NIST Response to the World Trade Center Disaster

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

Part III – Baseline Performance

April 5, 2005

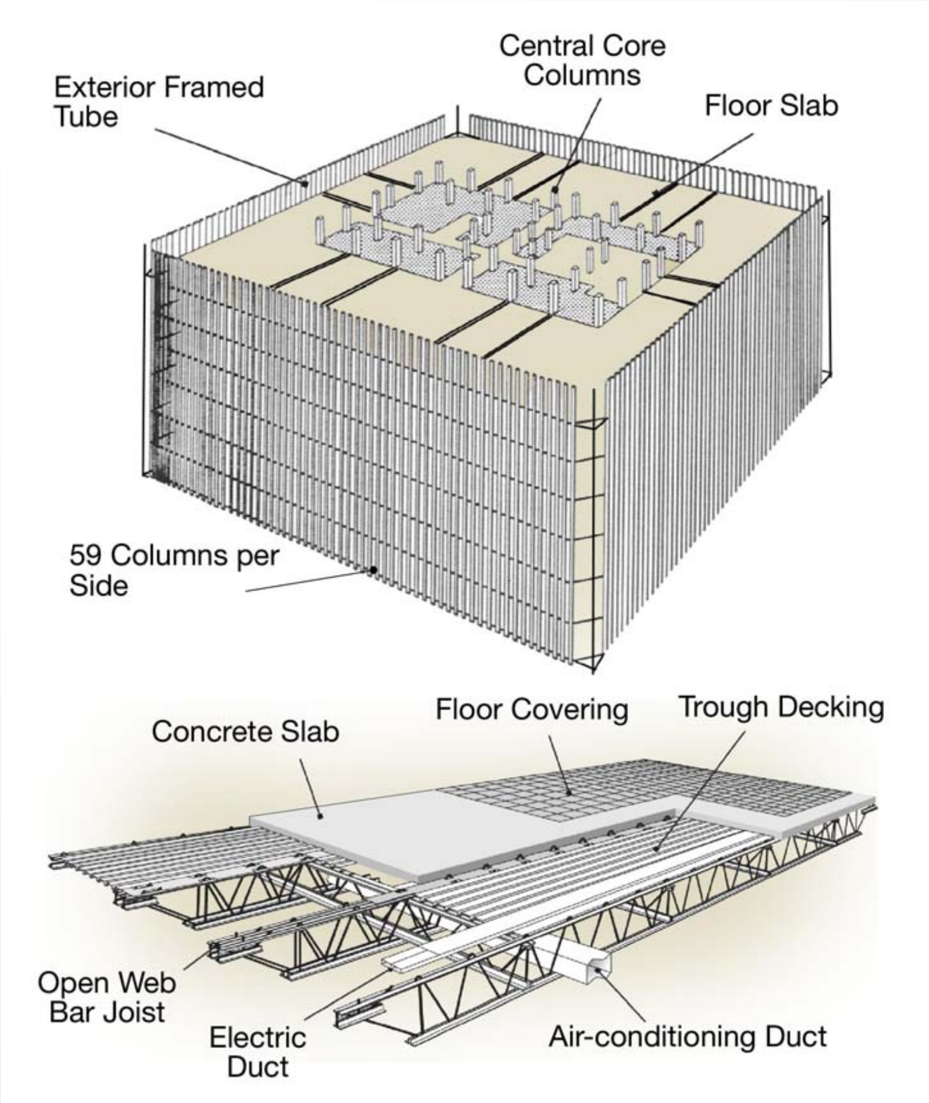
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

NIST

Baseline Performance Analysis

- Standard fire resistance of WTC floor system
  - Effects of scale, restraint condition, fireproofing thickness
- Quality and properties of structural steel
  - Identification and location of recovered WTC steel
  - Mechanical properties of steel (room/elevated temperatures, high rates)
  - Comparison with testing and construction specifications
- Design wind loads
  - Estimation of wind effects using wind tunnel testing
  - Comparison with prescriptive code requirements
- Response of WTC towers to design wind loads
  - Estimation of drift ratios; comparison with limits used in practice but not required by codes
  - Estimation of component demand-to-capacity ratios

Innovative WTC Tower Structural System



- Innovative structural system when built; incorporated many new and unusual features
- Two features require additional consideration:
    - Composite floor truss system using long span open-web bar joists and spray-applied fireproofing
    - Design for wind loads and control of wind-induced vibrations

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Fire Performance of Composite Floor System

- Fire-protection of a truss-supported floor system with spray-on fireproofing was innovative and not consistent with then-prevailing practice.

- **No evidence found of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
  - 1/2 in. specified when WTC towers were built to maintain Class 1-A (not 1-B) fire rating requirement of the NYC Building Code
  - 1-1/2 in. specified for upgrades some years prior to 2001
  - 2 in. for similar floor system in an unrestrained test (model code evaluation service recommendation in June 2001, unrelated to WTC buildings)

- **No evidence that full-scale fire resistance test of the WTC floor system was conducted** to determine the required fireproofing thickness; in 1966, the Architect of Record and, in 1975, the Structural Engineer of Record stated that the fire rating of the WTC floor system could not be determined without testing.

NYC Building Code Provisions (Fire Resistance in hours)

	1938	1968*	2001**
Columns	4	4/3	2
Floors	3	3/2	1-1/2

*** Building code governing original design and occupancy (the architect/owner could choose either Class 1-A or 1-B)**

**** Sprinklers required for buildings of unlimited height**

Fireproofing Thickness in NIST-Sponsored Tests at UL

Condition	Primary Trusses	Bridging Trusses	Metal Deck
Original Specified	1/2 in	0 in	No Overspray
As-Applied	3/4 in	3/8 in	Overspray

- Three tests were conducted in the as-applied condition:
  - 35-foot span; restrained test
  - 35-foot span; unrestrained test
  - 17-foot span; restrained test
- One test was conducted in the original specified condition:
  - 17-foot span; restrained test

Results From NIST-Sponsored Tests at UL

Test	Description	Times to Reach End-Point Criteria (min)					Test Termin-ated (min)	Standard Fire Test Rating		
		Temperature on Unexposed Surface		Steel Temperatures		Failure to Support Load		ASTM E 119-61	ASTM E 119-00	
		Average (Ambient +250ºF)	Maximum (Ambient +325ºF)	Average (1100ºF)	Maxi-mum (1300ºF)			Rating (hr)	Restr-ained Rating (hr)	Unrestr-ained Rating (hr)
1	35 ft, restrained, ¾ in fireproofing	---	111	66	62	(3)	116(1)	1½	1½	1
2	35 ft, unrestrained, ¾ in fireproofing	---	---	76	62	(3)	146(2)	2	---	2
3	17 ft, restrained, ¾ in fireproofing	180	157	86	76	(3)	210(2)	2	2	1
4	17 ft, restrained, ½ in fireproofing	---	58	66	58	(3)	120(1)	¾	¾	¾

(1) Imminent collapse
(2) Vertical displacement exceeded capability to measure accurately
(3) Did not occur

The end-point criterion that determined the rating is shown in matching color.

Findings of Standard Fire Resistance Tests

- The test structures were able to withstand standard fire conditions for between 45 minutes and 2 hours. The floor system did not fail to support loads in any test.
- The 1968 New York City building code—the code that the WTC towers were intended but not required to meet when they were built—required a 2-hour fire rating for the floor system.
- **The 45-minute fire resistance for the standard 17-foot test with the specified 0.5 inch fireproofing did not meet the 2-hour requirement of the NYC building code.** This test had no fireproofing on the bridging trusses nor on the underside of the metal deck.
- **The 2-hour fire resistance for the standard 17-foot test with the as-applied average 0.75 inch fireproofing met the 2-hour requirement of the NYC building code.** This test had half the fireproofing thickness on the bridging trusses and overspray on the underside of the metal deck.
- **The difference in test results is not due to the fireproofing thickness on the trusses, but possibly due to moisture content differences in the concrete deck and the presence or lack of fireproofing overspray on the underside of the metal deck.**

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Role of Fire Resistance Tests

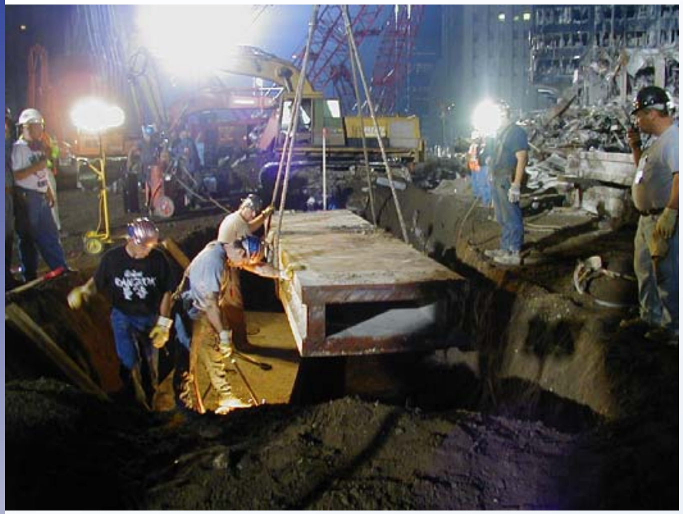
- **The fire resistance tests cannot be used to determine the actual performance of the floor systems in the collapse of the WTC towers, nor can the tests determine whether or not the actual floor systems *as built* met code requirements. Further, the PANYNJ could have taken the highly unusual step of reclassifying the structure to Class 1-C, with a 1-1/2 hour required rating for floors and a 2 hour rating for columns, when installation of the sprinkler system was completed just prior to September 11, 2001.**

- The fire resistance tests provided valuable insights into the behavior of the floor systems for use in analyzing the thermal response and collapse of the WTC tower structures.

- The occurrence and spread of jet-fuel due to the terrorist attacks on September 11, 2001 ignited multi-floor fires in the WTC towers. These fires were significantly different from the fires to which floor systems in standard U.S. fire rating tests are subjected. Consider, for example:
  - Combustible fuel load of the hijacked jets.
  - Extent and number of floors involved in fires.
  - Rate of fire spread across and between floors.
  - Ventilation conditions in the fire-affected floors.

- The probable collapse sequences for the WTC towers are based on the behavior of thermally weakened structural components that had extensive damage to fireproofing or gypsum board fire protection induced by the debris field generated by aircraft impact.

Steel from WTC Towers



Clean weld fracture of Interior columns

Failure at connection between floor system and exterior columns

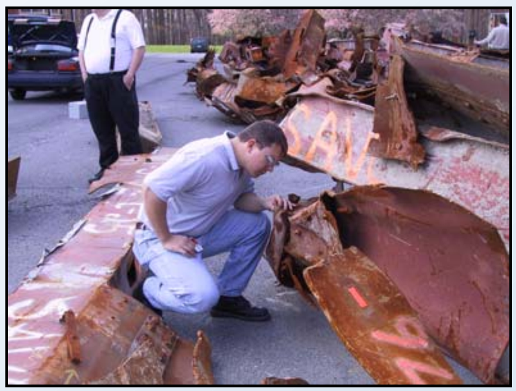
Dr. John Fisher (Lehigh) and Robert Duvall (NFPA)

WTC steel columns

Dr. John Gross (NIST)

NIST

WTC Steel at NIST



Ten different steel companies fabricated structural components for the WTC towers, using steel from at least 8 different suppliers. Four fabricators supplied the major structural components of the 9th to the 107th floors.

Inventory of Steel Pieces at NIST

- NIST has catalogued a total of 236 pieces of recovered WTC steel, including:
  - 94 perimeter columns panel sections
  - 44 wide flange sections
  - 11 built-up box columns
  - 23 floor trusses
  - 25 channels
  - 7 coupons from WTC 5
  - 2 “bow-tie” pieces
  - 30 miscellaneous (isolated bolts, floor hanger components, and other)
- Steel in NIST’s possession represents roughly 1/2 percent of the 200,000 tons of structural steel used in the construction of the WTC towers.
- NIST inventory includes pieces from the impact and fire regions, perimeter columns, core columns, floor trusses, and other pieces such as truss seats and wind dampers.
- Original, as-built locations of 42 recovered perimeter panels and 12 recovered core columns were determined, based on markings and geometry of the columns.
- A significant number of structural pieces were recovered from locations in or near the impact and fire damaged regions of the WTC towers, including 4 perimeter panels directly hit by the airplanes and 3 core columns located within these areas.

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Analysis of Recovered WTC Steel

- NIST's collection of 236 WTC steel pieces was adequate for determining the quality and properties of steel for the investigation (reconstruction of the impacted/fire zone was not attempted).
  - Impact/fire damage region emphasized
  - All 10 grades of steel used for perimeter panels (12 grades were specified)
  - Both grades for steel trusses
  - Two grades (representing 99%) for core columns

- Based on stampings on steel and mechanical tests, analysis indicated that the **correct specified materials were provided for specified elements**; when these data are combined with available pre-collapse photographs, aircraft impacted pieces from WTC 1 were in precise locations specified in design drawings

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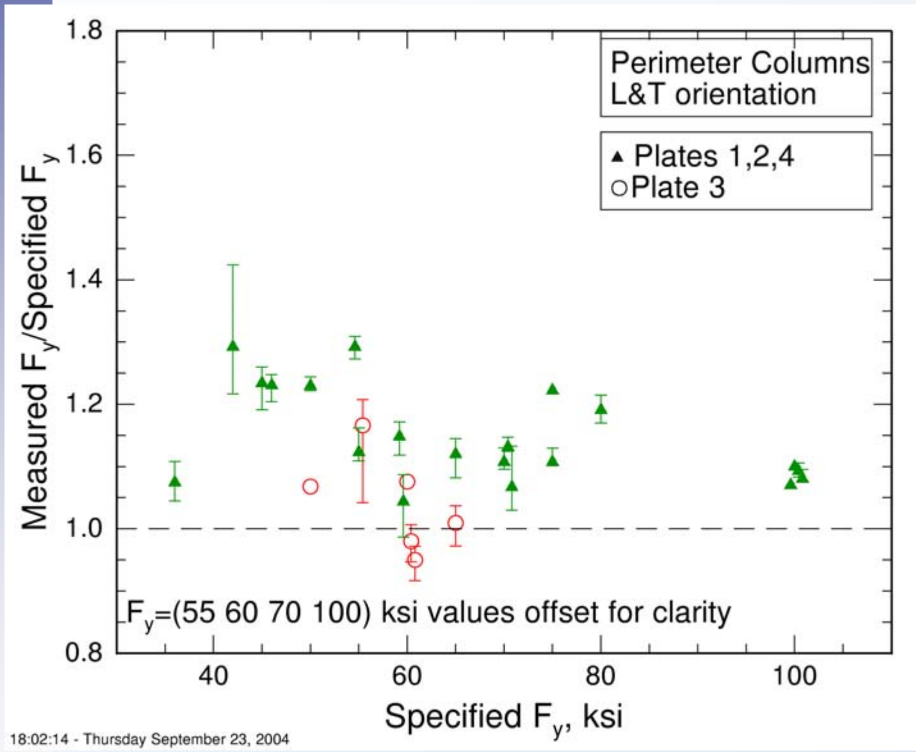
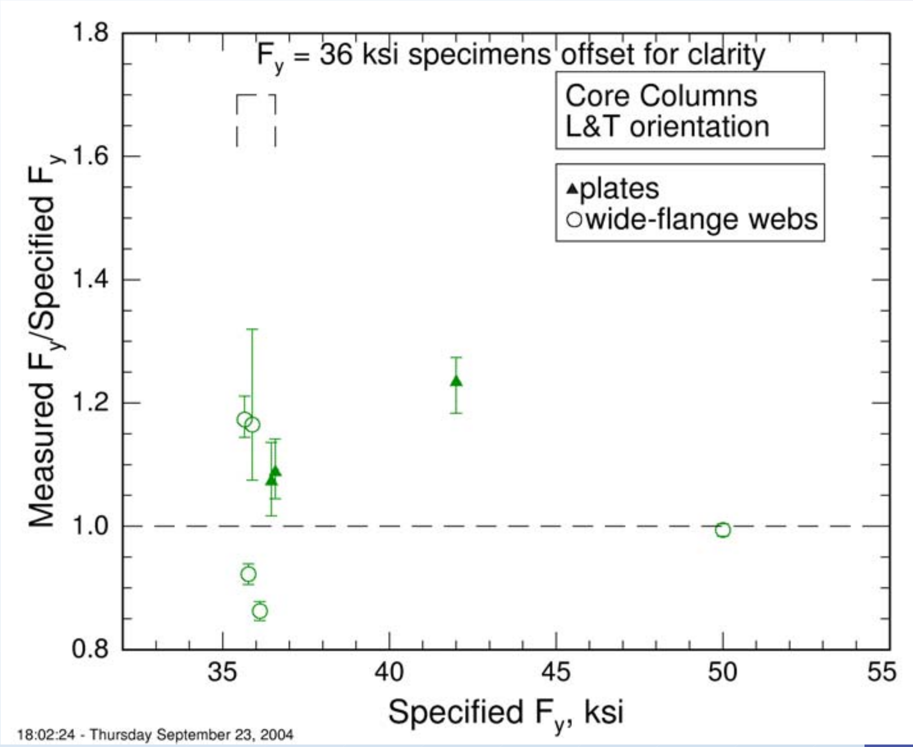
Comparison of Specified Properties with Measured Properties at Room Temperature

Perimeter Columns



Core Columns



The safety of the WTC towers on September 11, 2001 was most likely not affected by the fraction of steel that, according to NIST testing, did not meet the specified minimum yield strength. The typical factors of safety in allowable stress design can accommodate the measured property variations below the minimum.

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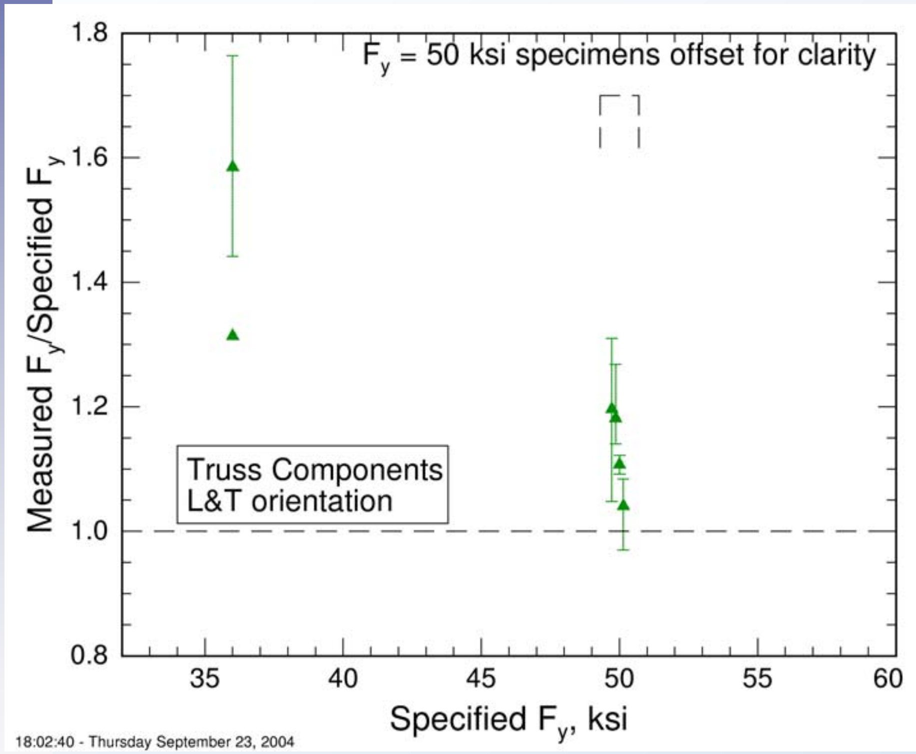
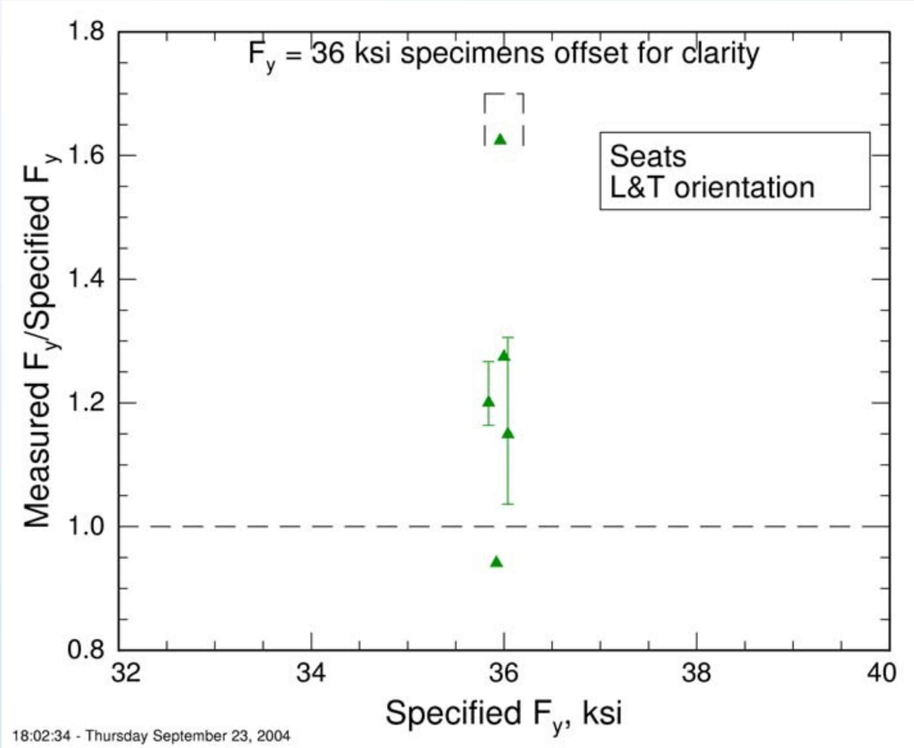
Comparison of Specified Properties with Measured Properties at Room Temperature

Floor Truss Components



Truss Seats



The safety of the WTC towers on September 11, 2001 was most likely not affected by the fraction of steel that, according to NIST testing, did not meet the specified minimum yield strength. The typical factors of safety in allowable stress design can accommodate the measured property variations below the minimum.

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Findings on Mechanical Properties of WTC Steel

- **Approximately 87 percent of the tested steel specimens exceeded the required minimum yield strengths specified in design documents.**
- **Approximately 13 percent of test results on the damaged steel did not meet the required minimum yield strength specified in design documents.** The results are not unexpected since:
  - Change in test procedure from mill tests could account for 2-3 ksi
  - Loss of yield point due to damage to steel accounts for 2-4 ksi in several cases
- The distribution of wide flange core column properties is lower than expected from historical data; the distributions for other components are consistent with historical data.
- **The safety of the WTC towers on September 11, 2001 was most likely not affected by the fraction of steel that, according to NIST testing, did not meet the specified minimum yield strength. The typical factors of safety in allowable stress design can accommodate the measured property variations below the minimum.**

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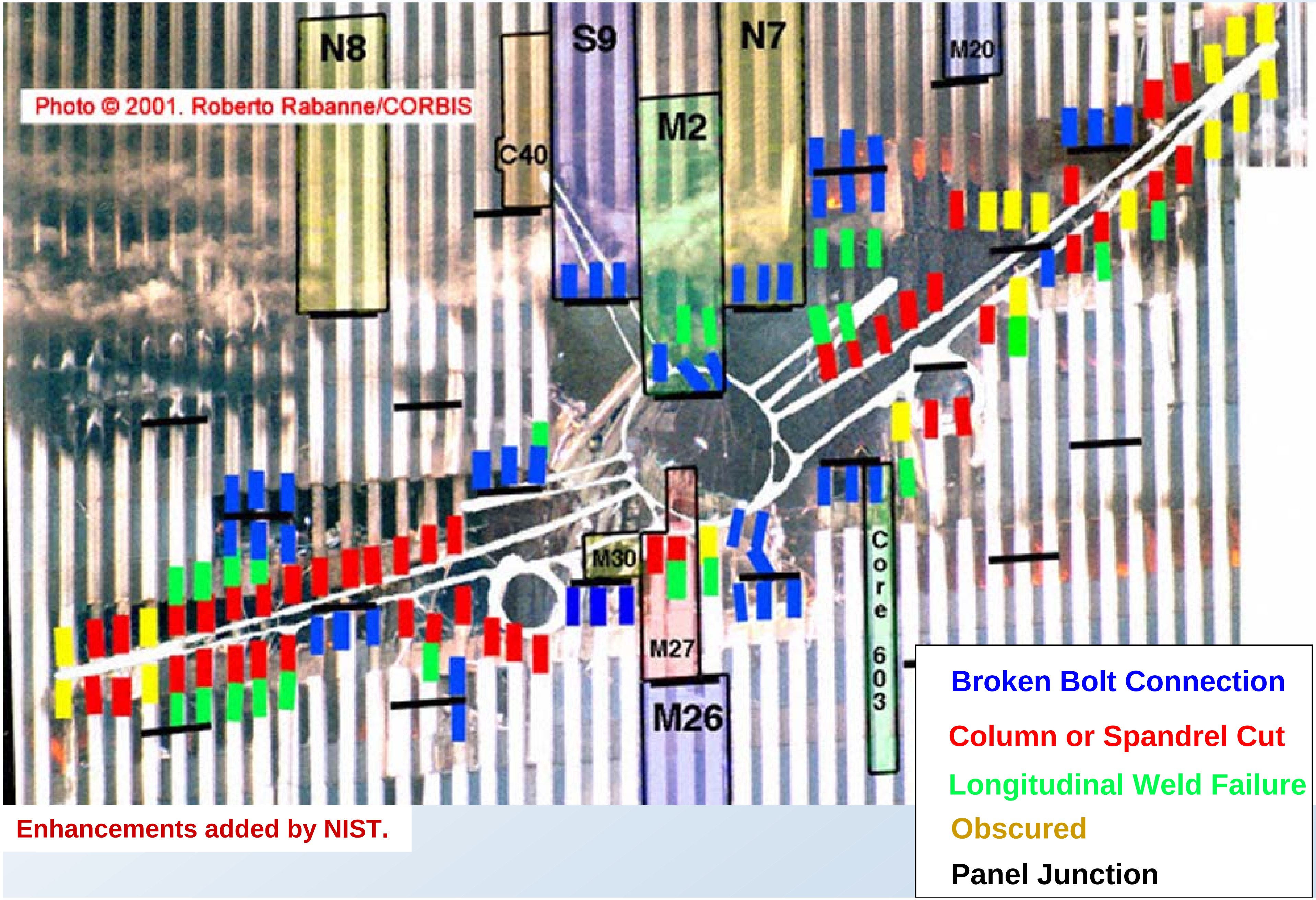
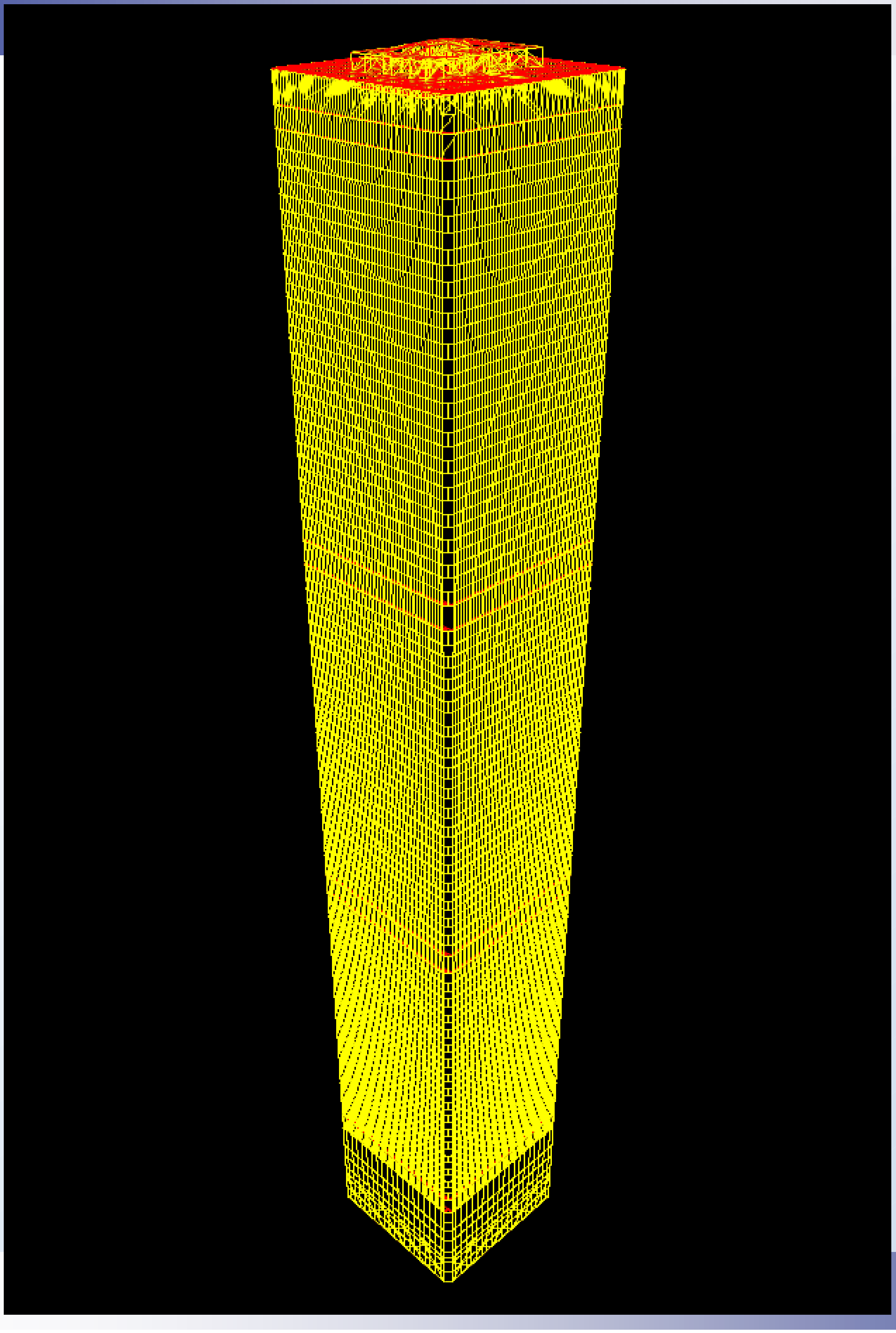


Enhancements added by NIST.



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
Decmber 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.

Use of Wind Tunnel Testing to Estimate Loads

- **Wind loads were a major governing factor in the design of the components that made up the WTC tower structures, especially the perimeter frame-tube system.**

- Wind loads are relevant to evaluating:
  - The baseline performance of the WTC towers.
  - **The reserve capacity of the structures to withstand unanticipated events such as major fires or impact damage.**
  - Design practices and procedures that were used.

- NIST has completed an independent analysis to establish the baseline performance of the WTC towers under the original design wind loads and has compared those results with then-prevailing code requirements.

- In July 2004, the designer provided NIST with interpretation of technical information contained in original source documents that was needed to determine the design wind loads used for the WTC towers. NIST now has a better understanding based on this information.

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Design Wind Loads for the WTC Towers

Wind loads being considered include:

- ***Original WTC design wind loads*** determined from wind tunnel testing in the 1960's
- Wind loads based on two recent ***state-of-the-practice wind tunnel studies*** conducted by CPP and RWDI for insurance litigation, 2002
- ***Refined wind load estimates*** developed by NIST based on the RWDI data, and reviewed by SOM under contract to NIST, 2004

Baseline Performance Analysis

- **Load Combinations**
  - Original WTC design loads case:
    - WTC design gravity (dead and live) loads
    - Original WTC design wind loads (98 mph 20-min average at 1,500 ft above ground; equivalent to 67-75 mph fastest mile at 33 ft above ground).
  - 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 at 33 ft above ground).
  - Refined NIST estimate case:
    - Current ASCE 7 Standard (a national standard) live loads
    - Wind loads developed by NIST based on refinements that consider current state of the art in wind engineering (88 mph fastest mile at 33 ft above ground).

Wind Load Estimates for WTC 2

Source	Year	Base Shear 10^3 kips			Base Moment 10^6 kips-ft		
		N-S	E-W	Resultant	About N-S	About E-W	Resultant
NYC Building Code	Prior to 1968	5.3	5.3		4.2	4.2	
NYC Building Code	1968 - 2001	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 / ASCE 7-02	2004	12.2	14.0	15.6	12.8	11.6	14.3
Original WTC Design (Clarified by designer in July 2004)	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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Wind Load Estimates for WTC 1

Source	Year	Base Shear 10^3 kips			Base Moment 10^6 kips-ft		
		N-S	E-W	Resultant	About N-S	About E-W	Resultant
NYC Building Code	Prior to 1968	5.3	5.3		4.2	4.2	
NYC Building Code	1968 - 2001	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 / ASCE 7-02	2004	14.1	13.0	16.1	12.4	13.1	15.1
Original WTC Design (Clarified by designer in July 2004)	1960's	9.8	10.6	14.0	10.3	9.1	13.7

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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Findings on Design 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 WTC towers were destroyed).**
- The original design wind load estimates were higher than those required by other selected building codes of the era (Chicago, New York State), including the relevant national model building code (BOCA).
- Refined estimates of the resultant wind loads developed by NIST are higher by as much as about 15% than the resultant original design wind loads for WTC 1, and lower by about 5% than the resultant original design loads for WTC 2.
- **Estimated wind-induced loads on the towers vary by as much as 40% between two wind tunnel/climatological studies conducted in 2002 by independent laboratories, voluntarily provided to NIST by parties to insurance litigation concerning the WTC towers; the state-of-knowledge in wind engineering is evolving.**

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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)

Baseline Performance Analysis

- Analysis completed by LERA under contract to NIST. Results presented reviewed by NIST and SOM under contract to NIST.
- Lateral drift ratios estimated and compared with drift limits considered in practice.
- Demand/Capacity Ratios (DCRs) for structural components estimated using Allowable Stress Design (ASD).

Results and Findings 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

- The calculated drift ratios correspond to a damping ratio of 2.5% in estimated wind loads.
- Typical drift ratios considered in practice for serviceability, stability, and safety (not required by building codes):
  - H/500 in Chicago (~ 32.9 in.)
  - H/400 in New York City (~ 41.0 in.)
- **Under the original design wind loads, the WTC towers would need to have been between 1.2 to 1.5 times stiffer to achieve a H/400 drift limit, and between 1.5 to 1.9 times stiffer to achieve a H/500 drift limit;** this could be efficiently achieved by increasing exterior column areas in lower stories and/or significant additional damping.

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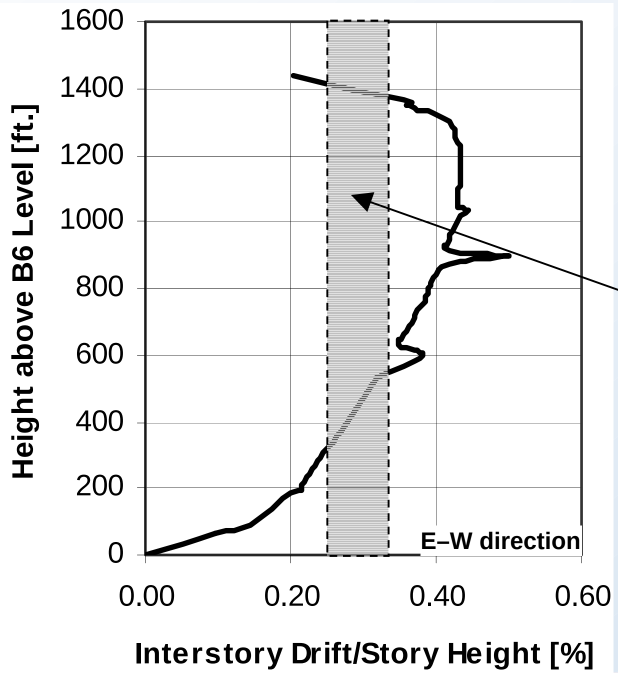
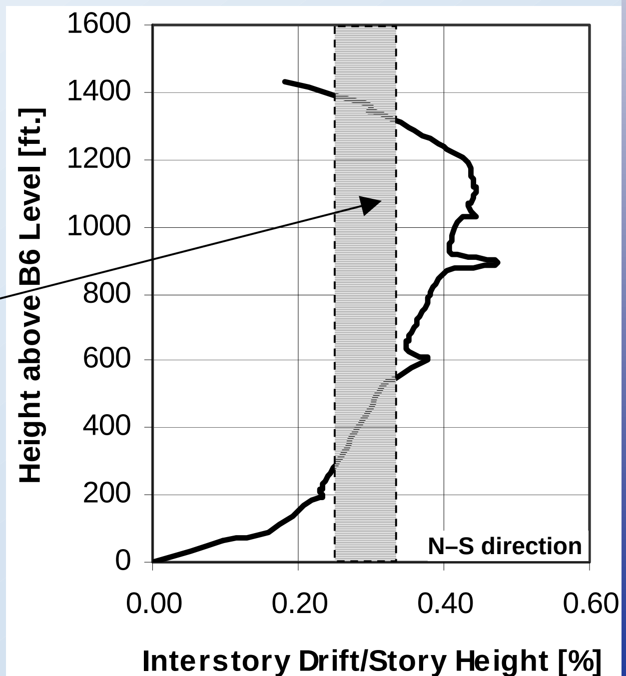
Maximum Inter-story drift for WTC 1 and WTC 2

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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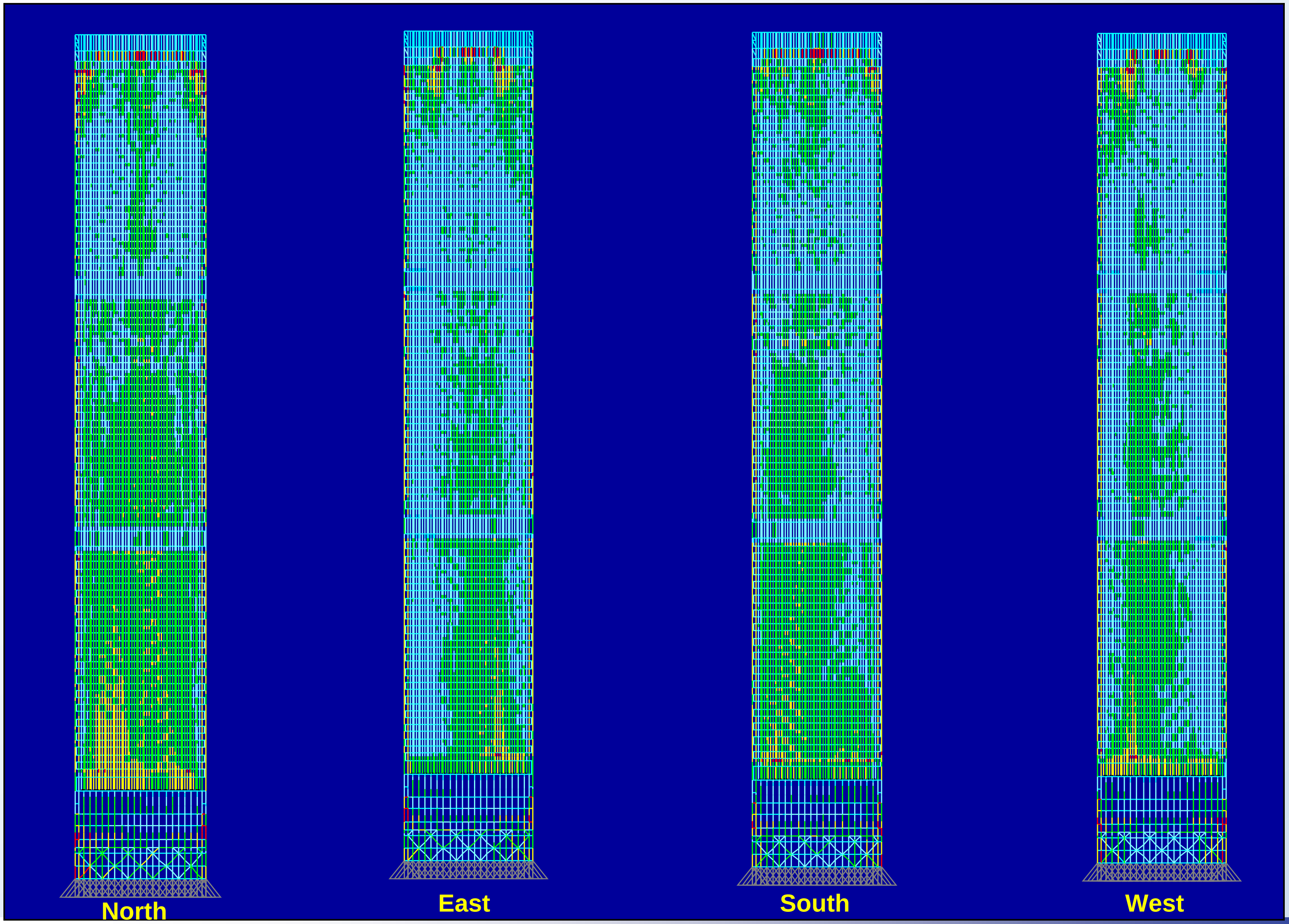
Results of Baseline Analysis for WTC 1

- DCRs for Structural Components under Original WTC Design Loads



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.

Findings of Baseline Performance Analysis

- **Normal design practice is intended to ensure that demand is less than capacity.**
- 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.
- DCRs from the **refined NIST estimate case** exceed those from the original design and state-of-the-practice cases due to the following reasons:
  - The refined NIST estimate wind loads are higher than those used in the lower bound SOP case by about 25 percent. Note that the refined NIST 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 for the allowable dead load induced stresses.

Findings of Baseline Performance Analysis

- The allowable stress design method 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 refined NIST estimate 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 have 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 percent of the design live loads.
- On September 11, the wind loads were minimal, thus allowing significantly more reserve capacity for the exterior walls (demand on exterior columns was about 1/5 their capacity).
- **The safety of the WTC towers on September 11 was most likely not affected by the fraction of members for which the demand exceeded allowable capacity.**

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WTC Technical Information Repository, Stop 8610,
100 Bureau Drive, Gaithersburg, MD 20899-8610.

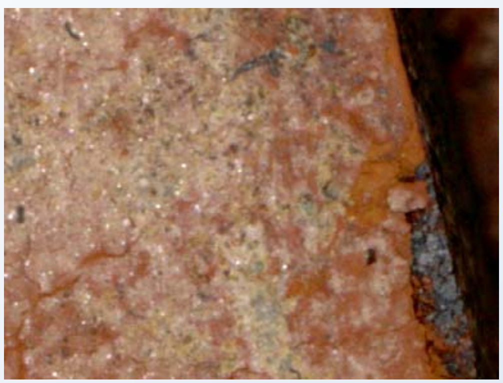
NIST

Background Slides

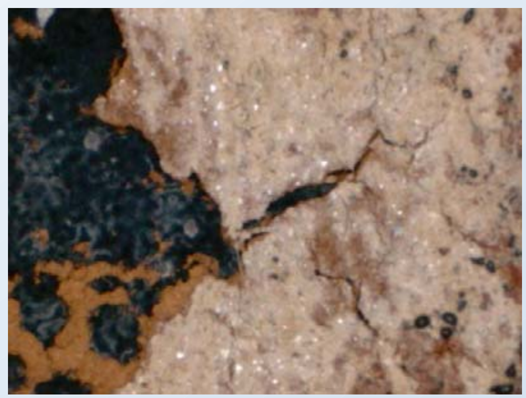
Burn Tests on Primer Paint

No burn
faint cracks from drying of paint 1 mm

250 deg C for an hour
mud cracks much more visible



700 deg C for an hour
mud cracks partially obscured by formation of whiteish "sandy" phase on surface
delamination easy with finger



1000 deg C for an hour
wholescale spalling of paint, falls off
thick scale forms between paint and steel

Observations of condition of primer paint could be used to detect pieces that did not exceed 250 °C, and those that exceeded 250 °C but did not exceed 750 °C