NIST Response to the World Trade Center Disaster

World Trade Center Investigation Status

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Outline

- Background and Schedule
- Investigation Objectives
- Collapse Hypotheses for WTC 1 and 2
- Fire Performance of Floor System
- Analysis of Recovered Steel
- Baseline Performance Analysis
  - Design Wind Loads
  - Structural Performance
- Evacuation and Occupant Behavior
- Emergency Response and Communications
- Issues Related to Practice, Standards, and Codes

Background

- Good, solid technical progress on investigation; drawing on talent from NIST, outside experts, and contractors; $16 million investigation; $5.5 million awarded in contracts.

- Two public updates issued (December 2002, December 2003); two technical progress reports issued (May 2003, June 2004).

- NYC Public Meeting (February 12, 2004) to solicit comments on (1) technical aspects of investigation, (2) additional information that NIST might consider, (3) areas to be considered for recommendations.

- Second technical progress report released June 18, 2004; 1,054 pages; full text available on Web site http://wtc.nist.gov.

- Public release of information following June 2004 Advisory Committee meeting:

    - Locations of WTC decedents at time of impact, July 20, 2004.
    - Fire endurance tests of WTC floor system at Underwriters Laboratories, August 25, 2004.
    - Design wind loads for the WTC towers, September 17, 2004.

- Investigation is ongoing; current findings may be revised and additional findings will be presented in final report.

- **NIST is not making any recommendations at this time; all recommendations will be made in the final report.**

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Schedule for Completion of Investigation

- Most technical work is complete; major focus is on writing the Investigation reports.
- NIST plans to release a draft of the final report for public comment in December 2004 or January 2005
- Public comment period of 4-6 weeks after release of the draft reports.
- NIST plans to release final Investigation report in April or May 2005.
- WTC 7 report will be issued as a supplement to the main report: draft in May 2005; final in July 2005.
  - Decoupling of WTC 7 report necessary to accommodate overlapping staffing needs for work on WTC towers.
  - This change affects mainly the collapse analysis; other WTC 7 work will be reported with the other Investigation reports.
- WTC Conference: Putting Recommendations into Practice, June 2005.

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Report Hierarchy

Some technical topic reports may be combined; others may be integrated with program reports.

NIST WTC Investigation Objectives

- Determine:
  - why and how the WTC Towers collapsed following the initial impact of the aircraft, and
  - why and how the 47-story WTC 7 collapsed
- Determine why the numbers of injuries and fatalities were so low or high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response
- Determine the procedures and practices that were used in the design, construction, operation, and maintenance of the WTC buildings
- **Identify, as specifically as possible, areas in national building and fire codes, standards, and practices that warrant revision**

Some Specific Questions

- How and why did WTC 1 stand nearly **twice** as long as WTC 2 before collapsing (103 min. vs. 56 min.) though they were hit by virtually identical aircraft?
- What factors related to **normal** building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?
- Would the undamaged WTC towers have remained standing in a **conventional** large building fire scenario?
- What factors related to **normal** building and fire safety considerations, if any, could have saved additional WTC occupant lives or could have minimized the loss of life among the ranks of first responders?
- How well did the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings **conform** to accepted national practices, standards, and codes?

Context of Findings

- Buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners. While documents from the Port Authority of New York and New Jersey (PANYNJ) indicate that the impact of a Boeing 707 flying at 600 mph, possibly crashing into the 80th floor, was analyzed during the design of the WTC towers in February/March 1964, the effect of the subsequent fires was not considered. Building codes do not require building designs to consider aircraft impact.

- Buildings are not designed for fire protection and evacuation under the magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001.

- The load conditions induced by aircraft impacts and the extensive fires on September 11, 2001, which triggered the collapse of the WTC towers, fall outside the norm of design loads considered in building codes.

- Prior evacuation and emergency response experience in major events did not include the total collapse of tall buildings such as the WTC Towers and WTC 7 that were occupied and in everyday use; instead, that experience suggests that major tall building fires result in burnout conditions, not overall building collapse.

- The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the building and fire codes of any local, state, or federal jurisdiction. The PANYNJ's longstanding stated policy is to meet and, where appropriate, exceed requirements of local building and fire codes.

Analysis of Probable Collapse Sequence

NIST developed and used a comprehensive approach to determine the probable collapse sequences, from aircraft impact to collapse initiation. The approach:

- Combined mathematical modeling, well-established statistical and probability-based analysis methods, laboratory experiments, and analysis of photographic and videographic evidence.
- Allowed for evaluation and comparison of possible collapse sequences based on different damage states, fire paths, and structural load redistribution paths.
- Accounted for variations in models, input parameters, analyses, and observed events.

Analysis of Probable Collapse Sequence

- NIST simulated highly-complex structural failures and fires at the component, subsystem, and system levels to determine the probable collapse sequences. **In many instances, NIST tested the limits of current engineering software and computational platforms.** The computational models developed by NIST include:
  - A detailed structural model of a typical truss-framed floor of the WTC towers with over 40,000 elements and 166,000 degrees of freedom.
  - A detailed structural model of a typical beam-framed floor of WTC towers with over 12,000 elements and 35,000 degrees of freedom.
  - A detailed global model of WTC 1 structure with over 80,000 elements and 218,000 degrees of freedom (with 17 flexible and other rigid diaphragm floors).
  - A similar detailed global model of WTC 2 structure with over 78,000 elements and 200,000 degrees of freedom.
  - A structural model of a typical turbofan engine of the Boeing 767-200ER aircraft with over 60,000 elements and 100,000 nodes.
  - A comprehensive structural model of the Boeing 767-200ER aircraft, including engines, airframe, landing gear, fuel tanks, passenger cabin, and cargo bay, with over 530,000 elements and 740,000 nodes.
  - A computational fluid dynamics model of the fires and thermal environments that encompasses 8 floors and 1,200,000 cells in WTC 1 and 6 floors and 900,000 cells in WTC 2.
  - A fire-structure interface model that maps the thermal environment onto and within the structural model, comprising 500,000 floor elements and 300,000 column nodes per building floor.

- The first four models described above were used to evaluate the baseline performance of the WTC towers under design gravity and wind loads. They also served as *reference* models for analyses of aircraft impact damage and response of the thermally-insulated WTC structures to subsequent fires.

Leading Hypothesis for Collapse of WTC 1

The following chronological sequence of major events led to the eventual collapse of WTC 1; specific load redistribution paths and damage scenarios are being refined to determine the probable collapse sequence:

- Aircraft impact damage to perimeter columns, mainly on the North face, resulted in redistribution of column loads, mostly to the adjacent perimeter columns and to a lesser extent to the core columns.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, damaging floor framing, core columns, and fireproofing. Loads on the damaged columns were redistributed to other intact core and perimeter columns mostly via the floor systems and to a lesser extent via the hat truss.
- The subsequent fires, influenced by the impact damaged fireproofing condition:
  - Softened and buckled the core columns and caused them to shorten, resulting in a downward displacement of the core relative to the perimeter which led to the floors (1) pulling the perimeter columns inward, and (2) transferring vertical loads to the perimeter columns.
  - Softened the perimeter columns on the South face and also caused perimeter column loads to increase significantly due to restrained thermal expansion.
- Due to the combined effects of heating on the core and perimeter columns, the South perimeter wall bowed inwards, and highly stressed sections buckled.
- The section of the building above the impact zone began tilting to the South as the bowed South perimeter columns buckled, and instability rapidly progressed horizontally across the entire South face and then across the adjacent East and West faces.
- The change in potential energy due to downward movement of building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued.

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Leading Hypothesis for Collapse of WTC 2

The following chronological sequence of major events led to the eventual collapse of WTC 2; specific load redistribution paths and damage scenarios are being refined to determine the probable collapse sequence:

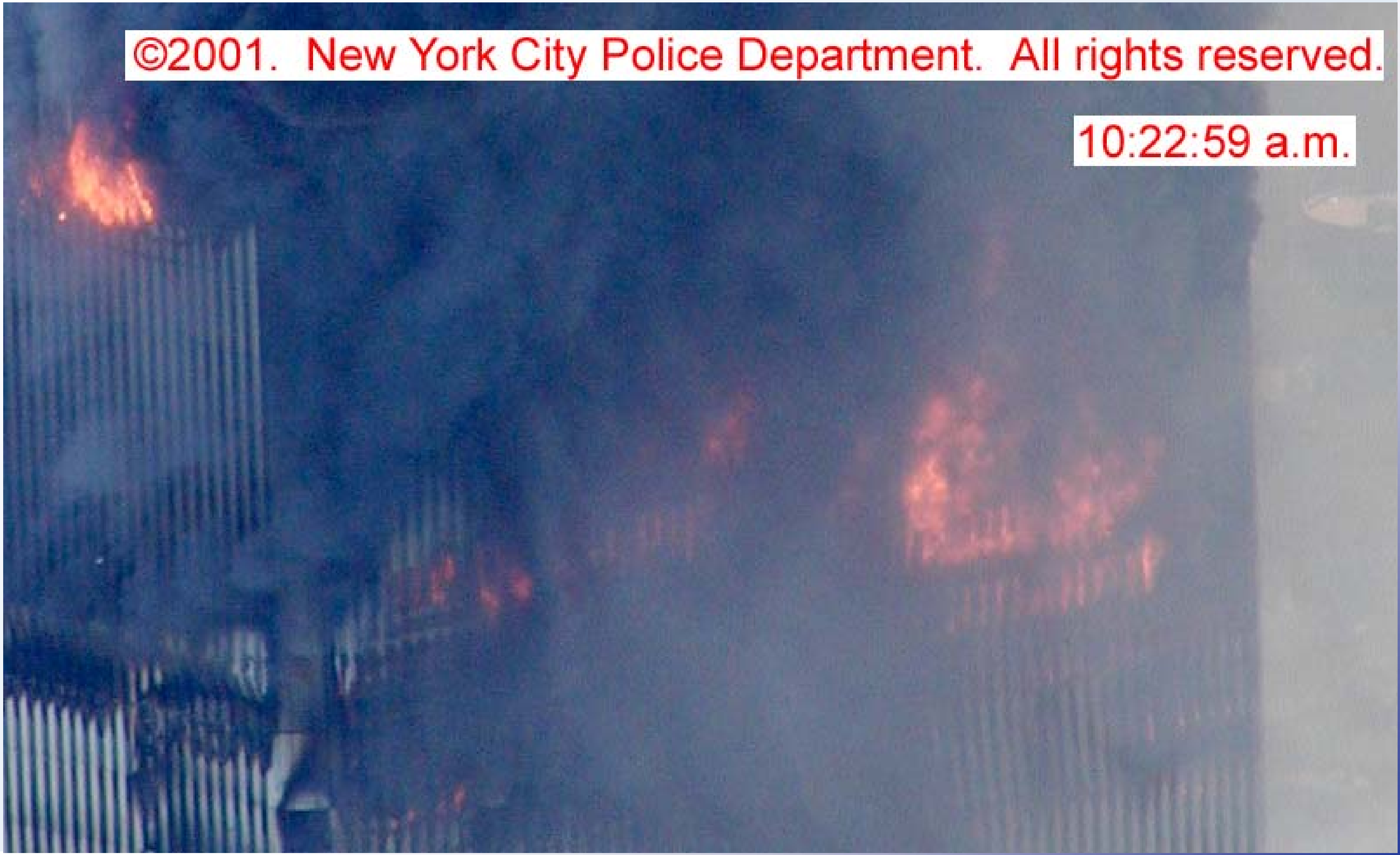
- Aircraft impact damage to perimeter columns mainly on the South face, resulted in redistribution of column loads, mostly to the adjacent perimeter columns and to a lesser extent to the core columns.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, damaging floor framing, core columns, and fireproofing. Loads on the damaged columns were redistributed to other intact core and perimeter columns mostly via the floor systems and to a lesser extent via the hat truss.
- The subsequent fires, influenced by the impact damaged fireproofing condition:
  - Caused significant sagging of floors on the East side which induced the floors to pull the perimeter columns inward on the East face.
  - Softened and buckled the core columns on the East side and caused them to shorten, which transferred significant additional load to the perimeter columns on the East face primarily through the floor system and to a lesser extent through the hat truss.
  - Softened some of the perimeter columns that were exposed to high temperatures towards the northern half of the East face.
- Due to the additional loads on the perimeter columns on the East face and the inward pulling of those perimeter columns, the East perimeter wall bowed inwards, and highly stressed sections buckled.
- The section of the building above the impact zone began tilting to the East and South as both the East perimeter columns and the impact-damaged South perimeter columns buckled, and instability rapidly progressed horizontally across both faces and across the North face.
- The change in potential energy due to downward movement of building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued.

Working Hypothesis: Factors Evaluated

- Innovative structural system
- Aircraft impact and subsequent fires
- Post-impact condition of fireproofing
- Quality and properties of structural steel
- Relative roles of the perimeter and core columns and the composite floor system, including connections

Working Hypothesis is consistent with all evidence currently held by NIST, including photographs and videos, eyewitness accounts, and emergency communication records

Inward Bowing of Perimeter Columns Some Minutes Prior to Collapse: WTC 1 South Face



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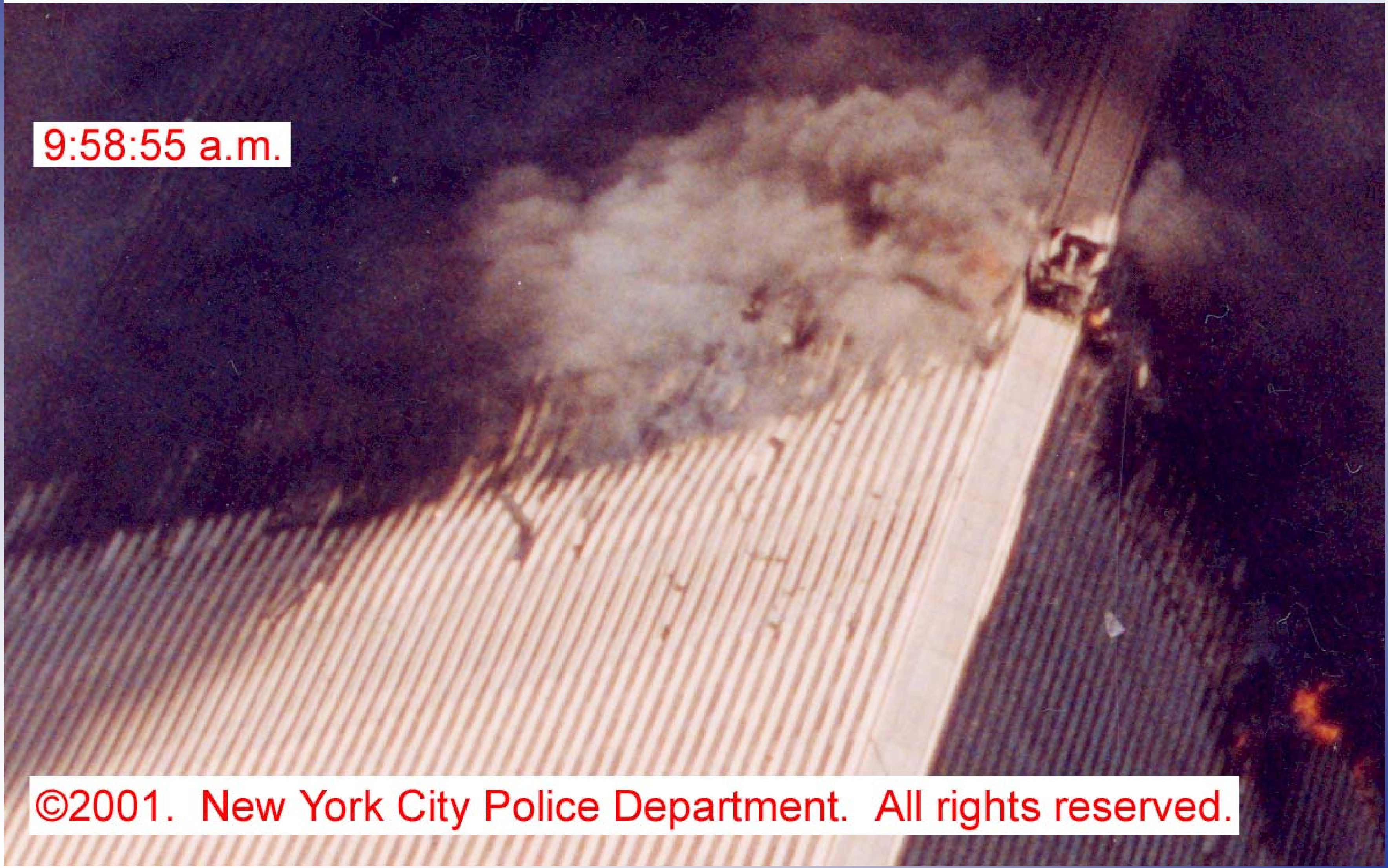
Inward Bowing of Perimeter Columns Some Minutes Prior to Collapse: WTC 2 East Face



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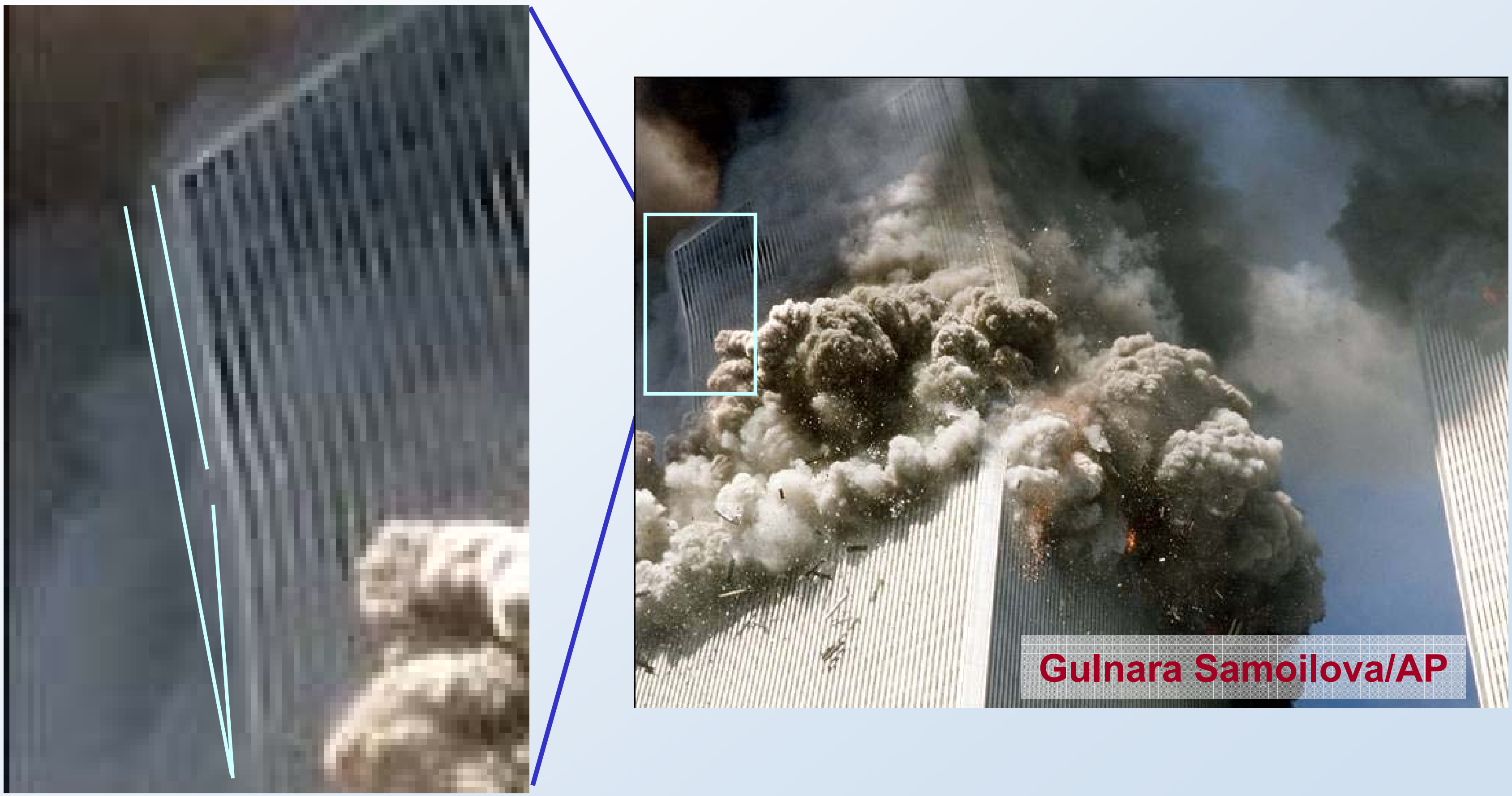
Kink Observed at 106th Floor of WTC 2

- Likely associated with inward pulling by hat truss or rigid structure provided by beam-framed upper floors due to core column impact/fire damage.

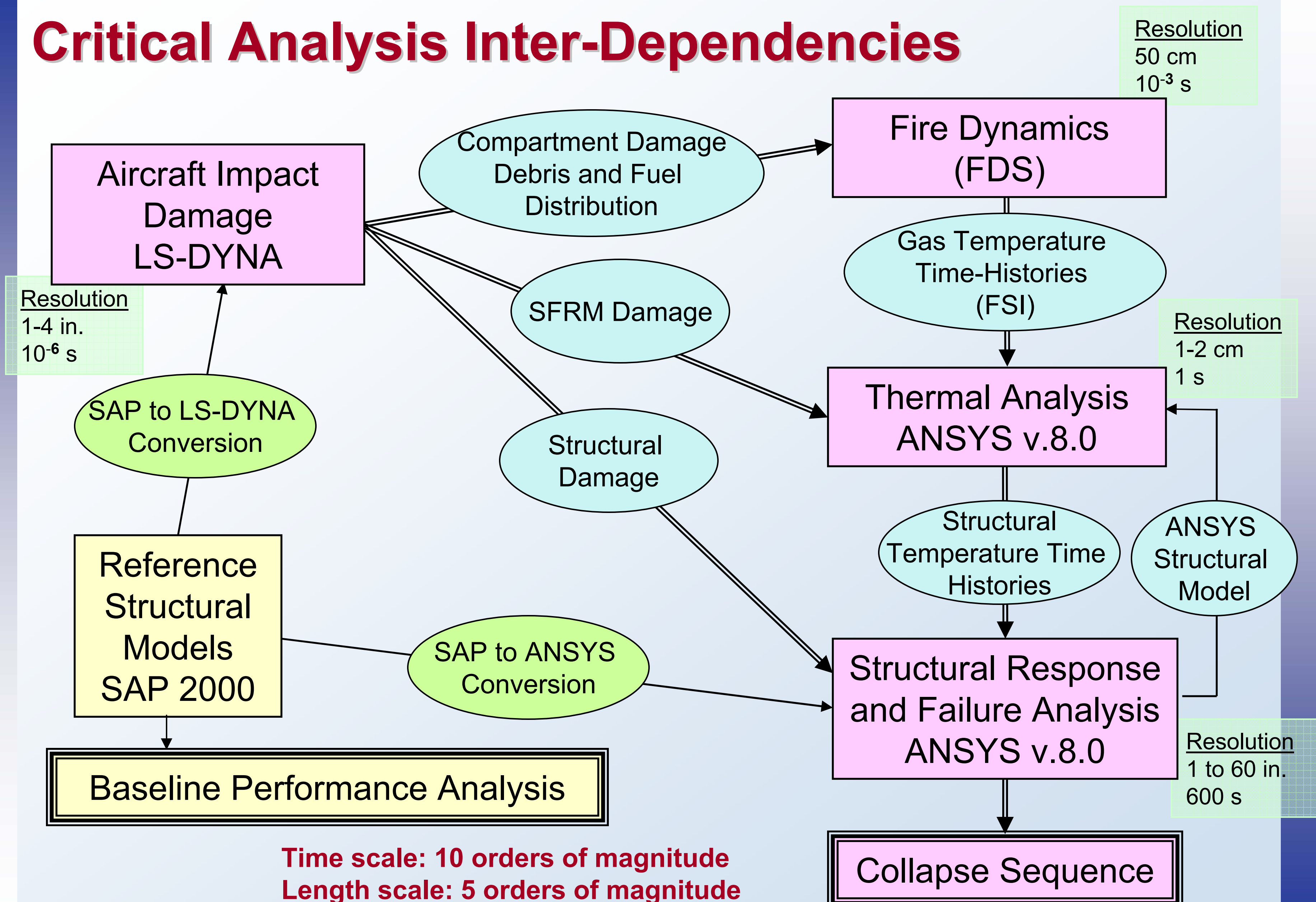


Tilting of Building Sections

Initiation of global collapse was first observed by the tilting of building sections above the impact regions of both WTC towers.

WTC 1 tilted to the south; WTC 2 tilted to the east and south and twisted in a counterclockwise motion

Critical Analysis Inter-Dependencies



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Determining the Probable Collapse Sequence

- Conduct extensive sensitivity analyses to determine most influential factors for each analysis step.
- Determine three sets of most influential factors for each analysis step: realistic case, more severe case, less severe case.
- The set of most influential factors is highly correlated for the different analysis steps (i.e., they are not independent). For example, the more severe case of aircraft impact damage, results in the more severe case of fire dynamics, and they in turn lead to the more severe case of thermal analysis, and together they led to the more severe case of structural response analysis.
- The first analysis sequence considers the set of factors for the ***realistic case*** in each of the steps.
- A second analysis sequence is conducted to confirm the results for the realistic case.
  - If the results for the realistic case suggest the possibility of more damage due to impact and fire, the second analysis sequence considers the set of factors for the ***more severe case*** in each of the steps.
  - If the results for the realistic case suggest the possibility of less damage due to impact and fire, the second analysis sequence considers the set of factors for the ***less severe case*** in each of the steps.
- The analysis sequence is repeated with additional cases for the set of factors to determine the probable collapse sequence that best matches the observations.

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Aircraft Impact Damage to WTC 1

Column Damage

Fireproofing and Partitions

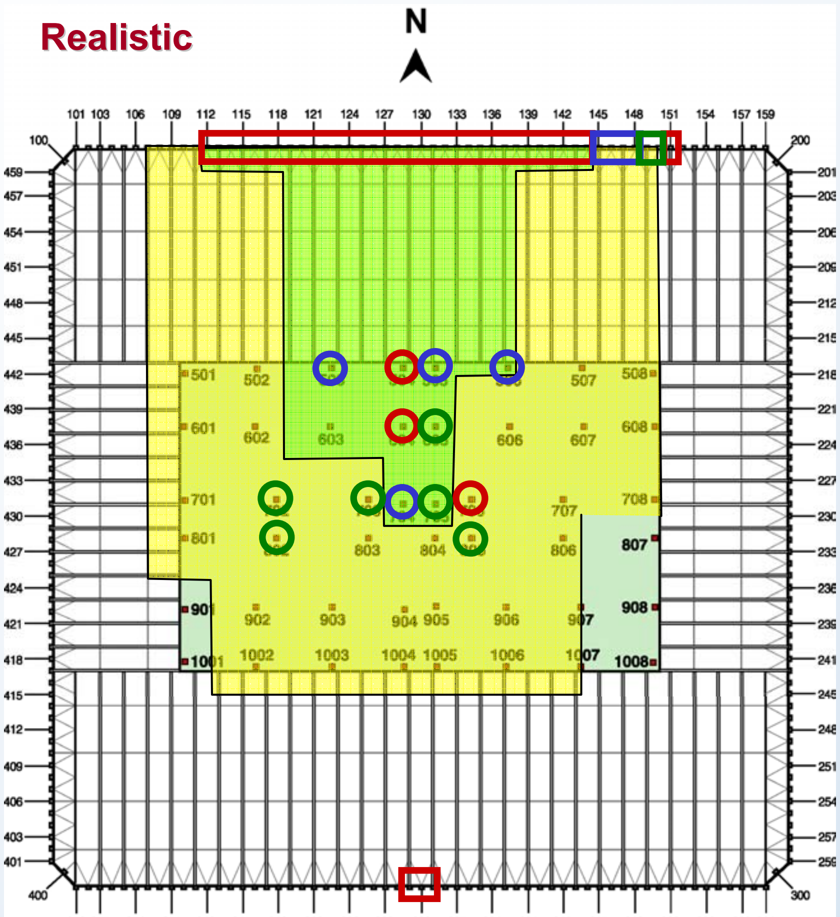
Floors

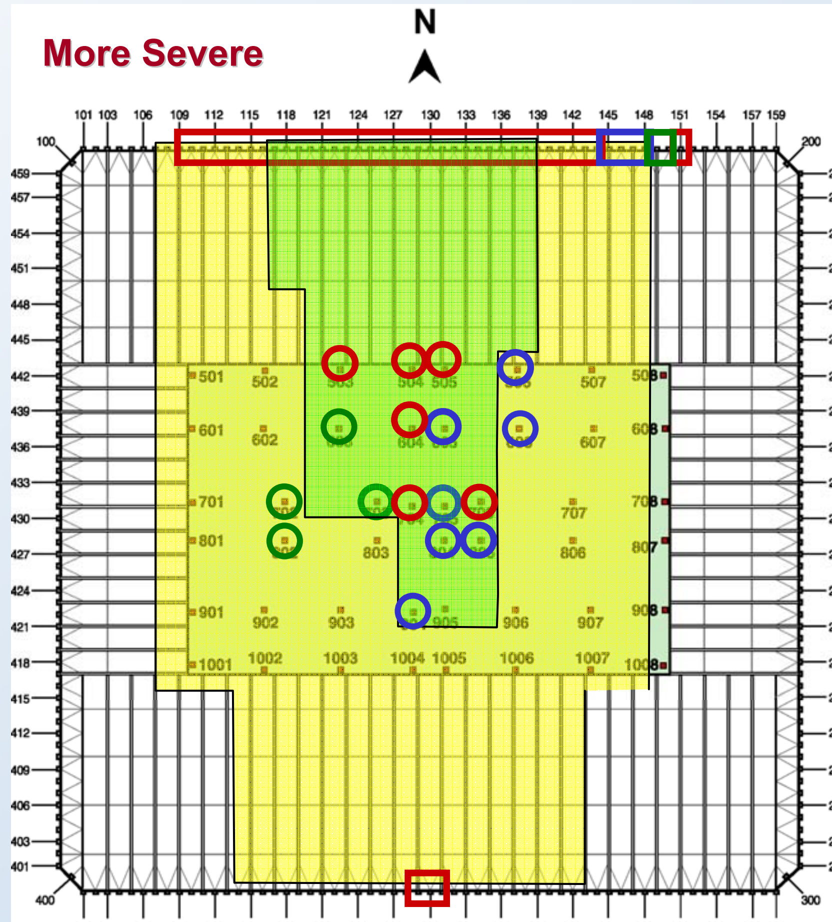
Column Damage

Severed

Heavy Damage

Moderate Damage





Aircraft Impact Damage to WTC 2

Column Damage

Fireproofing and Partitions

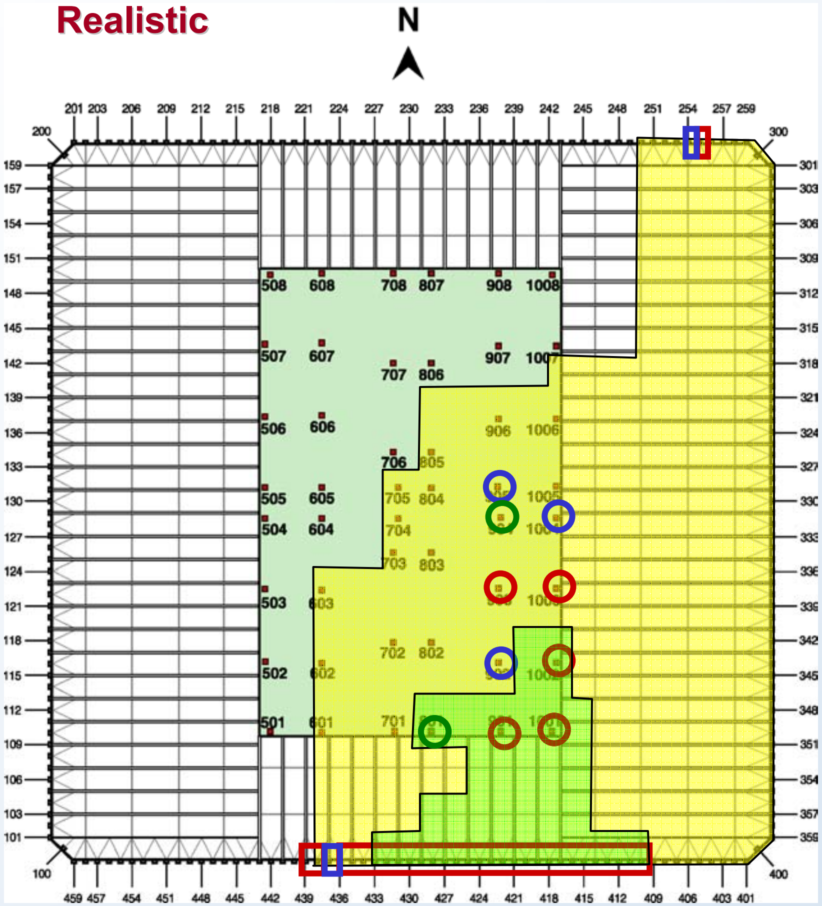
Floors

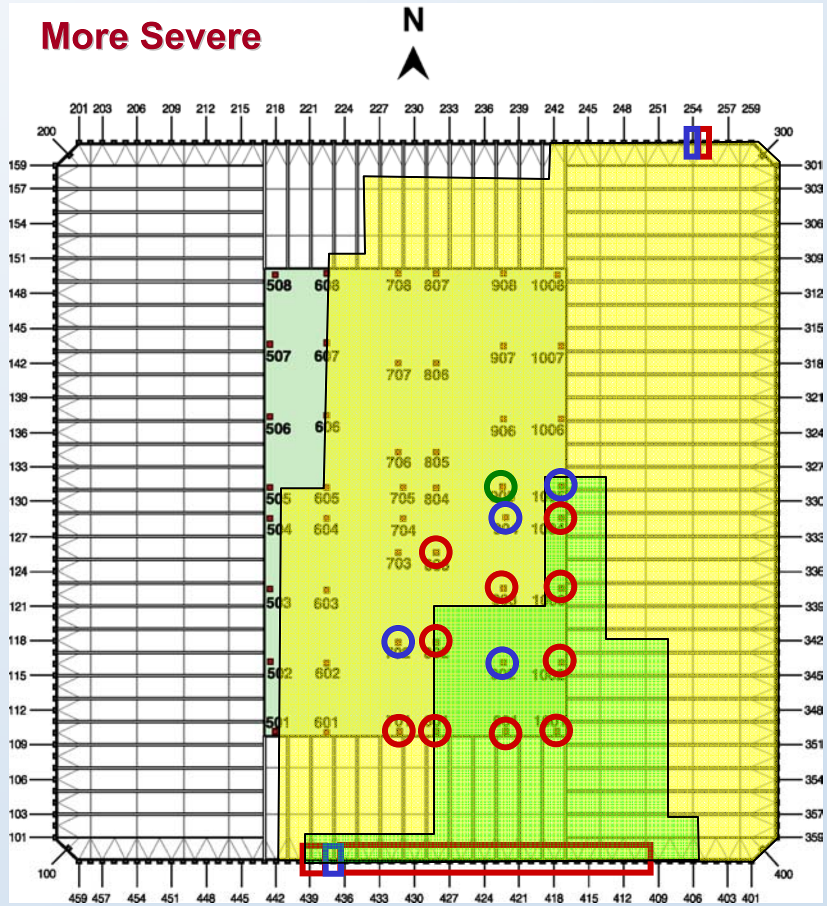
Column Damage

Severed

Heavy Damage

Moderate Damage



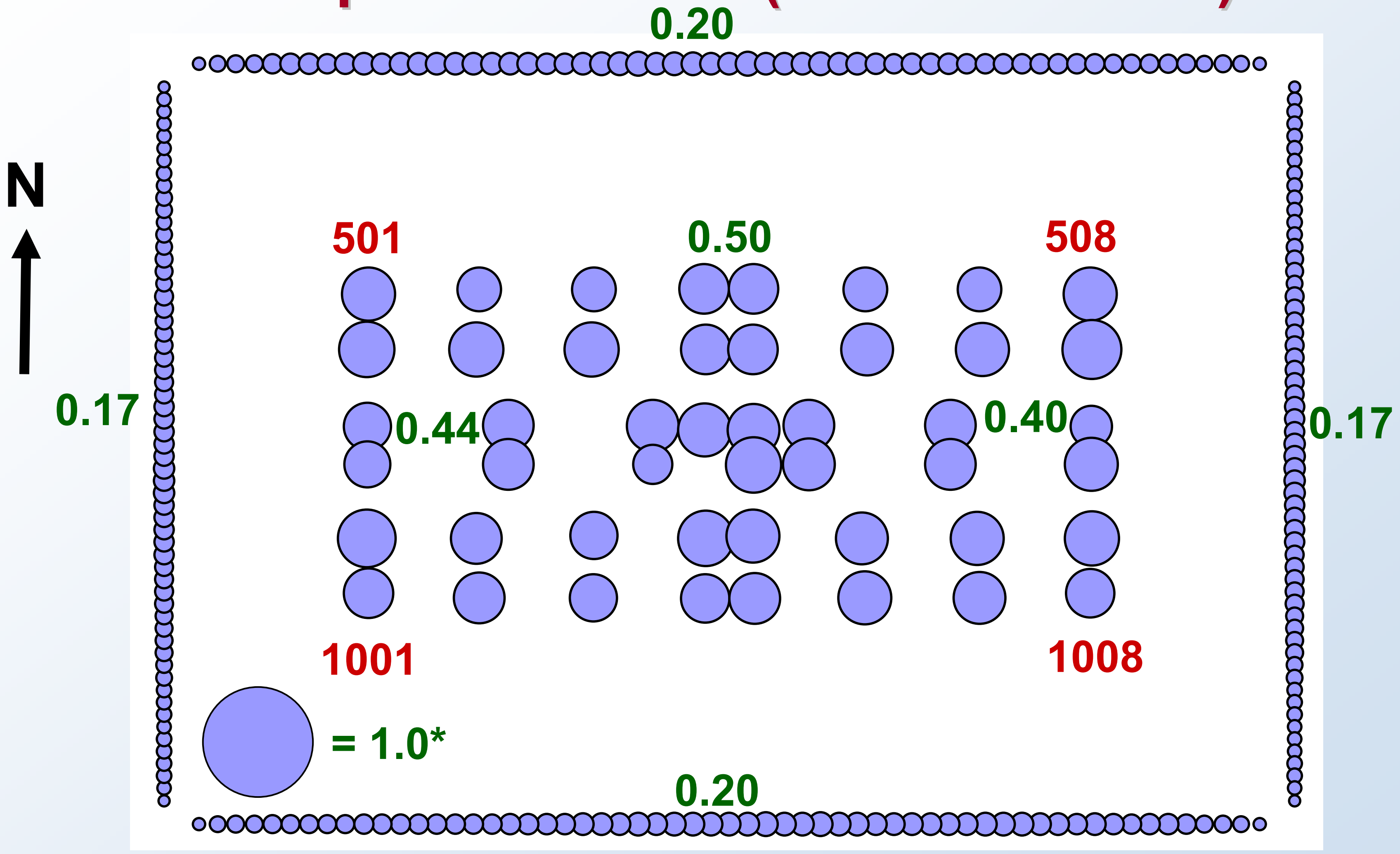


Comparison of Damage to Core Columns with Prior Studies

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

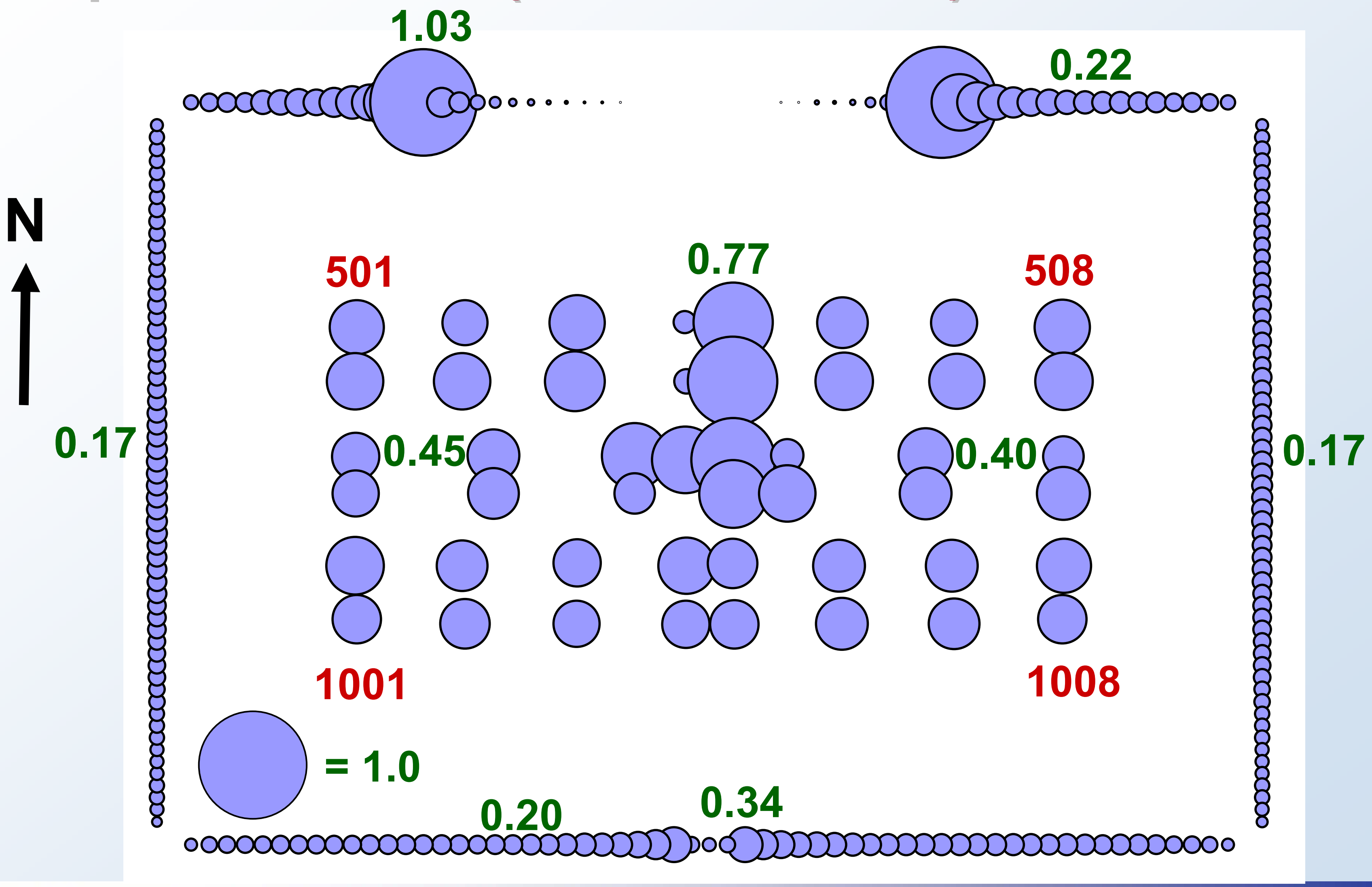
MIT study reported in Chapter 4 of a collection of essays by MIT researchers "The Towers Lost and Beyond," 2002.
Weidlinger study prepared for Silverstein Associates as part of insurance litigation involving the WTC towers, 2002.

Column Demand/Capacity Ratios Before Aircraft Impact in WTC 1 (Floors 93 to 98)



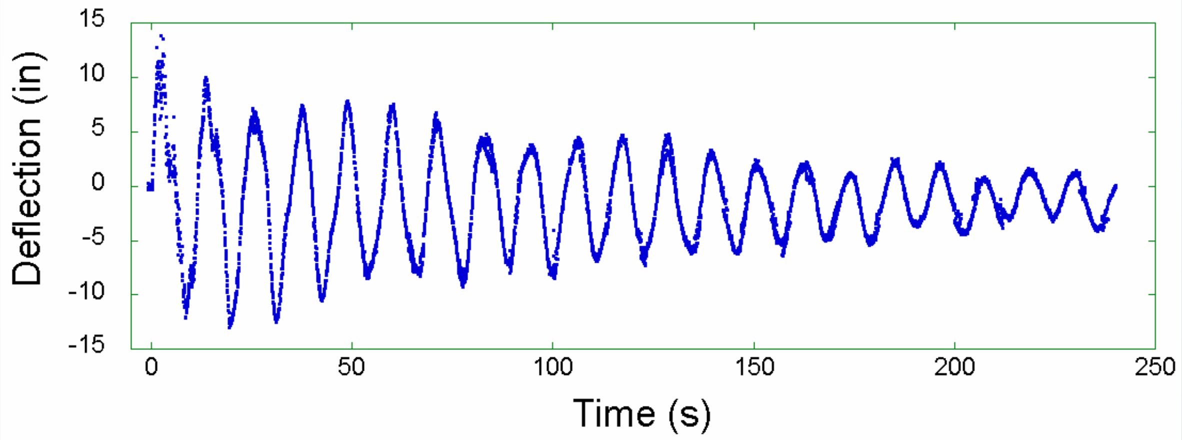
*Design intent is for columns with DCR < 1; plastic deformations can accommodate DCR > 1

Column Demand/Capacity Ratios After Aircraft Impact in WTC 1 (Floors 93 to 98)



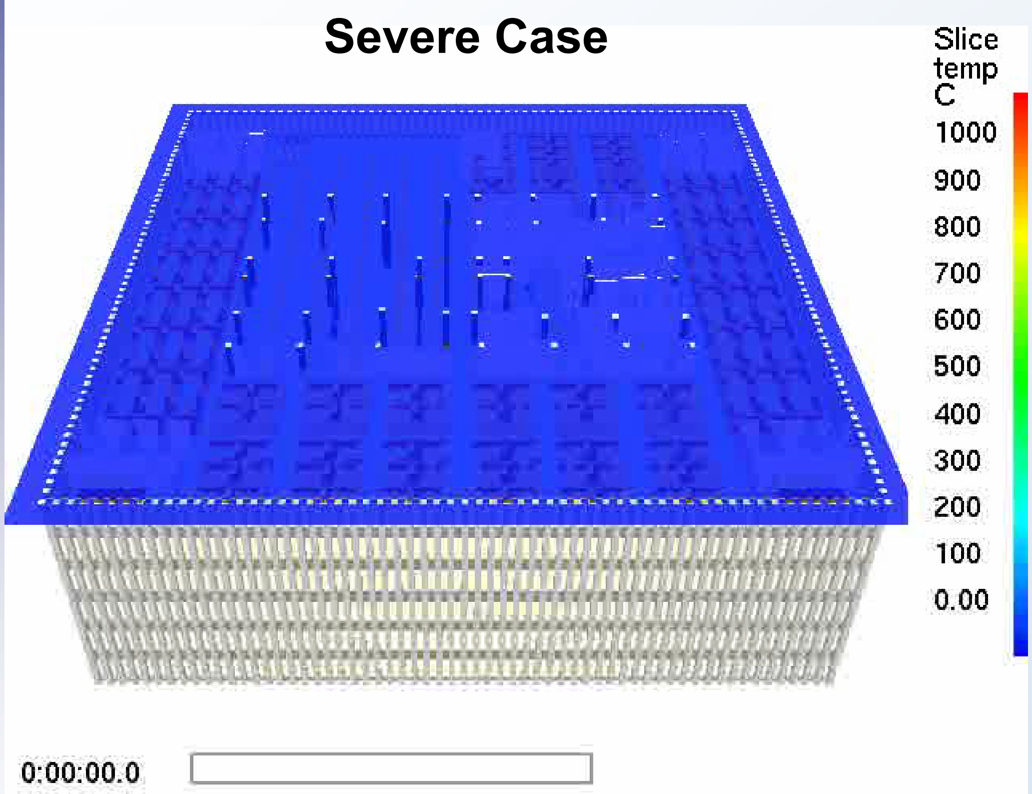
Aircraft Impact Damage to WTC Tower Structures

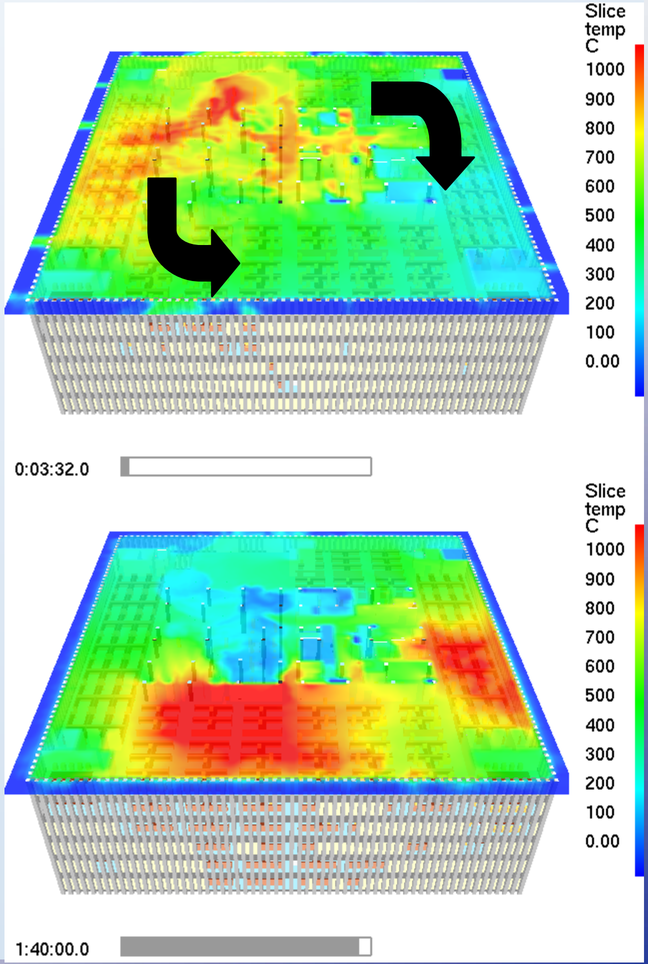
- The two WTC towers withstood the initial impact of virtually identical aircraft (Boeing 767-200ER) during the terrorist attacks of September 11, 2001.
- The robustness of the perimeter frame-tube system and large dimensional size of the WTC towers helped the buildings withstand the aircraft impact.



- The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were about 40 percent of the amplitudes for design wind conditions expected by the building designers and an oscillation period nearly equal to that measured for the undamaged building.
- **Calculations of demand to capacity ratios due to aircraft impact damage showed that for the floors affected by the aircraft impacts, the majority of the core and perimeter columns in both towers continued to carry their loads after the impact. The loads from damaged and severed columns were taken over by nearby undamaged columns.**
- **The above finding supports the fact that the WTC towers withstood the initial aircraft impact and the finding that they would have continued to remain standing indefinitely but for another significant event such as the subsequent fires.**

Upper Layer Temperatures (WTC 1, Floor 97)

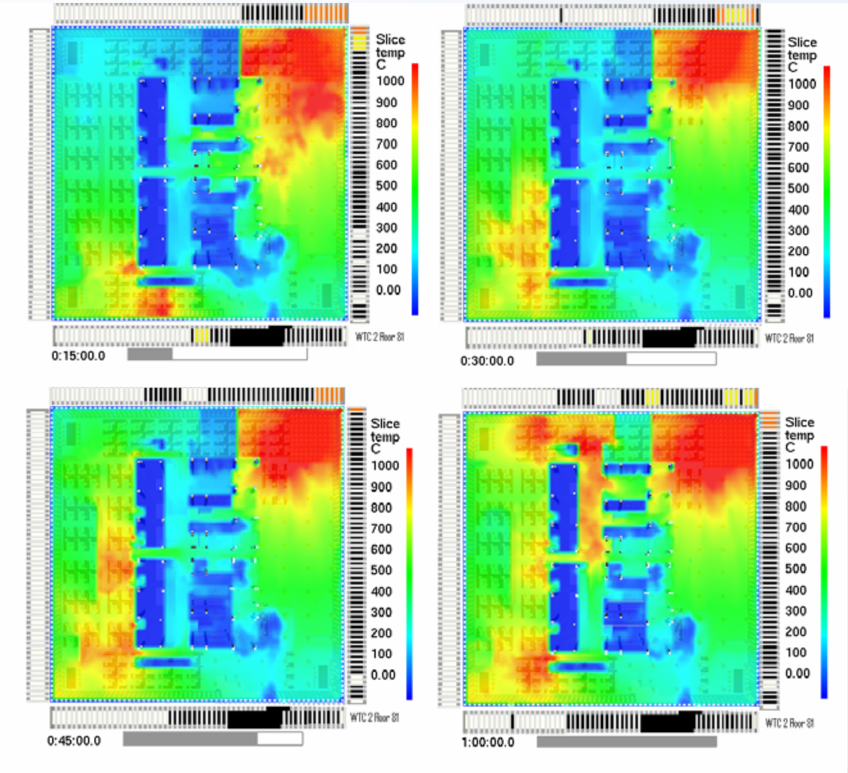




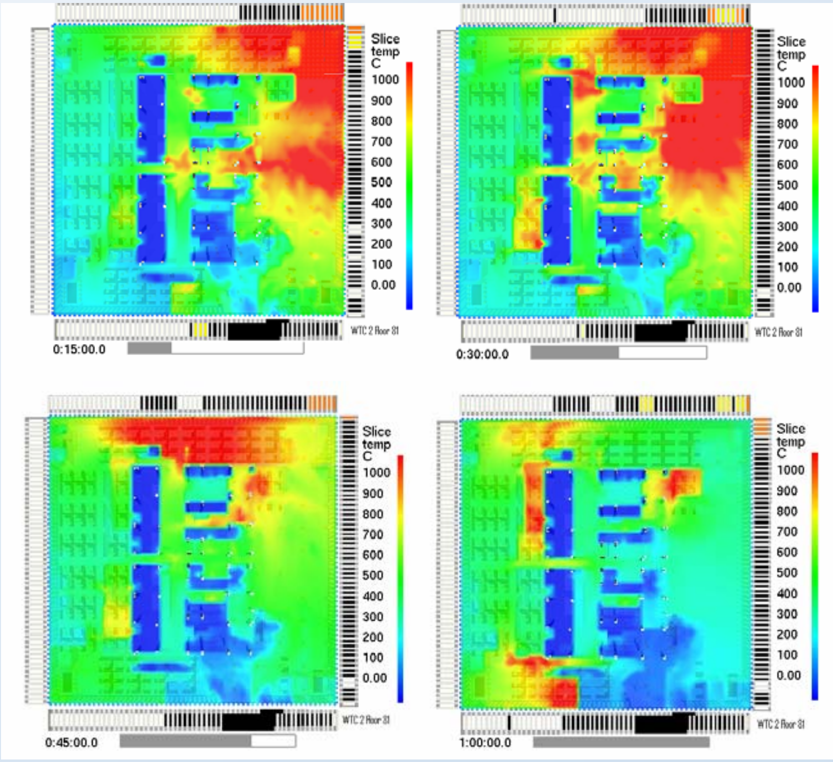
Reconstruction of Fires (WTC 2, 81st Floor)

Combustible Load more critical in WTC 2

Realistic Case



More Severe

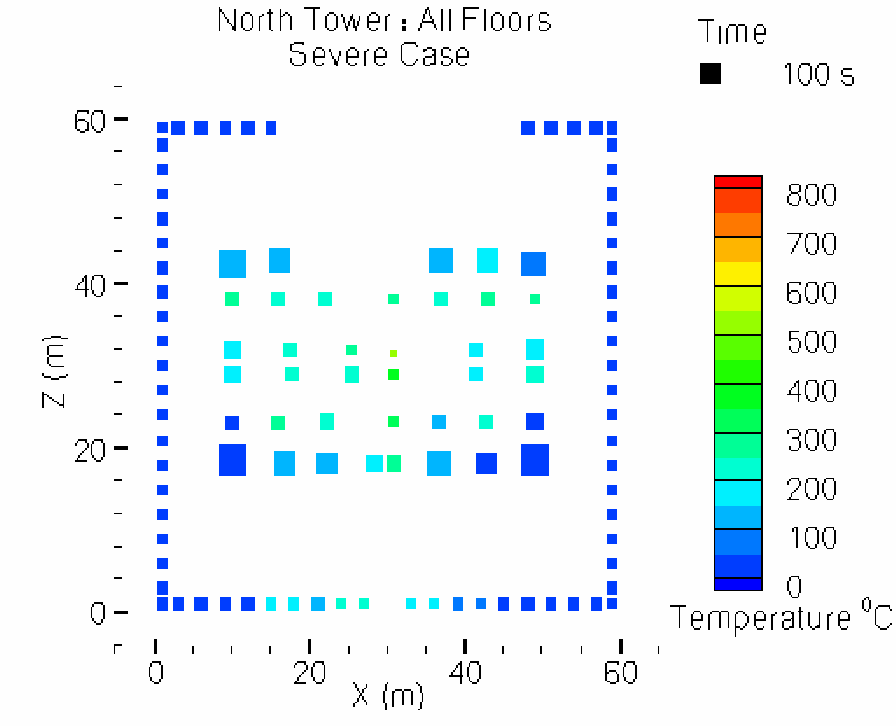


Relative Roles of Aircraft Impact and Fires

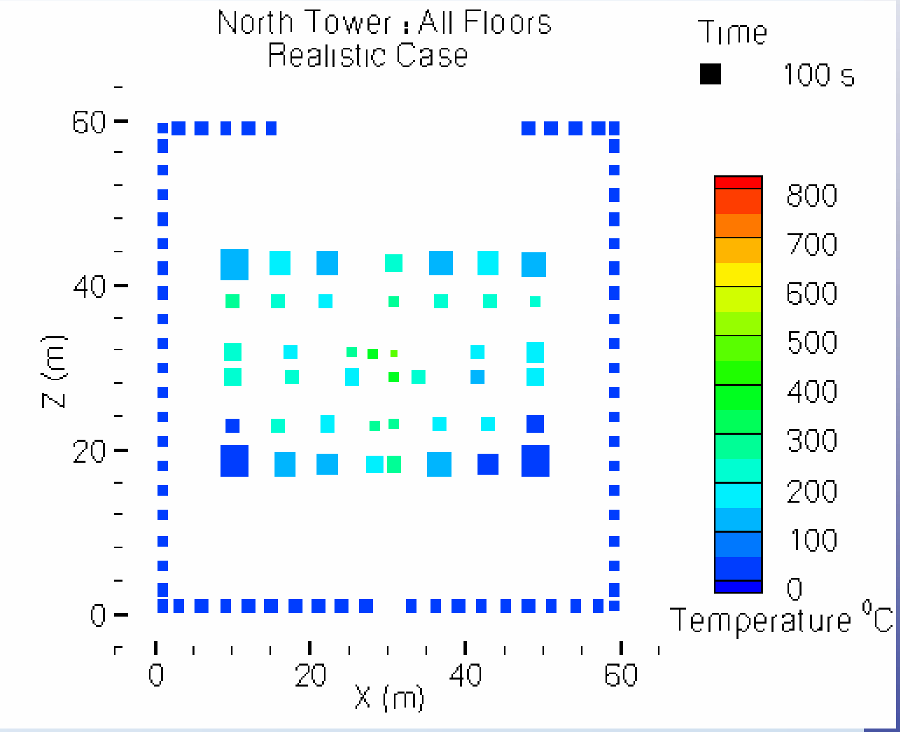
- **Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires** by:
  - Compromising the sprinkler and water supply systems;
  - Dispersing jet fuel and igniting building contents over large areas;
  - Creating large accumulations of combustible matter containing aircraft and building contents;
  - Increasing the air supply into the damaged buildings that permitted significantly higher energy release rates than would normally be seen in ventilation limited building fires, allowing the fires to spread rapidly within and between floors; and
  - Damaging ceilings that enabled "unabated" heat transport over the floor-to-ceiling partition walls and to structural components.
- **The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.**
- **Typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor. The typical floor had on average about 4 psf of combustible materials on floors.** Mass of aircraft solid combustibles was significant in the immediate impact region of both WTC towers.

Results of Thermal Analysis for WTC 1

Severe Case

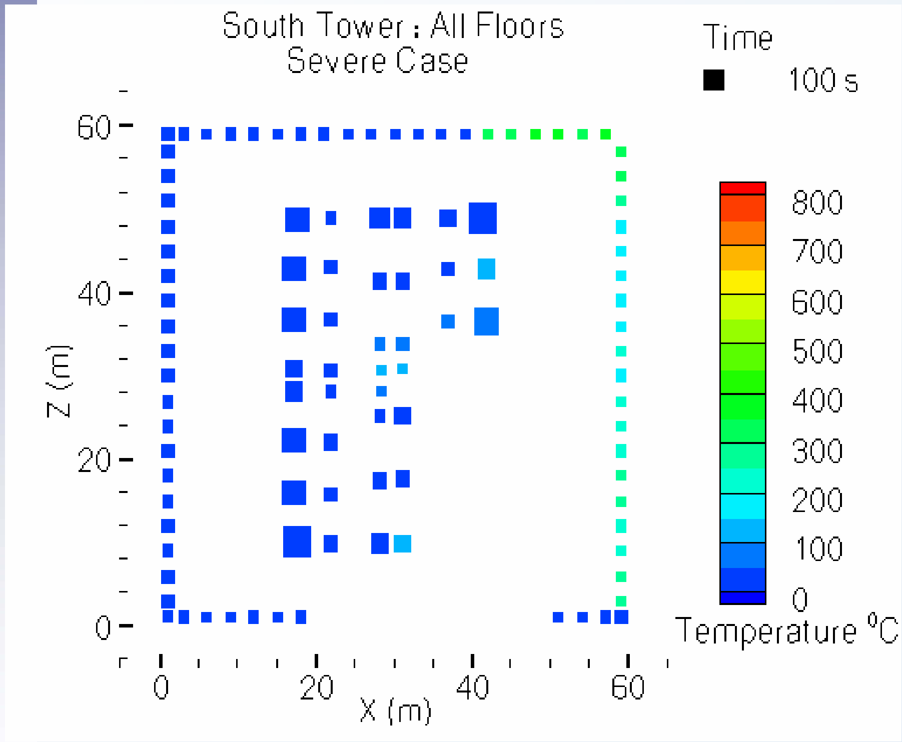


Realistic Case

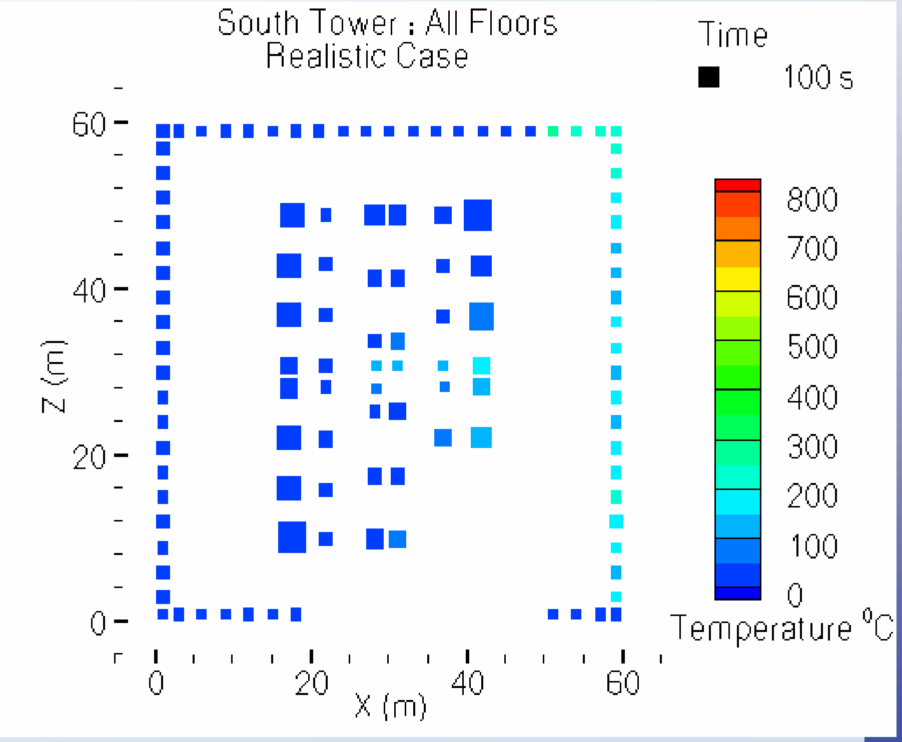


Results of Thermal Analysis for WTC 2

Severe Case



Realistic Case



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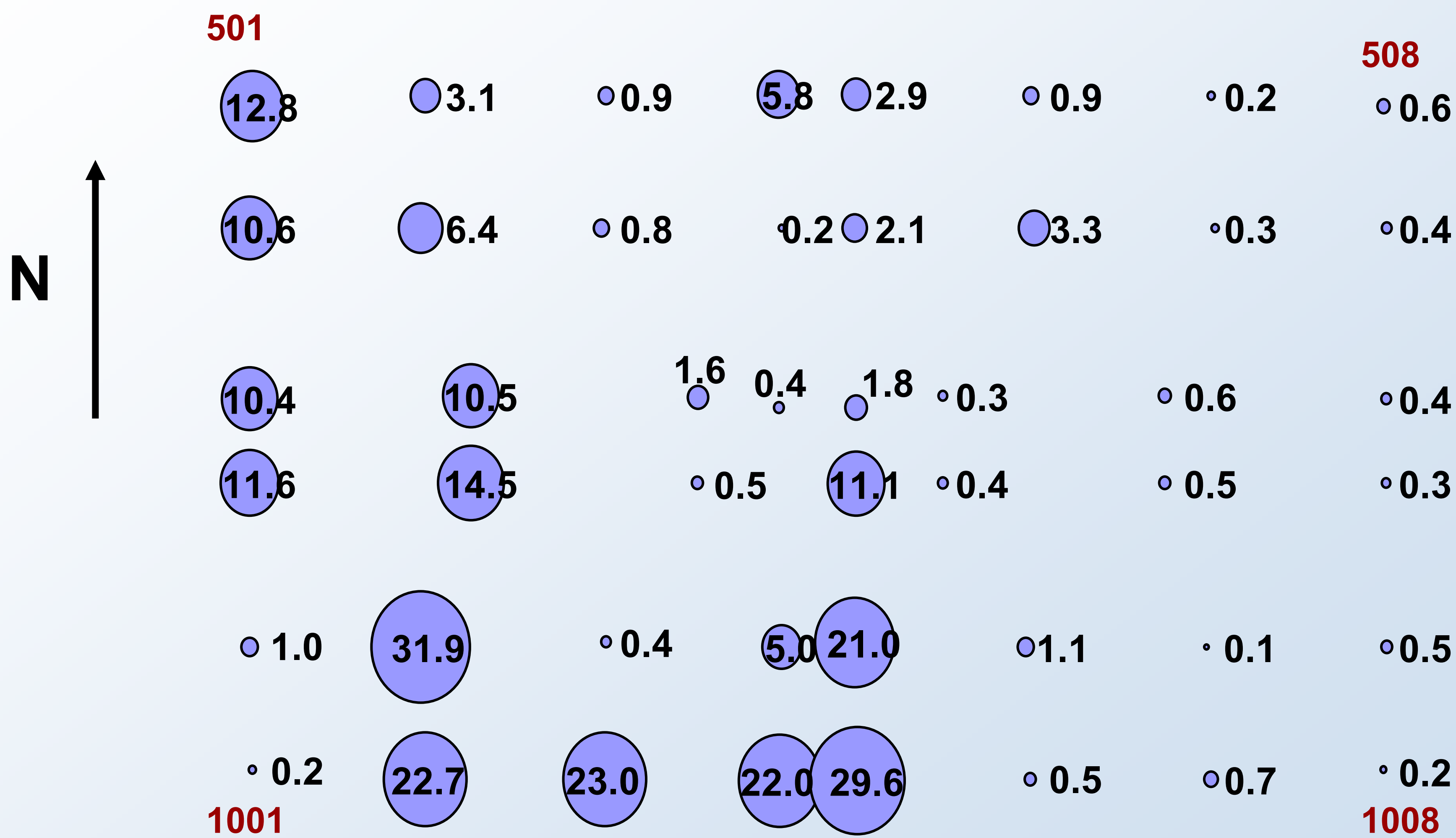
Column Shortening in WTC 1 Measured by Ratio of Plastic-to-Elastic Strain (Ductility) at 6000 s



Creep and nonlinear buckling will increase core shortening

Findings on Leading Collapse Hypotheses

- **The time delay between the collapses of the WTC towers was due primarily to:**
  - **The asymmetric structural damage due to aircraft impact in WTC 2 compared to WTC 1.**
  - **The time it took for heat to soften and buckle, and thereby shorten, the core columns that had fireproofing dislodged by debris impact.**
  - **The structure's ability to redistribute loads as the core columns shortened.**
  - **The time it took for the fires to traverse from their initial location to the face of the towers where perimeter columns were bowing inwards, as seen only minutes prior to the collapse of each tower (the traverse time of fires to the South face of WTC 1 was much longer than on the East face of WTC 2 where the fires already existed).**
  - **The time it took for heat to soften and buckle those perimeter columns.**

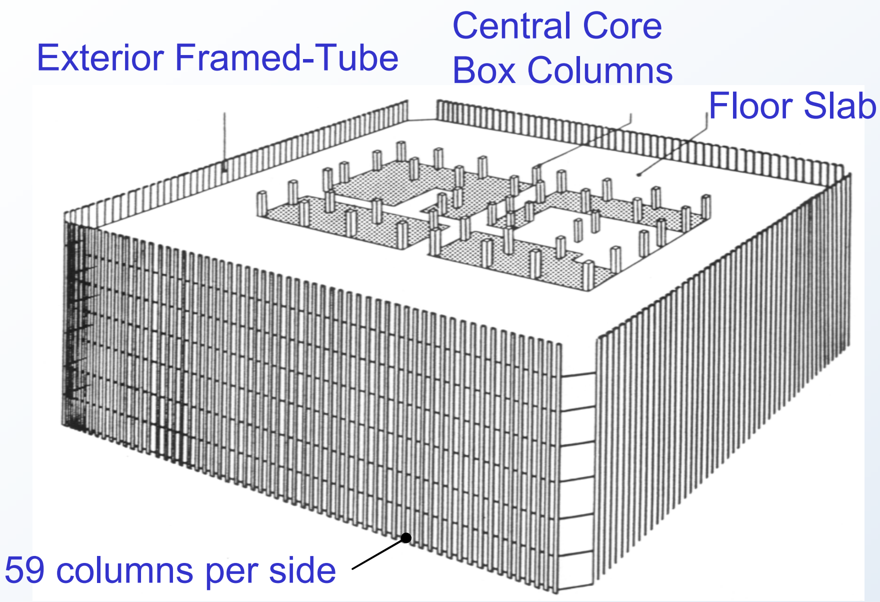
- **The composite trussed floor system pulled the perimeter columns inwards on the South face of WTC 1 and East face of WTC 2.** The inward pulling by the floor system was induced by shortening of the core columns and, augmented in WTC 2, by significant sagging of the floor system on the East side.

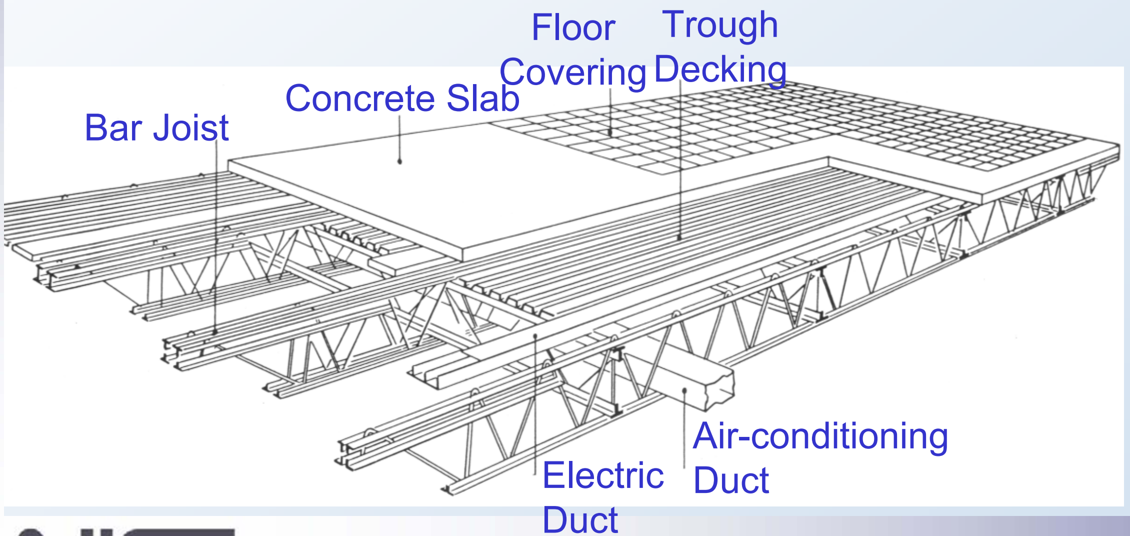
- **The heating of the structural members was more sensitive to the effect of dislodged fireproofing due to debris from aircraft impact than to episodic regions of missing fireproofing or thinness of fireproofing.**

- The debris field generated by aircraft impact removed significant fireproofing and gypsum board boxing, as well as some of the walls. **The structural components that became thermally weakened were generally determined by the debris field. Had the fireproofing not been dislodged by the debris field, the temperature rise of structural components would likely have been insufficient to induce global collapse.**

- **The time to destructive heating was determined by the fires,** whose extent and intensity was determined by the jet fuel and the nature and (rather low) loading of combustibles, **the sparseness of initial or surviving building partitions, and the ease with which windows were displaced.**

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

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 of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
  - 1/2 in. specified when WTC towers were built
  - 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	3	2
Floors	3	2	1-1/2

*   **Building code governing original design and occupancy**
** **Sprinklers required for buildings of unlimited height**

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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 all tests.
- 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 and 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 likely cause of the difference in results is not the fireproofing thickness on the trusses themselves, but the presence or lack of fireproofing 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.**

- 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 fire conditions in the WTC towers due to the terrorist attacks on September 11, 2001 were far more extreme than those 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.

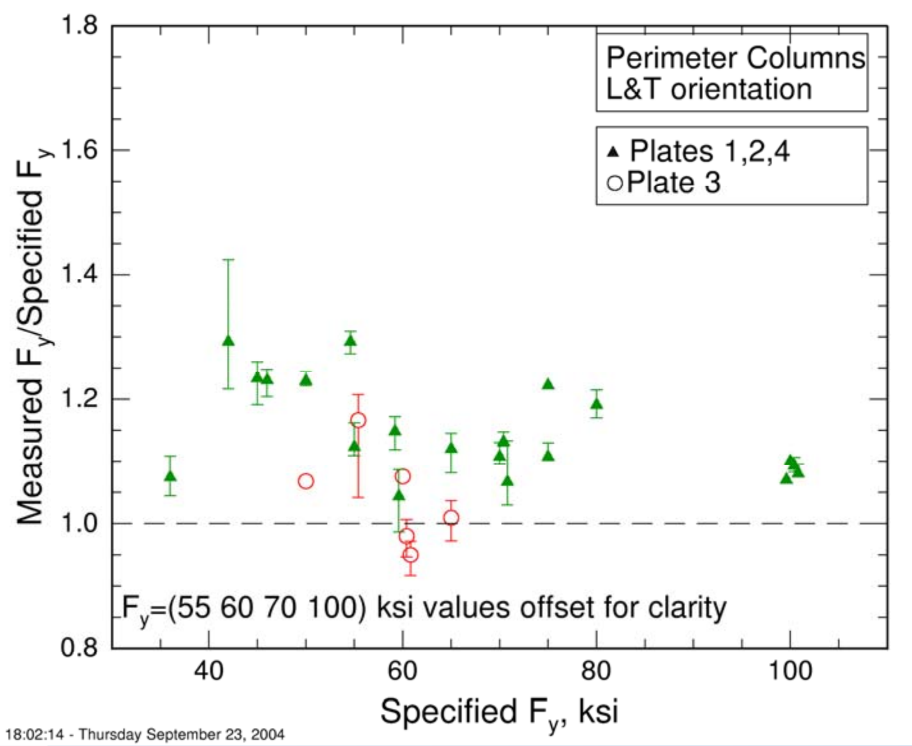
- The leading collapse hypotheses for the WTC towers are based on the behavior of thermally weakened structural components that had extensive damage to fireproofing or gypsum board fire protection induced by the debris field generated by aircraft impact.

Analysis of Recovered WTC Steel

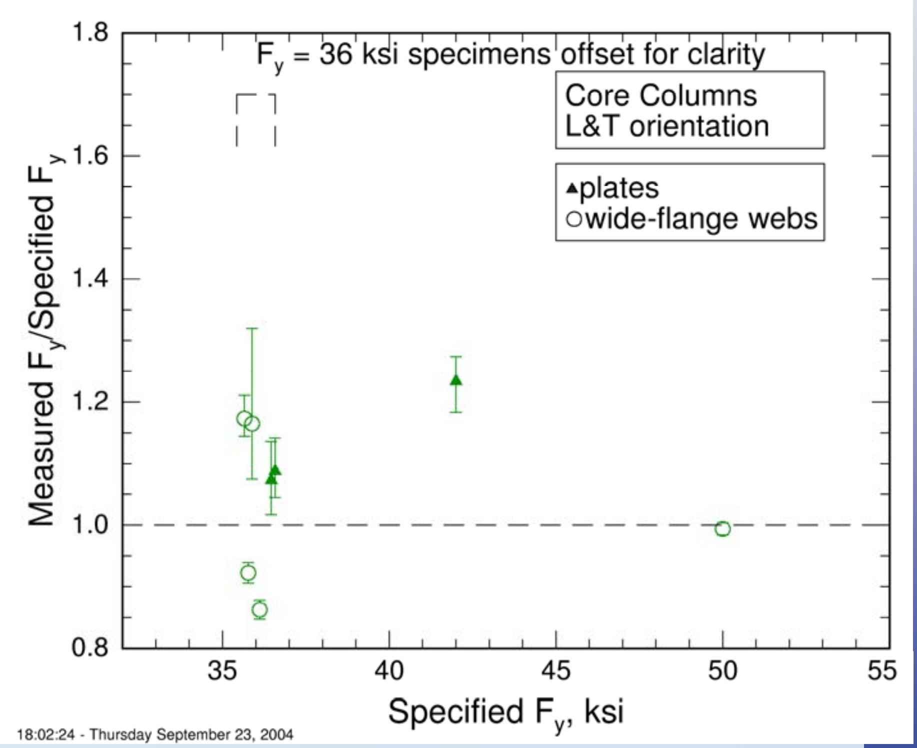
- NIST has a total of 236 WTC steel pieces in its possession; collection was adequate for determining the quality and properties of steel for the investigation.
  - Impact/fire damage region emphasized
  - All 14 grades of steel for perimeter columns
  - Both grades for steel trusses
  - Two grades (representing 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

Comparison of Specified Properties with Measured Properties at Room Temperature

Perimeter Columns



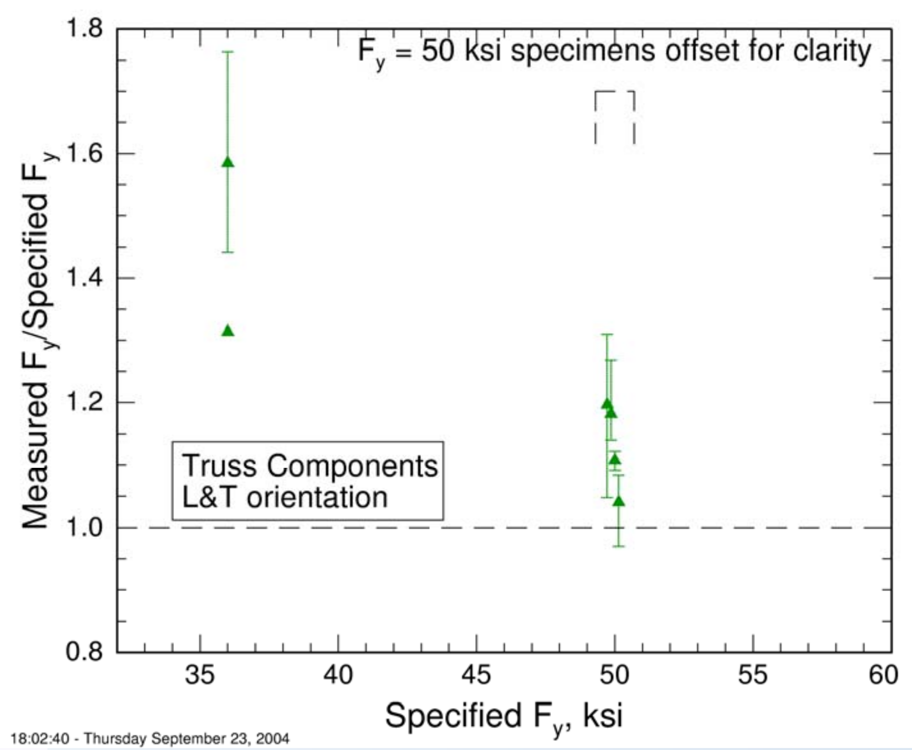
Core Columns



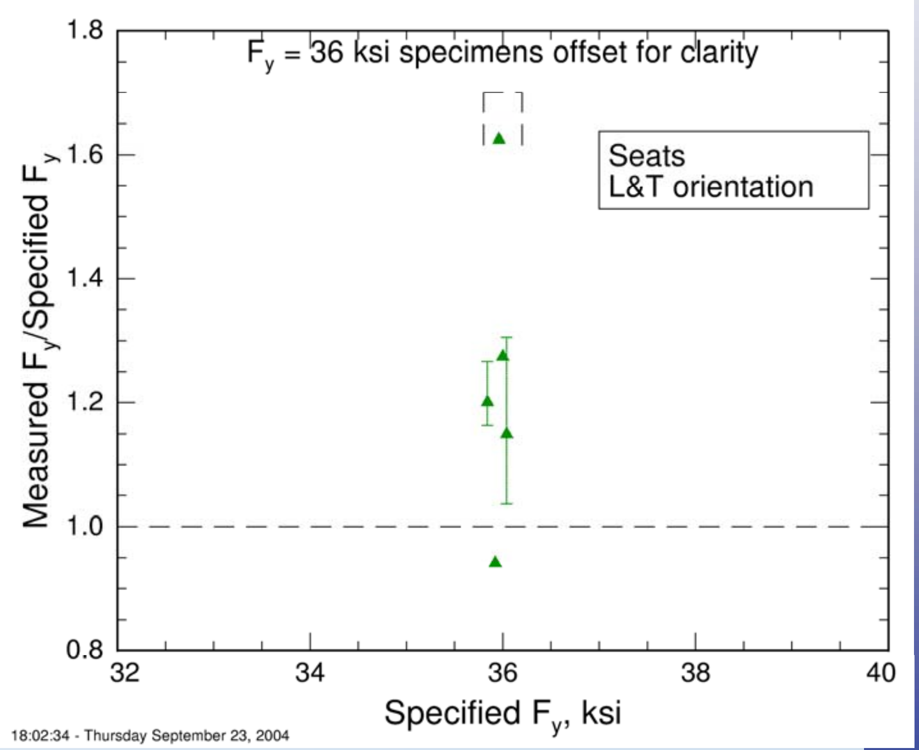
NIST

Comparison of Specified Properties with Measured Properties at Room Temperature

Floor Truss Components



Truss Seats



NIST

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 required minimum yield strength. The typical factors of safety in allowable stress design can accommodate the measured property variations below the minimum.**

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 information in original source documents to determine design wind loads for the WTC towers.

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
- Wind load estimates developed by NIST, based on ***state-of-the-art considerations*** applied to the RWDI data, and reviewed by SOM under contract to NIST, 2004

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

NIST

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).
- Resultant wind load estimates developed by NIST based on state-of-the-art considerations 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.**

NIST

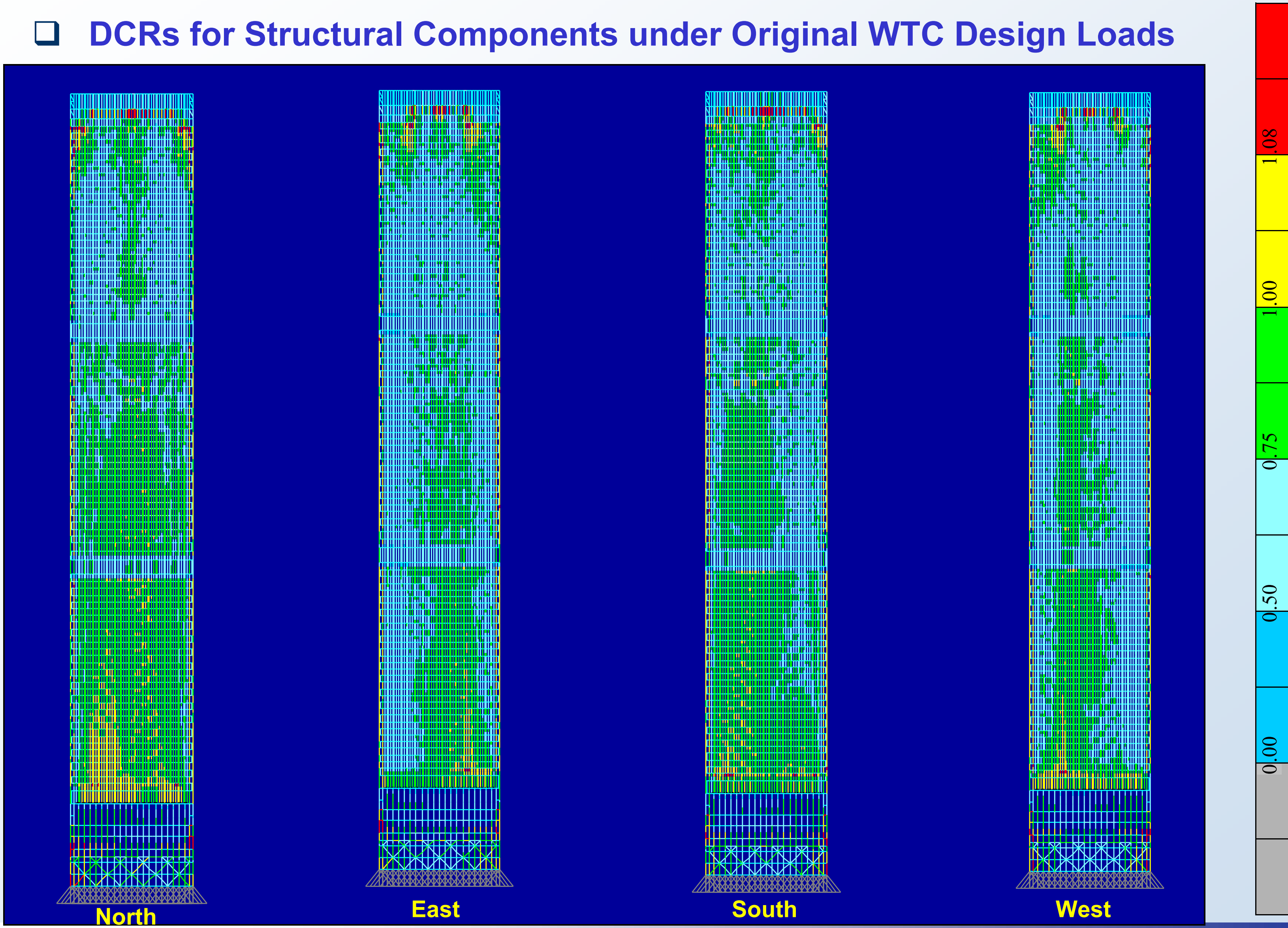
Results of Baseline Analysis

- Analysis completed by LERA under contract to NIST. Results presented reviewed by NIST and SOM under contract to NIST.
- Demand/Capacity ratios (DCRs) for structural components estimated using Allowable Stress Design (ASD).
- Calculated drift (maximum sway at roof) due to original design wind loads:
  - WTC 1: 4 ft – 8.6 in. (~ H/300)
  - WTC 2: 5 ft – 5.4 in. (~ H/260)
- Typical drift ratios considered in practice (not required by building codes):
  - H/500 in Chicago (~ 2 ft – 8.9 in.)
  - H/400 in New York City (~ 3 ft – 5.0 in.)

NIST

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

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

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 **state-of-the-art case** exceed those from the original design and state-of-the-practice cases due to the following reasons:

  - SOA wind loads are higher than those used in the lower bound SOP case by about 25 percent. Note that SOA wind loads are 20 percent smaller than those obtained by CPP (an upper bound SOP case).

  - The current national standard for loads (ASCE 7-02) does not allow the 1/3 increase of allowable stresses under wind loads.

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 SOA case.
  - 1.26 and 1.44 for perimeter columns in the original design and SOP case (discounting the 1/3 increase in allowable stress under wind loads).
- After reaching the yield strength, structural steel components continue to possess significant reserve capacity, thus allowing for load redistribution to other components that are still in the elastic range.
- On September 11, the towers were subjected to in-service live loads, which are considered to be approximately 25 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 capacity.**

NIST

Evacuation and Emergency Response

Based on interviews of over 1,000 WTC surviving occupants:

- **It is estimated that 17,400 occupants (± 1,200) were present in the WTC towers on the morning of September 11, 2001.** The initial population of each tower was similar: 8,900 (± 750) in WTC 1 and 8,500 (± 900) in WTC 2. Of those present on September 11, 2001, 16 percent were also present during the 1993 bombing.

- **About 6 percent of the surviving occupants reported a pre-existing limitation to their mobility.** These limitations included obesity, heart condition, needing assistance to walk, pregnancy, asthma, being elderly, chronic condition, recent surgery or injury, and other.

- **About 7 percent of the surviving occupants reported having special knowledge about the building.** These included fire safety staff, floor wardens, searchers, building maintenance, and security staff. Searchers assist the floor wardens in facilitating evacuation.

Decedent Analysis

September11Victims.com: This site is dedicated to the victims of September 11, 2001 tragedy.

Portraits: 9/11/01: Published by the New York Times in 2003, this book includes short interviews with family members of many decedents.

CNN.com In-Depth Special (http://www.cnn.com/SPECIALS/2001/memorial/index.html): Tribute site for people to write remembrances of decedents.

Badge List maintained by Port Authority of New York and New Jersey: Includes name, employer, building, and floor for all occupants with badge-access to WTC 1 or WTC 2.

Numerous memorial sites maintained by companies which lost employees: Includes names and remembrances of decedents. Examples include the Port Authority, Fire and Police Departments, Marsh & McLennan Companies, EuroBrokers, Fiduciary Trust, and others.

Newsday.com: Includes short stories written about specific decedents.

NIST Interviews with occupants and family members

* Where possible, eyewitness accounts were used to place individuals. Where no specific accounts existed, employer and floor information was used to place individuals.

Likely Location at Time of Impact*		
World Trade Center 1 Occupants		**1,466**
At or Above Impact	1,355	
Below Impact	111	
World Trade Center 2 Occupants		**624**
At or Above Impact	617	
Below Impact	7	
Confirmed Below Impact in WTC 1 or WTC 2		**30**
Unknown Location Inside WTC 1 or WTC 2		**26**
First Responders (Total)		**421**
FDNY	343	
NYPD	23	
PAPD	37	
Hospital/Paramedic	7	
Federal	2	
Volunteer Responders	9	
Bystander/Nearby Building Occupant		**18**
American Flight 11		**87**
United Flight 175		**60**
No Information		**17**
Total		**2,749**

Background Information on Evacuation

- **Two-thirds of surviving occupants reported having participated in a fire drill in the 12 months prior to September 11, 2001, while 17 percent reported that they received no training during that same period.** Of those participating in fire drills, 93 percent were instructed about the location of the nearest stairwell. Overall, slightly over half of the survivors, however, had never used a stairwell at the WTC prior to September 11, 2001.

- Two thousand one hundred forty-six building occupants (1,466 in WTC 1, 624 in WTC 2, and 56 in either WTC 1 or 2) and an additional 421 first responders, including security guards but not aircraft passengers and crew or bystanders, were reported to have lost their lives on September 11, 2001.

- Approximately **87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully**.

- Rough estimates indicate that about **20 percent or more of the 2,567 building occupants and first responders who were in the WTC towers and lost their lives may have been alive in the buildings just prior to their collapse**. This estimate includes 118 occupants below the floors of impact who died but not the large but unknown number of occupants above the floors of impact who may have been alive prior to collapse.

Evacuation Findings: First-Person Interviews

- Overall, about 7,900 survivors evacuated WTC 2 in 73 min (i.e., from the instant the WTC 1 was struck by aircraft until WTC 2 collapsed); while about 7,500 survivors evacuated WTC 1 in 103 min. **The overall evacuation rate in WTC 2 (108 survivors per min) was about 50 percent faster than that in WTC 1 (73 survivors per min).**

- **Functioning elevators allowed many (roughly 3,000) survivors to self-evacuate WTC 2 during the 16 minutes prior to aircraft impact.** All but one of the 99 elevators in WTC 1 were not functioning, and survivors could only use the stairways.

- The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.
  - **One of the stairwells in WTC 2 (Stairwell A on the North side) was passable in the region of aircraft impact for some period of time after WTC 2 was attacked.**
  - All three stairwells in WTC 1 and the two other stairwells in WTC 2 were rendered impassable in the region of aircraft impact.

- **Occupant preparedness:**
  - **Occupants were often unprepared for the physical challenge of full building evacuation.** Numerous occupants required one or more periods of rest during stairwell descent or turned to elevators after finding the stairwells strenuous.
  - **Occupants were often unprepared to encounter transfer hallways during the stairwell descent.** Groups of evacuees occasionally hesitated or debated a course of action upon encountering a transfer hallway. (Note, however, that NYCLL 5 prohibits requiring occupants to practice stairwell evacuation.)
  - **Mobility challenged occupants were not universally identified or prepared for full building evacuation.** One occupant, for example, reported being ‘left’ on their floor by colleagues, called authorities for assistance, and was eventually assisted by strangers (occupants).

Evacuation Rates in the WTC Towers

- After the first airplane struck WTC 1 and before the second airplane struck WTC 2, the survivors in WTC 2 were twice as likely as those in WTC 1 to have already exited the building (41 percent versus 21 percent). The rate of evacuation completion in WTC 2 was twice the rate in WTC 1 during that same period.
  - Approximately 75 percent of WTC 2 occupants above the 78th floor at 8:46 am successfully descended below the 78th floor prior to the aircraft strike at 9:03 am.

- Soon after WTC 2 was struck by the airplane until about 20 min before each building collapsed, the survivors in WTC 2 and WTC 1 exited at about the same rate (the prior evacuation rate of WTC 1).

- During the last 20 min before each building collapsed, the evacuation rate in both buildings slowed to about one-fifth the immediately prior evacuation rate. This suggests that **for those seeking and able to reach and use undamaged exits and stairways, the egress capacity (number and width of exits and stairways) was adequate to accommodate survivors**.

- Based on a report by a first responder from a floor in the 20s in WTC 2, a group of occupants was making its way down the stairwell some minutes before building collapse. Among other possibilities, this group may have come from above the floors of impact by finding a way through the only passable stairwell (Stairwell A).

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Evacuation Rates in the WTC Towers

- **Even though a percentage of evacuees reported that they perceived counterflow (firefighter ingress) to be problem, it was found <u>not</u> to be a significant factor in the total evacuation time of occupants in WTC 1 when compared to other factors, including evacuation initiation delay, evacuation interruption, and encountering obstacles in the evacuation path (environmental cues) such as smoke, water, or debris.**

- Based on use of existing egress models and actual evacuation time on September 11, 2001, it is estimated that **a full capacity evacuation of each WTC tower with 25,000 people—three times the number present on September 11, 2001—would have required about 4 hours**. To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).

- In WTC 1, the average surviving occupant spent 48 seconds per floor descending the stairwell. This translates to approximately 0.2 m/s (0.65 ft/s), which is about 50% of the slowest speed measurement presented in the SFPE Handbook of Fire Protection Engineering for non-emergency evacuations.

- In WTC 1, each stairwell door exited approximately 37 people per minute, averaged over 100 minutes, which is comparable to the slowest measurement presented in the SFPE Handbook of Fire Protection Engineering for non-emergency evacuations.

- **Thus the average surviving occupants moved slower down stairs and through stairwell exits than previously reported for non-emergency evacuations.**

Roof Evacuation

- The PANYNJ's standard occupant evacuation procedures and drills required the use of stairways to exit at the bottom of the WTC towers. The standard procedures were to keep the doors to the roof locked with a key being required to gain roof access. **The PANYNJ reports that it never advised tenants to evacuate upward.**

- There were at least two decedents who had tried to get to the roof and found the roof access locked to both the WTC towers. In addition, a PANYNJ employee trapped on Floor 105 of WTC 2 was unable to walk down the stairs, or go to the roof as instructed on radio by another PANYNJ employee (PANYNJ Channel Y).

- **The NYPD and FDNY policies for roof operations were focused mainly on providing first responders with access into the building above the fire floors for firefighting, conventional rescue, and comforting occupants. Roof rescue was considered a measure of last resort to be used, for example, to assist occupants with medical emergencies.**

- The NYPD aviation unit arrived at the WTC site soon after WTC 1 was attacked. Despite repeated attempts to examine the possibility of roof access/rescue, smoke and heat conditions at the top of the WTC towers prevented the conduct of safe roof operations.

- **Considering the capacity of typical helicopters and travel times, it is not clear what fraction of the large number of occupants could have been evacuated from the WTC towers prior to their collapse had roof rescue been possible on September 11, 2001.**

Public Address System Announcements

- Damage to the 22nd floor communication closet likely disabled the building-wide announcement capability in WTC 1. Many announcement attempts were made from the lobby command station.

- Announcements in WTC 2 were heard by occupants building-wide before the second aircraft struck at 9.03 am. Announcements were also heard in at least the upper regions (including above the impact area) after the second aircraft struck at 9.03 am.

  - At 9:00 am an announcement stated "There is a fire condition in WTC 1. WTC 2 is secure. **Please return to your offices**."

  - At 9.02 am an announcement stated "May I have your attention please. The situation is in Building 1. However, if conditions on your floor warrant, **you may wish to start an orderly evacuation**."

  - At 9.20 am an announcement was made updating occupants on the condition of the building and progress of the evacuation and informing occupants that **if they wished to leave, they could then use the concourse.**

  - Prior to 9.37 am an announcement instructed occupants to **"go down" the stairs.**

Emergency Communications to WTC Occupants

- Occupants called 9-1-1 and the Port Authority seeking assistance and advice.

- **Opportunities to improve occupant's situational awareness were often lost. Specific knowledge about location of fires and impact damage was only occasionally communicated to occupants who requested the information and was without apparent coordination.**

- Some operators advised sheltering (e.g., many 9-1-1 operators), while others advised evacuation (e.g., many PA Police Desk operators); some permitted window breaking while others instructed occupants not to break windows.

Role of Emergency Responders

FDNY - Established operational control and the Incident Command Post for the WTC operations, conducted evacuation and rescue operations, and fought fires at the disaster.

PAPD - Established security at the WTC and conducted evacuation and rescue operations.

NYPD - Established traffic control, perimeter security at the site, security for command posts, and conducted evacuation and rescue operations inside the WTC. The aviation units supplied observation capabilities and assessed the potential for roof rescue.

OEM - Functioned as a multi-agency command resource center and provided support for all agencies and departments working at the disaster.

FDNY Operations at the WTC

Three operational strategies:

Outside Command Posts & Inside Command Communicating with the Outside Command Post - Fires in the buildings were too large and were located too high in the buildings to accomplish fire fighting activities that could save the lives of occupants above the fires. The objective was to evacuate and rescue all below the fires.

Command Officers for Inside Operations - The fires were too large to extinguish. The objective was to get enough personnel and equipment upstairs to cut a path through the fire to rescue occupants above the fires, and also evacuate and rescue all below the fires.

Company Level Command - They saw this as a conventional but large high-rise fire. The objective was to get up to the fire floors and extinguish the fires. In some cases, firefighters were persuaded by higher ranking officers to switch from the idea of fire fighting to evacuation and rescue operations.

No first responder interviewed by NIST thought that the WTC towers would collapse.

Emergency Responder Operations

Situational Awareness:

- Emergency responders working outside of the WTC buildings that could view building conditions and communicate over radios had adequate situational awareness.

- Situational awareness for personnel that observed the building damage and fires from outside the buildings before entering experienced difficulty maintaining their awareness after entering the buildings.

- Emergency responders working inside of the WTC buildings, who could not see what was happening outside and had poor radio communications, had poor situational awareness.

- Emergency responders working inside of the WTC buildings who could not see what was happening outside and had good radio communications had better situational awareness than those with poor radio communications.

FDNY Access to the WTC Towers

- **After aircraft impact, only two elevators out of 198 were operating inside the two WTC towers.** WTC 1, from the lobby to the 16th floor. WTC 2, from the lobby to the 40th floor.
- The stairways were filled with occupants evacuating the buildings. **FDNY personnel and other emergency responders reported difficulty attempting to climb the stairs due to this counterflow.**
- Counter flow in the staircases made it difficult for emergency responders to carry equipment up the stairways.
- Counter flow in the staircases caused teams of emergency responders to become separated, causing delays and disrupting team operations.

Emergency Responders & High-Rise Buildings

- First responding FDNY units took from 4 to 10 minutes to get to the WTC complex. They then got their equipment and received assignments, another 3 to 5 minutes. Time to begin operations 7 to 15 minutes.

- Of the 27 emergency responders interviewed that were inside WTC 1, maximum floor height achieved before WTC 2 collapsed, a time period of 1 hour 13 minutes.

  1 – A police officer carrying no extra equipment and in a patrolman's uniform climbed to the 44th floor.

  8 – Emergency responders (FDNY, PAPD, NYPD) climbed to the 30's
  Two FDNY took an elevator to the 16th floor.

  16 – Emergency responders (mostly FDNY) climbed to the 20's.

  2 – Emergency responders (NYPD) climbed to the teens.

- **Estimated climbing rate based on a 60 minute climbing period to their maximum height: 1.4 to 2 minutes/floor**

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High-Rise Buildings & Emergency Response

Example: Fire department response to a 60 story high-rise building, occupants trapped above fires on the 58th floor and no operating elevators.

Firefighters carrying equipment and wearing PPE ~ 125 minutes
Firefighters carrying no equipment and not wearing PPE ~ 90 minutes

Firefighters carrying equipment and wearing PPE ~ 70 minutes
Firefighters carrying no equipment and not wearing PPE ~ 50 minutes

Firefighters begin to climb 10 minutes
Fire department arrival 4 minutes

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Radio Communications

- All three of the responding departments, FDNY, NYPD & PAPD experienced difficulties with radio communications.

- Each of the departments was aware of the shortfalls associated with their radio communications systems as they related to operations in high-rise buildings.

- Two basic issues with radio communications:

  1. Normal function of the radio equipment in high-rise environments. (Radio signal attenuation in steel and concrete buildings)

  2. The volume of radio traffic

Emergency Communication Recordings

- NIST reviewed audio communications tapes recorded by the PANYNJ, including a recording of the FDNY's city-wide high-rise Channel 7 (Port Authority Police Department's [PAPD] Channel 30) radio repeater that was located at the WTC.
- NIST reviewed audio tapes copied from original NYPD communications tapes, including NYPD internal department operations.
- **FDNY communications recordings from the WTC location on September 11, 2001, are not available because the primary field communication truck was in the shop for repairs. A back-up field-communications van used in its place—which did not have a recording capability—was destroyed when the WTC towers collapsed.**
- **The best record of radio communications reflecting fire department operations came from the FDNY Channel 7/PAPD Channel 30 and first person accounts provided by FDNY personnel during their interviews.**
- The PANYNJ installed the radio repeater system for use by FDNY after the 1993 bombing.

Analysis of Emergency Communications

- After the first aircraft struck WTC 1, there was an approximate **factor of 5 peak increase in traffic level over the normal level of emergency responder radio communications**, followed by an approximate factor of 3 steady increase in the level of subsequent traffic.

- **A surge in communications traffic volume made it more difficult to handle the flow of communications and delivery of information**.

- Roughly a third to a half of the radio messages transmitted during these radio traffic surge conditions **were not complete messages nor understandable**.

- **FDNY's city-wide high-rise Channel 7 (PAPD Channel 30) radio repeater at the WTC site was operating.**

- NYPD aviation unit personnel reported critical information about the **impending collapse** of the WTC towers several minutes prior to their collapse. **No evidence has been found to suggest that the information was further communicated to all emergency responders at the scene.**

WTC High-Rise Radio Repeater System

- **Analysis of the FDNY City-wide, high-rise, channel 7 (PAPD channel 30) repeater recording indicates that the World Trade Center high-rise repeater was operating.**

- At approximately 9:05 a.m. the repeater's recording system recorded the WTC 1 Lobby Command Post attempts to check repeater operations. Handset and handie-talkie radio communications were recorded.

- It is possible that one or both of the following conditions complicated the radio check that took place at the WTC 1 Lobby Command Post:
  - The radio repeater handset earpiece was broken.
  - The radio repeater handset volume was not turned up.

- **It is unlikely that the repeater's antenna was broken or misdirected by debris since radio signals were received during the radio check from inside WTC 1 and the communications that followed from inside WTC 2.**

- The repeater's system recorded radio communications that took place between several different firefighters and several different FDNY officers as they worked inside WTC 2.

Command and Control

- **First responders— including key incident commanders—did not have adequate information (voice, video, and data) on, nor an overall perspective of, the conditions in the WTC buildings and what was happening elsewhere at the WTC site. Interagency information sharing was inadequate.**

- **FDNY command and control was seriously affected by the lack of good communications.**

- **Large numbers of fire fighters were dispatched to the WTC site before adequate command posts and staff could be assembled to manage them.**

- **Self-dispatch complicated command and control at the site.** FDNY and EMS command and control was affected by many self-dispatched private and volunteer ambulance units that contributed to clogging the streets so that other responders assigned to the WTC had difficulty getting through.

- FDNY apparatus had to be moved to allow some ambulances to get through and exit the site with victims.

Command and Control

- **FDNY's system for maintaining records of unit assignments at each command post was not capable of managing the numbers of units and personnel being assigned to the incident.**

- **FDNY, NYPD, and PAPD: there was no means to back-up the unit assignment records generated at the command posts.**

- **A significant amount of evidence (first person interviews, reports, and photographic data) shows that the different agencies were working together during the WTC disaster.**

- **Inter-agency operations were detrimentally affected with the loss of the OEM command center that was located inside WTC 7.** First person interview data and photographic data show that OEM functions became dispersed, the computer systems and other supporting systems were lost, and the unified operations structure was diminished. OEM personnel were working with different emergency responder departments and were located at the various department command posts.

- First responder interviews suggest that inter-agency competition had minimal effect on operations at the WTC complex on the morning of September 11, 2001. The data also suggest that some of the problems experienced were due to personnel not understanding the operating practices of the other agencies.

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Mobility Impaired Occupants

- As the emergency responders started evacuating WTC 1 after the collapse of WTC 2, they found mobility impaired occupants still in the staircases going down.

- Ambulatory mobility impaired occupants typically walked down the stairs with one hand on each hand rail and took one step at a time going down. In addition, they were typically accompanied by one person, another occupant or an emergency responder. This blocked others behind them from moving more rapidly down the stairs.

- **FDNY and PAPD personnel found 40 to 60 mobility impaired occupants on the 12^{th} floor of WTC 1 as they went down and attempted to clear each floor on their way out.** These impaired individuals had been placed on this floor in an attempt to clear the stairways.

- **Emergency responders were assisting approximately 20 of these mobility impaired people down the staircase just prior to the collapse of WTC 1.** It is unknown how many fatalities occurred with this group.

Active Fire Protection Systems

- The smoke management systems in the WTC towers were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional was very low due to the damage inflicted by the aircraft impacts.

- Analysis indicates that the disruption of the **HVAC (heating, ventilation, and air-conditioning) system, particularly the aircraft impact rupture of large return air shafts and related ductwork created a major path for vertical smoke spread in the buildings.**

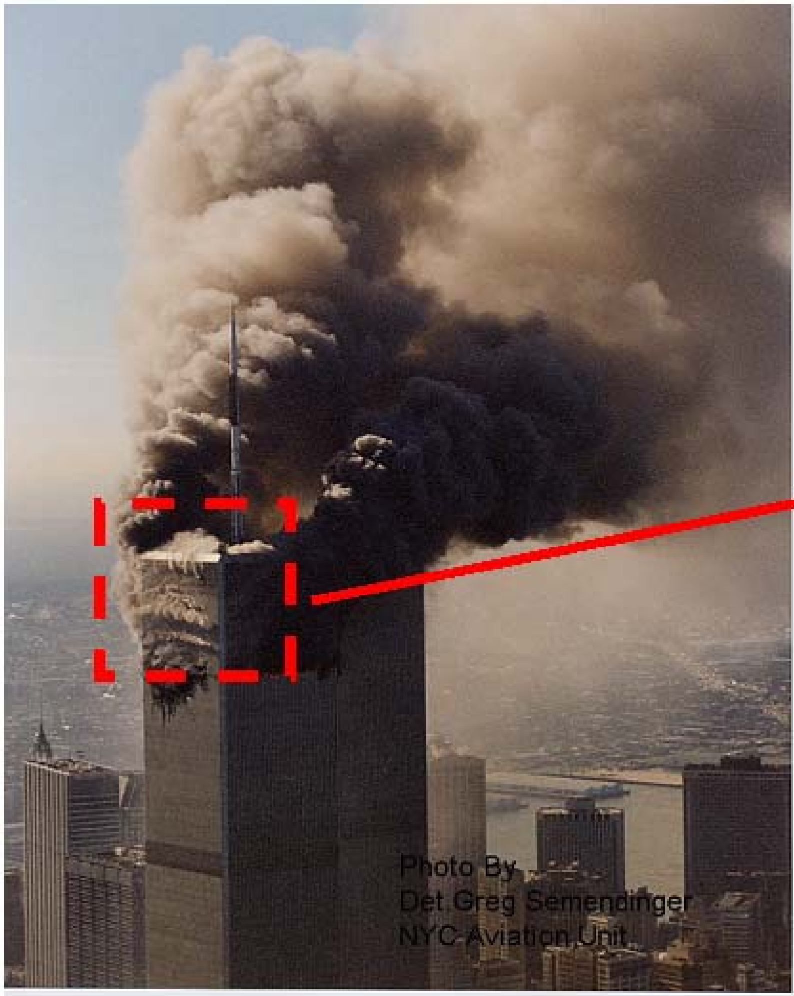
- Analysis indicates that **stair pressurization systems would have provided minimal resistance to the passage of smoke in WTC 1 and WTC 2 had they been installed on September 11, 2001.**

- The fire alarm system in WTC 7 sent only one signal (at 10:00:52 a.m. shortly after WTC 2 collapsed) to monitoring company indicating a fire condition. The signal did not contain any specific information about the location of the fire within the building.

- **The resistance to failure of the fire alarm system communications paths between the fire command station and occupied WTC tower floors could have been enhanced if fiber optic cable had been used instead of copper lines, which were not permitted by the NYC building code at the time of building construction.**

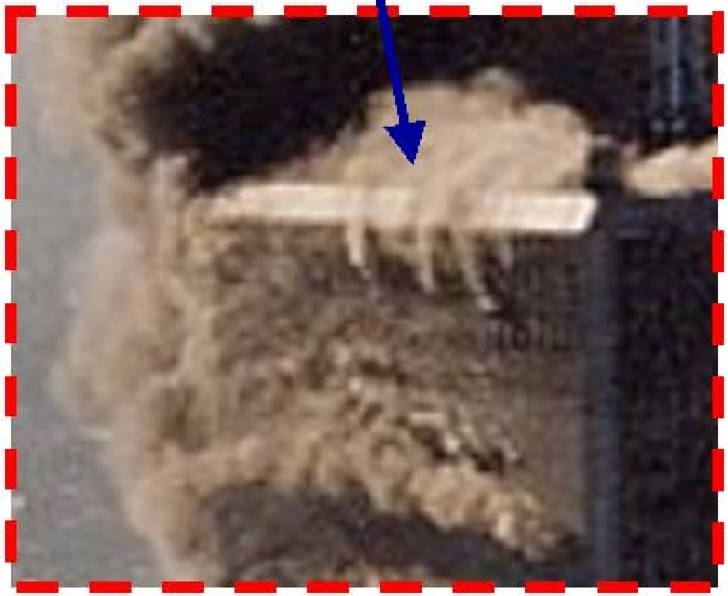
- Although the fire sprinkler system was damaged by aircraft impact, the **water supply riser system lacked redundancy**, and the potential existed for single point failure of the water supply connection on each floor.

Example of Vertical Smoke Spread



North Face – WTC 1

Smoke Exits NW Interior
Ventilation Zone Supply Inlet



Applicable Building Codes

- Although not required to conform to NYC codes, the PANYNJ elected to adopt the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect.

- **The 1968 edition had less restrictive provisions** compared with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:
  - Eliminated a fire tower as a required means of egress;
  - Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
  - Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
  - Changed partition loads from 20 psf to one based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings);
  - Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).

- **The NYC Department of Buildings reviewed the WTC tower drawings** in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code.

Applicable Building Codes

- In 1993, the PANYNJ and the NYC Department of Buildings entered into a memorandum of understanding that:
  - **Restated the PANYNJ's longstanding policy to assure that its facilities in the City of New York meet and, where appropriate, exceed the requirements of the NYC Building Code.**
  - Provided specific commitments to the NYC Department of Buildings regarding procedures to be undertaken by the PANYNJ to assure that buildings owned or operated by the PANYNJ are in conformance with the Building Standards contained in the NYC Building Code.
- In 1993, the PANYNJ adopted a policy providing for implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a PANYNJ facility, and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility. Later in 1993, the PANYNJ entered into an agreement with FDNY which reiterated the policy adopted by the PANYNJ and set forth procedures to assure that new or modified fire safety systems are in compliance with local codes and regulations.
- While the PANYNJ entered into agreements with the NYC Department of Buildings in the 1990s with regard to conformance of PANYNJ buildings constructed in New York City to the NYC Building Code, **the PANYNJ did not yield jurisdictional authority for regulatory and enforcement oversight to the NYC Department of Buildings.** The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not governed by the building and fire codes of any local, state, or federal jurisdiction.

Rationale for the Selection of the 1968 NYC Building Code for the WTC Towers

June 22, 1965 letter from John M. Kyle, Chief Engineer to Malcolm Levy, Chief, Planning Division, WTC:

"This will confirm my advice that, **in view of the more liberal provisions of the proposed new New York City Building Code, I feel we should take advantage of its provisions.**

This decision is based on the following:

1. **The new code has received thorough review by interested technical groups and representatives of the City and has been modified to meet all major objections.**
2. It is scheduled to be officially submitted to the City in September and should be approved well before we construct our buildings.
3. **The Commissioner has stated that he favors the approach taken by the Port Authority in using advanced techniques in the design of the World Trade Center.** He also stated that the Port Authority is not subject to the provisions of the Building Code."

Rationale for the Selection of the 1968 NYC Building Code for the WTC Towers

September 29, 1965 letter from Malcolm P. Levy, Chief, Planning Division, WTC to Minoru Yamasaki, Architect:

"… Generally the tower core should be redesigned to eliminate the fire tower and **to take advantage of the more lenient provisions regarding exit stairs**…"

May 19, 1966 memorandum from Guy F. Tozzoli, Director, World Trade Department to John M. Kyle, Chief Engineer:

"The decision to follow the new Code was, as you pointed out, in your memorandum to Mr. Levy of June 22, 1965, based on the fact that: (1) **The new Code had been thoroughly review by interested technical groups and was modified to meet all major objections;** (2) it would probably be adopted before we constructed our buildings; and **(3) the Commissioner favored the approach of using advanced techniques in the design of the World Trade Center** and that the Port Authority, according to him, was not subject to the provisions of the Building Code."

Rationale for the Selection of the 1968 NYC Building Code for the WTC Towers

Memorandum dated January 15, 1987, from Lester S. Feld (Chief, Structural Engineer, World Trade Department, PANYNJ) to Robert J. Linn (Deputy Director for Physical Facilities, WTD, PANYNJ): Subject: The World Trade Center – Towers and Plaza Buildings Fire Rating per NYC Building Code Revision Effective 12-6-68.

Paragraph 2. B. states:

> "**For office buildings there is no economic advantage in using Class 1A Construction, and ER&S used Class 1B Construction for the WTC Towers and Plaza Buildings which are Occupancy Group "E" (Business) with a fire index of 2 hours.** As such, columns must have a three hour rating and floor construction with a 2 hour rating."

Approach to Recommendations

- In the United States, state and local governments are responsible for promulgating and enforcing building and fire regulations.
- With some exceptions, the state and local regulations are based on national model building and fire codes developed by private sector organizations.
- The model codes, in turn, reference voluntary consensus standards developed by a large number of private sector standards development organizations (SDOs) accredited by the American National Standards Institute (ANSI).
- NIST does not set building codes and standards, but provides technical support to the private sector and other government agencies in the development of U.S. building and fire practices, standards, and codes.
- NIST recommendations are given serious consideration by private sector organizations that develop national standards and model codes – which provide minimum requirements for public welfare and safety.

Approach to Recommendations (2)

- The NIST building and fire safety investigation of the WTC disaster has not yet formulated recommendations. However, **in formulating its recommendations, NIST will consider** the following:
    - **Findings from the first three independent investigation objectives** related to building performance, evacuation and emergency response, and procedures and practices.
    - **Whether findings relate to the unique circumstances surrounding the terrorist attacks** of September 11, 2001, **or to normal building and fire safety considerations, including evacuation and emergency response**.
    - **What technical solutions are needed, if any, to address potential risks to buildings, occupants, and first responders**, considering both identifiable hazards and the consequences of those hazards.
    - **Whether the risk is in all buildings or limited** to selected building types (e.g., distinct height and area or type of structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions.

Issues Related to Practice, Standards, and Codes

- Based on the Investigation findings, NIST has identified issues related to practice, standards, and codes that will provide the basis for formulating the Investigation's recommendations.

- Issues arising from the investigation are grouped under the following major categories:
  - Increased Structural Integrity
  - Enhanced Fire Protection
    - Passive Fire Protection
    - Active Fire Protection
  - Improved Building Evacuation
    - Egress System Design
    - Emergency Communications to Occupants
    - Occupant Preparedness
    - Egress Technology
  - Improved Emergency Response
    - Access and Firefighting
    - Emergency Communications
    - Command and Control

Categories of Issues

Level 1

- Practices
- Standards, codes and regulations
- Adoption and enforcement
- R&D/further study
- Education and training

Level 2

- All tall buildings (buildings over 10 stories in height)
- Selected tall buildings (buildings over 10 stories in height that are at risk due to design, location, use, iconic status, contents, etc.)
- Selected other buildings (buildings that are at risk due to design, location, use, historic/iconic status, contents, etc.)

Level 3

- Related to 9/11 outcome
- Unrelated to 9/11 outcome

Issues – Increased Structural Integrity

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Availability of explicit standards, code provisions, methodology, analytical design tools, and practical design guidance for designing structures to resist progressive collapse in the event of abnormal loads.	✓	✓	✓				✓	✓	✓	
Availability of analytical methodologies for prediction of complex failure phenomena of structural systems under abnormal loads.			✓	✓		✓		✓		✓
Availability of standards for wind tunnel tests and for methods to estimate wind effects from test results for design purposes.		✓	✓				✓	✓		✓
Availability of protocols for selection of site-specific wind speed and directionality.	✓	✓	✓				✓	✓		✓
Adequacy of prescriptive wind load standards for very tall buildings.		✓	✓			✓				✓

Issues - Enhanced Fire Protection

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Availability of standards, codes, methodology, analytical design tools, and practical design guidance to permit considering fire as a design condition for the structure as a whole system.	✓	✓	✓	✓		✓				✓
Standardized design-basis fire scenarios for design of fire protection systems and analysis of structural and thermal response do not account for building-specific conditions.	✓		✓			✓		✓		✓
Availability of regulations that would adopt code provisions using the “structural frame” approach to fire resistance ratings, which requires structural members to be fire protected to the same rating as columns.		✓		✓	✓	✓		✓		✓
Conformance of applied passive fire protection to conditions in actual or equivalent tests used to establish fire resistance rating of the building component or assembly.	✓	✓	✓		✓	✓			✓	
Adequacy of ASTM E 119 to provide guidance on: ▪Criteria for determining structural limit states, including failure, and means for measurement ▪Scale of test assembly versus prototype application ▪Effect of end restraint conditions on test results, including influence of stiffness ▪Structural connections ▪Combination of loading and exposure (temperature profile) represent expected conditions ▪Procedures to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element ▪Repeatability and reproduceability of test results ▪Relationships between prescriptive ratings and performance of the assembly in realistic building fires		✓	✓			✓				✓
Technical basis for construction classification and fire rating requirements for tall buildings (fire rating, sprinkler-tradeoff, compartmentation)	✓	✓	✓			✓			✓	

Issues – Enhanced Fire Protection

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Evaluation of presently available fire-resistant steels; comparison with conventional steels; and test protocols and acceptance criteria.	✓		✓			✓		✓	✓	
Sensitivity of the level of performance of active fire protection systems (sprinklers, standpipes/hoses, fire alarms, smoke management) to the size and height of the building, compartmentation, building population, activities, transient fuel loads, fire department response, and threat profile.	✓	✓	✓			✓		✓	✓	
Ability of fire alarm and communications systems to provide continuous, reliable, accurate, and sufficient information on conditions, so building fire emergencies including the evacuation process, if needed, can be managed using that information.		✓	✓			✓			✓	
The quantity and reliability of information available to emergency responders at the fire/emergency command station.		✓	✓			✓		✓	✓	
Survivability of fire alarm system information records of alarms during emergency events for investigation purposes.		✓				✓		✓		✓
Available means to transmit outside a building the status of emergency conditions in the building from information in the fire alarm system and other monitored building systems.	✓	✓	✓			✓		✓	✓	

Issues – Improved Building Evacuation: Egress System Design

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
The egress path may be compromised prior to evacuation of the affected population due to a variety of scenarios (e.g., wind, earthquake, overpressure, impact, fire).	✓	✓					✓		✓	
Building egress systems are not designed to accommodate full building evacuation. Full building evacuation is foreseeable under conditions of widespread power outage, earthquake, fire, or terrorist attack.	✓	✓		✓		✓			✓	
Lack of adequate egress models and performance-based egress design methodology accounting for human behavior during evacuation.			✓				✓		✓	
Stairwells can be physically proximate yet considered remote by a "walking path" measurement; does not adequately meet separation requirements under non-fire conditions.		✓					✓		✓	
Mobility-challenged occupants: areas of refuge create a delay in evacuation; insufficient procedures for identifying those with challenges and assisting them. Some mobility-challenged occupants are not capable of effecting their own escape.	✓	✓		✓		✓			✓	
Required professional training or accreditation for egress system designers (often architects).	✓			✓		✓				✓

Issues - Improved Building Evacuation: Emergency Communications to Occupants

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Inadequate situational awareness from missed opportunities to better communicate information among occupants, 911 operator dispatch, fire department dispatch, and emergency management dispatch and site security	✓	✓		✓		✓		✓	✓	
A building may have no capacity for public address announcements or instructions through the floor warden system		✓				✓			✓	
The electro-mechanical systems (e.g., elevators) integral to life safety may be compromised by a single event		✓				✓			✓	
Use of emergency broadcast system for major emergencies such as that which occurred on September 11, 2001	✓			✓		✓			✓	

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Issues – Improved Building Evacuation: Occupant Preparedness

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Emergency plans are filed to achieve regulatory compliance, but are not adequately implemented in practice. In addition, occupants are often unprepared to evacuate a building. Preparedness includes adequate knowledge of the evacuation procedures and systems, and adequate means for pathway illumination.	✓			✓		✓			✓	
Layouts (i.e., transfer floors) can be confusing to unprepared occupants.		✓				✓			✓	
Need for floor wardens.			✓				✓			✓

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Issues – Improved Building Evacuation: Egress Technology

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
The electro-mechanical systems (e.g., elevators) integral to life safety may be compromised by a single event		✓				✓			✓	
Egress systems do not enable all occupants an equal opportunity for evacuation. Hardened elevators, exterior escape devices, or stairwell navigation devices not considered.		✓	✓			✓			✓	
Elevator door restrictor plate can entrap building occupants in the event of an emergency.			✓			✓			✓	

Issues – Improved Emergency Response: Access and Firefighting

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Physiological impact on firefighters with equipment climbing more than 10 to 12 floors during an emergency.	✓	✓	✓				✓		✓	
Adequacy of capacity for egress and firefighter access during full evacuation of fully occupied tall buildings (access to tall buildings by first responders is hindered by counter flow, egress capacity, and lack of available elevators).		✓	✓				✓		✓	
Distance (i.e., remoteness) between stairwells where standpipes are located.		✓				✓				✓

Issues – Improved Emergency Response: Emergency Communications

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Lack of rigorous pre-emergency inspection and testing of radio communications systems within high-rise buildings to identify performance gaps and inadequacies.	✓		✓	✓		✓			✓	
Performance requirements for emergency communication systems in high-rise buildings (i.e., design, testing, certification standards and maintenance and inspection requirements).		✓	✓		✓	✓			✓	
Lack of communications network architecture (interoperability) and operational protocols for intra- and inter-agency communication at all levels of organizational hierarchy. This includes: •Overall network architecture that covers local networking at incident sites, dispatching, and wide-area urban and rural networks. •Scalability in terms of the number of first responders using the system and in providing radio coverage in large buildings with challenging radiofrequency propagating environments. •Interoperability with existing legacy emergency communication systems. •Localization techniques to identify first responders within indoor building environments. •Conventional two-way versus wireless network systems	✓		✓				✓		✓	

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Issues – Improved Emergency Response: Command and Control

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Availability of detailed procedures and methods for gathering, processing, and delivering situational information to all first responders, including 911 operators, wardens, incident commanders, etc.; this covers voice, video, and data integration.	✓	✓	✓	✓	✓	✓			✓	
Availability of effective codes and protocols for establishment and uninterrupted operation of the incident command and control system and for preservation and dissemination of information managed by command posts. •Command posts established within the collapse zone of buildings that received serious structural damage and contained large multi-floor fires. •Establishing the command post prior to dispatching needed units. •Effects of self-dispatch and free-lancing of first responders and ambulances, especially teams lacking protective clothing and medical equipment. •Robustness of assignment and tracking (accountability) system for large scale emergencies.	✓	✓	✓				✓		✓	
Secure location of state and local emergency operation centers (EOCs).	✓					✓			✓	
Rapid adoption and execution of a unified emergency response mission by all first responder ranks.	✓				✓	✓			✓	
The dispatch of large numbers of personnel and apparatus and the ability of management to maintain accountability in a timely manner associated with arrival and deployment of personnel and the ability of the incident site to effectively accommodate large numbers of personnel and apparatus.		✓	✓	✓		✓		✓	✓	

Issues – Other Major Issues

Issue	Level 1					Level 2			Level 3	
	Practices	Standards, Codes, Regulations	R&D/study Further	Education & Training	Adoption and Enforcement	All Tall Buildings	Selected Tall Buildings	Selected Other Buildings	Related to 9/11 Outcome	Unrelated to 9/11 Outcome
Availability of regulatory requirements for retention of documents related to the design, construction, operation, maintenance, and modifications of buildings, including retention offsite and accessibility of building plans for emergency response. •Maintenance and storage of documents. •Accessibility of building plans for emergency response.	✓	✓			✓	✓				✓
Structural principles education for fire protection engineers and fire protection principles education for structural engineers; structural and fire protection principles education for architects.				✓		✓				✓
Creation of broad training opportunities for rigorous use of computational fire dynamics and thermostructural analysis tools.				✓		✓				✓

Approach to Recommendations (3)

- **NIST urges organizations responsible for building and fire safety at all levels to carefully consider the findings and issues.**
- In its final report, a draft of which is expected to be released in December 2004 or January 2005, NIST will recommend appropriate improvements in the way buildings are designed, constructed, maintained and used. It will be important for those recommendations to be thoroughly and promptly considered by the many organizations responsible for building and fire safety.
- NIST will welcome comments from the public on the draft final report.
- As part of NIST's overall WTC response plan, the Institute has begun to reach out to these organizations to pave the way for timely, expedited consideration of recommendations stemming from this investigation. NIST will hold a major conference in June 2005 to reinforce the importance of its findings and recommendations from the Investigation and encourage their implementation in practice. NIST also has expanded its research in areas of high priority need.

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