



NIST Response to the World Trade Center Disaster

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

**Media and Public Briefing
April 5, 2005**

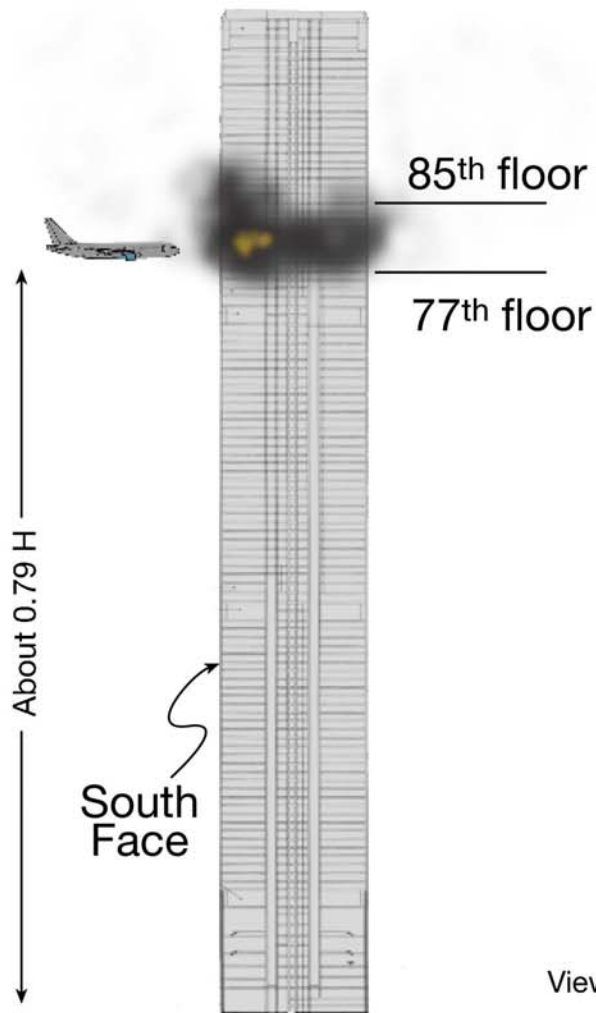
**Dr. S. Shyam Sunder
Acting Deputy Director and Lead Investigator
Building and Fire Research Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce**

Outline

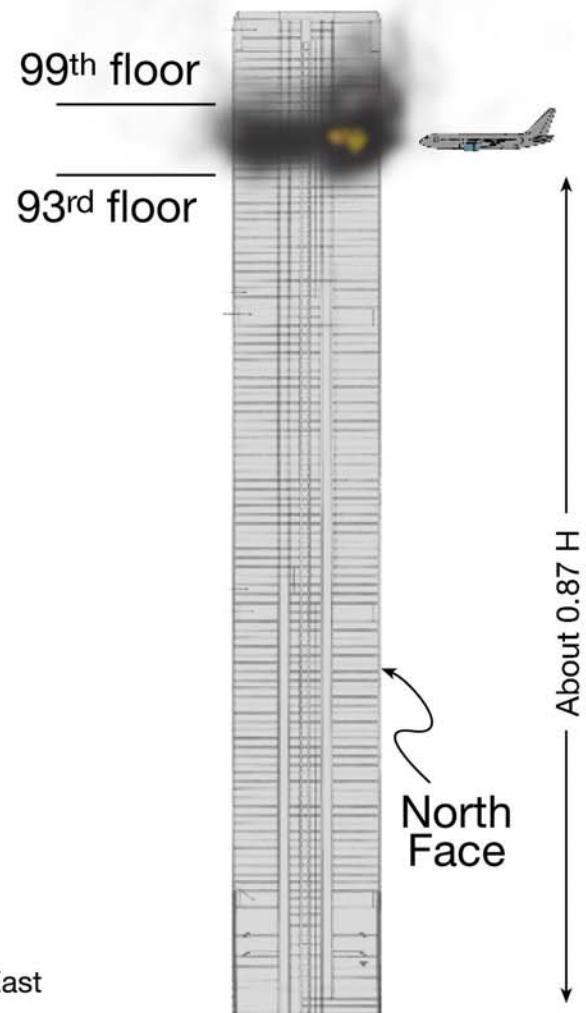
- WTC Investigation Status and Schedule
- Probable Collapse Sequences for the WTC towers
- Life Safety
 - Occupant Behavior, Egress, and Emergency Communications
 - Fire Service Technologies and Guidelines
- Procedures and Practices
 - Analysis of Building and Fire Codes and Practices

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 current national building and fire model codes, standards, and practices that warrant revision**



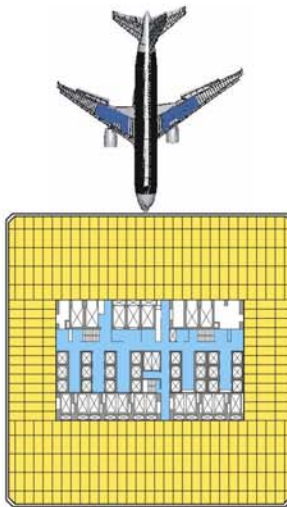
WTC 2: Hit at 9:02:59 a.m.
Collapsed after 56 minutes



WTC 1: Hit at 8:46:30 a.m.
Collapsed after 102 minutes

View from the East

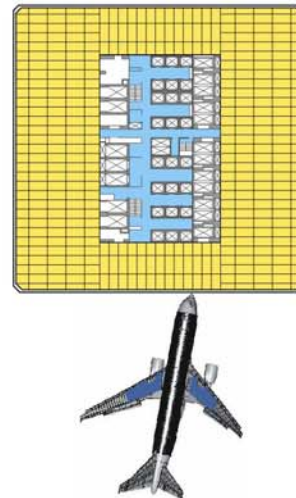
Point of impact:
Close to the center
and nearly normal
to the building



WTC 1



Point of impact:
Close to the corner
and with an angle



WTC 2

Some Specific Questions

- ❑ How and why did WTC 1 stand nearly **twice** as long as WTC 2 before collapsing (102 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.

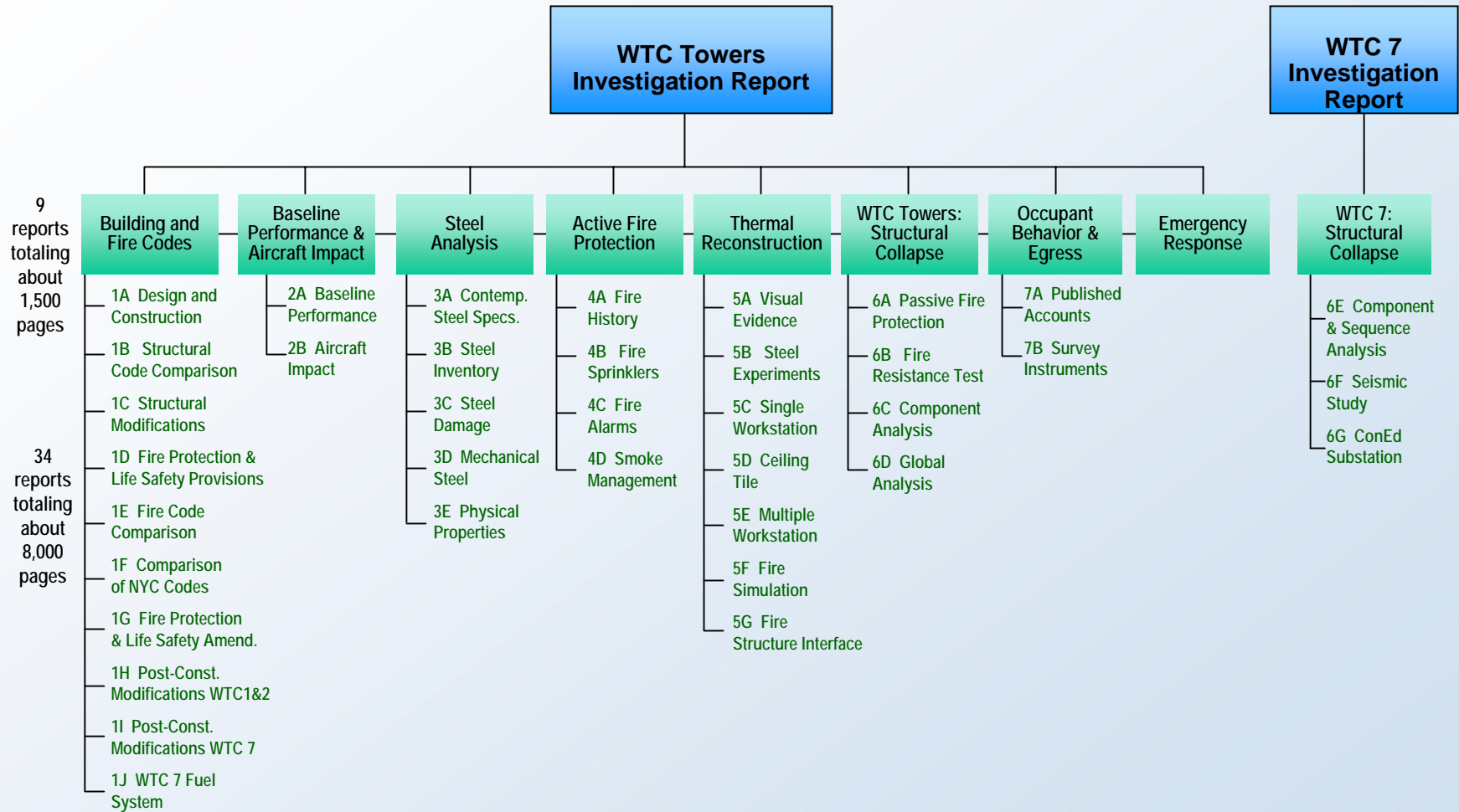
WTC Investigation Status

- Investigation nearing completion; drew 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). Full text available on Web site <http://wtc.nist.gov>.
- Three public meetings held:
 - June 24, 2002 (NYC) to present draft WTC investigation plan and solicit comments on the plan.
 - February 12, 2004 (NYC) to solicit comments on (1) technical aspects of investigation, (2) additional information that NIST might consider, (3) areas to be considered for recommendations.
 - August 24, 2004 (Chicago) to observe fire resistance test of WTC floor system at Underwriters Laboratories
- Six media/public briefings on investigation progress, extensive briefings at six meetings of the National Construction Safety Team Advisory Committee, and one meeting (April 2003) to solicit public input for first-person interviews of occupants and first responders.
- Current findings may be revised and additional findings may be presented in final report.
- **NIST is not making any recommendations at this time; all recommendations will be made in the final report.**

Schedule for Completion of Investigation

- Major focus is on writing the Investigation reports; technical work is complete.
- The time required to write and review the comprehensive set of draft documents that constitute final WTC investigation findings and recommendations is driving the release date of the report.
- The NIST reports include the overall investigation report for the WTC towers, 8 separate project reports, and 34 supporting technical reports, totaling some 10,000 pages. This enormous task has taken NIST longer to accomplish than originally anticipated.
- NIST is committed to putting accuracy, quality, and completeness ahead of schedule, taking whatever time is required to do the job right.
- NIST plans to release a draft of the final report for public comment in June 2005; public comment period of about 6 weeks after release of the draft report; NIST plans to release the final Investigation report in September 2005.
- WTC 7 report will be issued as a supplement to the main report: draft planned for October 2005; final for December 2005.
 - Decoupling of WTC 7 report necessary to accommodate overlapping staffing demands 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, September 13-15, 2005.

WTC Investigation Reports



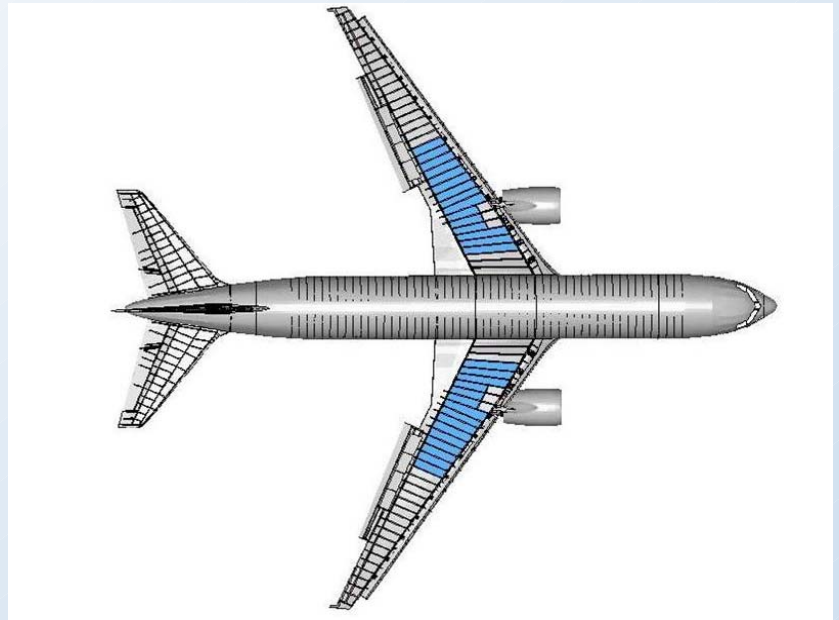
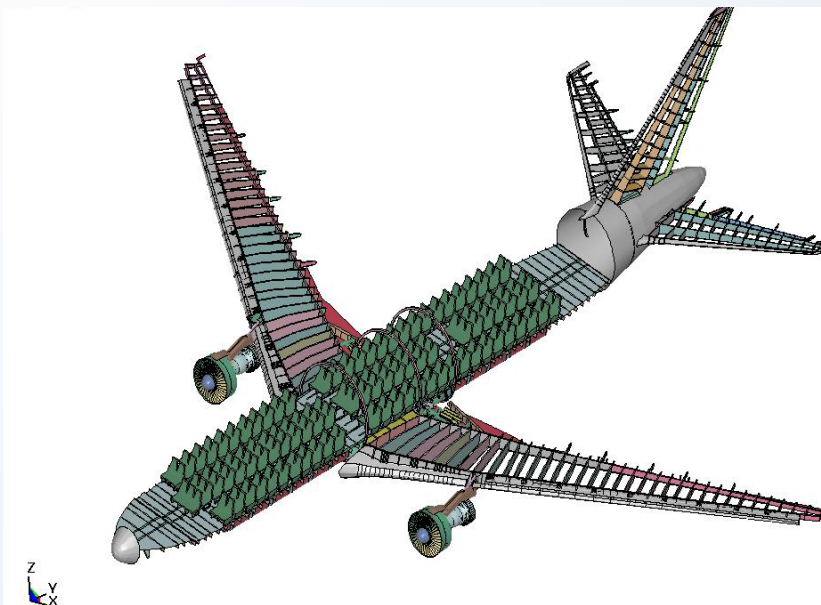
43 reports for WTC Towers; 5 reports for WTC 7

Analysis of Probable Collapse Sequence

NIST developed and used a series of rigorous and comprehensive models to determine the probable collapse sequence for the WTC towers, from aircraft impact to collapse initiation. The approach:

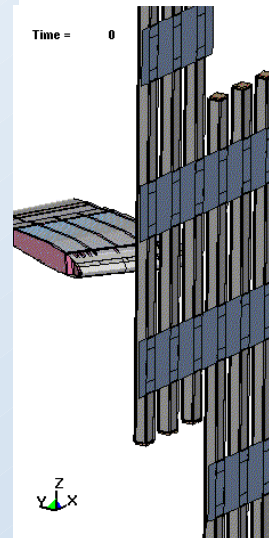
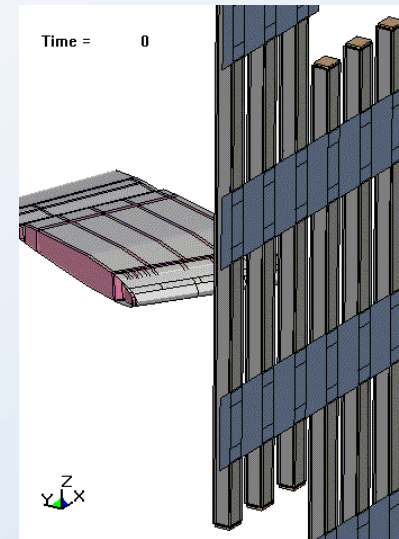
- ❑ Combined mathematical modeling, well-established statistical and probability-based analysis methods, laboratory experiments, and analysis of visual and physical evidence—**significantly advancing the current state-of-the-art and testing the limits of current computational capabilities.**
- ❑ Analyzed the complete sequence of events from aircraft impact to the spread of jet-fuel-ignited multi-floor fires, thermal weakening of structural components, and the progression of local structural failures that ultimately initiated collapse of the buildings.
- ❑ 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.
- ❑ Required use of **advanced strategies for managing computational demands due to unprecedented analysis complexity and sophistication; adequately captured the physics of phenomena essential to determining the probable collapse sequence.**

High Fidelity Aircraft Models

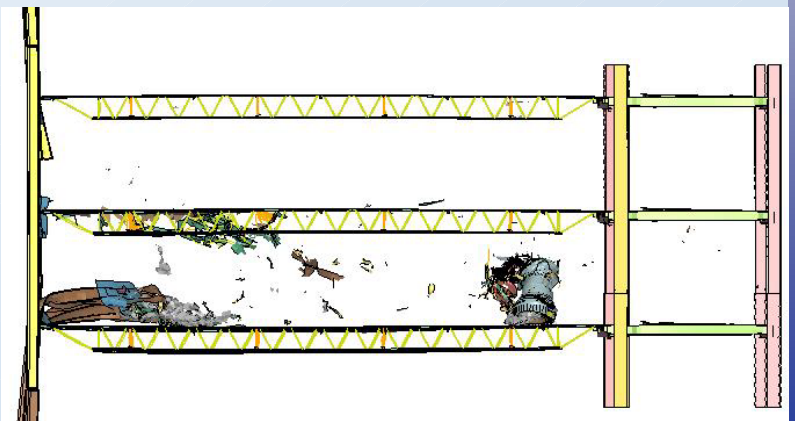
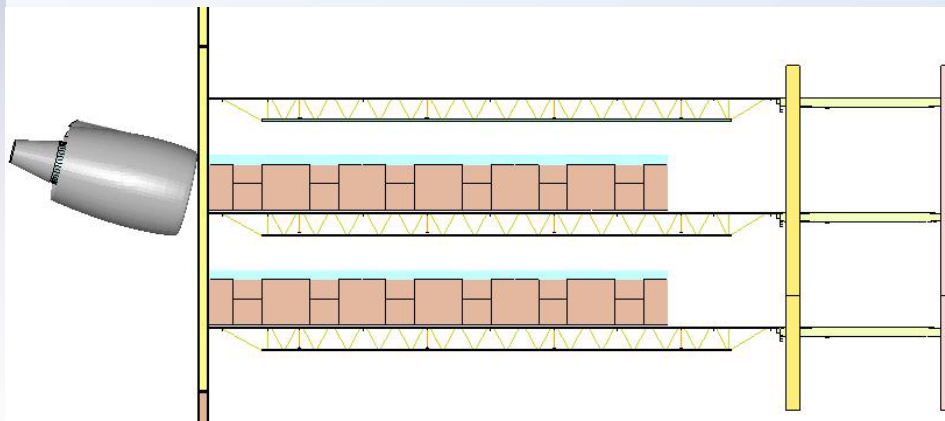
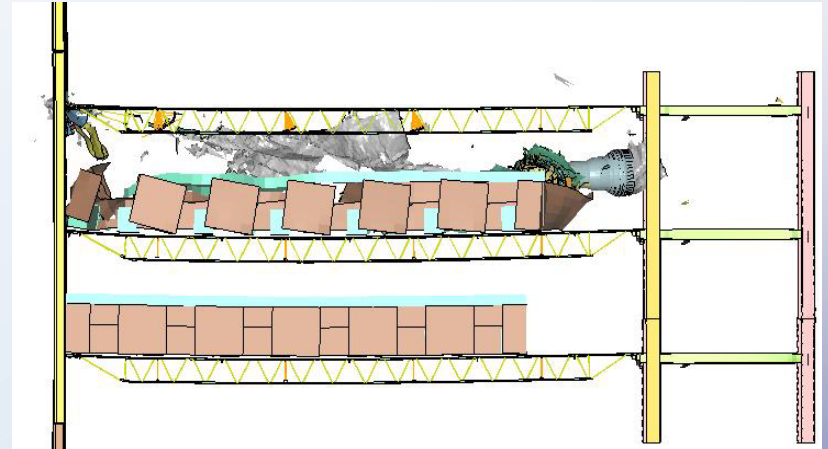
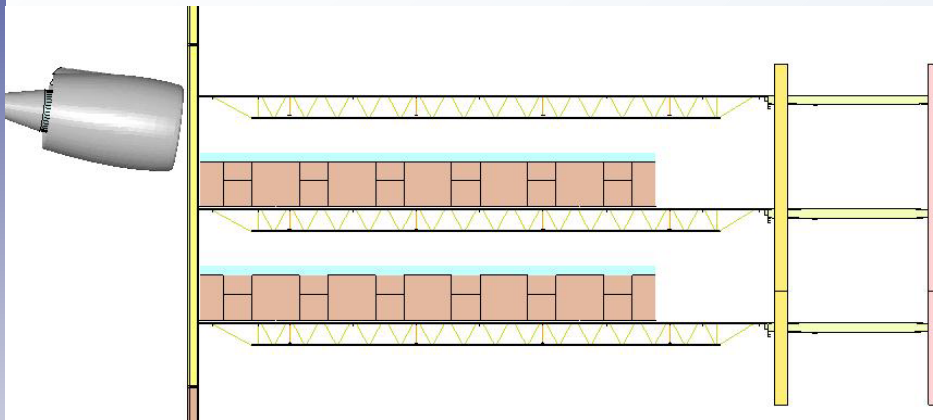


Preliminary Aircraft Impact Damage Analysis

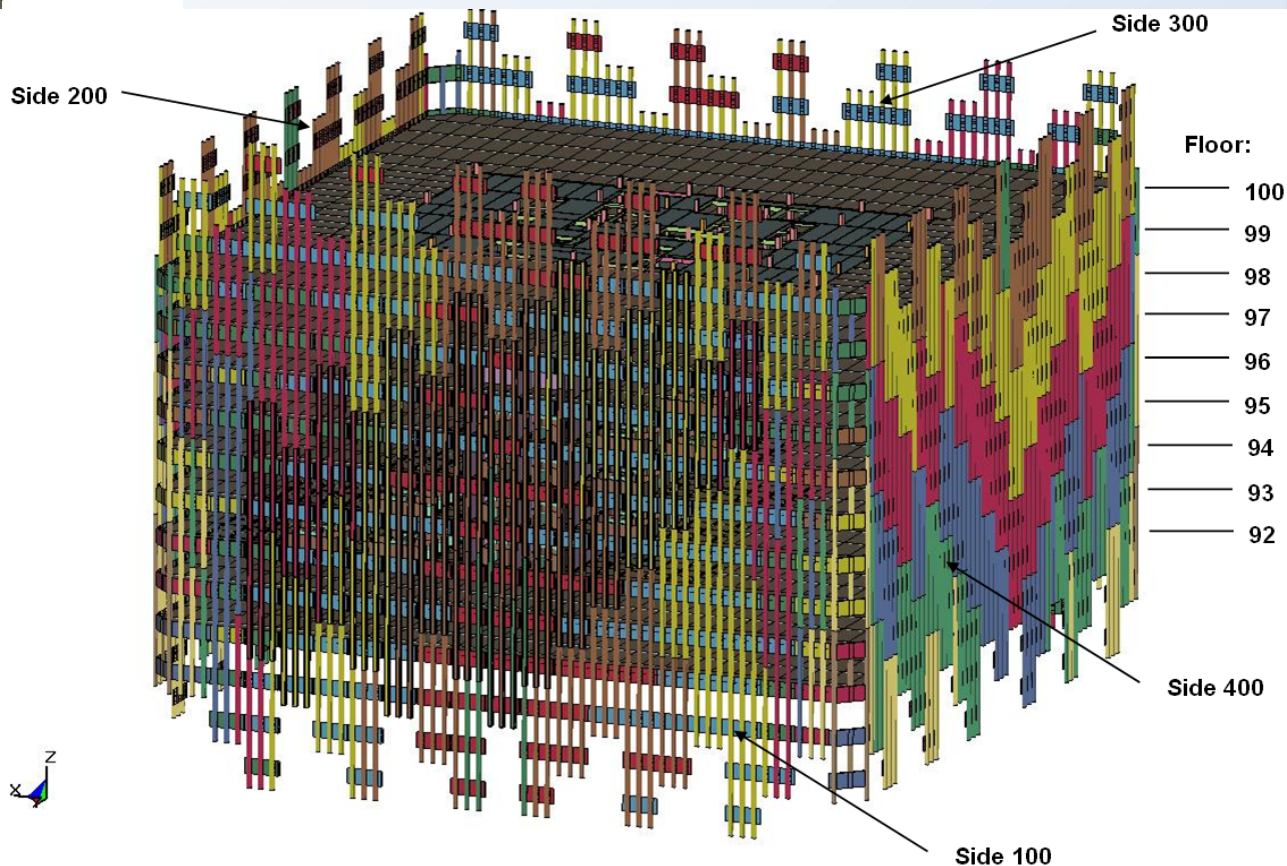
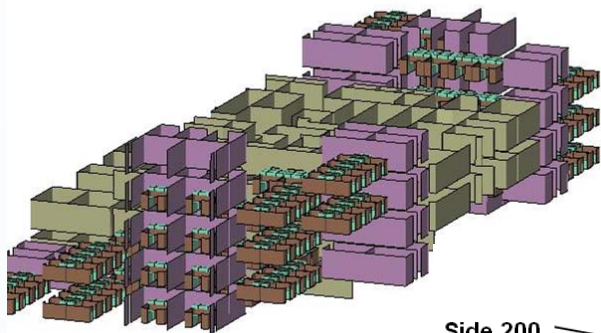
- ❑ The impact of the exterior wall by an empty wing segment produces significant damage to the perimeter columns, not necessarily complete failure.
- ❑ The impact of a fuel-filled wing section results in extensive damage to the exterior wall panel, including complete failure of the perimeter columns.



Effect of Engine Impact Location



WTC 1 Tower Model for Aircraft Impact Analysis



AA 11 (WTC 1) Aircraft Impact Initial Conditions

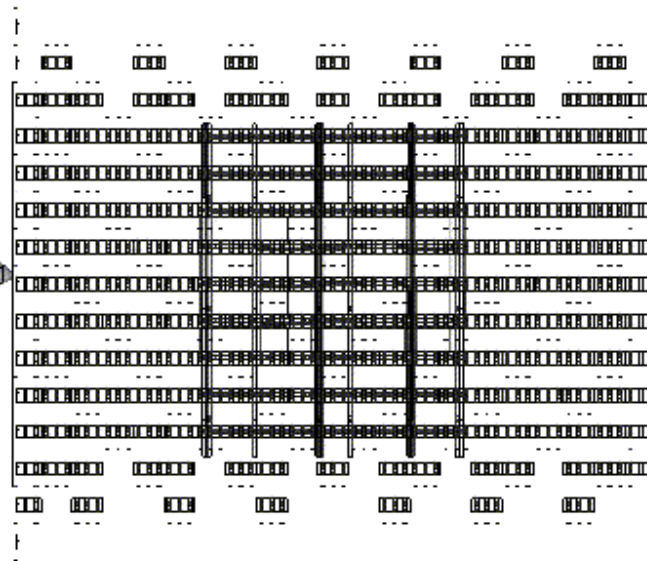
	FEMA	Hart-Weidlinger	MIT	NIST Simplified Analysis	NIST
Best Estimate Speed (mph)	470	500	429	466	443
Speed Error Estimate (mph)		+ 30 / - 50	± 51	± 34	± 30
Lateral Approach Angle (clockwise)		4.3°			0.3° ± 4°
Vertical Approach Angle (downward)		6.2°			10.6° ± 3°
Aircraft Roll (left wing down)		20.7°			25° ± 2°

UAL 175 (WTC 2) Aircraft Impact Initial Conditions

	FEMA	Hart-Weidlinger	MIT	NIST Simplified Analysis	NIST
Best Estimate Speed (mph)	590	550	503	545	542
Speed Error Estimate (mph)			± 38	± 18	± 24
Lateral Approach Angle (clockwise)		11.7°	15°		13° ± 2°
Vertical Approach Angle (downward)		2.7°	0°		6° ± 2°
Aircraft Roll (left wing down)		30.1°			38° ± 2°

WTC 1

Time = 0



WTC 1 Damage: Composite Summary for Floors 93 to 98

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

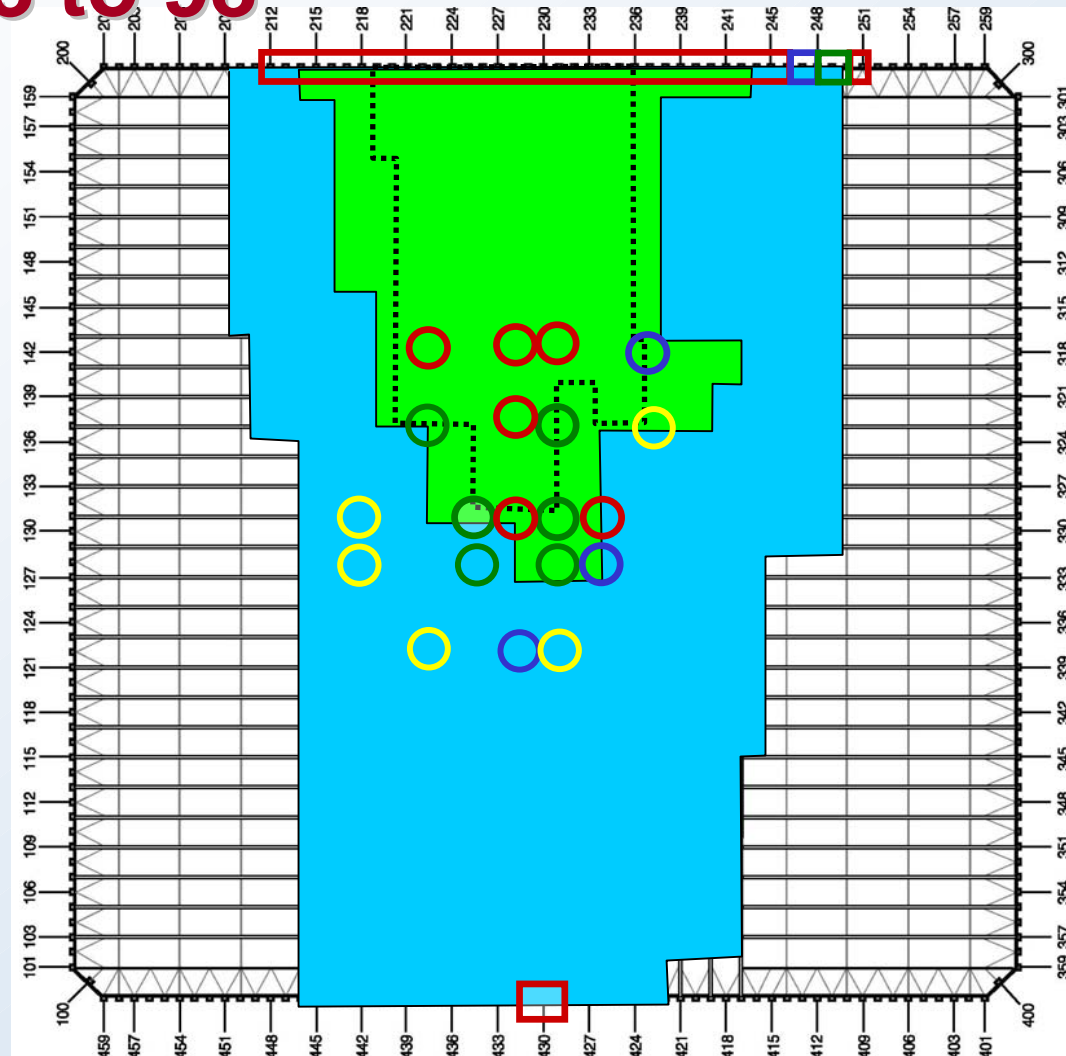
Column Damage

Severed 

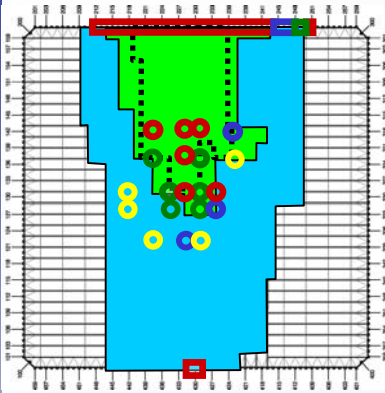
Heavy Damage 

Moderate Damage 

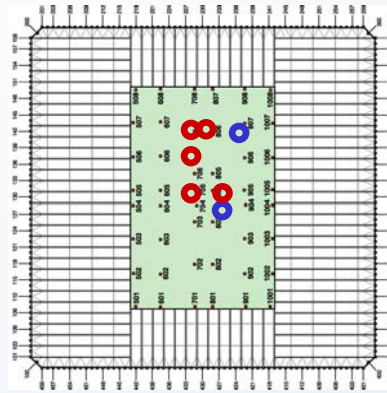
Light Damage 



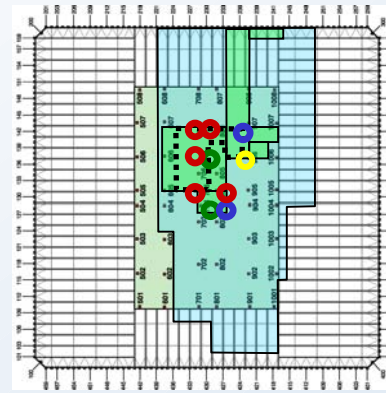
WTC 1 Damage by Floor



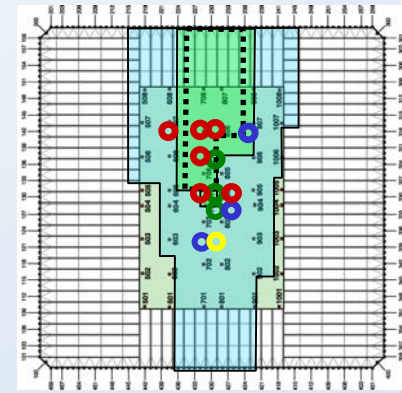
Floors 93 to 98
Cumulative Damage



Floor 93



Floor 94



Floor 95


Severe Floor Damage


Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

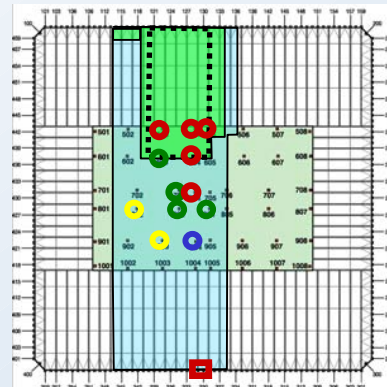
Column Damage

Severed 

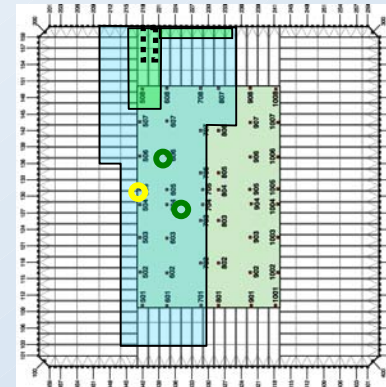
Heavy Damage 

Moderate Damage 

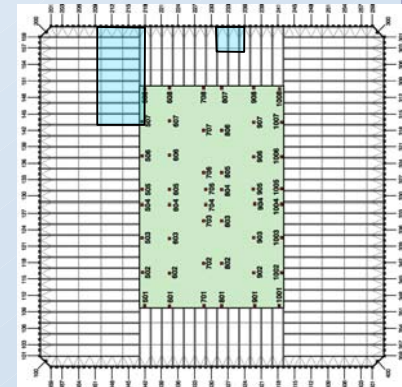
Light Damage 



Floor 96



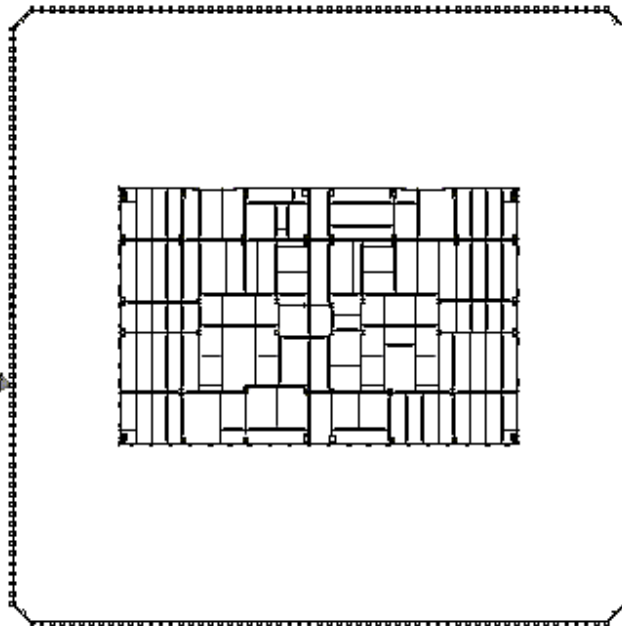
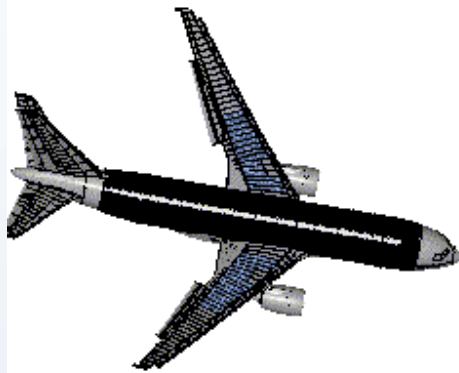
Floor 97



Floor 98

WTC 2

Time = 0



WTC 2 Damage: Composite Summary for Floors 78 to 83

Floor Damage

- Fireproofing and partitions
- Floor system structural damage
- Floor system removed

Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage

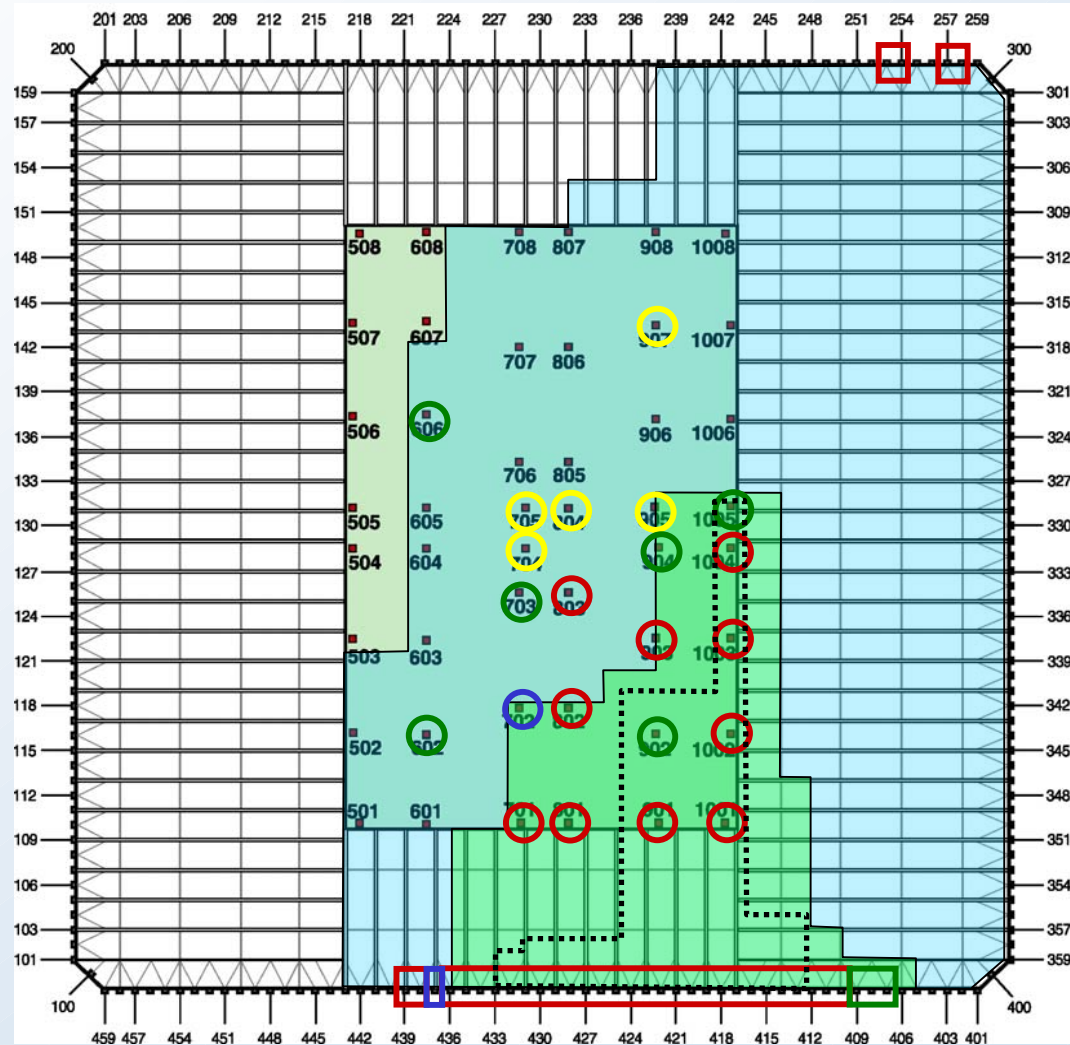
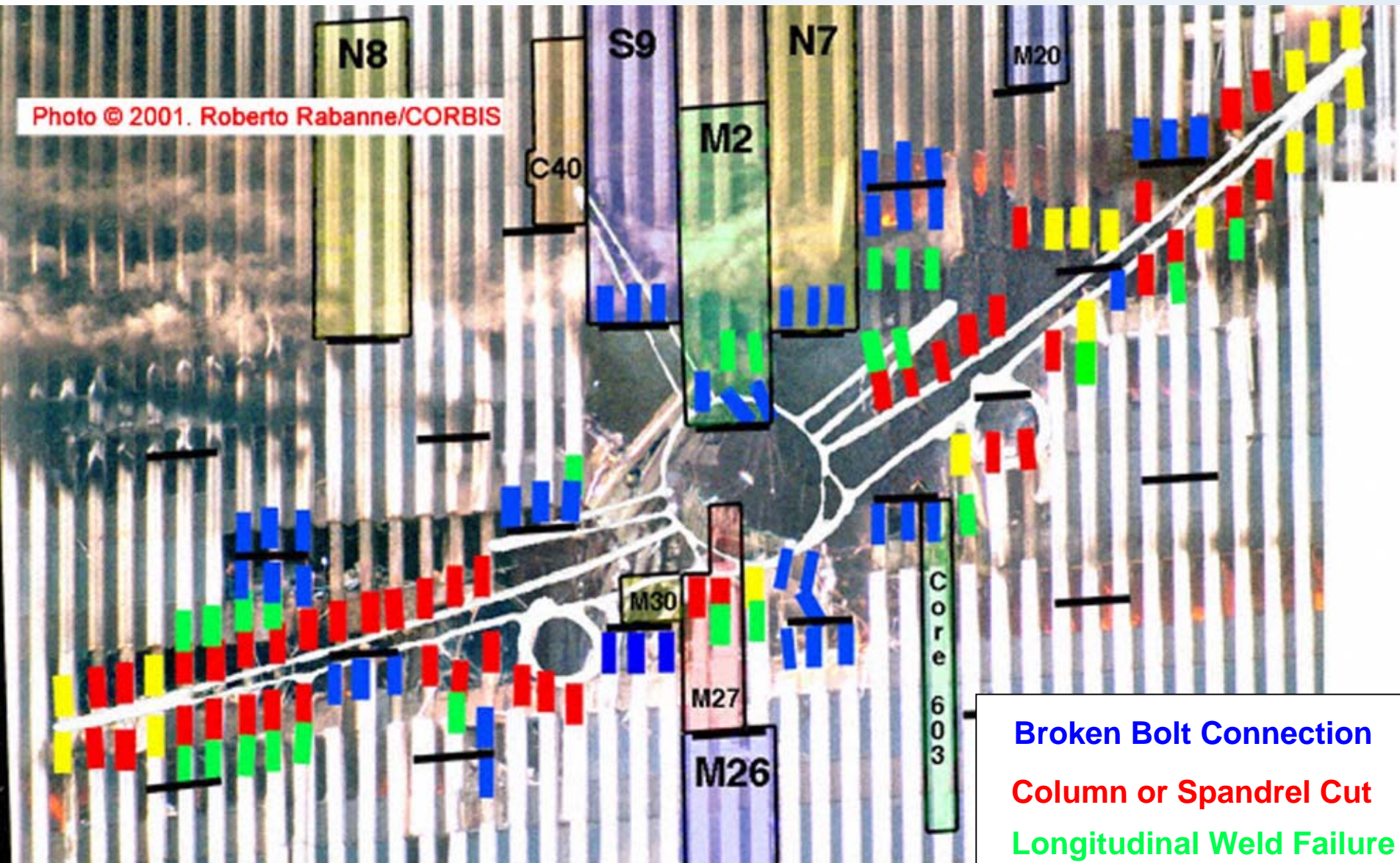


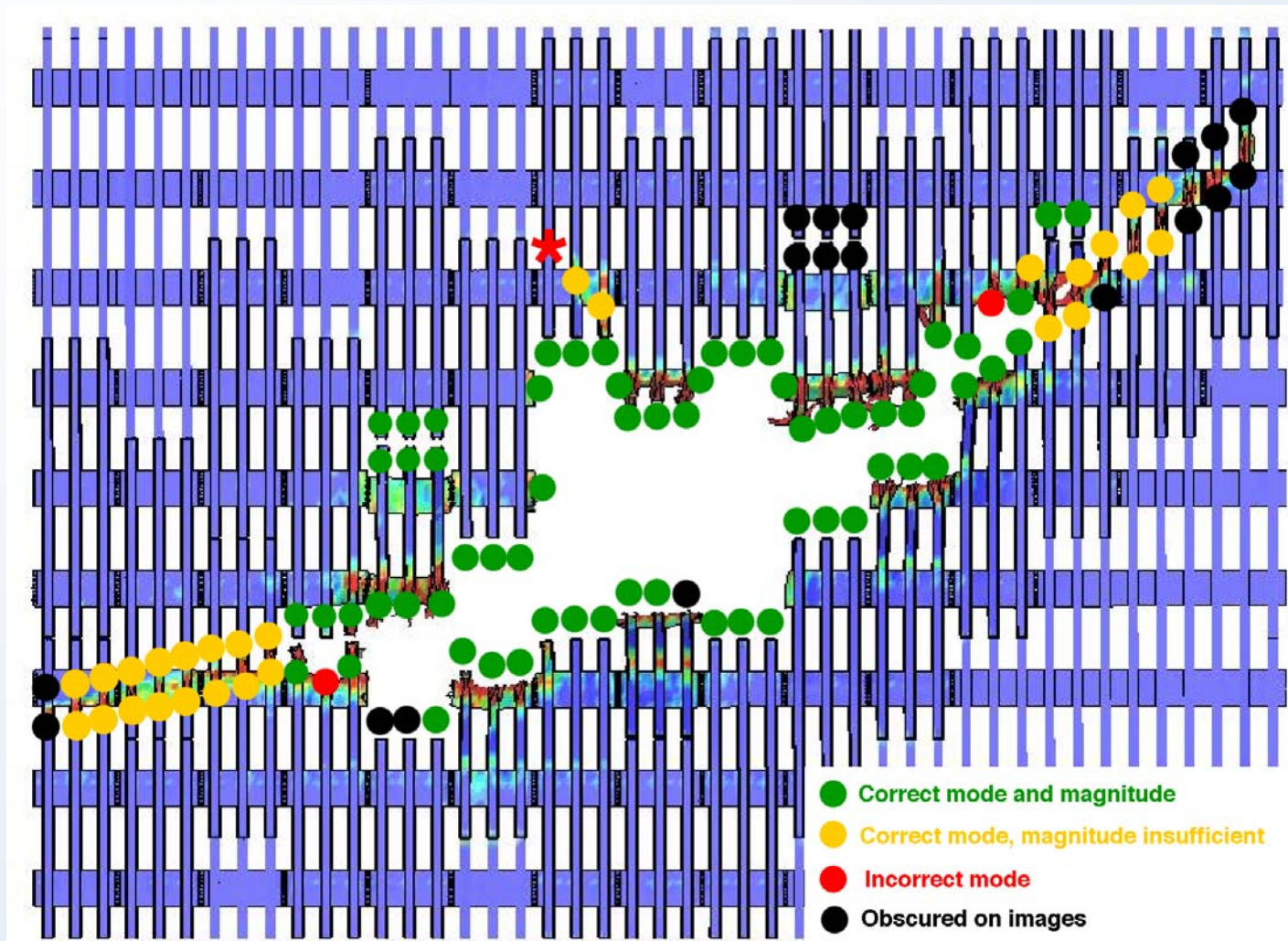
Photo © 2001. Roberto Rabanne/CORBIS



- Broken Bolt Connection
- Column or Spandrel Cut
- Longitudinal Weld Failure
- Obscured
- Panel Junction

Enhancements added by NIST.

Validation of Aircraft Impact Model Prediction With Observations for WTC 1



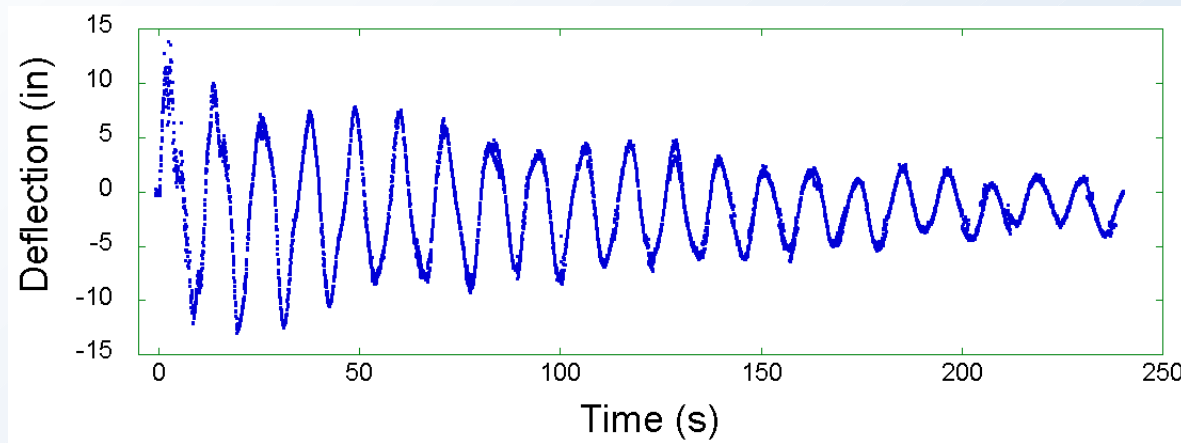
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© Scott Myers

Clock

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 more than about 1/3 of the design wind sway from the baseline analysis and an oscillation period nearly equal to the average 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 redistributed to 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.**

Relative Roles of Aircraft Impact and Fires

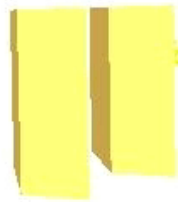
- **Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires and the thermal response of the structures by:**
 - Compromising the sprinkler and water supply systems;
 - Dispersing jet fuel and igniting building contents over large areas;
 - Creating large accumulations of combustible matter containing aircraft debris 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 on multiple floors;
 - Damaging and dislodging fireproofing from structural components in the direct path of the debris and due to the strong vibrations generated by aircraft impact; and
 - Damaging ceilings that enabled “unabated” heat transport over the floor-to-ceiling partition walls and to structural components.

Relative Roles of Aircraft Impact and Fires (2)

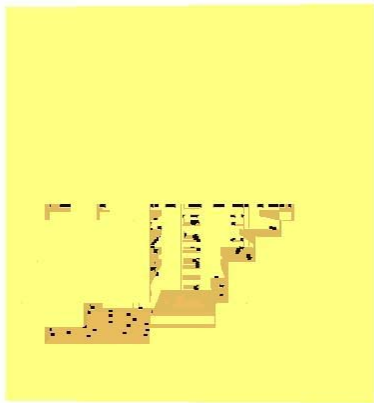
- **The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.**
- **Typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor.** No structural component, however, was subject to intense fires for the entire period of burning. The duration of intense burning impacting any specific component was controlled by:
 - **The availability of combustible materials**
 - **Fuel gases released by those combustibles**
 - **Combustion air in the specific area**
- **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.

Initial Fire and Smoke Simulations: Fall 2001

NIST Smokeview 2.0Beta1_0831 - DO NOT CITE



Frame: 0
Time: 1.2



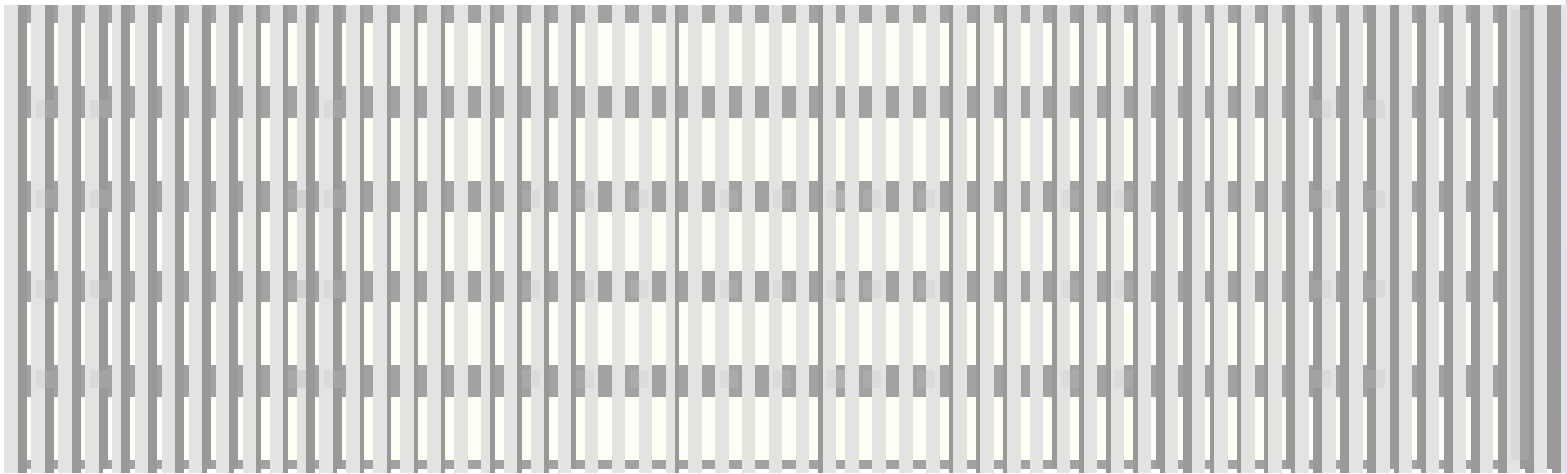
NIST Smokeview 3.0 Alpha - Jan 18, 2002



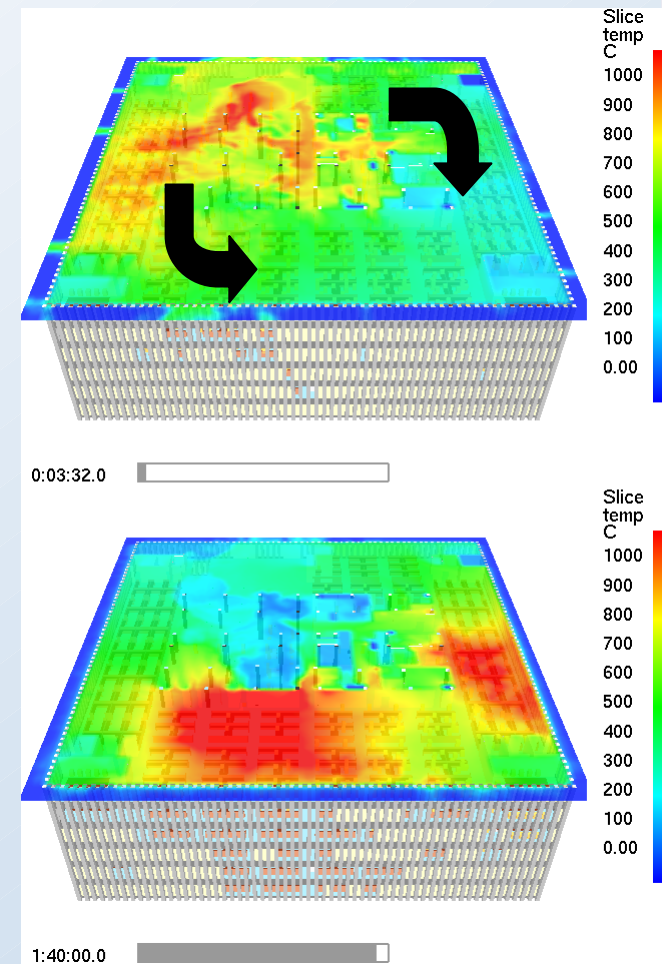
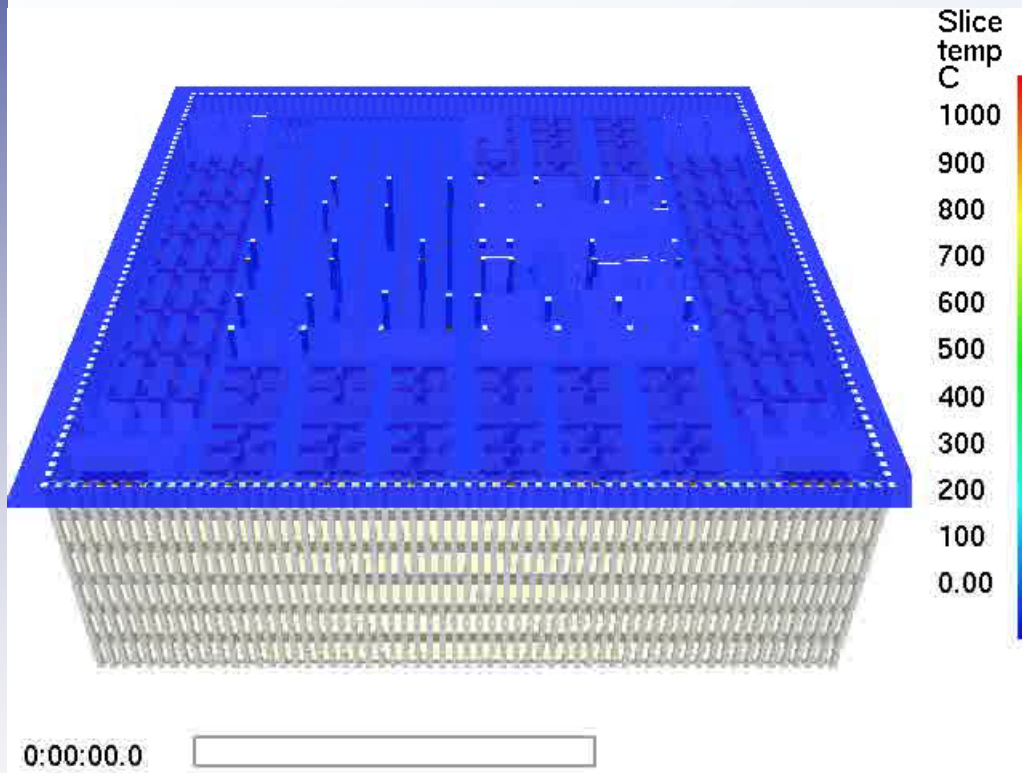
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Time: 0.0

Reconstruction of the WTC Fires

NIST

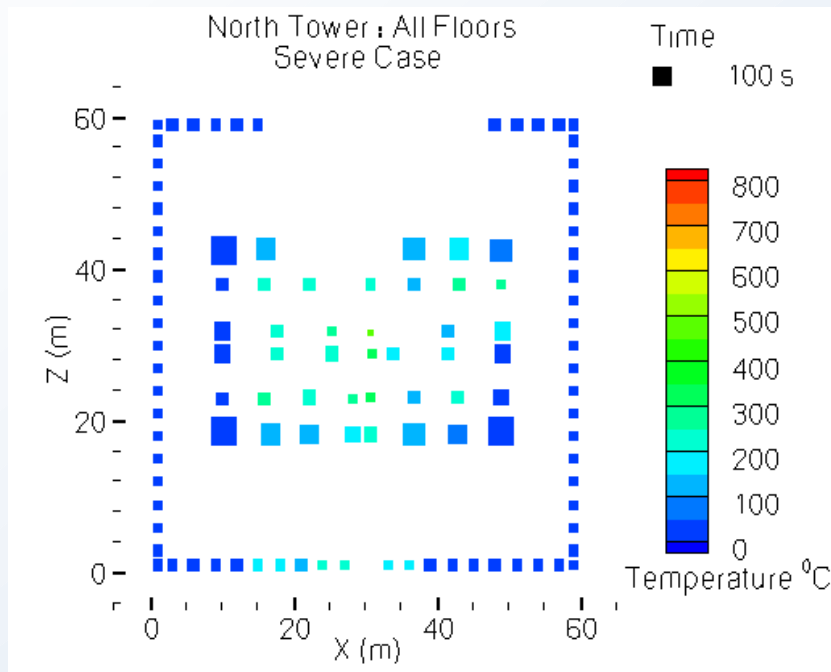


Upper Layer Temperatures (WTC 1, Floor 97)

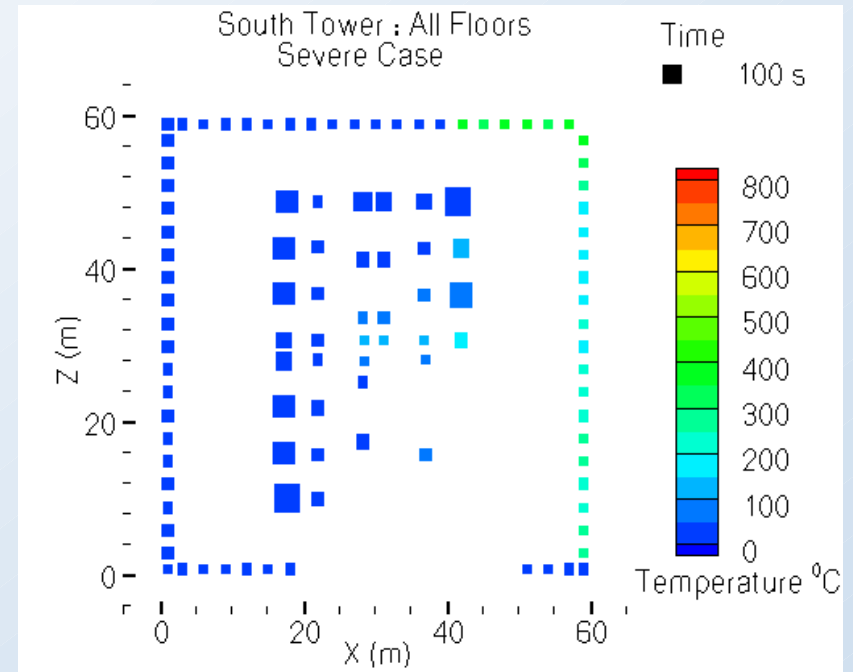


Results of Thermal Analysis

WTC 1



WTC 2



Shows maximum temperature reached by each column.

Structural Analysis Progression

Component Analyses

- ❑ Knuckle
- ❑ Truss seat connections
- ❑ Single truss and concrete slab
- ❑ Full floor
- ❑ Column splice connection
- ❑ Single story column
- ❑ Nine story column
- ❑ Nine story-nine column exterior wall panel

Detailed nonlinear analyses to determine component behaviors and failure mechanisms



Subsystem Analyses

- ❑ WTC 1
 - Isolated Core
 - South Exterior Face
 - Floors 93 to 99
- ❑ WTC 2
 - Isolated Core
 - East Exterior Face
 - Floors 79 to 83

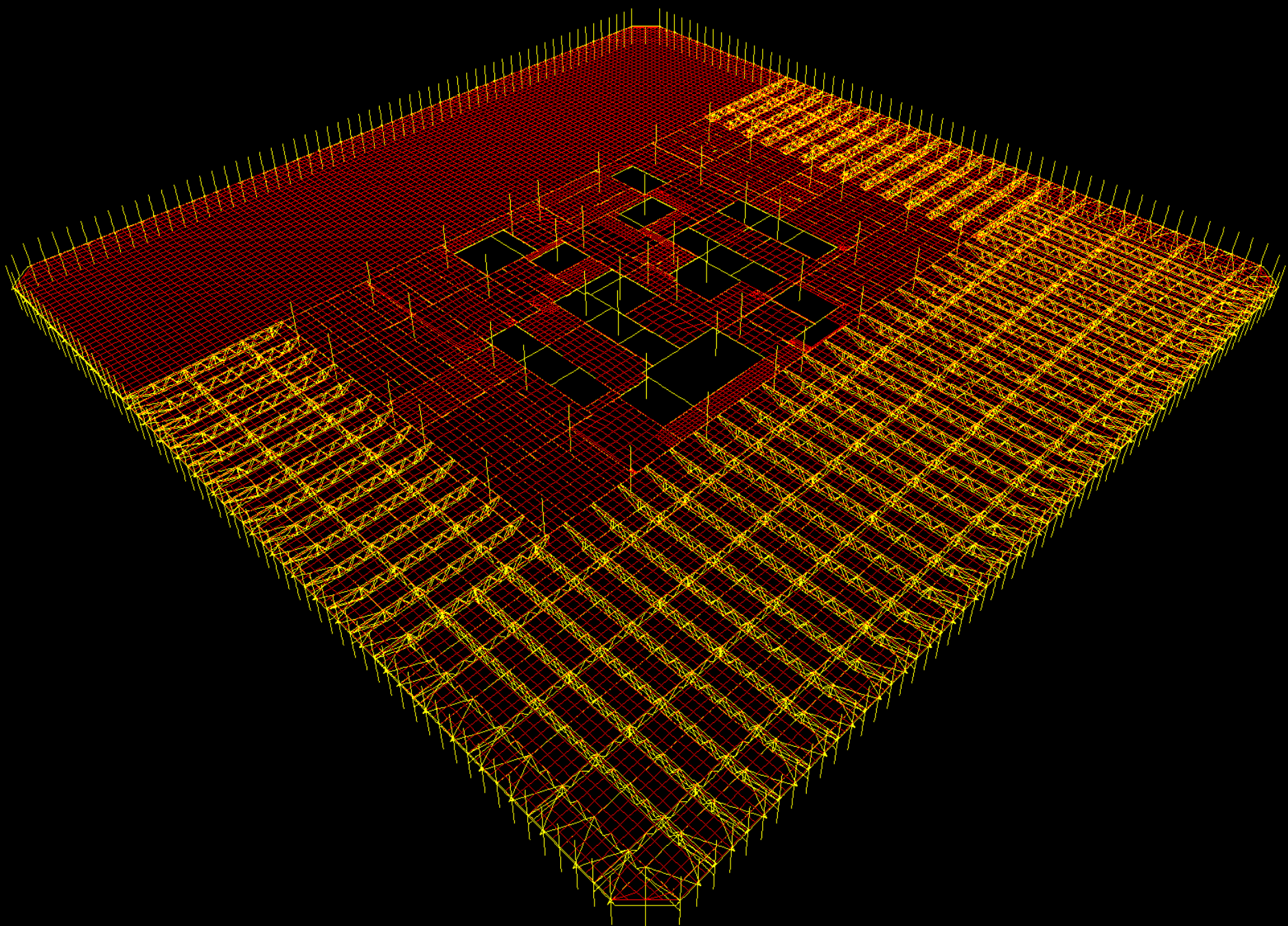
Nonlinear analyses with component simplifications and failure mechanism simplifications to determine major subsystem behavior and sequential failure mechanisms.

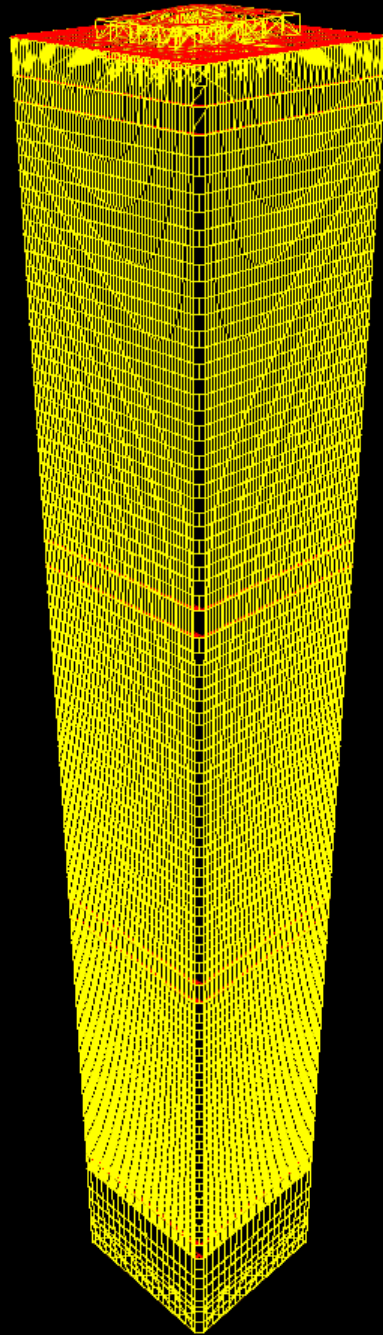


Global Analyses

- ❑ WTC 1
- ❑ WTC 2

Nonlinear analyses to determine global behavior and sequential failure mechanisms.





Progress in Determining Collapse Sequences

- **Possible Collapse Hypotheses** (May 2003) – not building specific; key events not identified
- **Working Collapse Hypothesis** (June 2004) – single hypothesis for both WTC towers; identifies chronological sequence of major events
- **Leading Collapse Hypotheses** (October 2004) – separate hypothesis for each WTC tower; identifies building-specific load redistribution paths and damage scenarios in addition to chronological sequence of major events
- **Probable Collapse Sequences** (April 2005) – refined building specific collapse sequences with chronological sequence of major events, load redistribution paths, and damage scenarios.

Probable Collapse Sequence for WTC 1

1. Aircraft Impact Damage:

- Aircraft impact severed a number of exterior columns on the North wall from floors 93 to 98, and the wall section above the impact zone moved downward.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, severing floor framing and core columns at the North side of the core. Core columns were also damaged toward the center of the core and, to a limited extent on the South side of the core. Fireproofing was damaged from the impact area to the South perimeter wall, primarily through the center of WTC 1 and at least over a third to a half of the core width.
- Aircraft impact severed a single exterior panel at the center of the South wall between floors 94 and 96.
- The impact damage to the exterior walls and to the core resulted in redistribution of severed column loads, mostly to the columns adjacent to the impact zones. The hat truss resisted the downward movement of the North wall, and rotated about the East-West axis.
- As a result of the aircraft impact damage, the North and South walls each carried about 7 percent less gravity loads after impact, and the East and West walls each carried about 7 percent more loads. The core carried about 1 percent more gravity loads after impact.

Probable Collapse Sequence for WTC 1 (2)

2. Effects of Subsequent Fires and Impact Damaged Fireproofing:

A. Thermal Weakening of the Core:

- The undamaged core columns developed high plastic and creep strains over the duration the building stood, since both temperatures and stresses were high in the core area. The plastic and creep strains exceeded thermal expansion in the core columns.
- The shortening of the core columns (due to plasticity and creep) was resisted by the hat truss which unloaded the core over time and redistributed loads to perimeter walls.
- As a result of the thermal weakening (and subsequent to impact and prior to inward bowing of the South wall), the North and South walls each carried about 10 percent more gravity loads, and the East and West walls each carried about 25 percent more loads. The core carried about 20 percent less gravity loads after thermal weakening.

B. Thermal Weakening of the Floors:

- Floors 95 to 99 weakened with increasing temperatures over time on the long-span floors and sagged. The floors sagged first and then contracted due to cooling on the North side; fires reached the South side later, the floors sagged, and the seat connections weakened.
- Floor sagging induced inward pull forces on the South wall columns.
- About 20 percent of the connections to the South perimeter wall on floors 97 and 98 failed due to thermal weakening of the vertical supports.

C. Thermal Weakening of the South Wall:

- South wall columns bowed inward as they were subjected to high temperatures and inward pull forces in addition to axial loads.
- Inward bowing of the South wall columns increased with time.

Probable Collapse Sequence for WTC 1 (3)

3. Collapse Initiation

- The inward bowing of the South wall induced column instability, which progressed rapidly horizontally across the entire South face.
- The South wall unloaded and tried to redistribute the loads via the hat truss to the thermally weakened core and via the spandrels to the adjacent East and West walls.
- The entire section of the building above the impact zone began tilting as a rigid block (all four faces; not only the bowed and buckled South face) to the South (at least about 8°) as column instability progressed rapidly from the South wall along the adjacent East and West walls.
- 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.

Probable Collapse Sequence for WTC 2

1. Aircraft Impact Damage:

- Aircraft impact severed a number of exterior columns on the South wall from floors 78 to 84, and the wall section above the impact zone moved downward.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, severing floor framing and core columns at the Southeast corner of the core. Fireproofing was damaged from the impact area through the East half of the core up to the North and East perimeter walls. The floor truss seat connections over about 1/4 to 1/2 of the East side of the core were severed on floors 80 and 81 and over about 1/3 of the East perimeter wall on floor 83.
- Aircraft impact severed a few columns near the East corner of the North wall between floors 80 and 82.
- The impact damage to the exterior walls resulted in redistribution of severed column loads, mostly to the columns adjacent to the impact zones. The impact damage to the core columns resulted in redistribution of severed column loads mostly to other intact core columns and the East exterior wall. The hat truss resisted the downward movement of the South wall, and rotated about the East-West axis.
- As a result of the aircraft impact damage, the core carried 6 percent less gravity loads after impact and the North face carried 10 percent less loads. The East face carried 24 percent more gravity load, while the West face and the South face carried 3 percent and 2 percent more gravity load, respectively.
- After impact, the core was leaning toward the East and South perimeter walls. The perimeter walls acted to restrain the core structure.

Probable Collapse Sequence for WTC 2 (2)

2. Effects of Subsequent Fires and Impact Damaged Fireproofing:

A. Thermal Weakening of the Core:

- Several of the undamaged core columns near the damaged and severed core columns developed high plastic and creep strains over the duration the building stood, since both temperatures and stresses were high in the core area. The plastic and creep strains exceeded thermal expansion in the core columns.
- The core continued to tilt toward the East and South due to the combination of column shortening (due to plasticity, creep, and buckling) and the failure of column splices at the hat truss in the Southeast corner.
- As a result of thermal weakening (and subsequent to impact), the East wall carried about 5 percent more gravity loads and the core carried about 2 percent less loads. The other three walls carried between 0 and 3 percent less loads.

B. Thermal Weakening of the Floors:

- Floors 79 to 83 weakened with increasing temperatures over time on the long-span floors on the East side and sagged.
- Floor sagging induced inward pull forces on the East wall columns.
- About an additional 1/3 of the connections to the East perimeter wall on floor 83 failed due to thermal weakening of the vertical supports.

C. Thermal Weakening of the East Wall:

- East wall columns bowed inward as they were subjected to high temperatures and inward pull forces in addition to axial loads.
- Inward bowing of the East wall columns increased with time.

Probable Collapse Sequence for WTC 2 (3)

3. Collapse Initiation

- The inward bowing of the East wall induced column instability, which progressed rapidly horizontally across the entire East face.
- The East wall unloaded and tried to redistribute the loads via the hat truss to the weakened core and via the spandrels to the adjacent North and South walls.
- The entire section of the building above the impact zone began tilting as a rigid block (all four faces; not only the bowed and buckled East face) to the East (about 7° to 8°) and South (about 3° to 4°) as column instability progressed rapidly from the East wall along the adjacent North and South walls. The building section above impact continued to rotate to the East as it began to fall downward, and rotated to at least 20 to 25 degrees.
- 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.

Validation of Probable Collapse Sequence

- NIST evaluated the key factors related to:
 - Innovative structural system
 - Aircraft impact and subsequent fires: How safe was each building immediately after aircraft impact but before fire weakened the structures?
 - 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
 - Role of compartmentation (i.e. areas divided by fire-rated walls)
- NIST made concerted efforts to validate results with key observations obtained from its extensive collection of over 7,000 photographs and over 150 hours of videotape documenting the events at the World Trade Center on September 11, 2001
- The probable collapse sequences are supported by the evidence held by NIST, including photographs and videos, recovered steel, eyewitness accounts, and emergency communication records

Collection and Analysis of Photographic and Video Images

- Visual database contains:
 - Well in excess of 7,000 photographs taken by more than 185 photographers
 - 150 hours of videotape from major media outlets and more than 20 individuals
- From the analysis of the visual images to date, NIST has identified significant events for WTC 1 and 2 related to aircraft impact, fire development, and building damage
- **NIST has developed detailed mappings for the fire, smoke, and the condition of windows at several specific times for each WTC tower; work is nearing completion for WTC 7**



Time to Collapse Initiation

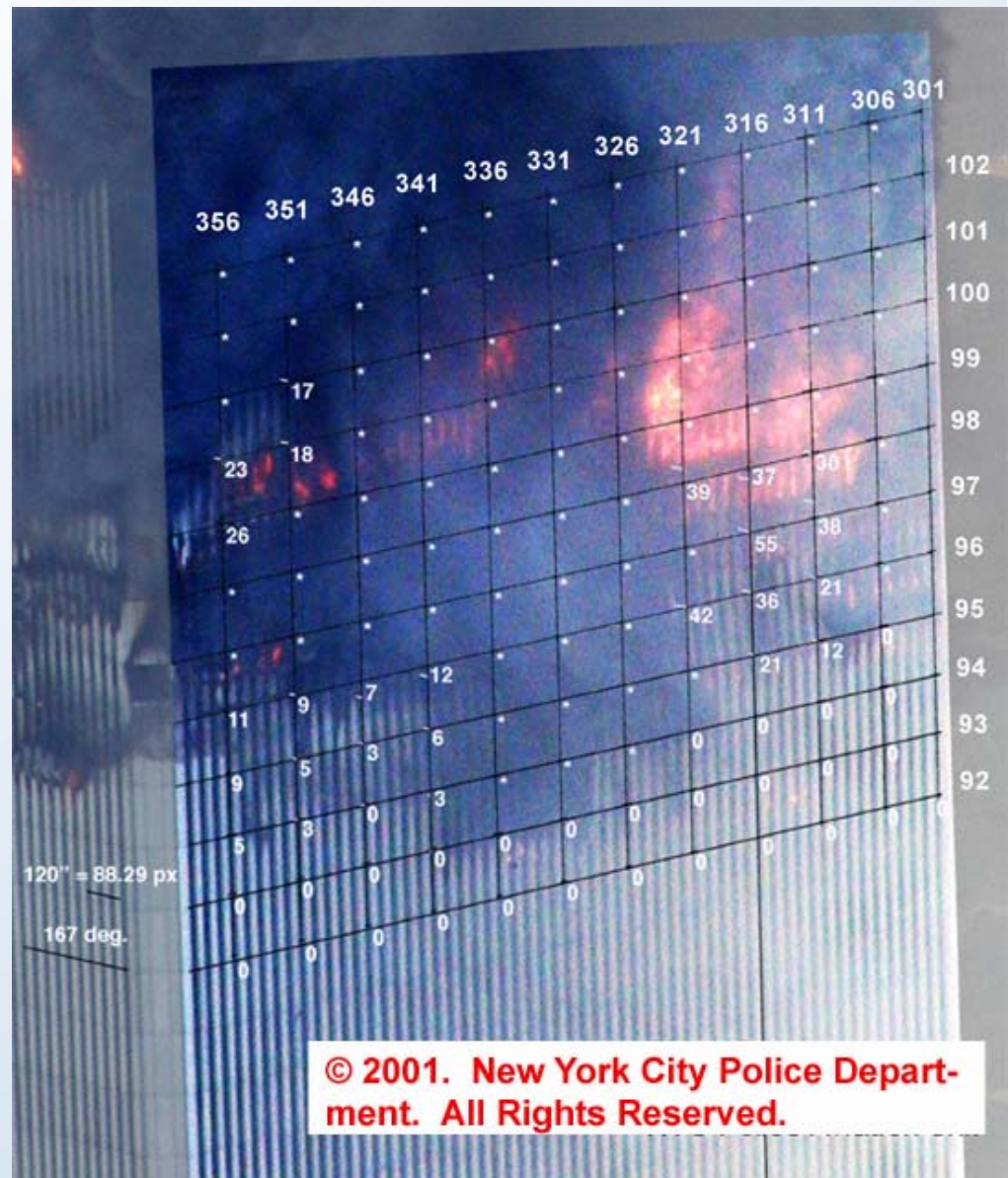
	WTC 1	WTC 2
Actual Time	102 min	56 min
Estimated Time*	100 min	42 min

* The exact times are sensitive to the factors that control the inward bowing of the exterior columns. The sequence of events leading to collapse is not sensitive to these factors.

South Face of WTC1

- Time: 10:22 AM
- Measurements of inward bowing (inches)
- **Maximum = 55 inches**
(uncertainty ~ +/- 6 inches)

- Floor locations approximate
- Blue tinted region digitally enhanced



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

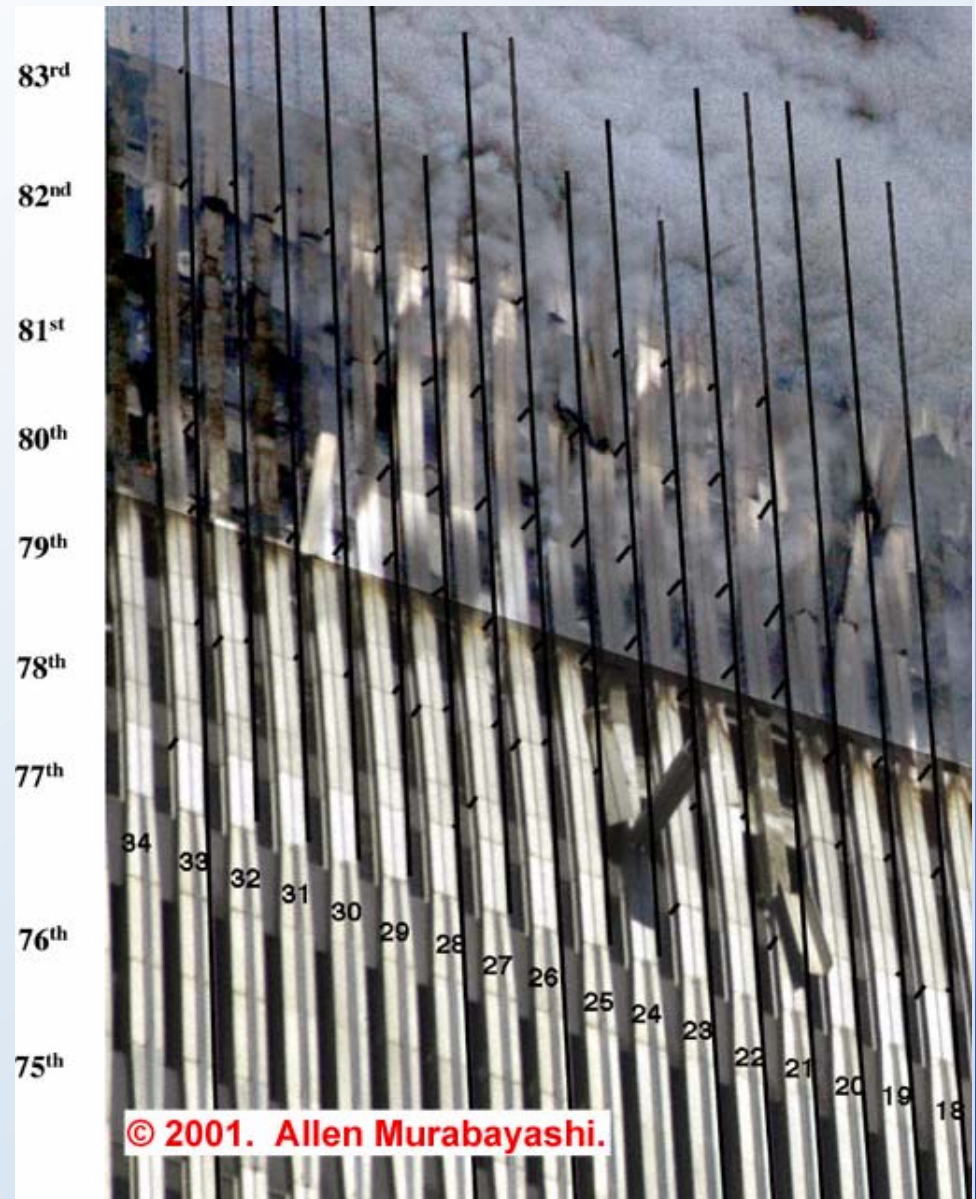
9:58:56 a.m.

©2001. New York City Police Department. All rights reserved.

WTC2: East Face

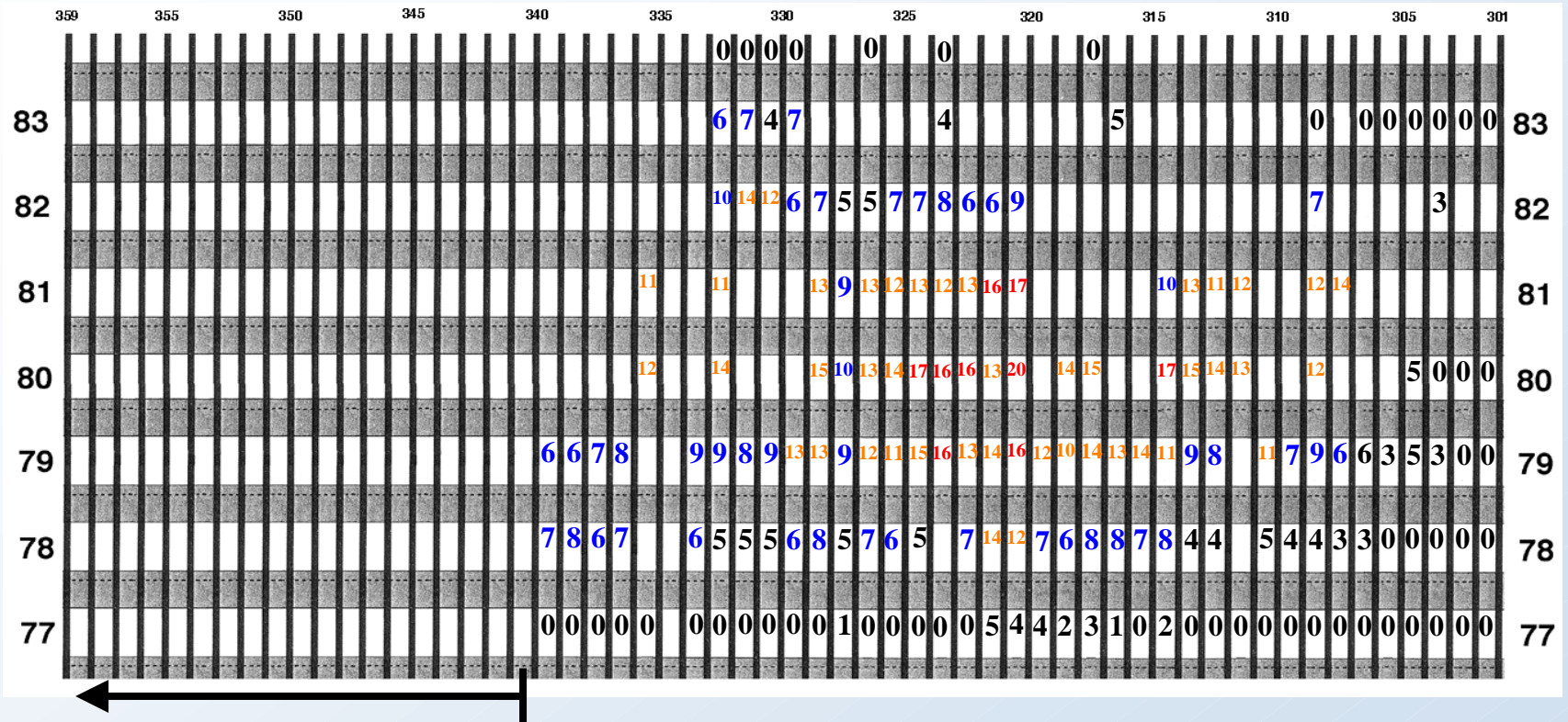
Time: 9:21:29 AM
~18 minutes post impact

Maximum inward bowing of
columns approximately
10 inches



Map of Inward Bowing: East Face of WTC 2

Time: 9:52:54 AM to 9:53:04 AM



Obscured in Photos

Pull-in (inches)

Estimated uncertainty: +/- 1 inch

Empty regions have no data (smoke, damaged aluminum, could not establish true vertical, etc.)

Tilting of Building Sections

© 2001 Dean Riviere

WTC 1 tilted to the south; WTC 2 tilted to the east and south.



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

WTC 1: First Responder Communications

- 10:06 am NYPD aviation unit advises everybody to evacuate the area in the vicinity of Battery Park City and states that, about 15 floors from the top, it is totally glowing red on the inside and collapse was inevitable.

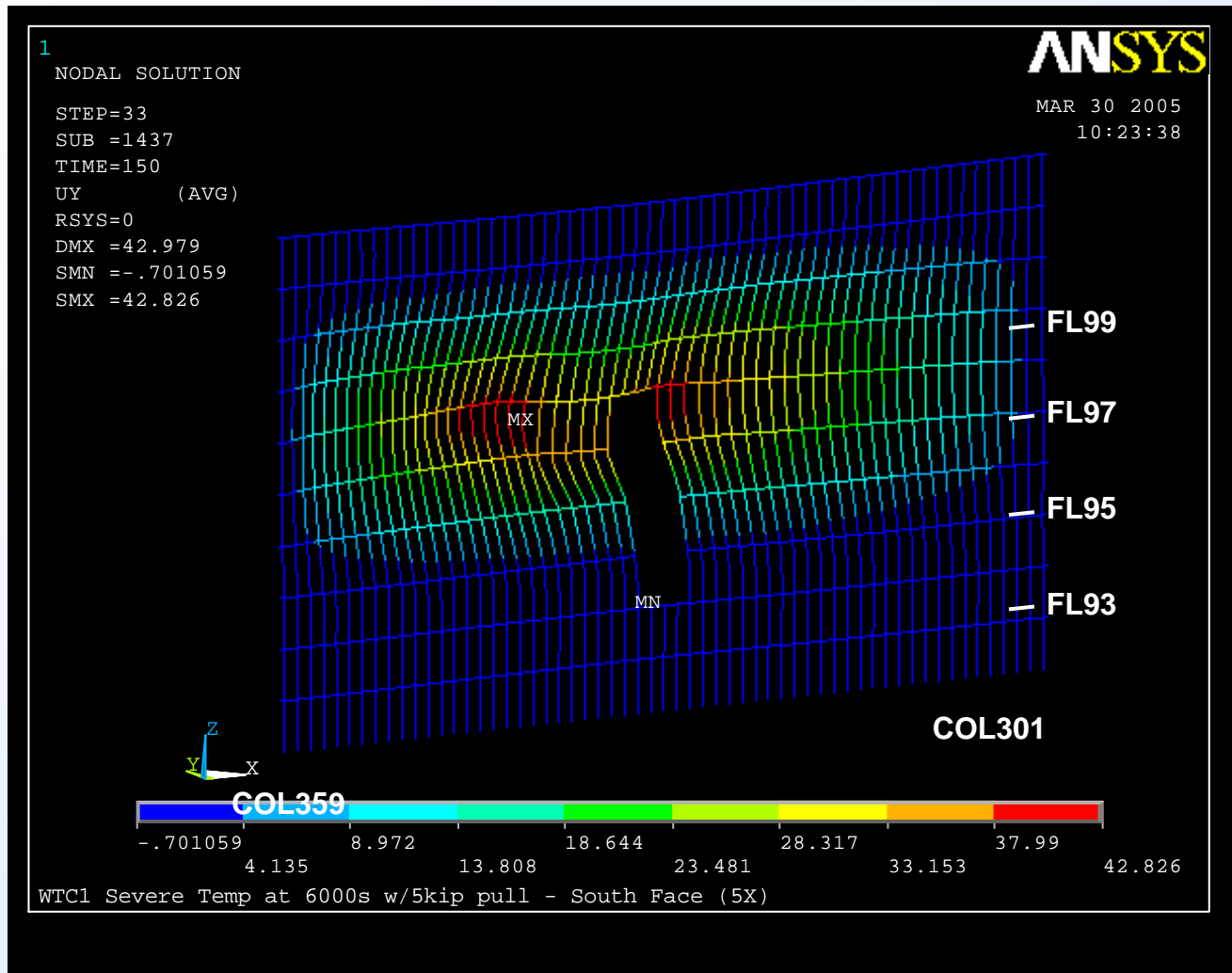
NYPD officer advises that it isn't going to take much longer before the North tower comes down and to pull emergency vehicles back from the building.
- 10:21 am NYPD aviation unit first reports that the top of the tower might be leaning, then confirms that it is buckling and leaning to the South.

NYPD aviation unit reports that the North tower is leaning to the Southwest and appears to be buckling in the Southwest corner.

NYPD officer advises that all personnel close to the building pull back three blocks in every direction.
- 10:28 am NYPD aviation unit reports that the roof is going to come down very shortly.

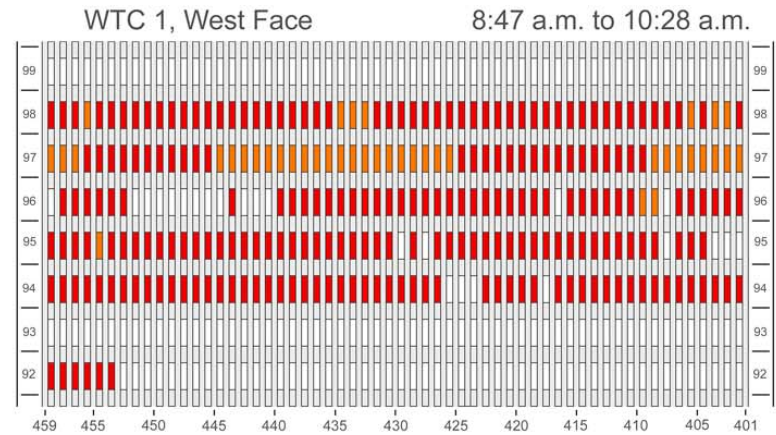
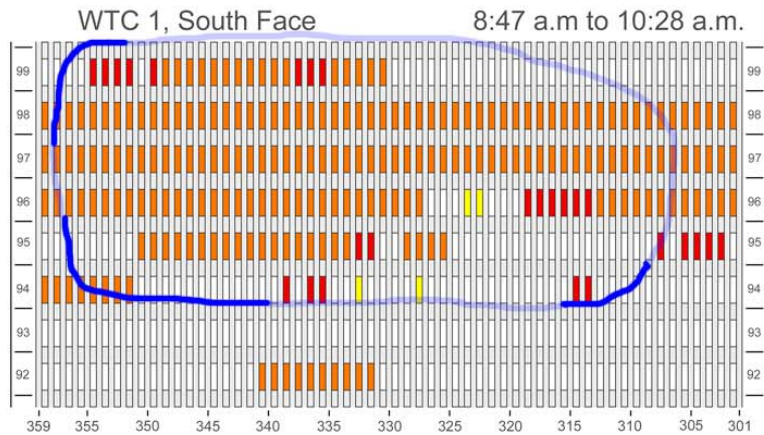
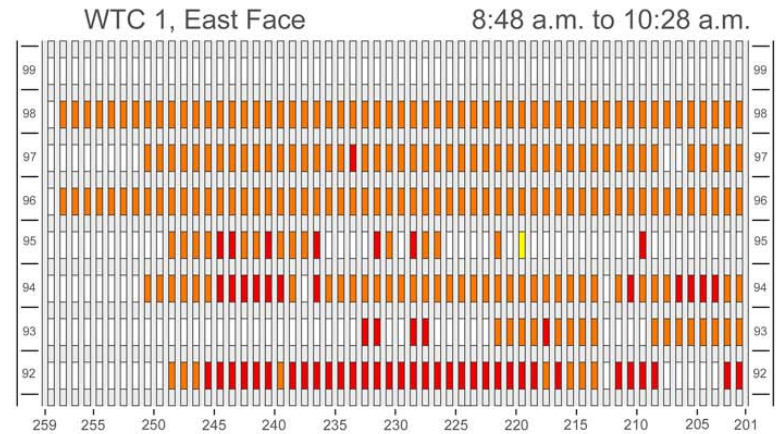
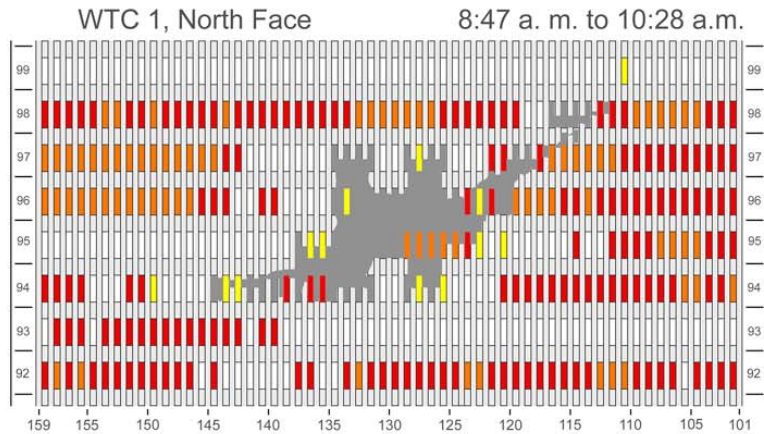
NYPD officer reports that the tower is collapsing.

Inward Bowing of the WTC 1 South Face at 6000 s



Maximum Inward Displacement = 43 in.
Looking from the outside of the building
Inward displacement is shown as positive displacement

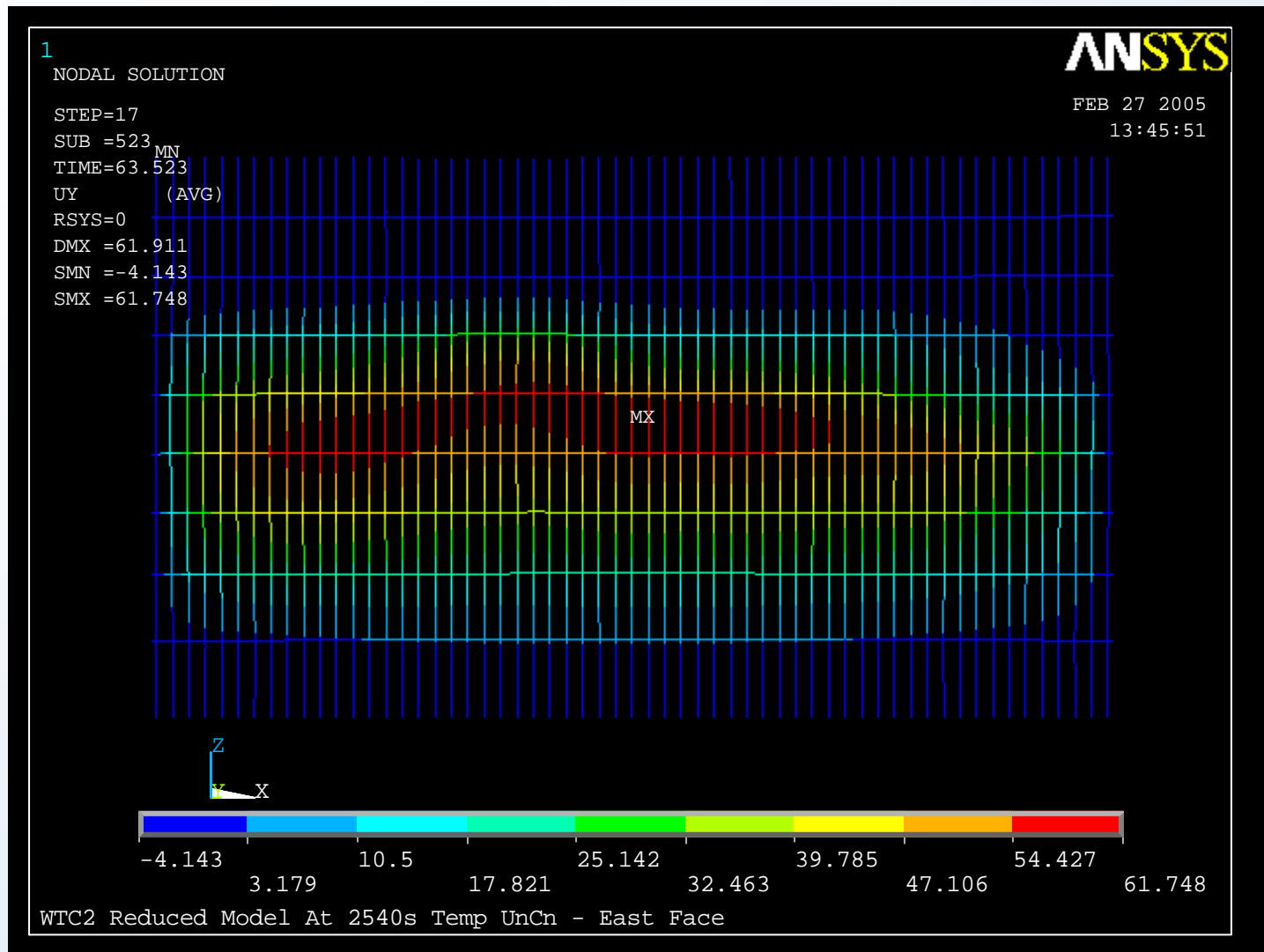
Visual Evidence of Fires in WTC 1



Dark blue line indicates extent of inward bowing observed in visual images.

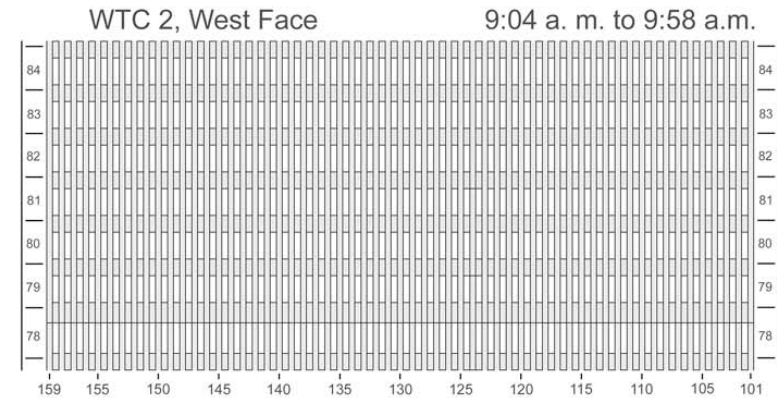
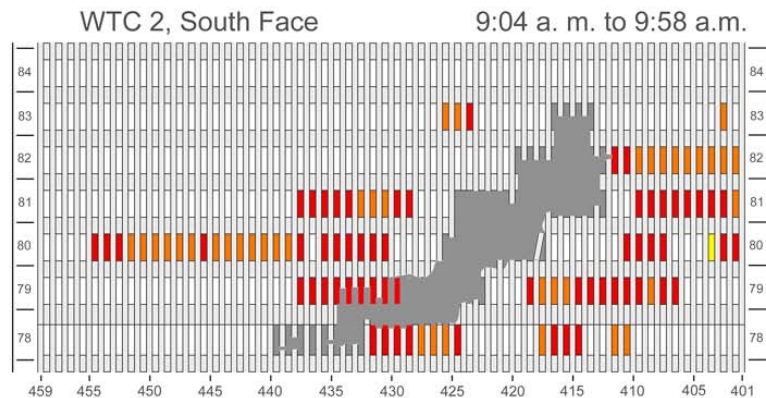
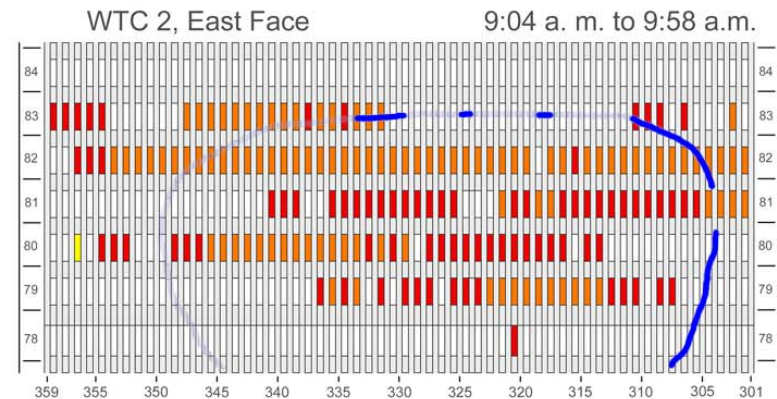
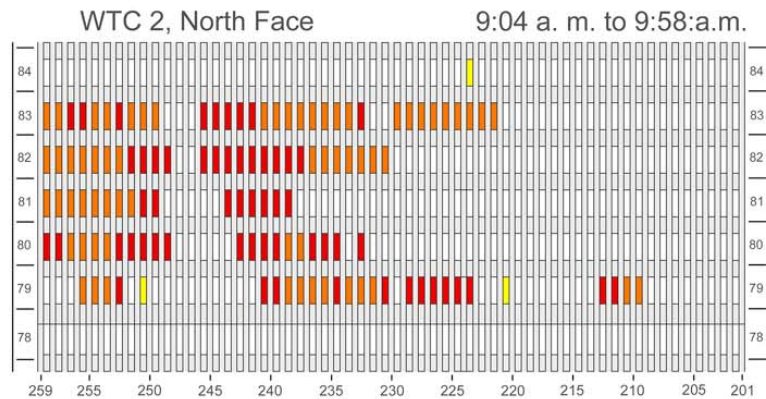
Light blue line is estimated region of inward bowing where visual images were obscured.

Inward Bowing of the WTC 2 East Face at 2,540 s



Maximum inward displacement = 60 in.

Visual Evidence of Fires in WTC 2



Dark blue line indicates extent of inward bowing observed in visual images.
Light blue line is estimated region of inward bowing where visual images were obscured.

Fireproofing Conditions

- In general, the affected floor systems in WTC 1 had upgraded or thicker fireproofing (1.5 in. specified); affected floors in WTC 2 had the original fireproofing (0.5 in. specified).
- **Structural response is sensitive to variability in fireproofing thickness along the length of components; it is possible to determine a thermally equivalent uniform thickness that should be greater than the specified thickness. The thermally equivalent thicknesses were used in the analysis.**

Status	As-Applied Avg. (COV*)	Thermally Equivalent	Specified
Original	0.75 (0.4)	0.6	0.5
Upgraded	2.5 (0.24)	2.2	1.5

* Coefficient of Variation

- **In the analysis under the original condition, the fireproofing thickness on the bridging trusses was considered to be *one-half* the thickness for the primary trusses from interpretation of photographic evidence. For the upgraded condition, the fireproofing thickness on the bridging trusses was considered to be *equal* to the thickness for the primary trusses.**

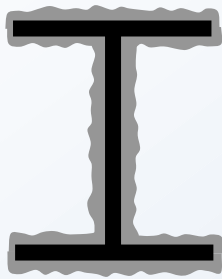
Analysis of Fireproofing Damage

- **NIST developed and used a rigorous technical approach to evaluate the role of the post-impact condition of the fireproofing in the collapse of the WTC towers.**
- **The technical approach was based on a comprehensive aircraft impact analysis that predicted in detail (1) the damage to structural components and building partitions and furnishings (the partitions and modular office workstations were modeled explicitly in the impact region), (2) the path of the debris field that was generated by aircraft impact, and (3) the dispersion of jet fuel.**
- **NIST determined the most influential parameters that governed the results of the aircraft impact damage analysis based on formal statistically-based methods. NIST then conducted analyses for two sets of values for the most influential parameters for each WTC tower to estimate the range of damage caused by aircraft impact.**
- **NIST determined conservative estimates for the extent of dislodged fireproofing by considering fireproofing damage only to structural components in the direct path of debris.**

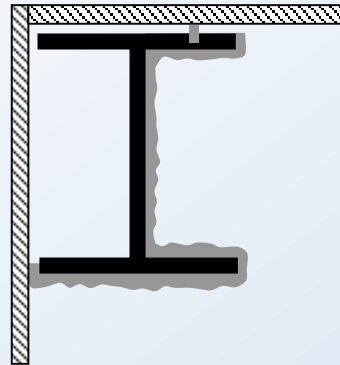
Analysis of Fireproofing Damage (2)

- **Consistent with a conservative approach, NIST estimates ignored the possibility that fireproofing on structural components in a much larger region that was not in the direct path of the debris was dislodged by shock or strong vibrations.**
 - The WTC towers shook vigorously *during* the 0.5-0.7 seconds of aircraft impact. Video analysis showed that WTC 2 vibrated for over 4 minutes *after* aircraft impact with amplitudes in excess of 20 inches at the roof top.
 - Considerable photographic evidence shows fireproofing dislodged from perimeter columns not directly impacted by debris.
 - First-person interviews of building occupants indicate that building vibrations due to aircraft impact were strong enough to dislodge ceiling tiles and collapse walls throughout the height of both WTC towers and to cause nearly all elevators to stop functioning.
 - Difficult to establish robust criteria to generate a coherent pattern of vibration-induced dislodging.
 - The variation of influential parameters used in determining the probable collapse sequence included some variation in the extent of dislodged fireproofing.

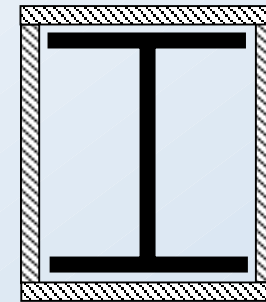
Examples of Types of Core Column Fireproofing



SFRM Only



SFRM +
Wallboard



Wallboard
Only

SFRM – Sprayed fire resistive material

Wallboard – Gypsum wallboard enclosure

Types of Fireproofing on Core Columns in Fire-Affected Floors

WTC 1

Floor	% SFRM only	% SFRM + Wallboard	% Wallboard only
94	13%	49%	38%
95	9%	49%	43%
96	11%	45%	45%
97	11%	45%	45%
98	11%	45%	45%
All	11%	46%	43%

Information from original design drawings

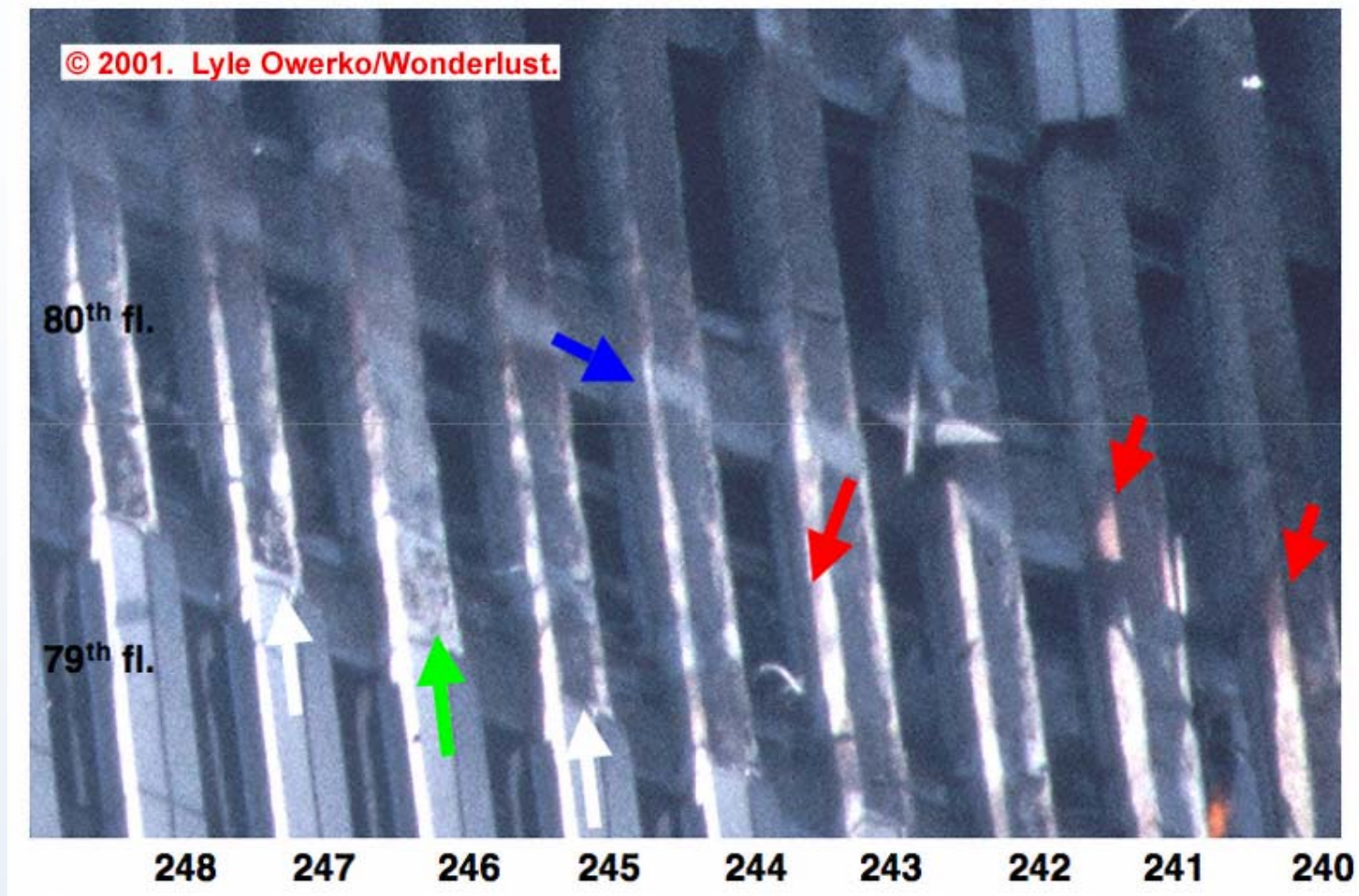
SFRM – Sprayed fire resistive material

Wallboard – Gypsum wallboard enclosure

WTC 2

Floor	% SFRM only	% SFRM + Wallboard	% Wallboard only
78	38%	49%	13%
79	19%	68%	13%
80	17%	51%	32%
81	17%	51%	32%
82	23%	55%	21%
83	15%	57%	28%
All	22%	55%	23%

Damaged SFRM - North Face of WTC 2



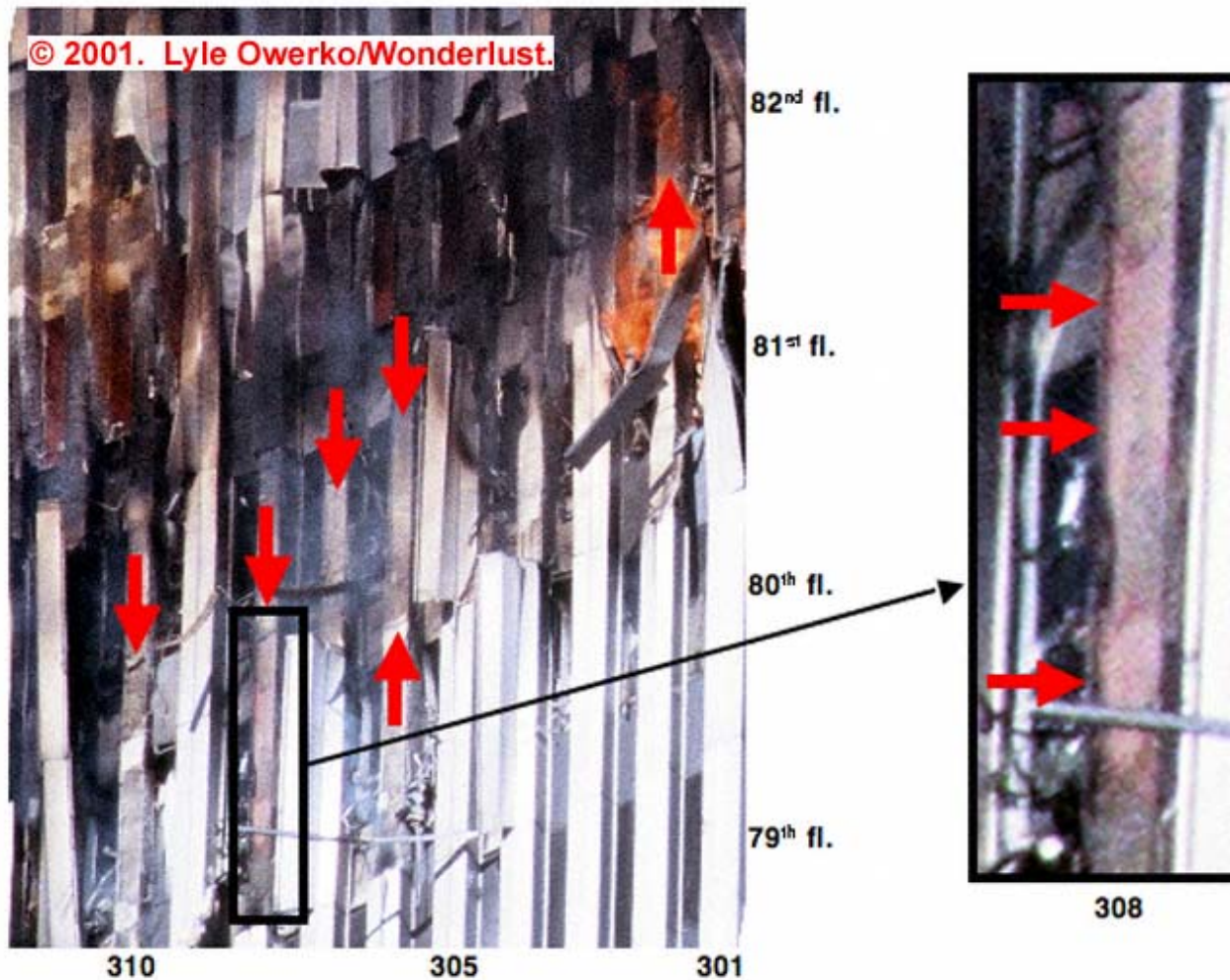
Removed from flanges (red)

Intact (green)

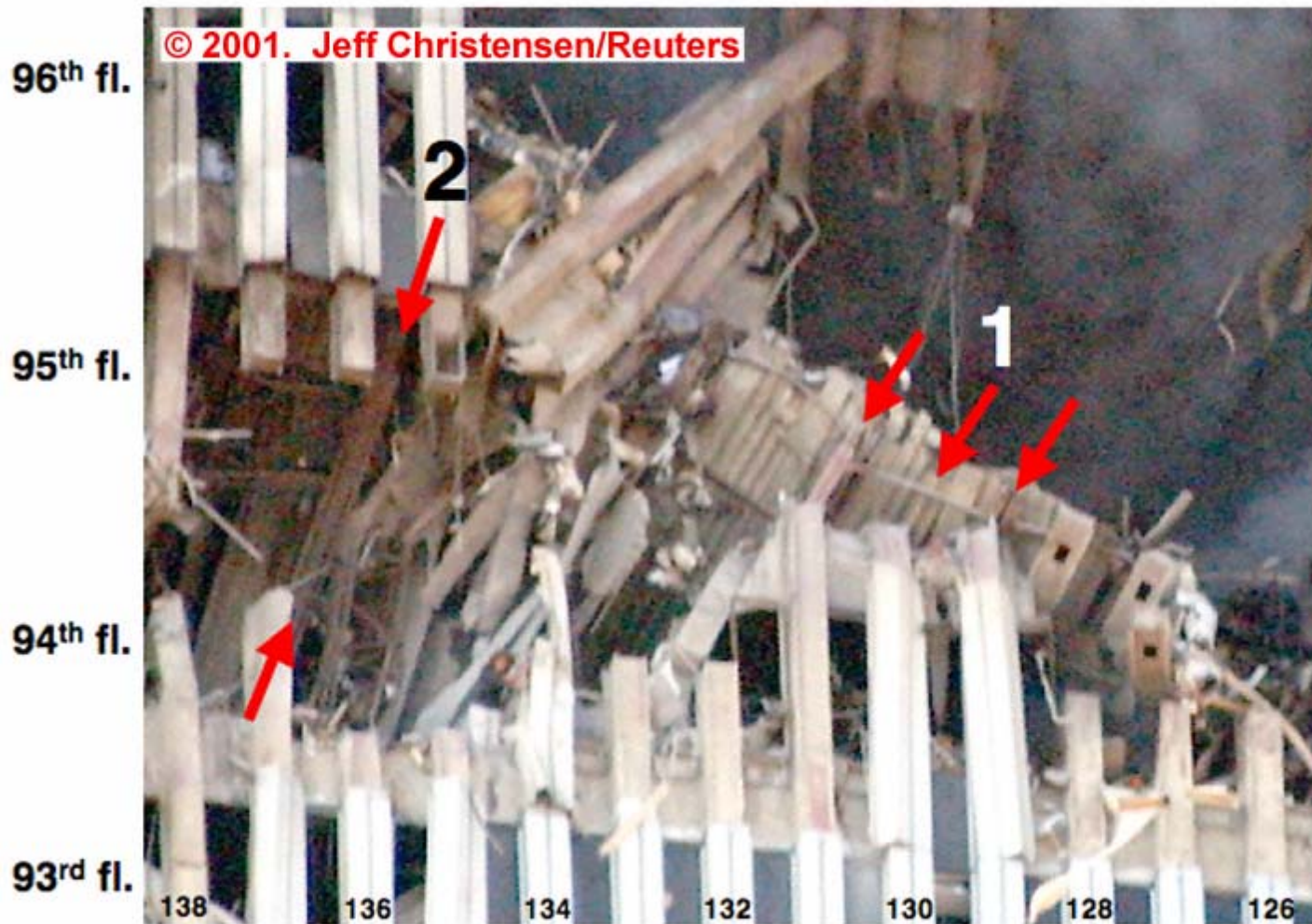
Removed from outer web (white)

Covered by weatherproofing coating (blue)

Damaged SFRM - East Face of WTC2



Damaged SFRM - North Face of WTC 1: Missing from Trusses



Factors that Enhanced Building Performance on September 11, 2001

- The unusually dense spacing of perimeter columns, coupled with deep spandrels, that was an inherent part of both the architectural and structural design of the exterior walls, resulted in a robust building that was able to redistribute loads from severed perimeter columns to adjacent intact columns.
- The wind loads used for the WTC towers, which governed the design of the perimeter frame-tube system, significantly exceeded the prescriptive requirements of the New York City building code and selected other building codes of the era (Chicago, New York State), including the relevant national model building code (BOCA).
- The robustness of the perimeter frame-tube system and the large dimensional size of the WTC towers helped the buildings withstand the aircraft impact.
- The composite floor system with open-web bar joist elements, framed to provide two-way flat plate action, enabled the floors to redistribute loads without collapse from places of aircraft impact damage to other locations, avoiding larger scale collapse upon impact.

Factors that Enhanced Building Performance on September 11, 2001 (2)

- The hat truss resisted the significant weakening of the core, due to aircraft impact damage and subsequent thermal effects, by redistributing loads from the damaged core columns to adjacent intact columns and, ultimately, by redistributing loads to the perimeter walls from the thermally weakened core columns that lost their ability to support the buildings' weight.
- **As a result of the above factors, the buildings would likely not have collapsed under the combined effects of aircraft impact and the subsequent jet-fuel ignited multi-floor fires, if the fireproofing had not been dislodged or had been only minimally dislodged by aircraft impact. The existing condition of the fireproofing prior to aircraft impact and the fireproofing thickness on the WTC floor system did not play a significant role in initiating collapse on September 11, 2001.**

Future Technologies and Practices that Potentially Could Have Improved Performance on September 11, 2001 (Requires Analysis)

- Fireproofing not dislodged or only minimally dislodged by aircraft impact.
- Perimeter columns and floor framing with greater mass to enhance thermal and buckling performance.
- Other passive and active fire protection features (e.g., compartmentation to retard spread of building fires; thermally-resistant window assemblies to limit air supply and retard the spread of fires; fire-protected and structurally-hardened elevators for firefighter access with continuous, redundant water supply for standpipes).
- Steels with improved high-temperature properties (e.g., yield strength and stiffness) and creep behavior.

There is far greater knowledge of how fires influence structures in 2005 than was the case in the 1960s. The analysis tools available to calculate the response of structures to fires are also far better now than they were when the WTC towers were built.

Analysis of Life Safety

- Nearly 1,200 first person interviews of occupants and emergency responders plus 700 published media accounts
- Review of emergency communication records (radio communications, 9-1-1 calls, 500 plus post-9/11 FDNY interviews)
- Evacuation and occupant behavior:
 - Building population demographics; analysis of decedents
 - Evacuation rates; roof evacuation; communications to occupants; mobility impaired occupants; building damage observations
- Emergency response:
 - First responder roles; situational awareness; access; high-rise operations; radio communications; command and control
- Active fire protection systems:
 - Significant pre-9/11 fires; sprinkler and standpipe system; fire alarm system; smoke management system

Evacuation and Emergency Response

Based on 1,056 interviews of surviving WTC occupants and 116 interviews of emergency responders.

- **It is estimated that 17,400 occupants ($\pm 1,200$) 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.
- **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 emergency 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.

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*	Modified April 5, 2005
World Trade Center 1 Occupants	1,462
At or Above Impact	1,355
Below Impact	107
World Trade Center 2 Occupants	630
At or Above Impact	619
Below Impact	11
Confirmed Below Impact in WTC 1 or WTC 2	30
Unknown Location Inside WTC 1 or WTC 2	24
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

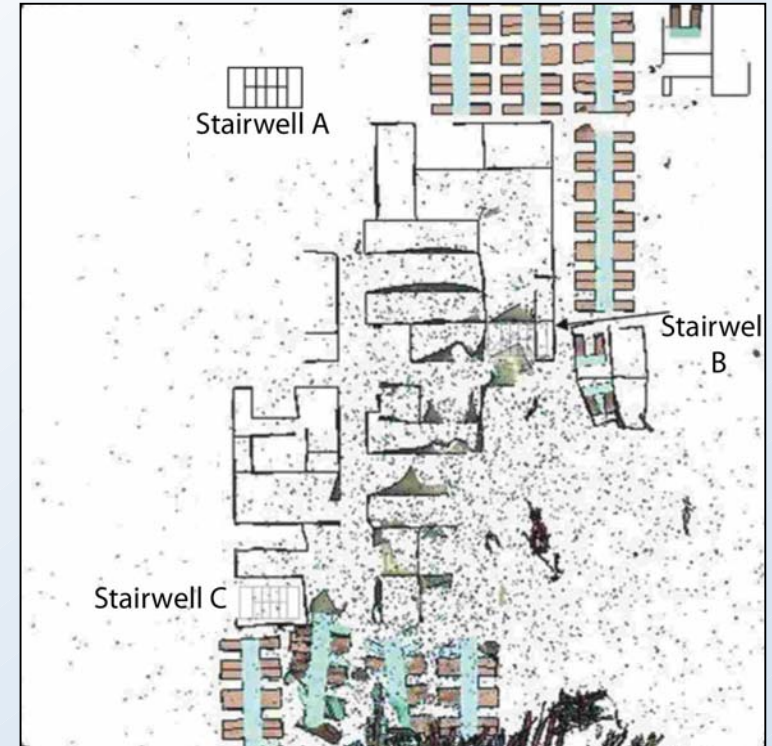
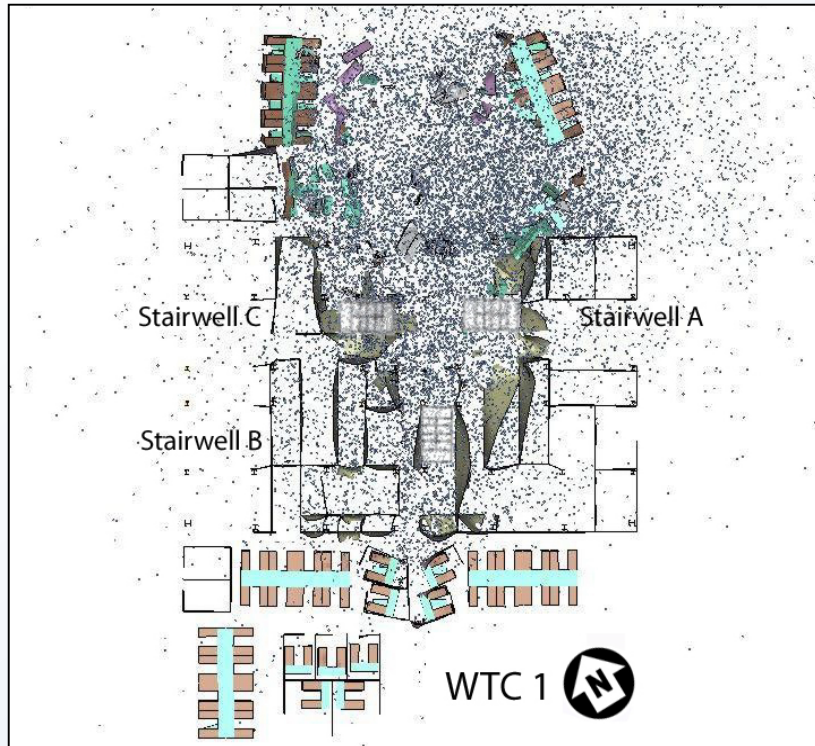
Evacuation Rates in the WTC Towers

- **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).** 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.
- **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.
 - **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.
- 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.**

Evacuation Rates in the WTC Towers (2)

- Even though a percentage of evacuees reported that they perceived **counterflow (firefighter ingress)** to be a problem, it **was found not 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. Had the buildings been full, it is possible that as many as 14,000 people may have lost their lives based on rough estimates using existing models.** To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways). **The egress capacity required by current building codes and practice is based on a “phased” evacuation strategy, not “full” evacuation.**
- **The average surviving occupants moved slower down stairs and through stairwell exits than previously reported for non-emergency evacuations.**
 - 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.

Condition of Stairwells



- 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 Northwest 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.

Findings on Stairwell Remoteness

- The 1968 NYC Building Code required stairwells to be as ‘far apart as practicable.’
- **Stairwell separation in WTC 1 and WTC 2 ranged from 70 ft (Floors 83 and above, including the impact region in WTC 1) to 200 ft (Floors 79 – 82, including the impact region in WTC 2), demonstrating that large stairwell separations in the WTC towers were practicable.**
- The maximum travel distance for the WTC towers was about 180 ft. **The stairwell separation was consistent with the 2001 NYC building code requirement of one-third the travel distance or 60 ft.**
- **On some WTC floors (e.g., the floors of impact in WTC 2), the separation of stairwells A and C exceeded the typical model code requirement (98 ft sprinklered; 147 ft unsprinklered); on other floors (e.g., the floors of impact in WTC 1), the stair separation was *not consistent* with these model code criteria.**
- The advantages of moving stairwell locations on the floor plan include reclamation of core space for occupant use above terminated elevator shafts and overcoming obstructions posed by equipment installed on mechanical floors.
- A walking path measurement may allow two stairwells to be physically proximate, yet have a significant walking path distance between doors (i.e., scissor stairs), although the IBC credits scissor stairs as a single stairwell.

Occupant Preparedness

- **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** (NYC Local Law 5 prohibits **requiring** occupants to practice stairwell evacuation.)
- **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.
- **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).

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. **The PANYNJ reports that it never advised tenants to evacuate upward.** Roof access required use of an electronic swipe card to get through the first two doors and a security officer watching a closed-circuit camera on the 22nd floor of WTC 1 to open the third door via a buzzer.
- The 1968 BCNYC required access to roofs with slopes less than 20 degrees from at least one stair in buildings greater than 3 stories (or 40 ft) in height.
 - The Code does not state the purpose of this access but, since it is in the section on Stair Construction and not Means of Egress it does not necessarily imply roof rescue but more likely providing fire department access to flat roofs.
 - The current code (2003) permits such access from a stair, ladder or scuttle, even more clearly not intended for rescue. There is no prohibition of locking this access, which is consistent with fire department use since they have the means to open locked doors.
- 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).

Roof Evacuation (2)

- **The NYPD and FDNY policies for roof operations were focused mainly on providing emergency 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.
- **Due to the limited capacity of a typical helicopter and travel time, roof rescue was never considered as a viable strategy for general evacuation; even if it had been possible for a helicopter to gain access to the roof, possibly only a very small fraction of the large number of people trapped above the impact zone could have been rescued 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. The closet was located in a hallway adjacent to an elevator shaft in the core of the building. 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 Responder Operations

Situational Awareness:

- Emergency responders working outside the WTC buildings who could view building conditions and communicate over radios had adequate situational awareness.
- Situational awareness for personnel who 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**

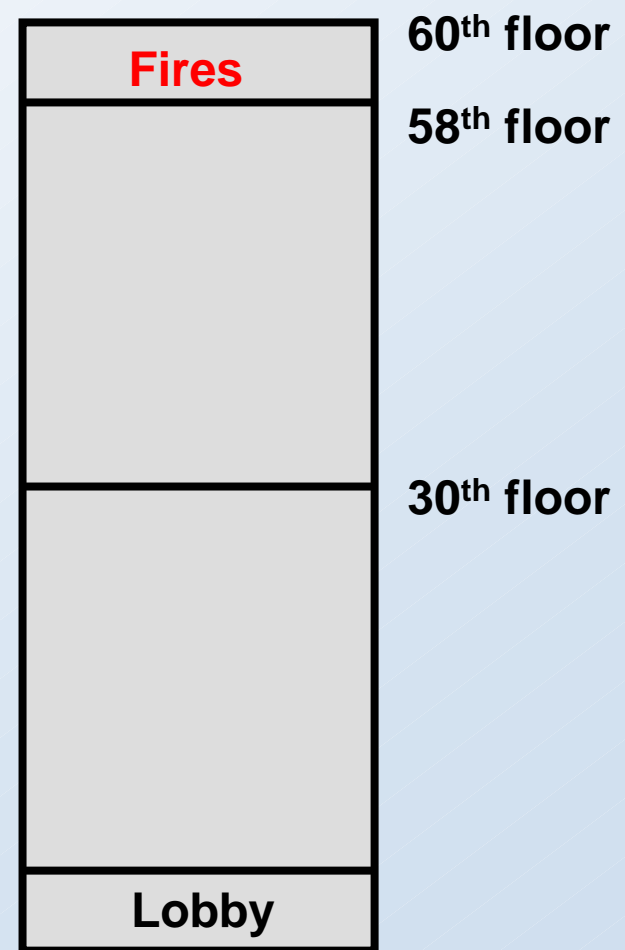
High-Rise Buildings & Emergency Response

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

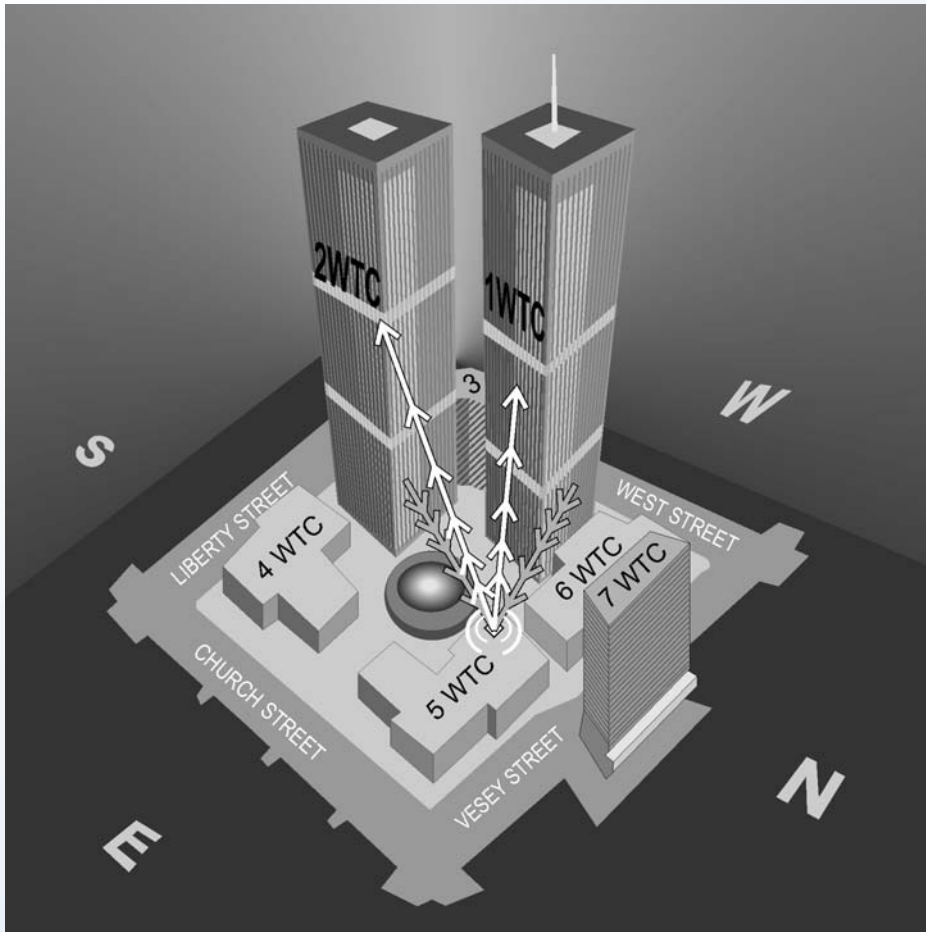
Firefighters carrying equipment and wearing PPE ~ 125 minutes
Firefighters carrying no equipment and not wearing PPE ~ 90 minutes

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



Radio Communications in High-Rise Buildings



Schematic of WTC Radio Repeater System

- Challenging radio-frequency propagation environment: steel and reinforced concrete buildings.
- Large scale operations.
 - Number of first responders.
 - Communications hierarchy and protocols.
 - Surge in traffic; doubling.
- Interoperability of radio communication technologies among different emergency responder organizations.
- Identification, location, tracking first responders.

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, although communications problems were perceived in WTC 1.**
- 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. Even if the repeater was functioning, it is possible the quality of communications was inadequate.**
- 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

- **Emergency 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.**
- **A preponderance of evidence indicates that lack of timely information sharing and inadequate communication capabilities likely contributed to the loss of emergency responder lives.** Statement extracted from an emergency responder interview: **If communications were better, more firefighters would have been saved.**
- **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 (2)

- **FDNY's system for maintaining records of unit assignments at each command post was not capable of managing the numbers of units and personnel assigned to the incident.**
- **FDNY, NYPD, and PAPD: there was no means to back-up the unit assignment records generated at the command posts.**
- **Interagency operations were detrimentally affected with the loss of the OEM command center that was located inside WTC 7 due to the decision made to evacuate the building at about 9:44 am before WTC 2 collapsed.** 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.
- A significant amount of evidence (first person interviews, reports, and photographic data) shows that:
 - **In general, all departments attempted to work together to save as many lives as possible and protect the citizens of New York City on the morning of September 11, 2001.**
 - **At times some issues related to a given department's operational responsibility and the competitive nature of departments did exist during the WTC operations; some of the problems experienced were due to personnel not understanding the operating practices of other agencies.**
- **Emergency responder interviews suggest that inter-agency competition had minimal effect on operations at the WTC complex before the towers collapsed.**

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 12th 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.

Factors that Enhanced Life Safety on September 11, 2001

- Since the buildings were occupied by only about 1/3 of the building's full capacity of 25,000 occupants, the egress capacity (number and width of exits and stairways) was adequate for those survivors seeking and able to reach and use undamaged exits and stairways.
- Functioning elevators in WTC 2 enabled nearly 3,000 occupants to self-evacuate prior to aircraft impact.
- Greater remoteness of stairwells in the impact areas of WTC 2 that enabled one of the stairwells to remain marginally passable after aircraft impact.
- Participation of a large number (two-thirds) of surviving occupants in a fire drill in the prior 12 months, with almost all of those (93 percent) instructed about the location of the nearest stairwell.
- Upgrades made to the life safety system components after the 1993 bombing.
- Evacuation assistance provided by emergency responders to building occupants.
- **As a result of the above factors, approximately 87 percent of the WTC tower occupants, including more than 99 percent below the floors of impact, were able to evacuate successfully.**

Future Practices and Technologies that Potentially Could Have Improved Life Safety on September 11, 2001 (Requires Analysis)

- Improved performance to delay or prevent building collapse.
- Improved stairwell integrity via increased remoteness of stairwells and/or enhanced structural integrity of stairwell enclosures.
- Better communications to occupants and among first responders via improved systems and timely information sharing.
- Better command and control for large-scale incident management (e.g., location of command posts and physical assets; interagency coordination).
- Better evacuation training (e.g., practice stairwell evacuation, roof rescue not presently feasible as a standard option, existence of transfer hallways).
- Other life safety features (e.g., fire protected and structurally hardened elevators available for occupant use during emergencies; vibration protected elevators such as those used in seismic regions; self-evacuation capability for mobility impaired occupants; operational smoke and fire control systems).

Procedures and Practices

- Applicable building codes and policies
 - NYC codes; PANYNJ policy and rationale; PANYNJ MOU with NYC
 - Comparison with contemporaneous codes
- Building design and construction
 - Structure; fire safety; egress; elevators
 - Design criteria and requirements
 - Comparison with code requirements
 - Innovative features; code variances
 - Fabrication and construction inspections
- Maintenance and modifications
 - Local laws; modifications after 1993 bombing
 - Tenant alteration review manuals
 - Condition surveys and structural inspections
- WTC 7 Fuel System

Condition Surveys and Structural Inspections

- PANYNJ developed the Standards for Structural Integrity Inspection of the World Trade Center Towers A & B in 1986.
- Beginning in 1990, PANYNJ implemented a systematic facility condition survey program for the WTC Towers. Prior to 1990, both WTC 1 and WTC 2 were inspected occasionally.
- WTC 7, which was not owned by PANYNJ, was also inspected based on the criteria in the Standards.
- The condition survey program included:
 - WTC 2 condition survey, 1990, PANYNJ Engineering Quality Assurance Division
 - WTC 1 condition survey, 1991, Office of Irwin G. Cantor, Consulting Engineers
 - WTC 7 survey, 1997, Ammann & Whitney
 - Due diligence physical condition survey of WTC 1 and WTC 2, 2000, Merritt and Harris
- Periodic inspections under the Structural Integrity Inspection Program were conducted by LERA and other engineering firms.

Structural Integrity Inspection Program

- In general, the structural integrity inspections (SII) found that the structural systems of WTC 1, 2, and 7 were in good condition. The inspection consultants made numerous routine and some priority recommendations for repairs to the PANYNJ.
- The SII reports identify some of the same deficiencies from report to report, including missing fireproofing on structural steel members.
- According to the PANYNJ, all of the construction records on repairs following the inspections were lost on September 11, 2001. Thus, it cannot be determined whether all of the recommended repairs were performed.
- Fireproofing was reported to be missing or damaged in the floors below the Plaza Level (Levels B1 to B6 of WTC 1 and WTC 2) and in the hat-truss zone.
- Fireproofing on beams and columns was also found missing or damaged in elevator shafts. The causes for missing and damaged fireproofing were attributed to high-speed traveling of elevator cabs and elevator cables hitting fireproofing on structural members. It is also noted that a large portion of missing or damaged fireproofing in elevator cores occurred at lower levels of the towers.

Structural Integrity of Means of Egress

- **Building codes lack minimum structural integrity provisions for the means of egress (stairwells and elevator shafts) in the building core that are critical to life safety.**
- In most tall buildings the core is designed to be part of the vertical gravity load carrying system of the structure. However, in many of those buildings, especially in regions where earthquakes are not dominant, the core may not be part of the lateral load carrying system of the structure. Thus, the core may be designed to carry only vertical gravity loads with no capacity to resist lateral loads, i.e., overturning moment and shear loads. In such situations, the structural designer may prefer the use of partition walls over structural walls in the core area to reduce building weight.
- The decision to have the core carry a specified fraction of the lateral design loads or be made part of a dual system to carry lateral loads, each of which would enhance the structural integrity of the core if structural walls were used, is left to the discretion of the structural engineer.
- Alternatively, stairway/elevator cores built with concrete or reinforced concrete block, which are not part of the lateral load carrying system, may be able to provide sufficient structural integrity if they meet, for example, ASTM E1996-03, or other more appropriate tests for impact resistance.
- In the case of the WTC towers, the core had 2 h fire-rated partition walls with little structural integrity, and the core framing was required to carry only gravity loads. **Had there been a minimum structural integrity requirement to satisfy normal building and fire safety considerations, it is conceivable that the damage to stairways in the WTC towers, especially above the floors of impact, may have been less extensive.**

Selected Findings on Codes and Practices

- The 1968 New York City Building Code was comparable to other codes of the era (1964 New York State, 1967 Chicago, and 1965 BOCA/BBC national model code).
- **Documents suggest that the WTC towers generally were designed and maintained consistent with the requirements of the 1968 New York City Building Code. Areas of concern included fireproofing of WTC floor system, height of tenant separation walls, and egress requirements for the assembly use space for the Windows of the World in WTC 1 and Top of the World observation deck in WTC 2.**
- The PANYNJ developed and periodically updated a Tenant Alteration Review Manual that contained the technical criteria, standards, and requirements used to guide modifications and alterations over the life of the buildings.
- The PANYNJ developed and implemented a formal facility condition survey and structural integrity inspection program. The buildings generally were found to be in good condition. Frequent recommendations were made to repair or replace missing fireproofing at different locations, particularly in elevator shafts and floors below the plaza level.

Disclaimer No. 1

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose. Nor does such identification imply a finding of fault or negligence by the National Institute of Standards and Technology.

Disclaimer No. 2

The policy of NIST is to use the International System of Units (metric units) in all publications. In this document, however, units are presented in metric units or the inch-pound system, whichever is prevalent in the discipline.

Disclaimer No. 3:

Pursuant to section 7 of the National Construction Safety Team Act, the NIST Director has determined that certain evidence received by NIST in the course of this Investigation is “voluntarily provided safety-related information” that is “not directly related to the building failure being investigated” and that “disclosure of that information would inhibit the voluntary provision of that type of information” [15 USC 7306(c)].

In addition, a substantial portion of the evidence collected by NIST in the course of the Investigation has been provided to NIST under nondisclosure agreements.

Disclaimer No. 4:

NIST takes no position as to whether the design or construction of a WTC building was compliant with any code since, due to the destruction of the WTC buildings, NIST could not verify the actual (or as-built) construction, the properties and condition of the materials used, or changes to the original construction made over the life of the buildings. In addition, NIST could not verify the interpretations of codes used by applicable authorities in determining compliance when implementing building codes. Where an Investigation report states whether a system was designed or installed as required by a code *provision*, NIST has documentary or anecdotal evidence indicating whether the requirement was met, or NIST has independently conducted tests or analyses indicating whether the requirement was met.

Use in Legal Proceedings

No part of any report resulting from a NIST investigation into a structural failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by P.L. 107-231).

Web site <http://wtc.nist.gov>

Email to wtc@nist.gov

Facsimile to (301) 975-6122

Regular mail:

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

Background Slides

Challenges Addressed

- Strong, conflicting public perspectives
- Competing collapse hypotheses
- Need for significant advances in state-of-the-art
- Need for developing NCST rules, human subjects protocols
- Coordination with 9/11 Commission and local authorities
- Blending “investigation” needs with “research” culture
- Leading and managing an extended investigation team of 236 people (85 staff from 3 NIST Laboratories; 124 contractors and technical experts; 27 secretariat/institutional support staff)

The Extended WTC Investigation Team

• WTC Investigation Team	14
• Other NIST Technical Staff	71
• Secretariat/Institutional Support	27
• Contractor Staff	112
• Experts (Contract/Employee)	12
	=====
Total	236

NCST Advisory Committee

- Appointed by the NIST Director.
- Functions...
 - Review procedures and reports
 - Evaluate activities of teams
 - Assess implementation of recommendations
 - Annual report to Congress
- Reviewed WTC Investigation plan, progress, findings, and draft recommendations at 6 meetings.
- Reviewed all WTC progress reports and final reports
- Membership balances broad scope of disciplines and interests

Members

Dr. Charles Thornton, Co-Chairman,
Thornton-Tomasetti.

Dr. Robert Hanson, Professor Emeritus,
University of Michigan.

Mr. Philip DiNenno, President, Hughes
Associates.

Professor Glenn Corbett, John-Jay
College, NYC.

Dr. Kathleen Tierney, University of
Colorado, Boulder.

Mr. Paul Fitzgerald, FM Global,
(retired).

Mr. David Collins, The Preview Group.

Professor Forman Williams, University
of California at San Diego.

Dr. John Barsom, President, Barsom
Consulting.

Examples of Extensive Media Coverage...

- **Newspapers**

- *The New York Times*
- *The Washington Post*
- *The Wall Street Journal*
- *The International Herald Tribune*
- *The Guardian (UK)*
- New York City newspapers
- Major U.S. newspapers
- International newspapers

- **Magazines and Books**

- *The 9/11 Commission Report*
- *City in the Sky* (Glanz & Lipton)
- *102 Minutes* (Dwyer & Flynn)
- *Engineering News-Record*
- *Popular Mechanics*

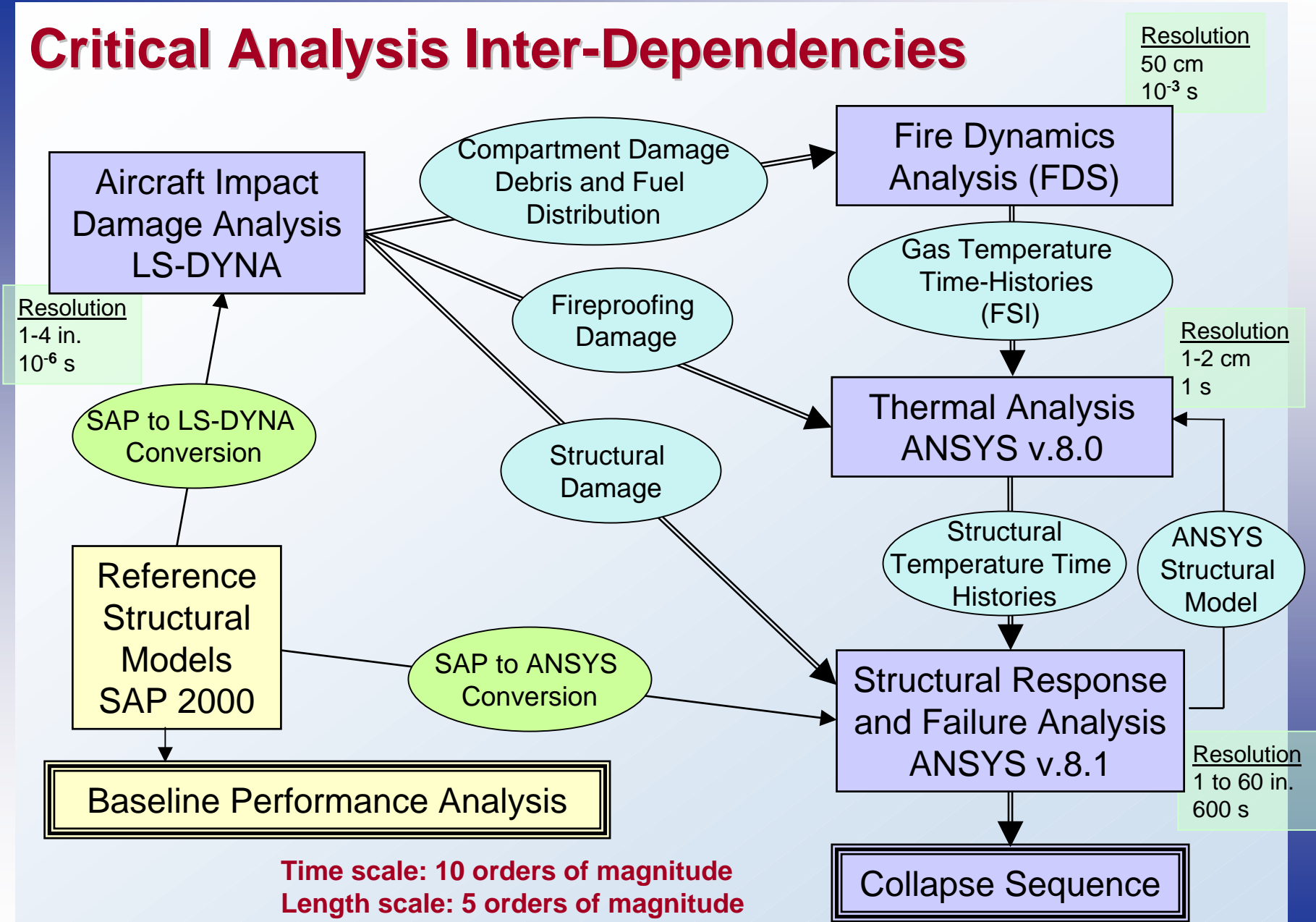
- **Wire Services**

- *Associated Press*
- *Reuters*
- *United Press International*

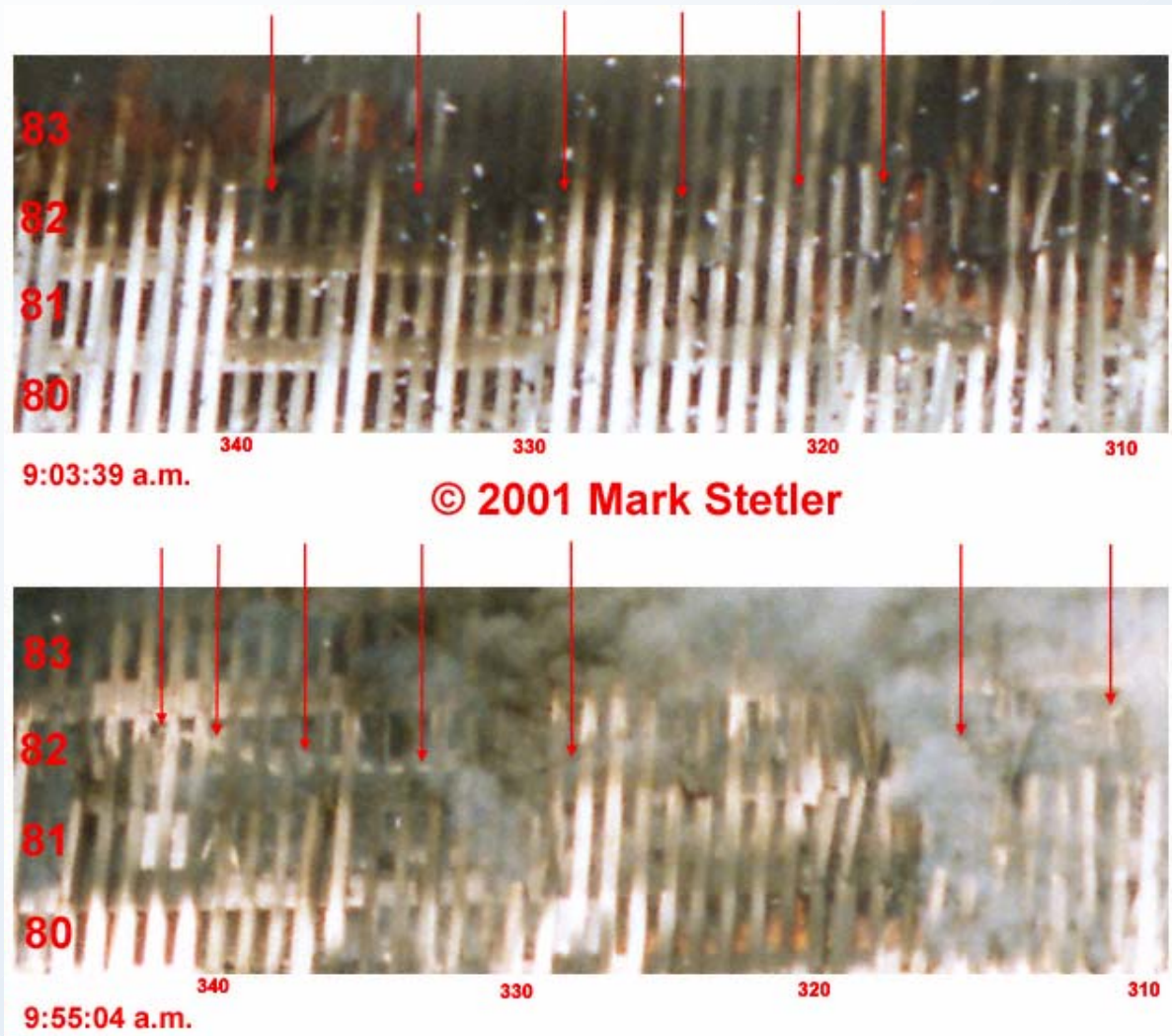
- **TV and Radio Networks**

- *CBS Evening News*
- *CNN International*
- *WABC*
- *WNBC*
- *Fox News*
- *NY1*
- *C-Span*
- *NPR*
- *WNYC* (NY Public Radio)
- *Metro Radio Network*

Critical Analysis Inter-Dependencies

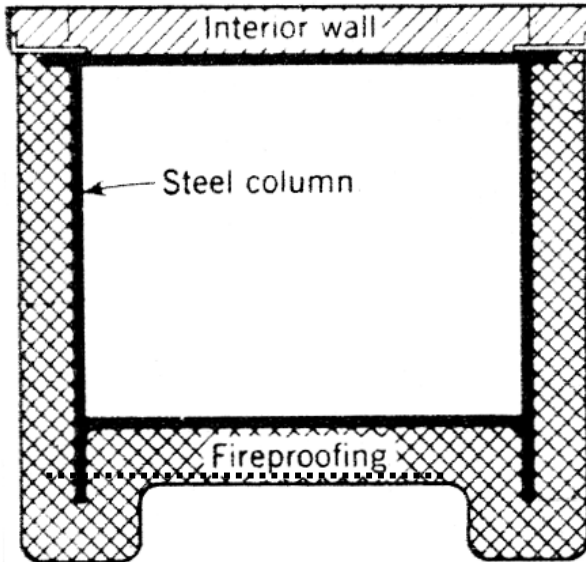


Photographic Evidence of Hanging Floor Slab

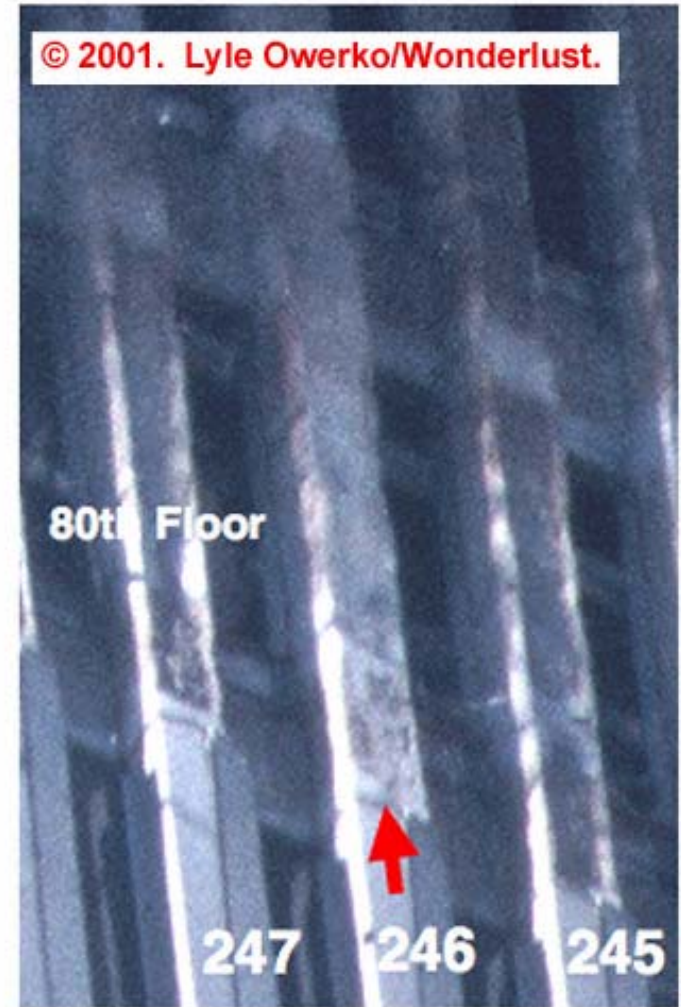


Amount and extent of floor sag increased over the 51 minute period.

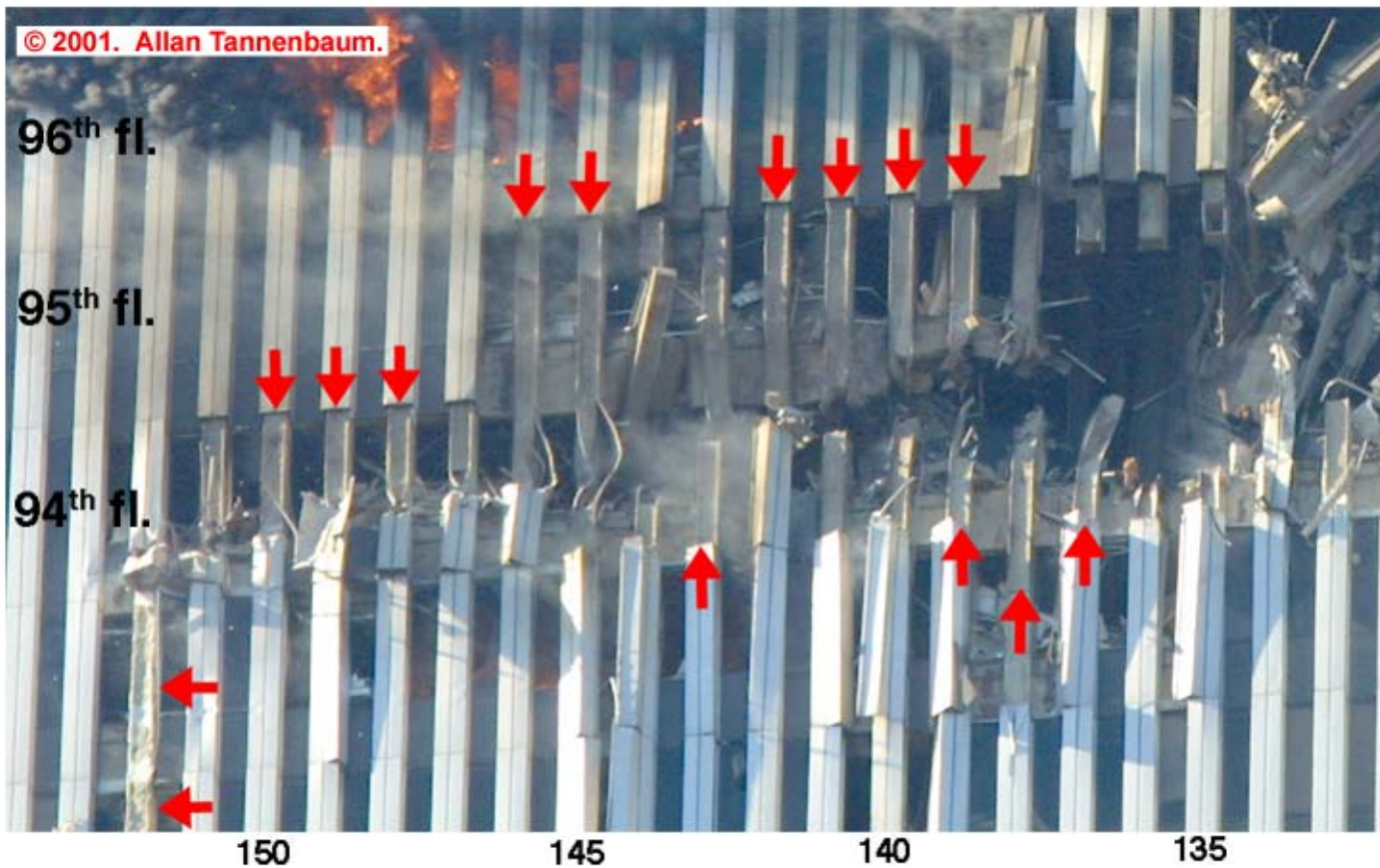
Application of SFRM to External Columns



- By design, uniform thickness
- As applied, region between flange tips filled (for example, see column 246 at right)
- Missing SFRM from outer flange indicated by shadowing and exposed red paint



Damaged SFRM - North Face of WTC 1: Left Side of Impact Hole



Findings on Probable Collapse Sequences (1)

- Inward bowing and primary tilting direction at collapse initiation in WTC 1 and WTC 2:
 - Not observed on face where aircraft impact occurred.
 - Observed on face parallel to the longer dimension of the building core.
 - Observed on face associated with less stiff (longer period) direction of the building.
 - Occurred on face associated with long span direction of floor system; truss chord demand-to-capacity higher in long span direction.
- Inward bowing on South face and Southward tilting for WTC 1:
 - Extent of fires similar on all faces; somewhat more extensive on East and West faces; similar in extent on North and South faces.
 - Although North face had extensive impact damage, inward bowing occurred on South face and building tilted to South at collapse initiation.
 - Thermal weakening of perimeter columns with floor sagging (which induced inward pull and occurred on South side) caused inward bowing on South face and tilting in that direction.
- Inward bowing on East face and primary tilting towards East for WTC 2:
 - Fires more extensive on East face; less extensive on North face and South face, though significant on East side of both faces; no observed fires on West face.
 - Although South face had extensive impact damage, inward bowing occurred on East face and building tilted more to the East and less to the South at collapse initiation.
 - Thermal weakening of perimeter columns with floor sagging caused inward bowing on East face and primary tilting in that direction (with additional Southward tilting due to the aircraft impact damage).

Findings on Probable Collapse Sequences (2)

- The time it took for each WTC tower to collapse was due primarily to:
 - Asymmetric structural damage resulting from aircraft impact in WTC 2 compared to WTC 1; and greater damage (severed or heavy damage) to core columns in WTC 2 than in WTC 1; higher aircraft speed/impact energy and impact location (shorter floor span resistance and off center position) caused greater WTC 2 core damage.
 - Time it took for the fires, in combination with aircraft impact damage, to weaken the core.
 - Time it took for fires to traverse from their initial location to the critical side of the towers, and:
 - time it took for heat to weaken and sag floor system, resulting in inward pull on adjacent face;
 - time it took for heat to weaken perimeter columns observed to be bowing inward prior to collapse of each tower (traverse time of fires to South face of WTC 1 was much longer than on East face of WTC 2 where fires already existed).
 - Time it took for heat to weaken and buckle those perimeter columns that were simultaneously subject to inward pull forces and, to a lesser extent in WTC 2, additional vertical loads redistributed from core.

Findings on Probable Collapse Sequences (3)

- **The time to destructive heating was determined by the fires**, whose extent and intensity was determined by the large mass and wide distribution of the jet fuel, the nature and (rather low) loading of combustibles, **the sparseness of initial or surviving building partitions, and the ease with which windows were broken allowing oxygen to feed the fires.**
- **Separate analyses showed that heating of structural members was more sensitive to effect of dislodged fireproofing due to debris from aircraft impact than to episodic regions of missing fireproofing or thinness of fireproofing in fire-affected region. As-built fireproofing conditions elsewhere did not play a role in fire-induced collapse.**
- Debris field generated by aircraft impact removed significant fireproofing and gypsum board enclosures, as well as some of the walls. Structural components that became thermally weakened were generally determined by impact of the debris field. **Had fireproofing not been dislodged by debris field, temperature rise of structural components would likely have been insufficient to induce global collapse.**

Findings on Probable Collapse Sequences (4)

- **Role of the Building Core**

- Core weakened significantly due to aircraft impact damage and thermal effects (thermal effects dominated WTC 1; aircraft impact damage dominated WTC 2).
- Loads redistributed to perimeter faces; additional axial loads on perimeter columns not significant (only about 20-25 percent on average)

- **Role of the Building Floors**

- Primary role was to provide inward pull forces that induced inward bowing of columns on exterior face (South face of WTC 1; East face of WTC 2).
- Sagging floors continued to support floor loads despite extensive fires and dislodged fireproofing; there would be no inward pull forces if floors had failed/disconnected.

- **Role of Exterior Frame-Tube**

- Column instability over an extended region of the exterior face ultimately triggered system failure (loads could not be redistributed via hat truss to already weakened building core; load transfer via spandrels propagated column instability to adjacent faces) causing initiation of building collapse.
- Column instability induced by thermal weakening of columns, inward pull forces from sagging floors, and to a much lesser degree, additional axial loads from the core.

Findings on Probable Collapse Sequences (5)

- **Performance of WTC floor system with *intact* fireproofing:**
 - **WTC 1 did not collapse during the major 1975 fire which engulfed about 9,000 ft² on the Southeast quadrant of the 11th floor** and spread mostly via utility closets to 10 floors. At the time, office spaces in the WTC towers were unsprinklered. **The fire caused minimal damage to the floor system, and at no time was the load carrying capacity of the floor system compromised.** The fire “did not damage a single primary, fireproofed element. Some top chord members (not needed for structural integrity), some bridging members (used to reduce floor tremor and the like) and some deck support angles (used only as construction devices) were buckled in the fire—all were unfireproofed steel.” (SCHR Letter Report 1975).
 - **The load carrying capacity of the floor system was not compromised by the furnace temperatures in any of the four fire resistance (ASTM E 119) tests** conducted in August 2004 up until the time they were stopped which was approximately 2 hours. **The applied loads were about twice those on September 11, 2001.** The high temperature conditions in the tests were at least as severe and lasting as the WTC fires (although the top of the slab was not heated)
 - **A detailed thermal-structural analysis, which did not include slab delamination/spalling effects, showed that a full collapse of the WTC floor system would not occur even with a number of failed trusses or connections.**
 - The horizontal and vertical capacity of the floor connections to the perimeter and core columns exceeded the demand under design load conditions.

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 sequence 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.

Limitations and Uncertainties in Determining Probable Collapse Sequences

- NIST recognized the inherent limitations and uncertainties in the analyses performed for determining the probable collapse sequences:
 - As-built condition of the WTC towers, as well as occupancy and use.
 - Estimated aircraft impact damage to WTC towers (structure, partitions, debris, fireproofing, jet fuel dispersion, material failure criteria, model size limitations and uncertainties) not observable from exterior of buildings
 - Estimated growth and spread of building fires (fuel load from building and aircraft contents, ventilation within the core, compartmentation, fire dynamics model size limitations and uncertainties), especially interior building fires
 - Estimated response of the aircraft-impact damaged WTC tower structures to the fires (extent of fireproofing damage, material and structural failure criteria, thermal and structural model size limitations and uncertainties)
- **NIST validated the probable collapse sequences with available factual evidence, carefully considering the sensitivity of its results to these uncertainties.**

Findings on Stairwell Remoteness

- New York City Local Law 16 (1984) amended the 1968 NYC Building Code to require the minimum distance between exit door openings in all buildings to be 30 feet or one-third the maximum travel distance of the floor, whichever is greater.
- IBC 2003, NFPA 5000, & the NFPA Life Safety Code require that at least two stairwells on any floor shall be located at least:
 - One-third of the diagonal of the area served, if fully sprinklered;
 - One-half of the diagonal of the area served, if not fully-sprinklered, measured from door edge to door edge along a straight line or along the *walking path* between the doors, if the corridors have walls that are rated for at least one hour.
- Tenant floors in WTC 1 and WTC 2 had a diagonal distance of 294 ft. Therefore, one-third of the diagonal distance would have been 98 ft and one-half of the diagonal distance would have been 147 ft. The corridor walls in the WTC Towers were two hour rated; the 1996 due diligence review suggests that some of the corridor separation walls did not run slab-to-slab and would have been considered unrated since they terminated at the suspended ceiling.

Uncertainties and Limitations Associated with Evacuation and Emergency Response

- NIST recognized the inherent limitations and uncertainties in its analyses of the evacuation and emergency response:
 - Human factors associated with building occupants (training; situational awareness; evacuation initiation time)
 - Human factors associated with emergency response (situational awareness; effective communications; command and control; interagency coordination)
 - Effect of building design on evacuation and emergency response (collapse time; stairwells; elevators; sprinkler and standpipe systems; self-evacuation systems for mobility impaired; emergency communication systems)
- **In developing its findings and results, NIST carefully considered these uncertainties within the context of available factual evidence from documents, recordings, first-person interviews, analyses, and visual data.**

Applicable Building Codes and Policies

- 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 proposed 1968 edition allowed the PANYNJ to **take advantage of less restrictive provisions and of technological advances** 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 loads 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).
 - Permitted wind tunnel testing using models to establish design values for the wind load.

Applicable Building Codes and Policies (2)

- **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. All of the issues identified in the NYC review appear to deal with egress issues, not with any of the innovative features of the buildings.
- 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.

Applicable Building Codes and Policies (3)

- 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 and sought review and concurrence as required by the agreements, **the PANYNJ was not required to yield, and appears not have yielded, approval authority to New York City.** The PANYNJ was created as an interstate entity, a “body corporate and politic”, under its charter, pursuant to Article 1 Section 10 of the U.S. Constitution permitting compacts between states, and like many other nongovernmental and quasi-governmental entities in the United States is not subject to building and fire safety code requirements of any governmental jurisdiction.

Standards for Structural Integrity Inspection

- Statistical inspections:
 - Periodic visual inspection of selected structural components in “higher-potential trouble prone areas” supplemented by occasional visual inspections when the structure was exposed during tenant remodeling or general maintenance work.
- Review of maintenance and tenant complaint reports:
 - Examination of various reports to shed light on underlying structural problems – maintenance reports of non-structural repairs; water leakage; and tenant complaints about unusual building movements, vibration, noise, etc.
- Building movement and deformation measurements:
 - Performance of systems within buildings evaluated through measurement of movement or deformation using appropriate tests and instruments. Measurements were to be performed on individual components in the towers as well as on the entire towers themselves.

Retention of Building Documents

- State and local jurisdictions do not require retention of documents related to the design, construction, operation, maintenance, and modification of buildings, with few exceptions. These documents are in the possession of building owners, contractors, architects, engineers, and consultants.
- **Building documents are not archived for more than about 6 to 7 years, and there are no requirements that they be kept in safe custody physically remote from the building throughout its service life.**
- **In the case of the WTC towers, the PANYNJ and its contractors and consultants maintained an unusually comprehensive set of documents, a significant portion of which had not been destroyed in the collapse of the buildings but could be assembled and provided to the NIST investigation.**
- In the case of WTC 7, several key documents could not be reviewed since they were lost in the collapse of the building.

Roles of Architects and Engineers

- Consistent with the practice at the time, the code architect was responsible for specifying the fire protection and designing the egress system for the WTC Towers in accordance with the prescriptive provisions of the NYC building code.
 - The architect and owner engaged the services of structural engineers to perform the structural design and to ensure that his/her design was properly implemented.
 - At that time the fire protection engineering profession was not sufficiently mature to require the same standard of care employed with the structural design.
 - There is no reason to believe that the involvement of a fire protection engineer at that time would have resulted in any differences in the design or performance of the fire protection systems.
- **Today, particularly when designing a building employing innovative features, the involvement of a fire protection engineer in a role similar to the structural engineer, and under the overall coordination of the Design Professional in Responsible Charge is central to the standard of care.**
 - The technical base and sophistication of the practice of fire protection engineering today is well advanced of where it was during the design and construction of the WTC towers.
- **When designing the structure of selected tall buildings or selected other buildings to resist fires, or evaluating the fire resistance of such structures, it is essential for the structural engineer and the fire protection engineer to jointly provide the needed standard of care.**

Standard Fire-Resistance Tests

- **Code provisions with detailed procedures do not exist to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element.**
- **Based on available data and records, no technical basis was found for selecting the spray-applied fire resistive material (SFRM) used (two competing materials were under evaluation) or its thickness for the large-span open-web floor trusses of the WTC towers.**
- The assessment of the fireproofing thickness needed to meet the 2 h fire rating requirement for the untested WTC floor system evolved over time:
 - In October 1969, the PANYNJ directed the fireproofing contractor to apply ½ in. of fireproofing to the floor trusses.
 - In 1999, the PANYNJ issued guidelines requiring that fireproofing be upgraded to 1½ in. for full floors undergoing alterations.
 - Unrelated to the WTC buildings, an International Conference of Building Officials (ICBO) Evaluation Service report (ER-1244), re-issued June 1, 2001, using the same SFRM, recommends a minimum thickness of 2 in. for “unrestrained steel joists” with “lightweight concrete” slab.

Standard Fire-Resistance Tests (2)

- **Code provisions are needed to require the conduct of a fire resistance test if adequate data do not exist from other building components and assemblies to qualify an untested building element.**
- Instead, several alternate methods based on other fire-resistance designs or calculations or alternative protection methods are permitted with limited guidance on detailed procedures to be followed.
- **Both the architect-of-record (in 1966) and the structural-engineer-of-record (in 1975) stated that the fire rating of the floor system of the WTC towers could not be determined without testing.**
- **NIST has not found evidence indicating that such a test was conducted to determine the fire rating of the WTC floor system. The PANYNJ informed NIST that there are no such test records in its files.**

Fire-Resistance Ratings (1)

- Use of the “structural frame” approach, in conjunction with the prescriptive fire rating, would have required the floor trusses, the core floor framing, and perimeter spandrels in the WTC towers to be 3 h fire-rated, like the columns for Class 1B construction in the 1968 NYC Building Code.
- Neither the 1968 edition of the NYC Building Code which was used in the design of the WTC towers, nor the 2001 edition of the code, adopted the “structural frame” requirement.
- The “structural frame” approach to fire resistance ratings requires structural members, other than columns, that are essential to the stability of the building as a whole to be fire protected to the same rating as columns.
- This approach, which appeared in the Uniform Building Code (a model building code) as early as 1953, was carried into the 2000 International Building Code (one of two current model codes) which states:

“The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and bracing members designed to carry gravity loads.”
- The WTC floor system was essential to the stability of the building as a whole since it provided lateral stability to the columns and diaphragm action to distribute wind loads to the columns of the frame-tube system.

Fire-Resistance Ratings (2)

- **A technical basis is needed to establish whether the construction classification and fire rating requirements in modern building codes are risk-consistent with respect to the design-basis hazard and the consequences of that hazard.**
- The fire rating requirements, which were originally developed based on experience with buildings less than about 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggested considerable conservatism in those requirements.
- **For tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant, say, on the first floor.**
 - **It is not apparent how the current height and area tables in building codes consider the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings, that are much greater than about 20 stories in height, where access by firefighters without the availability of firefighter elevators is limited by physiological factors.**
 - The maximum required fire rating in current codes applies to any building more than about 12 stories in height. There are no additional categories for buildings above, for example, 40 stories and 80 stories, where different building classification and fire ratings requirements may be appropriate, recognizing factors such as the time required for stairwell evacuation without functioning elevators (e.g., due to power failure or major water leakage), the time required for first responder access without functioning elevators, the presence of sky lobbies and/or refuge floors, and limitations on the height of elevator shafts.
- The 110-story WTC towers, initially classified as Class IA based on the 1938 NYC Building Code, were classified as Class 1B before being built to take advantage of the provisions in the 1968 edition of the code. This re-classification permitted a reduction of 1 h in the fire rating of the components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).

Fire-Resistance of Structural Connections

- **Code provisions are needed to ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements.**
- The provisions that were used for the WTC towers and WTC 7 did not require specification of a fire rating requirement for connections separate from those for the connected elements.
- **It is not clear what the fire rating of the connections in the WTC towers were when the connecting elements had different fire ratings and whether the applied fireproofing achieved that rating.**

Fireproofing: Field Application and Inspection

- **Rigorous field application and inspection provisions and regulatory requirements are needed to assure that the as-built condition of the passive fire protection, such as SFRM, conforms to conditions found in fire-resistance tests of building components and assemblies.**
 - Provisions are not available to ensure that the as-applied average fireproofing thickness and variability (reflecting the quality of application) is thermally equivalent to the specified minimum fireproofing thickness.
 - Requirements are not available for in-service inspections of passive fire protection during the life of the building.
- The adequacy of the fireproofing of the WTC towers posed an issue of some concern to the PANYNJ over the life of the buildings, and the availability of accepted requirements and procedures for conducting in-service inspections would have provided useful guidance.

Fireproofing: Requirements for In-Service Performance

- **A technical basis is needed to establish whether the minimum mechanical and durability related properties of SFRM are sufficient to ensure acceptable in-service performance in buildings.**
- **While minimum bond strength requirements exist, there are no serviceability requirements for such materials to withstand typical shock, impact, vibration, or abrasion effects over the life of a building.**
- There are existing testing standards for determining many of these properties, but the technical basis is insufficient to establish serviceability requirements. Knowledge of such serviceability requirements would have assisted in assessing the post-impact fireproofing condition of the WTC towers.

Fire Protection Hierarchy

- Building fire protection is based on a four-level hierarchical strategy comprising detection, suppression (sprinklers and firefighting), compartmentation, and passive protection of the structure.
 - Detectors are typically used to activate fire alarms and notify building occupants and emergency services.
 - Sprinklers are designed to control small and medium fires and to prevent fire spread beyond the typical water supply design area of about 1,500 ft².
 - Compartmentation mitigates the horizontal spread of more severe but less frequent fires and typically requires fire-rated partitions for areas of about 12,000 ft². Active firefighting measures also cover up to about 5,000 ft² to 7,500 ft².
 - Passive protection of the structure seeks to ensure that a maximum credible fire scenario, with sprinklers compromised or overwhelmed and no active firefighting, results in burnout, not overall building collapse. The intent of building codes is also for the building to withstand local structural collapse until occupants can escape and the fire service can complete search and rescue operations.

Compartmentation to Mitigate Fire Spread (2)

- The NYC Building Code and PANYNJ practice **required partitions to separate tenant spaces from each other and from common spaces** such as the corridors that served the elevators, stairs and other common spaces in the building core.
- Local Law 5 (1973) required compartmentation of unsprinklered spaces in existing office buildings over 100 ft in height “having air-conditioning and/or mechanical ventilation systems that serve more than the floor on which the equipment is located,” to be **subdivided by 1 hour fire separations into spaces or compartments not to exceed 7,500 ft². Floor areas could be increased up to 15,000 ft² if protected by 2 hour fire resistive construction and smoke detectors.**
- Shortly after the adoption of LL 5 (1973), the PANYNJ began to add the required compartmentation as a part of new tenant layouts as evidenced by several tenant alteration contracts at the time.
- **Following the 1975 fire** a fire safety consultant report recommended to PANYNJ that the buildings be **retrofit with sprinklers to address possible smoke problems**, and the PANYNJ realized that this would also **obviate the need for compartmentation** and permit the unobstructed views for which the buildings were known. The decision to sprinker the buildings left the arrangement again with **only partitions separating tenant spaces from each other and from exit access corridors or common spaces in the core, and with shaft enclosures.**

Compartmentation to Mitigate Fire Spread (3)

- **Building codes typically require 1 h fire-rated tenant separations but do not impose minimum compartmentation requirements (e.g., 12,000 ft²) for buildings with large open floor plans to mitigate the horizontal spread of fire.** This was the case with both the 1968 NYC Building Code, which did not require sprinklers in occupied spaces on or above the ground floor, and the 2001 NYC Building Code, which requires sprinklers in Group E (Business) buildings over 100 ft in height.
- The sprinkler option was chosen for the WTC towers in preference to the compartmentation option in meeting the subsequent requirements of Local Law 5, adopted by New York City in 1973.
- **If there was only one tenant on a WTC floor, there would be no horizontal compartmentation requirement. Conversely, if there were a large number of tenants on a WTC floor, it would be highly compartmented with separation walls.**
- **The fire-affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area.** Some floors had two tenants, and those spaces, like the core areas, were partitioned (slab to slab).
- **Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors.**
- **For the duration of about 50 to 100 min prior to collapse of the WTC towers that the fires were active, the presence of undamaged 1 h fire-rated compartments may have assisted in mitigating fire spread and consequent thermal weakening of structural components.**

Sprinkler Systems

- **State and local building regulations are needed that require installation of sprinklers in existing buildings on a reasonable time schedule, not as an option in lieu of compartmentation.**
- Functioning sprinklers can provide significant improvement in safety from most common building fires and can prevent them from becoming large fires.
- **NYC promulgated local laws in 1973 and 1984 to encourage installation of sprinklers in new buildings and is now considering a law to require sprinklers in existing buildings.**
- The WTC towers were fully sprinklered by 2001, about 30 years after their construction. Sprinklering of the tenant floors in the WTC towers was completed by October 1999, while sprinklering of the sky lobbies was still underway at that time.
- The sprinkler system in the WTC towers was installed in three phases:
 - Phase 1 was completed during initial building construction and included the sub-grade areas.
 - Phase 2 was completed in 1976, consistent with Local Law 5, and included sprinklering the corridors, storage rooms, lobbies, and certain tenant spaces.
 - Phase 3 was begun in 1983 and completed in 2001 and resulted in fully sprinklering the buildings.

Use of Elevators in Emergencies

- **With a few special exceptions, building codes in the United States do not permit use of fire-protected elevators for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants. The elevator use by emergency responders would additionally mitigate counterflow problems in stairwells.**
- **While the United States conducted research on specially protected elevators in the late 1970s, the United Kingdom along with several other countries that typically utilize British standards have required such “firefighter lifts,” located in protected shafts, for a number of years.**
- **Without functioning elevators, emergency responders carrying between 50 to 100 pounds of gear required about 1.4 minutes to 2 minutes per floor when using the stairs in WTC 1.**
 - **While it is difficult to maintain this pace for more than about the first 20 stories, it would take an emergency responder between 1-1/2 to 2 hours to reach, for example, the 60th floor of a tall building if that pace could be maintained.**
 - **Such a delay, combined with the resulting fatigue and physical effects on emergency responders that were reported on September 11, 2001, would make firefighting and rescue efforts difficult even in tall building emergencies not involving a terrorist attack.**
- Each of the WTC towers had 106 elevators, and WTC 7 had 38 elevators. By code, the elevators could not be used for fire service access or occupant egress during an emergency since they were not fire-protected, nor were they located in protected shafts. The elevators were equipped through normal modernization with fire service recall. All but one of the elevators were damaged in each WTC tower by the aircraft impacts; though prior to the impact in WTC 2 the elevators were functioning and contributed greatly to the much faster initial evacuation rate in WTC 2.