



**Building and Fire Safety:
Responding to
the World Trade Center Disaster**

Chicago Committee on High-Rise Buildings

September 9, 2004

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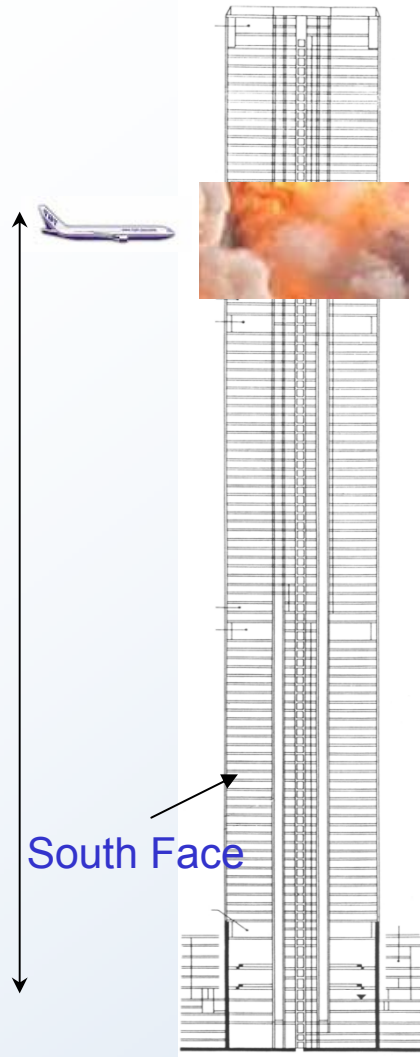
Background on WTC Investigation

- Good, solid technical progress on investigation; drawing on talent from NIST, outside experts, and contractors; \$16 million investigation; \$5.5 million awarded in contracts
- Two public updates issued (December 2002, December 2003); two technical progress reports issued (May 2003, June 2004)
- NYC Public Meeting (February 12, 2004) to solicit comments on (1) technical aspects of investigation, (2) additional information that NIST might consider, and (3) areas to be considered for recommendations
- Second technical progress report released June 18, 2004; 1,054 pages; full text available on Web site <http://wtc.nist.gov>
 - Investigation is ongoing; current findings may be revised and additional findings will be presented in final report
 - **NIST has not made any recommendations at this time; all recommendations will be made in the final report**
- NIST expects to release the draft of the final investigation report for public comment in **December 2004**

NIST WTC Investigation Objectives

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

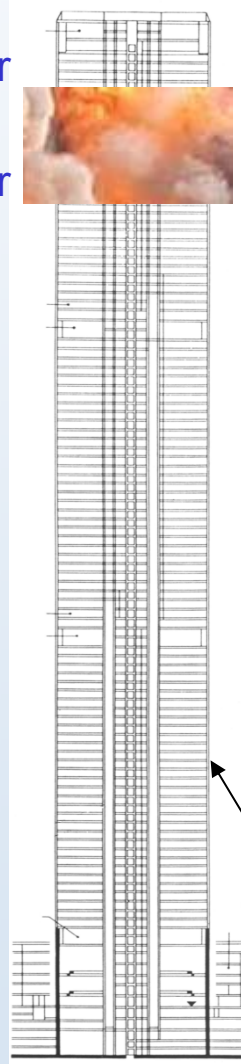
About 0.79 H



South tower: Hit at 9:02:59 AM
Collapsed after 56 minutes

99th floor

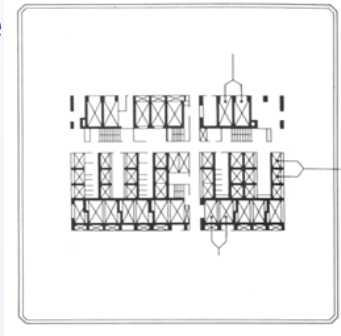
94th floor



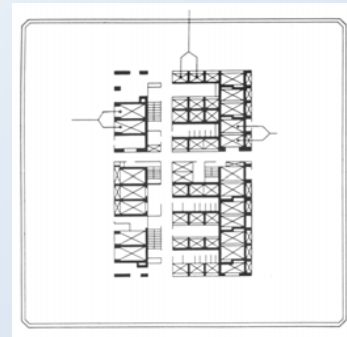
About 0.87 H

North tower: Hit at 8:46:31 AM
Collapsed after 103 minutes

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



North tower



South tower

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





Verizon Building

**7 WTC
(47 Stories)**

Old Post Office Building

Vesey St.

**6 WTC
(9 Stories)**

**5 WTC
(9 Stories)**

American Express Building

Fulton St.

Millenium Hotel

**1 WTC
(110 Stories)**

Austin J. Tobin Plaza

Day St.

Merrill Lynch Building

**3 WTC
(22 Stories)**

**2 WTC
(110 Stories)**

**4 WTC
(9 Stories)**

Cortlandt St.

1 Liberty Plaza Building

Liberty St.

90 West Building

Bankers Trust Building

Washington St.

Greenwich St.

Some Specific Questions

- ❑ How and why did WTC 1 stand nearly **twice** as long as WTC 2 before collapsing (103 min. vs. 56 min.) though they were hit by virtually identical aircraft?
- ❑ What factors related to **normal** building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?
- ❑ Would the undamaged WTC towers have remained standing in a **normal** major building fire?
- ❑ 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 would suggest 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 authority of any local, state, or federal jurisdiction, including local building and fire codes. The PANYNJ's longstanding stated policy is to meet and, where appropriate, exceed requirements of local building and fire codes.

Role of WTC Investigation

- Bring clarity to important technical issues related to the building collapses and loss of life based on objective and impartial analysis of the facts in the following areas:
 - Building performance (e.g., BPAT Recommendations)
 - Occupant behavior and evacuation
 - Emergency response procedures
- Develop findings and recommendations, as appropriate, to address technical issues affecting the safety of buildings and communities that face the risk of unusual (e.g., terrorist) threats
- Develop findings and recommendations, as appropriate, to address technical issues affecting the general safety of buildings and communities

Objective 1a: Collapse of WTC Towers

- ❑ **Working Hypothesis:** The following chronological sequence of major events led to the eventual collapse of the WTC towers; specific load redistribution paths and damage scenarios for each building are under analysis to determine the most probable collapse sequence for each building:
 - Aircraft impact damage to perimeter columns, resulting in redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;
 - After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;
 - The subsequent fires, influenced by the post-impact condition of the fireproofing, weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability;
 - Initiation and horizontal progression of column instability resulted when redistributing loads could not be accommodated any further. The collapses then ensued.

Working Hypothesis: Factors Being Evaluated

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

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

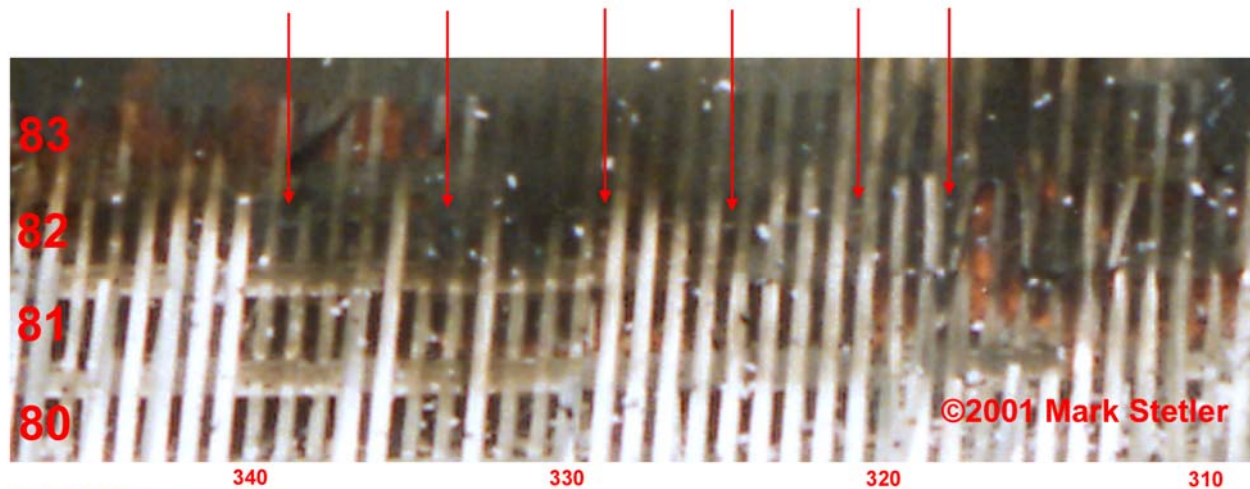
Photographic Evidence of Hanging Floor Slab



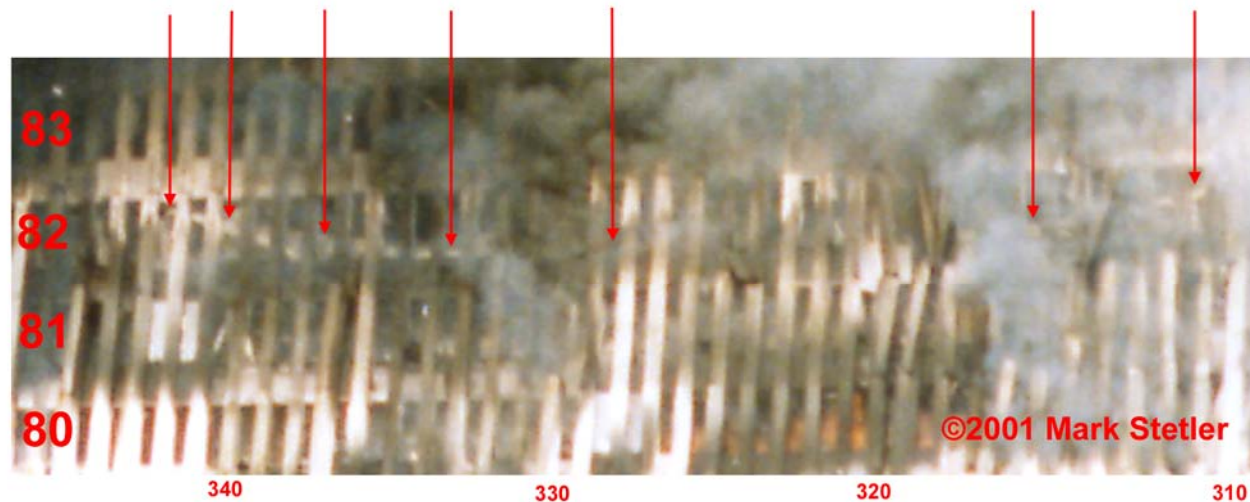
Photo by Allen Muarabayashi, 9:47:05 am \pm 5 s

East Face of the South Tower. Image shows what appear to be a floor slab from the 83rd floor hanging across window opening over a large fraction number of the 82nd floor.

Photographic Evidence of Hanging Floor Slab



9:03:41 a.m.



9:55:04 a.m.

Photographic Evidence of Hanging Floor Slab

© 2001 Reuters/Shannon Stapleton



North Face of the South Tower. Image shows what appear to be portions of several floor slabs hanging across window openings on Floors 80, 81, and 82

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

9:58:55 a.m.

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

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10:22:59 a.m.



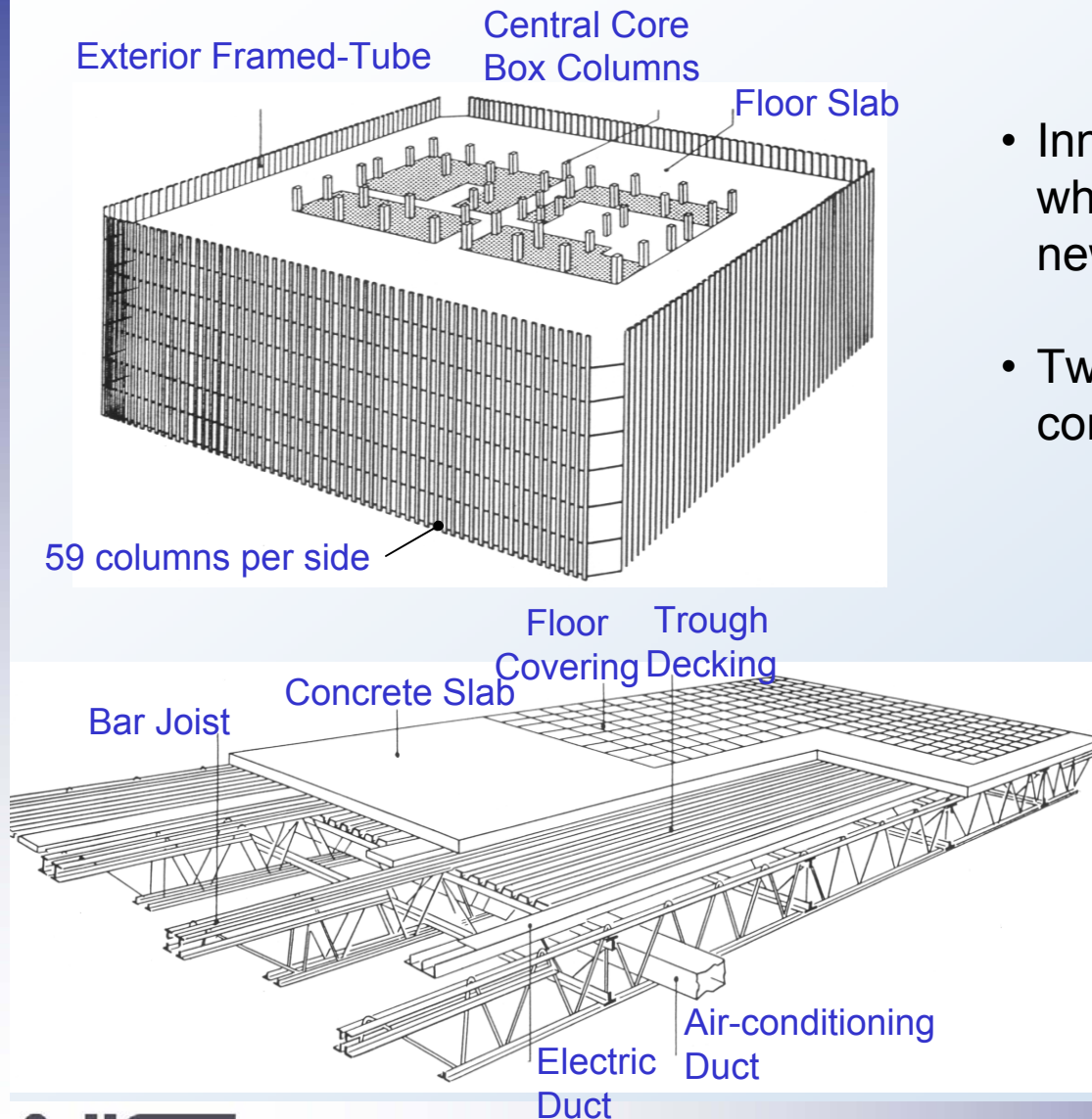
Tilting of Building Sections

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



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

Innovative WTC Tower Structural System



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

Fire Performance of Composite Floor System

- Fire-protection of a truss-supported floor system with spray-on fireproofing was innovative and not consistent with then-prevailing practice.
- **Lack of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
 - 1/2 in. specified when WTC towers were built
 - 1-1/2 in. specified for upgrades some years prior to 2001
 - 2 in. for similar floor system in an unrestrained test (model code evaluation service recommendation in June 2001, unrelated to WTC buildings)
- **No full-scale fire resistance test of the WTC floor system was conducted** to determine the required fireproofing thickness; in 1966, the Architect of Record and, in 1975, the Structural Engineer of Record stated that the fire rating of the WTC floor system could not be determined without testing.

NYC Building Code Provisions (Fire Resistance in hours)

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

* Building code governing original design and occupancy

** Sprinklers required for buildings of unlimited height

Results From NIST-Sponsored Tests at UL

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

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

Use of Wind Tunnel Testing to Estimate Loads

- Wind loads were a major governing factor in the design of the components that made up the WTC tower structures, especially the perimeter frame-tube system
 - Relevant to evaluating baseline performance of the WTC towers, reserve capacity of the structures to withstand unanticipated events such as a major fire or impact damage, and design practices and procedures; state-of-knowledge is evolving in the field of wind engineering
- Large differences in resultant forces, of as much as about 40 percent, in results from two sets of wind tunnel tests for the WTC towers conducted in 2002 by independent laboratories, and voluntarily provided to NIST by parties to an insurance litigation
- NIST is conducting an independent analysis to establish the baseline performance of the WTC towers under the original design wind loads and will compare those results with then-prevailing code requirements
 - In July 2004, the designer provided NIST with clearer interpretation of information in original source documents to determine the design wind loads used for the WTC towers

Wind Load Estimates for WTC 1

Source	Year	Base Shear 10 ³ kips			Base Moment 10 ⁶ kips-ft		
		N-S	E-W	Most Unfavorable Condition	About N-S	About E-W	Most Unfavorable Condition
NYC Building Code	Prior to 1968	5.3	5.3		4.2	4.2	
NYC Building Code	1968 - 2001	9.3	9.3		7.7	7.7	
RWDI / NYC Building Code	2002	11.4	10.5	13.0	10.1	10.5	12.2
RWDI / ASCE 7-98	2002	12.3	11.3	14.0	10.8	11.4	13.1
CPP / NYC Building Code	2002	NA	NA	NA	NA	NA	NA
CPP / ASCE 7-98	2002	NA	NA	NA	NA	NA	NA
NIST / third-party SOM review / ASCE 7-02	2004	14.1	13.0	16.1	12.4	13.1	15.1
Original WTC Design (Clarified by designer in July 2004)	1960's	9.8	10.6	14.0	10.3	9.1	13.7

Wind Load Estimates for WTC 2

Source	Year	Base Shear 10 ³ kips			Base Moment 10 ⁶ kips-ft		
		N-S	E-W	Most Unfavorable Condition	About N-S	About E-W	Most Unfavorable Condition
NYC Building Code	Prior to 1968	5.3	5.3		4.2	4.2	
NYC Building Code	1968 - 2001	9.3	9.3		7.6	7.6	
RWDI / NYC Building Code	2002	9.7	11.1	12.3	10.1	9.2	11.3
RWDI / ASCE 7-98	2002	10.6	12.2	13.5	11.1	10.1	12.4
CPP / NYC Building Code	2002	NA	NA	NA	NA	NA	NA
CPP / ASCE 7-98*	2002	15.1	15.3	17.1	15.5	14.0	17.0
NIST / third-party SOM review / ASCE 7-02	2004	12.2	14.0	15.6	12.8	11.6	14.3
Original WTC Design (Clarified by designer in July 2004)	1960's	13.1	10.1	16.5	8.8	12.6	15.2

Base Shears and Base Moments Due to Wind Loads from Different Building Codes

	1938 NYC Code	1968-2001 NYC Code	1964 NY State Code	1965 BOCA/BBC	1967 Chicago Municipal Code
Base Shear (10^3 kips)	5.3	9.3	9.5	9.8	8.7
Base Moment (10^6 kips-ft)	4.2	7.7	7.6	8.5	7.5

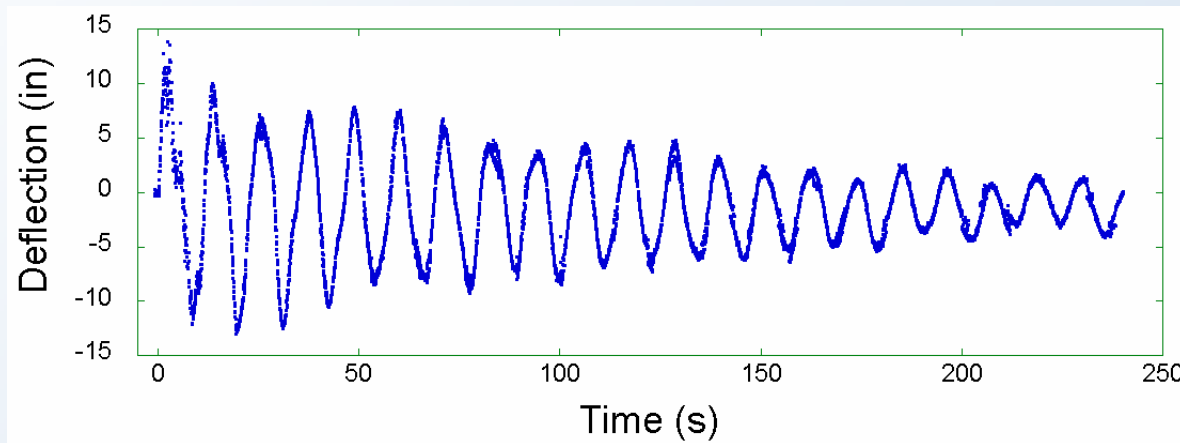
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Clock

Relative Roles of Aircraft Impact and Fires

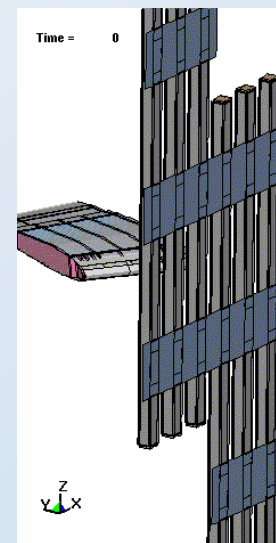
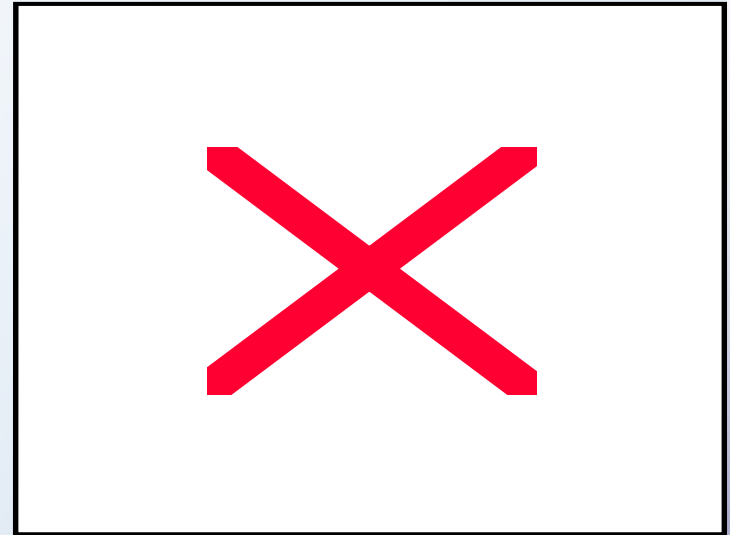
- The two WTC towers withstood the initial impact of virtually identical aircraft (Boeing 767-200ER) during the terrorist attacks of September 11, 2001.
- The robustness of the perimeter frame-tube system and large dimensional size of the WTC towers helped the buildings withstand the aircraft impact.



- The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were about half the amplitudes for design wind conditions expected by the building designers and an oscillation period nearly equal to that measured for the undamaged building.

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.



Preliminary Aircraft Impact Damage Analysis

- ❑ Engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted perimeter columns.
- ❑ The residual velocity and mass of the engine after penetration is sufficient to fail a core column in the event of a direct impact



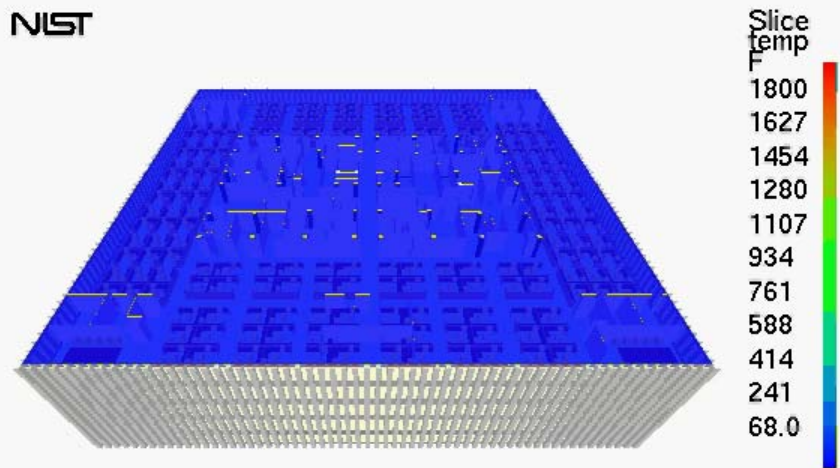
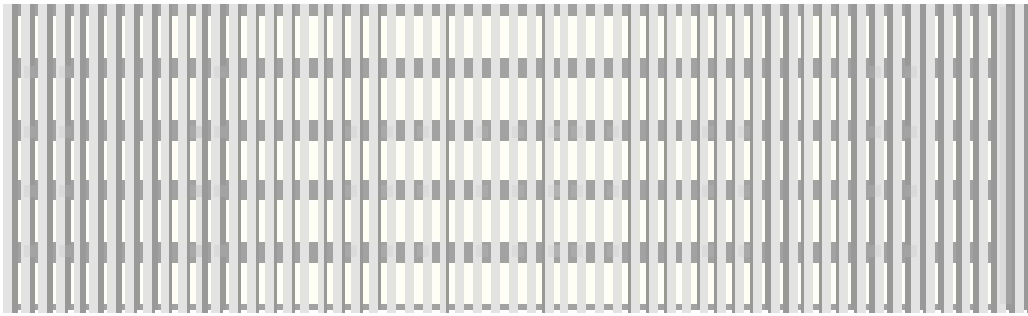
Relative Roles of Aircraft Impact and Fires

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

Relative Roles of Aircraft Impact and Fires

- Consistent with available photographic and videographic evidence, NIST computer simulations capture the broad patterns of fire movement around the floors, with **flames in a given location lasting for about 20 min before spreading to adjacent, yet unburned combustibles**; some observed instances where fires persisted longer in regions with accumulated combustible debris; other instances of sudden or interrupted fire spread.
- The **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 min to 100 min prior to building collapse 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.**
- Applying the 1968 NYC Building Code, the WTC towers were required to have 1 h fire-rated tenant separations, but the code did not impose any minimum compartmentation requirements (e.g., 7,500 ft²) to mitigate the spread of fire in large open floor plan buildings.

Reconstruction of the WTC Fires



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Collection and Analysis of Photographic and Video Images

- Visual database now contains:
 - Well in excess of 6,000 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**



Role of Fireproofing Conditions

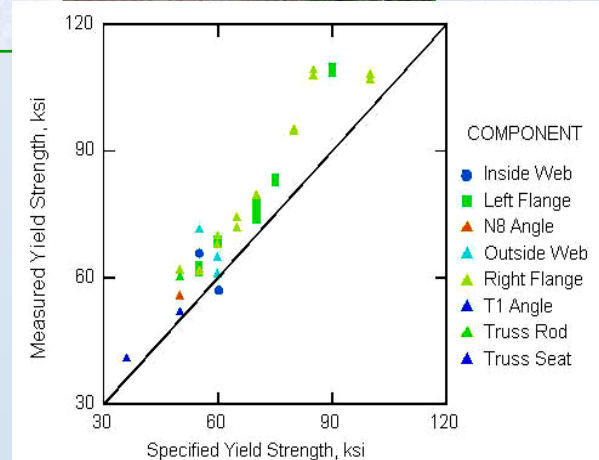
- NIST has developed a rigorous technical approach to evaluate the role of the post-impact condition of the fireproofing, including its thickness, on the collapse of the WTC towers.
- In general, the affected floor systems in WTC 1 had upgraded or thicker fireproofing (1.5 in. specified); affected floors 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.**

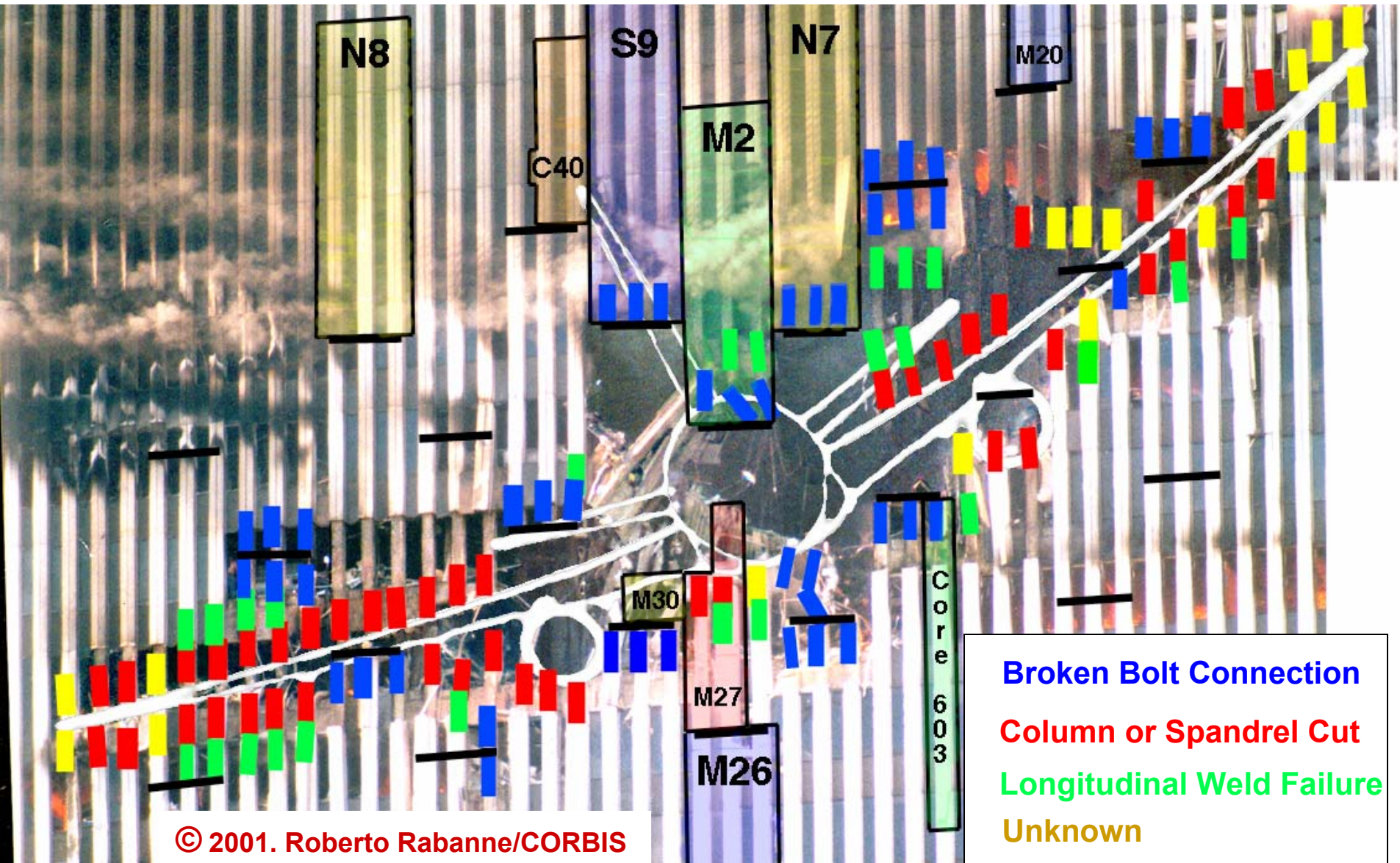
Status	As-Applied Avg. (COV)	Thermally Equivalent	Specified
Original	0.75 (0.4)	0.6	0.5
Upgraded	2.5 (0.24)	2.2	1.5

- Simple analytical models show that 100 g to 150 g acceleration would be required to dislodge fireproofing similar to that used in the WTC towers with typical thickness of 1 in.; experiments underway to verify results.
- Results of aircraft-impact damage analysis being used to estimate regions where fireproofing was dislodged from structural members

Analysis of Recovered WTC Steel

- ❑ NIST has a total of 236 WTC steel pieces in NIST's possession; collection is adequate for determining the quality and properties of steel for the investigation;
 - Impact/fire damage region emphasized
 - All 14 grades of steel for perimeter columns
 - Both grades for steel trusses
 - Two grades (representing 99%) for core columns
- ❑ Based on stampings on steel and mechanical tests, analysis indicates that the **correct specified materials were provided for specified elements**; when these data are combined with available pre-collapse photographs, aircraft impacted pieces from WTC 1 were in precise locations specified in design drawings
- ❑ Metallography and mechanical property tests indicate that the **strength and quality of the steel used in the towers was adequate, typical of the era, and likely met all qualifying test requirements.**
- ❑ **The room-temperature strength of steel used in the WTC towers met relevant standards** and, in many instances, exceeded requirements by 5 to 10 percent.





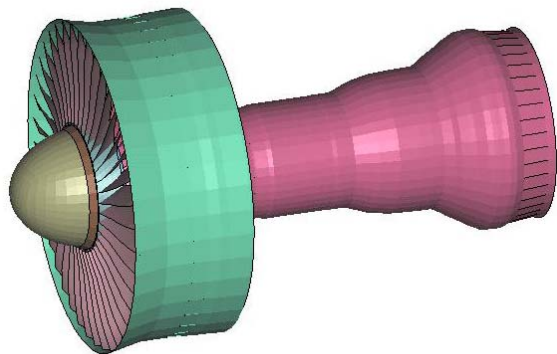
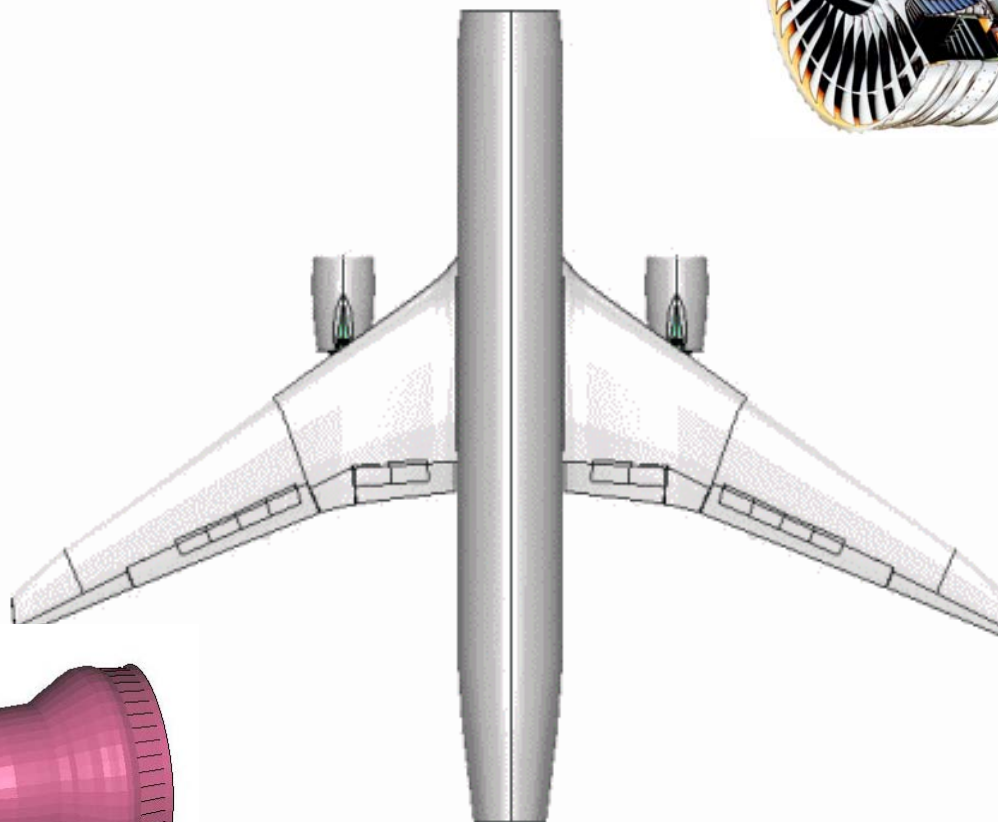
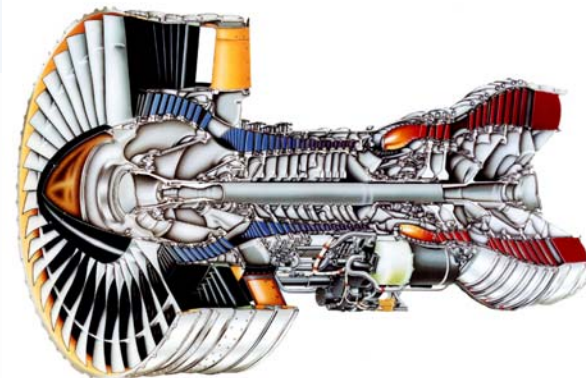
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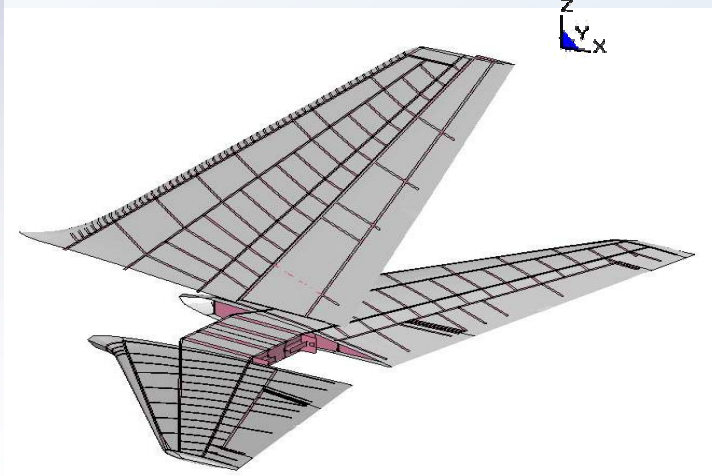
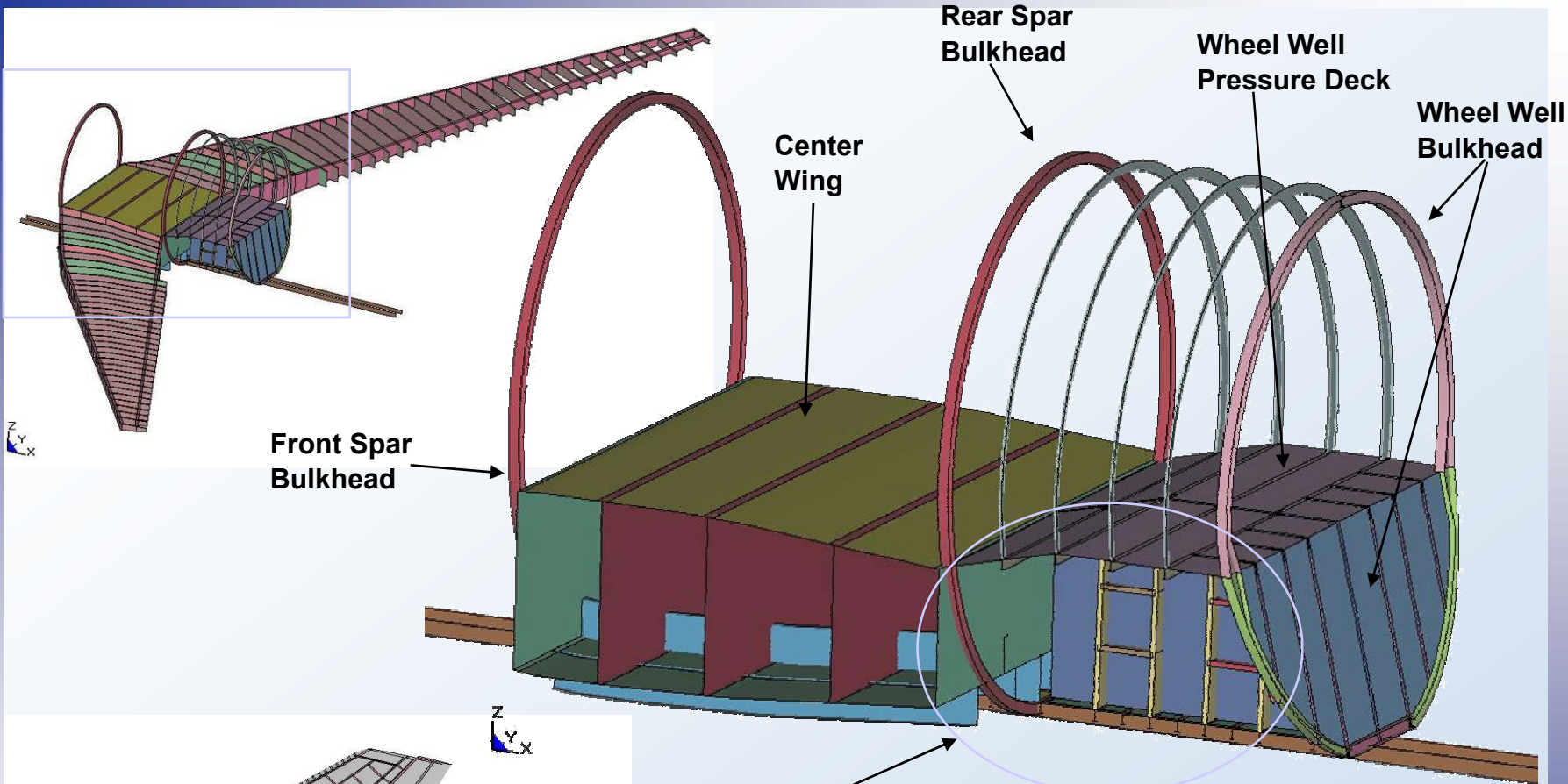
Enhancements added by NIST.

Analysis of Most Probable Collapse Sequence

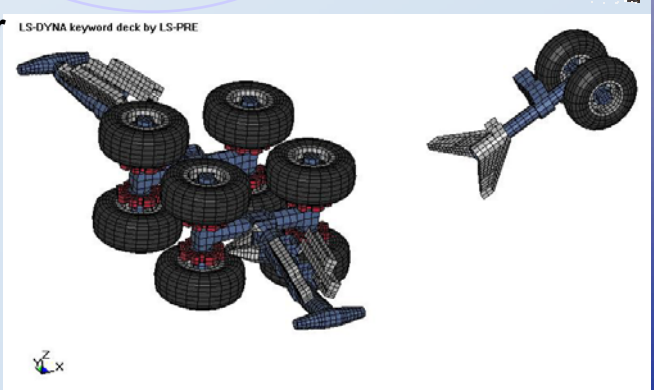
- NIST is simulating highly-complex failure modes at the component, subsystem, and system level to determine the most probable collapse sequence. **In many instances, NIST is testing the limits of current engineering software.**
- The computational models developed by NIST include:
 - A detailed model of a typical truss-framed floor of the WTC towers with over 40,000 elements and 166,000 degrees of freedom.
 - A detailed model of a typical beam-framed floor of WTC towers with over 12,000 elements and 35,000 degrees of freedom.
 - A detailed global model of WTC 1 with over 80,000 elements and 218,000 degrees of freedom (with 17 flexible and other rigid diaphragm floors).
 - A similar detailed global model of WTC 2 with over 78,000 elements and 200,000 degrees of freedom.
 - A model of a typical turbofan engine of the Boeing 767-200ER aircraft with over 60,000 elements and 100,000 nodes.
 - A comprehensive model of the Boeing 767-200ER aircraft, including engines, airframe, landing gear, fuel tanks, passenger cabin, and cargo bay, with over 530,000 elements and 740,000 nodes.
- The first four models described above are being used to evaluate the **baseline performance** of the WTC towers under design gravity and wind loads. They also serve as **reference** models for analyses of aircraft impact damage and response of the thermally-insulated WTC structures to subsequent fires.

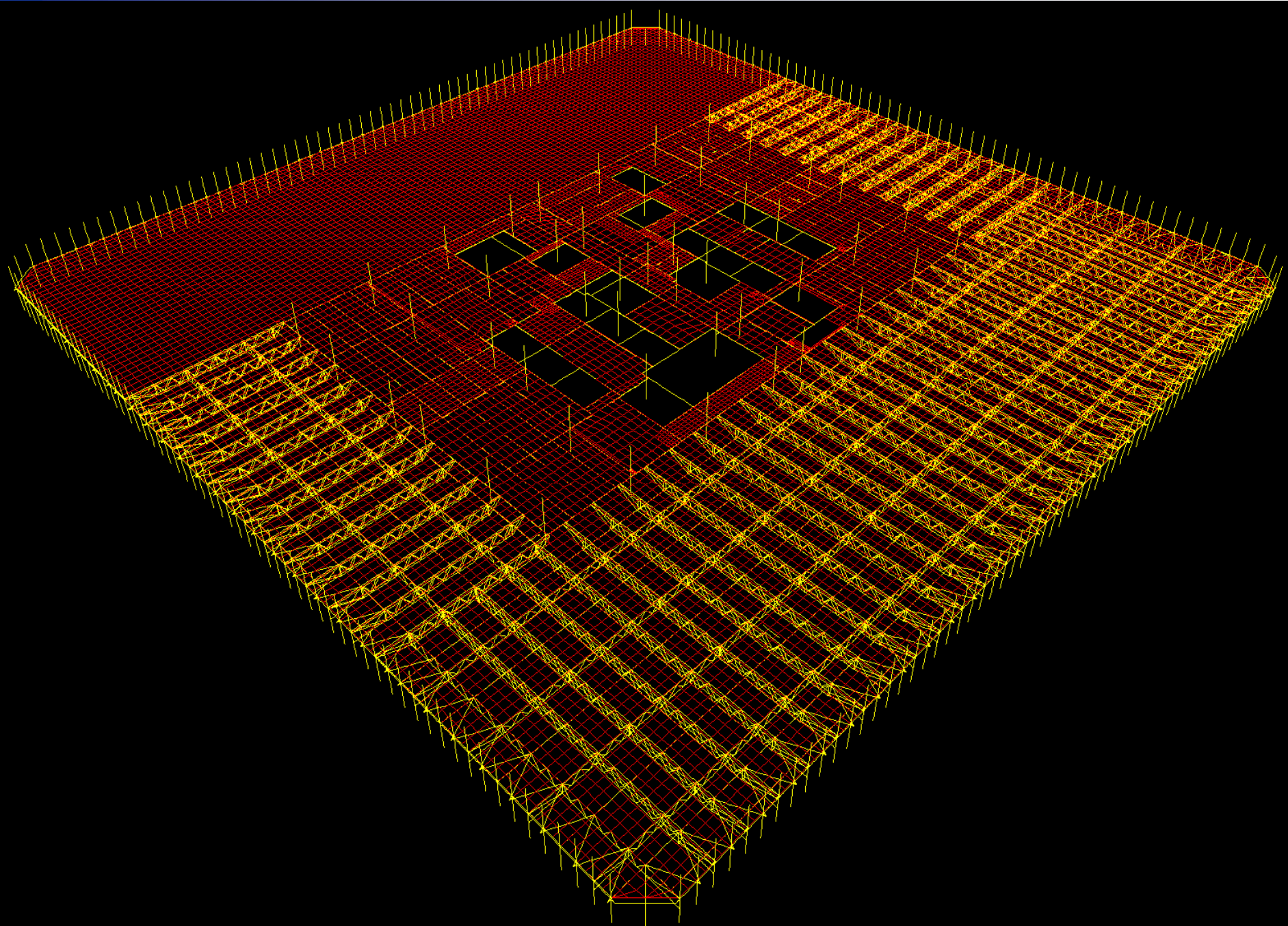
High Fidelity Aircraft Model

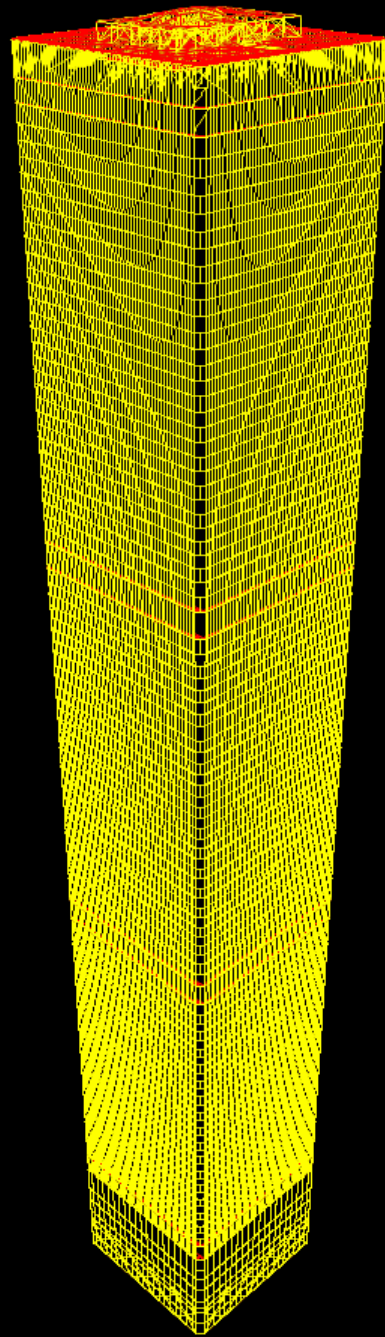




Main Landing Gear Wheel Well







Objective 1b: Collapse of 47-Story WTC 7

- ❑ **Working Hypothesis:** The working hypothesis for the collapse of the 47-story WTC 7 building, if it remains viable upon further analysis, suggests that it was a **classic progressive collapse** that included:
 - An initial local failure at the lower floors (below Floor 13) of the building due to fire and/or debris induced structural damage of a **critical column (the initiating event)**, which supported a large span floor area of about 2,000 ft²;
 - Vertical progression of the initial local failure up to the east penthouse, as large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse; and
 - Horizontal progression of the failure across the lower floors (in the region of Floors 5 and 7, that were much thicker than the rest of the floors), triggered by damage due to the vertical failure, resulting in **disproportionate collapse** of the entire structure.

Observed Sequence of Failures in WTC 7

© 2001 CBS News Archives



Visual Observations for WTC 7

- ❑ *The first exterior sign of structural failure in WTC 7 was the sinking of the east penthouse roof structure into the building.*
- ❑ *Witnesses reported structural damage to WTC 7 on its south face and southwest corner from WTC 1 debris.*



Visual Observations for WTC 7



Fires in WTC 7—which began soon after WTC 1 collapsed—were observed on Floors 7, 8, 9, and 11 near the middle about half an hour before collapse; Floor 12 was burned out by this time. Fires were also seen on Floors 12, 13, 22, 29, and 30 at various times during the day.

Fuel System for Emergency Power in WTC 7

- NIST has reviewed and documented the fuel system for emergency power in WTC 7
- **Floor 5—which did not have any exterior windows and contained the only pressurized fuel distribution system on the south, west and north floor areas—is considered a possible fire initiation location**, subject to further data and/or analysis that improve knowledge of fire conditions in this area.
- The two 6,000 gallon tanks supplying the 5th floor generators through a pressurized piping system were always kept full for emergencies and were full that day.
- Both tanks were found to be damaged by debris and empty several months after the collapse. Some fuel contamination was found in the gravel below the tanks and sand below the slab on which the tanks were mounted, but no contamination was found in the organic marine silt/clay layer underneath.
- This finding allows for the possibility, though not conclusively, that the fuel may have contributed to a fire on Floor 5.

Objective 2: Evacuation and Emergency Response

Based on interviews of WTC surviving occupants:

- **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.

Background Information on Evacuation

- Two-thirds of surviving occupants **reported having participated in a fire drill** in the 12 months prior to September 11, 2001, while 17 percent reported that they **received no training** during that same period. Of those participating in fire drills, 93 percent were instructed about the location of the nearest stairwell. Overall, slightly over half of the survivors, however, had never used a stairwell at the WTC prior to September 11, 2001.
- Two thousand one hundred forty-six building occupants (1,466 in WTC 1, 624 in WTC 2, and 56 others in WTC 1 and WTC 2) and an additional 421 first responders, including security guards but not aircraft passengers and crew or bystanders, were reported to have lost their lives on September 11, 2001.
- Approximately **87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully.**
- Rough initial estimates, which will be refined as data analysis is completed, indicate that about **20 percent or more** of the 2,567 building occupants and first responders who were in the WTC towers and lost their lives **may have been alive in the buildings just prior to their collapse.**

Evacuation Findings Based on First-Person Interviews

- Overall, about 7,900 survivors evacuated WTC 2 in 73 min (i.e., from the instant WTC 1 was struck by aircraft until WTC 2 collapsed) while about 7,500 survivors evacuated WTC 1 in 103 min.
- **The overall evacuation rate in WTC 2 (108 survivors per min) was about 50 percent faster than that in WTC 1 (73 survivors per min).**
- **Functioning elevators allowed many survivors to evacuate WTC 2 prior to aircraft impact.** Most of the elevators in WTC 1 were not functioning, and survivors could only use the stairways.
- The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.

Evacuation Rates in the WTC Towers

- After the first airplane struck WTC 1 and before the second airplane struck WTC 2, the survivors in WTC 2 were twice as likely as those in WTC 1 to have already exited the building (41 percent versus 21 percent). The rate of evacuation completion in WTC 2 was twice the rate in WTC 1 during that same period.
- 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 had 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 had slowed to about one-fifth the immediately prior evacuation rate. This suggests that **for those seeking and able to reach and use undamaged exits and stairways, the egress capacity (number and width of exits and stairways) was adequate to accommodate survivors.**
- Based on use of existing egress models and actual evacuation time on September 11, 2001, it is estimated that **a full capacity evacuation of each WTC tower with 25,000 people—three times the number present on September 11, 2001—would have required about 4 hours.** To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).

Emergency Communication Recordings

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

Preliminary 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 or understandable.**
- **FDNY's city-wide high-rise Channel 7 (PAPD Channel 30) radio repeater at the WTC site was operating.**
- NYPD aviation unit personnel reported critical information about the **impending collapse** of the WTC towers several minutes prior to their collapse. **No evidence has been found to suggest that the information was further communicated to all emergency responders at the scene.**

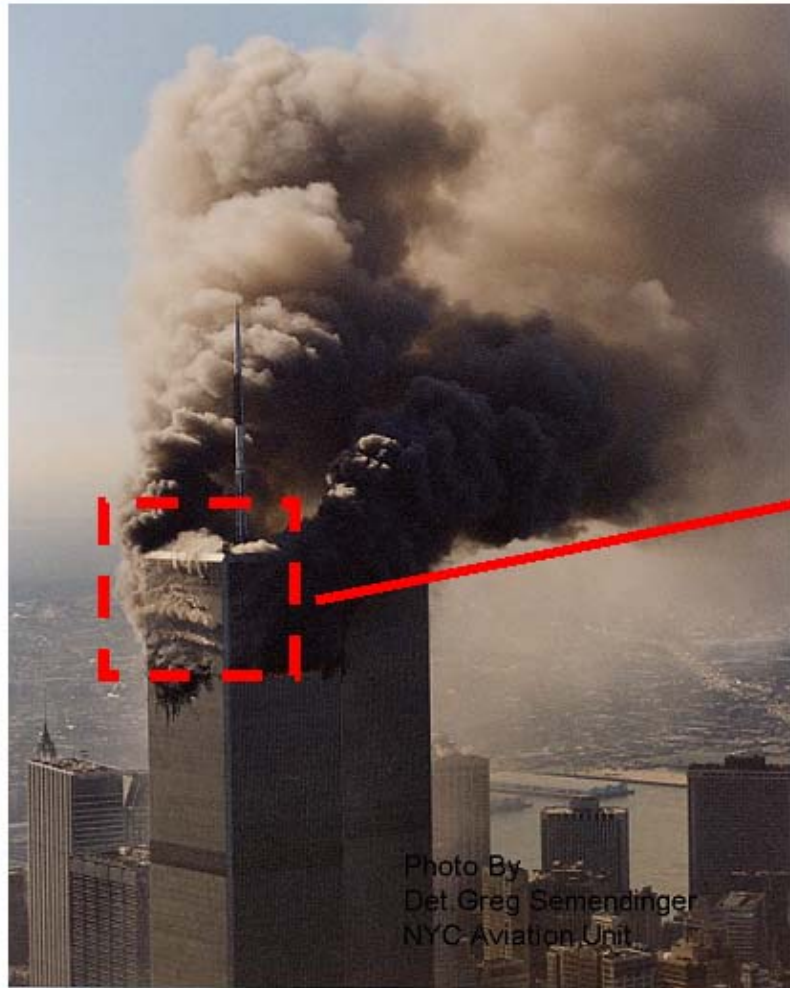
WTC High-Rise Radio Repeater System

- Several FDNY personnel at the incident site did not think that the high-rise radio repeater was working.
 - Based on tests conducted by two chief officers working inside WTC 1 when the first command post was being set up in that lobby.
 - Following test, a chief officer involved in the test chose to use different channels for command and tactical communications during the incident.
- As FDNY operations increased in WTC 2, it was determined by FDNY members that the high-rise repeater was functioning, and use of the channel developed.
- While preliminary analysis indicates that the repeater was operating, there also appears to have been some type of malfunction with the communications equipment that was detected, but not identified, by FDNY officers during initial test.
- **NIST continues to evaluate the repeater system and its operations, as well as the handheld radios, which were used on September 11, 2001.**
- These findings will be updated and additional findings will be documented when the investigation is complete.

Active Fire Protection Systems

- The smoke management systems in the WTC towers were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional was very low due to the damage inflicted by the aircraft impacts.
- Analysis indicates that **HVAC (heating, ventilation, and air-conditioning) ductwork was a major path for vertical smoke spread in the buildings.**
- Analysis indicates that **stair pressurization systems would have provided minimal resistance to the passage of smoke in WTC 1 and WTC 2 had they been installed on September 11, 2001.**
- The fire alarm system in WTC 7 sent only one signal (at 10:00:52 a.m. shortly after WTC 2 collapsed) to monitoring company indicating a fire condition. The signal did not contain any specific information about the location of the fire within the building.
- **The resistance to failure of the fire alarm system communications paths between the fire command station and occupied WTC tower floors could have been enhanced if fiber optic cable had been used instead of copper lines.**
- Although the fire sprinkler system was damaged by aircraft impact, the **water supply riser system lacked redundancy**, and there existed the potential for single point failure of the water supply connection on each floor.

Example of Vertical Smoke Spread

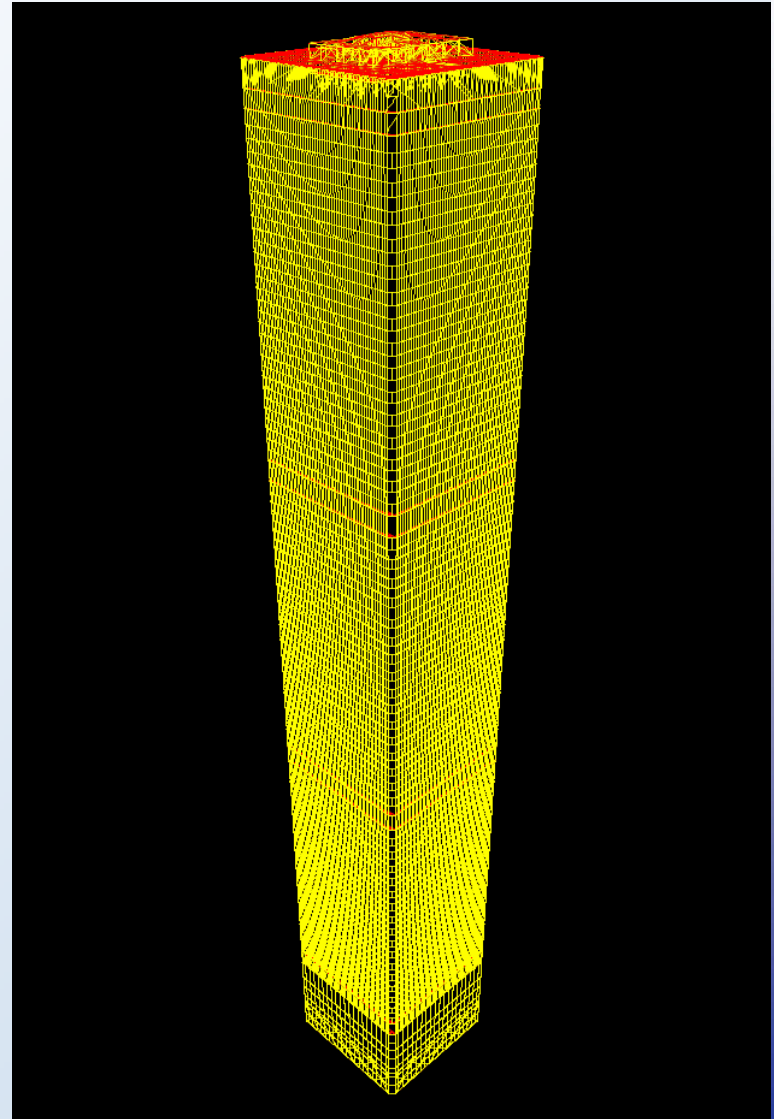


North Face – WTC 1
Smoke Exits NW Interior
Ventilation Zone Supply Inlet



Objective 3: Procedures and Practices

- The 110-story WTC towers were among the world's tallest buildings, while the 47-story WTC 7 represented a more typical tall building.
- These buildings provide case studies to document, review, and, if needed, improve the procedures and practices used in the design, construction, operation, and maintenance of tall buildings.
- This investigation objective is independent of other objectives which are focused specifically on the consequences of the attack on September 11, 2001, specifically the building collapses, evacuation, and emergency response.
- While some findings under this objective are directly relevant to the events of September 11, 2001, others are concerned with general building and fire safety procedures and practices.



Applicable Building Codes

- Although not required to conform to NYC codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect.
- **The 1968 edition allowed less restrictive provisions** compared with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:
 - Eliminated a fire tower as a required means of egress;
 - Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
 - Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
 - Changed partition loads from 20 psf to one based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings);
 - Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).
- **The NYC Department of Buildings reviewed the WTC tower drawings** in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code.

Standards, Codes, and Regulations

NIST has reviewed the then-prevailing and current standards, codes, and regulations relevant to assessing the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings.

That review raises the following issues that merit further consideration:

- **Detailed procedures** to analyze and evaluate data from fire resistance tests of other building components and assemblies **to qualify an untested building element.**
- **Requiring 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.
- Adoption of the “structural frame” approach to fire resistance ratings which 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.
- **Ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements.**

Standards, Codes, and Regulations (2)

- **Minimum mechanical and durability related properties of spray-applied fire resistive materials (SFRM)** to ensure acceptable in-service performance (typical shock, impact, vibration, or abrasion effects) over the life of a building.
- Assure that **as-built condition of the passive fire protection**, such as SFRM, **conforms to conditions found in fire resistance tests** of building components and assemblies.
- **In-service inspections of passive fire protection during the life of the building.**
- **Early installation of sprinklers in existing buildings, not as an option in lieu of compartmentation.**
- **Minimum structural integrity for the means of egress (stairwells and elevator shafts)** in the building core which are critical to life safety.

Standards, Codes, and Regulations (3)

- **Installation of fire-protected elevators** and their use for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants.
- **Explicit standards and code provisions for structural integrity that would mitigate progressive collapse.**
- **Conduct of wind tunnel tests and the methods used in practice to estimate design wind loads from test results.**
- **Retention of documents, over the service life of a building,** related to the design, construction, operation, maintenance, and modifications of buildings, including retention off-site.

Fire Safety and Egress Design Methods

- **Historical** fire loss data over more than half a century, for different high-rise building occupancies, suggests that **prescriptive** requirements in standards and codes have considerable built-in conservatism to adequately protect building occupants.
- As a result, there has been a **trend in recent decades to reduce fire rating and egress requirements**, sometimes in conjunction with addition of other new and complementary fire protection requirements (e.g., detectors and sprinklers).
- The lower fire rating requirements when combined with the considerable increases in building design efficiency that have been achieved, have also led to reductions in the thermal mass of buildings—an indicator of how much heat energy a building can absorb passively without damage.
- The empirical rules and test methods used in prescriptive design, which have evolved with experience over the years, **do not lend themselves readily to evaluating whether the performance of building fire safety and egress systems is risk-consistent**, considering both the hazards and the consequences of the hazards.
- **Performance-based methods that explicitly define the design objectives and specific design-basis fire hazards or evacuation events are better suited** to risk analysis, enabling appropriate protection to be provided where it is needed.

Fire Safety and Egress Design Methods (2)

The increasing use of performance-based methods, as an alternative to prescriptive design, in fire safety and egress design, raises **the following issues that merit further consideration:**

- **Considering fire as a design condition in structural design**, including evaluation of the fire performance of the structure as a whole system. This design approach is already being used in building design practice for earthquake and wind hazards (e.g., a two-level design that includes a higher probability operational event and a lower probability life safety event).
- **Detailed procedures to select appropriate design-basis fire scenarios** for performance-based design of the sprinkler system (e.g., a frequent but low severity fire), compartmentation (e.g., a moderate severity but less frequent fire), and passive protection of the structure (e.g., a maximum credible fire).
- **Validated and verified tools**, for use in performance-based design practice to analyze the dynamics of building fires and their effects on the structural system, that would allow engineers to evaluate structural performance under alternative fire scenarios and fire protection strategies.

Fire Safety and Egress Design Methods (3)

- **The technical basis to establish whether the construction classification and fire rating requirements are risk-consistent.** Specifically, 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 200 ft in height.
- Sprinklers improve safety in most common building fires and prevent them from becoming large fires. **The technical basis to establish the “sprinkler trade-off” in current codes**, considering fire safety risk factors such as the complementary functions of sprinklers and fire-protected structural elements and the need for redundancy should one system fail to function as intended, **is not available.** The sprinkler trade-off provides an economic incentive to encourage installation of sprinklers by allowing a lower fire rating for sprinklered buildings.
- **The design of egress systems to achieve a target performance** (e.g., evacuation rate or time) for a given occupant population by adequately considering travel distance, remoteness requirements, and human factors such as occupant size, stairwell environmental conditions, visibility, and congestion.

Objective 4: Approach to Recommendations

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

Approach to Recommendations (2)

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

Approach to Recommendations (3)

- **NIST urges organizations responsible for building and fire safety at all levels to carefully consider the interim findings contained in this report.**
- **NIST welcomes comments from technical experts and the public on these interim findings.** Comments can be sent by e-mail to wtc@nist.gov, facsimile to (301) 975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.
- **In its final report, a draft which is expected to be released in December 2004, NIST will recommend appropriate improvements in the way buildings are designed, constructed, maintained and used. It will be important for those recommendations to be thoroughly and promptly considered by the many organizations responsible for building and fire safety.**
- **As part of NIST's overall WTC response plan, the Institute has begun to reach out to these organizations to pave the way for timely, expedited consideration of recommendations stemming from this investigation. NIST also has expanded its research in areas of high priority need.**

<http://wtc.nist.gov>

Thank You