NIST Response to the World Trade Center Disaster

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

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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**

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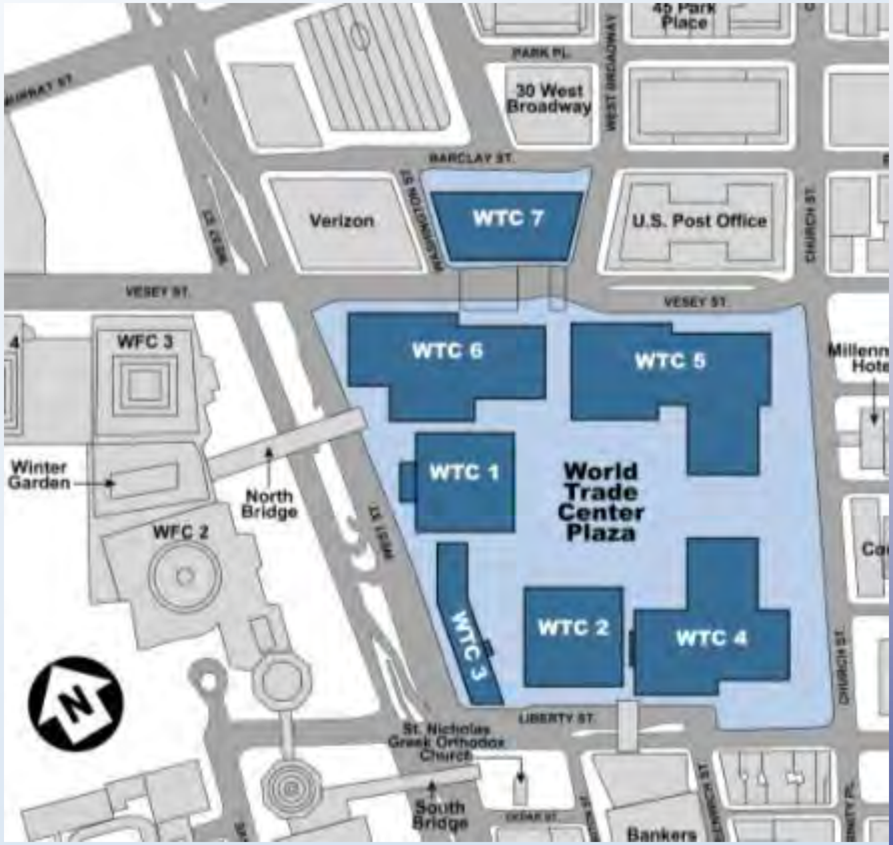
World Trade Center 7

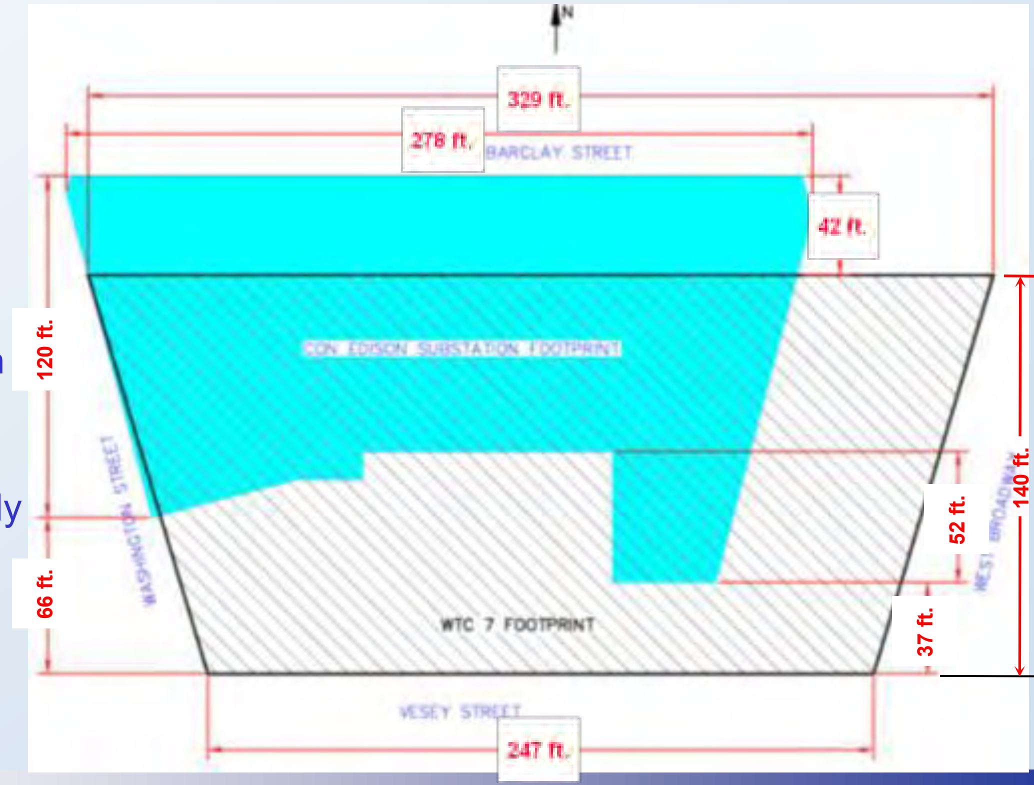
- WTC 7 was a 47 story office building located immediately to the north of the main WTC Complex.
  - Built on top of an existing Con Edison electric power substation, located on land owned by The Port Authority of New York and New Jersey.
  - On September 11, 2001, WTC 7 endured fires for almost seven hours, from the time of the collapse of the north WTC tower (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 two-story lobbies, one each on the center of the south side of the 1st and 3rd floors. The north side of the 1st and 2nd stories was the Con Edison substation.
  - Floors 5 and 6 were mechanical spaces. Between the 5th and 7th floor slabs were three transfer trusses and a series of eight cantilever transfer girders.
  - Floors 7 through 45 were tenant floors, all structurally similar to each other.
  - The 46th and 47th floors, while mainly tenant floors, were structurally reinforced to support special loads, such as the cooling towers and the water tanks for fire suppression.



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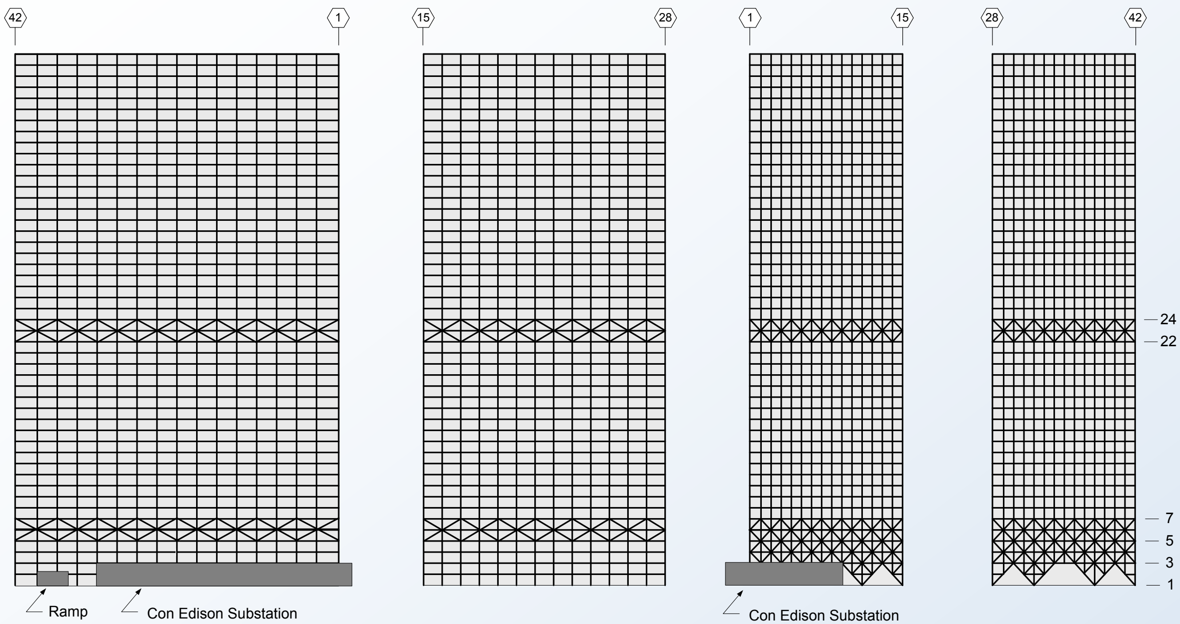
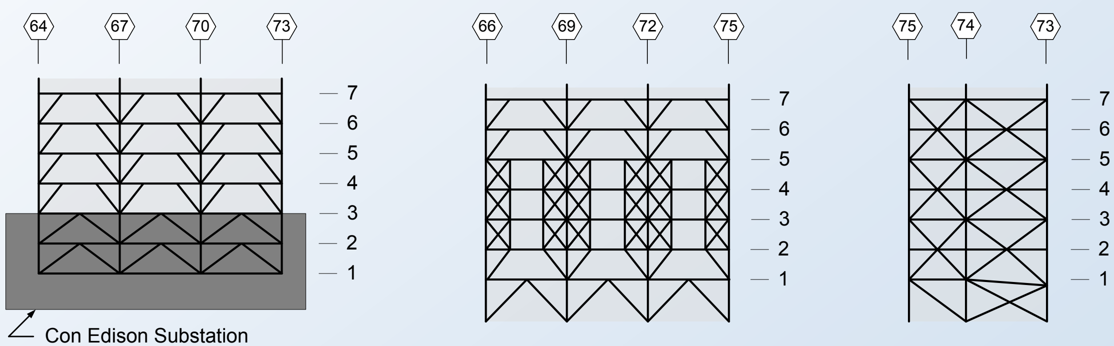
WTC 7 Framing



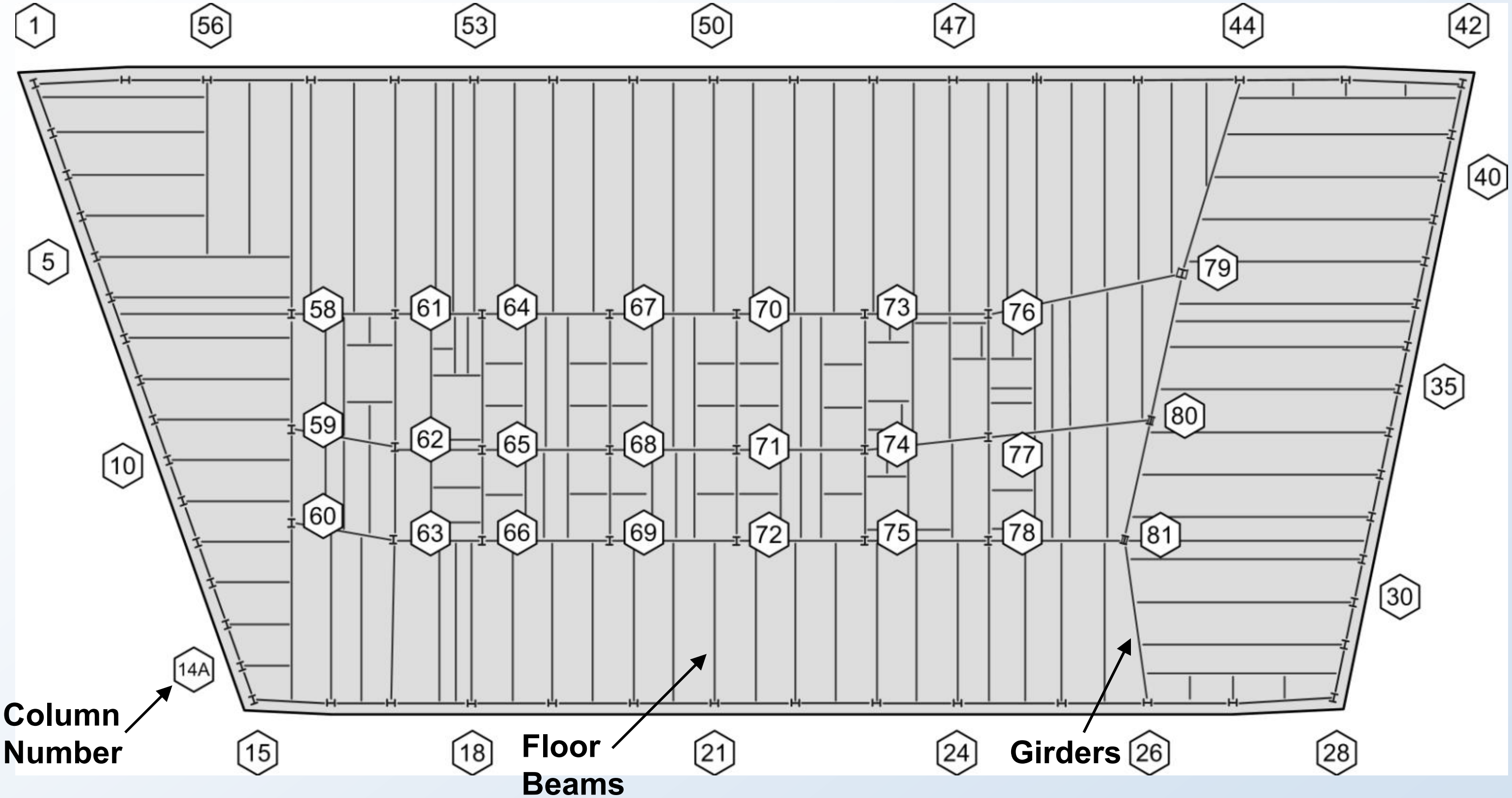
North Elevation South Elevation West Elevation East Elevation



North Elevation (Core) South Elevation (Core) East Elevation (Core)

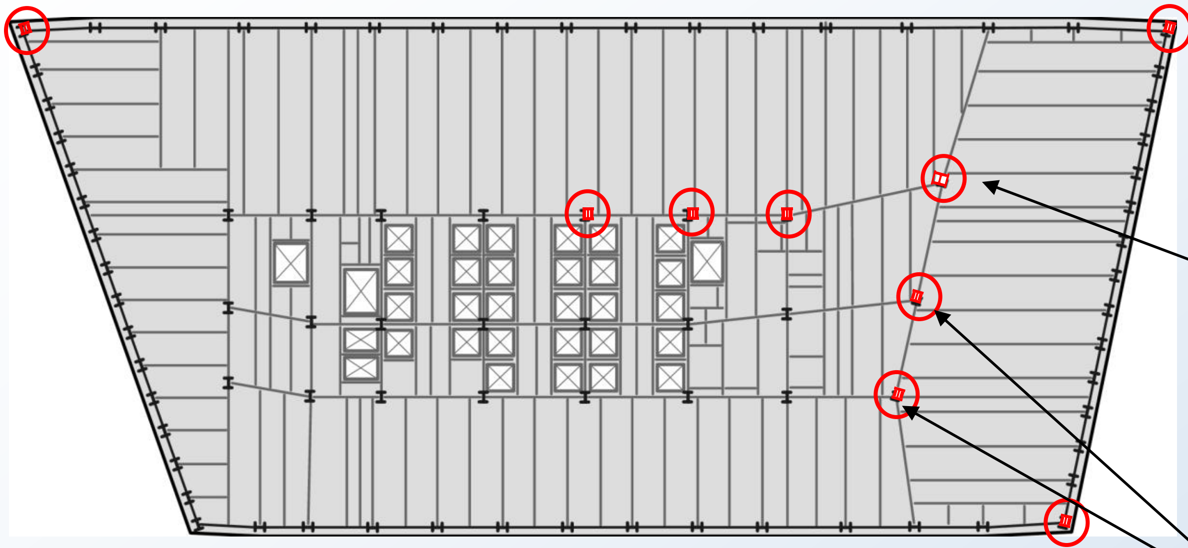
- The WTC 7 *structural system* was designed to distribute the weight of the building (gravity loads) and resist (lateral) wind loads.
- The frame included columns, floor assemblies, spandrel beams, girders, and transfer elements.
- The lateral loads were resisted by the exterior moment frame.
- The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

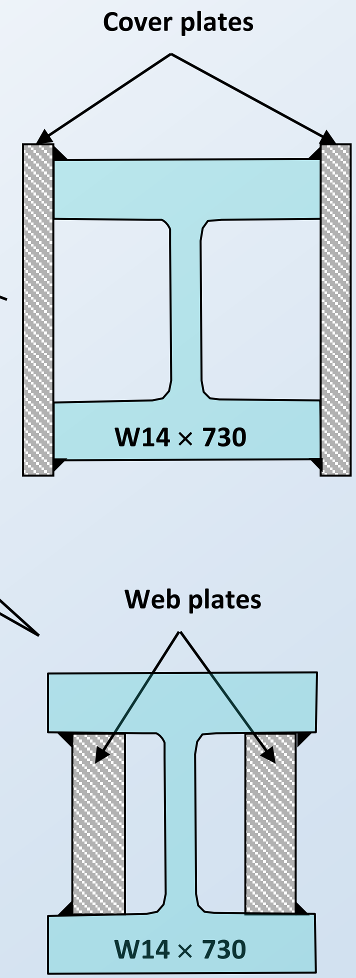
Typical WTC 7 Floor Framing



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



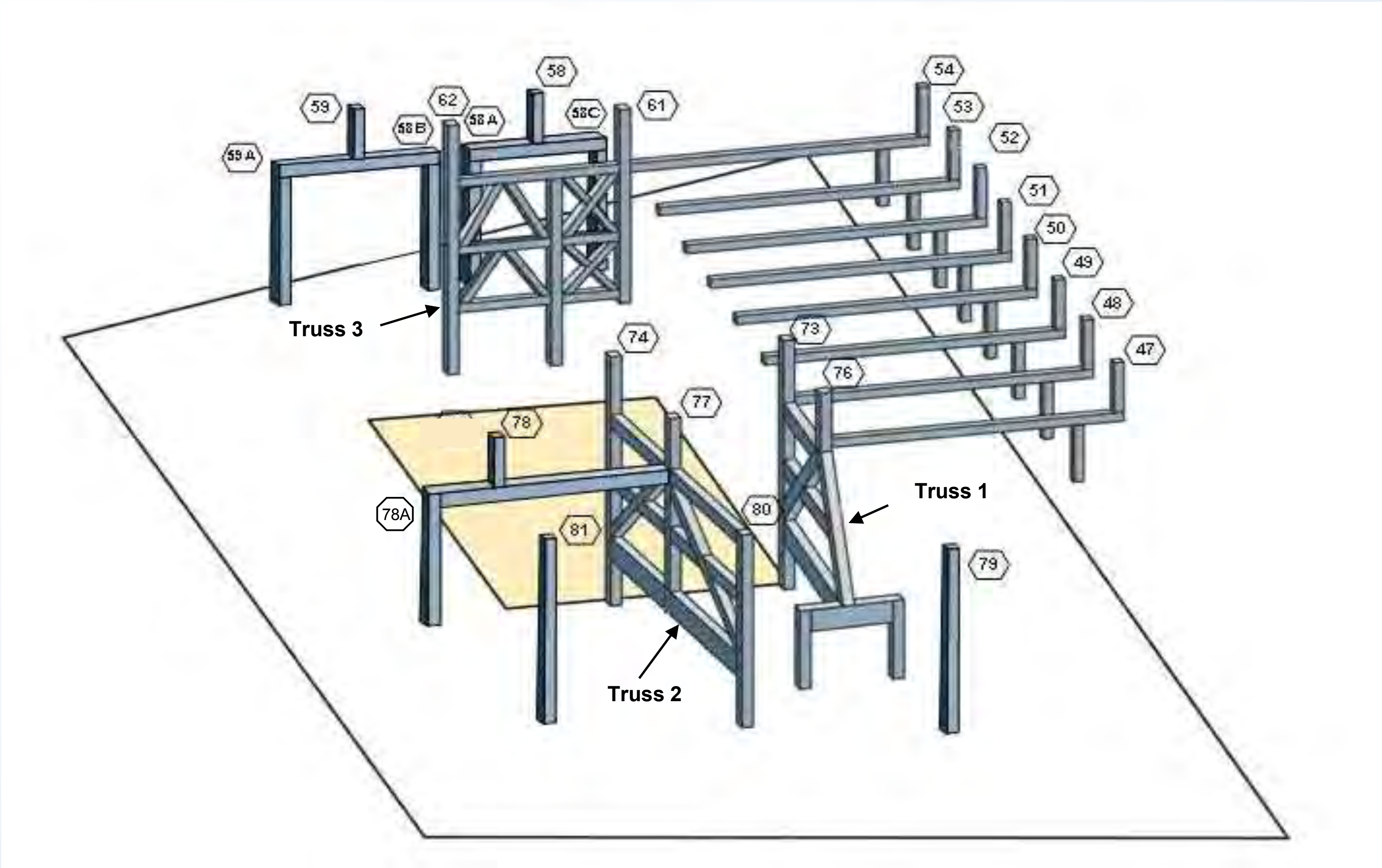


Built-up Column

Non Built-up Column

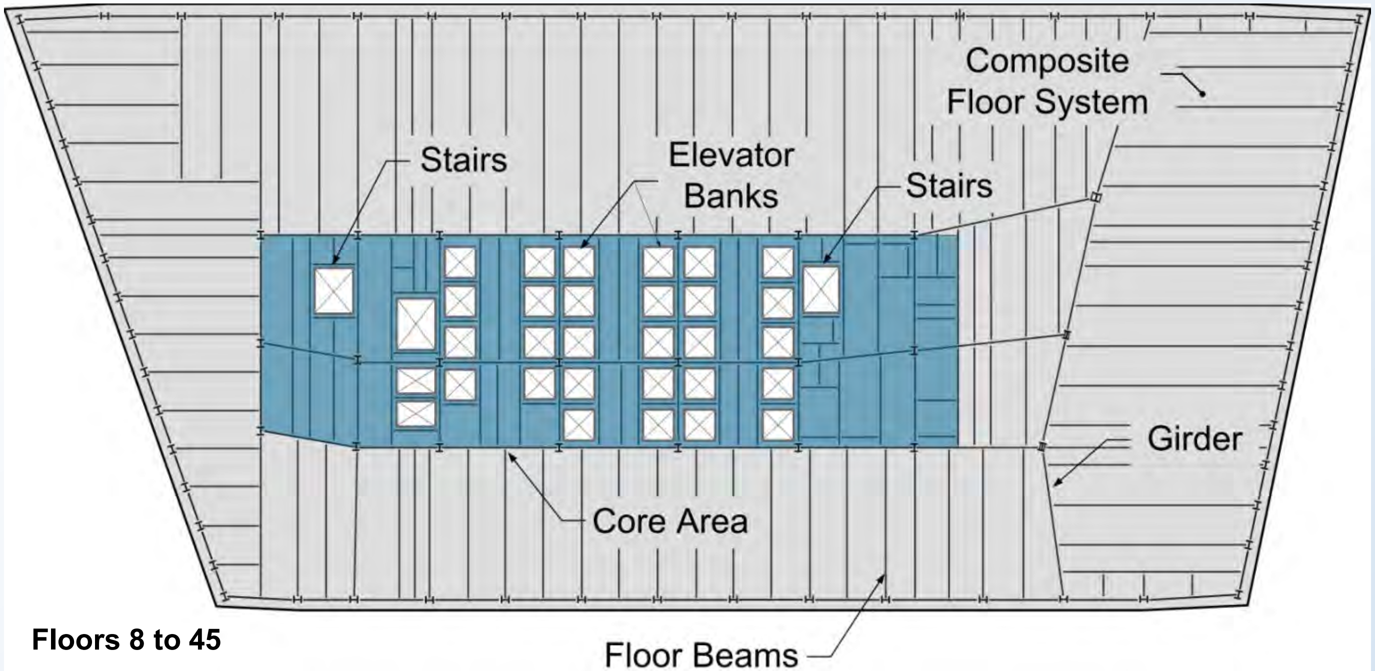
- Plate thickness ranged from 1.5 in to 8 in.
- Plate thickness t (in.) and steel grade were specified as follows:
  - $2 < t < 4$ ASTM A588 Grade 50
  - $4 < t < 6$ ASTM A572 Grade 42
  - $t > 6$ ASTM A588 Grade 42

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.

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 was 14 in. thick.
- On Floor 7, the south half of the floor had a poured 8 in. slab, and the north half had an 8 in. total slab thickness on a 3 in. deep metal deck.
- On Floors 8 through 47, the concrete was 5.5 in. thick.

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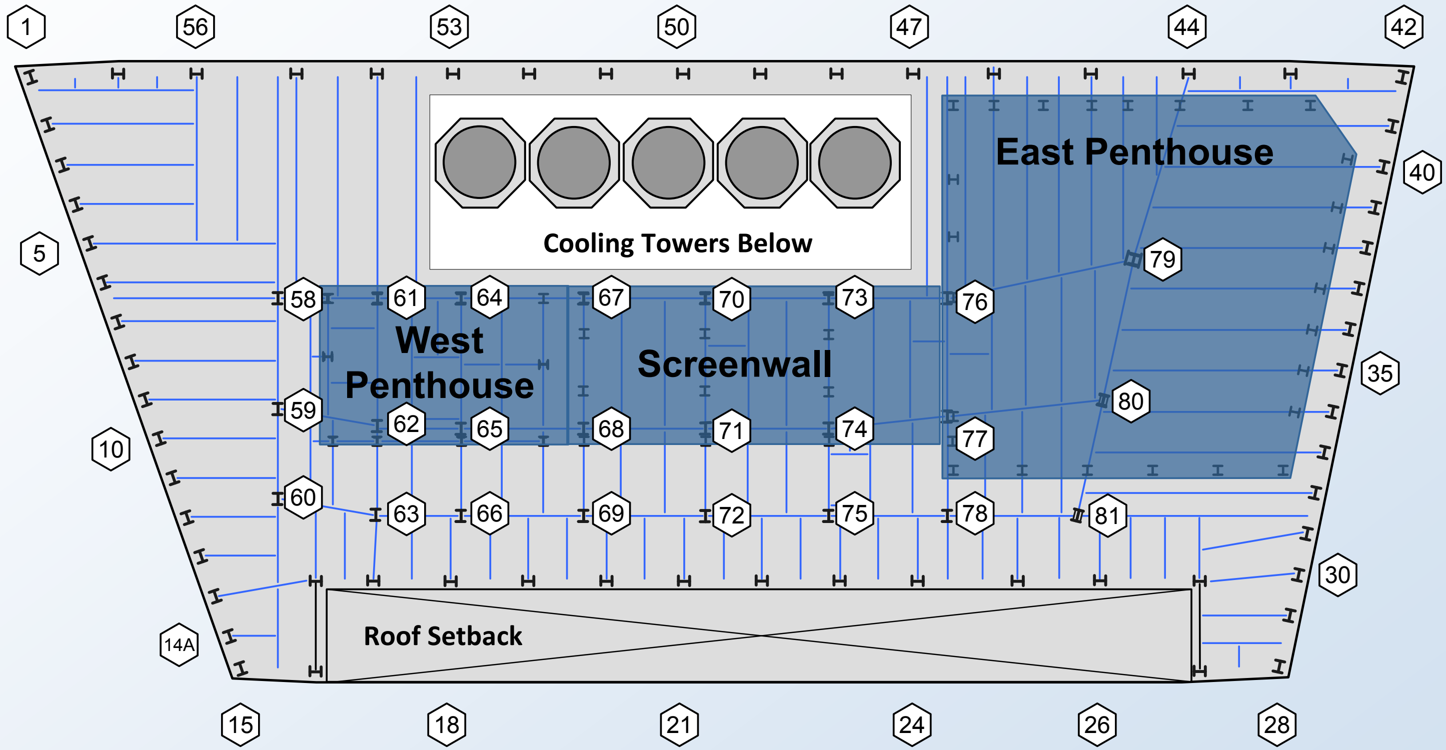
Roof Layout



1
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14A
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62
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80
60
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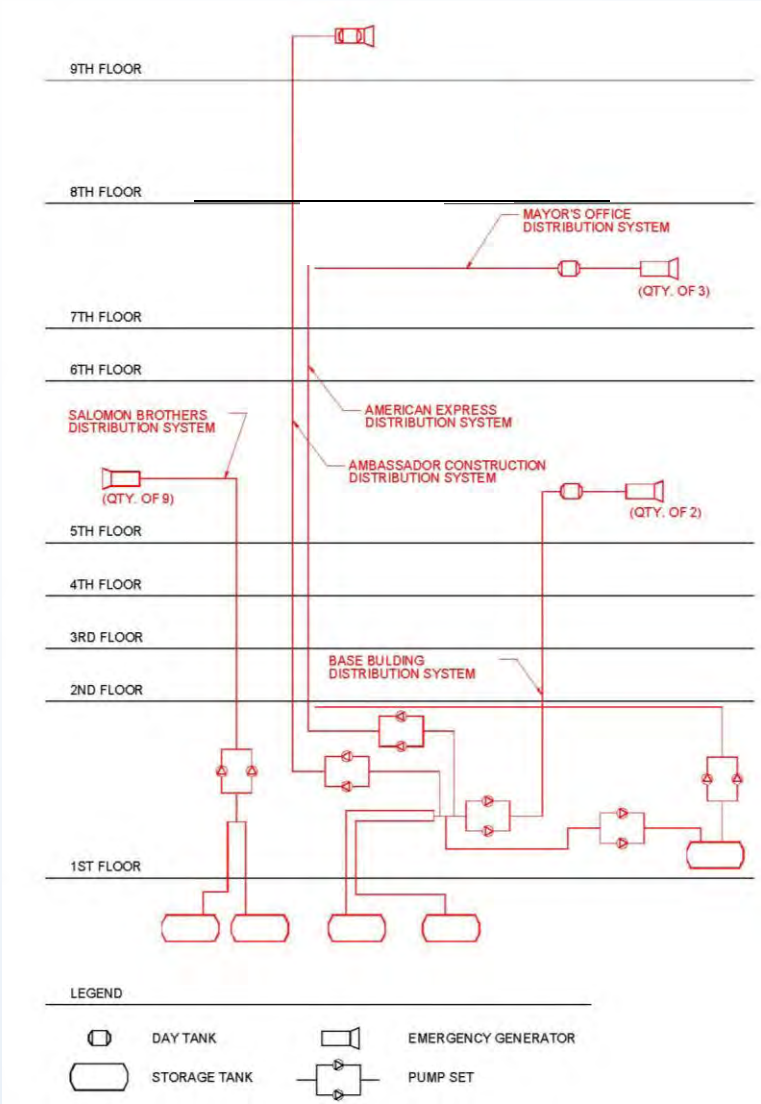
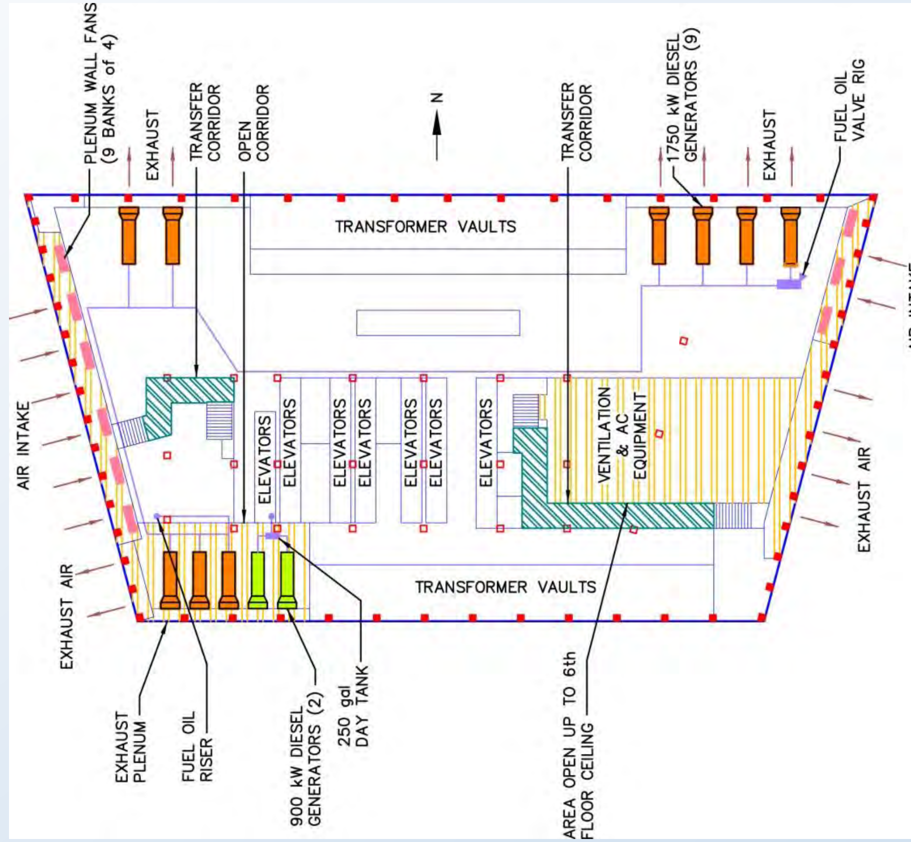
66
69
72
75
78
81
Cooling Towers Below
East Penthouse
West Penthouse
Screenwall
Roof Setback

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 46th 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 from 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.

WTC 7 Emergency Power Systems

	Base Building System	Salomon Smith Barney (SSB) System	Mayor's OEM System
Fuel Storage Tank Capacities	Two 12,000 gal tanks	Two 6,000 gal tanks	Single 6,000 gal tank
Tank Locations	Below the loading dock	Below the loading dock	1st floor
Locations of Generator(s)	Two on 5th floor	Nine on the 5th floor	Three on the 7th floor
Day Tanks and Locations	Single 275 gal tank on the 5th floor	None[a]	Single 275 gal day tank on the 7th floor
Day Tank Pump Locations and Capacities	Two, on the 1st floor; 4.4 gal/min	Two circulating pumps on 1st floor, 70 gal/min	Two, on the 1st floor, 12 gal/min
Ambassador Modification	Generator and 50 gal day tank on 9th floor; two pumps on the 1st floor, 2.4 gal/min		
American Express Modification	Generator and 275 gal day tank on 8th floor; two pumps on the 1st floor, 2.8 gal/min		

a The NYCBC had a limit of one day tank per floor. Since there was a day tank on the 5th floor for the base generators, the SSB system used a pressurized fuel distribution system, in which pumps continuously circulated fuel whenever the generators were running. There was enough fuel 35 gal in the valve rig and piping on the 5th floor to start the diesel engines, which, in turn, would supply power to operate the circulating pumps.

b The generator and day tank were removed prior to September 11, 2001.

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?

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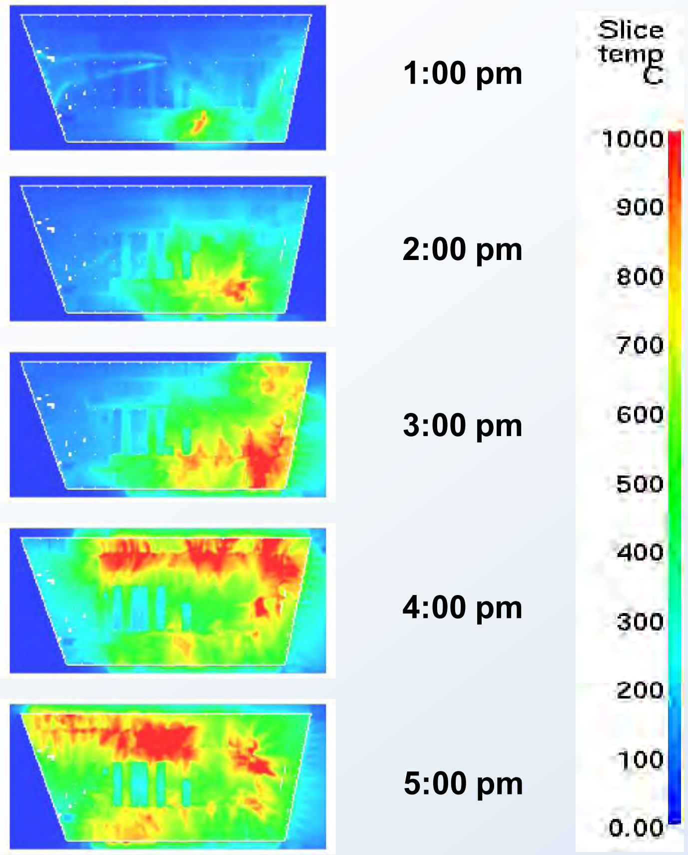
Analysis of Probable Collapse Sequence

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
- Considered possible fuel oil fires, hypothetical blast events, and role of Con Edison substation

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

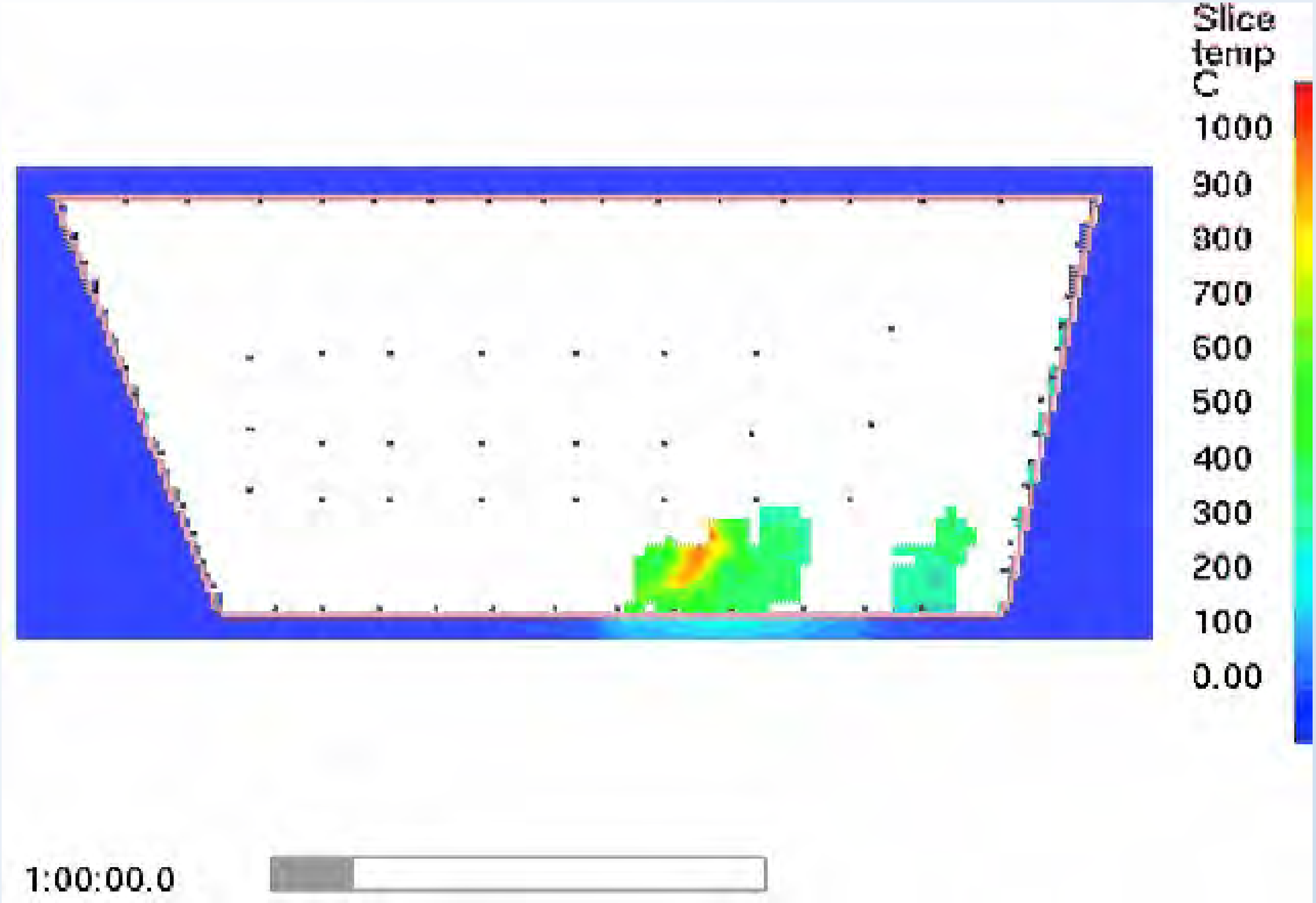
Fire Growth and Spread



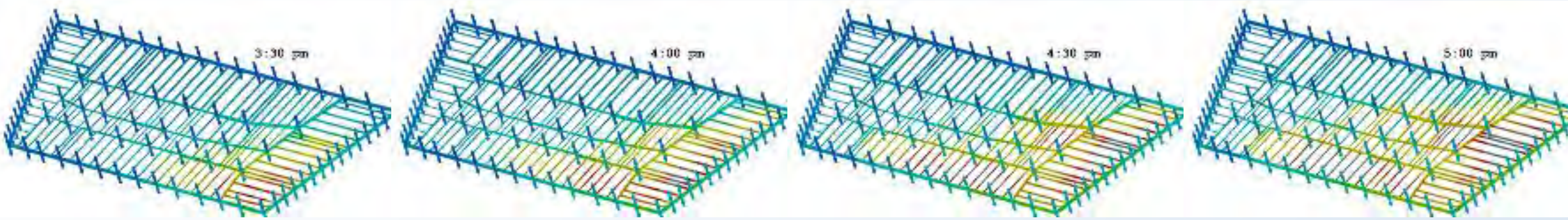
Progression of fires on Floor 12

- The major fires in WTC 7 were modeled using the Fire Dynamics Simulator (FDS) in a manner similar to those for the WTC towers.
- There were far fewer photographs and videos of WTC 7 than of the towers; thus, details of the WTC 7 fires were not as precise as for the towers.
- The fire simulations for WTC 7 were conducted for each floor individually; there were no obvious pathways for the flames and heat to pass from one floor to another, aside from the debris-damaged area in the southwest corner of the building.
- 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 incidence of the debris from the collapsing towers.
- A typical single floor simulation took up to two days on a Linux cluster with 8 processors.

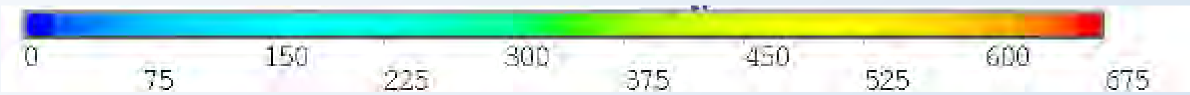
FDS Simulation of Fires on Floor 12

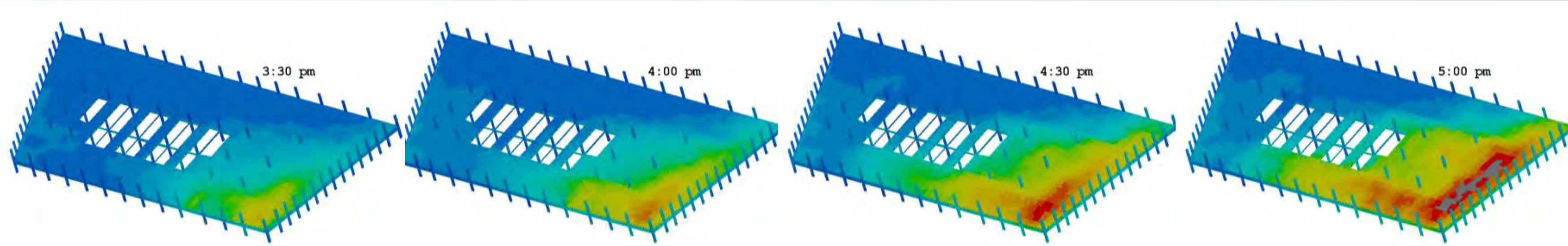


Thermal Response to Fire



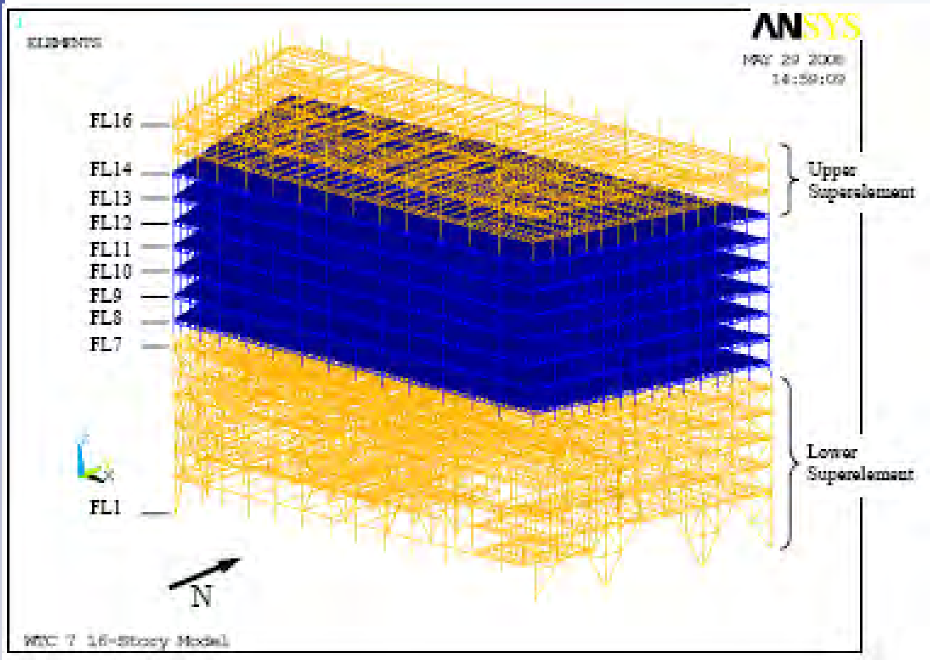
Temperature distribution (ºC) on the floor beams of Floor 13.





Temperature distribution (ºC) in the top layer of the floor slabs of Floor 12.

ANSYS Structural Response Model



- Fires were observed on Floors 7 to 9 and 11 to 13.
- The floors and columns in these areas were subject to heating and possible thermally induced failures.
- 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
    - 21,095 beam elements
    - 28,182 rigid beam elements
    - 34,461 shell elements
    - 7,658 contact elements
    - 9,961 break elements
- Computer
  - 64-bit workstation
  - quad-core, 3.0 GHz processor
  - 64 GB of random access memory (RAM)
- Analysis Time
  - approximately 6 months

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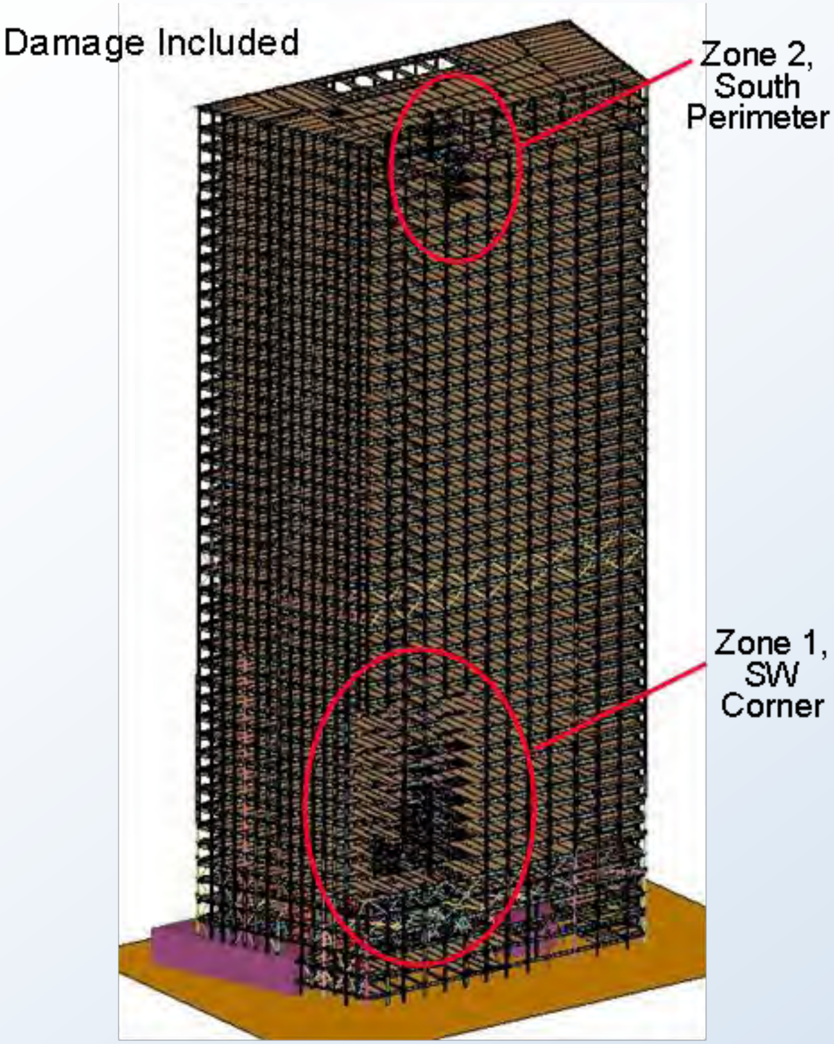
LS-DYNA Structural Response Model



- The LS-DYNA model was used to determine the sequence of events that led to collapse propagation and, ultimately, global collapse.
- Software: double precision version of LS-DYNA
- Model
  - 3,593,049 Nodes
  - 3,045,925 Elements
    - 3,006,910 shell elements
    - 33,364 discrete spring elements
    - 3,190 beam elements
    - 2,461 solid elements
- Computer
  - High speed Linux Beowulf compute cluster.
  - Head node - two 64-bit 2.4 GHz processors, 4 GB of RAM, 1.5 terabytes of RAID 5 disk storage
  - Each compute node - two 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)

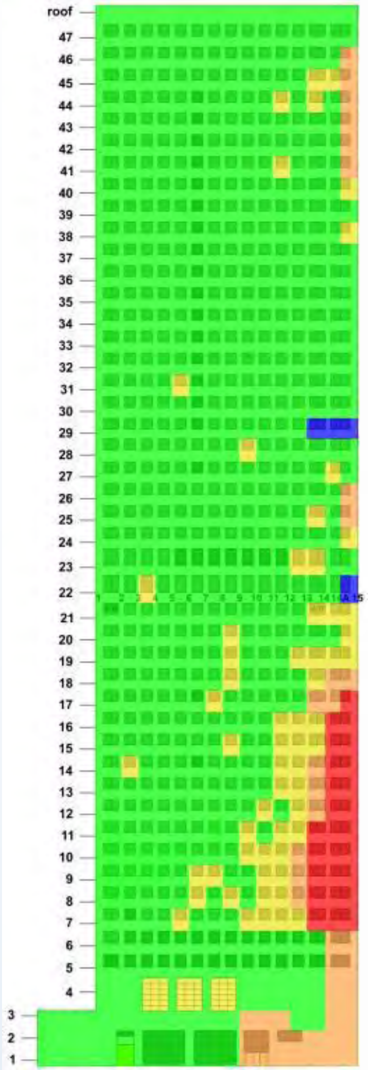
- <u>**Collapse of the WTC Towers.**</u>
  - **Collapse of WTC 2 did not cause any structural damage or start any fires in WTC 7.**
  - **Collapse of WTC 1 damaged seven exterior columns on the lower floors of the south and west faces and initiated fires on 10 floors between Floors 7 and 30.**

- **Aerial photograph shot 14 s ± 0.5 s after WTC 1 began to collapse.**
- **Arrows mark arcs formed by debris that seemed to be ejected outwards from the debris cloud**

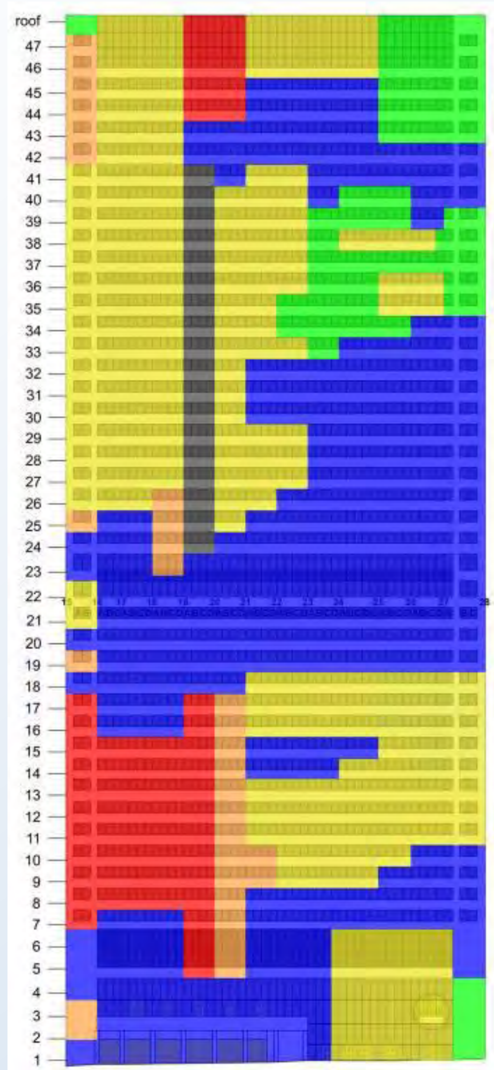
Debris Impact Damage to WTC 7

- **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

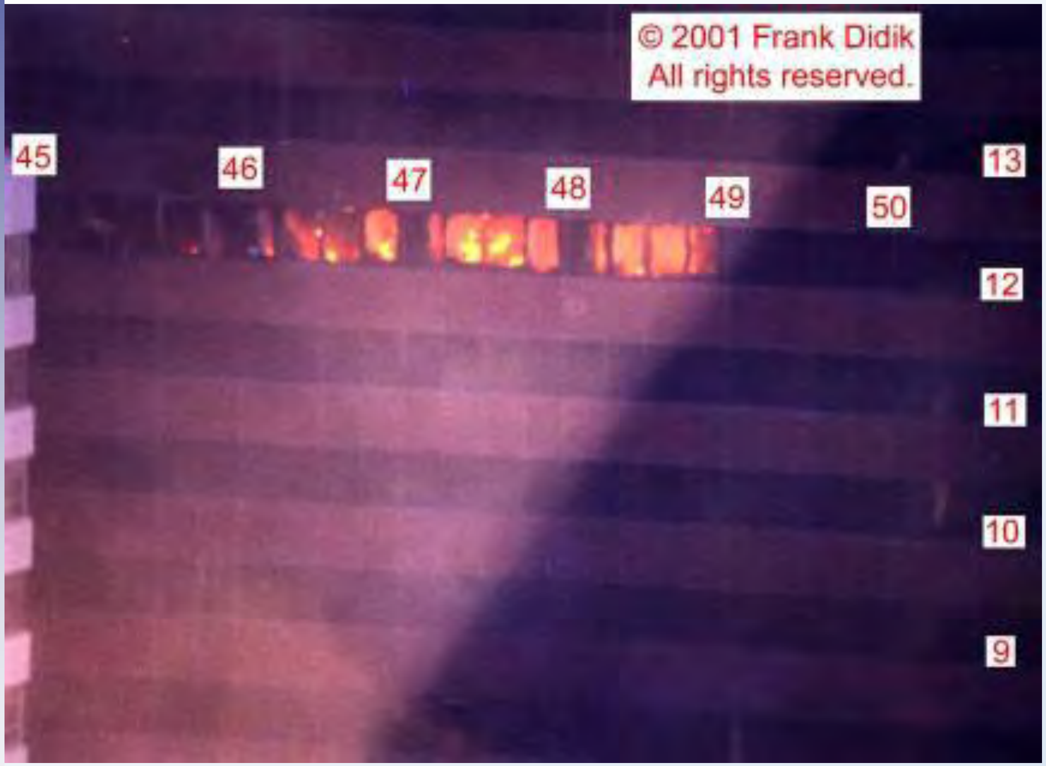
blue (■) – not visible due to smoke, dust, and intervening buildings.

Summary of Probable Collapse Sequence (2)

- **Growth and Spread of Fires.**
  - **Fires on the lower floors (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 of the northeast region beginning at about 3 p.m. to 4 p.m.**
  - **The local fires on the upper floors (Floors 19, 22, 29, and 30) were not observed after approximately 1 p.m.**

- **Cropped photograph showing east edge of the north face and oblique view of east face of WTC 7.**
- **It was likely taken between 3:20 p.m. and 3:40 p.m.**

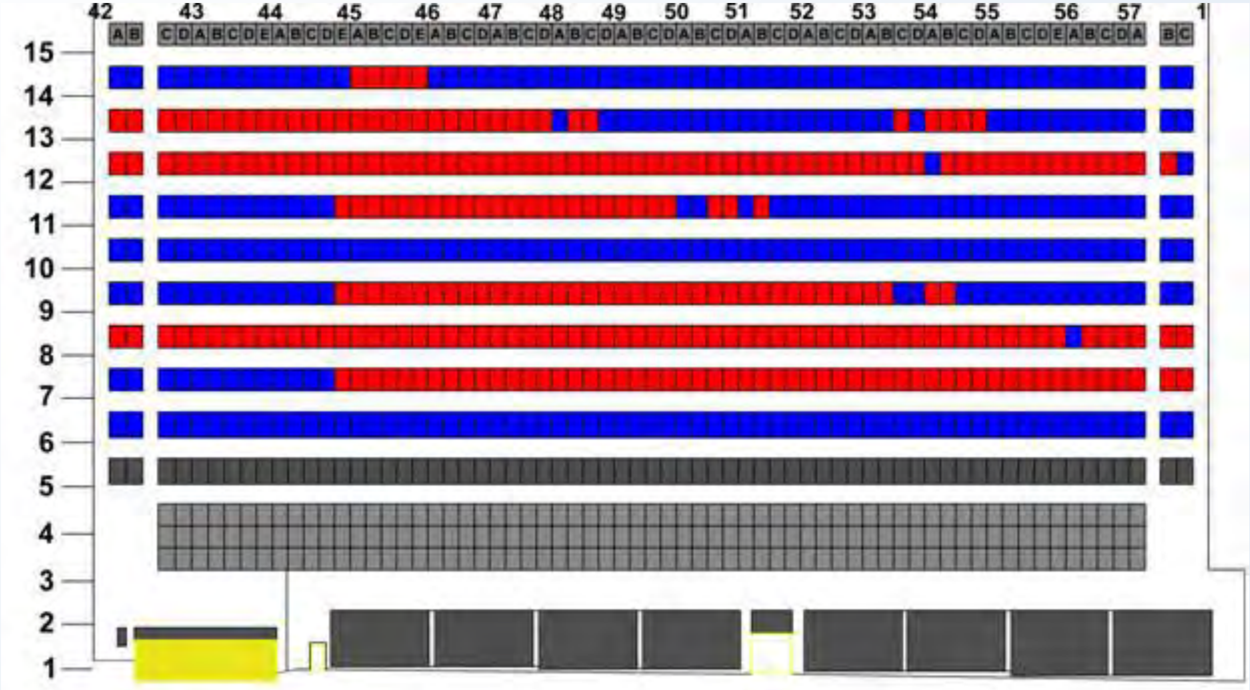
Observed Fires



- Cropped photograph of north face of WTC 7 taken between 3:11:15 p.m. and 3:16:51 p.m.

- Cropped photograph showing part of north face of WTC 7 at 4:39 p.m. ± 120 s.

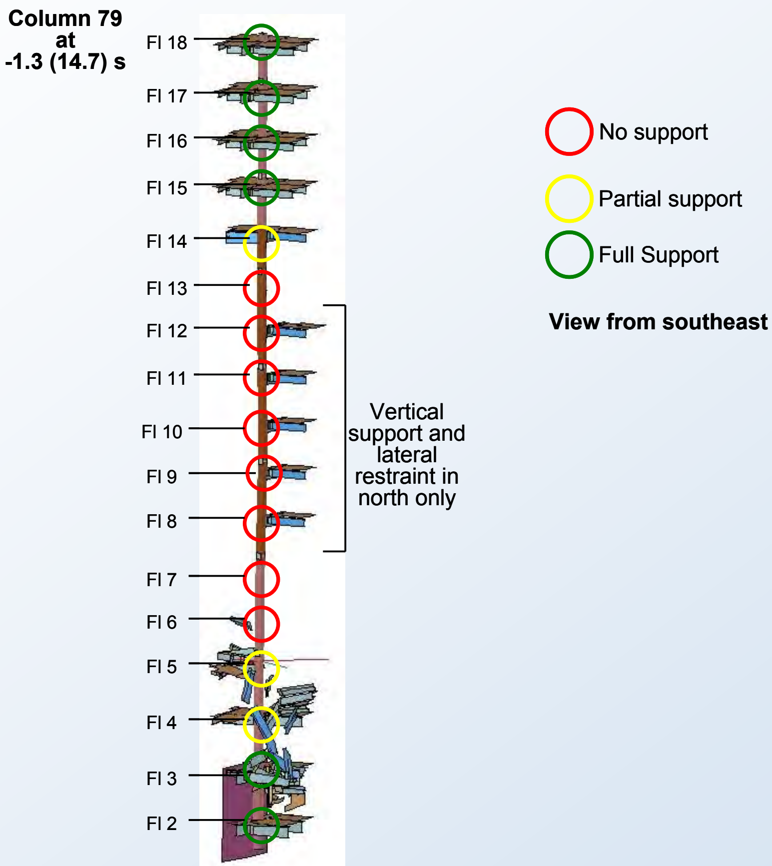
Summary of Fires on North Façade of WTC 7

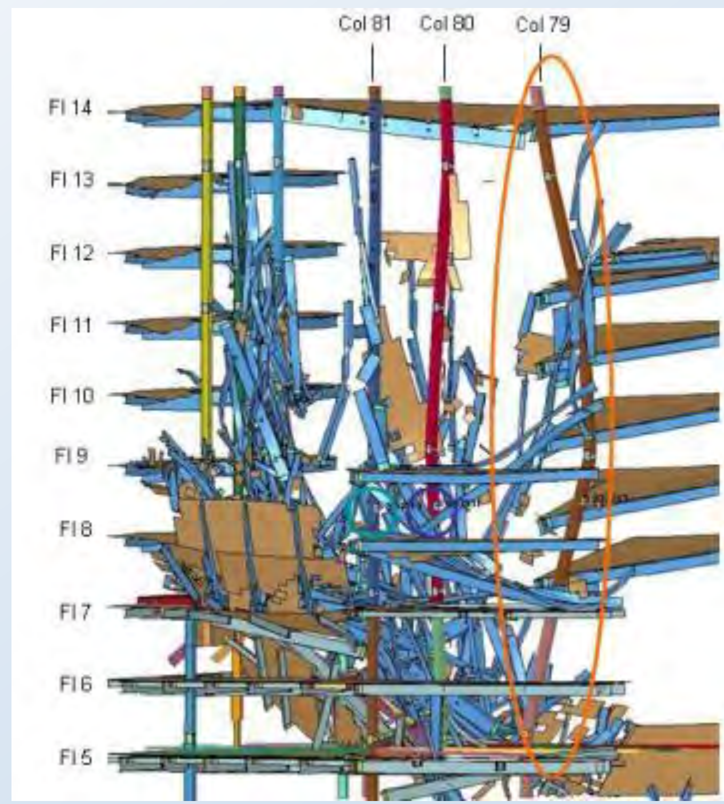


- **Façade map showing where windows were broken and/or fire was observed during the period when fire first appeared shortly before 3:00 p.m. until the building collapsed at 5:20:52 p.m.**
- **Red represents windows where the glass was broken out and/or fire was observed through the window. The remaining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

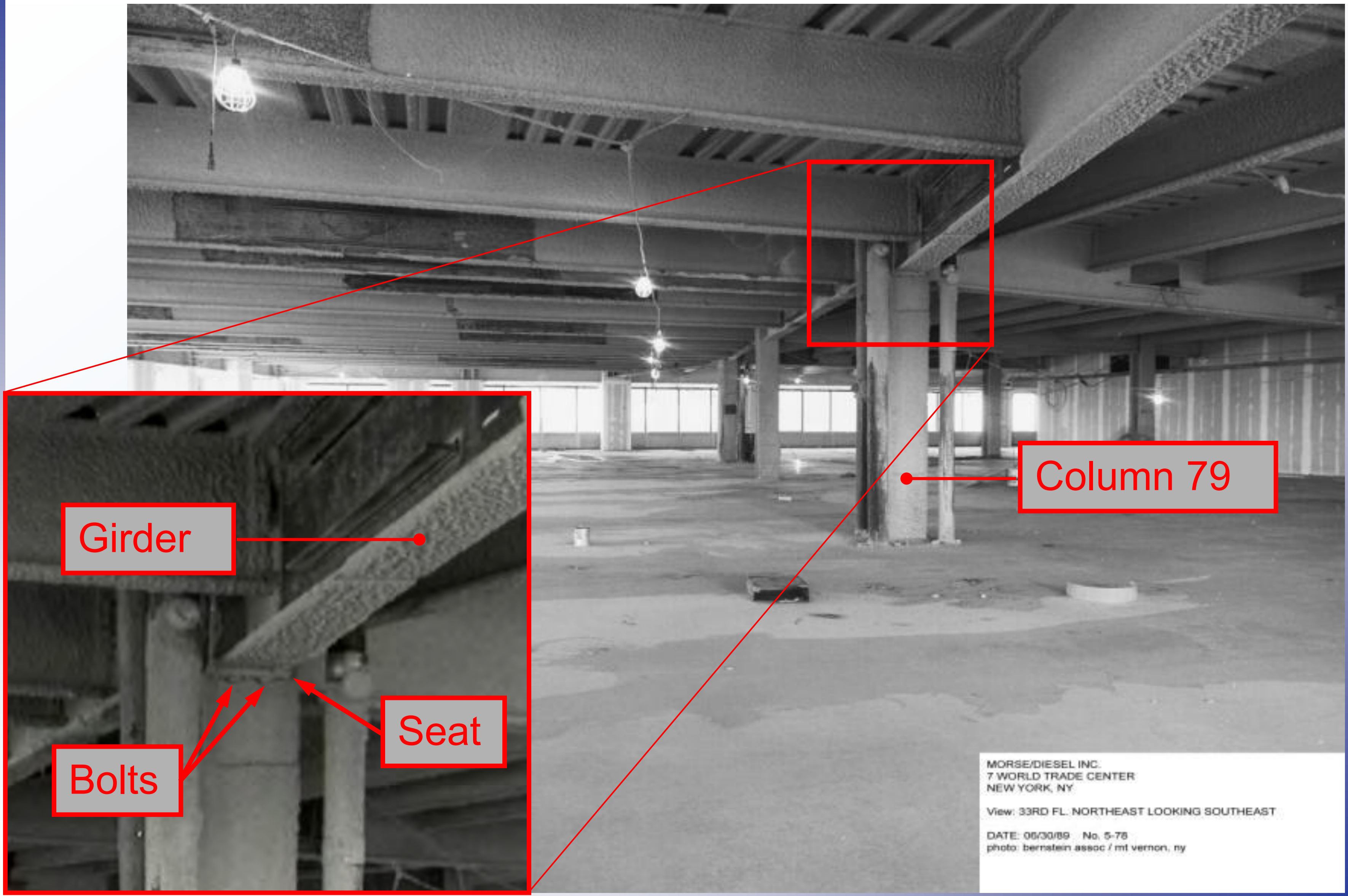
Summary Probable Collapse Sequence (3)

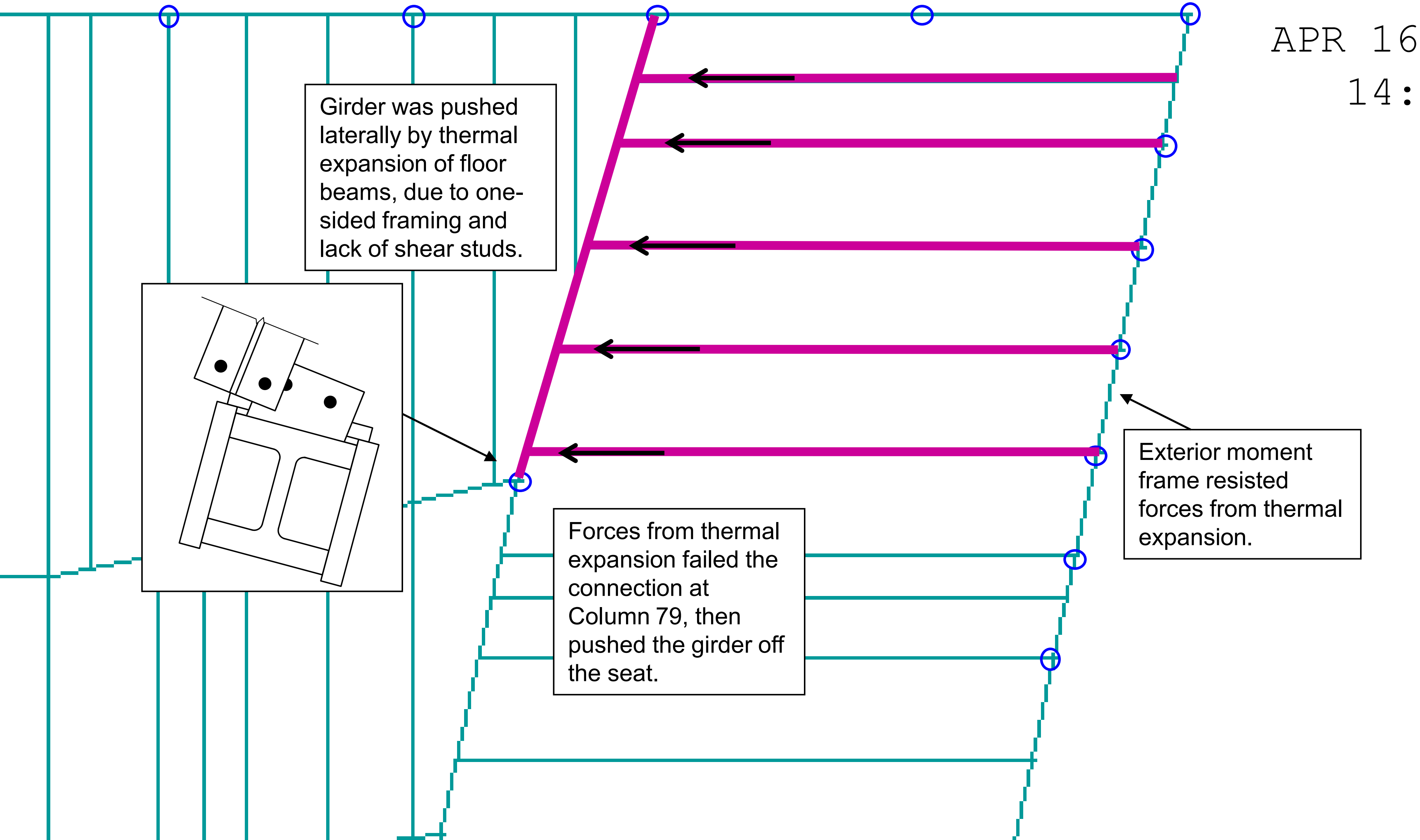
- **Initial Local Failure for Collapse Initiation.**
  - **Fire-induced thermal expansion of the floor system surrounding Column 79 led to collapse of Floor 13 that triggered a cascade of floor failures.**
  - **This, in turn, led to loss of lateral support to Column 79 over nine stories, resulting in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





North East Floor System Near Column 79



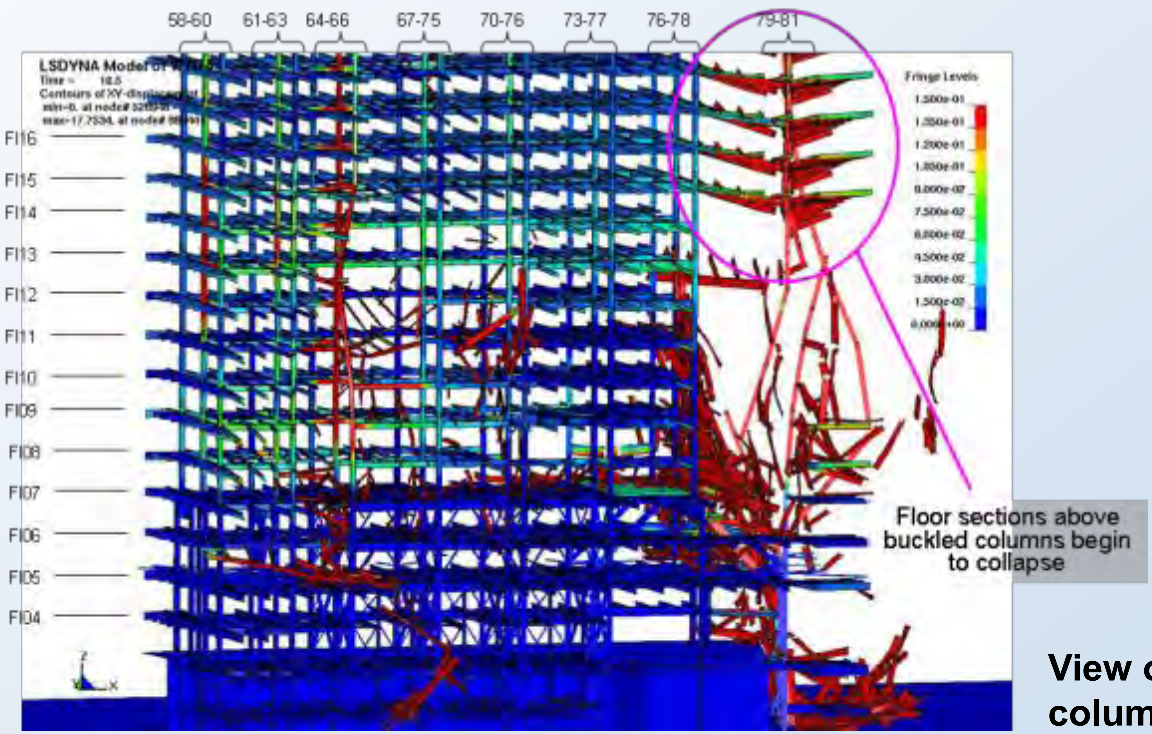

Girder was pushed laterally by thermal expansion of floor beams, due to one-sided framing and lack of shear studs.
Forces from thermal expansion failed the connection at Column 79, then pushed the girder off the seat.
Exterior moment frame resisted forces from thermal expansion.
APR 16
14:

Physics-Based Visualization of WTC 7 Collapse Initiation

View from South

Summary Probable Collapse Sequence (4)

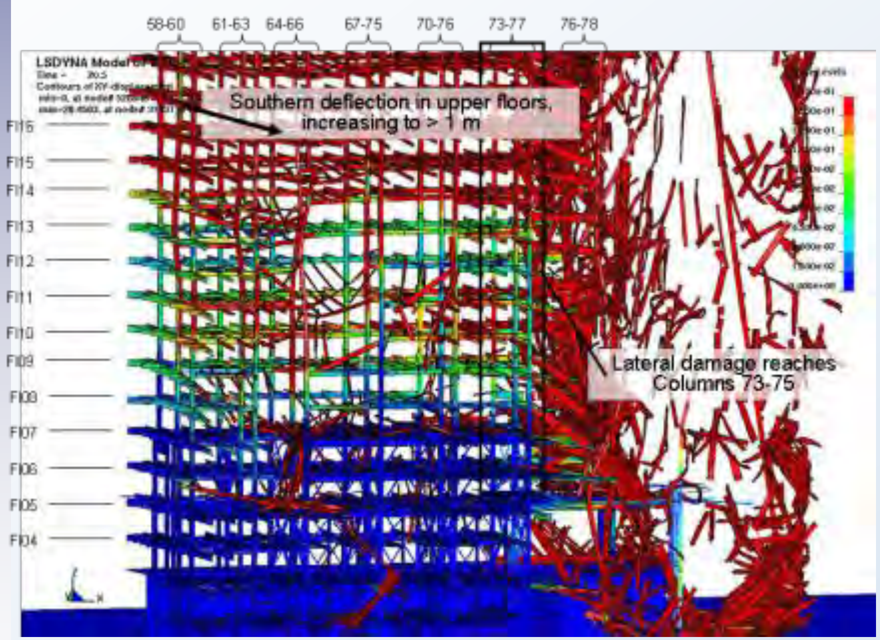
- **<u>Vertical Progression of Failure.</u>**
  - Buckling of Column 79 (the collapse initiation event) triggered a vertical progression of floor system failures to the east penthouse and subsequent cascading failure of the adjacent interior columns on the east side of the building (i.e., Columns 80 and 81).
  - Vertical progression of floor system failures spread to include the entire east region all the way to the top of the building.



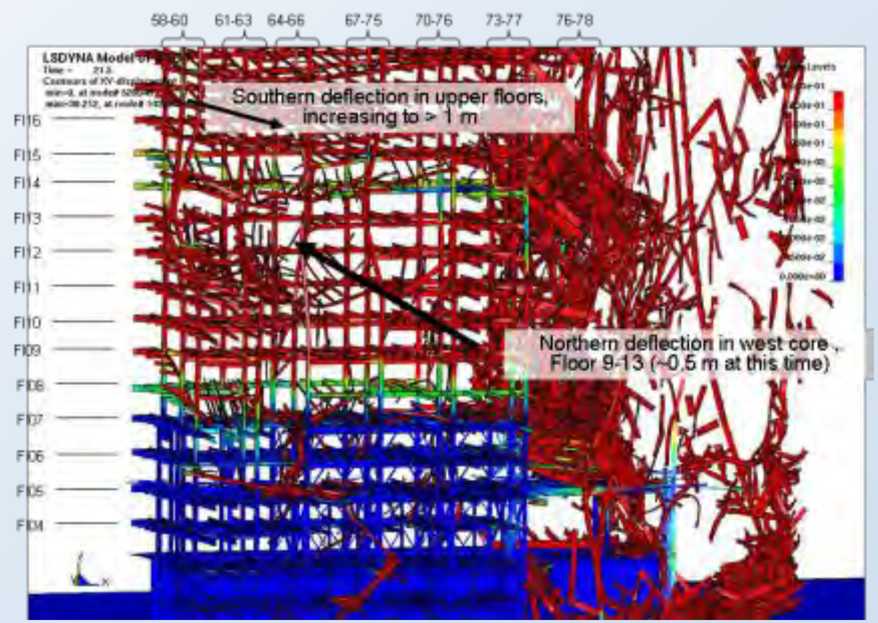
View of interior columns

Summary of Probable Collapse Sequence (5)

- **Horizontal Progression of Failure.**
  - The interior columns buckled in succession from east to west in the lower floors due to
    - loss of lateral support from floor system failures
    - forces exerted by falling debris
    - load redistributed from other buckled columns.



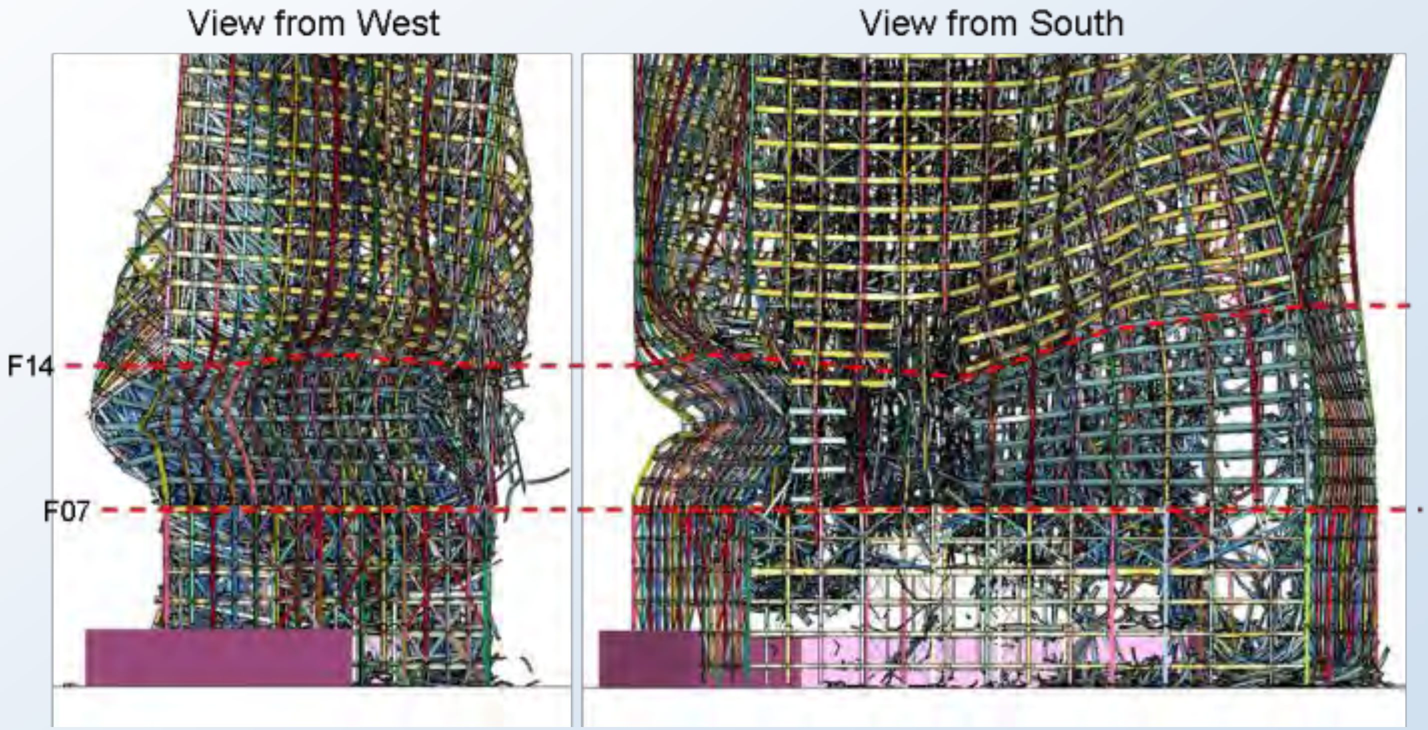
Failure progresses to the third line of interior columns from the east at 4.5 s following collapse initiation.



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

Summary Probable Collapse Sequence (6)

- **Global Collapse.**
  - The exterior columns buckled at the lower floors (between Floors 7 and 14) due to load redistribution to the exterior columns from the downward movement of the building core.
  - The entire building above the buckled-column region then moved downward in a single unit, as observed, completing the global collapse sequence.



Buckling of lower exterior columns.

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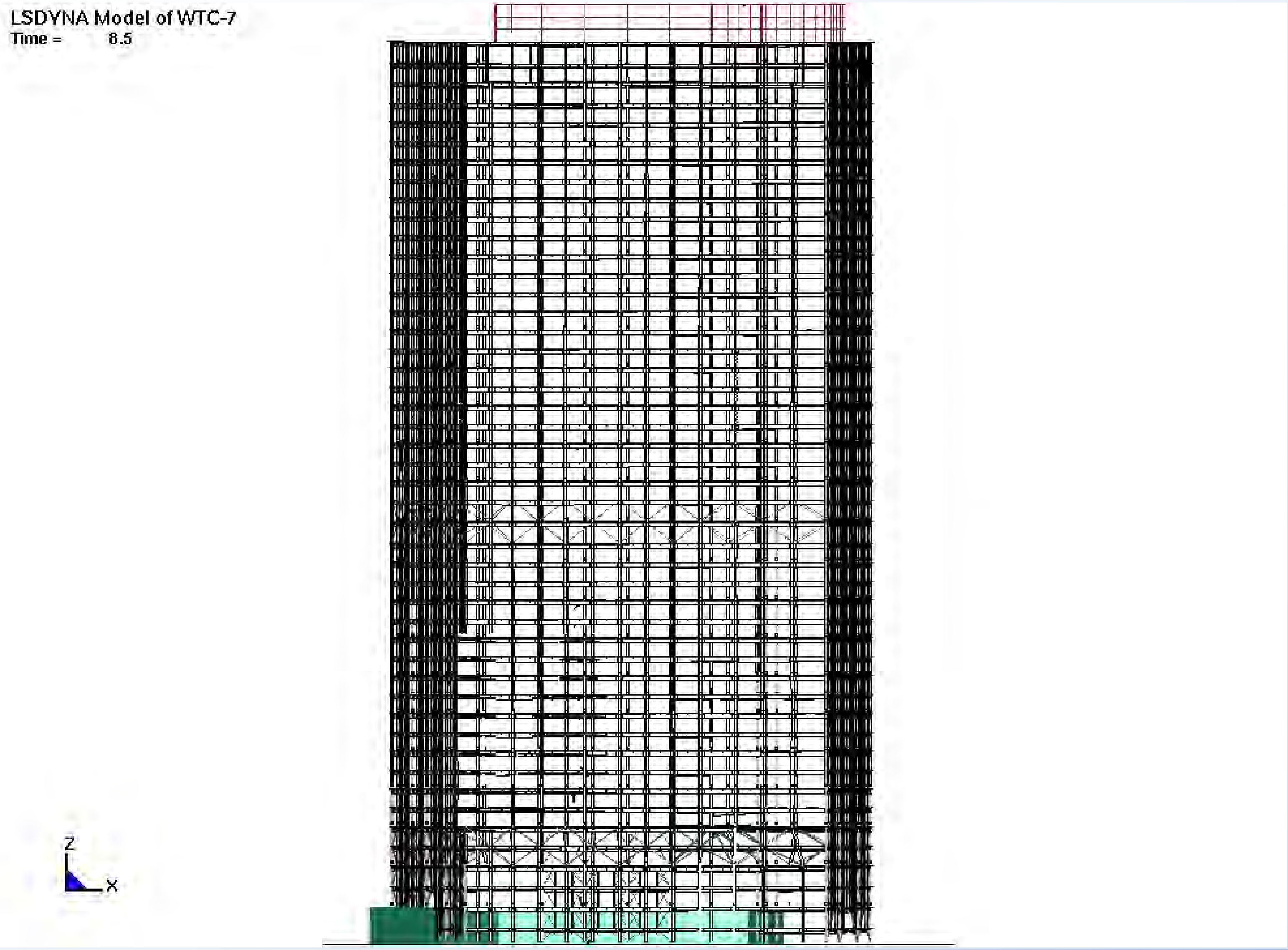
Video Evidence of WTC 7 Collapse

Physics-Based Visualization of WTC 7 Collapse

View from Northwest

Physics-Based Visualization of WTC 7 Collapse

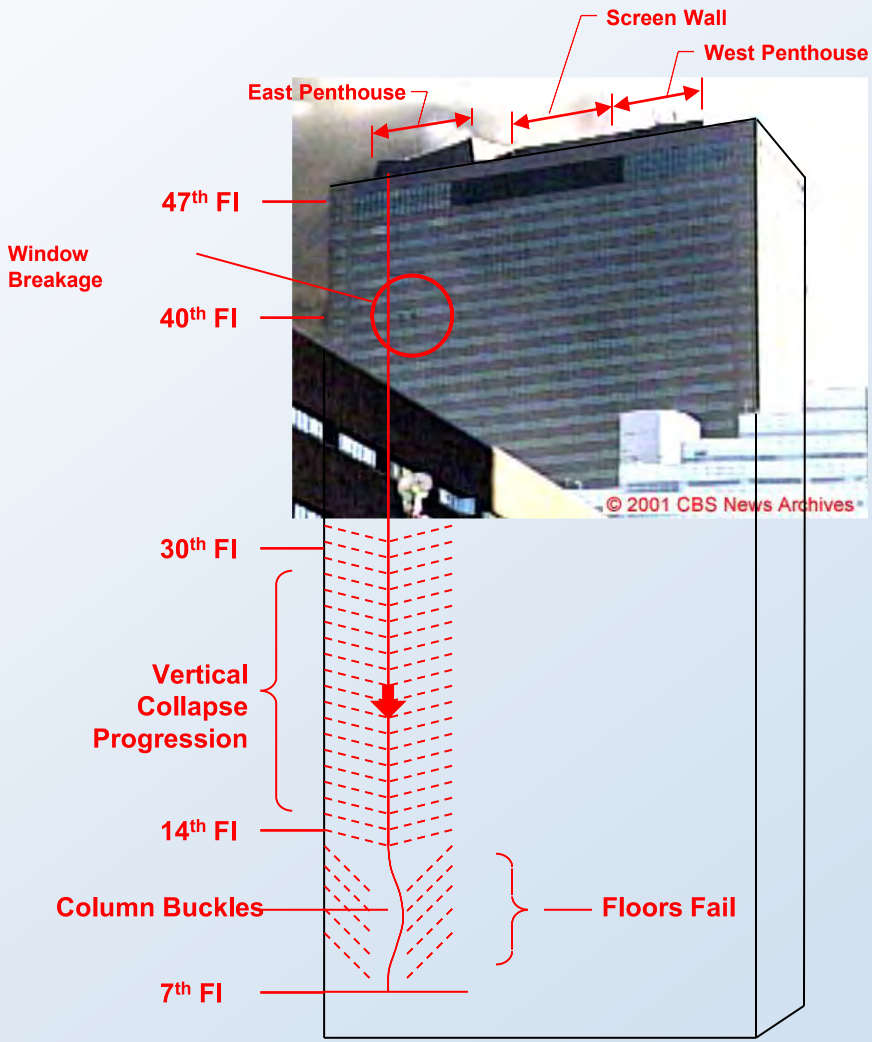


View from South

Collapse Initiation Observations

Exterior Observations

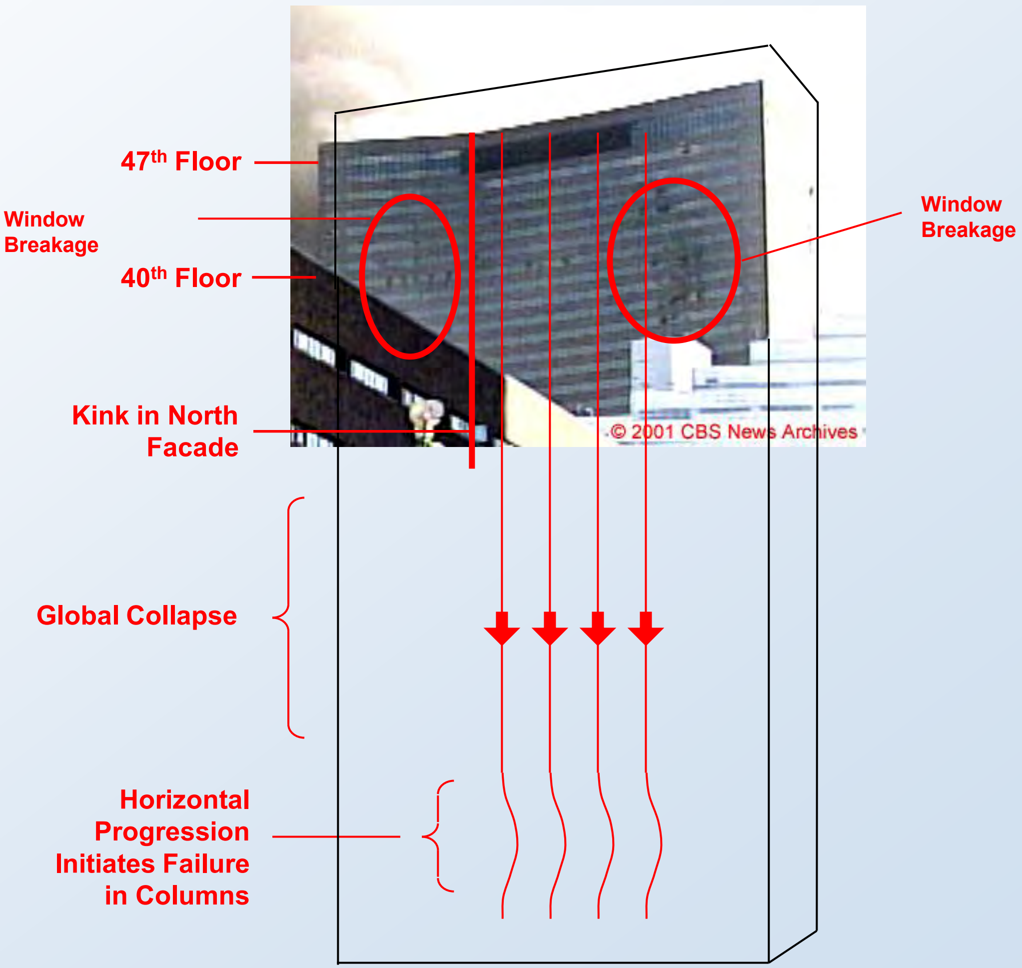
- East Penthouse Kinks
- Windows break on East Side of North Face



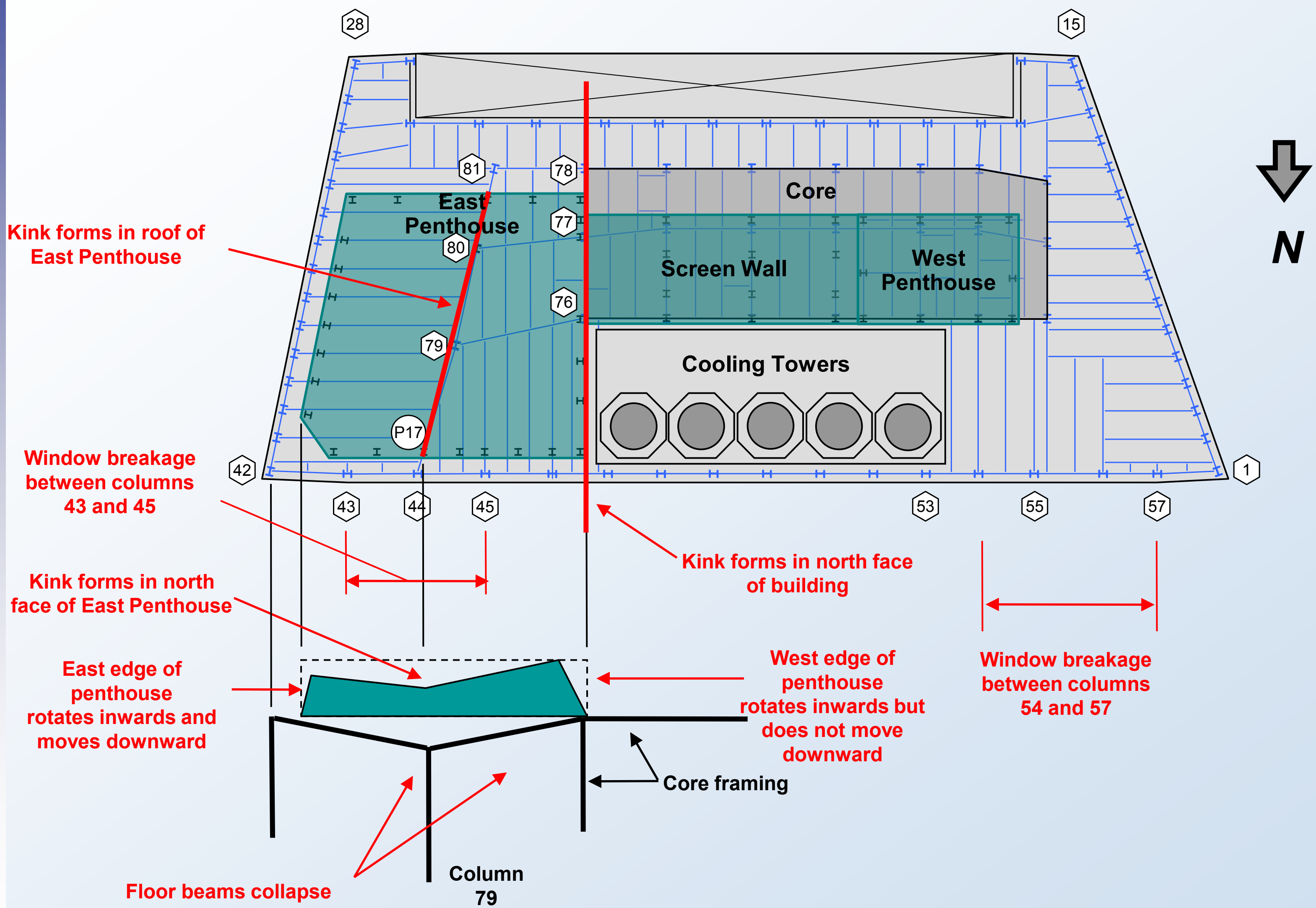
Global Collapse Observations

Exterior Observations

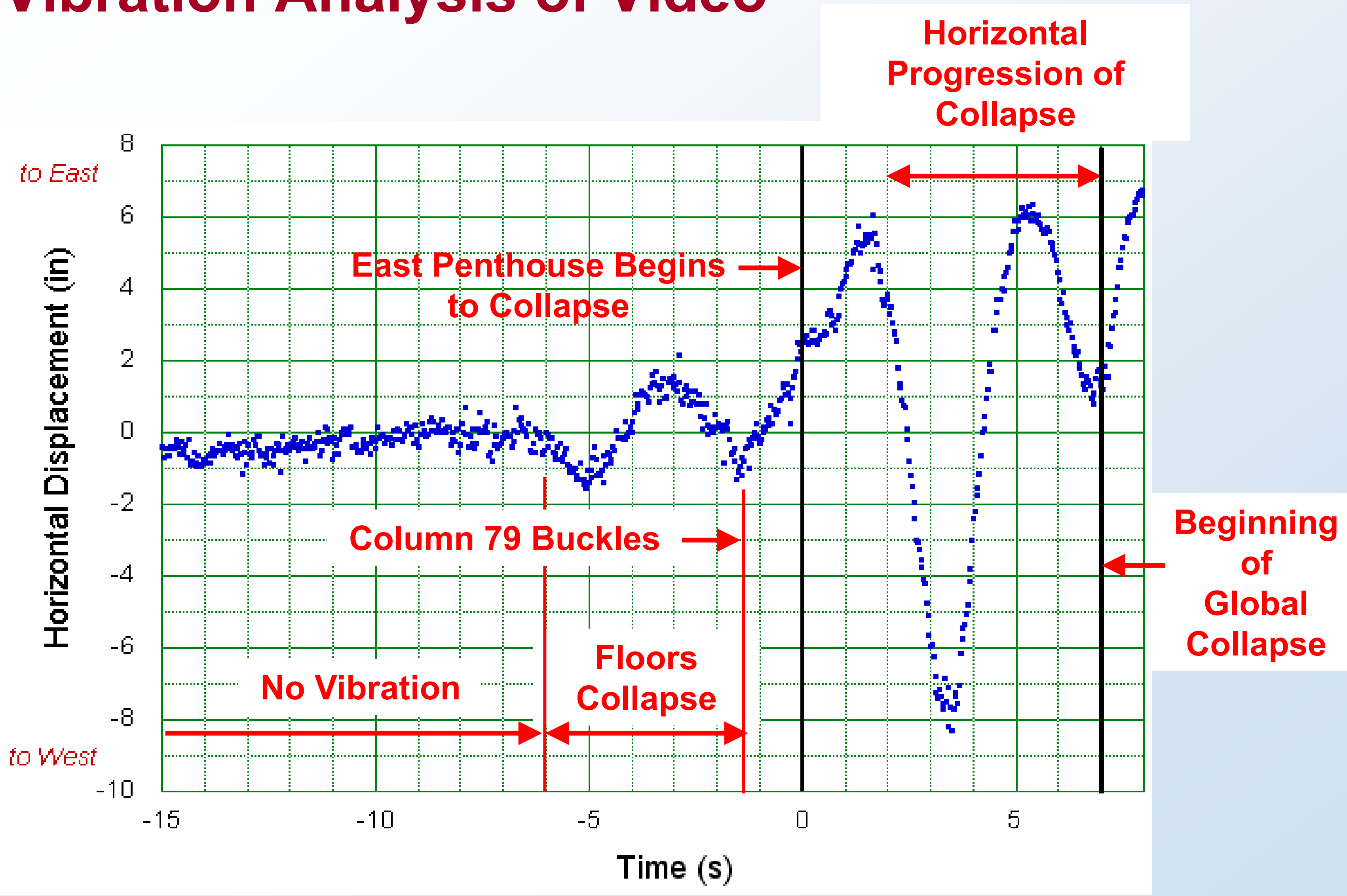
- Screenwall and West Penthouse Sink
- North Façade Kinks at Edge of Core
- Windows break on West Side of North Face



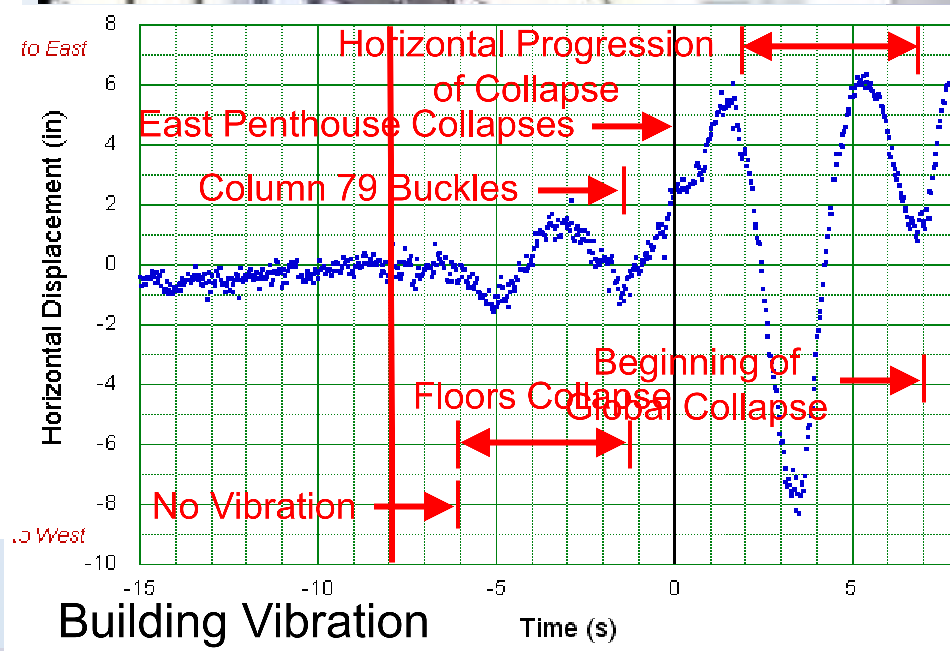
Collapse Observations



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 Time (s) w/Debris Damage	Analysis Time (s) w/o Debris Damage
Start of cascading failure of floors surrounding Column 79	≈ -6 s [a]	-6.6 s	-6.6 s
Buckling of Column 79, quickly followed by buckling of Columns 80 and 81	Not observable	-1.3	-1.4
Start of descent of east penthouse	**0.0**	**0.0**	**0.0**
Descent of east penthouse below roofline (First value: observed from the northwest and below; second value: observed from the north at the roofline)	2.0	2.4, 2.7	2.3, 2.6
Buckling of columns across core, starting with Column 76	Not observable	3.5-6.1	3.2-13.5
Initial downward motion of the north face roofline at the eastern section of the building	6.9	6.3	9.8
Descent of the east end of the screenwall below the roofline (First value: observed from the northwest and below, second value: observed from the north at the roofline)	8.5	7.3, 7.7	8.7, 9.2
Descent of the west penthouse below the roofline (First value: observed from the northwest and below, second value: observed from the north at the roofline)	9.3	6.9, 7.3	10.6, 10.9

[a] Based on vibration analysis

- **Agreement between observations and simulations is reasonably good, validating probable collapse sequence.**
- **Results with and without debris damage bound the observations; results with damage better match the observations of the overall global collapse sequence.**

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

NIST

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 gal tanks under the building.
  - Nearly all the fuel in these tanks was recovered months after the building collapse.
  - At most, 1000 gal of fuel was unaccounted from these tanks, which was equivalent to only about 5 percent of the office combustibles on a single floor.
  - The day tanks that supplied fuel to the emergency generators on these floors did not contain enough fuel to be a significant contributor to the combustible load on these floors.
    - 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 critical Column 79.
  - Fire did not reach the northeast region of the 7th, 8th, or 9th floors until about 4:00 p.m.

- **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 5th floor or that might have been pumped to that floor:**
  - Two types of over-ventilated fires in the vicinity of Column 79 (which was critical because observations and analysis indicated clearly that the failure of this column initiated collapse).
    - fuel burning sustained for the ≈ 7 h between the collapse of WTC 1 and the collapse of WTC 7.
    - burning rate double that of previous fire, i.e., a high intensity fire with significant duration.
  - Two types of under-ventilated fires in the vicinity of Column 79:
    - air handling system turned off and louvers closed; initial fuel burning rate fit to the air availability.
    - air handling system was turned off, but louvers were open.
  - An additional simulation of an over-ventilated fire near the breach in the south wall.

- **Hypothetical pool fires on the 5th and 6th 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 raise the temperature of 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 visible smoke that would have emanated from the exhaust louvers; however, 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. Once all 9 generators were down, there would have been no power to operate the fuel pumps, and the fires would have burned out well before columns in the region of the fire, including Column 79, experienced significant loss of strength.

Role of Fuel Oil Fires (3)

- The day tank on Floor 5 supplying the remaining 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 the location of critical 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 in the over-ventilated 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.
- FDNY personnel reported that they did not see any indication of burning liquid fuels before the building collapsed.

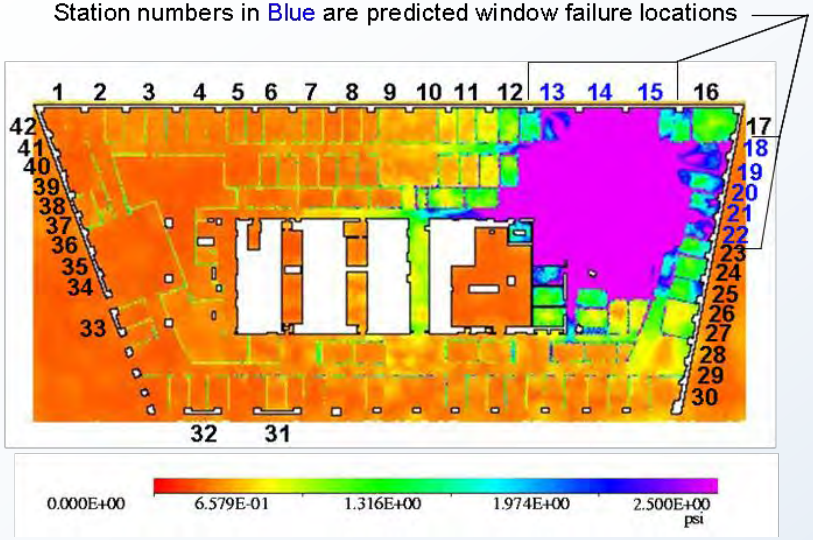
Other Possible Hypotheses: Role of Blast Events

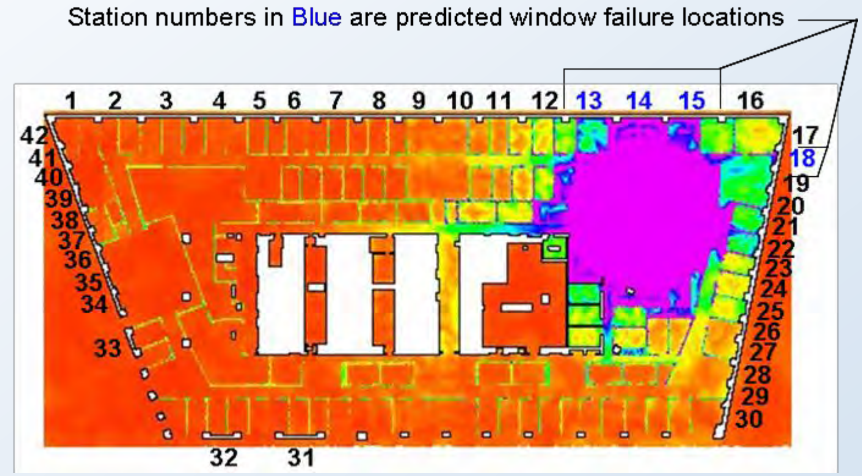
- Scenarios of a hypothetical blast event that could have occurred in WTC 7 on September 11, 2001, were assessed, including blast location, size, and timing.

- **Phase I: Identify hypothetical blast scenarios to initiate structural collapse.**
  - A scenario with the minimum amount of required explosive (9 pounds of linear shape charge of RDX) was identified, which was appropriate for the columns on the east side of the building.
  - The recommended column preparation for use of this shape charge required at least 30 minutes (cutting and placing).
  - Additional preparation time was required to clear the column for cutting, such as removing walls or other coverings that might have restricted access to bare steel at a column section.

- **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 case identified in Phase I.
  - Calculations were performed for a lesser charge size of 2 pounds to evaluate threshold explosive requirements for breaking windows.
  - There were 4 blast analyses performed in total, consisting of two different charge sizes (2 or 9 lbs of RDX) and two floor layouts with differing partition layouts in the tenant areas.

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.**
  - An acoustic analysis was performed to assess the distance from the building that the blast would have been audible.
  - Adjacent buildings and their effect on the sound propagation was not considered in this analysis; however, sound from a blast in an urban setting would be reflected and channeled down streets with minimum attenuation due to the hard building exteriors.
  - For all four scenarios, significant audible sound was predicted from all building faces.
  - If propagation was unobstructed the sound level from all building perimeter openings at 1 km would be 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 intentional demolition, walls and/or column enclosures and SFRM would have to be removed and replaced without being detected.
  - Preparing the column includes steps such as cutting sections with torches (which produces noxious and odorous fumes), and careful placement of charges and an initiation device.
  - A much larger charge would be required to fail the column without prior preparation, including cutting; the resulting sound level and extent of window breakage would be much greater.
  - Intentional demolition usually prepares most, if not all, interior columns in a building with explosive charges, not just one column.
  - It is unlikely that explosive charges would have been applied to just one column (that being the critical column) or 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 typical controlled demolition where charges are placed in multiple locations 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 into and out of the Con Edison substation 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.
  - At 4:33 p.m., the utility control center isolated the WTC 7 Con Edison substation by opening the 138 kV circuit breakers feeding the WTC 7 substation.

- 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, and stayed in alarm mode until the substation was isolated from incoming feeders at 4:33 p.m.
  - There were no other indications (e.g., no high temperature alarms from the transformers, no visible smoke emanating from the Con Edison substation) that a fire occurred within the substation during that period of time.
  - Likely causes of the fire alarm were the smoke and dust dispersed in the area of the substation 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—with SFRM applied to the underside of the metal deck—indicates that 0.5 in. of the SFRM product used in WTC 7 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**. (standard deviation 0.054 in. and coefficient of variation of 0.101). The 82 observations typically ranged between 0.425 in. and 0.630 in.
- **The SFRM thickness applied to the framing of the composite floor system was consistent with a 2 h fire resistance rating.**

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 resulted in seven exterior columns being severed and subsequently withstood 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. The collapse could not have been prevented without controlling the fires before most of the combustible building contents were consumed.
- **WTC 7 collapsed due to uncontrolled fires with characteristics similar to other tall buildings with uncontrolled fires.**
  - 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.
  - Fires for the range of combustible contents in WTC 7 (4.0 psf on Floors 7 to 9 and 6.4 psf on Floors 11 to 13) persisted in any given location for approximately 20 to 30 minutes.
  - 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 local fire origin on any given floor in WTC 7.**
  - In most instances, the fire on any given floor likely initiated near the damaged southwest region, though collapse initiation did not occur until nearly seven hours later in the northeast region.
  - Unlike the WTC towers, there was no dispersion of jet fuel in WTC 7 causing simultaneous fire initiation over extensive areas of multiple consecutive floors.

- **The probable collapse sequence that caused the global collapse of WTC 7 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, due to loss of lateral support to adjacent columns, forces exerted by falling debris, and load redistribution from other buckled columns.
  - 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 fire-induced 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.**
  - WTC 7 was prone to classic progressive collapse in the absence of fire-induced or debris impact damage when a section of Column 79 between Floors 11 and 13 was removed. The collapse sequence demonstrated a vertical and horizontal progression of failure upon the removal of the Column 79 section, followed by downward movement at the roofline due to buckling of exterior columns, which led to the collapse of the entire building.
- **The transfer elements (trusses, girders, and cantilever overhangs) and the –strong" 5th and 7th floors 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 (4)

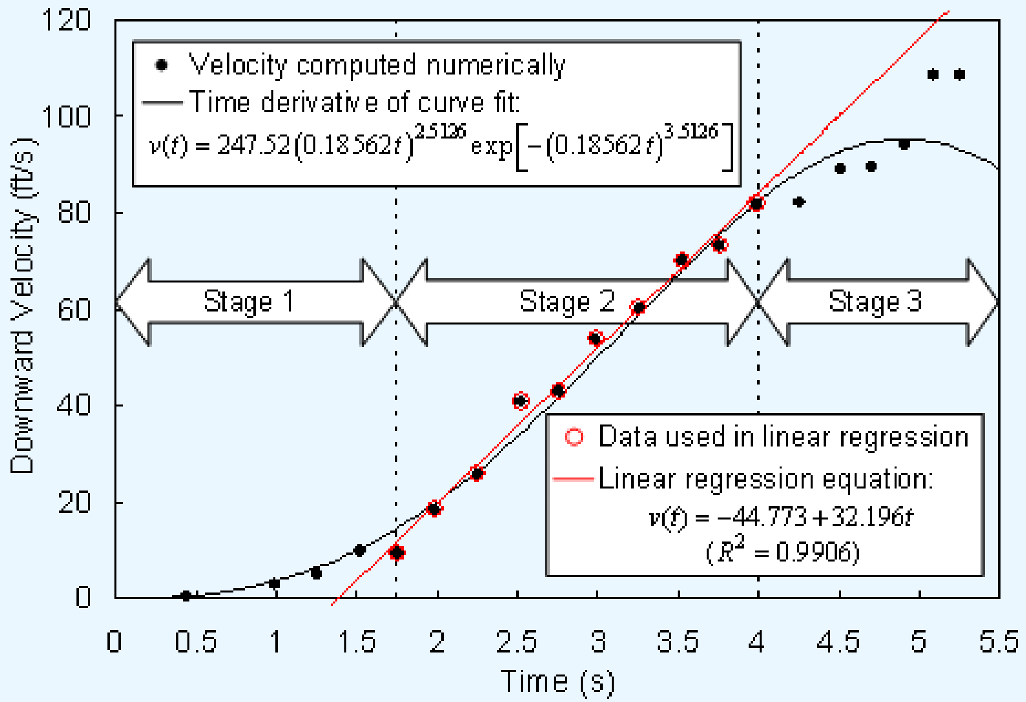
- There was no evidence of damage to the SFRM that was applied to the steel columns, girders, and beams, except in the vicinity of the structural damage from the collapse of WTC 1, which was near the west side of the south face of the building. This is consistent with observations NIST made in the 130 Liberty St building that suffered similar debris damage from the collapse of WTC 2.

- **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 core area adjoining the interior columns.

Principal Findings for Objective 1: Probable Collapse Sequence (5)

- **Collapse time of the north face (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 descend 18 stories, based on video evidence, was approximately 5.4 s and the computed free fall time was 3.9 s.
- **A detailed analysis of the descent of the north face found 3 stages:**
  - A slow descent at less than gravitational acceleration, corresponding to column buckling
  - A free fall descent at gravitational acceleration over approximately 8 stories
  - A decreasing acceleration, as the north face encountered resistance from the structure below.



Principal Findings for Objective 1: Probable Collapse Sequence (6)

- **Diesel fuel fires did not play a role in the collapse of WTC 7.** The worst-case scenarios associated with fires being fed by ruptured fuel lines (or from fuel stored in day tanks on the lower floors):
  - could not have been sustained long enough, or could not have generated sufficient heat, to raise the temperature of a critical column (i.e., Column 79) to cause significant loss of strength/stiffness
  - would have produced large amounts of visible smoke that would have emanated from the exhaust louvers. No such smoke discharge was observed.

- **Blast events did not play a role in the collapse of WTC 7.**
  - Based on visual and audio evidence and use of specialized computer modeling, NIST concluded that blast events did not occur, and found no evidence whose explanation required invocation of a blast event.
  - Blast from the smallest charge capable of failing a critical column (i.e., Column 79) would have resulted in a sound level of 130 dB to 140 dB at a distance of at least half a mile if unobstructed by surrounding buildings (such as along Greenwich Street or West Broadway); the sound be reflected and channeled with minimum attenuation down urban streets with hard building exteriors.
  - The sound level resulting from such a charge is 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.
  - 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 two 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 officials held the occupants in the building lobby until they identified an exit path that was safe from the debris falling from WTC 1 across the street.

- Evacuation of the building took just over an hour, about 30 min longer than the estimated minimum time if the elevators and stairs had been used to maximum advantage.
  - Occupants were able to use both elevators and stairs, which were as yet not damaged, obstructed, or smoke-filled.
  - Some of the additional evacuation time was due to the considerable crowding in the lobby.
  - Occupants arrived in the lobby from both stairwells, from the elevators, and from other WTC buildings, and were held in the lobby until a safe exterior 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.** It was not clear whether specific guidance was delivered to the occupants via the public address system.

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 were based on 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 on the contract for applying SFRM to the structural steel, indicate a type 1-B (3 h protected) classification.
- **The design of WTC 7 was generally consistent with the NYCBC.**
  - NIST did not conduct an exhaustive review of WTC 7 to determine its compliance with the NYCBC. NIST only has documentary or anecdotal evidence indicating compliance.

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.**
- **The passive fire resistance design of WTC 7 was based on catalogued ASTM E 119 test data, which is the practice today, and was in the 1980s. 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:**
  - ***important 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)

- **Determination of the actual fire performance of the WTC 7 structural system was not the responsibility of any of the design professionals associated with the design, construction, or maintenance of WTC 7. 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 that is needed for the structure to comply with the building code.
  - Architects are not required to explicitly evaluate the fire performance of the structure as a system (such as analyzing the effect of the thermal expansion or sagging of floor beams on girders, connections, and/or columns).
  - 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.***

- **The design of WTC 7 did not include a specific analysis of how the structure might perform in a real fire. 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

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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, which is not currently considered in design practice.
- 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

- Human performance factors 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.
- Other human performance factors 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.

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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.**
  - A few of the prior recommendations have been modified to reflect the findings of this Investigation.

- The **13 recommendations** for improvements to codes, standards, and practices fall into **7 of the 8 major groups that were identified for the recommendations from the investigation of the WTC towers**:

Increased Structural Integrity	**Structural Design**
Enhanced Fire Resistance of Structures	**Structural Design**
New Methods for Designing Structures to Resist Fires	**Structural Design**
Improved Active Fire Protection	**Life Safety Systems**
Improved Building Evacuation (not applicable for WTC 7)	**Life Safety Systems**
Improved Emergency Response	**Life Safety Systems**
Improved Procedures and Practices	**Practices & Development**
Education and Training Programs	**Practices & Development**

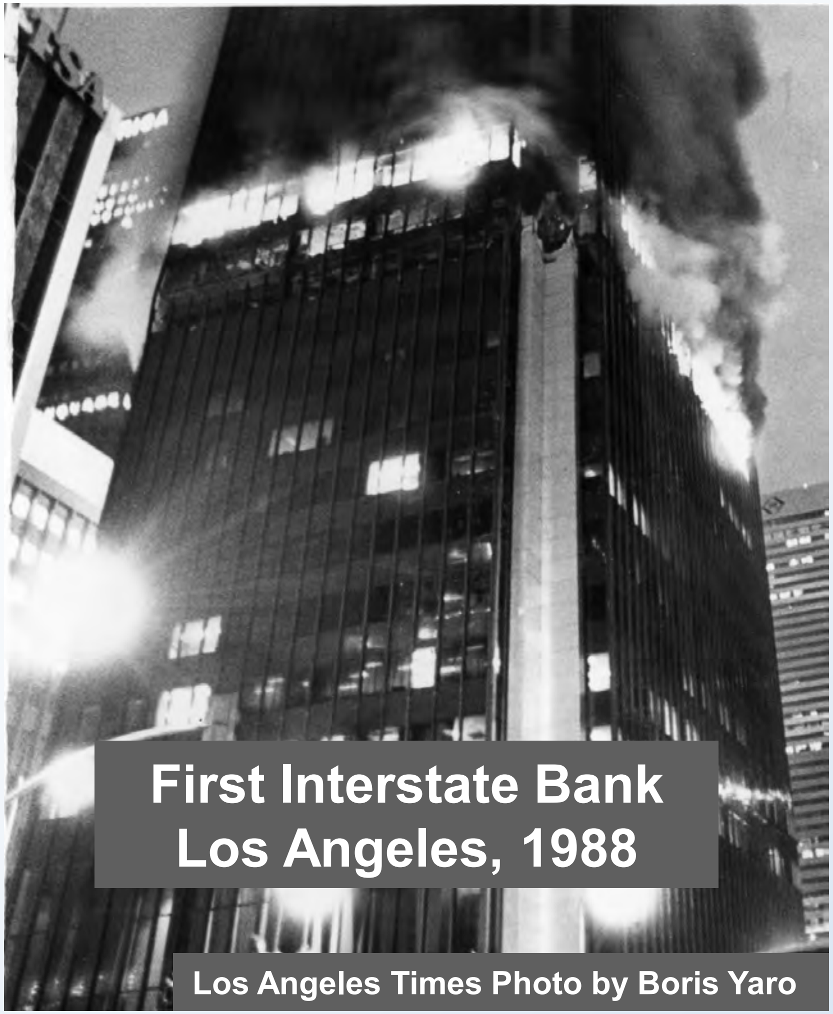
Comparison of WTC 7 and WTC Towers

- 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

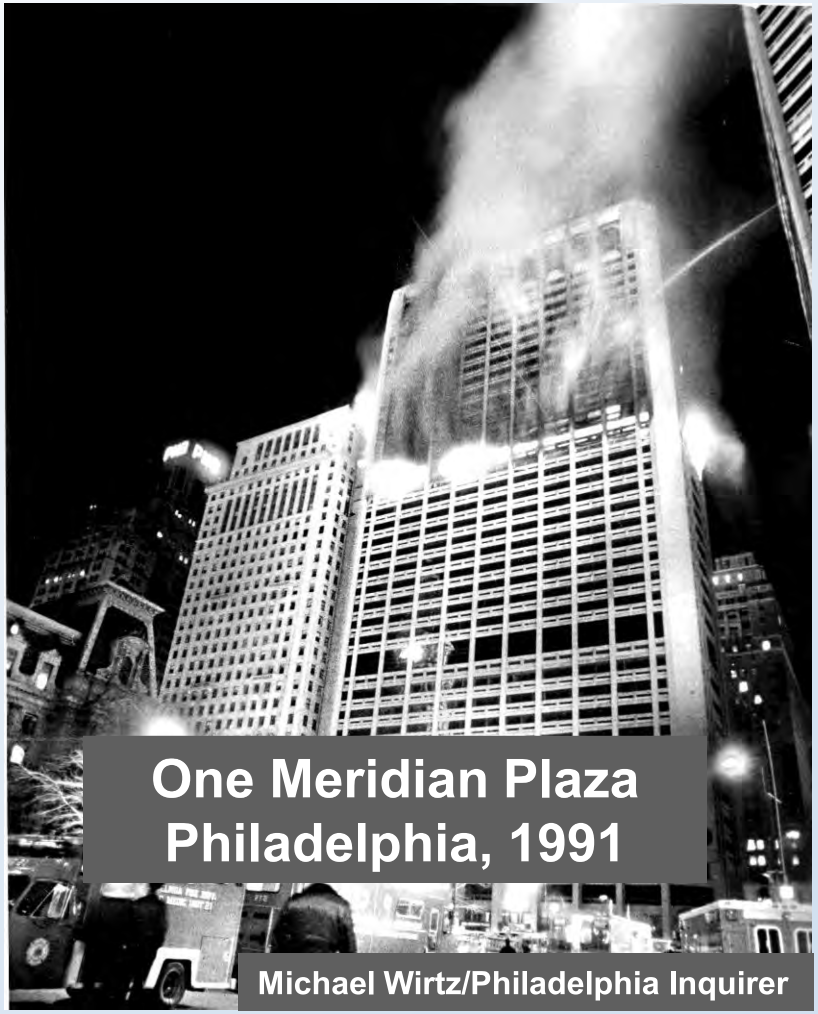
- The partial or total collapse of a building due to fires is an infrequent event.
- This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system.
- A properly designed and operating automatic sprinkler system will contain 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



First Interstate Bank
Los Angeles, 1988

Los Angeles Times Photo by Boris Yaro



One Meridian Plaza
Philadelphia, 1991

Michael Wirtz/Philadelphia Inquirer

Characteristics of Infrequent (Uncontrolled) 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 contemporaneous standards and practices been available to expressly design WTC 7 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 the adequate performance of the structural system under maximum credible (infrequent) design fires with any active fire protection system rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features:

- **long-span floor systems which experience significant thermal expansion and sagging effects,**
- **connection designs (especially shear connections) that cannot accommodate thermal effects,**
- **floor framing that induces asymmetric thermally-induced (i.e., net lateral) 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 free thermal expansion on the steel framing systems, especially for the long spans on the east side of WTC 7, were not considered in the structural design and led to the initiation of the building collapse.

NIST

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)

<u>Recommendation C (NIST NCSTAR 1 Recommendation 4)</u>. 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 now as much as possible—by explicitly considering factors including:

- **timely access by emergency responders and full evacuation of occupants, or the time required for burnout without partial collapse;**
- **the extent to which redundancy in active fire protection (sprinkler and standpipe, fire alarm, and smoke management) systems should be credited for occupant life safety;**
- **the need for redundancy in fire protection systems that are critical to structural integrity;**
- **the ability of the structure and local floor systems to withstand a maximum credible fire scenario without collapse, recognizing that sprinklers could be compromised, not operational, or non-existent;**
- **compartmentation requirements (e.g., 12,000 ft^2) to protect the structure, including fire rated doors and automatic enclosures, and limiting air supply (e.g., thermally resistant window assemblies) to retard fire spread in buildings with large, open floor plans;**
- **the effect of spaces containing unusually large fuel concentrations for the expected occupancy of the building; and**
- **the extent to which fire control systems, including suppression by automatic or manual means, should be credited as part of the prevention of fire spread.**

***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. Such evaluation is not required under current codes and standards.

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 temperatures lower than the endpoint criteria (593 C) 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 structural breakdowns that led to the initiating event and the eventual collapse of WTC 7 occurred at temperatures that were hundreds of degrees below the criteria that determine structural fire resistance ratings.
- **The United States currently does not have the capability for studying and testing these important fire-induced phenomena critical to structural integrity.**

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

Recommendation F (NCSTAR Recommendation 8). 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 not consumed the combustible building contents, yet collapse occurred.

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.** Standards development organizations, including the American Institute of Steel Construction, have already begun developing performance-based provisions to consider the effects of fire in structural design.

***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

Recommendation I (NIST NCSTAR 1 Recommendation 24). 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) was located in WTC 7 and was evacuated early in the day before key fire ground decisions had to be made. The location of OEM in WTC 7 contributed to the loss of robust interagency command and control on September 11, 2001.
- 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 (e.g., decisions not to fight the fires in WTC 7 and to turn off the power to the Con Edison substation) 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 evaluating the building condition), 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)

<u>Recommendation K (NIST NCSTAR 1 Recommendation 28)</u>**. 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 providing the standard of care 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 providing the standard of care 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 could have identified the potential for the failure and 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 fire protection engineers and architects in structural engineering principles and design,**
- **training structural engineers, architects, fire protection engineers, and code enforcement officials in modern fire protection principles and technologies, including fire-resistance design of structures, and**
- **training building regulatory and fire service personnel to upgrade their understanding and skills to conduct the review, inspection, and approval tasks for which they are responsible.**

The outcome would further the integration of the disciplines in effective fire-safe design of buildings.

***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*.

- NIST held a **conference** September 13-15, 2005 attended by **over 200 people, including *all major standards and codes developers.***

- NIST awarded a contract to the National Institute of Building Sciences—a Congressionally authorized non-profit, non-governmental organization—to **turn appropriate recommendations into code language suitable for submission** of code change proposals **to the two national model code developers.** NIBS has drawn upon broad, representative group of building code experts to carry out this task.

- **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.

Changes to Building Codes and Standards

- First comprehensive set of eight model building code changes based on recommendations from NIST's WTC investigation adopted by the International Building Code in the 2007 supplement to the 2006 IBC.

- A set of 23 comprehensive and far reaching model building code changes based on NIST's WTC recommendations were approved by the ICC for the 2009 edition of the IBC and the IFC.

- 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
  - Council on Tall Buildings and Urban Habitat

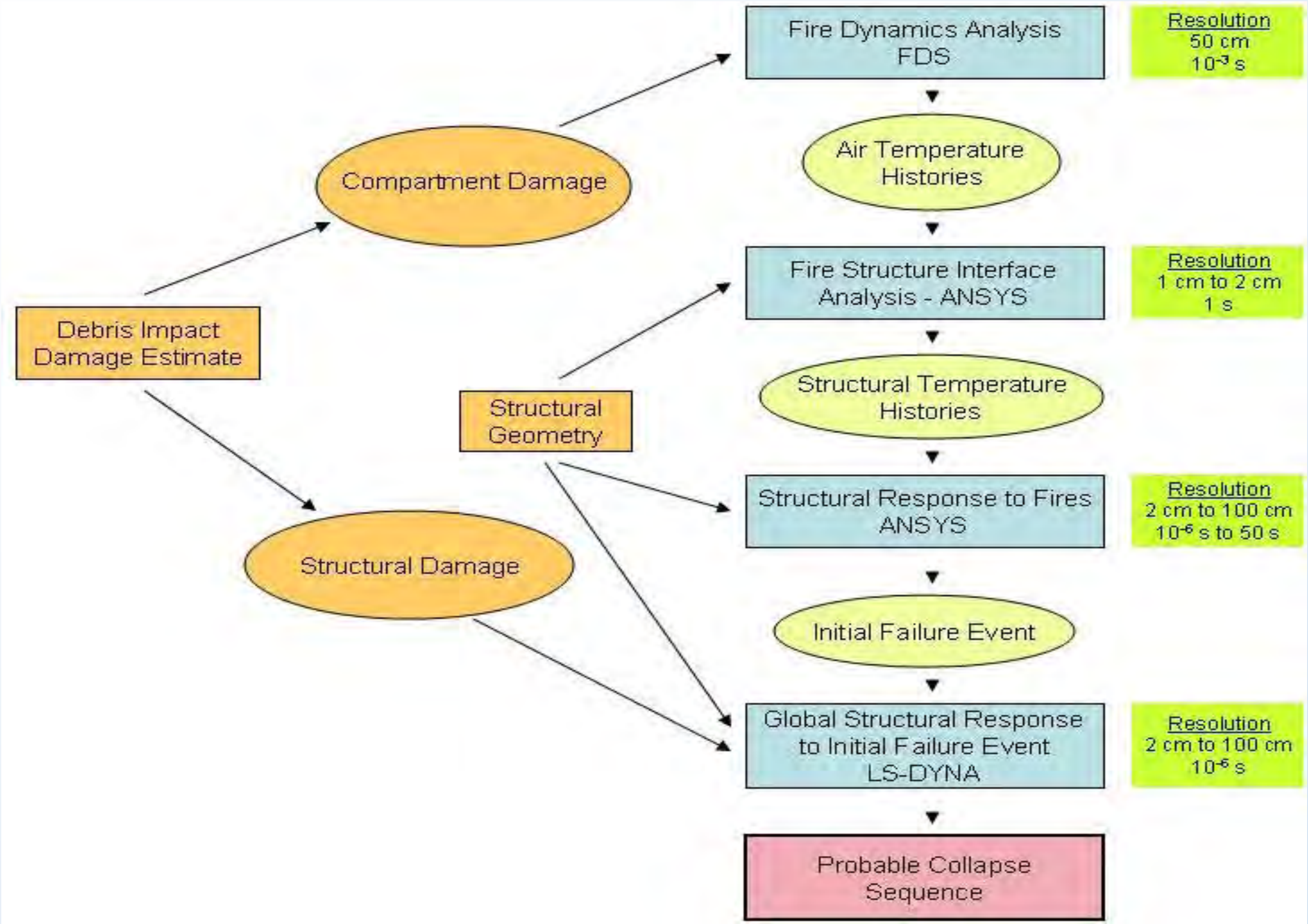
Web site http://wtc.nist.gov

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.

Critical Analysis Inter-Dependencies



Early Fire Development (10:28 am to 2:30 pm)

- Ignition of local fires on several floors of WTC 7 was likely caused by flaming debris, impact-induced electrical failures, etc., on the southwest corner due to collapse of WTC 1. Each ignition was likely a single workstation component or office furnishing item; growth over the full cluster of workstations or office took several minutes.
- Floors 7 through 9:
  - Initial fire spread by flame contact with an adjacent workstation.
  - Once a cluster was burning, radiative ignition of a nearby workstation would have occurred (across an aisle); by the time this second cluster was fully involved, the prior cluster would have burned out.
  - The path of the fires likely jumped from workstation to workstation, meandering toward the windows, toward the core, or parallel to the façade.
  - Eventually the upper gas layer over enough of the huge open space would likely be hot enough for radiatively enhanced ignition of multiple workstations, i.e., non-linear growth.
  - The fires on Floors 7 and 8 didn't enhance much by 2:30 p.m.
- Floors 11 through 13:
  - The fire would likely grow within an office, reaching flashover in several minutes.
  - After about 15 minutes, the ceiling tile system would likely fail and the hot gases would create a local hot upper layer.
  - Adjacent offices would likely ignite. Offices across a corridor would likely ignite more slowly.
- Fires on the 7th and 8th floors couldn't spread to the east along the south face because of barriers to spread or lack of combustibles. The interior layout of the 9th floor was not well documented; fires were not observed until about 4:00 pm. The office-to-office spread along the south of Floors 11 through 13 was slow due to presence of walls.

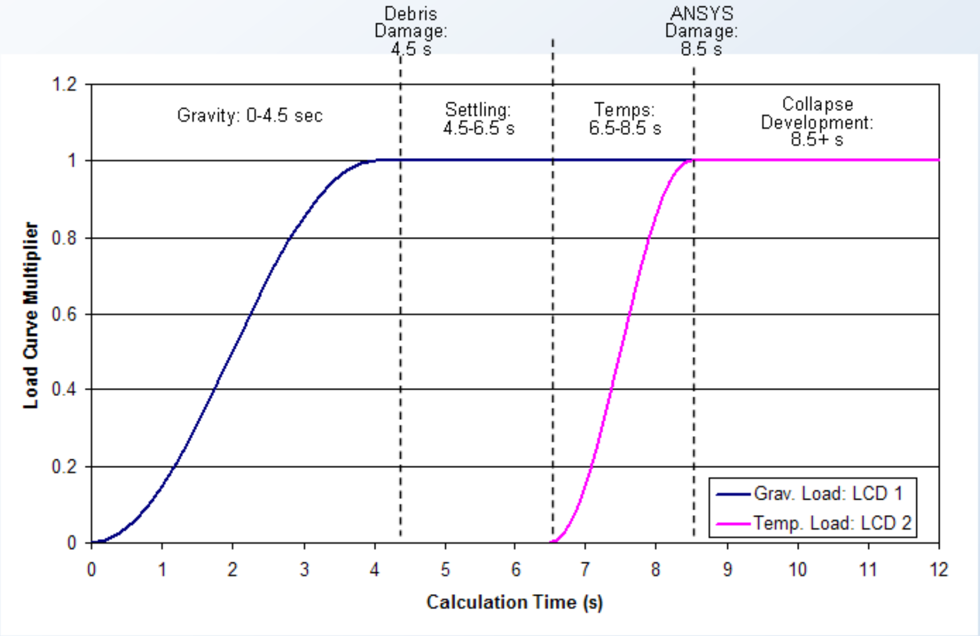
LS-DYNA Model Loading Sequence

1. Gravity loads were applied smoothly over 4.5 s using a sinusoidal curve to eliminate dynamic response.

2. Debris impact damage from the collapse of WTC 1 was then applied instantaneously by removing elements from the model. The structure was then allowed to damp residual vibrations over 2 s.

3. Elevated temperatures from the ANSYS thermal analysis were next applied smoothly over 2 s using a sinusoidal curve to eliminate dynamic response.

4. Fire-induced damage (buckled beams and connection capacities that were reduced) obtained from the 16-story ANSYS structural analysis was finally applied instantaneously and the computation model proceeded to initiate and propagate collapse, up to global collapse.

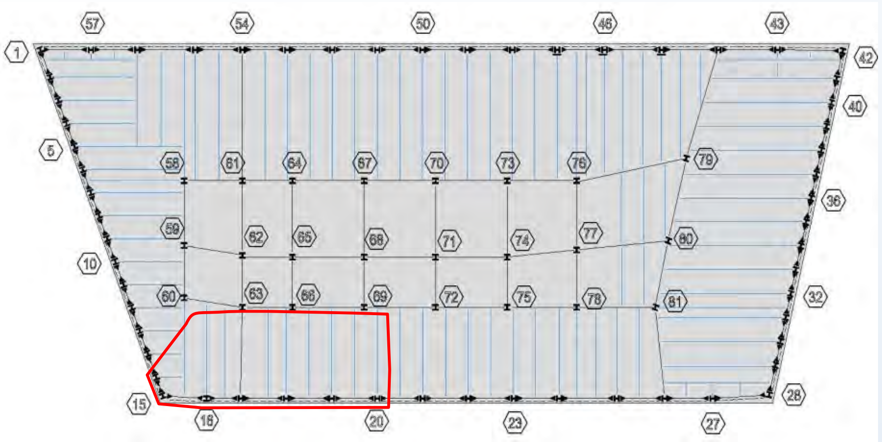


- The response of the building with fire-induced damage from the 16-story ANSYS analysis at 4.0 h (both with and without debris impact damage) was consistent with the timing of key events in the recorded videos of the collapse.

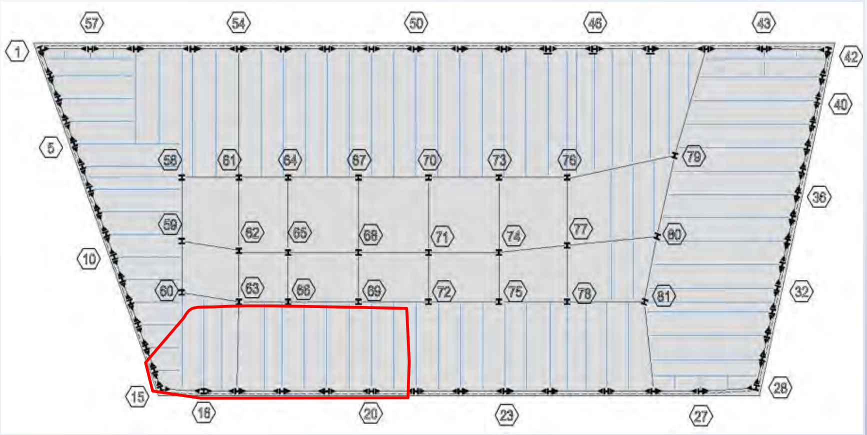
- The response of the building to fire-induced damage from the 16-story ANSYS analysis at 3.5 h (damage in the south and southeast regions of WTC 7 on multiple floors) did not result in collapse of the building.

- **The LS-DYNA analysis approach minimized any spurious dynamic effects associated with loading sequence.**

Estimated Debris Impact Damage by Floor

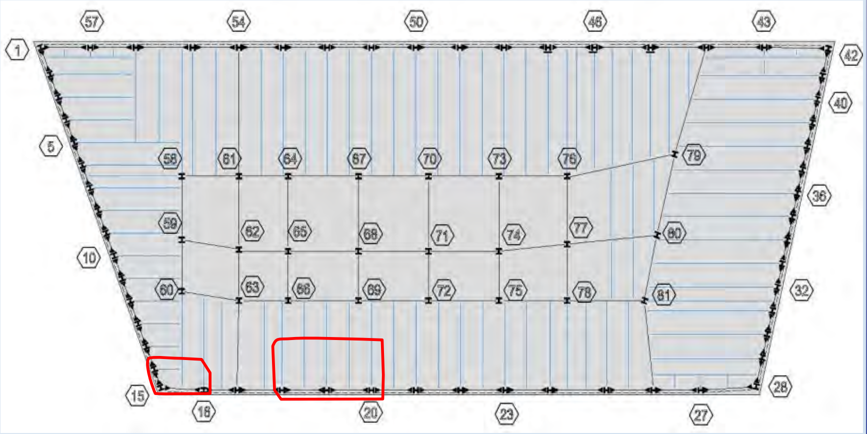


Floor 8



Floor 9

Floors 10 and 11



Floors 12 to 14

Details of Collapse Initiation (1)

- The simple shear connection between Column 79 and the girder that spanned the distance to the north face (to Column 44) failed on Floor 13.
  - The connection failed due to shearing of erection bolts, caused by lateral thermal expansion of floor beams supporting the northeast floor system.
  - Further thermal expansion of the floor beams pushed the girder off its seat.
  - The displaced girder and other local fire-induced damage led to the failure of the floor system surrounding Column 79 on Floor 13.
- The collapse of Floor 13 onto the floors below—some of which were already weakened by fires—triggered a cascade of floor failures in the northeast region.
- This, in turn, led to loss of lateral support to Column 79 in the east-west direction over nine stories (between Floors 5 and 14).
- The increase in unsupported length led to the buckling failure of Column 79, which was the collapse initiation event.

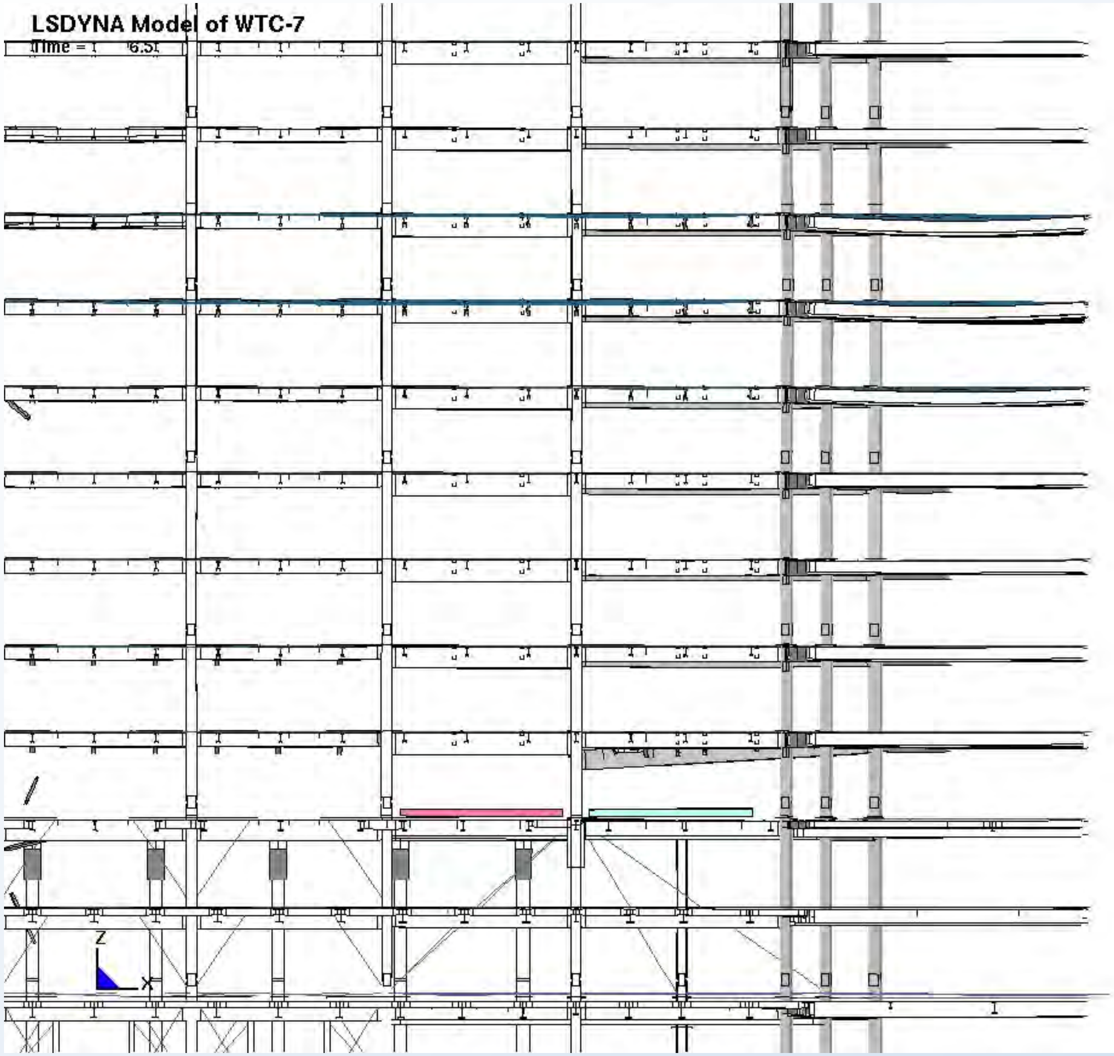
Details of Collapse Initiation (2)

- The failure of the girder-to-column connections was caused primarily by the thermal expansion of the large span-length northeast floor beams.
- Additional factors that contributed to the failure were the absence of girder shear studs that would have provided lateral restraint and the one-sided lateral support to the girder provided by the northeast corner floor beams.
- In addition to the complete failure of the connection to Column 79 for the girder spanning to Column 44 on Floor 13 with the most severe fire condition, the same connection on Floors 8 to 12 were partially damaged due to the failure of some or all of the 4 bolts.
- Complete failure of the connection required girder walk off in addition to the failure of all four bolts.
- The temperatures in the columns in WTC 7 did not exceed 300 °C and, therefore, the columns did not buckle due to direct fire-induced thermal expansion or weakening.
- The interior columns were not thermally restrained and, therefore, did not develop increased loads due to thermal expansion which could have led to buckling.

Details of Horizontal Progression

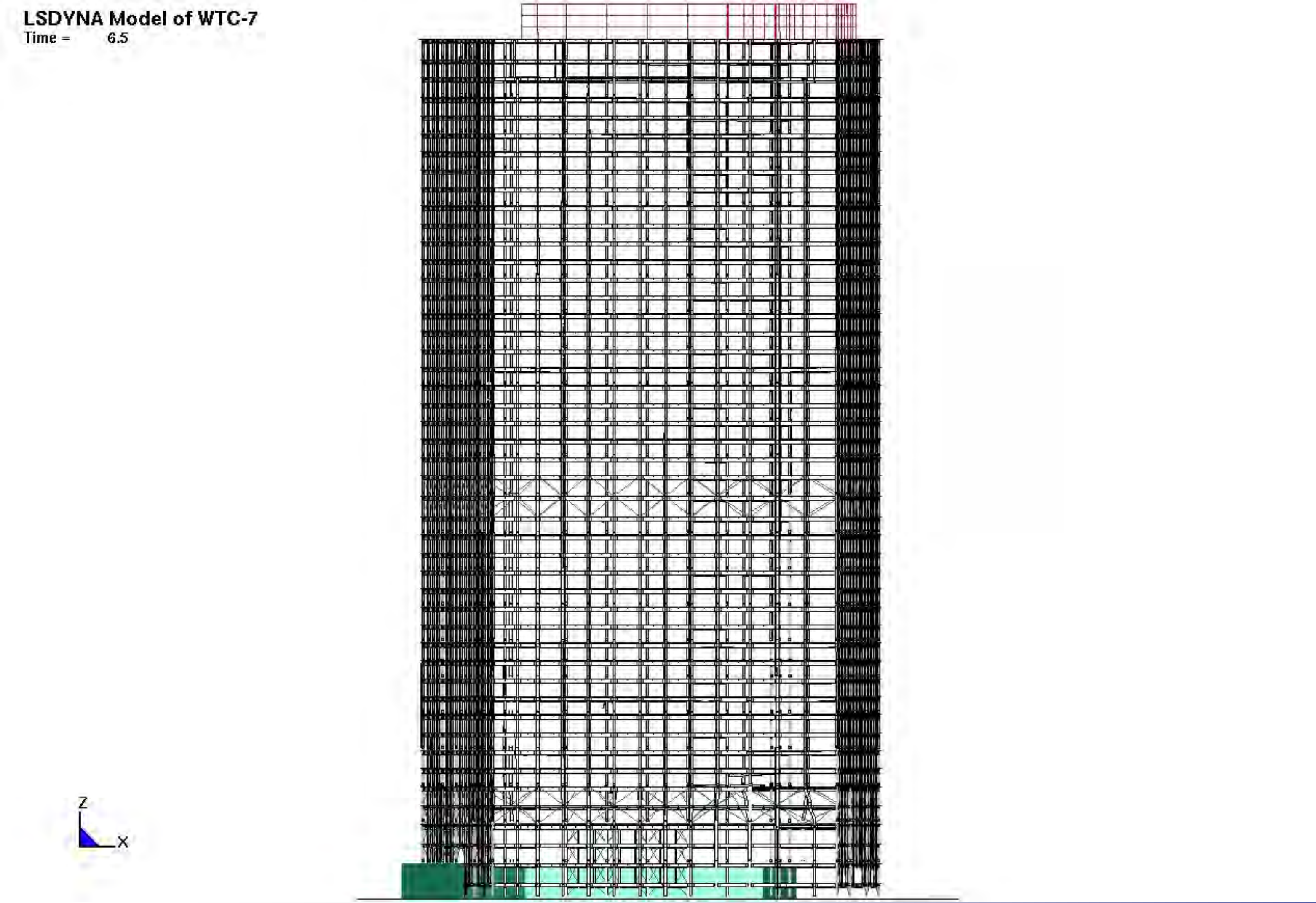
- The first north-south line of core columns (i.e., Columns 76 to 78) buckled since they had lost lateral support, were impacted by falling debris, and had loads redistributed to them from adjacent buckled columns.
- Truss 2, which collapsed due to accumulated weight and impact loads from falling debris, precipitated the buckling of Columns 77 and 78 a few moments earlier than Column 76. The failure of Truss 2 caused the failure of the transfer girder linking Columns 77 and 78A which supported Column 78.
- Truss 2 was not critical to the horizontal progression of failure.

WTC 7 Collapse Initiation w/o Debris Damage



View from South

WTC 7 Collapse Visualization w/o Damage



View from South

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

- The calculated stairwell capacity was insufficient to meet the requirements of the NYCBC in effect during the design and construction period, if the building were occupied at the calculated maximum level (≈ 14 000 people).
  - The capacity was sufficient for the normal occupancy of the building (≈ 8 000 workers plus visitors), estimated by NIST, and was more than sufficient for the occupancy on September 11, 2001 (≈ 4 000 people), also estimated by NIST.
  - The stairwell capacity met the requirement of the (subsequent) 2000 edition of the IBC, but not the 2003 edition of NFPA 5000.
- The separation of the stairwell doors met the requirement of the 1968 NYCBC.
  - On some floors, the separation of the stairwell doors was below the remoteness requirements in the 2000 IBC and the 2003 NFPA 5000.