NIST Response to the World Trade Center Disaster

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

August 26, 2008

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

Outline

- **Investigation Objectives**
- WTC 7 Building Design
- Probable Collapse Sequence
- Other Possible Hypotheses
- Principal Findings
- Factors that Could Have Changed The Outcome
- Recommendations

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**

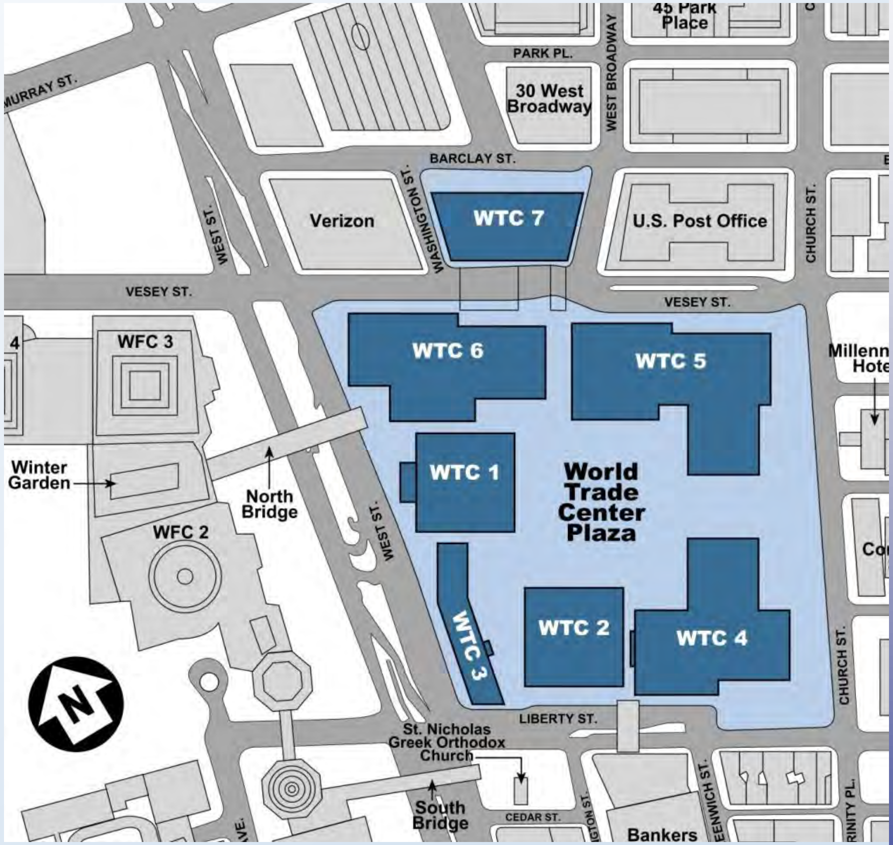
Outline

- Investigation Objectives
- **WTC 7 Building Design**
- Probable Collapse Sequence
- Other Possible Hypotheses
- Principal Findings
- Factors that Could Have Changed The Outcome
- Recommendations

NIST

World Trade Center 7

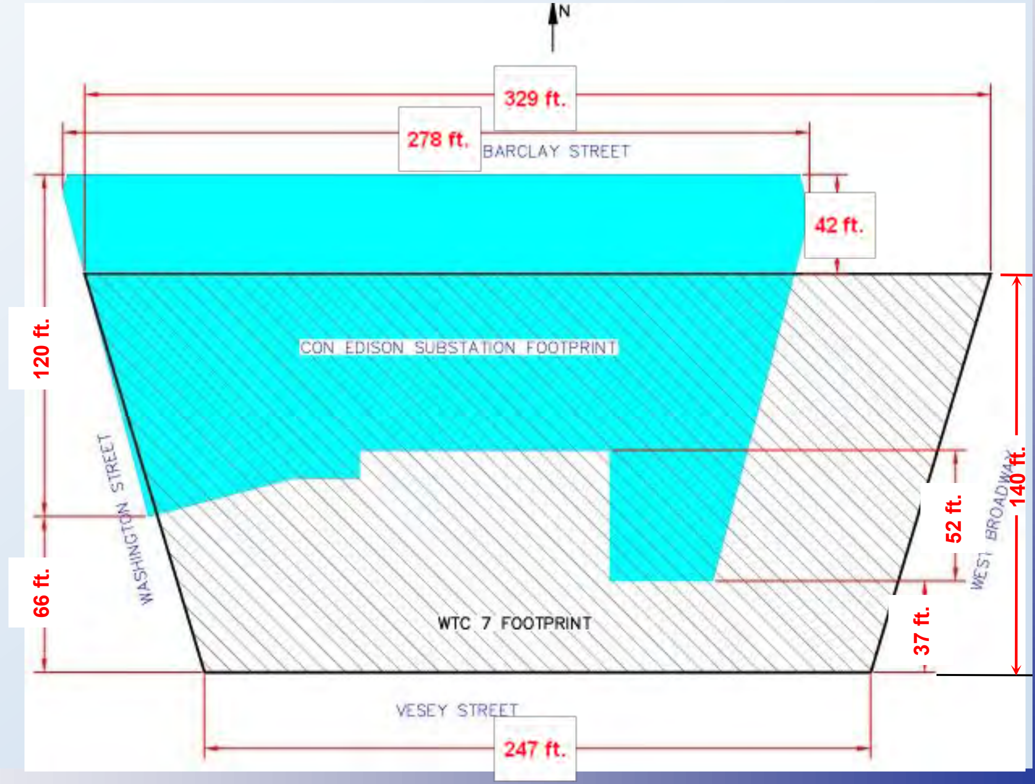
- WTC 7 was a 47 story office building located north of the WTC Complex.
  - Built over an existing Con Edison electric power substation, on land owned by The Port Authority of New York and New Jersey.
  - On September 11, 2001, fires burned for almost seven hours, from the collapse of WTC 1 at 10:28:22 a.m. until 5:20:52 p.m., when WTC 7 collapsed.
  - **The collapse of WTC 7 was the first known instance of the total collapse of a tall building primarily due to fires.**



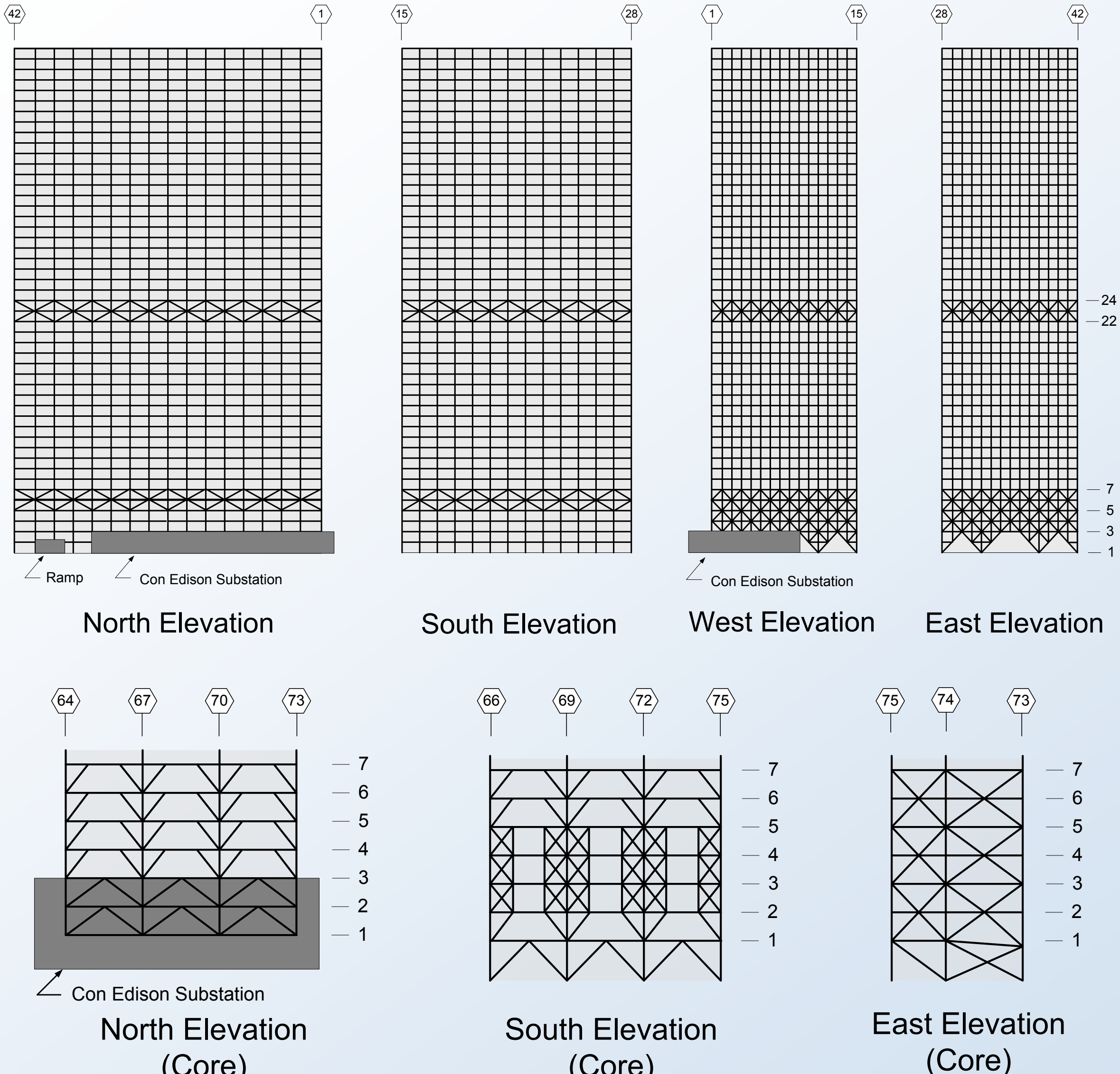
Con Edison Substation

WTC 7 Structural Concept

- The 47 story building contained approximately 200,000 m^2 (2 million ft^2) of floor area.
- Structurally, WTC 7 consisted of four "tiers“:
  - The lowest four floors housed two 2-story lobbies. The north side of the 1st and 2nd stories was the Con Edison substation.
  - Floors 5 and 6 were mechanical spaces with transfer elements.
  - Floors 7 through 45 were tenant floors.
  - The 46th and 47th floors, while mainly tenant floors, were structurally reinforced to support special loads, such as cooling towers.

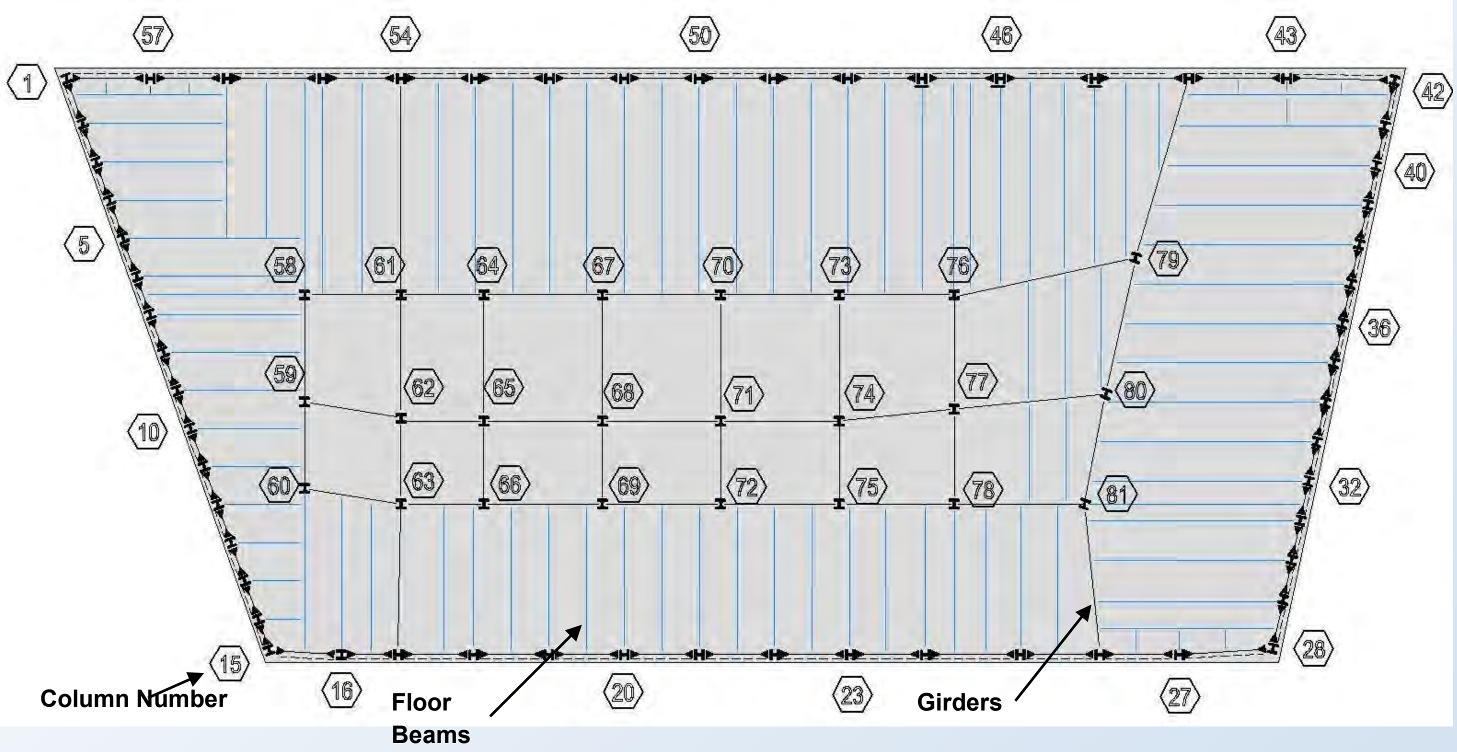


WTC 7 Framing



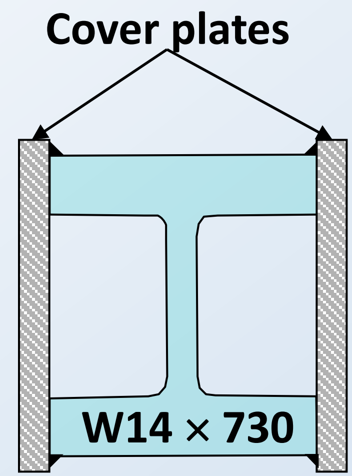
- The WTC 7 *structural system* was designed to distribute the weight of the building (gravity loads) and resist (lateral) wind loads.
- The frame included columns, floor assemblies, spandrel beams, girders, and transfer elements.
- The lateral loads were resisted by the exterior moment frame.
- The gravity loads were supported roughly equally by the 58 exterior columns and the 24 interior columns.

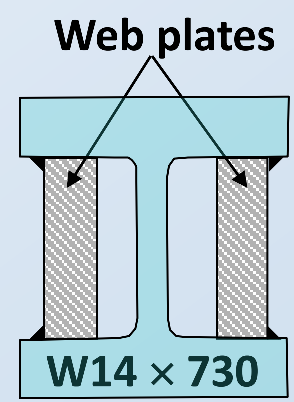
Typical WTC 7 Floor Framing



From the 7th floor to the 47th floor, WTC 7 was supported by 24 *interior columns* and 58 *exterior columns.* Columns 58 through 78 formed the building core. Columns 79, 80, and 81 were particularly large and supported long floor spans on the east side of the building.

Built-up Columns on Lower Floors



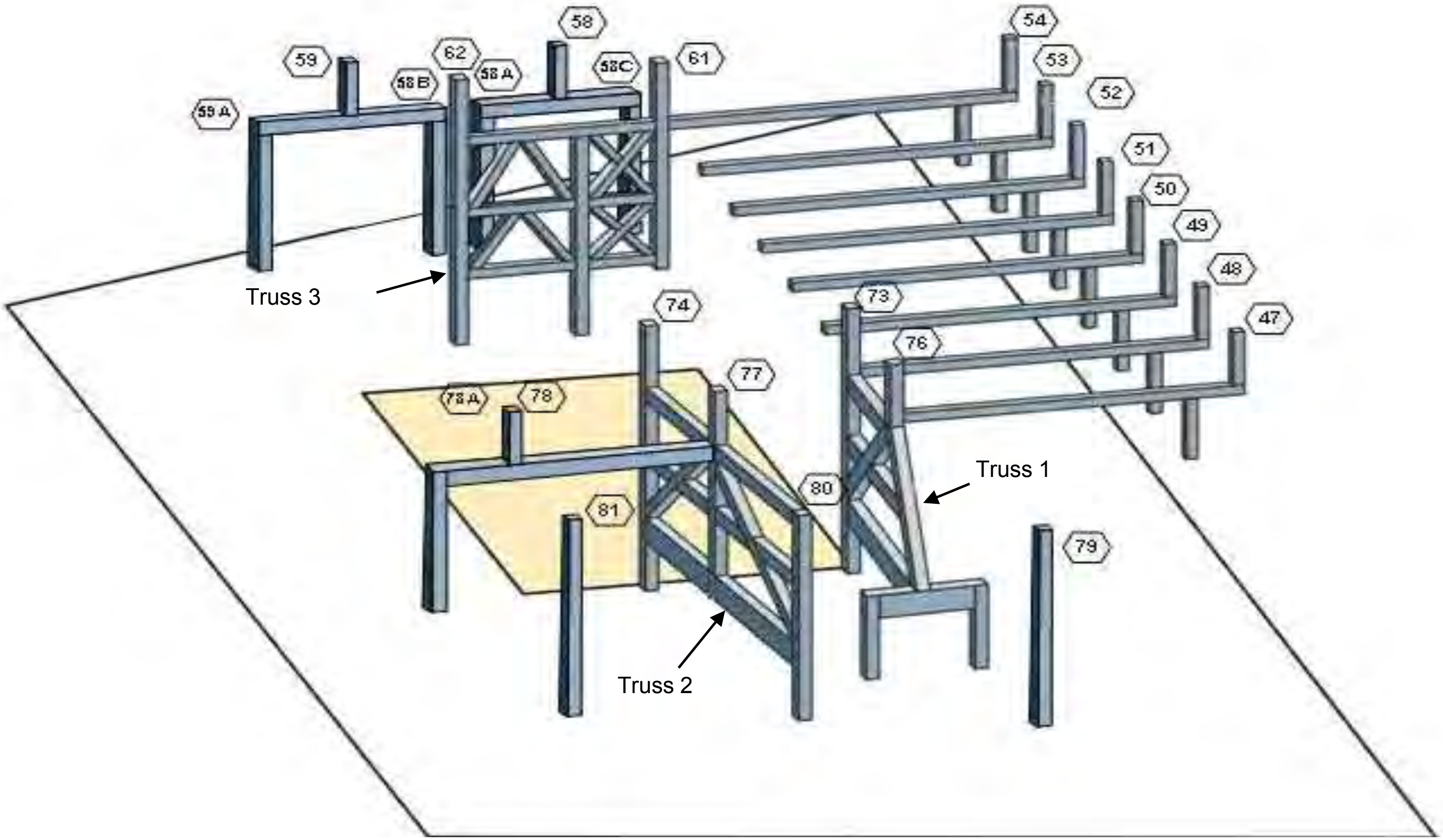


Built-up Column

Non Built-up Column

- Plate thickness ranged from 1.5 in to 8 in.
- Plate thickness t (in.) and steel grade were specified as follows:
  - $2 < t < 4$ ASTM A588 Grade 50
  - $4 < t < 6$ ASTM A572 Grade 42
  - $t > 6$ ASTM A588 Grade 42

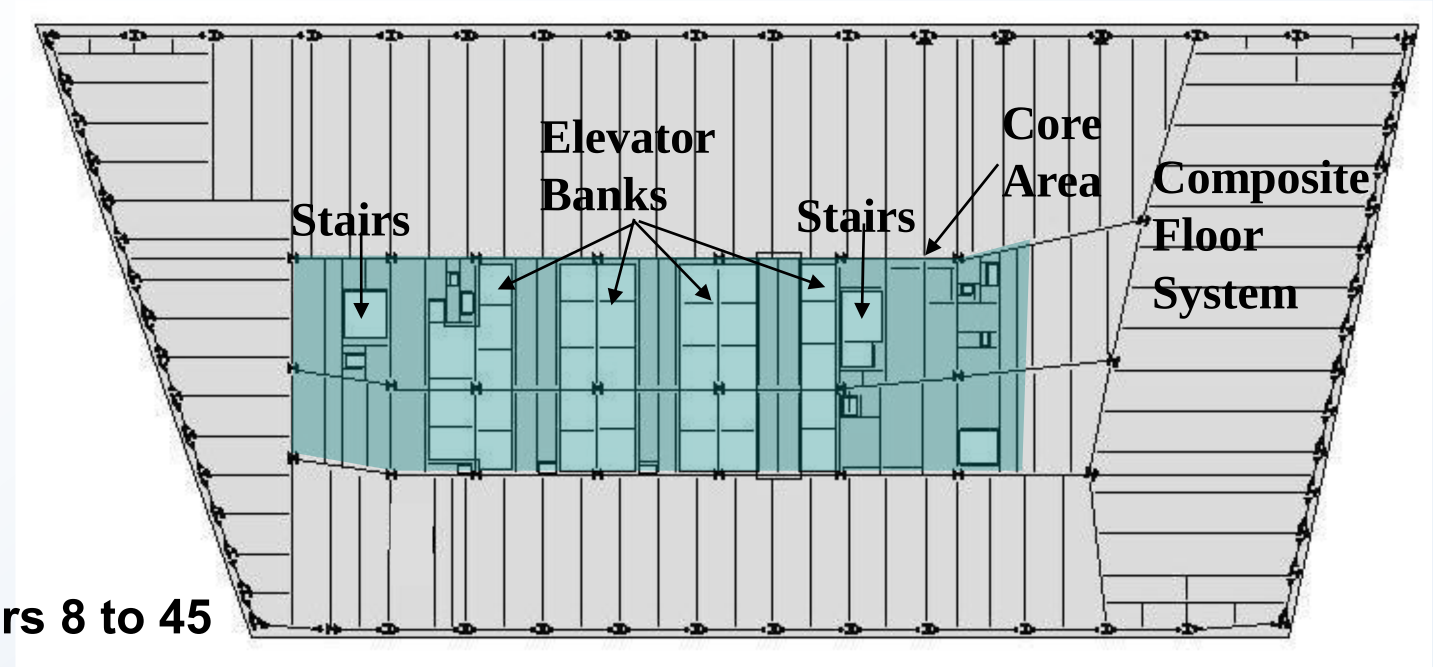
Transfer Trusses and Girders



The layout of the WTC 7 columns did not align with the building foundation and the Con Edison columns. Therefore, a set of *column transfers* were constructed between the 5th and 7th floor slabs.

NIST

WTC 7 Floor System

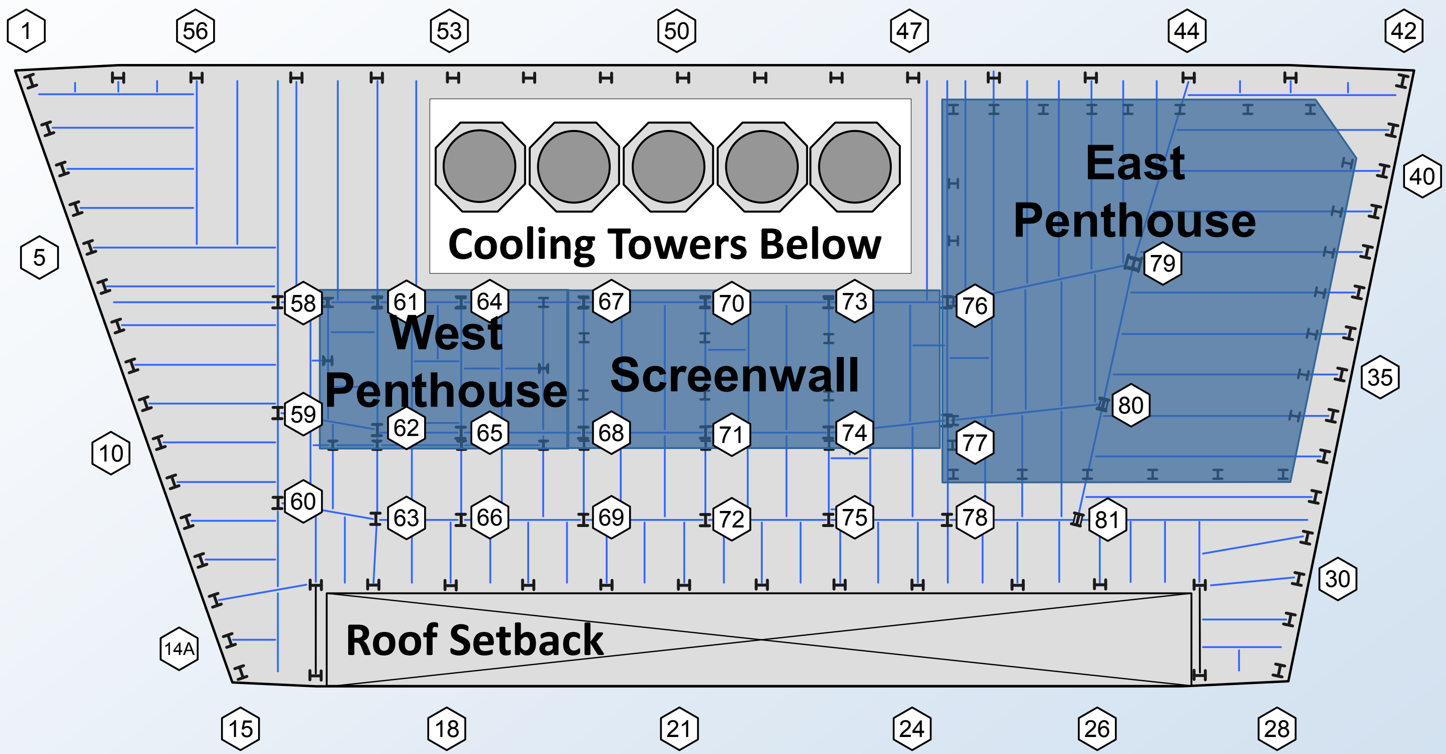


Floors 8 to 45

The *floor slabs* were reinforced concrete of varying thickness.

- The concrete on most floors was poured on a 3 in. corrugated metal deck.
- Floors 2, 3, 4, and 6 had a 6 in. total slab thickness.
- On Floor 5, the concrete slab was 14 in. thick.
- On Floor 7, had a 8 in. total slab thickness.
- On Floors 8 through 47, the concrete slab was 5.5 in. thick.

Roof Layout

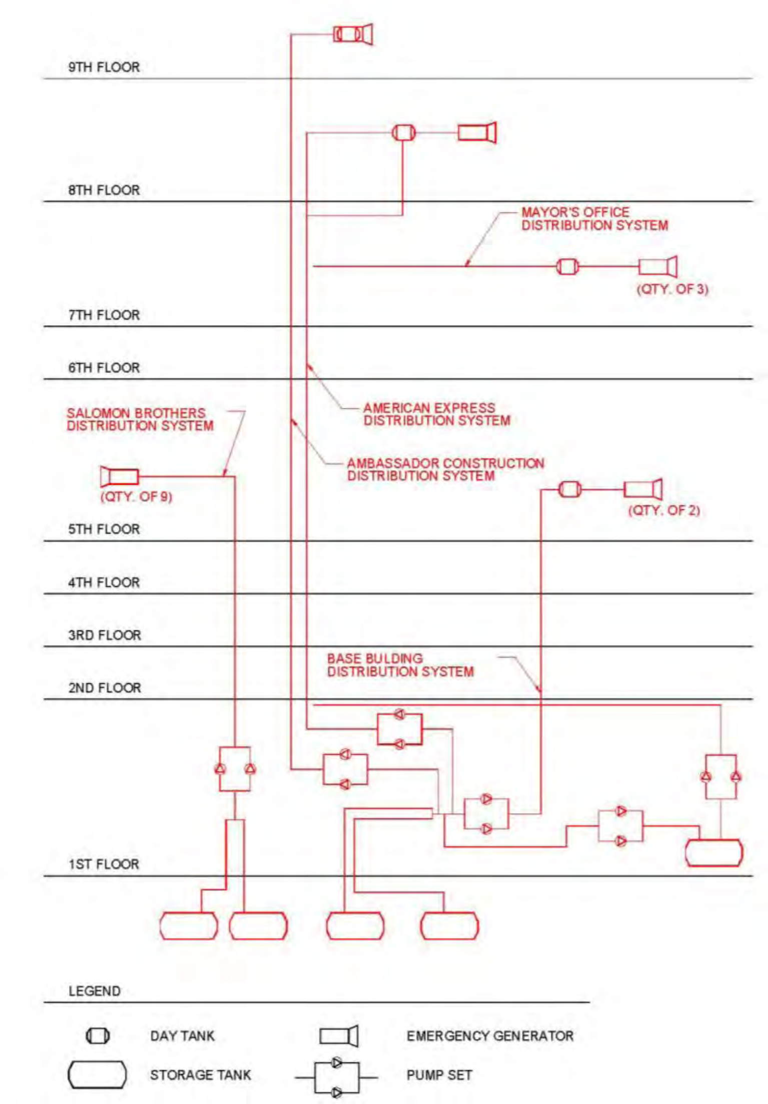


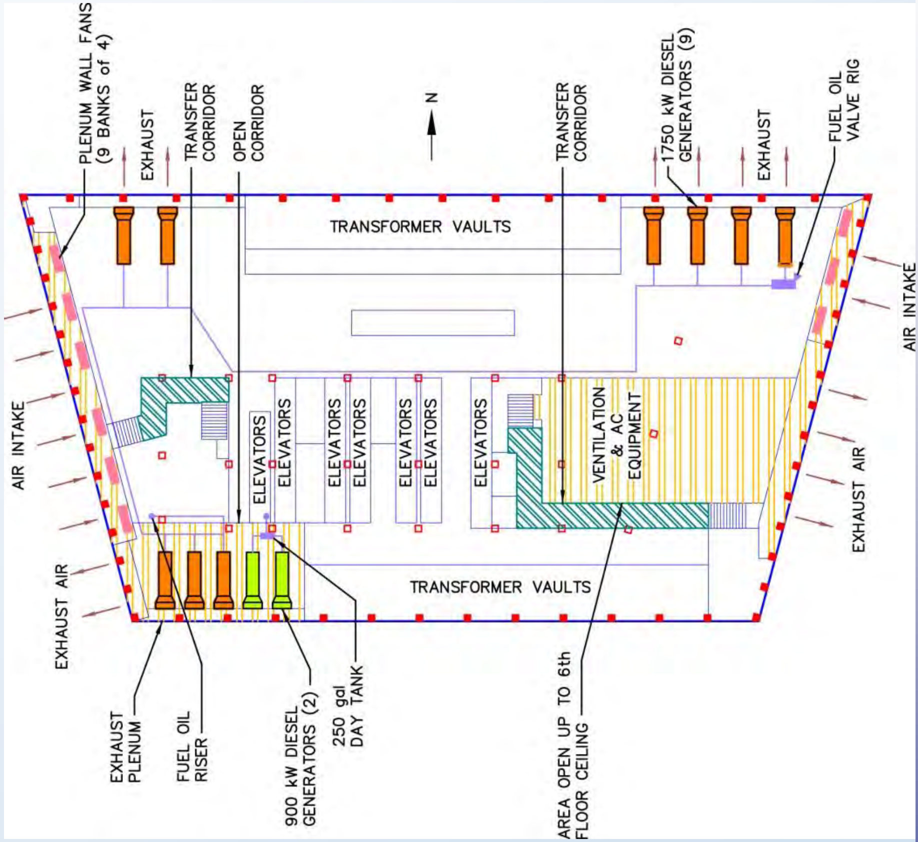
1
56
53
50
47
44
42
40
5
Cooling Towers Below
East
Penthouse
79
58
61
64
67
70
73
76
West
Penthouse
Screenwall
35
59
62
65
68
71
74
80
77
10
60
63
66
69
72
75
78
81
30
Roof Setback
14A
15
18
21
24
26
28

Active Fire Protection Systems

- WTC 7 had the following active fire protection systems:
  - fire alarms
  - smoke and heat detectors
  - manual pull stations
  - smoke control systems
  - automatic sprinklers.
- The standpipe and automatic sprinkler systems were divided into three zones. Each zone had a primary and secondary water supply.
  - The primary water supply for the high zone (Floors 40 through 47) and mid-level zone (Floors 21 through 39) was from two water storage tanks on the 46^{th} floor. The secondary supply was pumped from the city water main.
  - The primary water supply for the low zone (Floors 1 through 20), was a direct connection to the city water mains. The secondary supply was an automatic fire pump, which was connected to the city water main as well.

WTC 7 Emergency Power Systems





Schematic of 5th floor showing location of emergency power system components.

Some Specific Questions

- Why did WTC 7 collapse after having withstood fires for 7 hours?
- What role, if any, did transfer elements (trusses, girders, and cantilever overhangs) play in the collapse of WTC 7?
- What role, if any, did fuel oil systems for emergency power generators in WTC 7 play in the collapse?
- What role, if any, did hypothetical blast events play in the collapse of WTC 7?
- How well did design, construction, and maintenance practices conform to accepted practices?
- Would WTC 7 have collapsed even if there had been no structural damage induced by the collapse of the WTC Towers?

Outline

- Investigation Objectives
- WTC 7 Building Design
- **Probable Collapse Sequence**
- Other Possible Hypotheses
- Principal Findings
- Factors that Could Have Changed The Outcome
- Recommendations

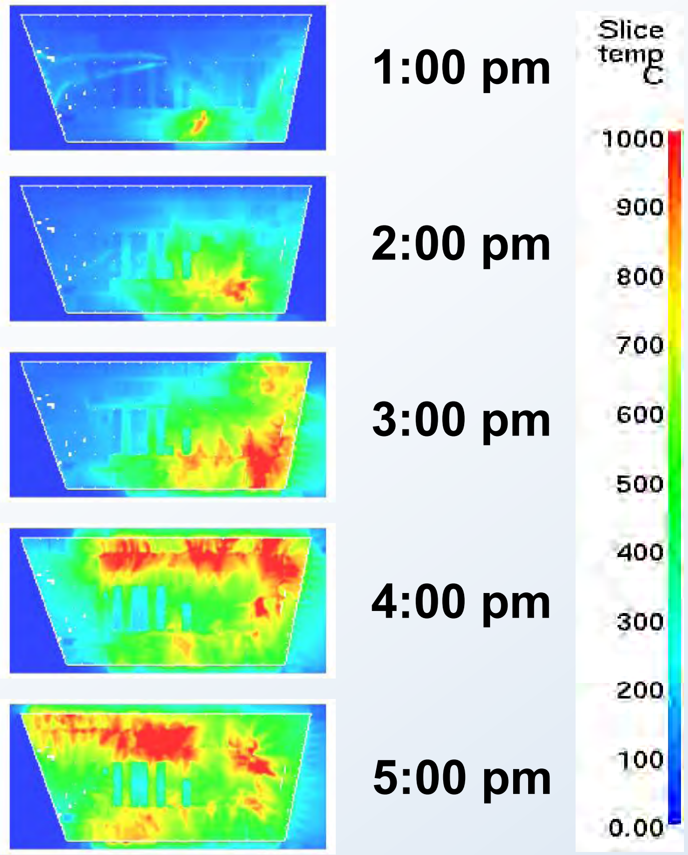
Analysis of Probable Collapse Sequence

NIST developed and used a series of rigorous and comprehensive models to determine the probable collapse sequence for WTC 7

- Analyzed complete sequence of events:
  - Initial damage due to collapse of WTC 1
  - Growth and spread of fires
  - Thermal response of structural components
  - Thermally-induced initial local failure for collapse initiation
  - Collapse propagation, resulting in global collapse
- Combined:
  - Physics-based mathematical modeling
  - Analysis of visual evidence (photographs and videos)
  - Analysis of design, construction, and inspection documents

Significantly advanced current state-of-the-art;
Tested limits of current computational capabilities

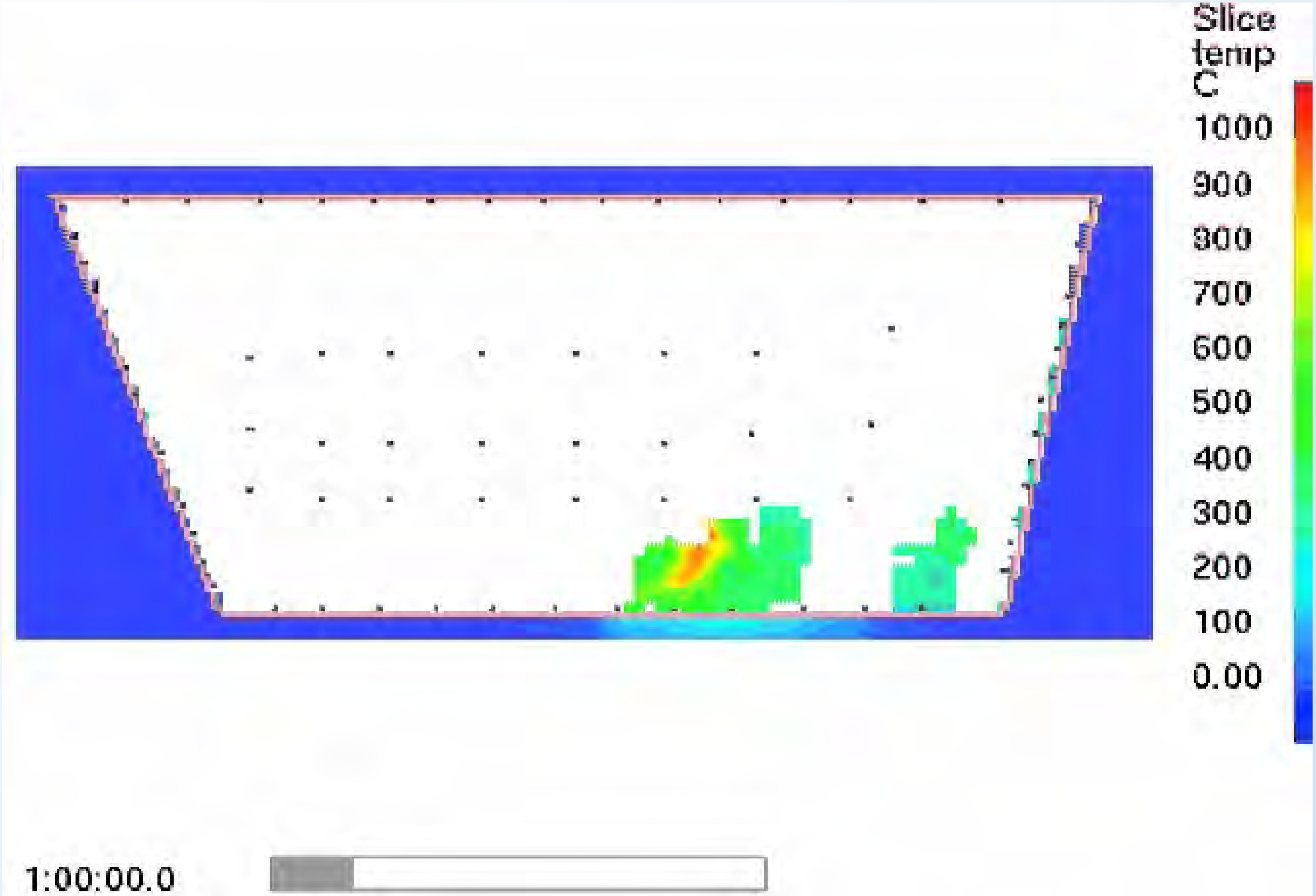
Fire Growth and Spread



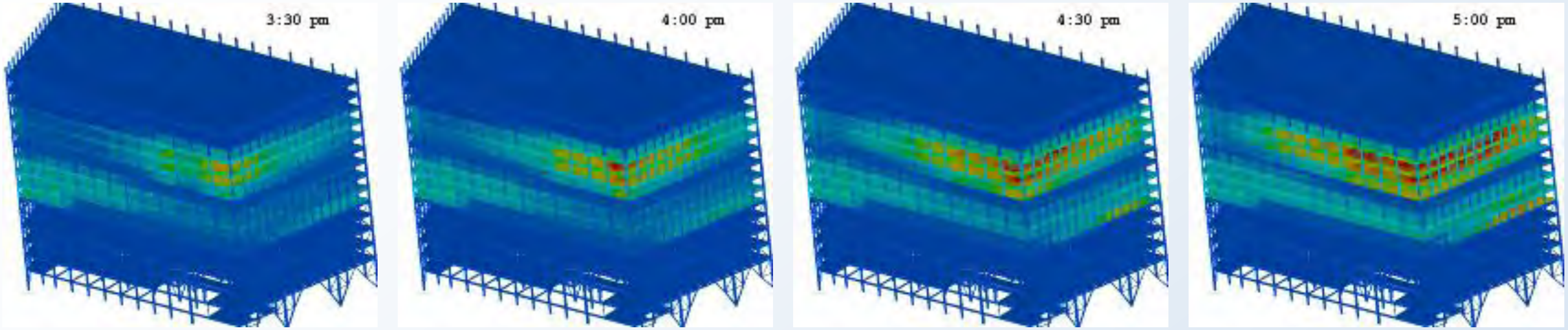
Progression of fires on Floor 12

- **The major fires in WTC 7 were modeled using the Fire Dynamics Simulator (FDS).**
- **There were far fewer photographs and videos of WTC 7 than of the towers.**
- **The fire simulations for WTC 7 were conducted for each floor individually.**
- **Sustained and/or late fires were observed only on Floors 7 through 9 and 11 through 13.**
- **The actual fires on these floors were most likely initiated at the time of the collapsing towers.**

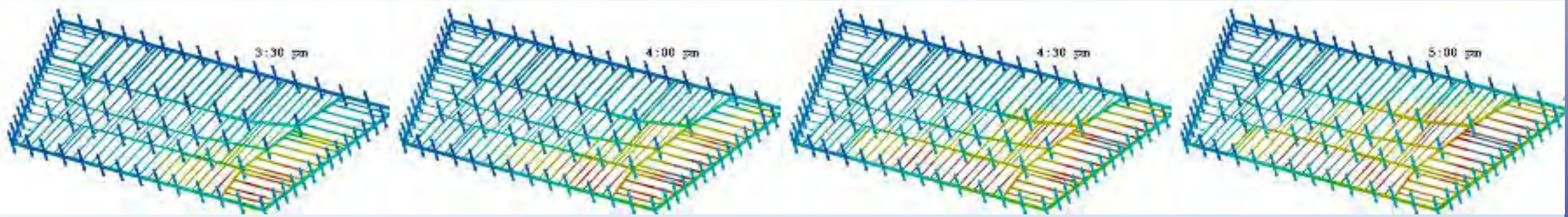
FDS Simulation of Fires on Floor 12



Thermal Response to Fire

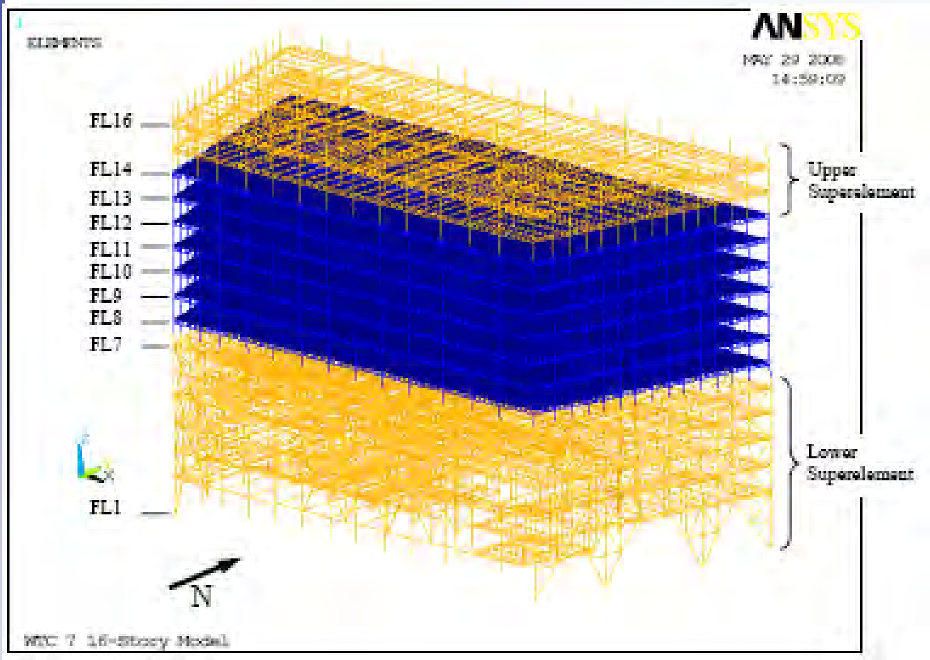


3:30 p.m. 4:00 p.m. 4:30 p.m. 5:00 p.m.



Temperature distribution (ºC) on the floor beams of Floor 13.

ANSYS Structural Response Model

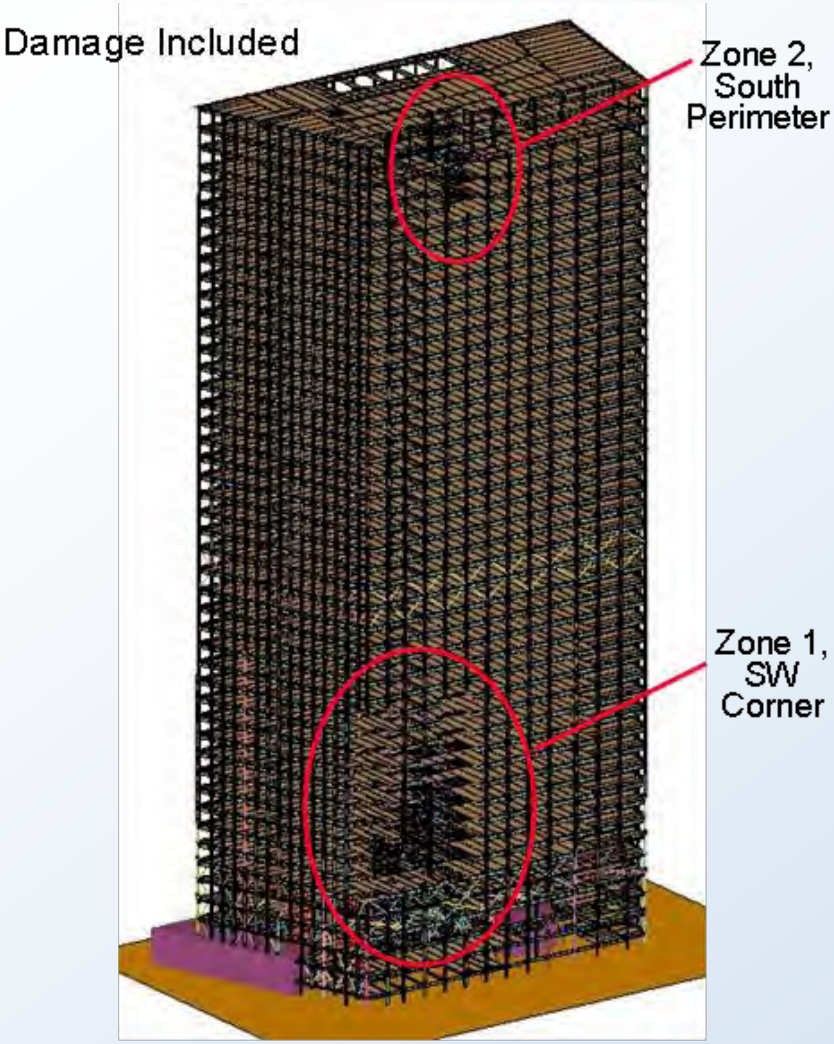


- Floor framing between Floors 8 and 14 and columns between Floors 7 and 14 were explicitly modeled while Floor 7 and below and Floors 15 and 16 were modeled using superelements.

- The 16-story ANSYS model was used to determine the sequence of events that led to fire-induced collapse initiation.
- Software: double precision version of ANSYS 11.0
- Model
  - 93,413 Nodes
  - 101,357 Elements
- Computer
  - 64-bit workstation
  - quad-core, 3.0 GHz processor
  - 64 GB of random access memory (RAM)
- Analysis Time
  - approximately 6 months

NIST

LS-DYNA Structural Response Model



- The LS-DYNA model was used to determine the sequence of events that led to global collapse.
- Software: double precision version of LS-DYNA
- Model
  - 3,593,049 Nodes
  - 3,045,925 Elements
- Computer
  - High speed Linux computer cluster.
  - 1.5 terabytes of RAID 5 disk storage
  - 64-bit 2.6 GHz processors, with 8 GB to 16 GB of RAM
- Analysis Time
  - Up to 8 weeks

Summary of Probable Collapse Sequence (1)

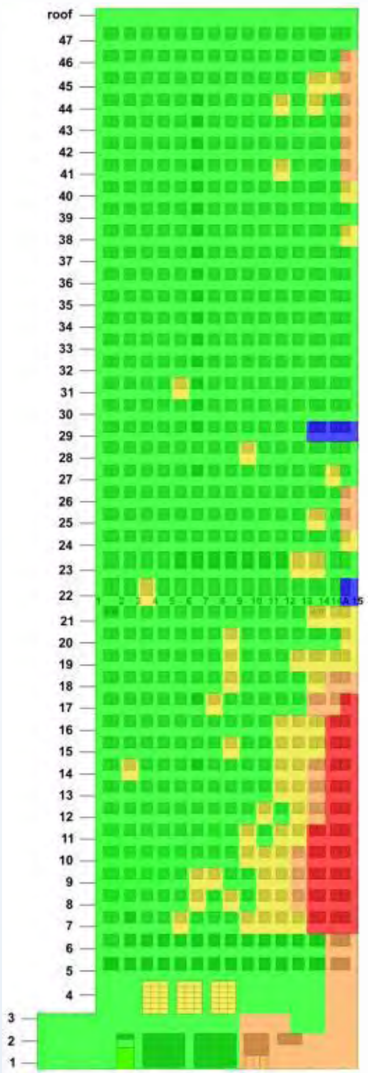
- **Collapse of the WTC Towers.**
  - Collapse of WTC 2 did not cause any structural damage or start any fires in WTC 7.
  - Collapse of WTC 1 damaged seven exterior columns on the lower floors of the south and west faces and initiated fires on 10 floors between Floors 7 and 30.

Aerial photograph shot 14 s ± 0.5 s after WTC 1 began to collapse.

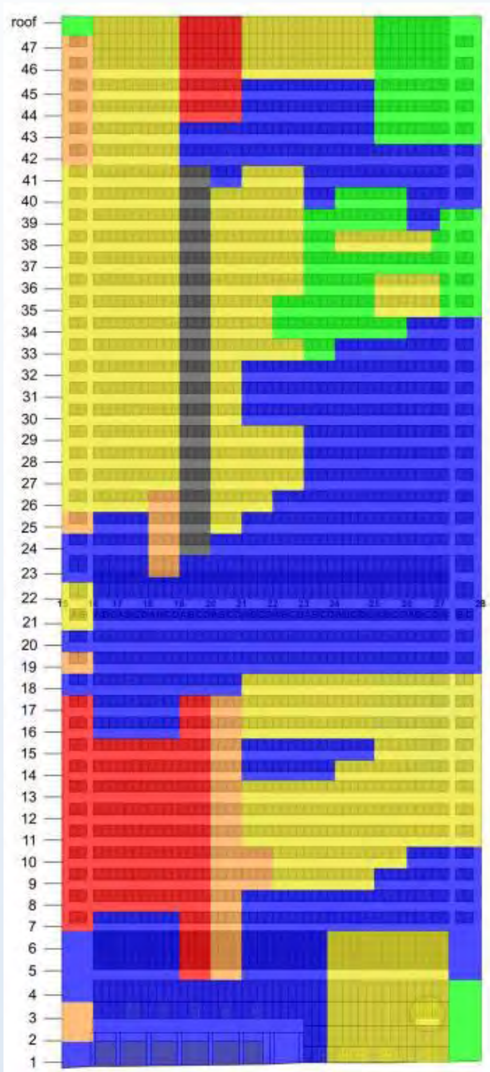
Debris Impact Damage to WTC 7

- **Enlargement of a photograph showing part of the west face of WTC 7.**
- **Arrows and floor numbers have been added for the corresponding rows of windows.**

Observed Debris Impact Damage to WTC 7



West Face



South Face

green ( )- no visible damage

yellow ( ) – window glass broken

orange ( ) – granite and underlying truss damage

red ( ) – damage to *exterior* structural steel

gray ( ) – vertical dark band

blue ( ) – not visible due to smoke, dust, and intervening buildings.

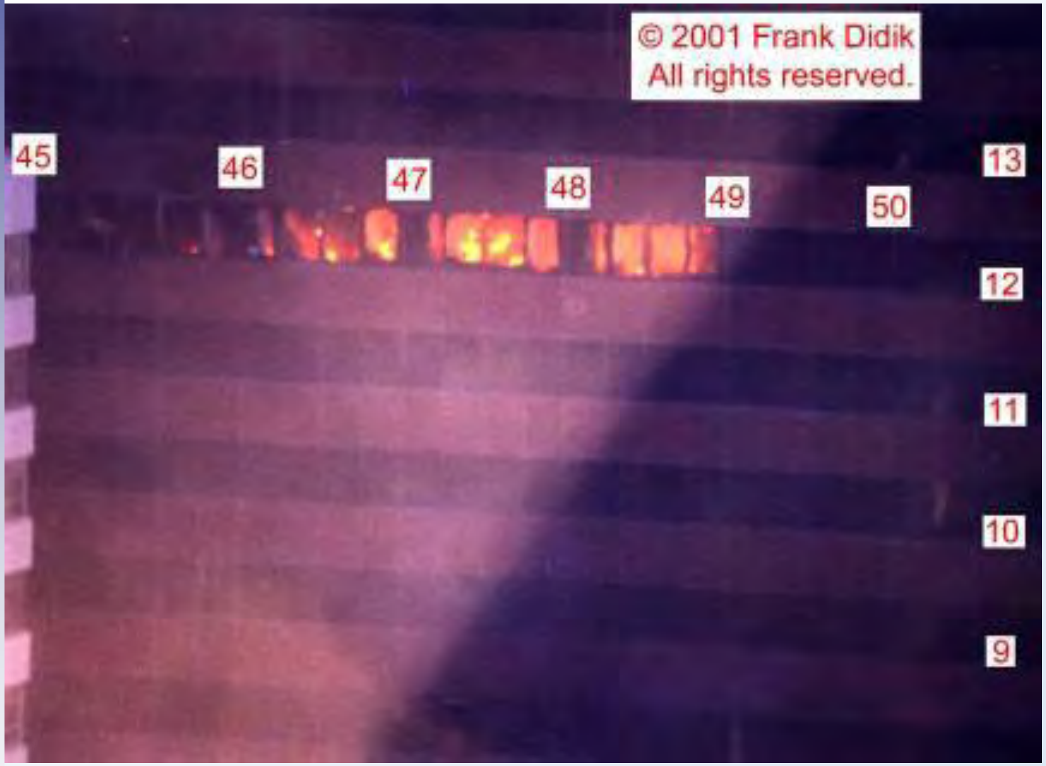
Summary of Probable Collapse Sequence (2)

- Photo showing north and east faces.
- Likely taken between 3:20 - 3:40 p.m.

- **Growth and Spread of Fires.**
  - Fires on Floors 7 to 9 and 11 to 13 grew and spread since they were not extinguished either by the automatic sprinkler system or by FDNY because water was not available.
  - Fires were generally concentrated on the east and north sides beginning at about 3 p.m. to 4 p.m.
  - The local fires on Floors 19, 22, 29, and 30 were not observed after ~ 1 p.m.

NIST

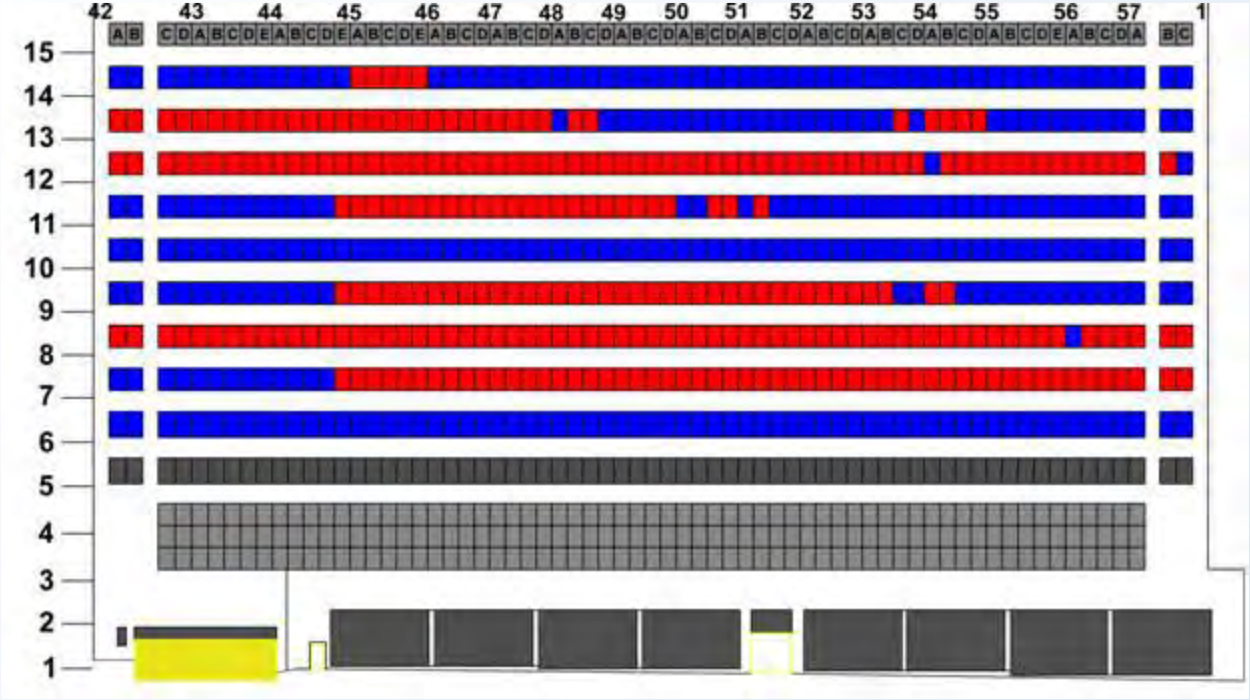
Observed Fires



- Cropped photograph of north face taken between 3:11:15 p.m. and 3:16:51 p.m.
- Cropped photograph showing part of north face at 4:39 p.m. ± 120 s.

NIST

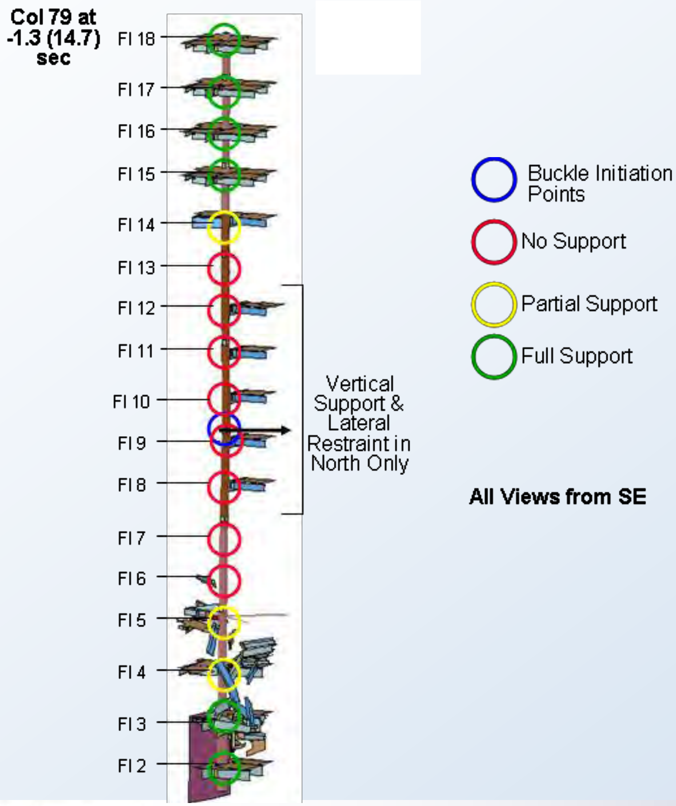
Summary of Fires on North Façade of WTC 7

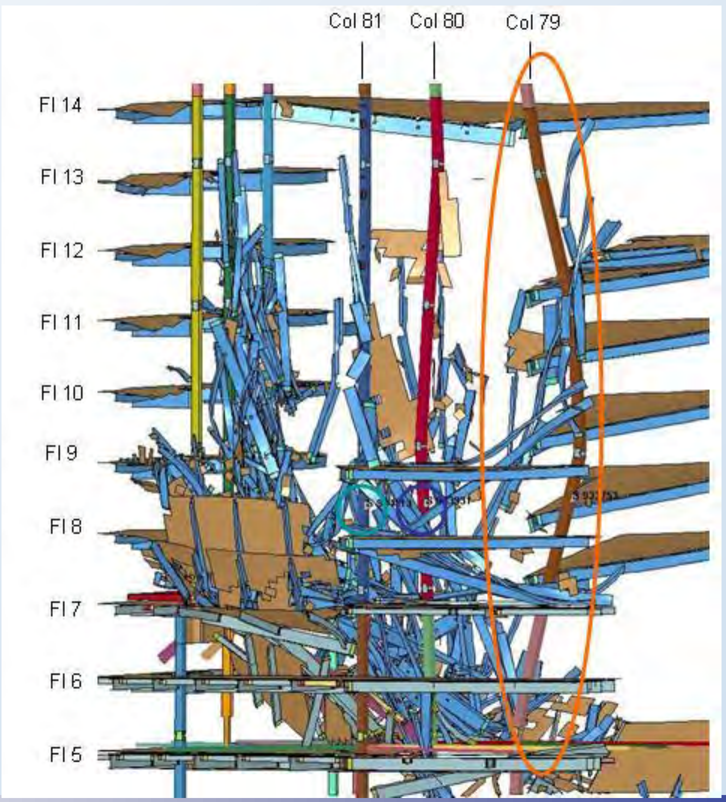


- **Façade map showing where windows were broken and/or fire was observed during the period when fire first appeared shortly before 3:00 p.m. until the building collapsed at 5:20:52 p.m.**
- **Red represents windows where the glass was broken out and/or fire was observed through the window. Blue indicates that no direct evidence was observed for fires at these locations.**

Summary Probable Collapse Sequence (3)

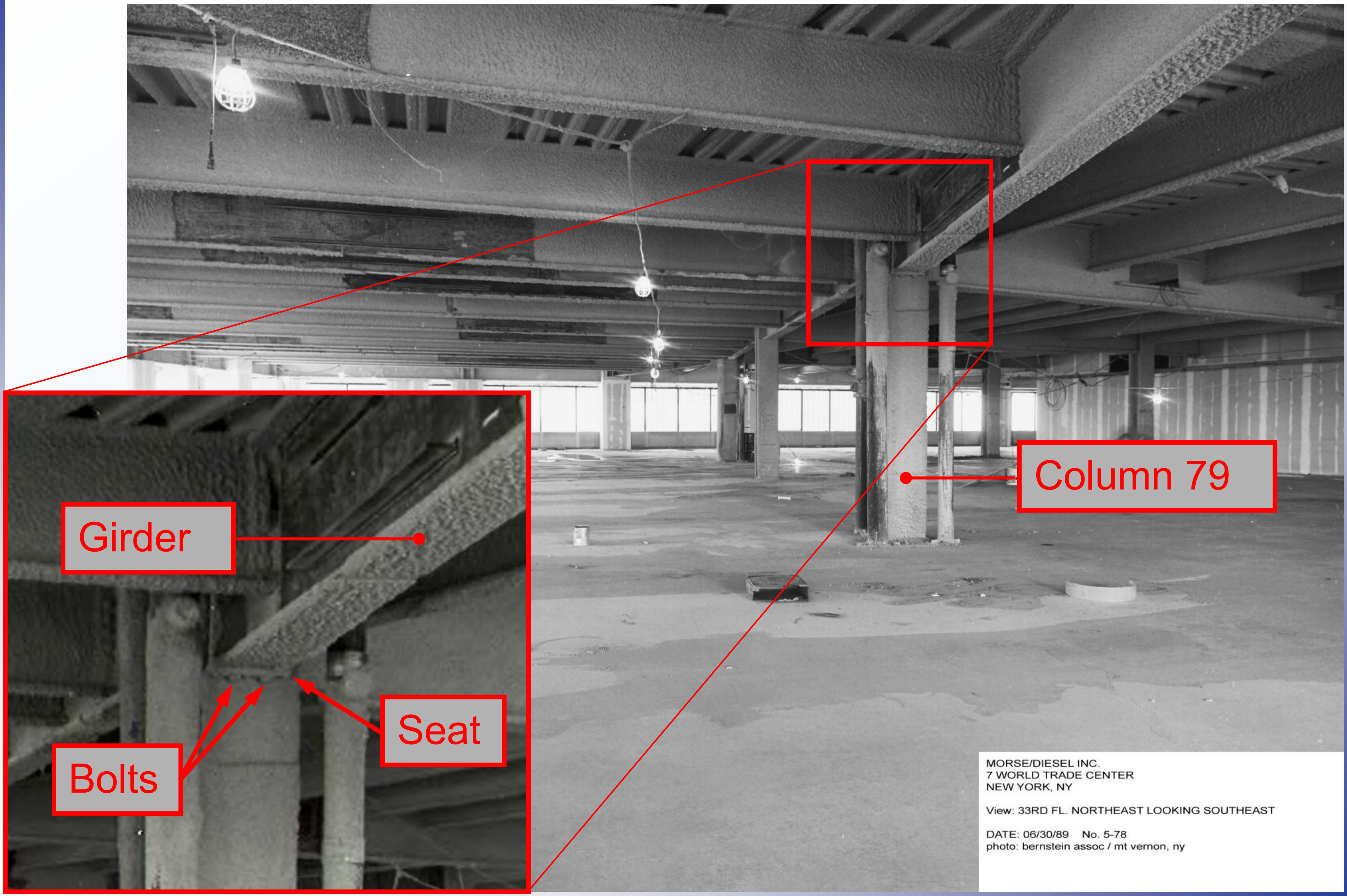
- **Initial Local Failure for Collapse Initiation.**
  - Fire-induced thermal expansion of the floor system surrounding Column 79 led to the collapse of Floor 13 and triggered a cascade of floor failures.
  - This, in turn, led to loss of lateral support to Column 79 over nine stories, resulting in the buckling failure of Column 79.



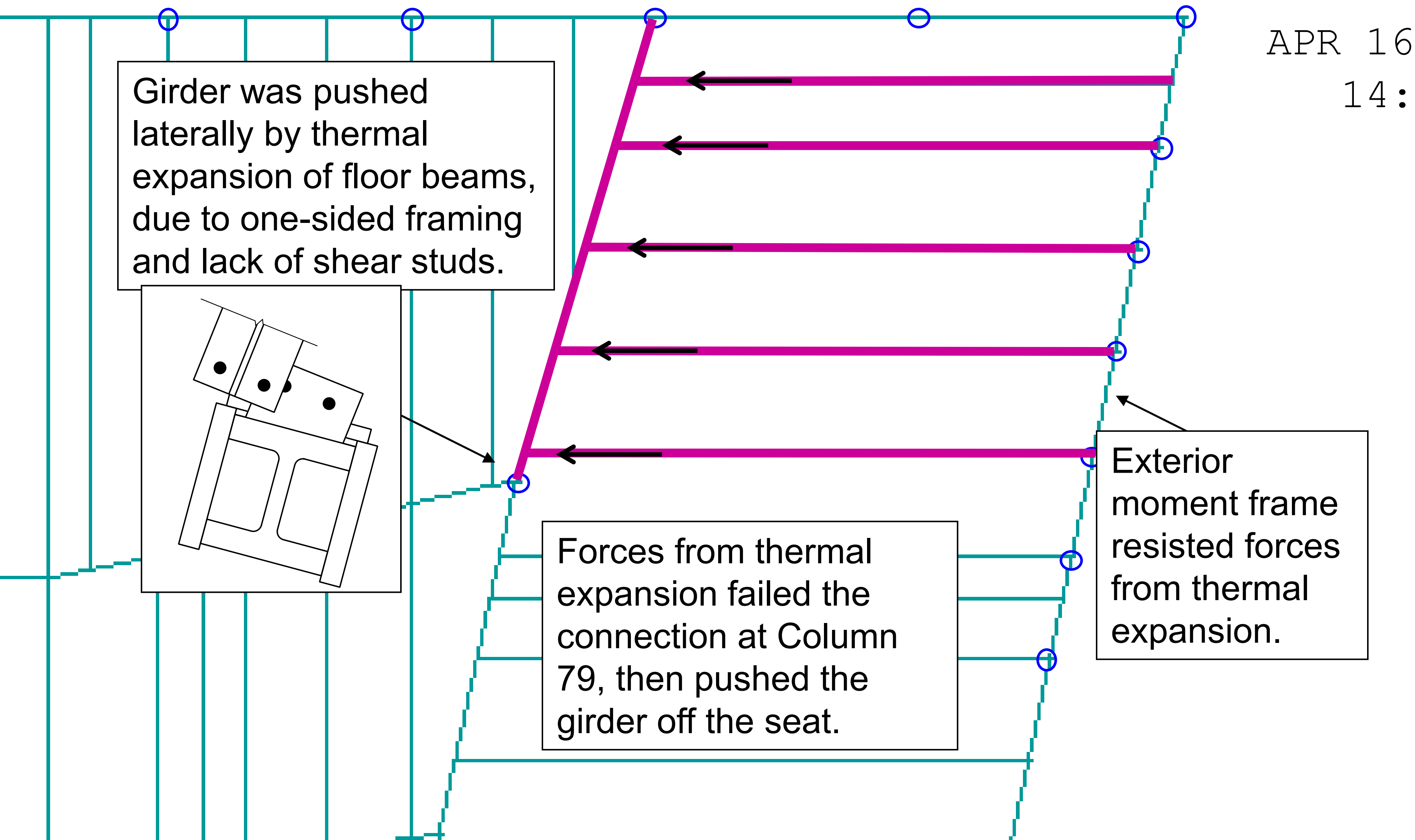


All Views from SE

North East Floor System Near Column 79



NIST

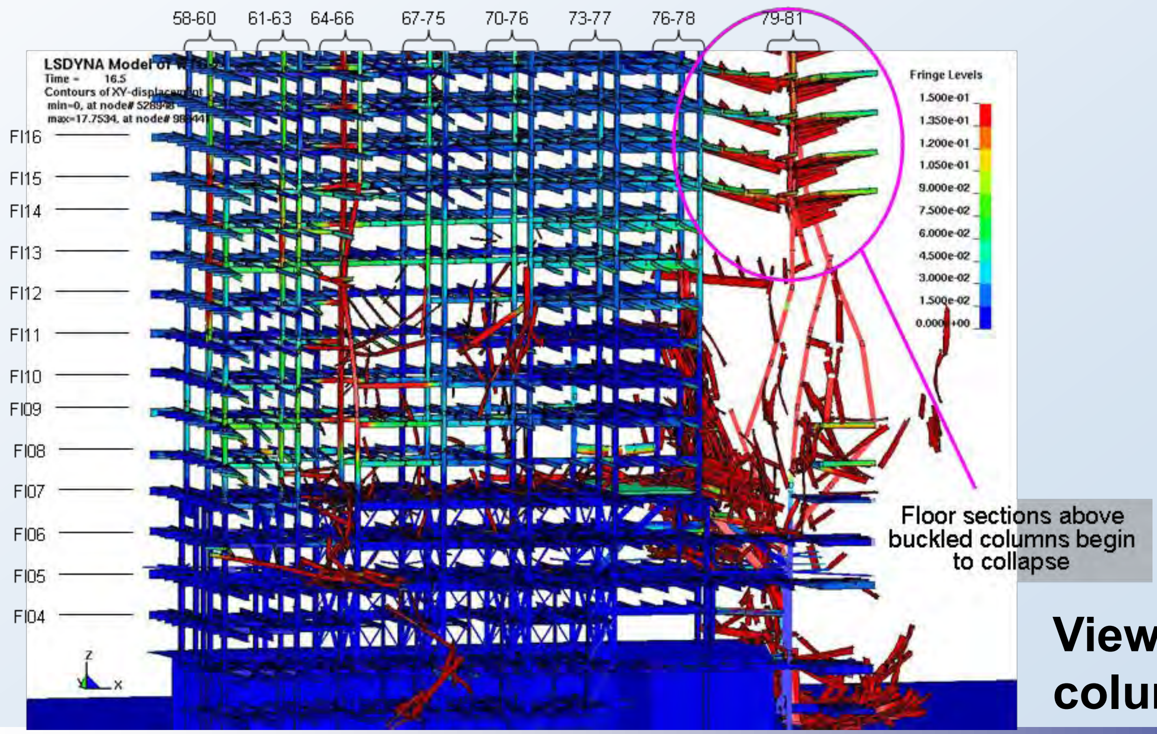

APR 16
14:
Girder was pushed laterally by thermal expansion of floor beams, due to one-sided framing and lack of shear studs.
Forces from thermal expansion failed the connection at Column 79, then pushed the girder off the seat.
Exterior moment frame resisted forces from thermal expansion.

Physics-Based Visualization of WTC 7 Collapse Initiation

View from South

Summary Probable Collapse Sequence (4)

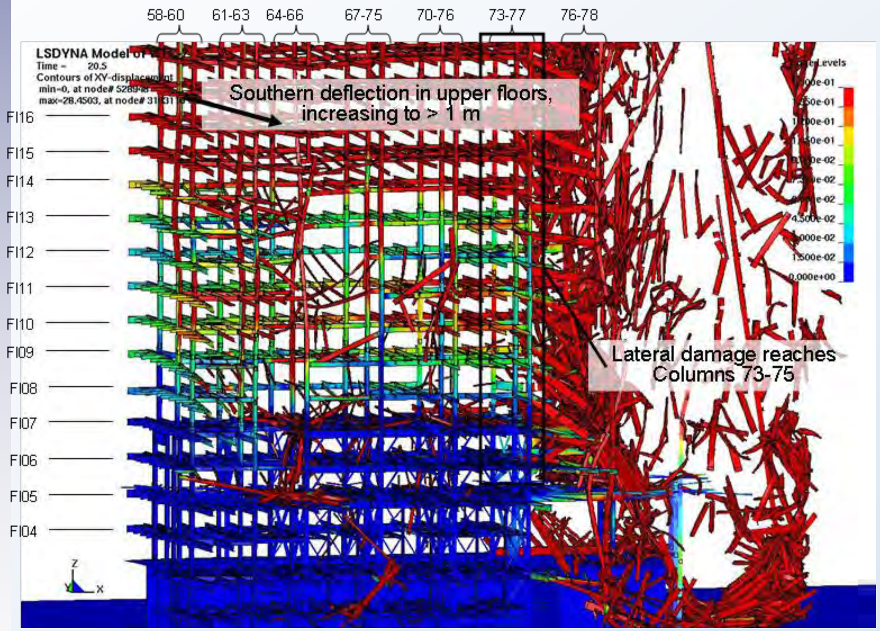
- **<u>Vertical Progression of Failure.</u>**
  - Buckling of Column 79 triggered a vertical progression of floor system failures to the east penthouse, and subsequent cascading failure of Columns 80 and 81 on the east side of the building, that spread to include the entire east region all the way to the top of the building.



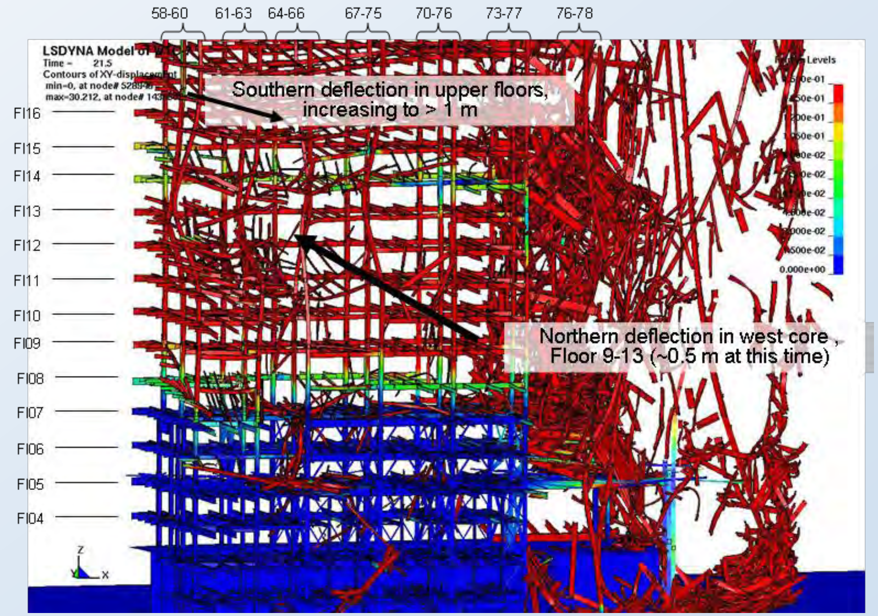
View of interior columns

Summary of Probable Collapse Sequence (5)

- **<u>Horizontal Progression of Failure.</u>**
  - Interior columns buckled from east to west in the lower floors due to (1) loss of lateral support from floor system failures, (2) forces exerted by falling debris, and (3) load redistributed from other buckled columns.



Buckling of third line of interior columns at 4.5 s following collapse initiation.



Buckling of all interior columns at 6.5 s following collapse initiation.

Summary Probable Collapse Sequence (6)

- **Global Collapse.**
  - The exterior columns buckled between Floors 7 and 14 due to load redistribution to these columns as the building core moved downward.
  - The entire building above the buckled-column region then moved downward in a single unit, as observed.

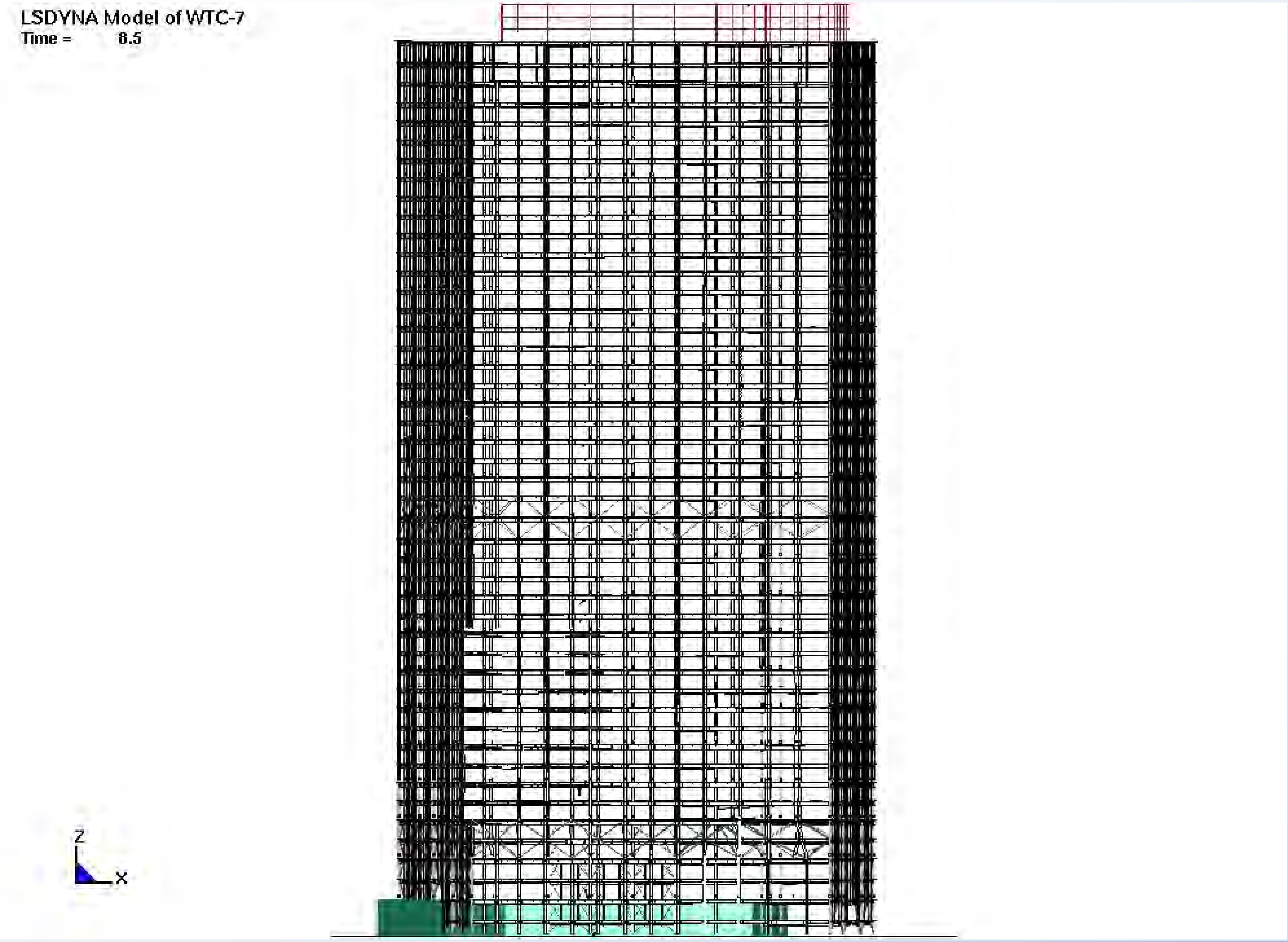
Buckling of lower exterior columns.

Video Evidence of WTC 7 Collapse

Physics-Based Visualization of WTC 7 Collapse

View from North-west

Physics-Based Visualization of WTC 7 Collapse

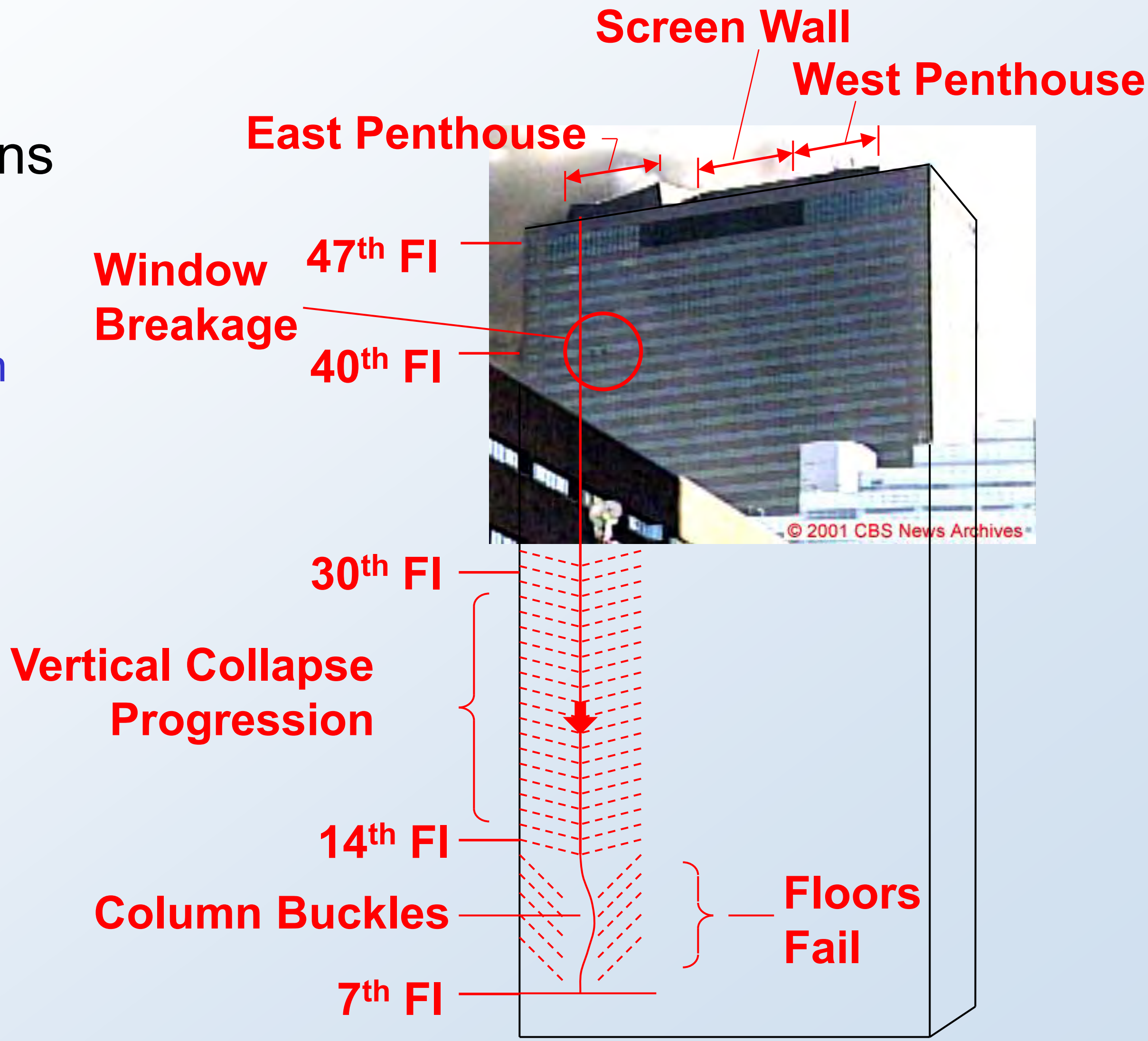


View from South

Collapse Initiation Observations

Exterior Observations

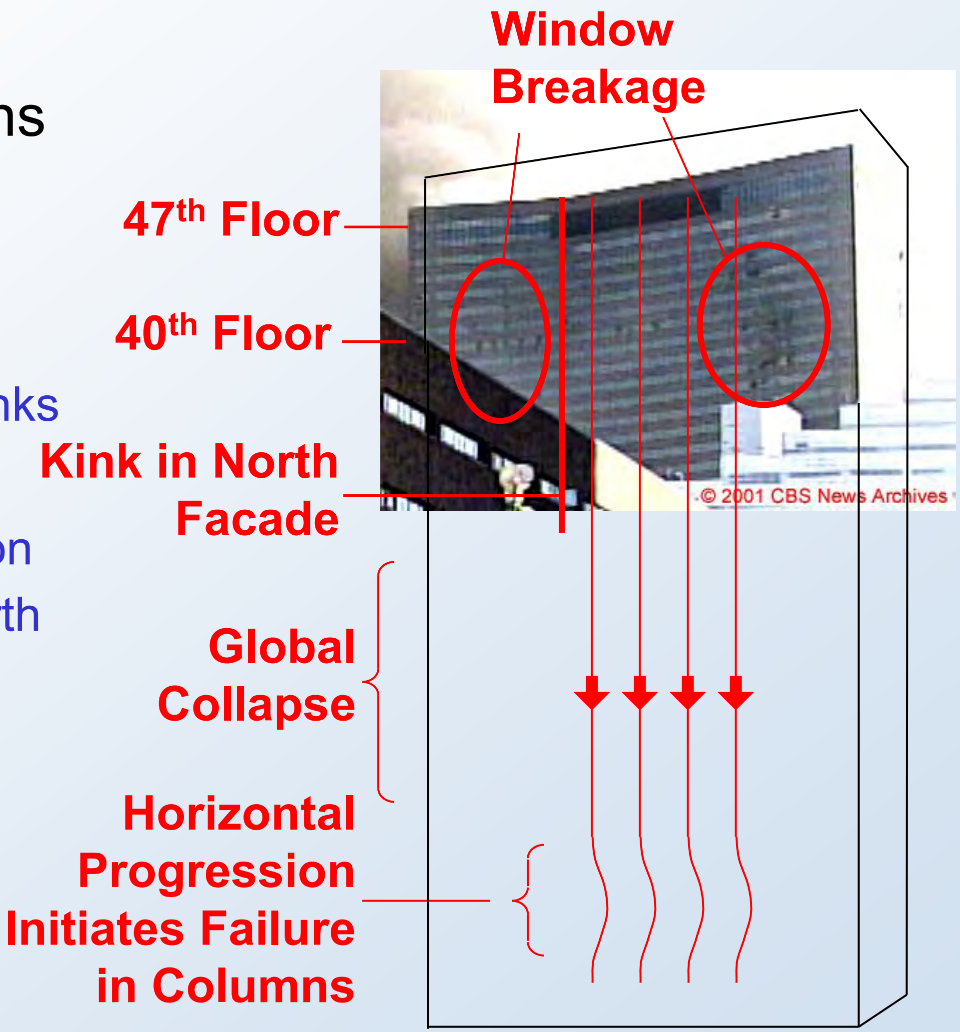
- East Penthouse Kinks
- Windows break on East Side of North Face



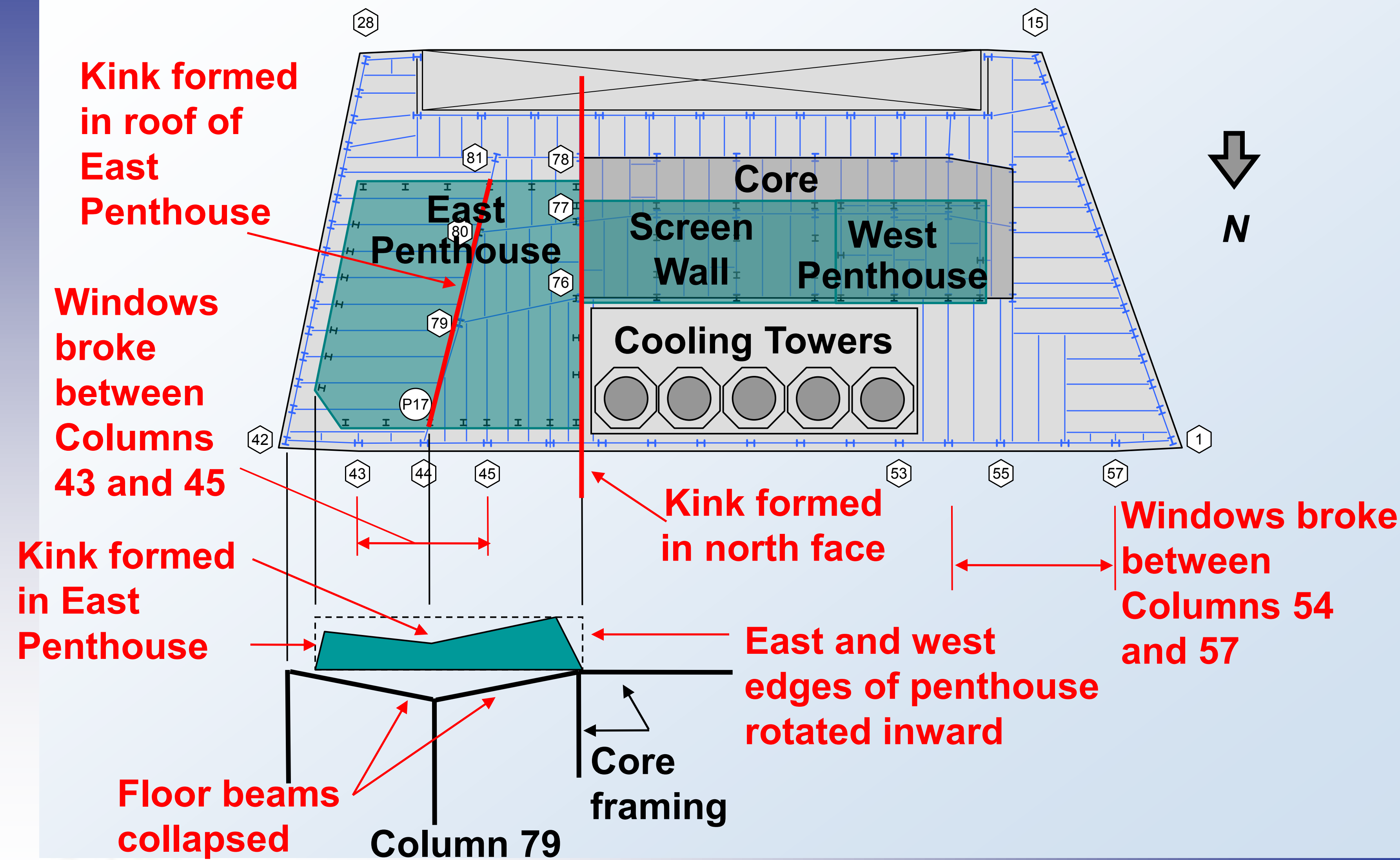
Global Collapse Observations

Exterior Observations

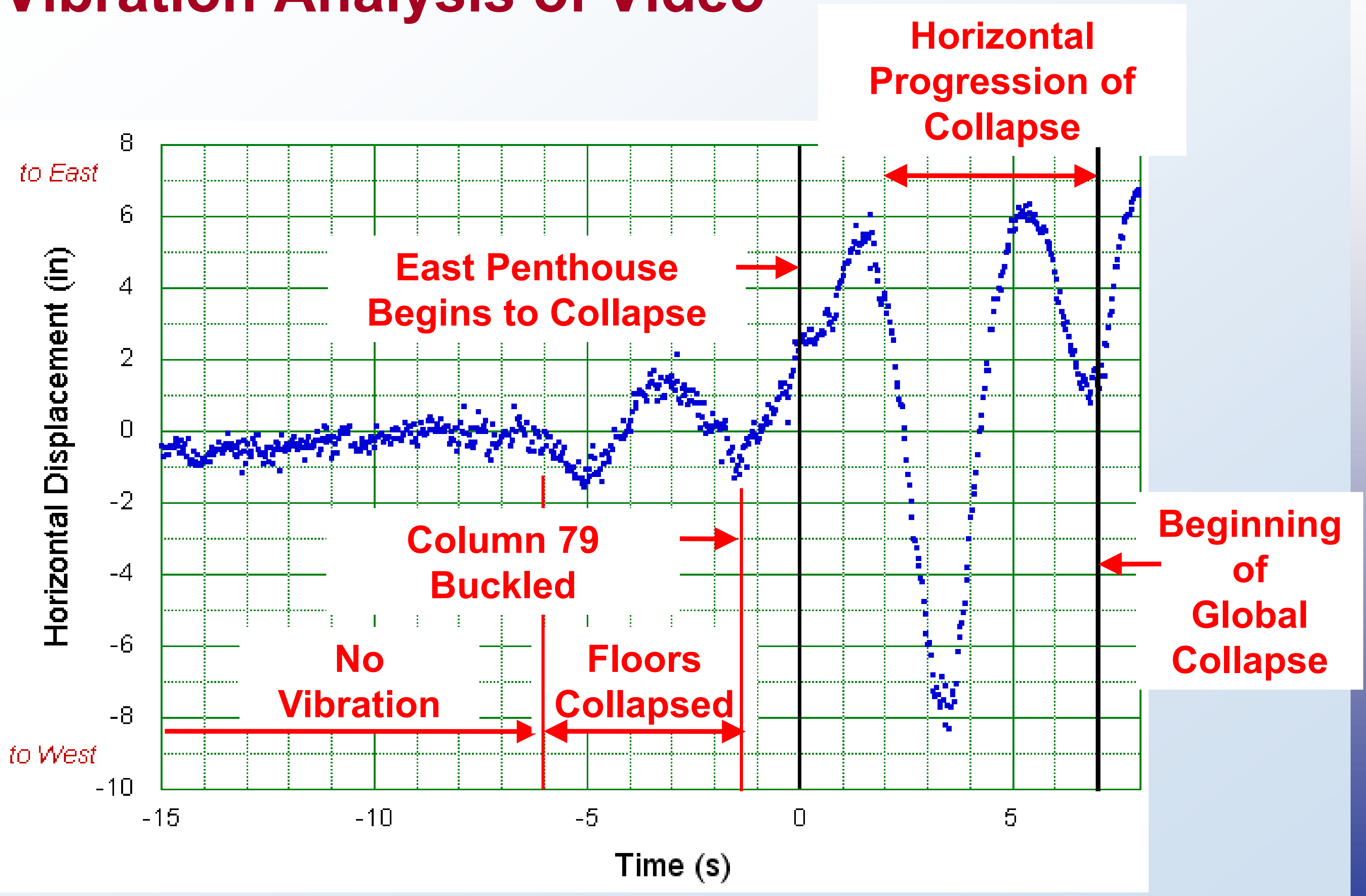
- Screenwall and West Penthouse Sink
- North Façade Kinks at Edge of Core
- Windows break on West Side of North Face



Collapse Observations



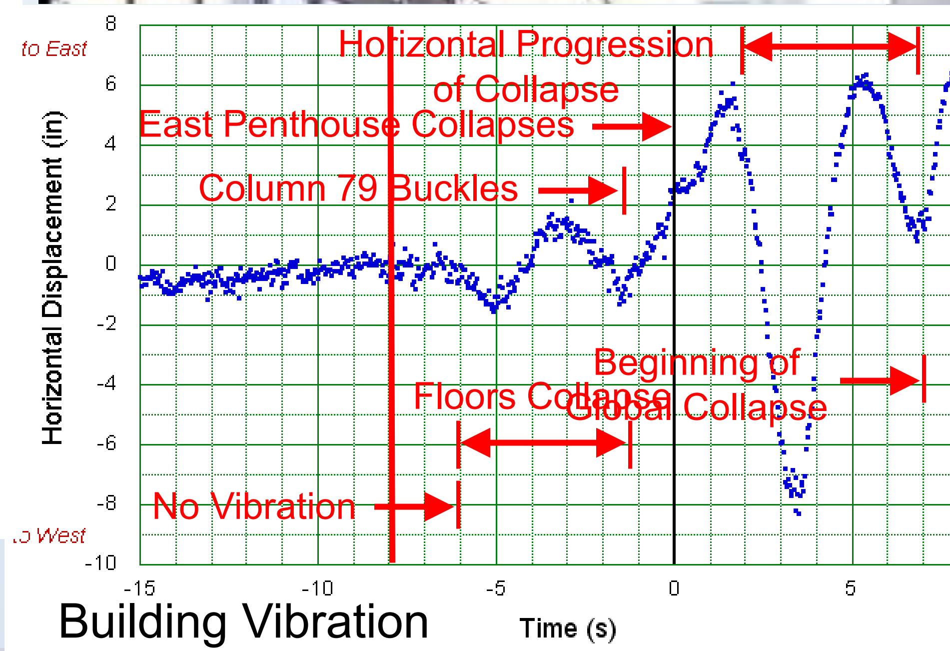
Vibration Analysis of Video



Comparison of Visualization and Video

LS-Dyna Visualization

Clock



Building Vibration

Accuracy of the Probable Collapse Sequence

Event	Observation Time (s)	Analysis w/Debris Damage (s)	Analysis w/o Debris Damage (s)
Cascading failure of floors surrounding Column 79	≈ -6 s	-6.6 s	-6.6 s
Buckling of Column 79, followed by Columns 80 and 81	Not observable	-1.3	-1.4
East penthouse starts to fall	**0.0**	**0.0**	**0.0**
East penthouse falls below roofline	2.0	2.4, 2.7	2.3, 2.6
Buckling of columns across core	Not observable	3.5-6.1	3.2-13.5
Initial downward motion of the north face roofline	6.9	6.3	9.8
East end of the screenwall falls below the roofline	8.5	7.3, 7.7	8.7, 9.2
West penthouse falls below the roofline	9.3	6.9, 7.3	10.6, 10.9

Agreement between observations and simulations is good; results with debris damage better match observations of overall global collapse sequence.

NIST

WTC 7 Collapse Visualization w/o Damage

View from Northwest

Outline

- Investigation Objectives
- WTC 7 Building Design
- Probable Collapse Sequence
- **Other Possible Hypotheses**
- Principal Findings
- Factors that Could Have Changed The Outcome
- Recommendations

Other Possible Hypotheses: Role of Fuel Fires

- **Hypothetical diesel fuel fires on the 7th, 8th, and 9th floors did not contribute to the collapse of WTC7.**
  - The generators on the 8th and 9th floors were supplied by two 12,000 gallon tanks.
  - Nearly all the fuel in these tanks was recovered after the building collapse.
  - At most, 1000 gal of fuel was unaccounted from these tanks, which was equivalent to about 5 percent of the office combustibles on a single floor.
  - The day tanks did not contain enough fuel to be a significant contributor.
- **The 5th Floor was the only floor with a pressurized fuel line supplying nine of the emergency power generators on that floor.** Two 6,000 gallon underground tanks supplied these 9 generators, which were always kept full for emergencies, and were full on September 11, 2001.
- **Both 6,000 gallon tanks were found to be damaged and empty in the rubble pile several months after the collapse.** This fuel might have contributed to a fire on Floor 5, a possibility that could not be distinguished from the fuel being consumed or dissipated in the burning rubble fire subsequent to the collapse of WTC 7.

Role of Fuel Fires (2)

- **NIST analyzed potentially severe pool fires that might have resulted from ignition of spillage of the diesel fuel present on the 5^{th} floor or that might have been pumped to that floor:**
  - Two types of over-ventilated fires in the vicinity of Column 79.
  - Two types of under-ventilated fires in the vicinity of Column 79:
  - An additional simulation of an over-ventilated fire near the breach in the south wall.
- **Hypothetical pool fires on the 5^{th} and 6^{th} floors did not contribute to the collapse of WTC 7.**
  - These worst-case scenarios could not be sustained long enough, or could not have generated sufficient heat, to heat a critical column (i.e., Column 79) to the point of significant loss of strength or stiffness; or
  - Such fires would have produced large amounts of smoke from the exhaust louvers; no such smoke discharge was observed; or
  - The gas temperatures would have exceeded the boiling point of the coolant for all 9 diesel generators in < 3 h, leading to engine failure.

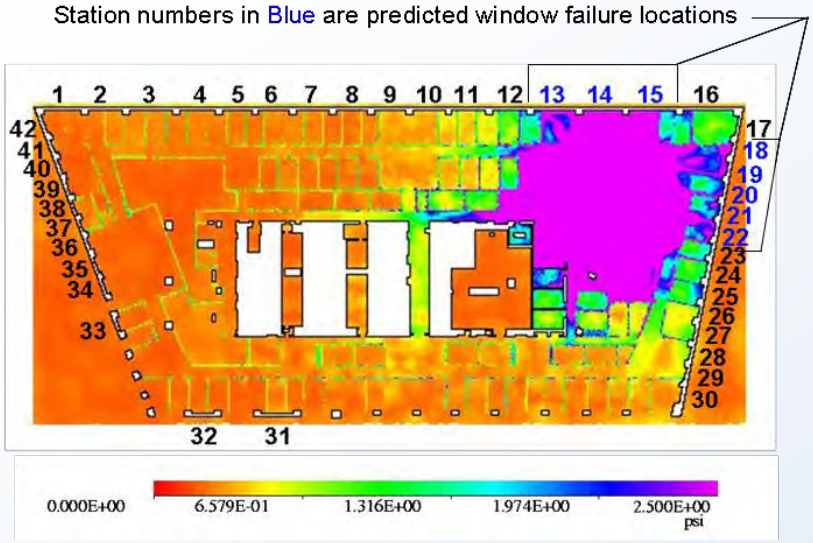
Role of Fuel Oil Fires (3)

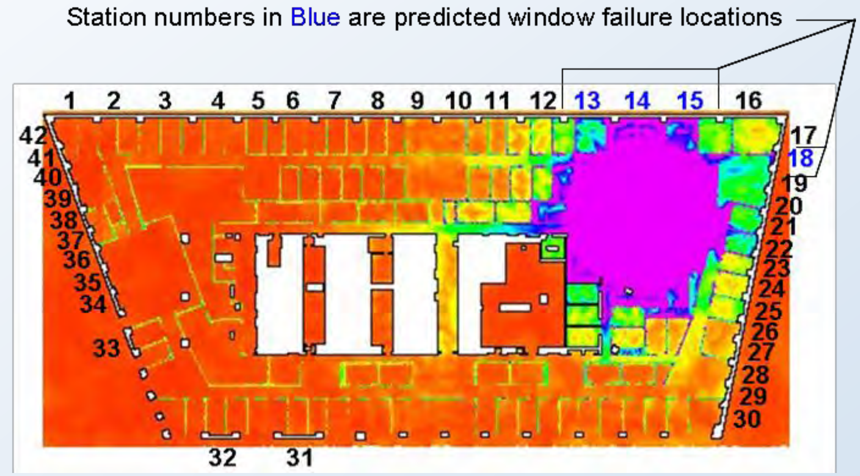
- **The day tank on Floor 5 supplying two emergency generators on that floor did not contain enough fuel for a fire that could threaten Column 79.**
  - The contained fuel was only equivalent to a few percent of the combustible furnishings on a tenant floor.
  - It is unlikely that the tanks would have been re-supplied because of multiple safeguards in the fuel delivery system.
  - None of the day tanks were located near Column 79.
- **A diesel fuel spray fire on Floor 5 would have been less damaging than a pool fire.**
  - A spray fire would have resulted from a small leak in the fuel supply piping, so the fuel escape rate would have been far less than a pool fire scenarios.
  - Even if the spray had directly hit Column 79, it would have heated only a small area of the steel.
  - Calculations showed that even if the entire column were immersed in a flame as hot as 1400 °C, it would have taken 6 h to heat the column to the point of significant loss of strength or stiffness.

Other Possible Hypotheses: Role of Blast Events

- Scenarios of a hypothetical blast event that could have occurred in WTC 7 on September 11, 2001, were assessed, including blast location, size, and timing.
- **Phase I: Identify hypothetical blast scenarios to initiate structural collapse.**
  - A scenario with the minimum amount of required explosive was identified.
  - The recommended column preparation required at least 30 minutes (cutting and placing).
  - Additional preparation time was required to prepare the column for cutting and placing charges.
- **Phase II: Assess the blast wave propagation inside the building and the corresponding response of the WTC 7 windows.**
  - 2-D SHAMRC blast propagation calculations were performed for the minimum explosive charge of 9 pounds.
  - Calculations were performed for a lesser charge size of 2 pounds to evaluate threshold explosive requirements for breaking windows.
  - Two partition layouts, based on the tenant area layouts, were analyzed.

Role of Hypothetical Blast Events (2)





Peak over pressures for 9 lb shaped charge (left) and 2lb charge (right).

- **Phase III: Assess the approximate distance from the building that the blast would have been audible in an urban setting.**
  - For all four scenarios, windows would have been broken and significant sound levels were predicted from all building faces.
  - The sound level at 1 km (1/2 mile) would have been approximately 130 to140 dB.

Role of Hypothetical Blast Events (3)

- Hypothetical blast events did not cause the collapse of WTC 7. NIST concluded that blast events did not occur and found no evidence of any blast events.
- The minimum explosive charge (lower bound) required to fail a critical column (i.e., Column 79) would have:
  - produced a pressure wave that would have broken windows on the north and east faces of the building near Column 79.
  - resulted in a sound level of 130 to 140 decibels (a sound level consistent with a gunshot blast, standing next to a jet plane engine, and more than 10 times louder than being in front of speakers at a rock concert), at least half a mile away.
  - generated a sound that would be reflected and channeled with minimum attenuation down urban streets with hard building exteriors.
- Although such a blast could be heard a mile away, there were no witness reports of such a loud noise, nor was such a noise heard on audio tracks of video tapes that recorded the WTC 7.

Role of Hypothetical Blast Events (4)

- Prior to preparing a column for demolition, walls and/or column enclosures and SFRM would have to be removed and replaced without being detected.
  - Preparing the column includes cutting sections with torches, careful placement of charges, and an initiation device.
  - A larger charge would be required to fail the column without prior preparation; the resulting sound level and window breakage would be much greater.
  - Demolition usually prepares many interior columns with explosive charges.
  - It is unlikely that such activity could have taken place without being detected.
- Observations for WTC 7 do not match the typical sequence of events for a controlled demolition.
  - Video evidence clearly supports a sequence of failures (initiation, vertical progression, horizontal progression, and global collapse) based on a single point of initiation.
  - The observed collapse sequence is inconsistent with a demolition where charges are placed across the building and detonated in rapid succession.

Role of Con Edison Substation

- **The Con Edison substation played no role in the fires that caused the collapse of WTC 7.**
  - Electronic communications show that the substation continued to operate until it was intentionally shut down at 4:33 p.m.
  - Additionally, there was no evidence of a fire in the Con Edison substation.
- Even though utility power to the rest of WTC 7 was lost at 9:59 a.m., auxiliary utility power to the Con Edison substation from transmission switching station feeders allowed internal operations to be maintained.
- Fire detector signals from the Con Edison substation were monitored off-site throughout the day.
  - One fire detector within the Con Edison substation gave an alarm when WTC 1 collapsed.
  - There were no other indications that a fire occurred within the substation during that period of time.
  - Likely causes of the alarm were smoke and dust from the collapse of WTC 1.

Role of Fire Resistance Ratings (1)

- Based on the BCNYC, a sprinklered high-rise office building (Class 1-C) would have required 1.5 hour fire resistance rating for the floors and an unsprinklered high-rise office building (Class 1-B) would have required a 2 hour fire resistance rating for the floors.
  - **Thus, the floor system should have had at least a 1.5 hour fire rating.**
  - **The floor system in WTC 7 was specified to have a 2 h fire rating in bid documents consistent with the Class 1-B unsprinklered building**.
- The Underwriters Laboratories directory listing for floor beams in composite floors indicates that 0.5 in. of the SFRM product would provide a 2 hour fire resistance rating.
- **A set of SFRM inspection reports indicated that the target thickness of the SFRM on the floor beams was 0.5 inch (for ―2 HR. BEAMS") while the applied thickness had an average value of 0.534 in**.
- **The SFRM thickness applied to the framing of the composite floor system was consistent with a 2 h fire resistance rating.**

NIST

Role of Fire Resistance Ratings (2)

- **Based on thermal calculations, it is unlikely that the collapse of WTC 7 would have been prevented had the insulation thickness on the floor beams been increased by 50 percent (from 0.5 in. to 0.75 in.).** NIST calculations indicated that the time to reach the steel temperature of 649 ^{o}C would have increased by about 10 to 20 min.

- **The ASTM E119 test does not capture critical behavior of structural systems, e.g., effect of thermal expansion or sagging of floor beams on girders, connections, and/or columns.**
  - **The thermal expansion of the WTC 7 floor beams that initiated the probable collapse sequence occurred at temperatures below approximately 400 ^{o}C.**
  - **Thus, to the extent that thermal expansion, rather than loss of structural strength, precipitates an unsafe condition, the current fire resistance rating system is not conservative.**

Outline

- Investigation Objectives
- WTC 7 Building Design
- Probable Collapse Sequence
- Other Possible Hypotheses
- **Principal Findings**
- Factors that Could Have Changed The Outcome
- Recommendations

Principal Findings for Objective 1: Probable Collapse Sequence

- WTC 7 withstood debris impact damage that severed seven exterior columns and subsequent conventional fires on several floors for almost seven hours.
- The collapse of WTC 7 represents the first known instance of the total collapse of a tall building primarily due to fires.
- **WTC 7 collapsed due to uncontrolled fires with characteristics similar to previous fires in tall buildings.**
  - The fires in WTC 7 were similar to those that have occurred previously in several tall buildings (One New York Plaza, 1970, First Interstate Bank, 1988, and One Meridian Plaza, 1991) where the automatic sprinklers did not function or were not present.
  - These three buildings, however, did not collapse because of differences between their structural designs and that of WTC 7.
  - Had a water supply for the automatic sprinkler system been available and had the sprinkler system operated as designed, it is likely that fires in WTC 7 would have been controlled and the collapse prevented.

Principal Findings for Objective 1: Probable Collapse Sequence (2)

- **Observations support a single point of fire ignition on any given floor.**
  - In most instances, the fire on any given floor likely initiated near the damaged southwest region.
  - Unlike the WTC towers, there was no dispersion of jet fuel in WTC 7 causing simultaneous fire initiation over extensive areas of multiple floors.
- **The probable collapse sequence was initiated by the buckling of Column 79, which was unsupported over nine stories, after local fire-induced damage led to a cascade of floor failures.**
  - The buckling of Column 79 led to a vertical progression of floor failures up to the east penthouse and to the buckling of Columns 80 and 81.
  - An east-to-west horizontal progression of interior column buckling followed.
  - The exterior columns then buckled as the failed building core moved downward, redistributing its loads to the exterior columns.
  - Global collapse occurred as the entire building above the buckled region moved downward as a single unit.

Principal Findings for Objective 1: Probable Collapse Sequence (3)

- **The collapse of WTC 7 was a progressive collapse.**
  - Progressive collapse—also known as disproportionate collapse—is defined as the spread of local damage, from an initiating event, from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it (ASCE 7-05).
  - Despite extensive thermal weakening of connections and buckled floor beams, **fire-induced damage in the floor framing surrounding Column 79 over multiple stories was the determining factor causing the buckling of Column 79 and, thereby, initiating progressive collapse.**
  - This is the **first known instance where fire-induced local damage** (i.e., buckling failure of Column 79; one of 82 columns in WTC 7) **led to the collapse of an entire tall building.**
- **The transfer elements (trusses, girders, and cantilever overhangs) did not play a significant role in the collapse of WTC 7. Likewise, the Con Edison substation did not play a significant role in the collapse of WTC 7.**

Principal Findings for Objective 1: Probable Collapse Sequence (3)

- Prior to the collapse, there was no damage to the SFRM that was applied to the steel columns, girders, and beams, except in the vicinity of the structural damage from the collapse of WTC 1.
- **Even without the initial structural damage caused by debris impact from the collapse of WTC 1, WTC 7 would have collapsed from fires having the same characteristics as those experienced on September 11, 2001.**
- Early stage fires in the southwest region did not play a role in the collapse of WTC 7. Unlike the northeast region where collapse initiated:
  - there were no columns supporting long span floors in the southwest region.
  - the fires in this region were not severe enough since they had not fully developed and there were few combustibles in the adjacent core area.
- **Collapse time of the north face of the upper 18 floors (the floors clearly visible in video evidence) was 40 percent greater than the computed free fall time.**
  - The actual time for the north face to fall 18 floors was ~ 5.4 s
  - The computed time for free fall (i.e., with no air friction) was 3.9 s.

NIST

Principal Findings for Objective 1: Probable Collapse Sequence (4)

- **Diesel fuel fires did not play a role in the collapse of WTC 7.** The worst-case scenarios for fires being fed by ruptured fuel lines or day tanks:
  - could not have been sustained long enough, or generated sufficient heat, to cause significant loss of strength/stiffness in a critical column
  - would have produced large amounts of smoke from the exhaust louvers. No such smoke discharge was observed.
- **Hypothetical blast events did not play a role in the collapse of WTC 7.**
  - Based on visual and audio evidence and computer modeling, NIST concluded that blast events did not occur, and found no evidence of a blast.
  - Blast from the smallest charge capable of failing a critical column would have resulted in a sound level of 130 dB to 140 dB at approximately half a mile.
  - This sound level is consistent with a gunshot blast, standing next to a jet engine, and 10 times louder than being in front of speakers at a rock concert.
  - There were no witness reports of such a loud noise, nor was such a noise heard on the audio tracks of video recordings of the WTC 7 collapse.

Principal Findings for Objective 2: Evacuation and Emergency Response

- **There were no serious injuries or fatalities because the estimated 4,000 occupants of WTC 7 reacted to the airplane impacts on the WTC towers and began evacuating before there was significant damage to WTC 7.**
  - **Evacuation drills that had been conducted every six months likely contributed to the speed and overall success of the evacuation.**
- Building evacuation took just over an hour, about 30 min longer than the estimated minimum time for the elevators and stairs.
  - Occupants were able to use both elevators and stairs.
  - Some of the evacuation time was due to crowding in the lobby.
  - Occupants arrived in the lobby from both stairwells, elevators, and other WTC buildings, and were held in the lobby until a safe exit was identified.
- The decision not to continue evaluating and fighting the fires was made hours before the building collapsed, so **no emergency responders were in or near the building when the collapse occurred.**
- **Evacuation management at every level did not provide timely evacuation instructions to building occupants during the event.**

Principal Findings for Objective 3: Procedures and Practices

- WTC 7 was designed and constructed as a “Tenant alteration project” of The Port Authority. Its design and construction followed the requirements of the 1984 edition of the Tenant Construction Review Manual.
- Although the PANYNJ was not subject to the NYCBC, the 1968 NYCBC, including amendments to January 1, 1985, appears to have been used for the design and construction provisions of WTC 7, based on citations in the construction documents.
- **The type of building classification used to design and construct the building was not clear from the available documents.**
  - Based on the height, area, primary occupancy classification, and installation of a fire sprinkler and standpipe system, the minimum construction type (permitted by NYCBC) was type 1-C (2 h protected) classification.
  - Some documentation, including some building drawings and specifications for bidders, indicate a type 1-B (3 h protected) classification.
- **The design of WTC 7 was generally consistent with the NYCBC.**

Principal Findings for Objective 3: Procedures and Practices

- **Consistent with the NYCBC, there was no redundancy in the source of water supply for the sprinkler system in the lower 20 floors of WTC 7. Since there was no gravity-fed overhead tank supplying these floors, the sprinkler system could not function when the only source of water, which was from the street mains, was not available.**
- **Current practice for the fire resistance design of structures, based on the use of ASTM E 119 standard test method, is deficient since the method was not designed to include key fire effects that are critical to structural safety. Specifically, current practice does not capture:**
  - ***thermally-induced interactions between structural subsystems, elements, and connections—especially restraint conditions***.
  - ***system-level interactions—especially those due to thermal expansion—***since columns, girders, and floor subassemblies are tested separately.
  - the ***performance of connections under both gravity and thermal effects***.
  - ***scale effects in buildings with long span floor systems.***

NIST

Principal Findings for Objective 3: Procedures and Practices (2)

- **Current practice does not require design professionals to possess the qualifications necessary to ensure adequate passive fire resistance of the structural system.** In current practice,
  - Architects typically rely on catalogued ASTM E 119 test data to specify the required passive fire protection to comply with the building code.
  - Structural engineers are not required to consider fire as a load condition in structural design.
  - Fire protection engineers may or may not be called upon to assist the architect in specifying the required passive fire protection.

  Thus, ***none of the key professionals is assigned the responsibility to ensure the adequate fire performance of the structural system.***
- **There is a critical gap in knowledge about how structures perform in real fires**, particularly considering: the effects of the fire on the entire structural system; the interactions between the subsystems, elements, and connections; and scaling of fire test results to full-scale structures (especially for structures with long span floor systems).

Outline

- Investigation Objectives
- WTC 7 Building Design
- Probable Collapse Sequence
- Other Possible Hypotheses
- Principal Findings
- **Factors that Could Have Changed The Outcome**
- Recommendations

Future Factors that Could Have Mitigated Structural Collapse

- More robust connections and framing systems to better resist the effects of thermal expansion on the structural system.
- Structural systems expressly designed to prevent progressive collapse. **The current model building codes do not require that buildings be designed to resist progressive collapse.**
- Better thermal insulation (i.e., reduced conductivity and/or increased thickness) to limit heating of structural steel and to minimize both thermal expansion and weakening effects. **Insulation has been used to protect steel strength, but it could be used to maintain a lower temperature in the steel framing to limit thermal expansion.**
- Automatic fire sprinkler systems with independent and reliable sources for the primary and secondary water supply.
- Improved compartmentation in tenant areas to limit the spread of fires.
- Thermally resistant window assemblies which limit breakage, reduce air supply, and retard fire growth.

Human Performance Factors

- There were factors that contributed to the outcome of no loss of life at WTC 7.
  - Reduced number of people in WTC 7 at the times of airplane impact on the towers.
  - Participation of the building occupants in recent fire drills.
  - Shortness of delay in starting to evacuate.
  - Evacuation assistance provided by emergency responders to evacuees.
  - Decision not to continue reconnaissance of the building and not to fight the fires within.
- There were also factors that did not play a life safety role in WTC 7 on September 11, 2001, but could have been important had the fires been more widespread, the building damage more severe, or the building occupancy at full capacity.
  - Accuracy and reliability of communications among emergency responders and building occupants.
  - Efficiency of management of large-scale emergency incidents.

Outline

- Investigation Objectives
- WTC 7 Building Design
- Probable Collapse Sequence
- Other Possible Hypotheses
- Principal Findings
- Factors that Could Have Changed The Outcome
- **Recommendations**

WTC 7 Recommendations

- Based on its findings, NIST identified ***one new recommendation*** and ***reiterated 12 recommendations*** from its Investigation of the WTC towers.
  - **The urgency of prior recommendations is significantly reinforced by their pertinence to the collapse of a tall building with a structural system design that is in widespread use.**
- The **13 recommendations** for improvements to codes, standards, and practices fall into **7 of the 8 major groups** :
  - ❑ Increased Structural Integrity
  - ❑ Enhanced Fire Resistance of Structures
  - ❑ New Methods for Designing Structures to Resist Fires
  - ❑ Improved Active Fire Protection
  - ❑ Improved Building Evacuation (not applicable for WTC 7)
  - ❑ Improved Emergency Response
  - ❑ Improved Procedures and Practices
  - ❑ Education and Training Programs

Structural Design (Enhanced Fire Resistance of Structures; New Methods for Designing Structures to Resist Fires)

Life Safety Systems (Improved Active Fire Protection; Improved Building Evacuation; Improved Emergency Response)

Practices & Development (Improved Procedures and Practices; Education and Training Programs)

Comparison of WTC 7 and WTC Towers

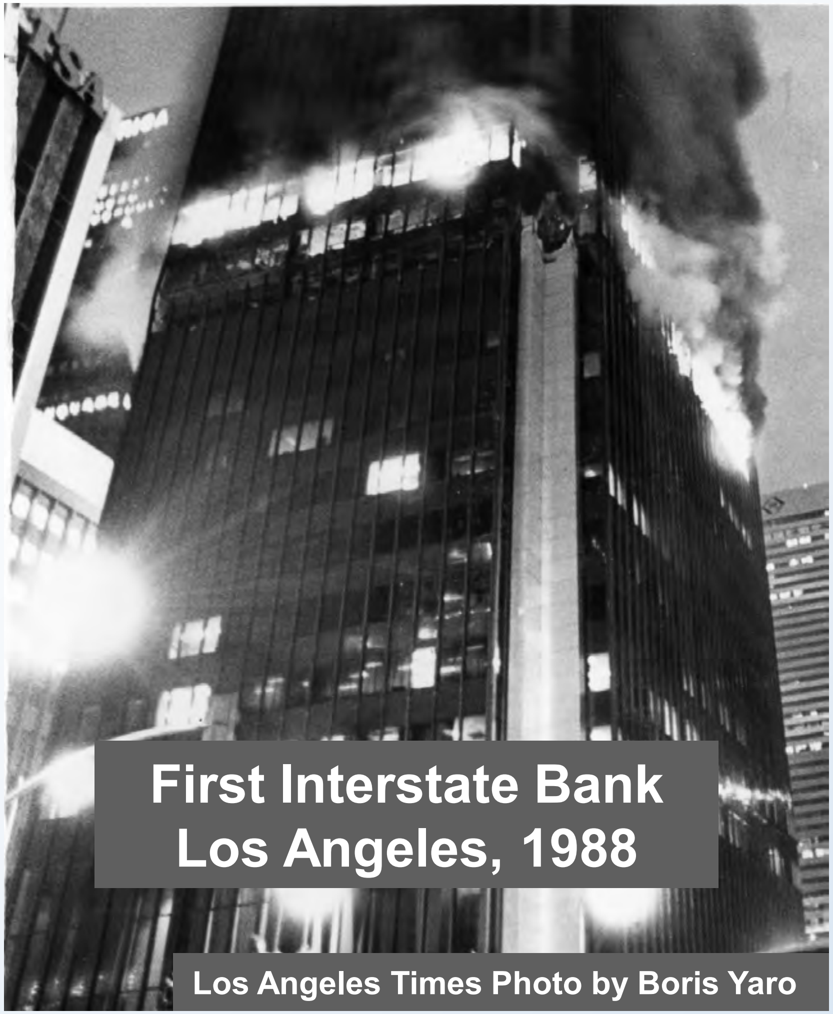
WTC 7 was unlike the WTC towers in many respects:

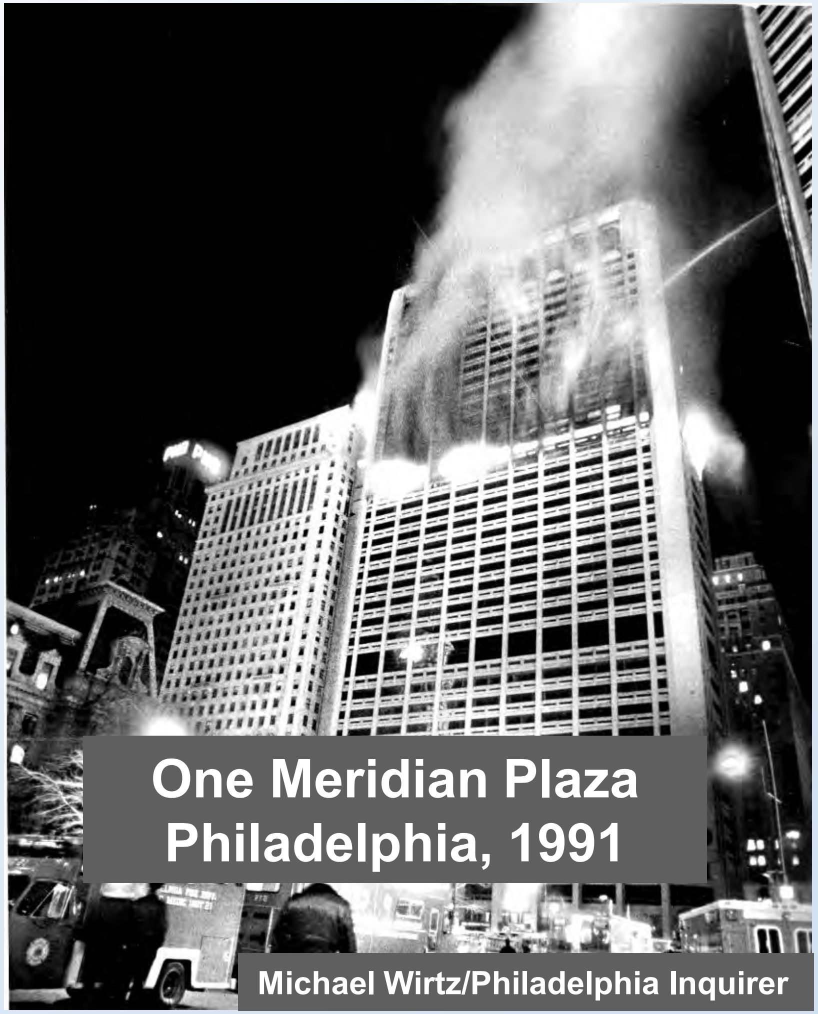
- It was a more typical tall building in the design of its structural system.
- It was not struck by an aircraft.
- The fires in WTC 7 were quite different from those in the towers. Since WTC 7 was not doused with thousands of gallons of jet fuel, large areas of any floor were not ignited simultaneously.
- Instead, the fires in WTC 7 were similar to those that have occurred in several tall buildings where the automatic sprinklers did not function or were not present.
- These other buildings did not collapse due to differences in structural design, while WTC 7 succumbed to its fires.

Key Premise

- The partial or total collapse of a building due to fires is an infrequent event.
- This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system.
- A properly designed and operating automatic sprinkler system will contain fires while they are small and, in most instances, prevent them from growing and spreading to threaten structural integrity.
- The intent of current practice, based on prescriptive standards and codes, is to achieve life safety, not collapse prevention.
- **Buildings, however, should not collapse in infrequent (worst-case) fires that may occur when active fire protection systems are rendered ineffective (e.g., when sprinklers do not exist, are not functional, or are overwhelmed by the fire).**
- Fire scenarios for structural design based on single compartment or single floor fires are not appropriate representations of infrequent fire events. Such events occurred in several tall buildings resulting in unexpected substantial losses.

Historic Tall Building Fires





Characteristics of Infrequent (Worst-Case) Fire Events for Structural Design Based on Historical Data

- Ordinary combustibles and combustible load levels.
- Local fire origin on any given floor.
- No widespread use of accelerants.
- Consecutive fire spread from combustible to combustible.
- Fire-induced window breakage providing ventilation for continued fire spread and accelerated fire growth.
- Concurrent fires on multiple floors.
- Active fire protection systems rendered ineffective (e.g., sprinklers do not exist, are not functional, or are overwhelmed by fire).

The fires in WTC 7 had all of these characteristics.

Recommendations for Group 1: Increased Structural Integrity

Recommendation A (NIST NCSTAR 1 Recommendation 1). **NIST recommends that:**

- **progressive collapse be prevented in buildings through the development and nationwide adoption of consensus standards and code provisions, along with the tools and guidelines needed for their use in practice; and**
- **a standard methodology be developed—supported by analytical design tools and practical design guidance—to reliably predict the potential for complex failures in structural systems subjected to multiple hazards.**

Relevance to WTC 7: Had WTC 7 been expressly designed for prevention of fire-induced progressive collapse, it would have been sufficiently robust to withstand local failure due to the fires without suffering total collapse.

Recommendations for Group 2: Enhanced Fire Endurance of Structures

Recommendation B (New), NIST recommends that buildings be explicitly evaluated to ensure adequate performance of the structural system under worst-case design fires with active fire protection systems rendered ineffective. Of particular concern are buildings with one or more of the following features:

> **long-span floor systems, connection designs that cannot accommodate thermal effects, floor framing that induces asymmetric thermally-induced forces on girders, shear studs that could fail due to differential thermal expansion in composite floor systems, and lack of shear studs on girders.**

Careful consideration should also be given to the possibility of other design features that may adversely affect the performance of the structural system under fire conditions.

Relevance to WTC 7: The effects of restraint of thermal expansion on steel framing systems, especially the long spans on the east side of WTC 7, were not considered in the structural design and led to the initiation of global collapse.

Details of Recommendation B (New)

- Typical floor span length in tall office buildings is in the range of 40 ft to 50 ft; this range is considered to represent long-span floor systems.

- Thermal effects (e.g., thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.

- **Building owners, operators, and designers are strongly urged to act upon this recommendation.** Engineers should be able to design cost-effective fixes to address any areas of concern identified by the evaluations using existing, emerging, or anticipated future capabilities.

- Industry should partner with the research community to fill **critical gaps in knowledge about how structures perform in real fires**, particularly considering:
  - the effects of fire on the entire structural system;
  - the interactions between subsystems, elements, and connections;
  - scaling of fire test results to full-scale structures, especially for structures with long span floor systems.

Recommendations for Group 2: Enhanced Fire Endurance of Structures (2)

Recommendation C (NIST NCSTAR 1 Recommendation 4). NIST recommends evaluating, and where needed improving, the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings)—and making related code changes.

***Relevance to WTC 7*:** The floor systems in WTC 7 failed at shorter fire exposure times than the specified fire rating (two hours) and at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the fire rating requirements in the construction classification, which are determined using the ASTM E 119 or equivalent testing standard.

Recommendations for Group 2: Enhanced Fire Endurance of Structures (3)

Recommendation D (NIST NCSTAR 1 Recommendation 5). NIST recommends that the technical basis for the century-old standard for fire resistance testing of components, assemblies, and systems be improved through a national effort. Necessary guidance also should be developed for extrapolating the results of tested assemblies to prototypical building systems. A key step in fulfilling this recommendation is to establish a capability for studying and testing the components, assemblies, and systems under realistic fire and load conditions.

***Relevance to WTC 7*:** The floor systems failed in WTC 7 at shorter fire exposure times than the specified fire rating (two hours) and at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the endpoint criteria when using the ASTM E 119 or equivalent testing standard.

- **The United States currently does not have the capability for studying and testing fire-induced phenomena critical to structural integrity.**

NIST

Recommendations for Group 2: Enhanced Fire Endurance of Structures (4)

Recommendation E (NIST NCSTAR 1 Recommendation 7). NIST recommends the adoption and use of the –structural frame" approach to fire resistance ratings.

- **The definition of the primary structural frame should be expanded to include bracing members that are essential to the vertical stability of the primary structural frame under gravity loading (e.g., girders, diagonal bracing, composite floor systems that provide lateral bracing to the girders) whether or not the bracing members carry gravity loads.**

***Relevance to WTC 7*:** Thermally-induced breakdown of the floor system in WTC 7 was a determining step in causing collapse initiation and progression. Therefore, the floor system should be considered as an integral part of the primary structural frame.

Recommendations for Group 3: New Methods for Fire Resistant Design of Structures

<u>Recommendation F (NCSTAR Recommendation 8)</u>. NIST recommends that the fire resistance of structures be enhanced by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse. Current methods for determining the fire resistance rating of structural assemblies do not explicitly specify a performance objective.

***Relevance to WTC 7*:** Large, uncontrolled fires led to failure of a critical column and consequently the complete collapse of WTC 7. In the region of the collapse initiation (i.e., on the east side of Floor 13), the fire had consumed virtually all of the combustible building contents, yet collapse was not prevented.

Recommendations for Group 3: New Methods for Fire Resistant Design of Structures (2)

Recommendation G (NIST NCSTAR 1 Recommendation 9). NIST recommends the development of:

- **performance-based standards and code provisions, as an alternative to current prescriptive design methods, to enable the design and retrofit of structures to resist real building fire conditions, including their ability to achieve the performance objective of burnout without structural or local floor collapse: and**
- **the tools, guidelines, and test methods necessary to evaluate the fire performance of the structure as a whole system.**

Relevance to WTC 7**:** A performance-based assessment of the effects of fire on WTC 7, had it considered all of the relevant thermal effects (e.g., thermal expansion effects that occur at lower temperatures), would have identified the vulnerability of the building to fire-induced collapse and allowed alternative designs for the structural system.

Recommendations for Group 4: Improved Active Fire Protection

Recommendation H (NIST NCSTAR 1 Recommendation 12). NIST recommends that the performance and possibly the redundancy of active fire protection systems (sprinklers, standpipes/hoses, fire alarms, and smoke management systems) in buildings be enhanced to accommodate the greater risks associated with increasing building height and population, increased use of open spaces, high-risk building activities, fire department response limits, transient fuel loads, and higher threat profile.

***Relevance to WTC 7*:** No water was available for the automatic suppression system on the lower 20 stories of WTC 7 once water from street-level mains was disrupted. This lack of reliability in the source of the primary and secondary water supply allowed the growth and spread of fires that ultimately resulted in collapse of the building.

Recommendations for Group 6: Improved Emergency Response

<u>Recommendation I (NIST NCSTAR 1 Recommendation 24)</u>. NIST recommends the establishment and implementation of codes and protocols for ensuring effective and uninterrupted operation of the command and control system for large-scale building emergencies.

***Relevance to WTC 7*:**

- The New York City Office of Emergency Management (OEM) in WTC 7 was evacuated before key decisions were made. The location of OEM in WTC 7 contributed to the loss of robust interagency command and control.
- Due to the collapse of the WTC towers and the loss of responders and fire control resources, there was an evolving site leadership during the morning and afternoon. Key decisions were reasonable and would not have changed the outcome on September 11, 2001, but were not made promptly. Under different circumstances (e.g., if WTC 7 had collapsed sooner and fire fighters were still in the building), the outcome could have been very different.

Recommendations for Group 7: Improved Procedures and Practices

Recommendation J (NIST NCSTAR 1 Recommendation 27). NIST recommends that building codes incorporate a provision that requires building owners to retain documents, including supporting calculations and test data, related to building design, construction, maintenance and modifications over the entire life of the building. Means should be developed for offsite storage and maintenance of the documents. In addition, NIST recommends that relevant building information be made available in suitably designed hard copy or electronic format for use by emergency responders. Such information should be easily accessible by responders during emergencies.

***Relevance to WTC 7*:** The efforts required in locating and acquiring drawings, specifications, tenant layouts, material certifications, and, especially, shop fabrication drawings, significantly lengthened the investigation into the collapse of WTC 7.

Recommendations for Group 7: Improved Procedures and Practices (2)

Recommendation K (NIST NCSTAR 1 Recommendation 28). NIST recommends that the role of the ―Design Professional in Responsible Charge" be clarified to ensure that:

- **all appropriate design professionals (including, e.g., the fire protection engineer) are part of the design team when designing buildings employing innovative or unusual fire safety systems, and**
- **all appropriate design professionals (including, e.g., the structural engineer and the fire protection engineer) are part of the design team when designing the structure to resist fires, in buildings that employ innovative or unusual structural and fire safety systems.**

***Relevance to WTC 7*:** Following typical practice, none of the design professionals in charge of the WTC 7 project (i.e., architect, structural engineer, and fire protection engineer) was assigned the responsibility to explicitly evaluate the fire performance of the structural system. Holistic consideration of thermal and structural factors during the design or review stage might have prevented the collapse of the building.

Recommendations for Group 8: Education and Training

Recommendation L (NIST NCSTAR 1 Recommendation 29). NIST recommends that continuing education curricula be developed and programs be implemented for training of:

- **fire protection engineers and architects in structural engineering principles and design,**
- **structural engineers, architects, fire protection engineers, and code enforcement officials in modern fire protection principles and technologies, including fire-resistance design of structures, and**
- **building regulatory and fire service personnel to upgrade their skills to conduct the tasks for which they are responsible.**

***Relevance to WTC 7*:** Discerning the fire-structure interactions that led to the collapse of WTC 7 required research professionals with expertise in both disciplines. Assuring the safety of future buildings will require that participants in the design and review processes possess a combined knowledge of fire science, materials science, heat transfer, and structural engineering and design.

Recommendations for Group 8: Education and Training

Recommendation M (NIST NCSTAR 1 Recommendation 30). NIST recommends that academic, professional short-course, and web-based training materials in the use of computational fire dynamics and thermostructural analysis tools be developed and delivered to strengthen the base of available technical capabilities and human resources.

***Relevance to WTC 7*:** NIST stretched the state-of-the-art in the computational tools needed to reconstruct a fire-induced building collapse. This enabled identification of the critical processes that led to that collapse. Making these expanded tools and derivative, validated, and simplified modeling approaches usable by practitioners could prevent future disasters.

Implementing the WTC Recommendations

- NIST believes these recommendations are realistic, appropriate, and achievable within a reasonable period of time.
- NIST strongly urges that immediate and serious consideration be given to these recommendations by the building and fire safety communities.
- Implementation of these recommendations will achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used—with the goal of making buildings safer in future emergencies.

Implementing the WTC Recommendations (2)

- NIST has assigned ***top priority*** **to work vigorously with the building and fire safety communities** to assure that there is a *complete understanding* of the recommendations and to provide needed *technical assistance*.

- **Key U.S. standards and codes development organizations are seriously considering the WTC recommendations and the *first comprehensive set of model building code changes have been adopted in the International Building Code*.**

- **The WTC recommendations already are having a significant impact on the construction of iconic high-rise buildings worldwide, including the *Freedom Tower.***

- NIST has implemented a web-based system so that the public can track progress on implementing the recommendations.

NIST

Changes to Building Codes and Standards

- First comprehensive set of eight model building code changes based on recommendations from NIST's WTC investigation were adopted by the International Building Code in 2007.
- Second set of eight model building code changes based on NIST's WTC recommendations were approved by technical committees and are awaiting approval, along with potential appeals on several other code changes, at the Final Action Hearing for the 2009 edition of the International Building Code
- NIST's WTC Recommendations have spurred actions to develop new provisions/ guidelines within other standards, codes, and industry organizations, such as:
  - National Fire Protection Association, American Society of Mechanical Engineers, ASTM International, American Society of Civil Engineers, and the Council on Tall Buildings and Urban Habitat

Process for Submitting Public Comments

- NIST welcomes comments from the public on the draft investigation reports for the WTC 7 building.

- The public is welcome to comment on any of the three draft reports issued by NIST, totaling about 1,000 pages.

- **NIST especially encourages public comment on the approximately 75-page draft summary report, which contains the principal findings and recommendations for changes to codes, standards, and practices.**

- NIST will consider all comments received from the public on the three draft reports before they are issued in final form.

Process for Submitting Public Comments (2)

- Comments must be as specific as possible.
- A short reason must be provided for any suggested change.
- Suggested language must be provided for the requested revision.
- All comments shall include the following information:

Name:

Affiliation:

Contact: Phone number or e-mail address where you can be contacted in case of questions.

Report Number: (e.g., NCSTAR 1A, NCSTAR 1-9, or NCSTAR 1-9A)

Page Number:

Paragraph/Sentence: (e.g., paragraph 2/sentences 2-4)

Comment:

Reason for Comment:

Suggestion for Revision:

Process for Submitting Public Comments (3)

- NIST will accept public comments on any of the draft reports until **12 Noon EDT, Monday, September 15, 2008.**

- Comments may be submitted:
  - through a link on the WTC Investigation web site: http://wtc.nist.gov
  - Via e-mail to wtc@nist.gov
  - By fax to 301-869-6275
  - By mail to:

WTC Technical Information Repository
Attention: Mr. Stephen Cauffman
National Institute of Standards and Technology
100 Bureau Drive Stop 8611
Gaithersburg, MD 20899-8611

Next Steps

- Following the public comment period, NIST will revise the WTC 7 report as appropriate and release the report in final form.

- NIST will continue to vigorously promote implementation of the recommendations from its investigation of the WTC towers and WTC 7 and provide necessary technical support to standards and code development organizations.

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.

NIST