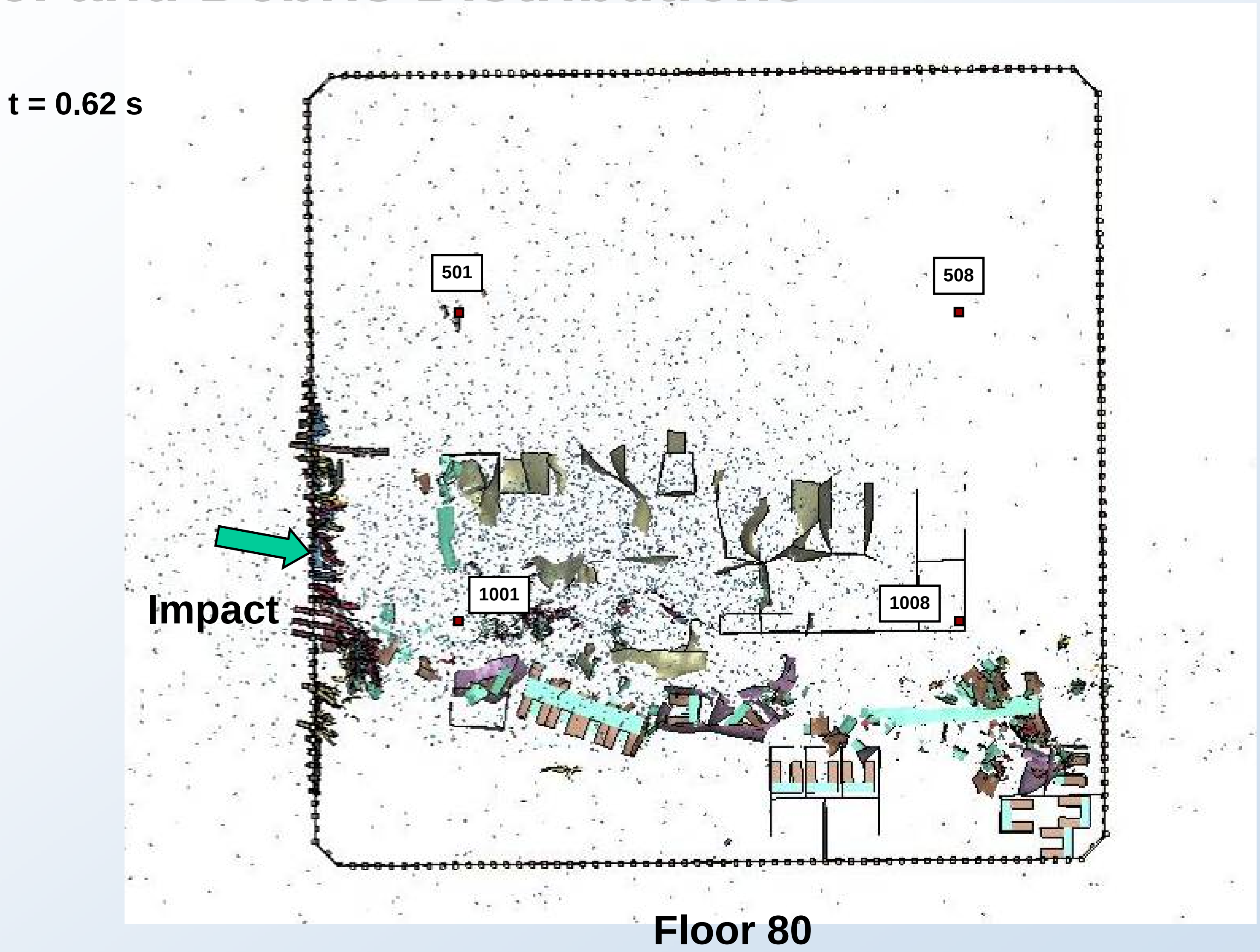
Aircraft Impact into WTC 2
Fuel and Debris Distributions



Aircraft Impact into WTC 2
Fuel and Debris Distributions

t = 0.62 s

Aircraft Impact into WTC 2
Fuel and Debris Distributions

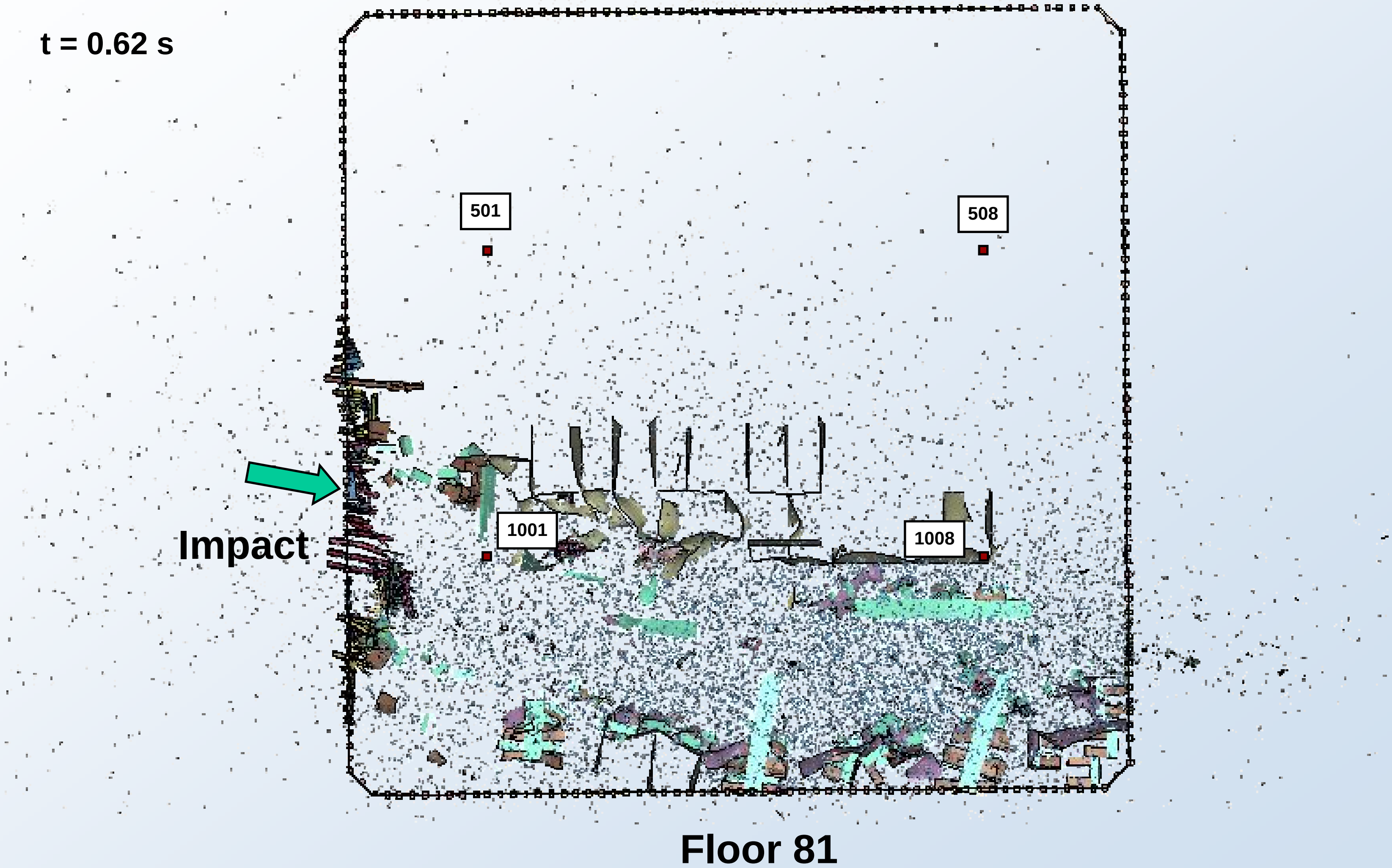


Aircraft Impact into WTC 2
Fuel and Debris Distributions

t = 0.62 s

Floor 80

Aircraft Impact into WTC 2
Fuel and Debris Distributions



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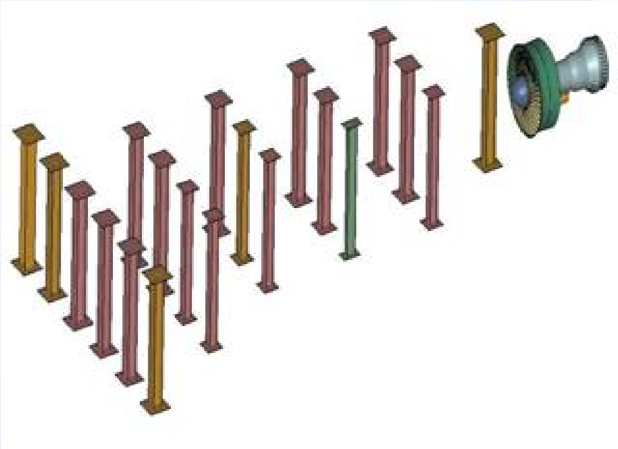
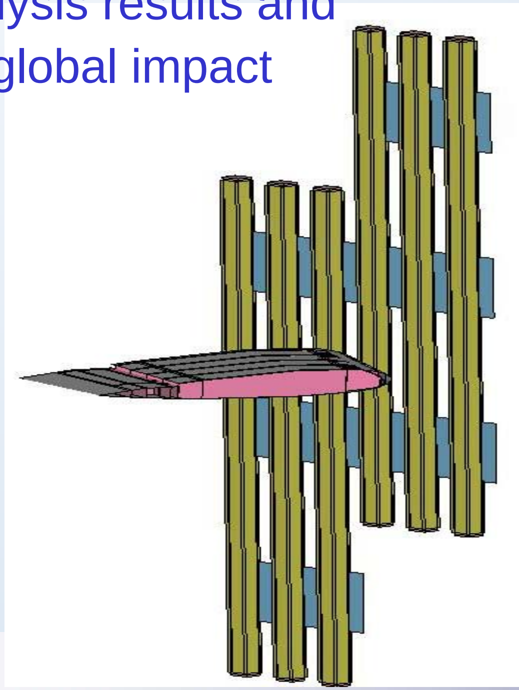
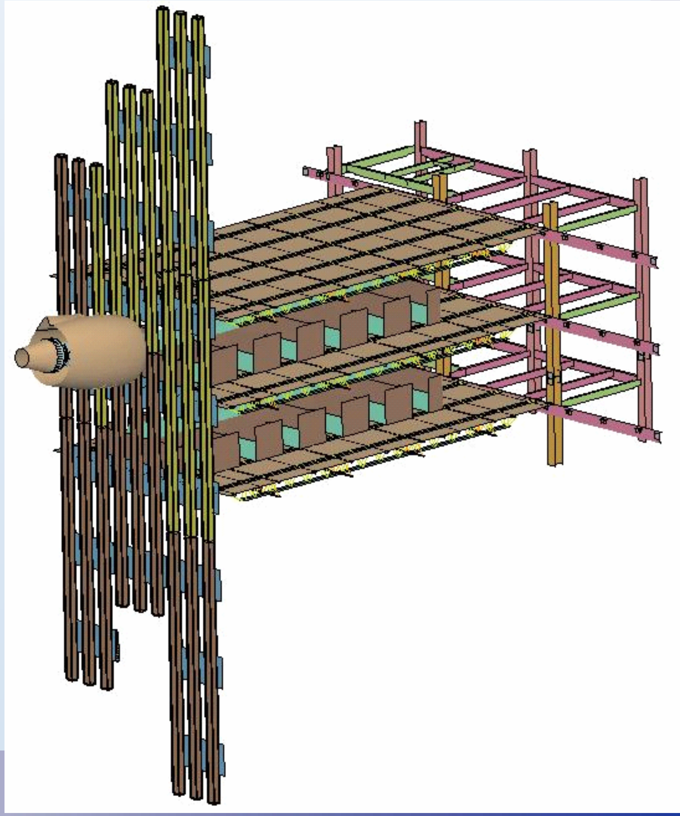
Uncertainty Analysis



- More than 25 parameters were considered in three experiments.
- Orthogonal factorial design was used to identify the most influential parameters.
- 8 parameters were found to be influential on analysis results and are varied in the global impact analyses.





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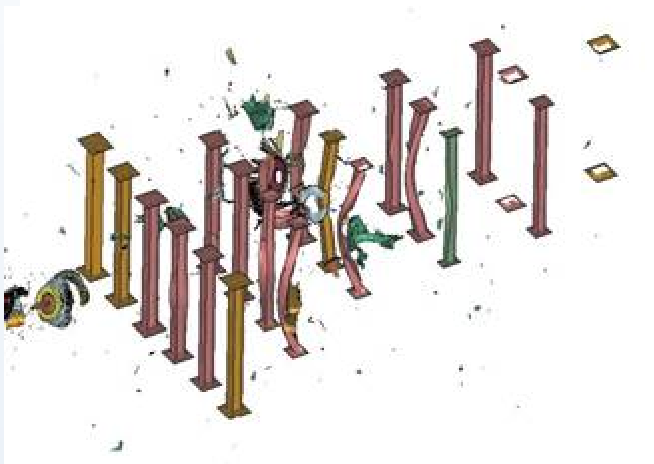
Uncertainty Analysis
Engine / Core Column



Parameters		ID
Flight	Vel.	1
Param.	Imp. Loc. V	2
	Imp. Loc. H	3
	Assignment Set #	4
Engine	Strength	5
Mat'l.	Failure Strain	6
	Strain rate	7
Tower	Strength	8
Mat'l.	Failure Strain	9
	Strain rate	10
	Erosion Param.	11
Model	Contact Param.	12
	Fric. Coeff.	13

Number of Runs

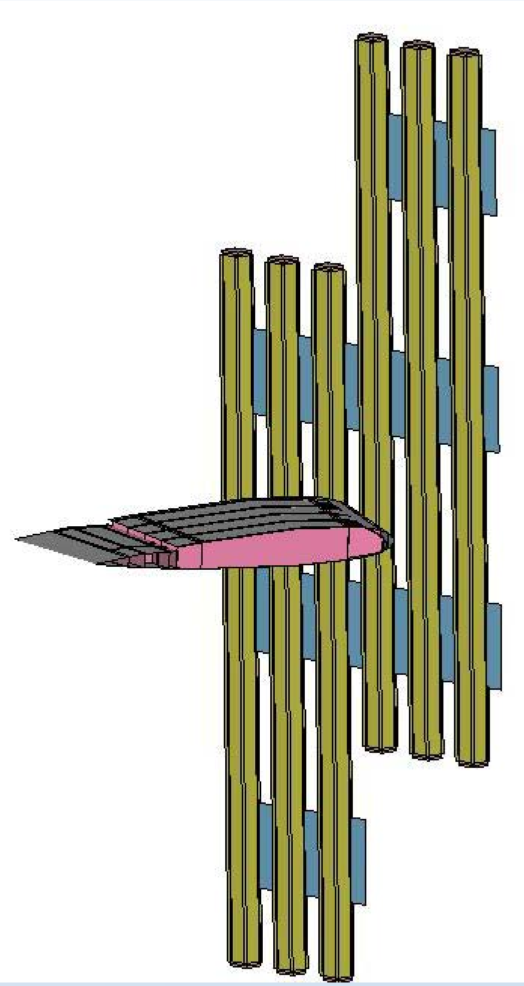
Stage 0	10
Stage I	9
Stage II	8
Stage III	9
Stage IV	8
Total	44

Uncertainty Analysis

Wing Component Without Fuel Impacting Exterior Panel

Parameters

Factor		ID	Min. -1	Base 0	Max. +1
Flight	Velocity (m/s)	1	185	198	211
	Impact Trajectory (°)	2	-4	0	4
Wing	Strength	3	-35%		+35%
	Failure Strain	4	-50%		+50%
	Rivet Connection Strength	5	-50%		+50%
	Weight Scale factor	6	1.5	2	3.0
Tower	Strength	7	-15%		+15%
Mat'l.	Failure Strain	8	-50%		+50%
	Strain rate effects	9	0.1	1	2
	Erosion Parameter	10	1	1	2
Model	Erosion Strain	11	0.2	0.3	0.4
	Contact Parameter	12	1	1	0
	Friction Coefficient	13	0	0.3	0.6



Residual linear momentum of the debris field used as the response parameter.

Findings -- Aircraft Impact, Cont.

- WTC 2 Impact:
  - Speed of aircraft at time of impact was estimated at 546±24 mph.
  - Aircraft impact caused significant damage to the south wall with about 28 columns completely severed and 1 column damaged. Good agreement was obtained between the calculated and observed damage to the south wall. Exterior damage characteristics are very similar to those of WTC 1.
  - The realistic damage analysis indicates significant damage to floor slabs, floor trusses, and core beams. Floor trusses had significant damage in the impact zone with the most severe damage on floor 81. Calculated impact response produced severe damage to the floor trusses in the primary impact path of the fuselage. The truss floor system on floors 79 and 81 had sufficient damage from the impact that truss floor sections were sagging downward due to impact.

Findings -- Aircraft Impact, Cont.

- WTC 2 Impact:
  - The realistic damage analysis indicates 5 severed core columns over multiple floors in addition to 5 damaged core columns. Affected core columns are mainly to the south and east of the core. Column splices located on floors 77, 80, and 83 contributed significantly to the failure of the core columns. This is particularly true for the heavy corner column number 1001 that failed at the three splice locations.
  - The bulk of the fuel and aircraft debris were deposited in floors 78 through 82 with the greatest concentration of aircraft debris on floor 80. About 55,700 lbs of debris and 10,600 lbs of the aircraft fuel were calculated to be outside of the tower at the end of the impact analysis, either rebounding from the impact face or passing through the tower.

Findings -- Aircraft Impact, Cont.

- Orthogonal factorial design was used in three experiments to identify the most influential variables that affect the damage estimates. About 25 parameters were considered. Only 8 variables were found to be most influential and were varied in the global analyses, thus allowing for a smaller number of global runs.
- Results of the more severe damage case shows larger damage to columns and floor systems of both towers. For example:
  - WTC 1: 6 severed and 11 damaged core columns instead of 3 severed and 10 damaged columns in the realistic case.
  - WTC 2: 10 severed and 5 damaged core columns instead of 5 severed and 5 damaged columns in the realistic case.