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

Baseline Structural Performance and Aircraft Impact Damage Analysis

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Contributors

- Contractors
  - A team of experts from Leslie E. Robertson Associates **(LERA)**: development of the structural databases, reference structural models, and the baseline performance analysis of the WTC towers.

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  - A team of experts from Skidmore, Owings, and Merrill **(SOM)**: third-party review of the structural databases, reference models, baseline performance analysis, and the refined NIST estimate of the wind loads on the towers.

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Contributors

- Contractors
  - A team of experts from Applied Research Associates **(ARA)**: analysis of aircraft impacts into the WTC towers.

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    Claudia Navarro

  - **Dr. David M. Parks**: provided expertise in the area of computational mechanics for the aircraft impact analysis.

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Contributors

- NIST
  - **Dr. Emil Simiu**: provided the wind engineering expertise required for the development of the wind loads on the WTC towers.
  - **Dr. Michael A. Riley** and **Dr. William P. Fritz** assisted with preliminary stability analyses of the towers. Dr. Fritz participated in the wind study.

Scope of Project

- Baseline Performance
  - Develop reference structural models of the WTC towers.
  - Establish the baseline performance of the towers under design loading conditions (gravity and wind).
- Aircraft Impact Damage
  - Simulate aircraft impacts into the towers to estimate probable damage to structural, mechanical, and architectural systems; and establish the initial conditions for the fire dynamics modeling (Project 5) and thermal-structural response and collapse initiation analysis (Project 6).

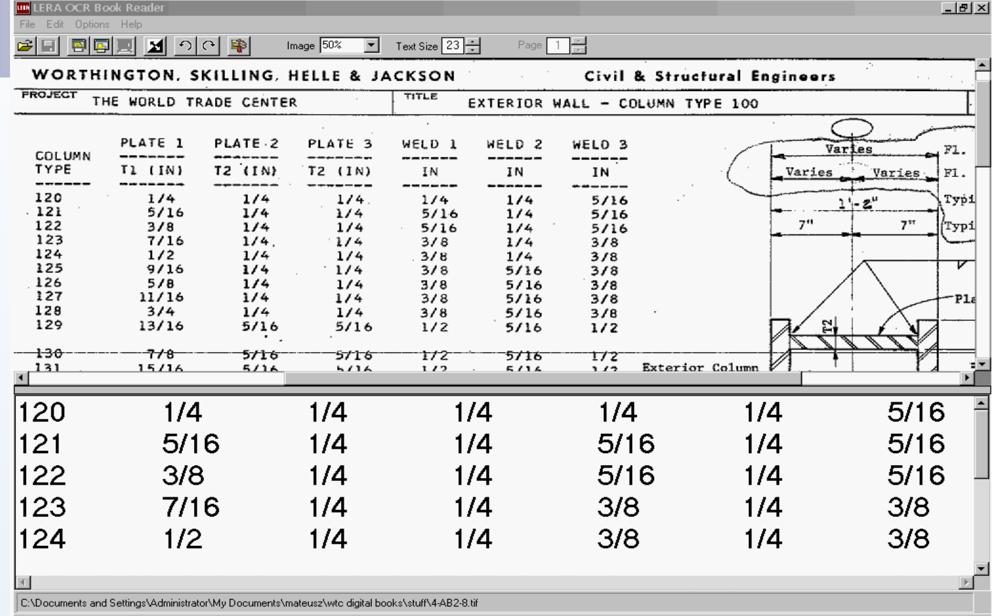
Baseline Performance of the Towers

- Tasks
  - ❑ Develop structural databases of primary structural components for each of the two towers
  - ❑ Develop reference structural models of the WTC towers
    - Typical floor models
    - Global models of the towers
  - ❑ Develop estimates of design wind loads on each of the two towers and evaluate current codes, standards, and practices
  - ❑ Establish baseline performance under wind and gravity loads
    - Demand/capacity ratios for components and connections
    - Total and inter-story drifts (building sway under design wind loads)

Baseline Performance of the Towers

- The baseline performance of the WTC towers under gravity and wind loads was established in order to assess the towers' ability to withstand those loads safely, and to evaluate the reserve capacity of the towers to withstand unanticipated events such as a major fire or impact damage.
- Wind loads were a governing factor in the design of the structural components that made up the frame-tube steel framing system. Wind load capacity is also a key factor in determining the overall strength of the towers and is important in evaluating:
  - The baseline performance of the WTC towers
  - The reserve capacity of the structures to withstand unanticipated events
  - Design practices and procedures that were used
- Accurate estimation of the wind load on tall buildings is a challenging task. The state of knowledge in wind engineering is evolving.

Structural Databases



Steps

- ❑ Scanning and digitization of the original drawing books
- ❑ A four-step quality control procedure
  - First check during OCR process
  - Second check: random, but methodical check by an engineer
  - Third check: ‘cross-check rectify’
    - Programmatically compare with database developed by a consultant of the leaseholder of the towers
  - Final review
- ❑ Cross section property calculations
- ❑ Development of the relational databases, using Microsoft Access, to link the generated database files into a format suitable for the development of the structural global models

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 Review

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

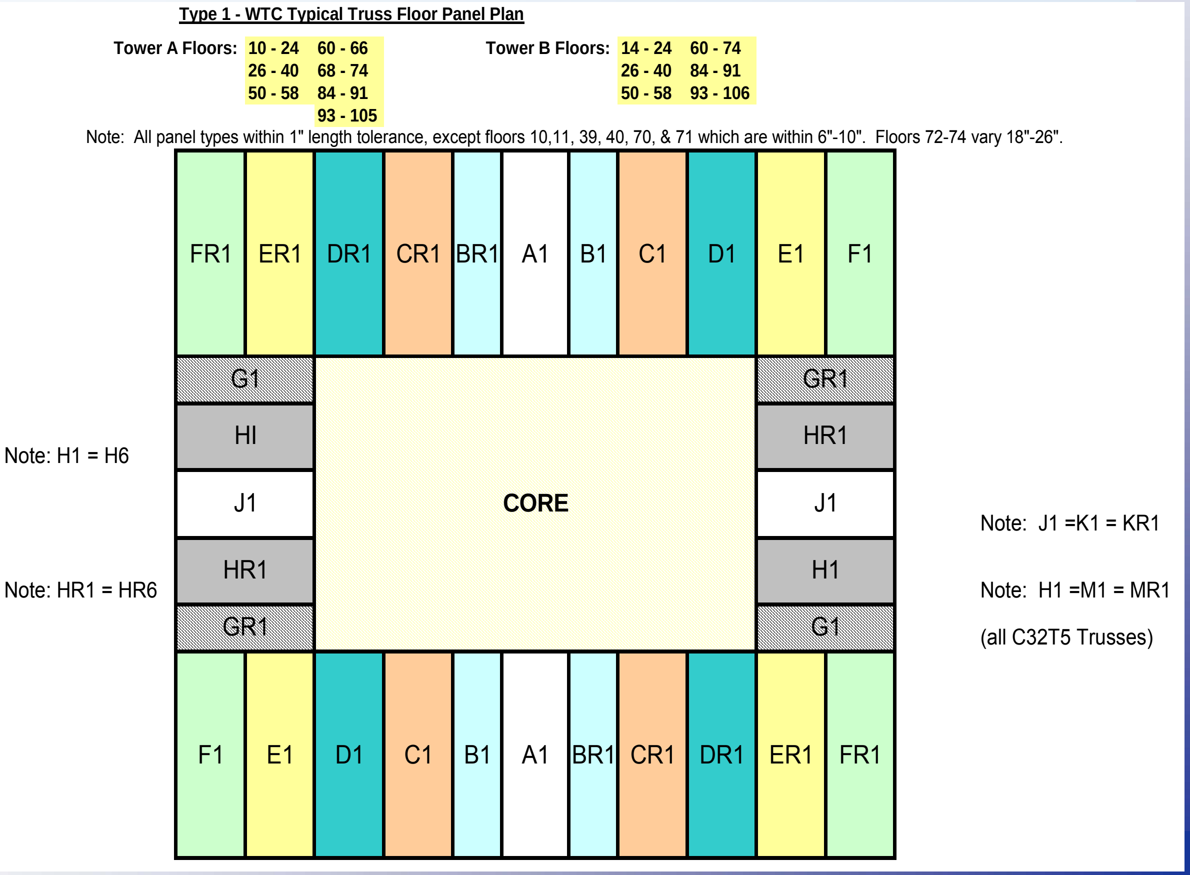
- Task objective: Use structural databases to develop reference, finite element structural models of the towers. Models developed using SAP2000 Version 8, and included:
  - Typical floor models
  - Global tower models
- Models were used:
  - to establish the baseline performance of the towers under design gravity and wind loads
  - as a reference for more detailed models used in the aircraft impact analysis (Project 2) and thermal-structural response and collapse initiation analysis (Project 6)

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)

Typical tenant floor systems



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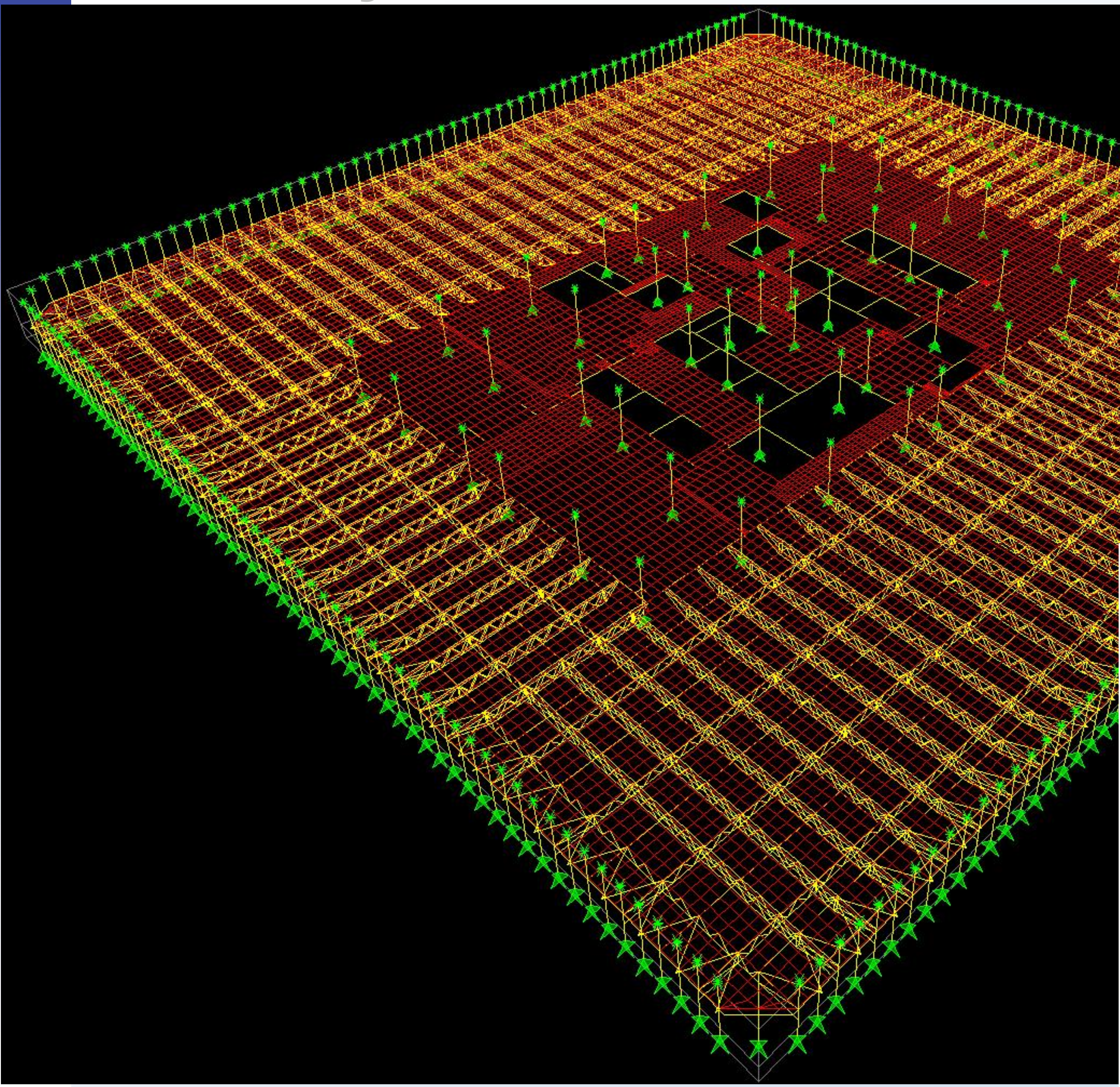
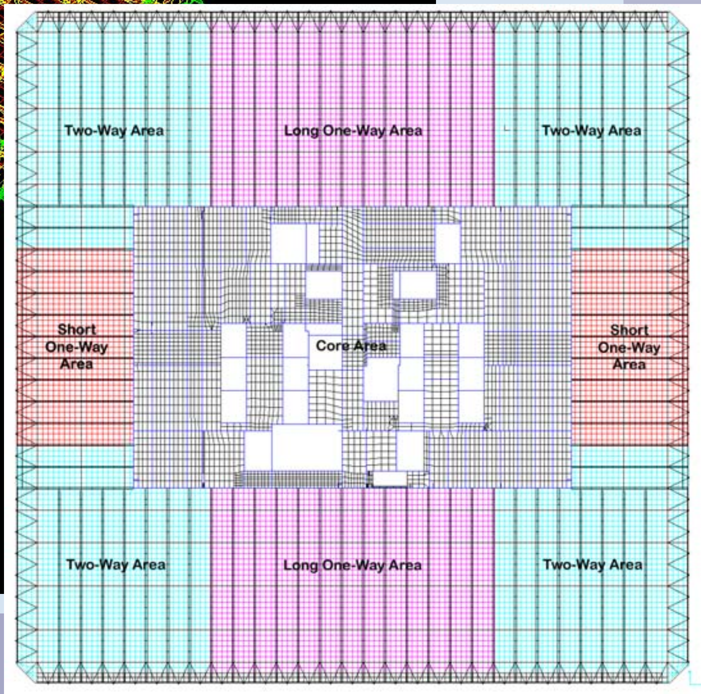
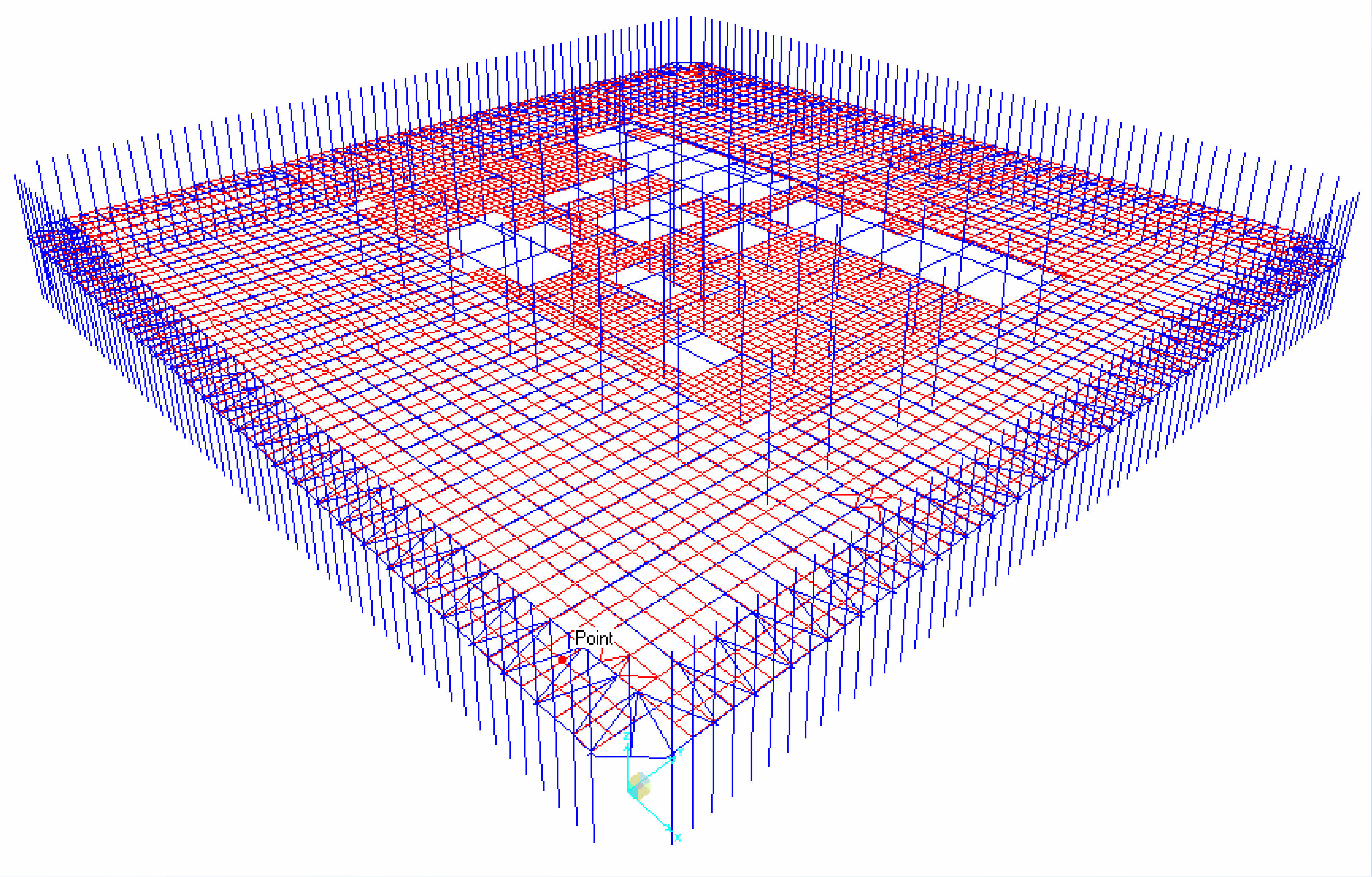
Floor Systems: *Floor 96-A Model*





Floor Systems: *Floor 75-B Model*



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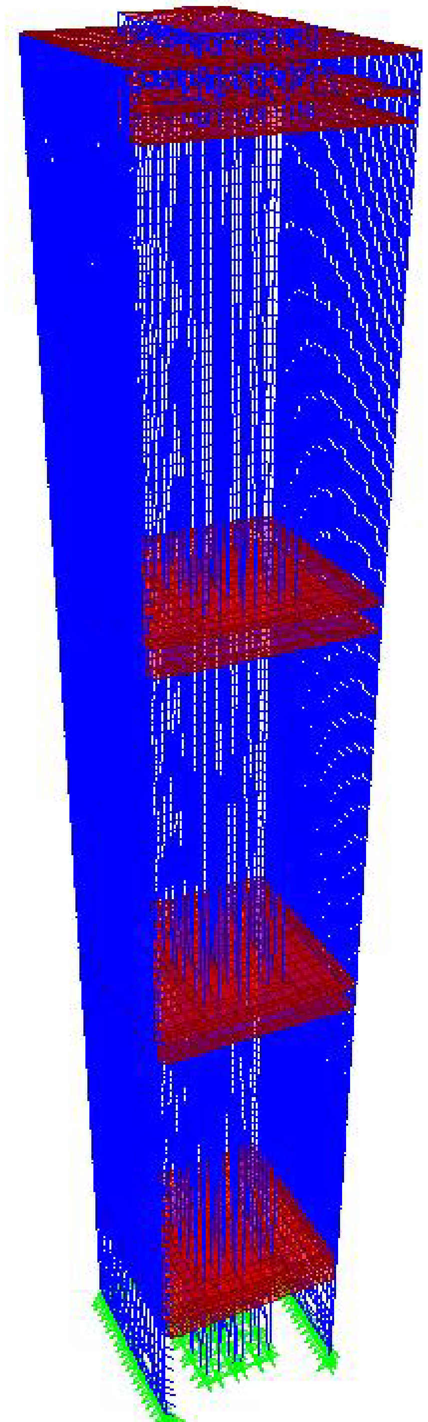
Global Tower Models

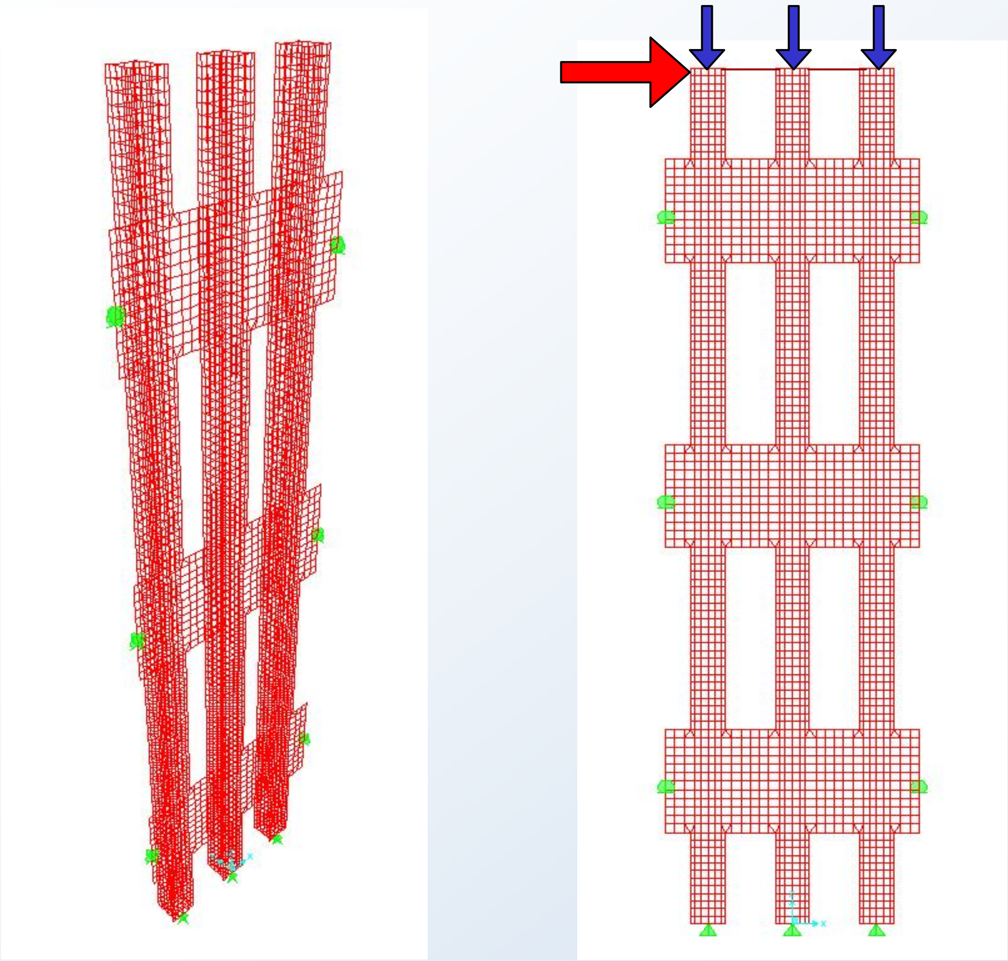
3-D models of the 110-story structure and basement floors of each of the two towers

Models included:

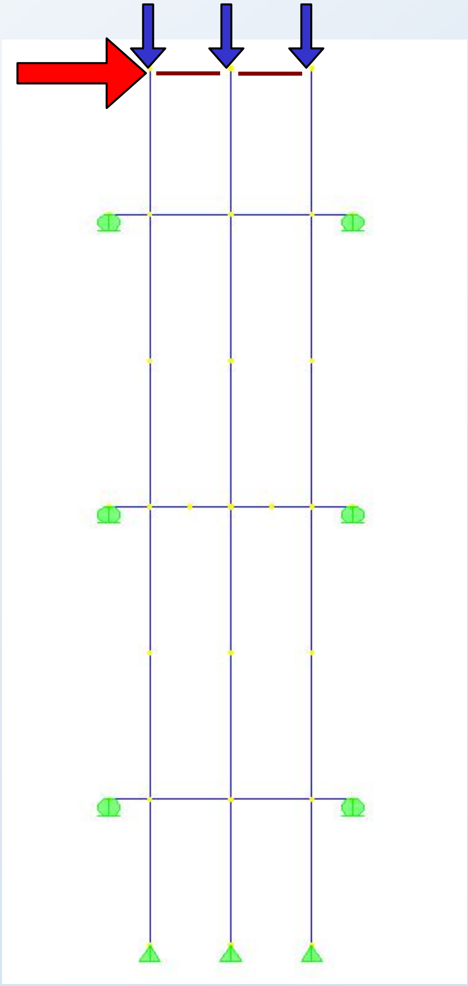
- ❑ Core columns
- ❑ Exterior walls
  - Foundation to floor 7
  - Trees (transition from 3'-4 to 10'-0 col. spacing)
  - Floor 9 to 106
  - Floor 107 to roof
- ❑ Hat truss
- ❑ Rigid floor diaphragms
- ❑ Flexible floor diaphragms



Modeling of Exterior Panels

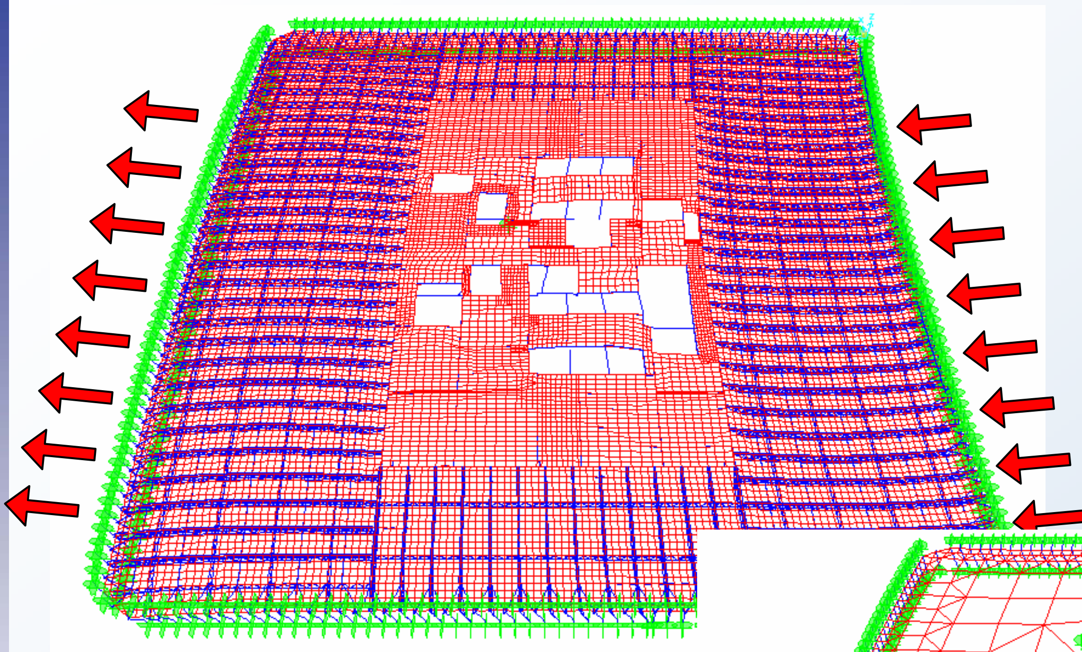


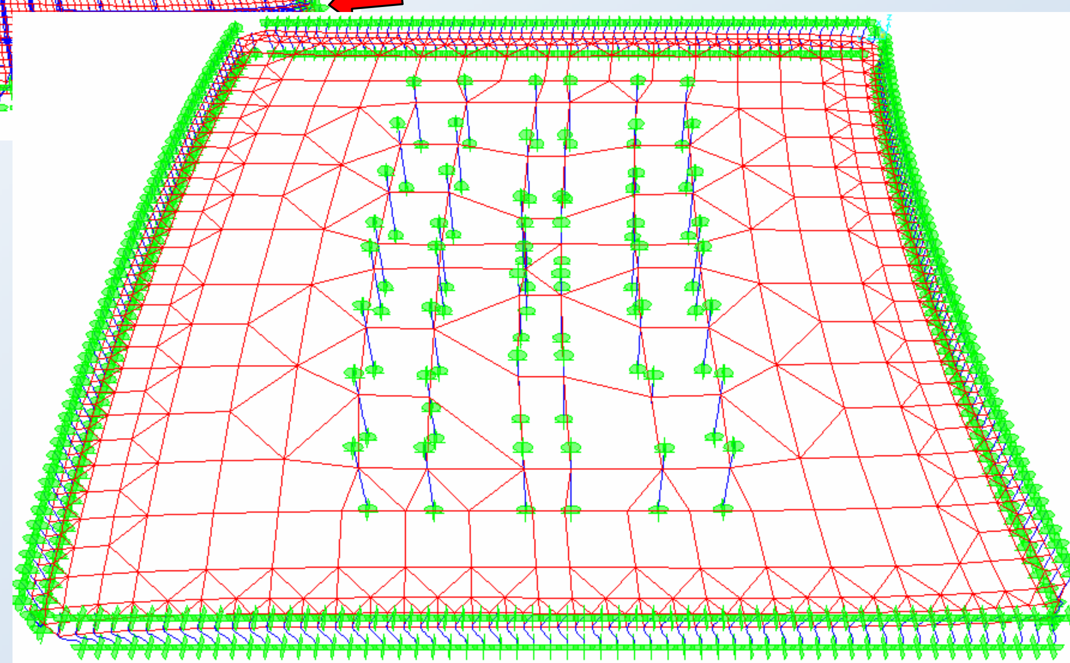
Detailed shell model of an exterior panel



Equivalent beam model of exterior panel

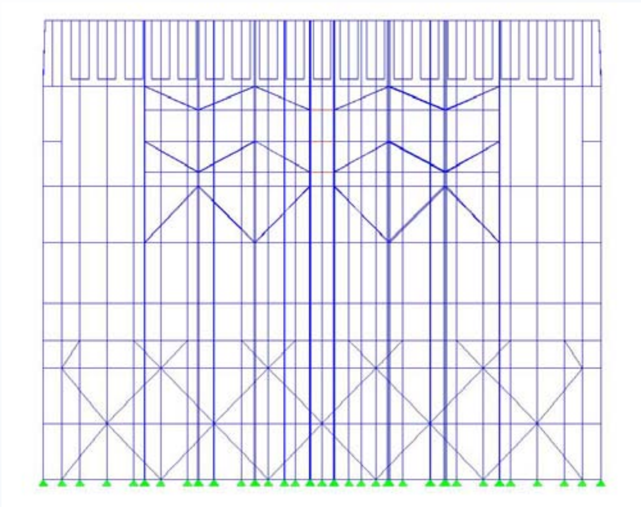
Modeling of Floor Diaphragm

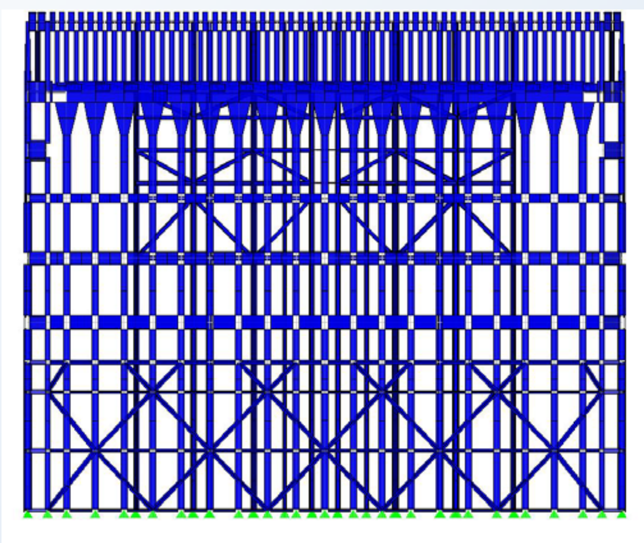




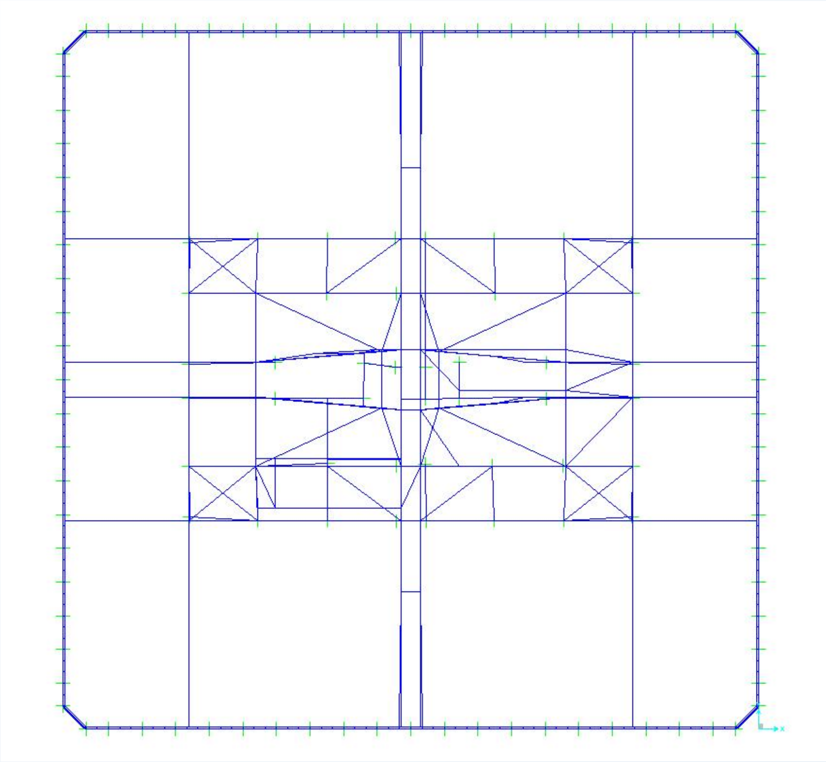
Equivalent floor diaphragm to capture the in-plane stiffness of the floor system

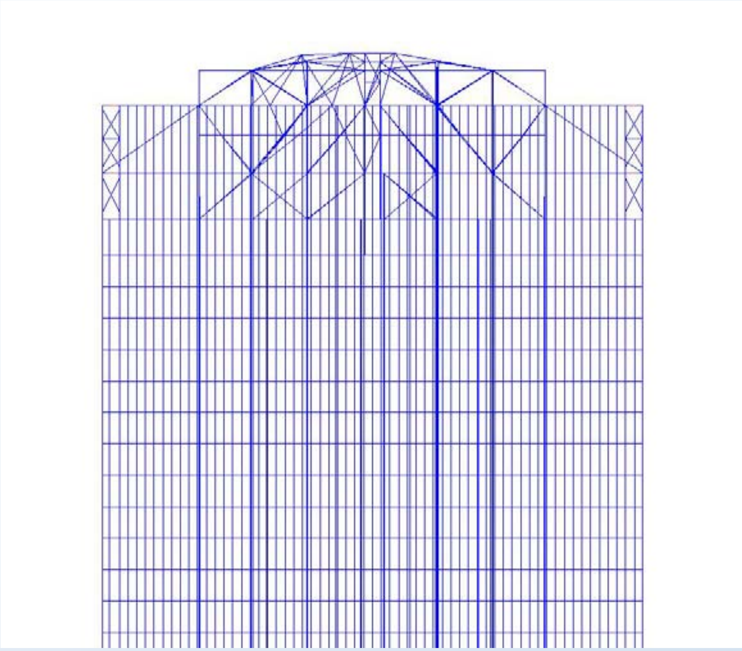
Global Tower Models: Below Floor 9

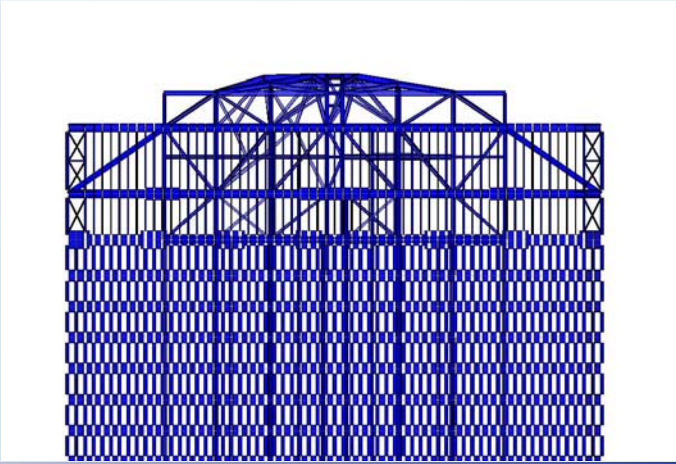




Global Tower Models: Hat Truss







Reference Structural Models

Model	Number of Joints	Degrees of Freedom	Number of Frame Elements	Number of Shell Elements	Total Number of Elements
WTC 1 global model	53,700	218,700	73,900	10,000	83,900
WTC 2 global model	51,200	200,000	73,700	4,800	78,500
Typical truss-framed model	28,100	166,000	27,700	14,800	42,500
Typical beam-framed model	6,500	35,700	7,500	4,600	12,100

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
- ❑ Workshop for NIST investigators and contractors on October 28, 2003 to review the reference models

Review of Reference Structural Models

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

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Calculated frequencies and periods without P-Δ effects for the WTC towers.

Direction of Motion	WTC 1			WTC 2		
	Mode	Frequency (Hz)	Period (s)	Mode	Frequency (Hz)	Period (s)
N–S	1	0.088	11.4	2	0.093	10.7
E–W	2	0.093	10.7	1	0.088	11.4
Torsion	3	0.192	5.2	3	0.192	5.2
N–S	4	0.233	4.3	5	0.263	3.8
E–W	5	0.263	3.8	4	0.238	4.2
Torsion	6	0.417	2.4	6	0.417	2.4

Calculated frequencies and periods with P-Δ effects for the WTC towers.

Direction of Motion	WTC 1			WTC 2		
	Mode	Frequency (Hz)	Period (s)	Mode	Frequency (Hz)	Period (s)
N–S	1	0.083	12.1	2	0.089	11.2
E–W	2	0.088	11.3	1	0.083	12.1
Torsion	3	0.189	5.3	3	0.192	5.2
N–S	4	0.227	4.4	5	0.250	4
E–W	5	0.250	4	4	0.227	4.4
Torsion	8	0.455	2.2	8	0.455	2.2

Comparison of Measured and Calculated Natural Frequencies and Periods of WTC 1

Data Source/ Event Date	Wind Speed & Direction	Frequency (HZ)			Period (s)		
		Direction of Motion			Direction of Motion		
		N-S	E-W	Torsion	N-S	E-W	Torsion
Historical Data							
October 11, 1978	11.5 mph, E/SE	0.098	0.105	0.211	10.2	9.5	4.7
January 24, 1979	33 mph, E/SE	0.089	0.093	0.203	11.2	10.8	4.9
March 21, 1980	41 mph, E/SE	0.085	0.092	0.201	11.8	10.9	5.0
December 11, 1992	-	0.087	0.092	-	11.5	10.9	-
February 2, 1993[1]	20 mph, NW	0.085	0.093	0.204	11.8	10.8	4.9
March 13, 1993[1]	32 mph, NW	0.085	0.094	0.199	11.8	10.6	5.0
March 10, 1994[1]	14 mph, W	0.094	0.094	0.196	10.6	10.6	5.1
December 25, 1994[2]	N	0.081	0.091	-	12.3	11.0	-
Average of Measured Data							
Average	-	0.088	0.094	0.202	11.4	10.6	4.9
Orginal Design - Predicted Values							
Theoretical Value	-	0.084	0.096	-	11.9	10.4	-
Reference Global Model							
LERA/NIST - WTC 1 without P-Delta		0.088	0.093	0.192	11.4	10.7	5.2
LERA/NIST - WTC 1 with P-Delta		0.083	0.088	0.189	12.1	11.3	5.3

Notes:

[1]Reported frequency value is the average of the SW corner, NE corner, and center core frequency measurements.

[2]Reported frequency is based on center core data only.

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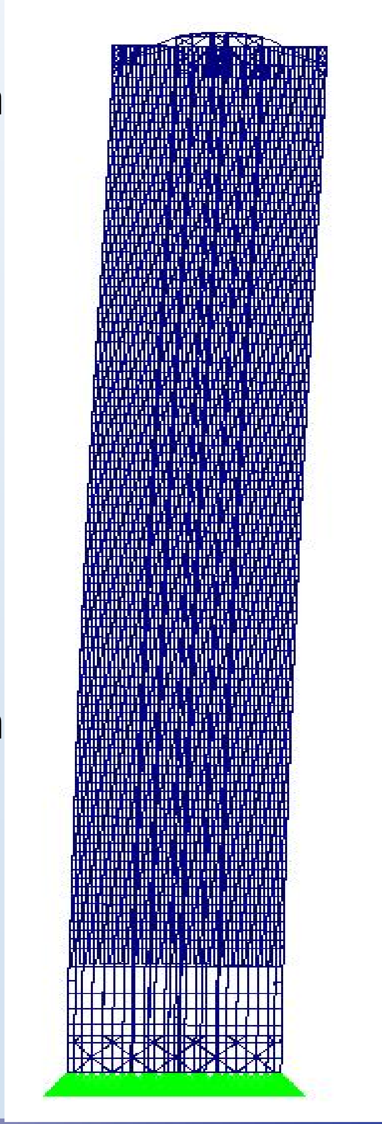
Natural Periods (s)

WTC 1 Analysis

	N-S	E-W	Torsion
Average measured	11.4	10.6	4.9
Theoretical value (original design)	11.9	10.4	--
Reference global model (without P-Δ effects)	11.4	10.7	5.2

WTC 2 Analysis

	N-S	E-W	Torsion
Average measured	--	--	--
Theoretical value (original design)	10.4	11.9	--
Reference global model (without P-Δ effects)	10.6	11.4	5.2



Wind Loading

Wind loads considered included:

- Original WTC design wind loads, 1960’s
- Wind loads based on two recent wind tunnel studies conducted by Cermak Peterka Peterson, Inc. (CPP) and Rowan Williams Davis and Irwin, Inc. (RWDI) for insurance litigation concerning the towers, 2002
- Refined estimates of wind loads 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

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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Comparison of Wind Speeds

Source	Wind Speed (fastest-mile at 33 ft above ground over open terrain)
ASCE 7-02	88 mph
NYCBC	80 mph*
Original WTC design	67 – 75 mph
NIST estimate	96 mph

* This wind speed is assumed to be defined as a fastest-mile speed, even though no such definition is explicitly included in the NYCBC.

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Refined NIST Estimates of Wind Loads

- **Task objective:** to provide estimates of wind-induced forces and moments on the towers, based on considerations related to the state of the art in wind engineering.
- NIST performed 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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Refined NIST Estimates of Wind Loads

- 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

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

- Both RWDI and CPP results indicate that the critical base moments occur for an angle of about 210 degrees.
- NIST 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 took into account a comparison between RWDI and CPP results for WTC 2.

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Refined NIST Estimates of Wind Loads

- 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% $(1.15/1.386 \approx 1/1.205)$.

Refined NIST Estimates of Wind Loads

- 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.

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Sources of Major Differences in Wind Load Estimation Methods Used in Current Practice

- Design wind speed (codes, standards, site-specific estimates)
- Hurricane wind profile (whether or not hurricane wind profiles are flatter than the profiles for extratropical windstorms)
- Estimation of “component” wind effects with a specified mean recurrence interval by integrating wind tunnel data with wind speed and direction information (e.g., up-crossing method, sector-by-sector method, storm passages approach)
- Estimation of “resultant” wind effects using load combination methods (e.g., principle of companion loads, companion point-in-time loads)

Refined NIST Estimates of Wind Loads

- 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 was 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 estimate, state-of-the-practice (SOP) 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).
  - Refined NIST estimate case:
    - Current ASCE 7 Standard (a national standard) live loads
    - Refined wind loads developed by NIST based on considerations related to the current state of the art in wind engineering.

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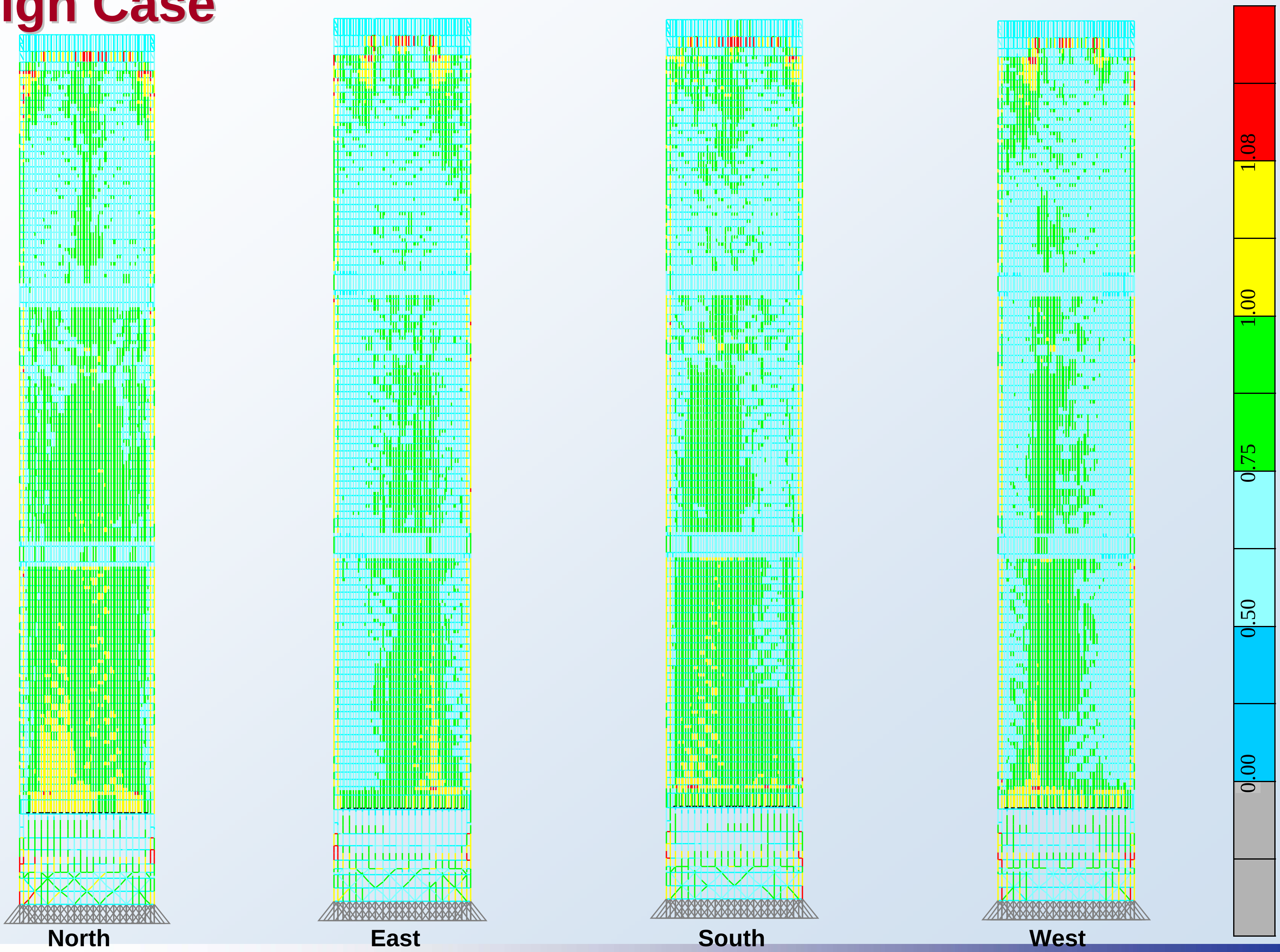
Calculation of Demand-to-Capacity Ratios (DCRs)

- DCRs were estimated using the Allowable Stress Design (ASD) procedure as specified in the American Institute of Steel Construction (AISC) Specification for Structural Steel Buildings – Allowable Stress Design and Plastic Design.

- Load Combinations:
  - Original WTC design loading case and the lower estimate SOP case: AISC Specification (1989) and the NYCBC 2001.
  - The refined NIST estimate case: ASCE 7-02 Standard.

DCRs for Exterior Walls of WTC 1 under Original Design Case



DCRs for Core Columns of WTC 1 under Original Design Case

TOWER A, DCR of CORE COLUMN — 600's COLUMN NUMBER

LEVEL	601	602	603	604	605	606	607	608
106 FL	0.94	1.03	1.29	1.01	1.01	1.05	1.15	0.80
105 FL	1.03	1.10	1.36	1.11	1.09	1.13	1.23	0.92
104 FL	1.12	0.98	1.13	0.94	0.96	0.95	1.12	0.84
103 FL	1.04	1.03	1.18	1.01	1.03	1.01	1.18	0.93
102 FL	1.11	1.08	1.24	1.08	1.09	1.07	1.25	1.02
101 FL	1.19	1.06	1.05	0.88	0.99	1.07	1.05	1.09
100 FL	1.10	1.11	1.10	0.93	1.05	1.13	1.10	1.18
99 FL	1.16	1.16	1.15	0.99	1.10	1.20	1.15	1.27
98 FL	1.23	1.01	0.96	0.96	1.02	1.06	1.00	1.18
97 FL	1.18	1.06	1.00	1.01	1.07	1.12	1.04	1.25
96 FL	1.24	1.10	1.04	1.06	1.12	1.17	1.09	1.33
95 FL	1.31	0.97	0.93	0.98	1.05	1.05	0.96	1.12
94 FL	1.13	1.01	0.96	1.02	1.10	1.09	1.00	1.18
93 FL	1.18	1.04	0.99	1.07	1.14	1.14	1.04	1.24
92 FL	1.23	0.98	0.93	0.83	0.98	1.03	0.98	1.07
91 FL	1.08	1.02	0.95	0.86	1.02	1.07	1.01	1.12
90 FL	1.12	1.05	0.98	0.89	1.05	1.12	1.05	1.17
89 FL	1.17	0.95	0.89	0.93	0.92	1.02	0.94	1.03
88 FL	1.04	0.98	0.92	0.96	0.96	1.06	0.97	1.08
87 FL	1.08	1.01	0.94	1.00	0.99	1.10	1.00	1.12
86 FL	1.12	0.96	0.93	0.87	0.88	1.09	0.99	1.00
85 FL	1.15	0.99	0.95	0.90	0.90	1.13	1.02	1.04
84 FL	1.20	1.01	0.98	0.93	0.93	1.16	1.05	1.08
83 FL	1.25	0.93	0.90	0.96	0.96	0.99	0.96	1.11
82 FL	1.01	0.97	0.93	0.99	0.99	1.02	1.00	1.16
81 FL	1.04	1.02	0.99	1.04	1.03	1.07	1.05	1.21
80 FL	1.08	0.88	0.93	0.72	0.82	1.07	0.86	0.97
79 FL	1.04	0.90	0.96	0.74	0.84	1.09	0.88	1.01
78 FL	1.08	0.92	0.98	0.76	0.87	1.12	0.90	1.05
77 FL	0.76	0.63	0.66	0.62	0.68	0.65	0.66	0.85
76 FL	0.78	0.67	0.70	0.65	0.70	0.68	0.70	0.86
75 FL	0.97	0.84	0.89	0.82	0.91	0.86	0.86	1.00
74 FL	0.97	0.85	0.89	0.82	0.92	0.86	0.86	1.01
73 FL	1.00	0.86	0.91	0.84	0.93	0.88	0.88	1.04
72 FL	1.00	0.83	0.87	0.82	0.85	0.83	0.85	0.99
71 FL	1.03	0.84	0.88	0.83	0.86	0.84	0.86	1.02
70 FL	1.05	0.85	0.90	0.85	0.88	0.86	0.88	1.04
69 FL	0.80	0.78	0.82	0.80	0.84	0.83	0.83	0.86
68 FL	0.84	0.81	0.85	0.84	0.88	0.87	0.87	0.91
67 FL	0.83	0.80	0.85	0.84	0.87	0.86	0.86	0.90
66 FL	0.89	0.82	0.89	0.87	0.89	0.88	0.89	1.07
65 FL	0.90	0.82	0.89	0.87	0.89	0.88	0.89	1.09
64 FL	0.92	0.84	0.92	0.90	0.92	0.90	0.91	1.12
63 FL	0.90	0.81	0.89	0.86	0.88	0.87	0.88	0.99
62 FL	0.91	0.83	0.90	0.88	0.89	0.88	0.89	1.01
61 FL	0.93	0.84	0.92	0.89	0.91	0.89	0.91	1.03
60 FL	0.90	0.81	0.86	0.90	0.87	0.87	0.87	1.05
59 FL	0.91	0.82	0.87	0.91	0.89	0.88	0.88	1.07
58 FL	0.93	0.83	0.88	0.93	0.90	0.89	0.89	1.09
57 FL	0.90	0.81	0.86	0.90	0.87	0.86	0.86	1.05
56 FL	0.92	0.82	0.87	0.92	0.88	0.87	0.87	1.07
55 FL	0.93	0.83	0.88	0.93	0.89	0.88	0.88	1.08
54 FL	0.87	0.81	0.86	0.90	0.91	0.86	0.83	1.04
53 FL	0.88	0.82	0.87	0.91	0.92	0.87	0.84	1.06
52 FL	0.89	0.83	0.88	0.93	0.93	0.88	0.85	1.08
51 FL	0.87	0.81	0.86	0.90	0.90	0.86	0.83	1.04
50 FL	0.89	0.82	0.87	0.91	0.91	0.87	0.83	1.05
49 FL	0.90	0.83	0.88	0.92	0.93	0.88	0.84	1.07
48 FL	0.88	0.81	0.86	0.93	0.90	0.84	0.82	1.03
47 FL	0.89	0.82	0.87	0.94	0.91	0.85	0.83	1.05
46 FL	0.91	0.83	0.88	0.96	0.92	0.86	0.84	1.07
45 FL	0.83	0.77	0.81	0.86	0.84	0.80	0.75	0.92
44 FL	0.85	0.78	0.83	0.89	0.86	0.81	0.77	0.95
43 FL	0.64	0.56	0.60	0.65	0.65	0.61	0.58	0.70
42 FL	0.66	0.56	0.63	0.68	0.68	0.64	0.61	0.72
41 FL	0.85	0.77	0.83	0.88	0.90	0.84	0.81	0.92
40 FL	0.85	0.76	0.82	0.88	0.90	0.84	0.81	0.92
39 FL	0.84	0.77	0.82	0.88	0.88	0.84	0.80	0.90
38 FL	0.85	0.78	0.83	0.90	0.89	0.85	0.81	0.91
37 FL	0.87	0.79	0.84	0.91	0.90	0.86	0.82	0.93
36 FL	0.85	0.78	0.81	0.88	0.87	0.84	0.81	0.91
35 FL	0.86	0.79	0.82	0.89	0.88	0.85	0.82	0.92
34 FL	0.88	0.80	0.82	0.91	0.90	0.86	0.82	0.93
33 FL	0.84	0.77	0.81	0.89	0.87	0.83	0.80	0.92
32 FL	0.85	0.77	0.82	0.90	0.88	0.84	0.81	0.93
31 FL	0.86	0.78	0.83	0.91	0.89	0.85	0.82	0.94
30 FL	0.82	0.77	0.82	0.89	0.87	0.84	0.81	0.92
29 FL	0.83	0.78	0.82	0.90	0.88	0.85	0.82	0.94
28 FL	0.84	0.78	0.83	0.91	0.89	0.86	0.83	0.95
27 FL	0.83	0.77	0.82	0.89	0.88	0.83	0.80	0.93
26 FL	0.84	0.78	0.82	0.90	0.88	0.84	0.81	0.94
25 FL	0.85	0.79	0.83	0.91	0.89	0.85	0.82	0.95
24 FL	0.82	0.78	0.81	0.89	0.88	0.82	0.80	0.94
23 FL	0.83	0.78	0.81	0.90	0.89	0.82	0.81	0.95
22 FL	0.84	0.79	0.82	0.91	0.89	0.83	0.82	0.96
21 FL	0.82	0.78	0.81	0.92	0.88	0.82	0.81	0.94
20 FL	0.83	0.79	0.82	0.93	0.89	0.83	0.82	0.96
19 FL	0.84	0.79	0.83	0.94	0.90	0.83	0.83	0.97
18 FL	0.82	0.78	0.81	0.92	0.88	0.82	0.80	0.93
17 FL	0.83	0.79	0.82	0.93	0.89	0.82	0.80	0.94
16 FL	0.84	0.79	0.83	0.94	0.90	0.83	0.81	0.95
15 FL	0.81	0.77	0.80	0.93	0.90	0.81	0.80	0.93
14 FL	0.82	0.78	0.81	0.93	0.91	0.82	0.80	0.94
13 FL	0.83	0.79	0.82	0.94	0.92	0.82	0.81	0.95
12 FL	0.82	0.78	0.81	0.93	0.90	0.82	0.79	0.94
11 FL	0.83	0.78	0.82	0.94	0.91	0.82	0.79	0.95
10 FL	0.84	0.80	0.83	0.95	0.92	0.84	0.80	0.96
09 FL	0.92	0.76	0.90	1.04	1.01	0.97	0.87	1.03
08 FL	0.92	0.81	0.90	1.04	1.02	0.98	0.87	1.04
07 FL	0.57	0.53	0.56	0.62	0.60	0.60	0.55	0.61
06 FL	0.59	0.55	0.57	0.63	0.62	0.62	0.56	0.62
05 FL	0.59	0.55	0.58	0.64	0.63	0.63	0.57	0.62
04 FL	0.57	0.54	0.56	0.62	0.61	0.61	0.55	0.60
03 FL	0.66	0.61	0.64	0.71	0.70	0.69	0.63	0.69
02 FL	0.69	0.62	0.66	0.74	0.72	0.71	0.64	0.72
01 FL	0.80	0.79	0.82	0.92	0.90	0.88	0.79	0.88
B1 FL	0.79	0.78	0.81	0.91	0.89	0.87	0.79	0.88
B2 FL	0.81	0.79	0.82	0.93	0.90	0.88	0.80	0.89
B3 FL	0.77	0.75	0.81	0.89	0.87	0.87	0.78	0.84
B4 FL	0.79	0.83	0.89	0.99	0.97	0.95	0.86	0.95
B5 FL	0.80	0.83	0.90	1.00	0.98	0.96	0.87	0.96

Line 600

TOWER A, DCR of CORE COLUMN — 900's COLUMN NUMBER

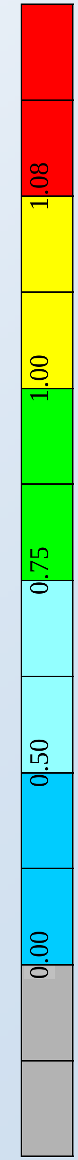
LEVEL	901	902	903	904	905	906	907	908
106 FL	0.76	0.98	0.97	0.80	0.85	1.10	1.02	0.76
105 FL	0.82	1.05	1.02	0.71	0.91	1.16	1.08	0.80
104 FL	0.83	0.95	0.94	1.13	0.75	0.96	0.97	0.80
103 FL	0.92	1.01	0.98	1.21	0.80	1.01	1.02	0.89
102 FL	1.01	1.07	1.03	0.89	0.88	1.05	1.07	0.97
101 FL	0.87	0.96	0.86	0.98	0.78	0.89	0.98	0.84
100 FL	0.94	1.01	0.88	1.04	0.84	0.93	1.03	0.91
99 FL	1.01	1.05	0.91	1.10	0.90	0.97	1.08	0.98
98 FL	1.02	0.92	0.81	0.99	0.88	0.90	0.94	1.00
97 FL	1.09	0.96	0.83	1.05	0.93	0.93	0.98	1.06
96 FL	1.16	1.00	0.86	1.10	0.99	0.97	1.02	1.13
95 FL	0.91	0.84	0.81	0.88	0.86	0.86	0.90	1.08
94 FL	0.96	0.88	0.83	0.92	0.91	0.89	0.94	1.14
93 FL	1.00	0.91	0.85	0.96	0.95	0.92	0.97	1.20
92 FL	0.89	0.86	0.78	0.90	0.90	0.86	0.87	1.04
91 FL	0.93	0.89	0.80	0.94	0.94	0.89	0.90	1.09
90 FL	0.97	0.92	0.82	0.98	0.98	0.92	0.93	1.14
89 FL	1.01	0.84	0.76	0.84	0.84	0.83	0.85	1.00
88 FL	1.05	0.86	0.78	0.87	0.88	0.85	0.88	1.05
87 FL	1.09	0.89	0.80	0.90	0.91	0.88	0.90	1.09
86 FL	0.97	0.85	0.75	0.93	0.78	0.87	0.86	0.97
85 FL	1.01	0.87	0.77	0.96	0.81	0.89	0.88	1.00
84 FL	1.04	0.90	0.79	0.99	0.83	0.92	0.91	1.04
83 FL	1.07	0.79	0.73	0.86	0.79	0.87	0.80	1.07
82 FL	1.11	0.81	0.75	0.89	0.82	0.89	0.82	1.11
81 FL	1.15	0.83	0.77	0.92	0.84	0.91	0.84	1.14
80 FL	1.19	0.86	0.85	0.95	0.87	0.94	0.86	1.19
79 FL	1.25	0.89	0.88	0.99	0.91	0.97	0.89	1.24
78 FL	1.30	0.92	0.90	1.03	0.94	1.00	0.92	1.30
77 FL	0.84	0.67	0.62	0.71	0.60	0.56	0.55	0.88
76 FL	0.85	0.71	0.65	0.73	0.63	0.60	0.60	0.90
75 FL	0.98	0.85	0.84	0.94	0.76	0.85	0.88	1.05
74 FL	0.98	0.85	0.84	0.95	0.77	0.85	0.88	1.06
73 FL	1.01	0.87	0.86	0.97	0.79	0.87	0.90	1.09
72 FL	0.95	0.89	0.79	0.92	0.77	0.82	0.85	1.03
71 FL	0.98	0.91	0.81	0.94	0.79	0.85	0.87	1.06
70 FL	1.00	0.93	0.82	0.96	0.81	0.87	0.88	1.08
69 FL	0.81	0.81	0.79	0.91	0.77	0.82	0.84	0.88
68 FL	0.88	0.87	0.82	0.96	0.82	0.88	0.89	0.95
67 FL	0.86	0.85	0.82	0.96	0.81	0.86	0.87	0.92
66 FL	1.01	0.93	0.85	0.98	0.83	0.88	0.89	1.09
65 FL	1.03	0.93	0.85	0.98	0.83	0.89	0.89	1.11
64 FL	1.06	0.97	0.88	1.02	0.87	0.92	0.92	1.14
63 FL	1.00	0.91	0.83	0.97	0.82	0.94	0.88	1.07
62 FL	1.03	0.93	0.84	0.99	0.84	0.96	0.89	1.10
61 FL	1.05	0.95	0.85	1.01	0.85	0.99	0.91	1.12
60 FL	0.99	0.90	0.83	0.97	0.83	0.93	0.87	1.06
59 FL	1.01	0.92	0.84	0.99	0.85	0.95	0.88	1.08
58 FL	1.03	0.93	0.86	1.01	0.87	0.97	0.90	1.10
57 FL	1.06	0.88	0.84	1.01	0.85	0.93	0.84	1.04
56 FL	1.08	0.90	0.85	1.02	0.86	0.94	0.85	1.06
55 FL	1.10	0.91	0.86	1.04	0.88	0.96	0.87	1.09
54 FL	1.04	0.93	0.84	1.01	0.86	0.91	0.88	1.11
53 FL	1.06	0.94	0.85	1.02	0.87	0.93	0.89	1.13
52 FL	1.08	0.96	0.87	1.04	0.89	0.95	0.91	1.15
51 FL	1.03	0.89	0.85	0.99	0.86	0.97	0.83	1.09
50 FL	1.05	0.90	0.86	1.01	0.87	0.98	0.85	1.11
49 FL	1.07	0.91	0.87	1.03	0.89	1.00	0.86	1.13
48 FL	1.09	0.83	0.83	0.97	0.86	0.89	0.83	1.08
47 FL	1.12	0.85	0.85	0.98	0.87	0.92	0.85	1.11
46 FL	1.14	0.87	0.86	1.00	0.89	0.93	0.87	1.13
45 FL	0.85	0.78	0.77	0.76	0.83	0.84	0.79	0.88
44 FL	0.87	0.80	0.79	0.78	0.85	0.86	0.81	0.90
43 FL	0.75	0.61	0.60	0.69	0.63	0.66	0.62	0.77
42 FL	0.77	0.63	0.63	0.72	0.66	0.68	0.64	0.79
41 FL	1.00	0.85	0.83	0.94	0.86	0.90	0.86	1.00
40 FL	1.00	0.85	0.83	0.94	0.85	0.90	0.86	1.00
39 FL	0.98	0.83	0.84	0.94	0.84	0.89	0.84	1.01
38 FL	1.00	0.84	0.85	0.96	0.85	0.90	0.85	1.02
37 FL	1.01	0.85	0.86	0.97	0.86	0.92	0.86	1.04
36 FL	1.02	0.84	0.85	0.95	0.84	0.90	0.85	1.01
35 FL	1.03	0.85	0.86	0.96	0.85	0.91	0.86	1.03
34 FL	1.05	0.86	0.87	0.97	0.87	0.92	0.87	1.04
33 FL	1.02	0.84	0.85	0.94	0.84	0.90	0.85	1.02
32 FL	1.04	0.85	0.87	0.96	0.85	0.91	0.86	1.03
31 FL	1.05	0.86	0.88	0.97	0.86	0.92	0.87	1.04
30 FL	1.04	0.85	0.86	0.94	0.83	0.91	0.86	1.02
29 FL	1.05	0.86	0.87	0.95	0.84	0.92	0.87	1.03
28 FL	1.06	0.87	0.89	0.96	0.85	0.93	0.88	1.04
27 FL	1.17	0.86	0.87	0.97	0.84	0.91	0.86	1.02
26 FL	1.18	0.87	0.88	0.98	0.85	0.92	0.87	1.03
25 FL	1.07	0.88	0.89	0.99	0.86	0.93	0.88	1.05
24 FL	1.05	0.86	0.88	0.97	0.85	0.91	0.85	1.03
23 FL	1.06	0.87	0.89	0.98	0.86	0.92	0.86	1.04
22 FL	1.07	0.88	0.90	0.99	0.87	0.93	0.87	1.05
21 FL	1.05	0.87	0.89	0.97	0.86	0.92	0.86	1.06
20 FL	1.07	0.88	0.90	0.98	0.87	0.93	0.87	1.07
19 FL	1.08	0.89	0.91	0.99	0.87	0.94	0.88	1.09
18 FL	1.08	0.87	0.88	0.96	0.87	0.92	0.87	1.06
17 FL	1.10	0.88	0.89	0.97	0.88	0.93	0.88	1.08
16 FL	1.11	0.89	0.90	0.98	0.89	0.94	0.89	1.09
15 FL	1.09	0.86	0.89	0.99	0.86	0.93	0.87	1.08
14 FL	1.10	0.87	0.90	1.00	0.87	0.94	0.88	1.09
13 FL	1.11	0.88	0.91	1.01	0.88	0.95	0.89	1.10
12 FL	1.09	0.87	0.90	0.98	0.86	0.94	0.87	1.08
11 FL	1.11	0.88	0.91	0.99	0.87	0.95	0.88	1.09
10 FL	1.13	0.89	0.93	1.01	0.89	0.96	0.89	1.11
09 FL	0.91	0.86	0.89	0.97	0.99	1.03	0.97	1.06
08 FL	0.98	0.91	0.95	1.03	1.00	1.04	0.97	1.06
07 FL	0.63	0.60	0.61	0.62	0.67	0.59	0.59	0.62
06 FL	0.65	0.62	0.63	0.64	0.69	0.61	0.60	0.64
05 FL	0.65	0.63	0.64	0.65	0.70	0.62	0.61	0.64
04 FL	0.63	0.61	0.62	0.63	0.67	0.60	0.59	0.62
03 FL	0.72	0.69	0.71	0.72	0.80	0.68	0.67	0.71
02 FL	0.75	0.71	0.73	0.74	0.83	0.70	0.69	0.74
01 FL	1.07	0.89	0.92	1.01	1.00	0.96	0.90	1.07
B1 FL	1.06	0.88	0.91	1.00	0.98	0.94	0.88	1.06
B2 FL	1.08	0.89	0.92	1.01	0.99	0.96	0.90	1.08
B3 FL	1.02	0.85	0.89	0.97	0.93	0.92	0.86	1.01
B4 FL	1.05	0.87	0.98	1.07	1.05	1.00	0.94	1.13
B5 FL	1.06	0.88	0.99	1.08	1.06	1.01	0.95	1.14

Line 900

TOWER A, DCR of CORE COLUMN — 1000's COLUMN NUMBER

LEVEL	1001	1002	1003	1004	1005	1006	1007	1008
106 FL	0.93	1.12	1.07	0.82	0.95	1.23	1.02	0.96
105 FL	0.99	0.84	1.13	0.91	1.01	0.94	1.11	1.03
104 FL	0.87	1.07	1.01	0.84	0.90	1.10	1.03	0.90
103 FL	0.93	1.15	1.07	0.91	0.95	1.18	1.10	0.95
102 FL	1.00	1.00	1.12	0.98	1.00	1.25	0.97	1.01
101 FL	0.83	1.00	0.93	0.85	0.89	1.03	0.97	0.83
100 FL	0.88	1.06	0.98	0.91	0.93	1.08	1.02	0.89
99 FL	0.93	1.12	1.02	0.96	0.97	1.14	1.08	0.94
98 FL	0.74	0.84	0.89	0.90	0.88	0.78	0.91	0.74
97 FL	0.78	0.89	0.93	0.95	0.92	0.82	0.95	0.78
96 FL	0.82	0.93	0.97	1.00	0.96	0.86	1.00	0.82
95 FL	0.66	0.82	0.75	0.87	0.85	0.76	0.83	0.66
94 FL	0.69	0.86	0.77	0.91	0.88	0.79	0.87	0.70
93 FL	0.72	0.89	0.80	0.95	0.91	0.82	0.90	0.73
92 FL	0.69	0.79	0.72	0.91	0.78	0.74	0.80	0.69
91 FL	0.71	0.82	0.75	0.95	0.80	0.77	0.83	0.72
90 FL	0.74	0.85	0.77	0.98	0.83	0.80	0.86	0.74
89 FL	0.81	0.77	0.66	0.86	0.78	0.70	0.77	0.81
88 FL	0.84	0.79	0.68	0.89	0.80	0.73	0.80	0.84
87 FL	0.87	0.82	0.70	0.92	0.83	0.75	0.83	0.87
86 FL	0.82	0.92	0.76	0.91	0.78	0.81	0.93	0.82
85 FL	0.85	0.95	0.78	0.94	0.81	0.84	0.96	0.85
84 FL	0.87	0.98	0.80	0.97	0.83	0.86	0.99	0.88
83 FL	0.90	0.92	0.74	0.92	0.77	0.81	0.93	0.90
82 FL	0.93	0.95	0.76	0.94	0.79	0.83	0.96	0.93
81 FL	0.96	0.97	0.78	0.97	0.81	0.86	0.98	0.96
80 FL	0.91	1.01	0.70	1.00	0.87	0.88	1.02	0.91
79 FL	0.94	1.04	0.72	1.03	0.89	0.92	1.05	0.94
78 FL	0.98	1.09	0.75	1.08	0.92	0.95	1.10	0.98
77 FL	0.66	0.73	0.65	0.71	0.67	0.68	0.73	0.67
76 FL	0.68	0.74	0.67	0.70	0.72	0.70	0.75	0.68
75 FL	0.88	0.91	0.86	0.93	0.93	0.89	0.92	0.89
74 FL	0.89	0.92	0.86	0.95	0.94	0.90	0.93	0.90
73 FL	0.91	0.94	0.88	0.97	0.95	0.92	0.96	0.92
72 FL	0.87	0.89	0.84	0.91	0.89	0.87	0.91	0.87
71 FL	0.89	0.91	0.85	0.94	0.91	0.89	0.93	0.89
70 FL	0.91	0.93	0.87	0.96	0.93	0.91	0.95	0.91
69 FL	0.84	0.87	0.84	0.92	0.88	0.84	0.88	0.84
68 FL	0.87	0.90	0.87	0.96	0.91	0.87	0.92	0.87
67 FL	0.87	0.91	0.87	0.96	0.91	0.88	0.92	0.88
66 FL	0.91	0.93	0.86	0.99	0.95	0.90	0.95	0.91
65 FL	0.92	0.95	0.87	1.01	0.96	0.92	0.96	0.93
64 FL	0.94	0.97	0.89	1.03	0.98	0.94	0.98	0.94
63 FL	0.91	0.93	0.85	1.01	0.95	0.89	0.93	0.91
62 FL	0.93	0.95	0.86	1.03	0.96	0.91	0.95	0.93
61 FL	0.94	0.97	0.88	1.05	0.98	0.92	0.97	0.95
60 FL	0.91	0.93	0.83	1.01	0.94	0.89	0.93	0.91
59 FL	0.92	0.94	0.84	1.03	0.95	0.91	0.95	0.92
58 FL	0.94	0.96	0.86	1.05	0.97	0.92	0.97	0.94
57 FL	0.92	0.93	0.83	1.02	0.94	0.89	0.93	0.92
56 FL	0.93	0.94	0.84	1.04	0.95	0.90	0.95	0.93
55 FL	0.95	0.96	0.85	1.05	0.97	0.92	0.97	0.95
54 FL	0.89	0.93	0.82	1.03	0.94	0.89	0.93	0.89
53 FL	0.91	0.94	0.83	1.04	0.95	0.90	0.95	0.91
52 FL	0.92	0.96	0.84	1.06	0.96	0.91	0.96	0.92
51 FL	0.90	0.93	0.82	1.00	0.93	0.88	0.93	0.91
50 FL	0.92	0.94	0.83	1.02	0.95	0.89	0.95	0.92
49 FL	0.93	0.95	0.84	1.04	0.96	0.91	0.96	0.93
48 FL	0.89	0.90	0.80	1.01	0.90	0.85	0.89	0.89
47 FL	0.90	0.92	0.81	1.03	0.91	0.86	0.90	0.90
46 FL	0.91	0.93	0.82	1.05	0.93	0.87	0.92	0.91
45 FL	0.83	0.84	0.74	0.96	0.86	0.79	0.82	0.83
44 FL	0.85	0.86	0.76	0.99	0.88	0.81	0.84	0.85
43 FL	0.66	0.65	0.59	0.74	0.68	0.62	0.64	0.66
42 FL	0.68	0.66	0.60	0.75	0.70	0.63	0.65	0.68
41 FL	0.89	0.88	0.80	0.97	0.88	0.83	0.87	0.89
40 FL	0.89	0.88	0.80	0.98	0.89	0.83	0.88	0.90
39 FL	0.88	0.87	0.81	0.99	0.87	0.83	0.86	0.89
38 FL	0.89	0.88	0.82	1.01	0.88	0.84	0.87	0.90
37 FL	0.91	0.89	0.83	1.02	0.89	0.85	0.88	0.91
36 FL	0.89	0.87	0.81	0.97	0.87	0.83	0.85	0.90
35 FL	0.91	0.88	0.82	0.99	0.87	0.84	0.86	0.91
34 FL	0.92	0.89	0.83	1.00	0.88	0.85	0.88	0.92
33 FL	0.88	0.87	0.81	0.98	0.85	0.84	0.86	0.89
32 FL	0.89	0.88	0.82	1.00	0.86	0.85	0.87	0.90
31 FL	0.91	0.89	0.83	1.01	0.87	0.86	0.88	0.91
30 FL	0.90	0.85	0.79	0.99	0.85	0.84	0.84	0.90
29 FL	0.91	0.86	0.80	1.01	0.86	0.85	0.85	0.91
28 FL	0.92	0.87	0.81	1.02	0.87	0.86	0.86	0.92
27 FL	0.89	0.85	0.80	1.00	0.85	0.84	0.84	0.89
26 FL	0.90	0.86	0.81	1.01	0.86	0.85	0.85	0.90
25 FL	0.91	0.87	0.82	1.02	0.87	0.86	0.86	0.91
24 FL	0.88	0.85	0.80	0.99	0.85	0.84	0.84	0.88
23 FL	0.89	0.86	0.81	1.00	0.86	0.85	0.85	0.89
22 FL	0.90	0.87	0.82	1.01	0.87	0.86	0.86	0.90
21 FL	0.88	0.85	0.81	1.00	0.85	0.84	0.84	0.88
20 FL	0.89	0.86	0.81	1.01	0.86	0.85	0.85	0.89
19 FL	0.89	0.87	0.82	1.02	0.86	0.86	0.86	0.90
18 FL	0.87	0.85	0.81	1.01	0.84	0.83	0.84	0.87
17 FL	0.88	0.86	0.82	1.02	0.84	0.84	0.85	0.88
16 FL	0.89	0.87	0.83	1.03	0.85	0.85	0.86	0.89
15 FL	0.87	0.85	0.81	1.00	0.84	0.83	0.85	0.87
14 FL	0.88	0.86	0.82	1.01	0.85	0.84	0.85	0.88
13 FL	0.89	0.87	0.83	1.02	0.85	0.85	0.86	0.89
12 FL	0.88	0.85	0.82	1.01	0.84	0.84	0.85	0.88
11 FL	0.89	0.86	0.82	1.02	0.85	0.85	0.86	0.89
10 FL	0.90	0.87	0.84	1.04	0.86	0.86	0.87	0.90
09 FL	0.96	0.84	0.81	0.98	0.80	0.84	0.90	0.89
08 FL	0.96	0.87	0.85	1.03	0.83	0.87	0.91	0.93
07 FL	0.79	0.73	0.73	0.87	0.73	0.74	0.75	0.79
06 FL	0.80	0.74	0.74	0.88	0.74	0.76	0.76	0.81
05 FL	0.81	0.75	0.75	0.89	0.74	0.76	0.77	0.81
04 FL	0.79	0.73	0.73	0.86	0.73	0.74	0.75	0.79
03 FL	0.86	0.79	0.79	0.94	0.78	0.80	0.81	0.86
02 FL	0.88	0.80	0.80	0.96	0.79	0.81	0.82	0.88
01 FL	0.84	0.83	0.79	0.95	0.83	0.81	0.83	0.84
B1 FL	0.83	0.82	0.78	0.94	0.83	0.80	0.82	0.83
B2 FL	0.84	0.83	0.79	0.95	0.84	0.81	0.83	0.84
B3 FL	0.86	0.82	0.79	0.92	0.81	0.82	0.80	0.87
B4 FL	0.92	0.83	0.85	0.99	0.86	0.83	0.86	0.88
B5 FL	0.93	0.83	0.85	1.00	0.86	0.83	0.86	0.88

Line 1000



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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	121*	1.31
Lower Estimate SOP Case	0.78	2	0.9	281*	1.44
Refined NIST Estimate 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 Estimate SOP Case	0.32	0	0	0	0.80
Refined NIST Estimate Case	0.52	0.5	0.3	109	1.32
Core Columns					
Original WTC Design Loads	0.86	10	5.3	278	1.36
Lower Estimate SOP Case	0.86	9.9	5.3	278	1.36
Refined NIST Estimate 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 Estimate SOP Case	0.45	0.4	0.4	1	1.26
Refined NIST Estimate Case	0.53	3.8	0.8	2	1.26

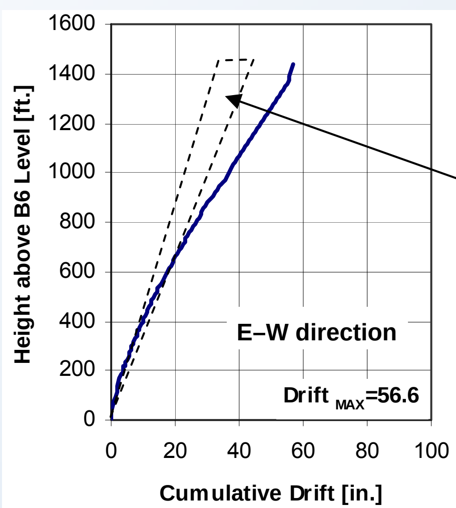
* Number of members includes columns with ½ floor height due to the presence of column splices.

The safety of the WTC towers on September 11, 2001 was most likely not affected by the fraction of members for which the demand exceeded allowable capacity.

NIST

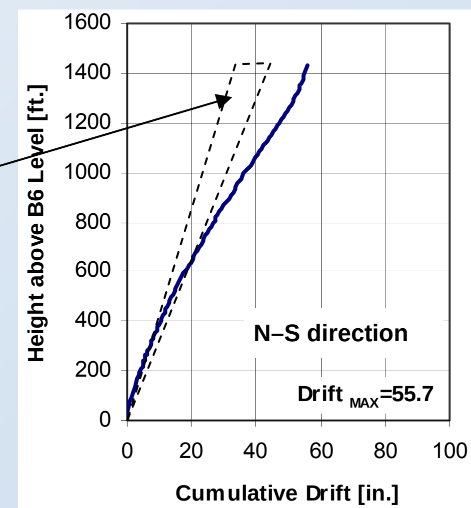
Results of Drift Analysis

Loading Case	WTC 1				WTC 2			
	E–W		N–S		E–W		N–S	
	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio
Original design case	56.6	H/304	55.7	H/309	51.2	H/335	65.3	H/263
SOP case	56.8	H/303	68.1	H/253	59.7	H/287	56.1	H/306
Refined NIST case	70.6	H/244	83.9	H/205	75.6	H/227	71.0	H/242



Cumulative drifts for WTC 1 under original design wind loads

Typical drift values considered in practice (not required by building codes) range from H/400 to H/500.



Results of Drift Analysis

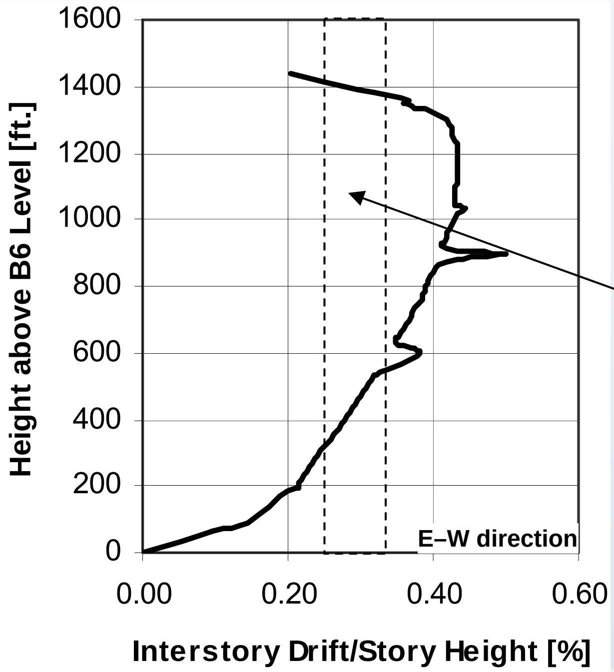
- Current building codes do not specify a drift limit for wind design. The ASCE 7-02 Standard states in Section B.1.2 that the drift of structures due to wind effects shall not impair the serviceability of the structure. The commentary to this section indicates that drift limits in common usage for building design are on the order of 1/400 to 1/600 of the building height to minimize damage to cladding and nonstructural walls and partitions.

- Structural engineers often use in their practice the criterion that total drift ratios should not exceed H/400 to H/500 for serviceability considerations and to enhance overall safety and stability (including P-Δ effects).

- Limiting total building drift under wind loads was not part of the original design. Instead, inter-story drifts were used during the design stage for serviceability considerations.

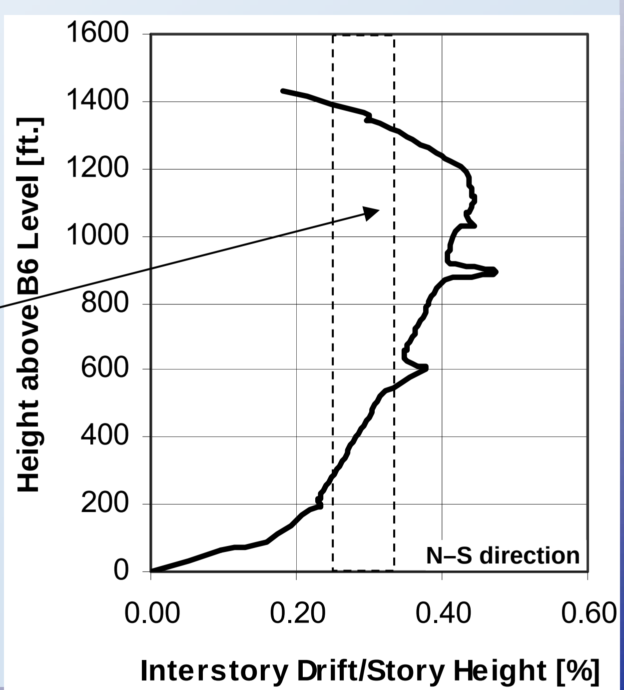
Maximum Inter-story drift for WTC 1 and WTC 2

Loading Case	WTC 1		WTC 2	
	E–W	N–S	E–W	N–S
Original design case	h/225	h/230	h/230	h/195
SOP case	h/225	h/185	h/200	h/215
Refined NIST case	h/180	h/150	h/160	h/175



Inter-story drifts for WTC 1 under original design wind loads

Typical inter-story drift values considered in practice for serviceability (not required by building codes) range from h/300 to h/400.



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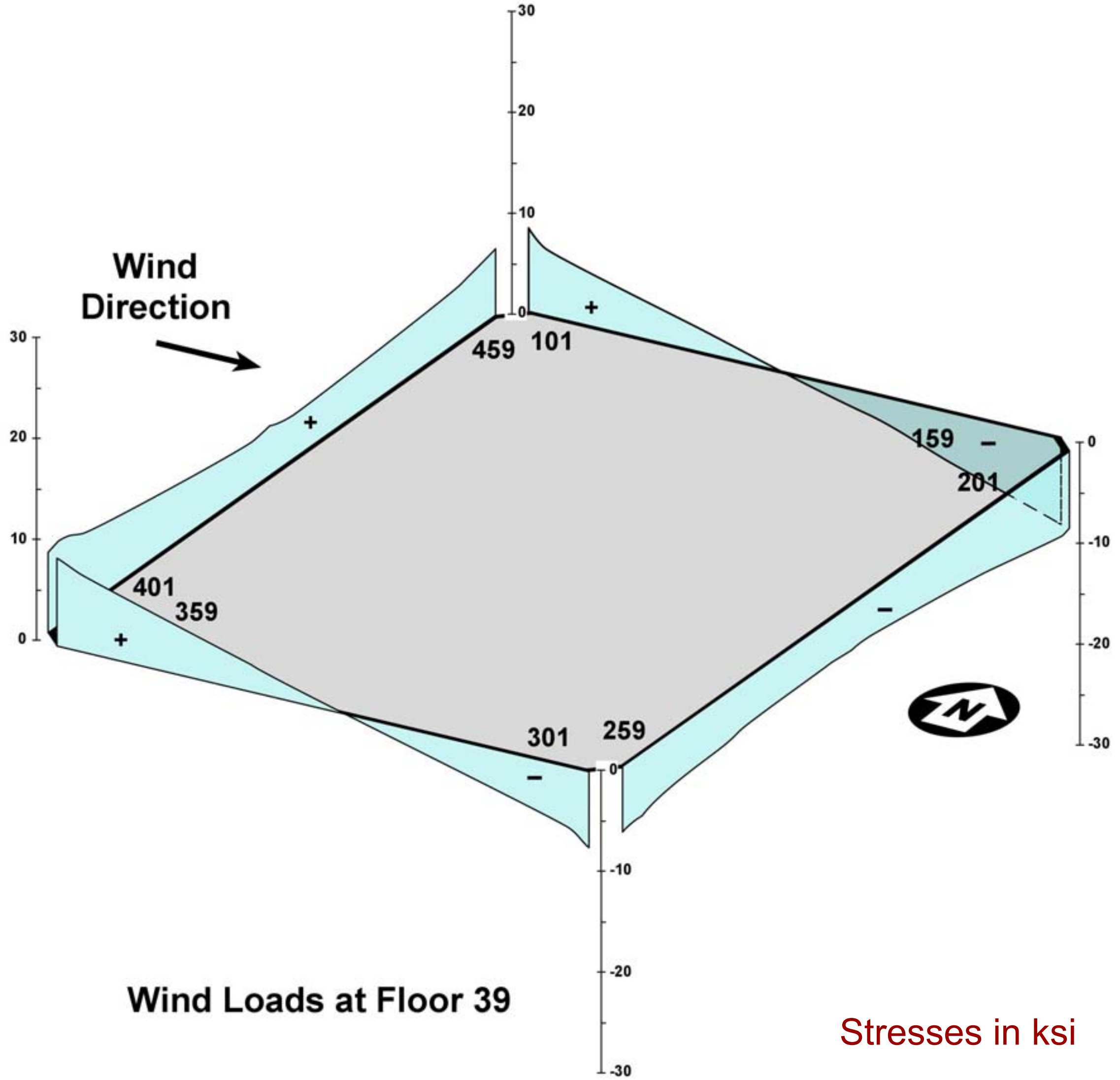
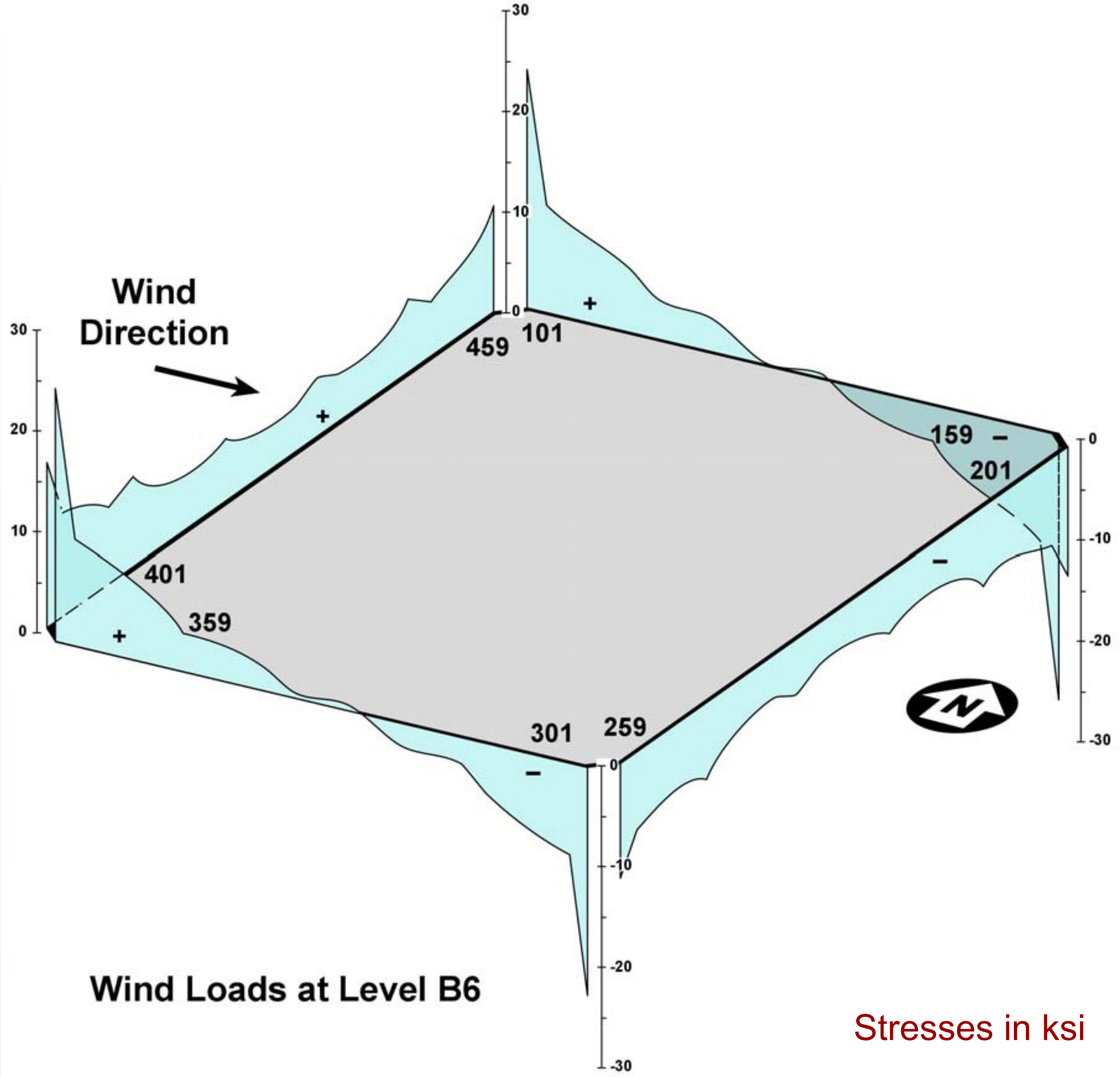
Performance of Exterior wall columns

- Distribution of normal stresses in the exterior walls at floor 39 of WTC 1 due to original wind loads only
- Behavior of the super-structure is that of a framed tube system.



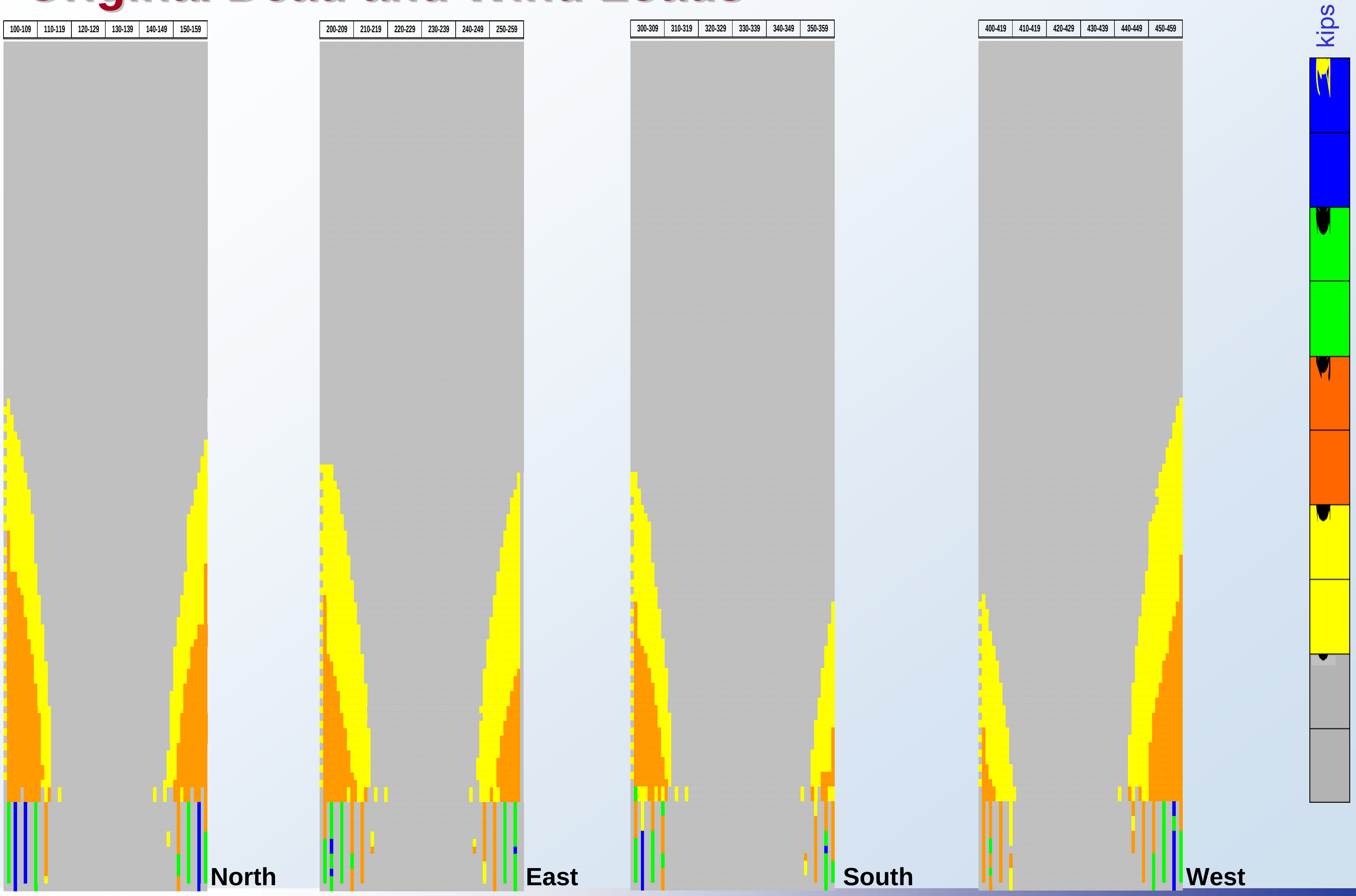
Performance of Exterior wall columns

- Distribution of normal stresses in the exterior walls at floor B-6 of WTC 1 due to original wind loads only
- Behavior of the lower portion of the tower at the basement floors resembled that of a braced frame.



Stresses in ksi

Tensile Forces in Exterior Wall Columns under Original Dead and Wind Loads



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

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Key Findings: Wind Loads

- The original design wind loads on the towers exceeded those established in the prescriptive provisions of the New York City Building Code (NYCBC) prior to 1968, when the WTC towers were designed, and up to and including 2001. The original design load estimates were also higher than those required by other selected building codes of the time (Chicago and New York State), including the relevant national model building code, Building Officials Conference America (BOCA). The prescriptive approach in these codes is oversimplified, and as a result, these codes are not necessarily appropriate for super-tall building design.
- In the majority of the cases, each of the two orthogonal shear components and of the two orthogonal overturning moment components at the base of the towers used in the original wind design were smaller than the CPP, RWDI, and refined NIST estimates. However, the most unfavorable combined peaks (resultant) from the original design were larger, or smaller, by at most 15 percent than estimates based on the CPP, RWDI, and NIST estimates. This is due to the conservative approach used to combine the loads in the original design.
- The estimated wind-induced loads on the towers varied by as much as 40 percent between the wind tunnel/climatological studies conducted in 2002 by CPP and RWDI. The primary reason for these differences was the different approaches used in those studies to (1) estimate extreme wind speeds; (2) estimate wind profiles; (3) integrate aerodynamic, dynamic, and extreme wind climatological information; and (4) combine wind effects in two orthogonal directions and in torsion. Such disparity is indicative of the limitations and inconsistencies associated with the current state of practice in wind engineering for tall buildings.

Key Findings: Baseline Performance

- Under the original WTC design loads, the cumulative drifts at the top of the WTC towers ranged from H/263 to H/335. For the lower-estimate SOP case, those drifts ranged from H/253 to H/306.

  Under design loading conditions, the maximum inter-story drift was as high as h/230 and h/200 for WTC 1 and WTC 2, respectively, where h is the story height. Maximum inter-story drifts under the SOP case were about h/184 and h/200 for WTC 1 and WTC 2, respectively.

  For the refined NIST estimate case, the cumulative and inter-story drifts were about 25 percent larger than those from the SOP case.

  Current building codes do not specify a drift limit for wind design. Structural engineers often use in their practice the criterion that total drift ratios should not exceed H/400 to H/500 for serviceability considerations and to enhance overall safety and stability (including P-Δ effects). For inter-story drifts, structural engineers often use in their practice an inter-story drift limit in the range of h/300 to h/400. Similar to total drift, inter-story drifts of the towers were larger than what is generally used in current practice.

Key Findings: Baseline Performance

- The DCRs based on the allowable stress design procedure, estimated from the original WTC design load case were in general close to those obtained for the lower-estimate SOP case. For both cases, a fraction of the structural components had DCRs larger than 1.0. These were mainly observed in both towers at:
  - The exterior walls: (1) at the columns around the corners, (2) where the hat truss connected to the exterior walls, and (3) below floor 9.
  - The core columns on the 600 line between floors 80 and 106 and at core perimeter columns 901 and 908 for much of their height.

  The DCRs obtained for the refined NIST estimate case were higher than those for the original WTC design and the lower-estimate SOP load cases, owing to:
  - The NIST estimated wind loads were larger than those used in the state-of-the-practice case by about 25 percent
  - The original WTC design and the SOP cases used NYCBC load combinations, which result in lower DCRs than the ASCE 7-02 load combinations used for the refined NIST case.
- The safety of the WTC towers on September 11, 2001 was most likely not affected by the fraction of members for which the demand exceeded allowable capacity due to: (1) the inherent factor of safety in the allowable stress design method, (2) the load redistribution capability of ductile steel structures, and (3) on the day of the attack, the towers were subjected to in-service live loads (a fraction of the design live loads) and minimal wind loads.

Aircraft Impact Analysis

- Buildings are not specifically designed to withstand the impact of fuel-laden commercial aircraft, and building codes in the United States do not require building designs to consider aircraft impact.
- Documents obtained from The Port Authority of New York and New Jersey indicated that the safety of the WTC towers and their occupants in an aircraft collision was a consideration in the original design. Such documents include:
  - Port Authority (February 1964), three-page white paper, “Salient points with regard to the structural design of The World Trade Center towers,” dated 2-3-64.
  - Port Authority (March 1964), three-page document, “period of vibration due to plane crash at 80^{th} floor.”
  - Alternative Insurance Works (2001), World Trade Center Property Risk Report, Prepared for Silverstein Properties, Inc.
  - *The New Yorker* (11/19/2001), “The Tower Builder” by John Seabrook, Interview with Leslie Robertson.
  - FEMA 403 (2002), *World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations.*
  - Glanz and Lipton (2003), *City in the Sky – The Rise and the Fall of The – World Trade Center,* Times Books, 2003.

Aircraft Impact Analysis

- The documents indicate that a Boeing 707, the largest commercial aircraft at the time, flying at 600 mph was considered and that the analysis indicated that such collision would result in only local damage which could not cause collapse or substantial damage to the building and would not endanger the lives and safety of occupants not in the immediate area of impact.
- No documentary evidence of the aircraft impact analysis was available to review the criteria and methods used in the analysis of the aircraft impact into the WTC towers, or to provide details on the ability of the WTC towers to withstand such impacts.

Aircraft Impact Analysis Objectives

- Provide estimates of probable damage to structural systems, including exterior walls, floor systems, and interior core columns
- Provide estimates of the aircraft fuel dispersion during the impact
- Provide estimates of debris damage to the building nonstructural contents, including partitions and workstations. The results were to be used to estimate the damage to fireproofing.
- Establish the initial conditions for the fire dynamics modeling and thermal-structural response and collapse initiation analyses.

Technical Approach

- Reference Structural Models of the Towers
- Material Constitutive and Failure Modeling
- WTC Towers Model Development
- Aircraft Data Collection and Model Development
- Component Impact Analyses
- Subassembly Analysis
- Aircraft Impact Initial Conditions
- Sensitivity Analysis
- **Global Impact Analyses**

NIST