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

Baseline Structural Performance and Aircraft Impact Damage Analysis

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Scope of Project

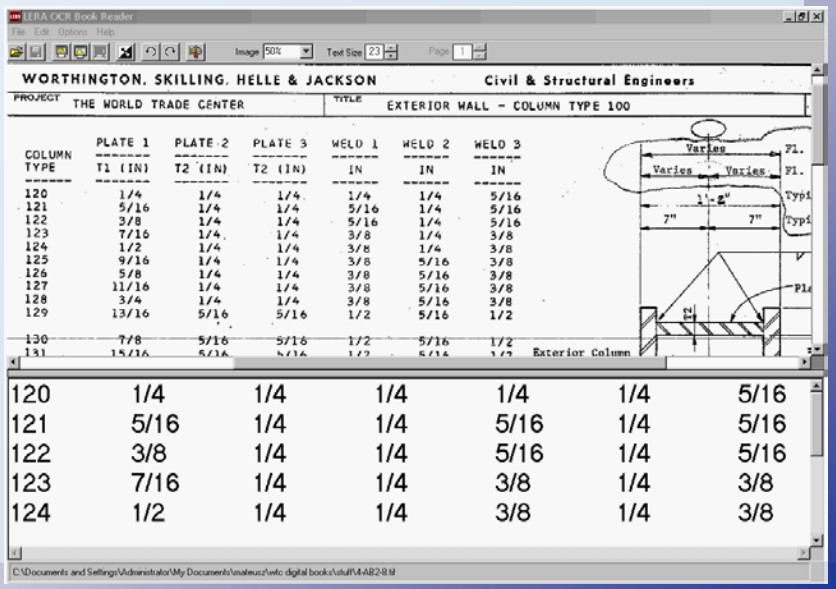
- Baseline Performance
  - ❑ Develop reference structural models of the WTC towers
  - ❑ Establish baseline performance under design loading conditions (gravity + wind)
- Aircraft Impact Damage
  - ❑ Simulate aircraft impacts into the towers to estimate probable damage to structural, mechanical, and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

Baseline Performance

- Tasks
  - ❑ T1: Develop structural databases for each of the two towers
  - ❑ T2: Develop reference structural models of the WTC towers
    - Typical floor models
    - Models of the whole towers
  - ❑ T3: Establish baseline performance under wind and gravity loads:
    - Estimate load vectors
    - Determine demand/capacity ratios (utilization ratios) for components and connections

Structural Databases

- WTC DB Development: Data Entry
  - ❑ Scanned tables and stored in TIFF files
  - ❑ Optical character recognition (OCR)
    - Converts to text format file
    - Modified to filter unnecessary characters
  - ❑ Raw text file split screen compared with image and cleaned
  - ❑ Text file imported into MS Excel



Structural Databases

- WTC DB Development: Quality Control
  - ❑ First check during OCR process
  - ❑ Second check: random, but methodical check by an engineer
  - ❑ Third check: ‘cross-check rectify’
    - Programmatically compared with database developed by a consultant of the leaseholder of the towers
  - ❑ Final review

Structural Databases

- WTC DB Development: Modifications to DB

Modifications to Members of the WTC-DB							
Item	Summary	Tower	Element	Floor	Element Effected	WTC-DB Modified	Archived
1	Core Column Reinforcing	A and B	Numerous	98-106	Core Columns	Book 3	Book 19
2	Fiduciary Bank Vault	B	Col. 508B and Col. 1008B	97-45	Core Columns	Book 3	LERA P209
3	Bombing of 26 February 1993 - Repair	A	Col. 324, Bracing G313A and G304A	B-2 Level	Perimeter Column and Bracing	NA	LERA P1003118
4	EXCO Stair	A	Col. 901A	26	Core Column	NA	LERA P1003249

Structural Databases

- Skidmore, Owings & Merrill (SOM) third-party review
  - Random checks of digitized databases and cross section properties
- Results
  - No discrepancies were found

Structural Databases

- NIST In-house Review
  - Line-by-line review of all files
  - Random checks by project leader
  - Calculate all cross section properties and compare with LERA database
- Results
  - Minor discrepancies were identified between the LERA DB and the drawing books
    - Examples: Book 1, entry 207 should be 287

      Book 3, entry 3010 should be 301D
  - No discrepancies were found for cross section properties

Reference Structural Models

- Task objective: Use structural databases to develop reference, finite element structural models of the towers. Models developed using SAP2000 Version 8, and include:
  - Floor models
  - Whole tower models

Reference Structural Models

Floor models:

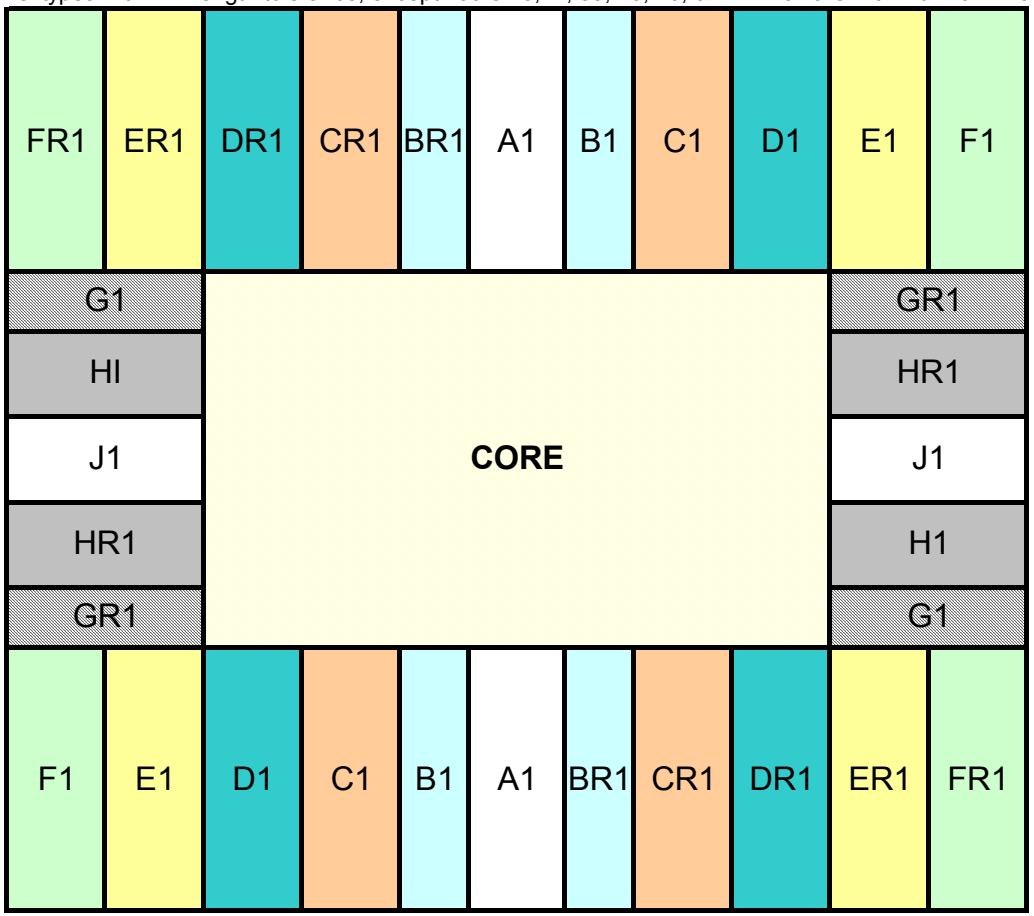
- 3-D models of typical floor systems:
  - A truss floor system (96th floor of WTC 1)
  - A mechanical floor (75th floor of WTC 2)
- Models are used:
  - To establish the baseline performance of the floor systems under gravity loads
  - To estimate the in-plane stiffness of the floor diaphragms and develop simplified models for the floor system that accurately capture the behavior of the floor diaphragms
  - As a reference for other significantly more detailed models to be developed in Projects 2 (impact analysis) and 6 (fire-structural analysis) with proper modifications

Typical Floor Systems

Type 1 - WTC Typical Truss Floor Panel Plan

Tower A Floors:		Tower B Floors:	
10 - 24	60 - 66	14 - 24	60 - 74
26 - 40	68 - 74	26 - 40	84 - 91
50 - 58	84 - 91	50 - 58	93 - 106
	93 - 105		

Note: All panel types within 1" length tolerance, except floors 10,11, 39, 40, 70, & 71 which are within 6"-10". Floors 72-74 vary 18"-26".



Note: H1 = H6

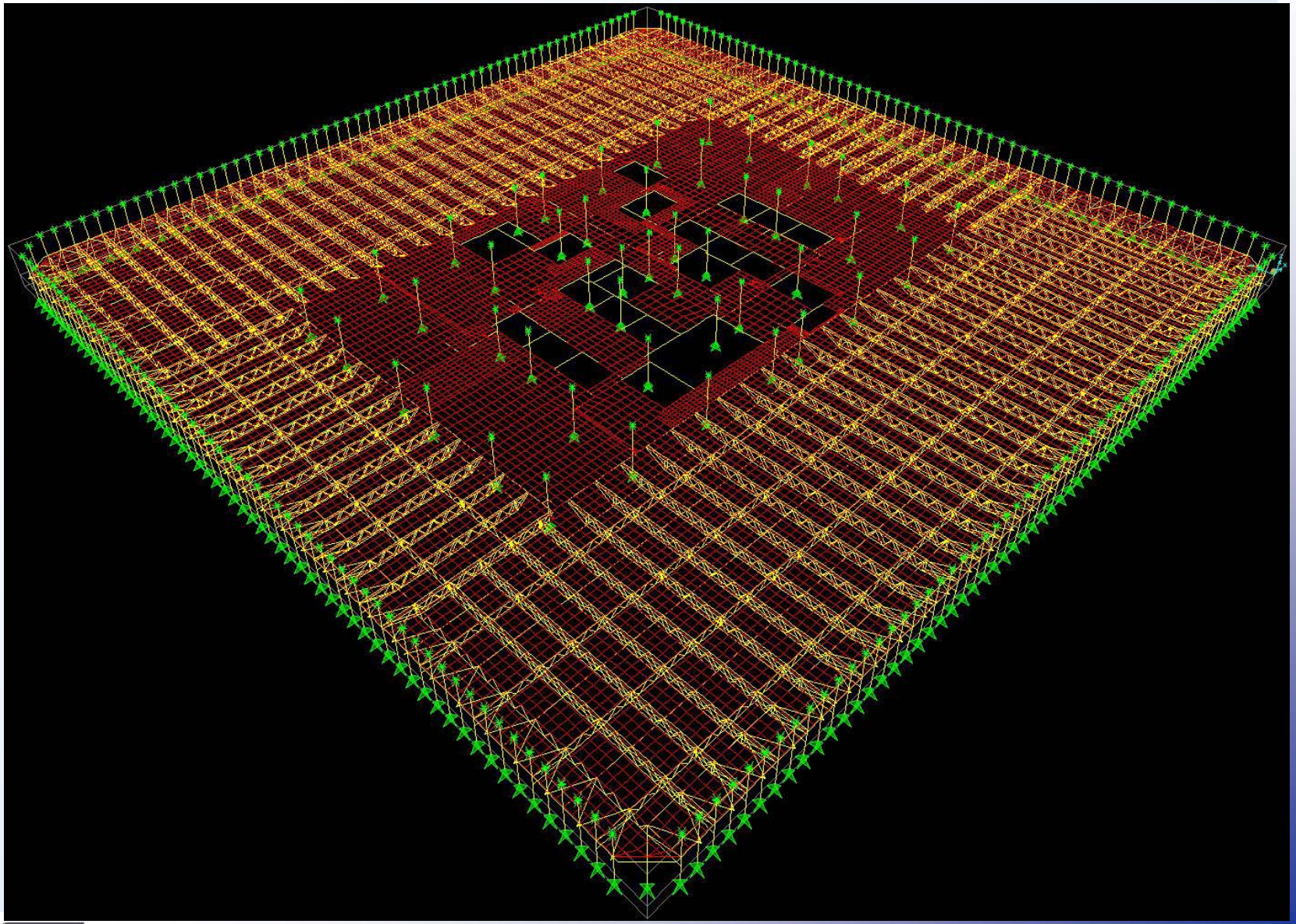
Note: HR1 = HR6

Note: J1 =K1 = KR1

Note: H1 =M1 = MR1

(all C32T5 Trusses)

Floor Systems: *Floor 96-A Model*



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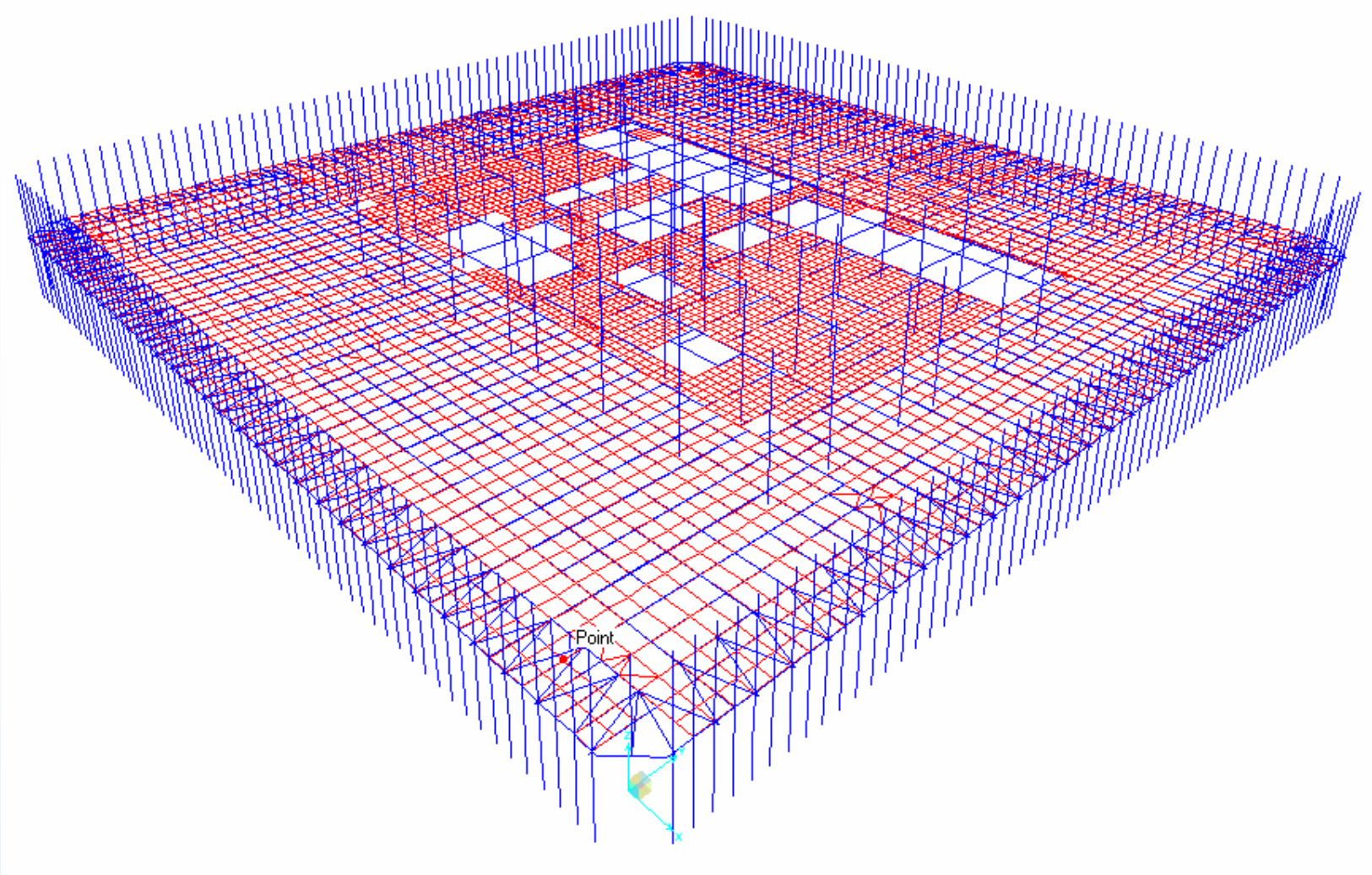
Floor Systems: *Floor 75-B Model*



Reference Structural Models

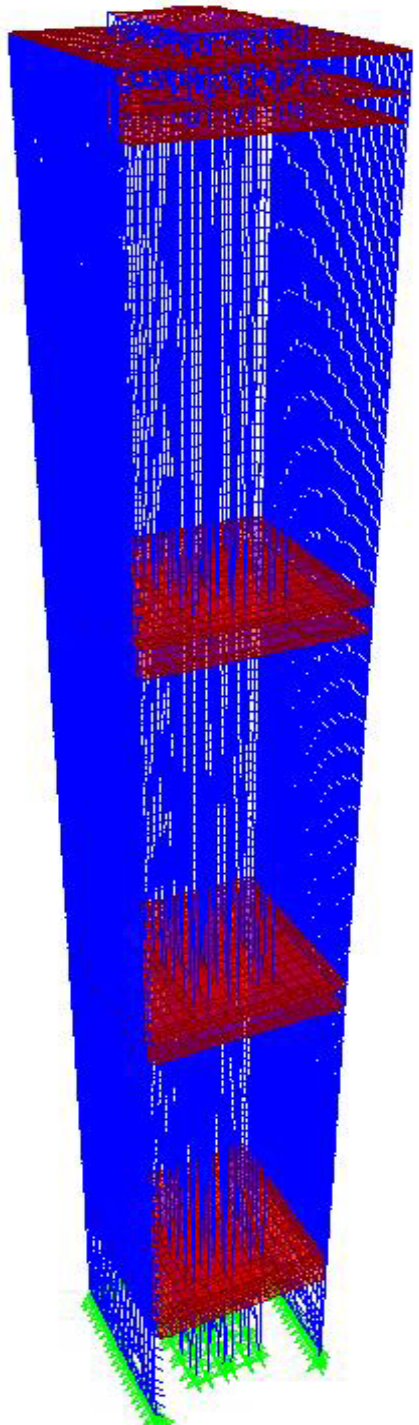
Whole tower models:

- 3-D models of the 110-story structure and basement floors of each of the two towers. Models include all primary structural elements including exterior columns, interior columns, columns and bracings in basement floors, spandrel beams, hat trusses, and simplified models for floor systems
- Models will be used to establish the baseline performance of each of the two towers under gravity and wind loads
- Reference for other significantly more detailed models to be developed in projects 2 (impact analysis) and 6 (fire-structural analysis)

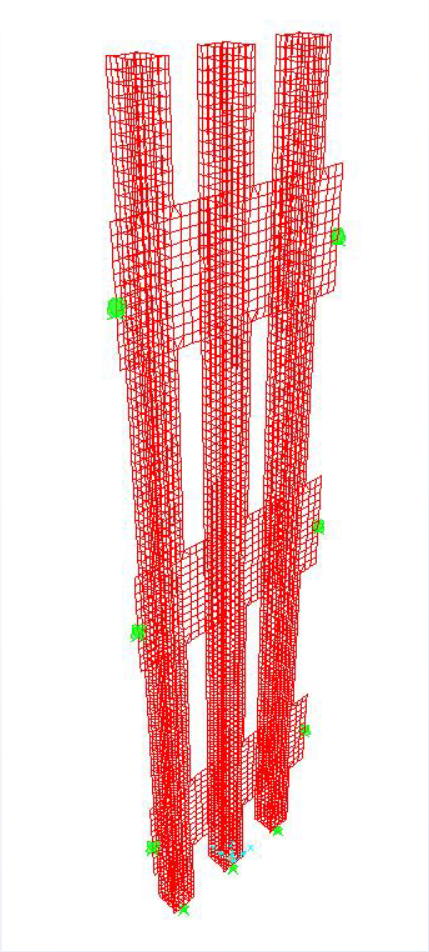
Tower Structural System FE Models (Global Model)

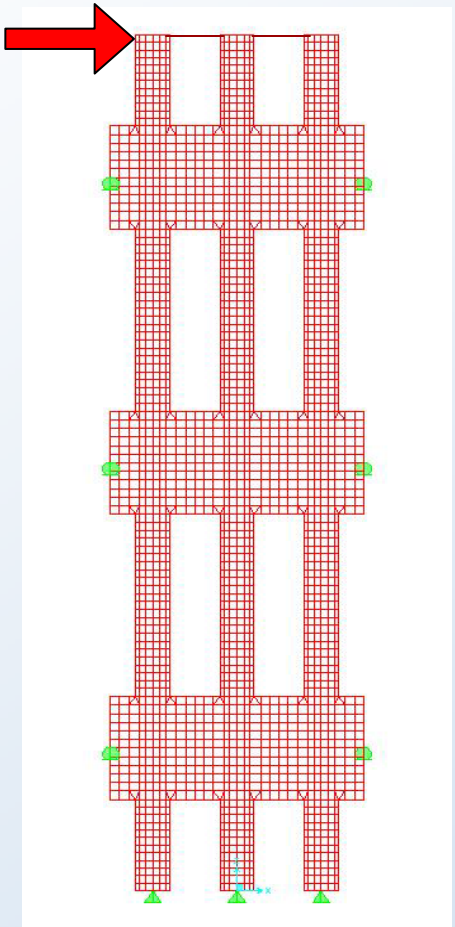
Models include:

- 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

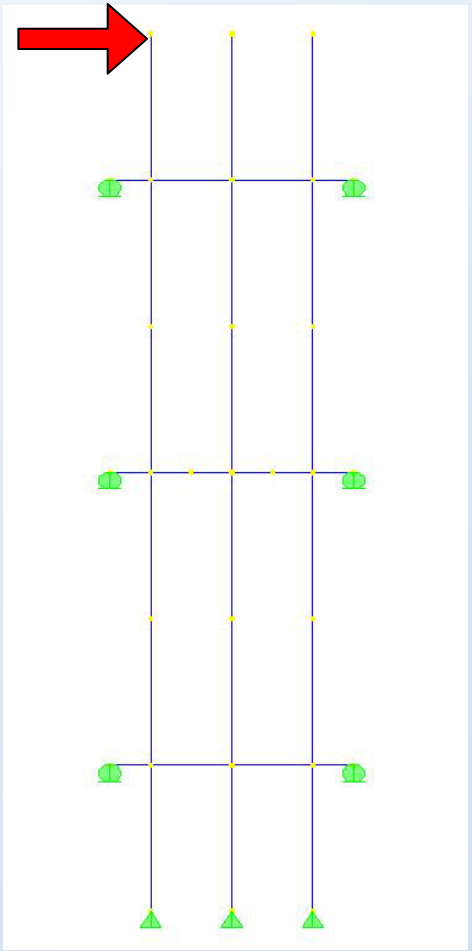


Modeling of Exterior Panels



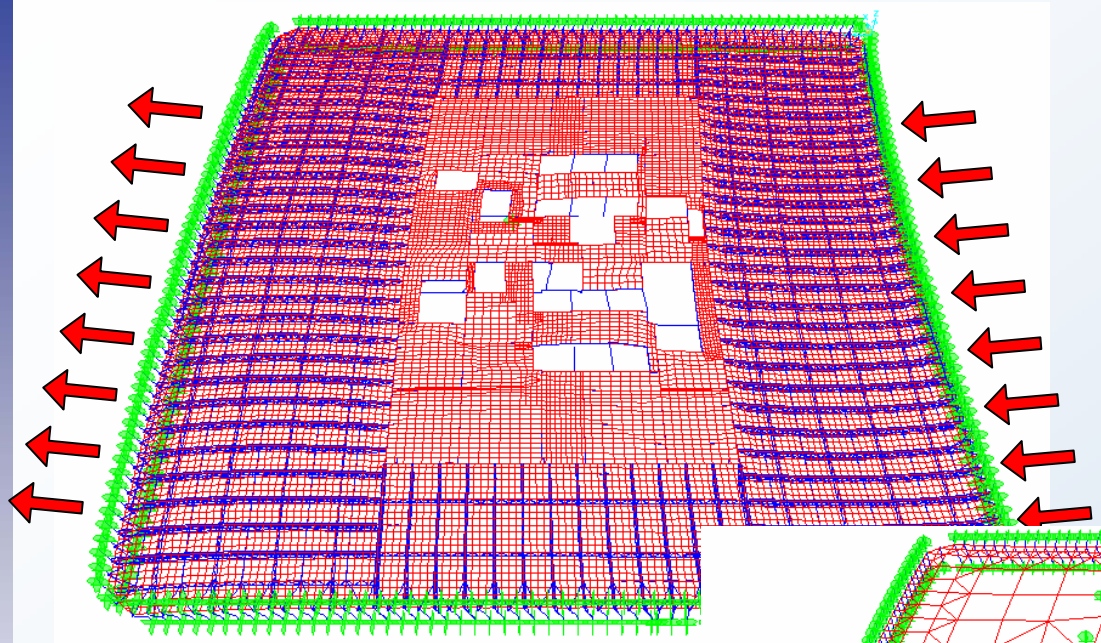


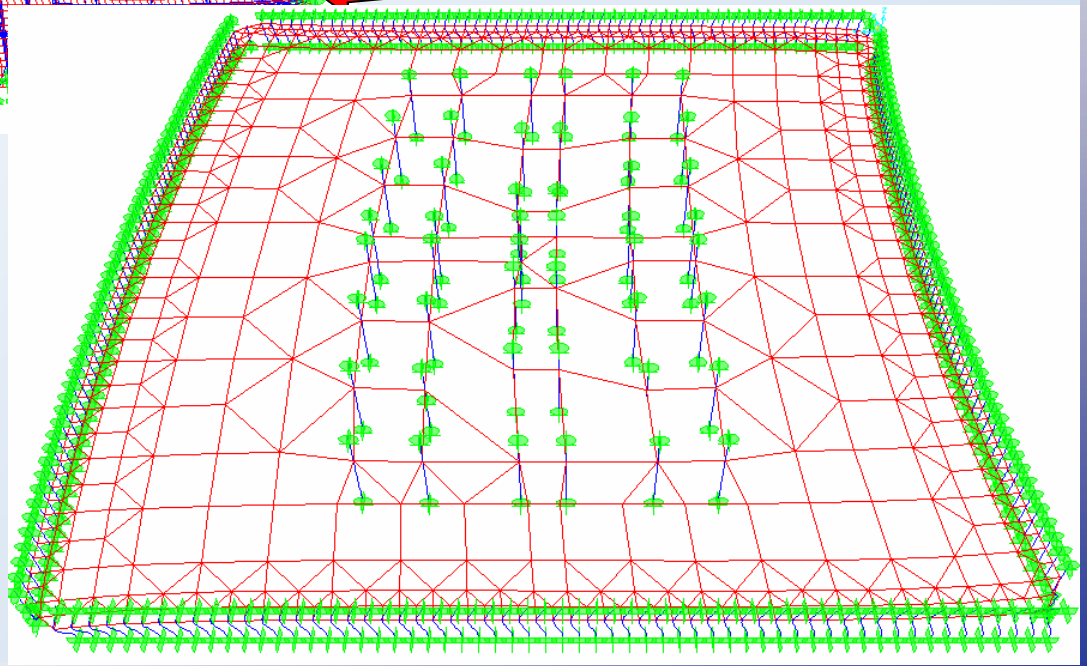
Detailed shell model of exterior panel



Equivalent beam model of exterior panel

Modeling of Floor Diaphragm





Equivalent floor diaphragm to capture the in-plane stiffness of the floor system

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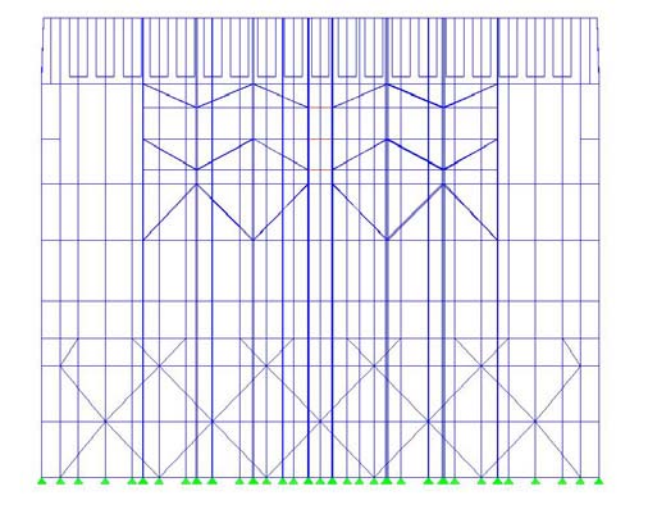
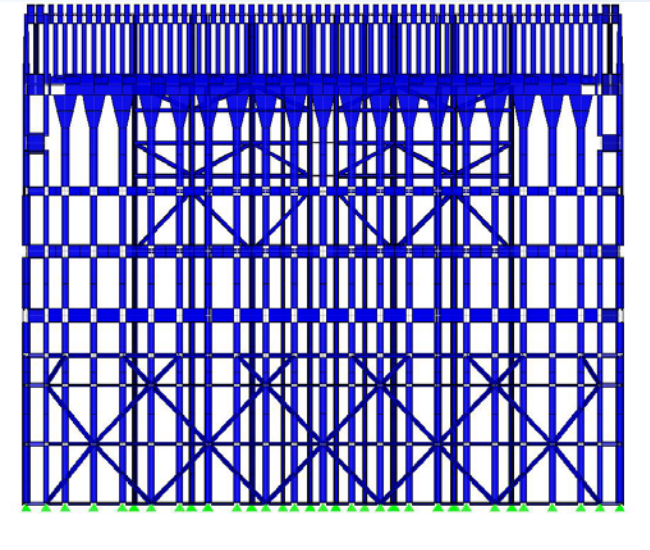
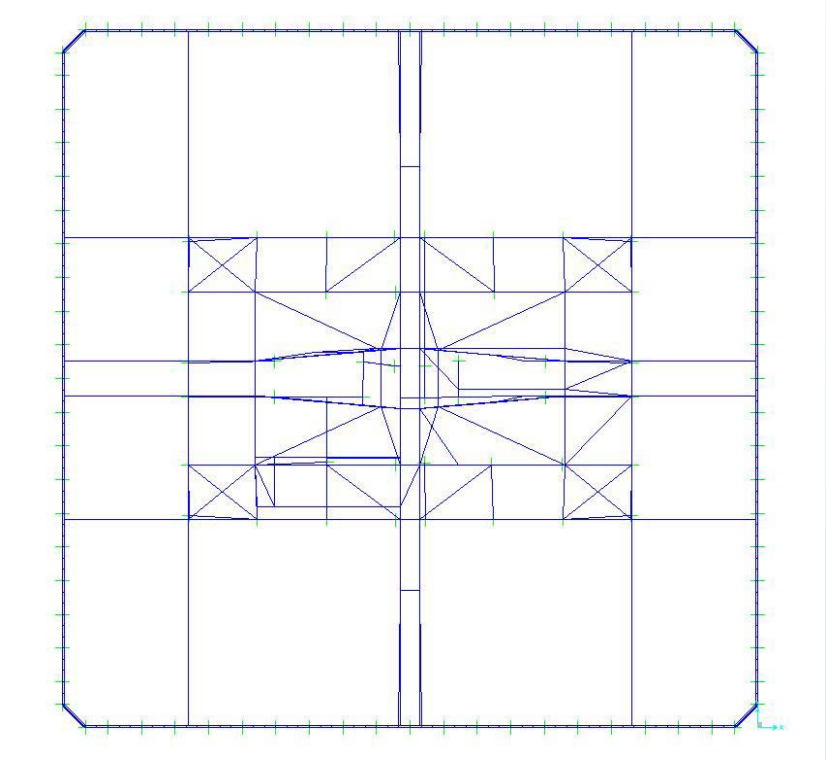
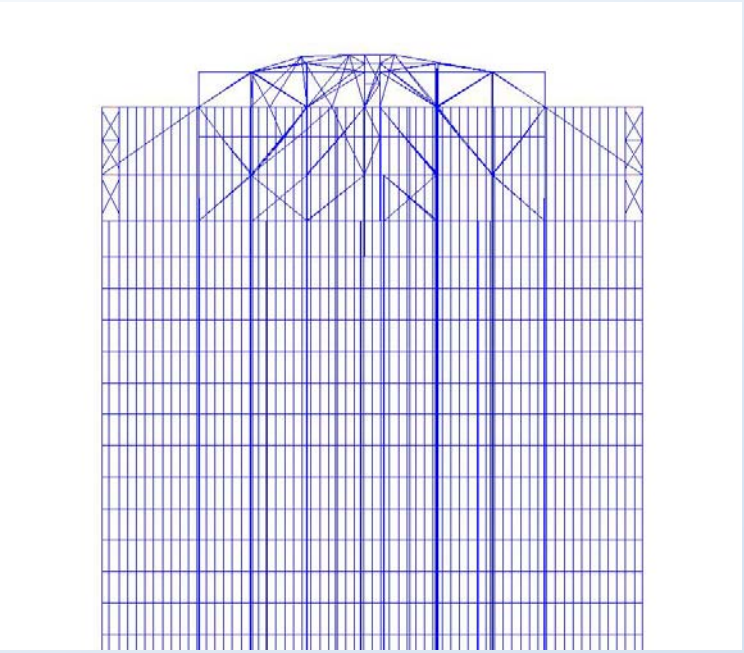
Whole Tower Models: Below Floor 9

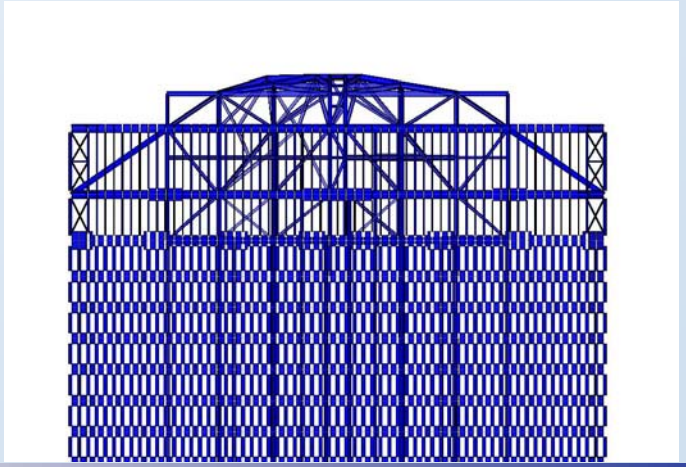




Whole Tower Models: Hat Truss







Structural Models Review and Validation

SOM Third-party Review

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

NIST In-House Review

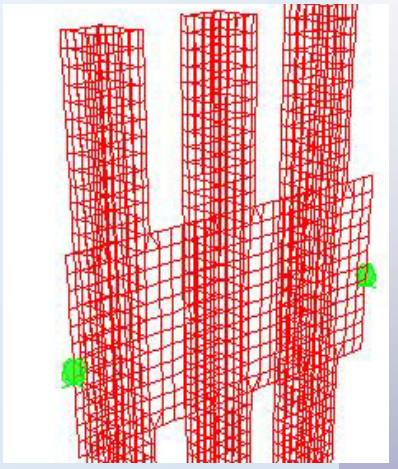
- Consistency with original design
  - Models geometry / cross section properties
  - Material properties
- Verification/validation of models
  - Review assumptions and level of detail
  - Perform analyses using various loading conditions to test the accuracy of the models

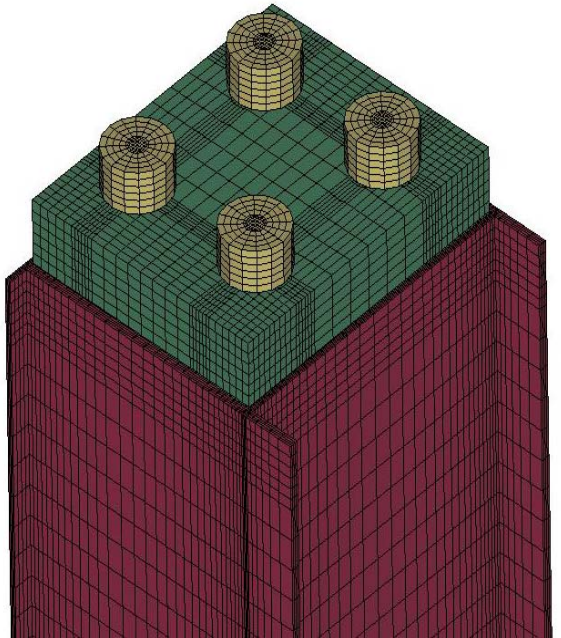
Structural Models Review and Validation

- Conducted workshop for NIST investigators and contractors on October 28, 2003 to review the reference models developed by LERA
  - Workshop Attendees (26 experts):
    - LERA (2 experts)
    - SOM (2 experts): third-party reviewer
    - Teng & Associates (1 expert): outside experts on probable structural collapse
    - Professor Kasper Willam: outside expert on thermal-structural analysis
    - Professor David M. Parks: outside expert on computational mechanics for aircraft impact analysis
    - ARA (2 experts): contractor on analysis of aircraft impact into the WTC towers
    - NIST (17 experts): all key investigators
  - Members of the NCST Advisory Committee invited
  - Minutes of the workshop are being prepared
  - Feedback from workshop will be included in the final review of the models (in progress)

Use of Reference Models in the Investigation

- NIST-approved models will be used as a reference for other significantly more detailed models to be developed in the investigation
  - ❑ Aircraft impact analysis
  - ❑ Thermal-Structural Response
  - ❑ Collapse Initiation Sequence Analysis
- Detailed models should be traceable back to the NIST-approved reference models.





Baseline Performance Analysis

- Conduct linear static, structural analyses of each of the two towers to establish their baseline performance under the following loads:
  - ❑ Gravity loads:
    - Dead loads
    - Live loads used in the original design of the towers
    - Live loads according to either current New York City building code or current ASCE 7 standard
  - ❑ Wind loads:
    - Wind loads used in the original design of the towers
    - Wind loads based on the state-of-the art in wind tunnel testing and extreme climatological information from available data and applicable standards

Baseline Performance Analysis

- Wind loads:
  - Reviewed original estimate of wind effects used in design of WTC towers. The estimates are consistent with the state of the art in wind engineering in the early 1960's: knowledge unavailable at that time for more scientific estimates to be made. Given the significant wind engineering advances made in subsequent years, those estimates can be improved upon now.
  - NIST is comparing the wind loads from wind tunnel tests with loads specified in building codes.
  - NIST has reviewed two sets of wind tunnel tests conducted for the insurance litigation in 2002. Both tests suggest that the wind load effects may be higher than in the original design.

Baseline Performance Analysis

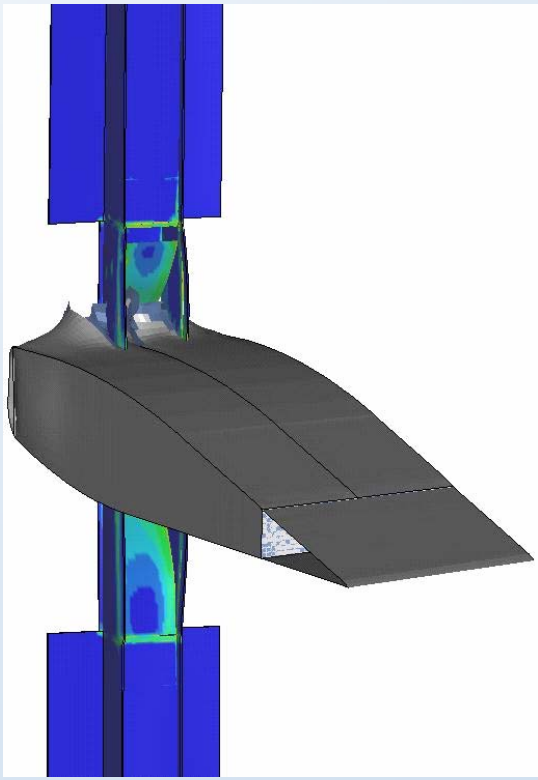
- Wind loads:
  - NIST is developing framework for analyzing effects of wind directionality on structural response to evaluate procedures used in the two 2002 studies.
  - NIST is developing wind loads on the WTC towers based on the two 2002 sets of wind tunnel tests for analysis of baseline performance and comparison with the original wind effects.

Aircraft Impact Analysis: Methodology

- The impact analysis will include the following levels of analyses:
  - ❑ Component Level Analysis
  - ❑ Subassembly Analysis
  - ❑ Global Analysis
  - ❑ Simplified/Approximate Analysis

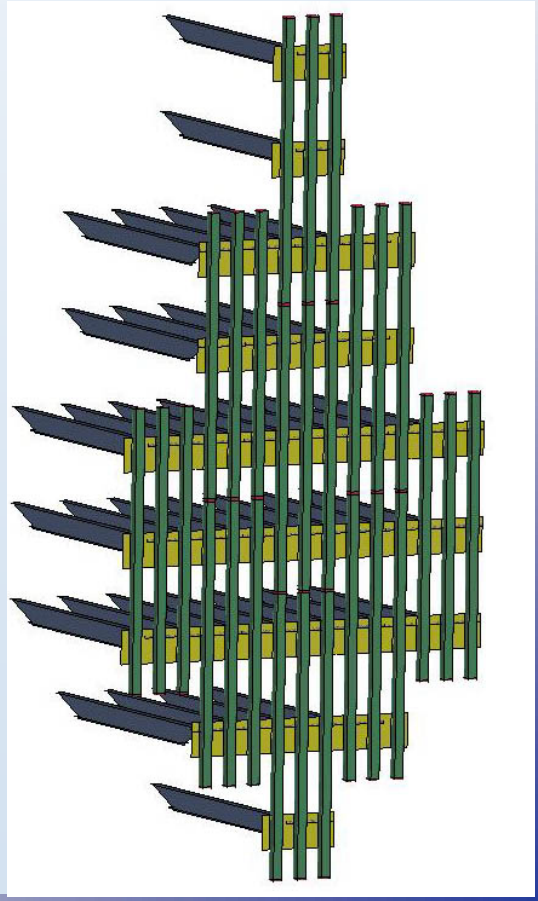
Aircraft Impact Analysis: Methodology

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



Aircraft Impact Analysis: Methodology

- Subassembly analysis:
  - ❑ Analysis of a strip from the exterior wall to the core impacted separately by:
    - A segment of the same width of an aircraft wing
    - An engine
  - ❑ Analysis objectives:
    - Study the interactive failure phenomenon of the aircraft and building components
    - Study sensitivity of damage estimates to various uncertainties
    - Identify the most influential parameters that affect the damage estimates



Aircraft Impact Analysis: Methodology

- Global analysis:
  - ❑ Develop finite element models of the towers:
    - Dense finite element mesh in the impacted floors
    - Coarser mesh below and above impacted floors (up to top of towers)
  - ❑ Develop Boeing 767 aircraft model
  - ❑ Aircraft impact initial conditions
    - Aircraft speed, location of impact, and orientation of aircraft
  - ❑ Examine tower stability after impact

Aircraft Impact Analysis: Methodology

- Simplified/approximate analysis:
  - ❑ Objective:
    - Serves as check on global FE Simulations.
    - Supports the sensitivity and probabilistic analyses.
  - ❑ Approach:
    - Simplified models of aircraft and towers.
    - Aircraft breakup and fragment loading.
    - Evaluation of damage to the tower structure.
    - Debris cloud effects.

Aircraft Impact Analysis: Methodology

- Expected outcomes:
  - ❑ Estimates of the damage to structural systems:
    - Exterior and interior columns: number and location of affected columns:
      - severed, severe damage, moderate damage, light damage
    - Floor systems: floor portions and trusses that have been destroyed
  - ❑ Estimates of deformations and accelerations:
    - Estimates and contours of components of accelerations and deformations, including localized effects, as a function of time.
    - Deformations and accelerations will be compared with the mechanical properties of spray-on fire resistant materials (SFRM) developed in an experimental and analytical study conducted by NIST to estimate the extent of damage to the fire proofing on columns and floor systems.

Aircraft Impact Analysis: Methodology

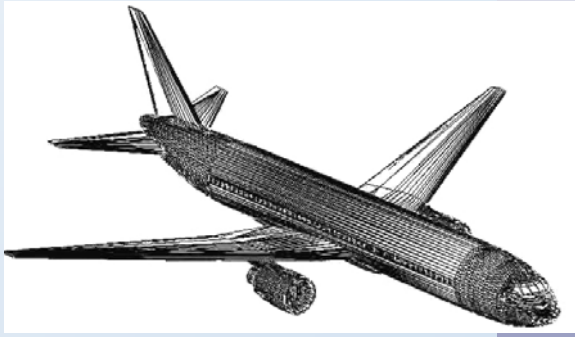
- Expected outcomes:
  - ❑ Estimates of the aircraft fuel dispersal during impact
  - ❑ Estimates of debris field:
    - Database of major fragments of aircraft and destroyed structural components of towers.
      - Spreadsheet format defining mass, approximate size, speed, and trajectory.
      - Trajectory of each fragment consists of initial point of entry, point of exit or resting place.
      - If fragment is deflected dramatically by a building obstruction, its path is broken up into several segments.

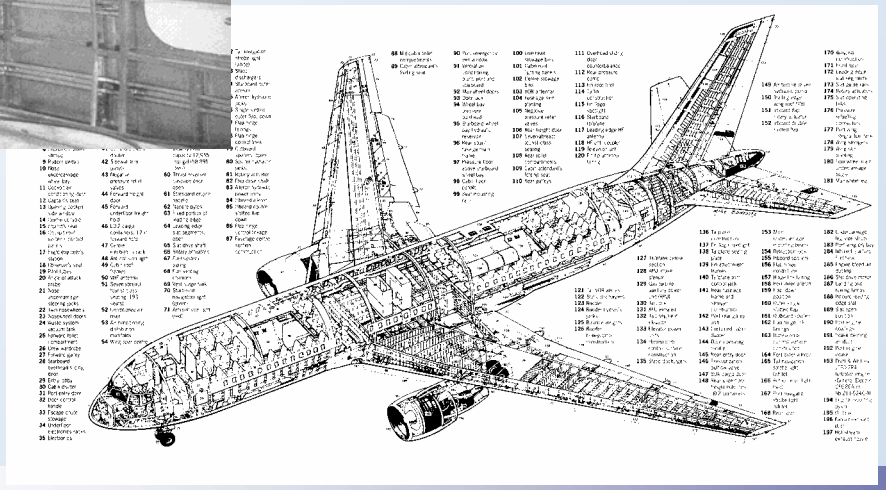
Aircraft Impact Analysis: Methodology

- Probabilistic Assessment:
  - ❑ Objectives:
    - Sensitivity analysis to assess the effects of variability associated with various parameters and identify the most influential parameters that affect the damage estimates
      - Orthogonal factorial design
      - Component level and subassembly analyses
    - Probabilistic analysis to determine the probabilities associated with different damage estimates
      - Event tree and Monte Carlo techniques
      - Global level analysis

Aircraft Impact Analysis: Status

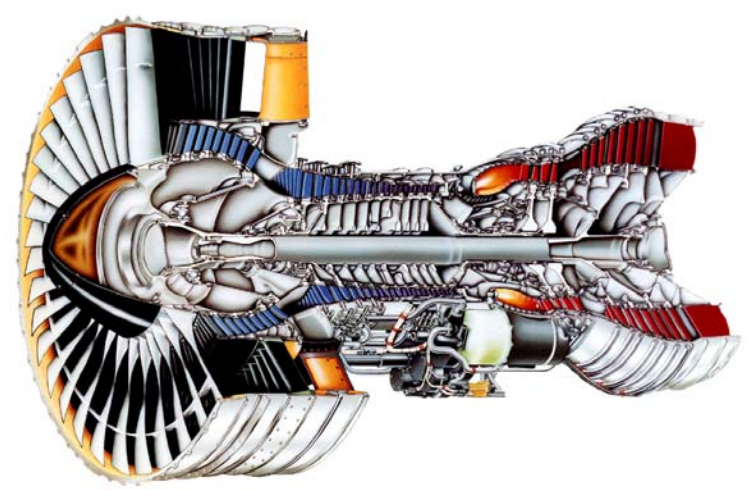
- Aircraft Model Development: Boeing 767-200ER
  - ❑ Documentary aircraft structural information
  - ❑ Data from measurements on 767 aircraft

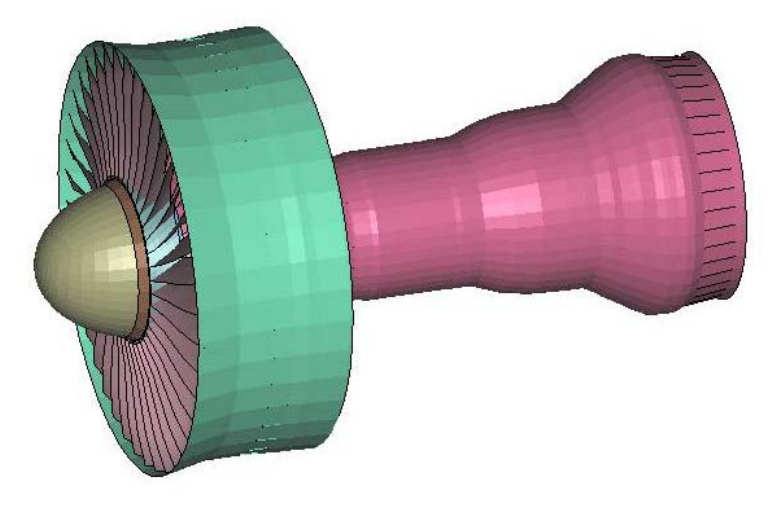




Aircraft Impact Analysis: Status

- Aircraft Engine Model Development

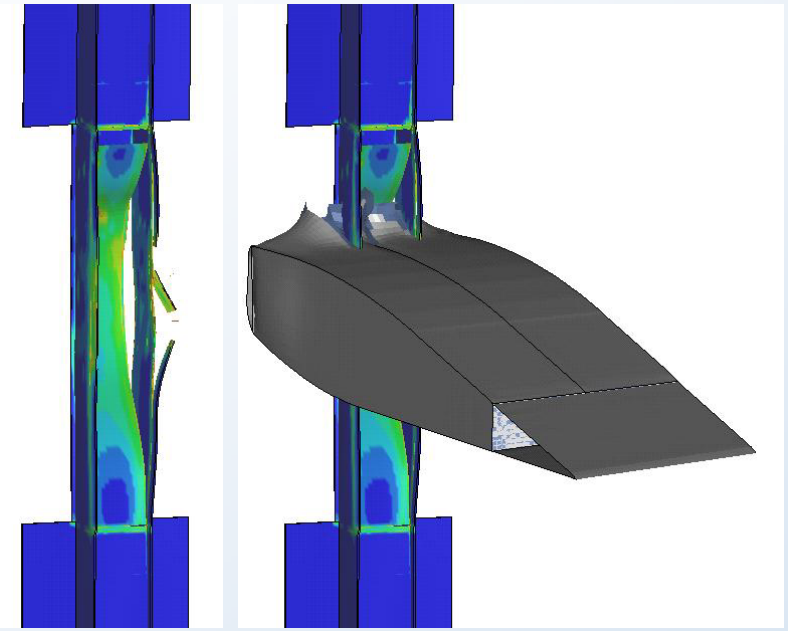




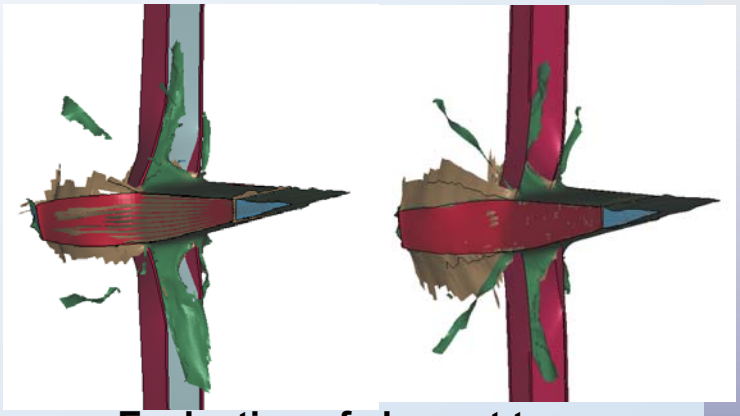
Detailed FE Model

Aircraft Impact Analysis: Status

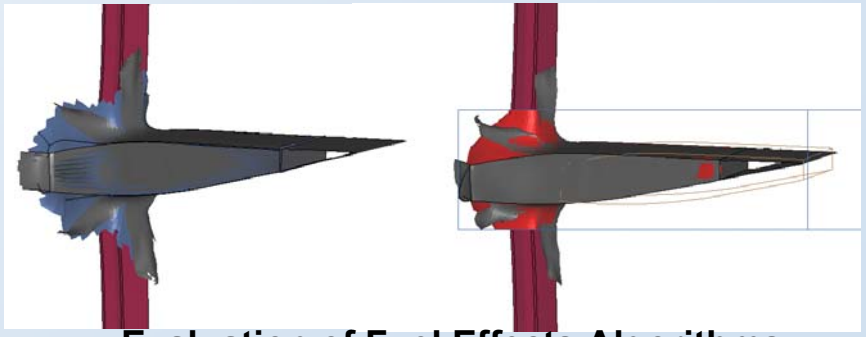
- Component level analyses
  - ❑ Investigate detailed response and modeling approaches



Exterior Column Analyses



Evaluation of element types (shell vs. brick elements)



Evaluation of Fuel Effects Algorithms (Lagrangian vs. Eulerian)

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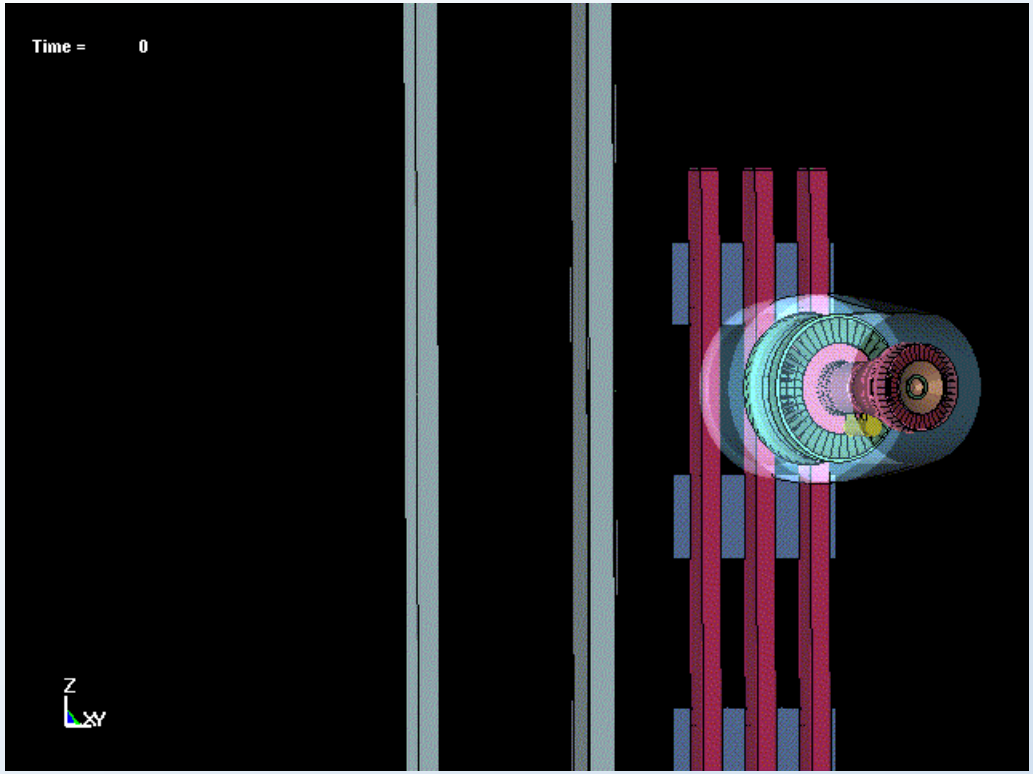
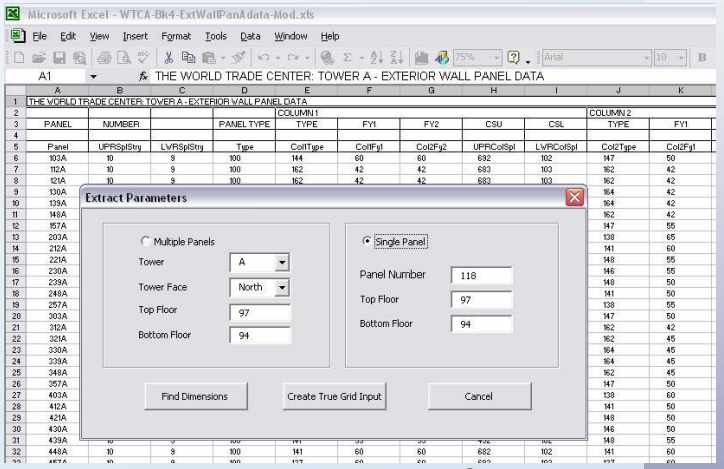
Aircraft Impact Analysis: Status

- Component level analyses: Preliminary engine impact analysis

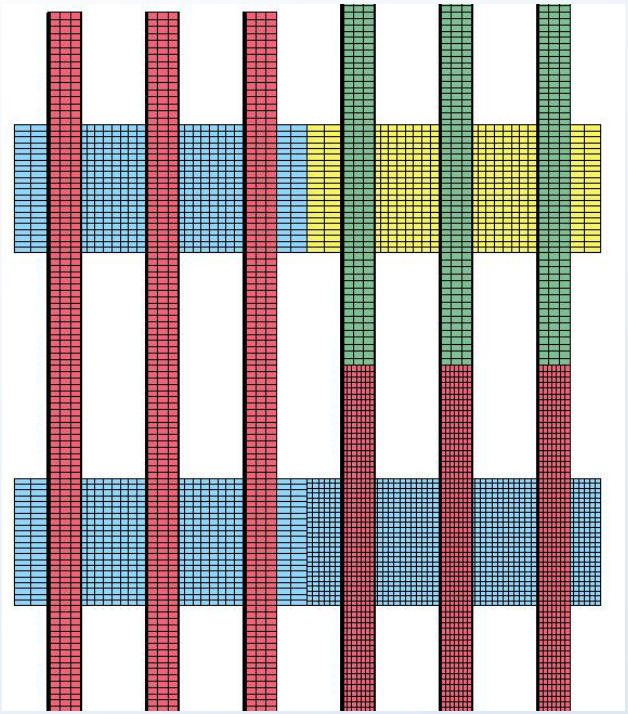


Aircraft Impact Analysis: Status

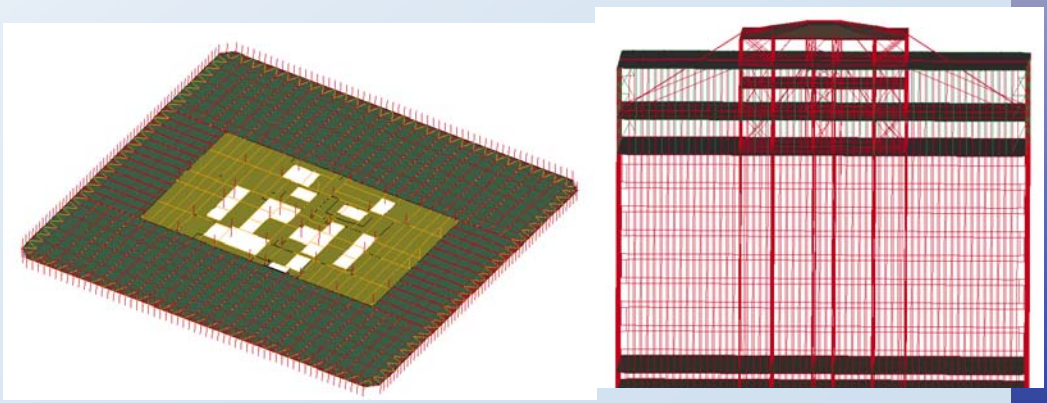
- Tower model development:
  - Using structural databases and reference tower models as a reference
  - Impact analyses have different modeling requirement



Automated extraction from database



Models for multiple panels



Reference models translated to LS-DYNA

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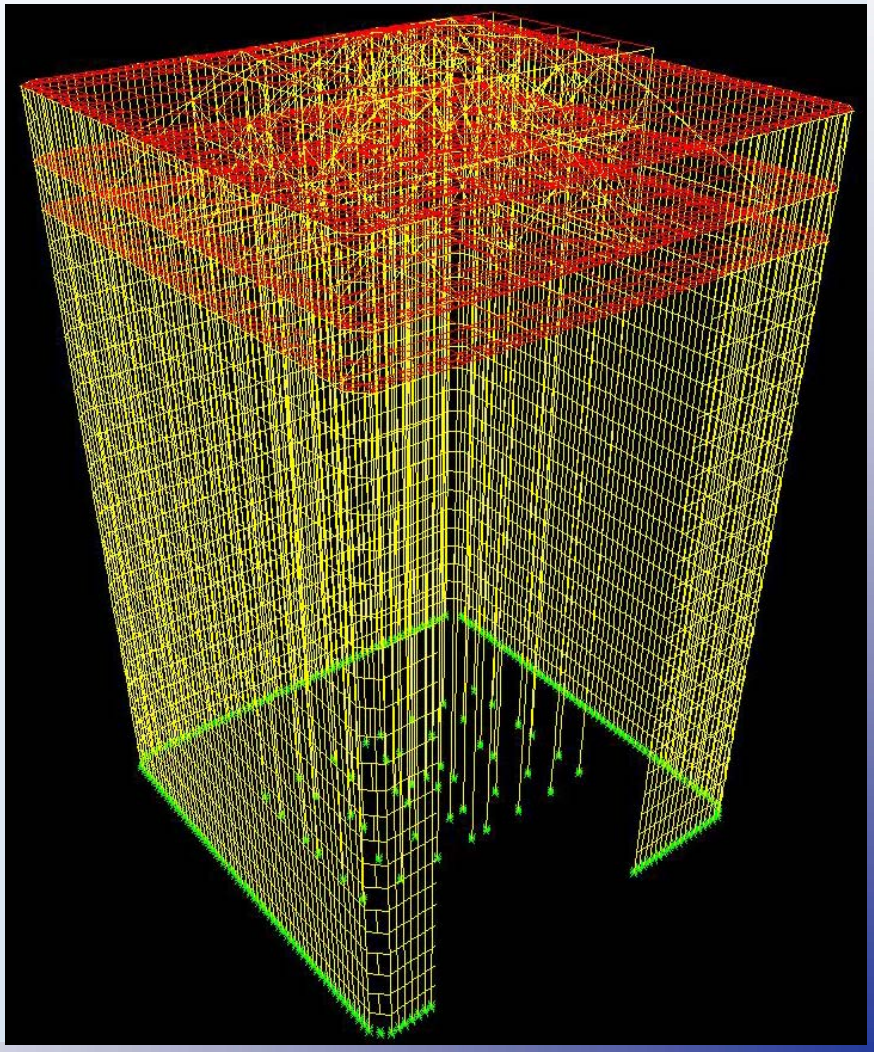
Simplified Stability Analysis of WTC Towers

- How many failed columns are needed to trigger loss of stability? Where do the failed columns need to be located?
- How many floors need to be removed to trigger loss of stability?

Simplified WTC tower models

- Bolted connection between exterior columns represented with equivalent rotational springs
- Load redistribution between columns occurs via hat truss
- Floors below the region of fire and impact (85th floor for WTC 1) represented with equivalent vertical springs
- Gravity loads represent service conditions and are estimated from detailed floor model



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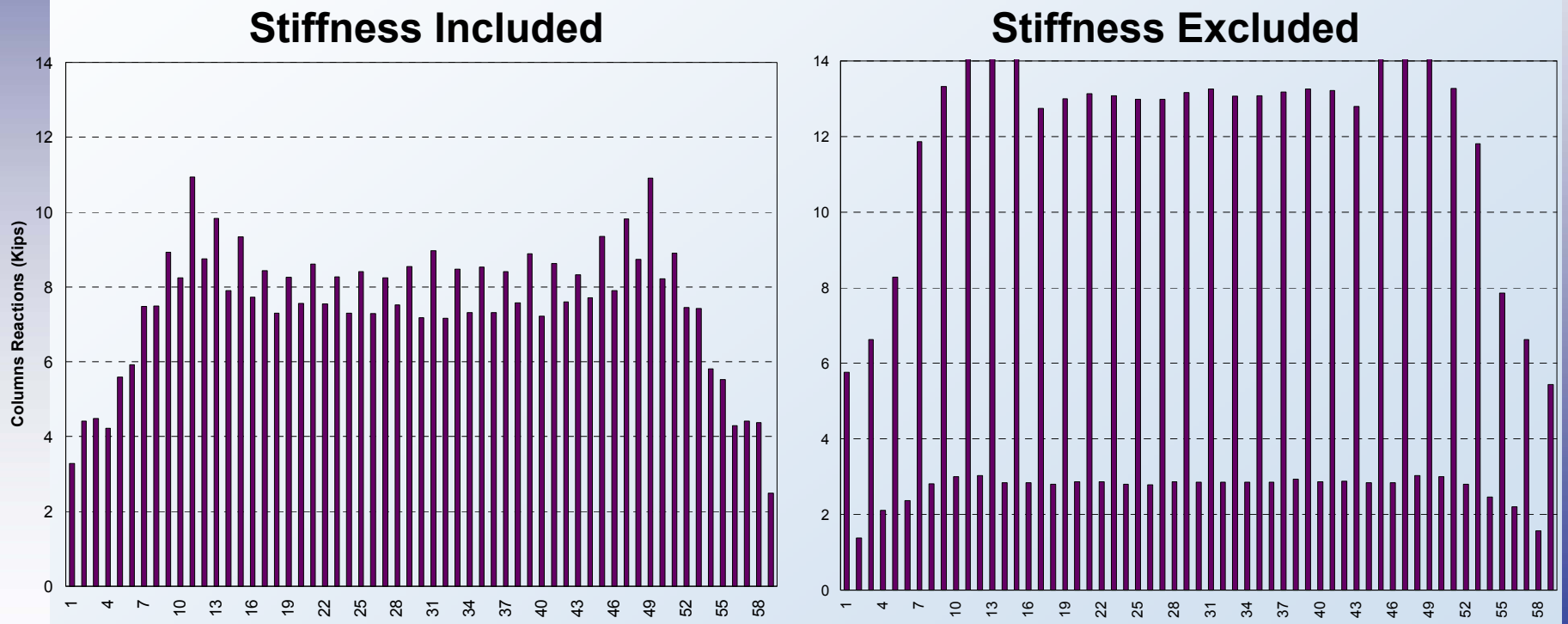
Effect of Spandrel Stiffness

- Spandrel stiffness plays a key role in transferring floor loads to columns and must be included in the model



North wall loads from a single floor

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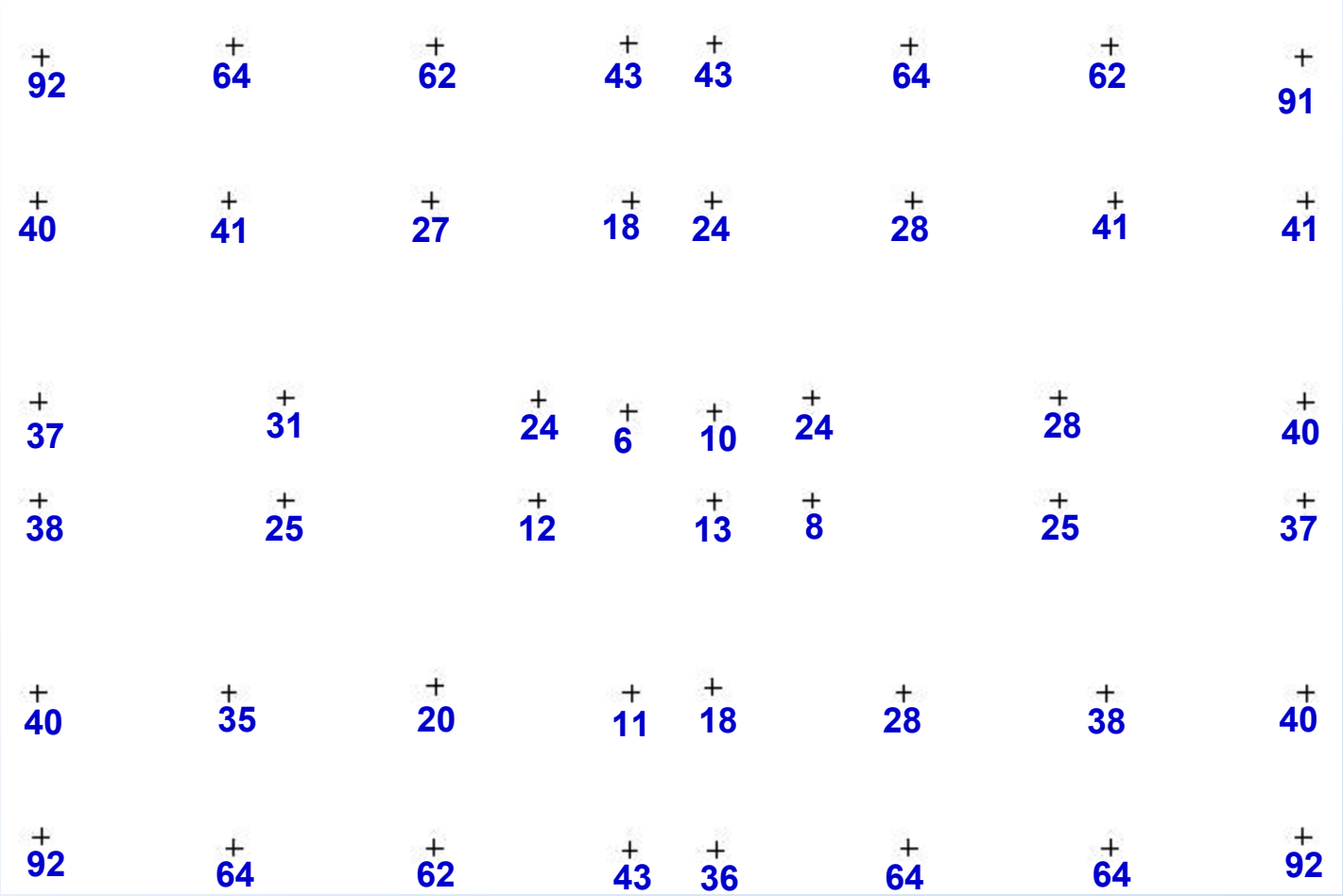
Core Column Loads (Kips) from a Single Floor



Status of Simplified Stability Analysis

Work is ongoing using three methods:

- Linear static demand-capacity analysis based on service loads
- Linear stability analysis to determine critical buckling loads and shapes
- Nonlinear stability analysis accounting for material and geometric nonlinearities

Summary

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