# NIST Response to the World Trade Center Disaster

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

**Presentation to the Subcommittee on Disaster Reduction**

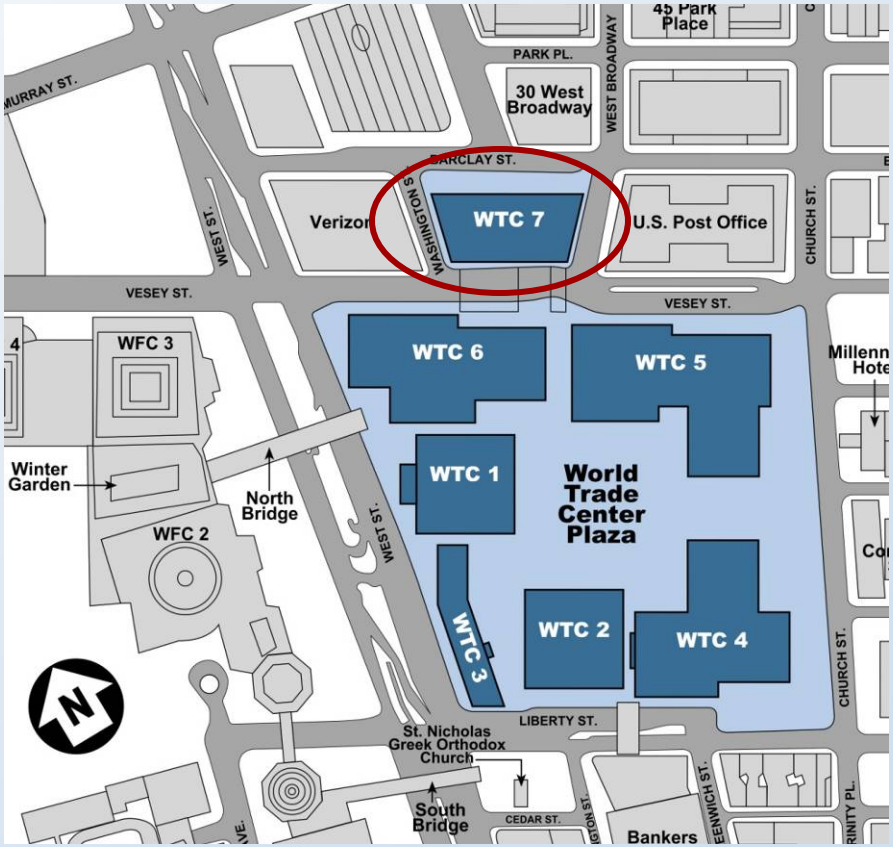
**William Grosshandler**
**Building and Fire Research Laboratory**
**National Institute of Standards and Technology**
**wgrossha@nist.gov**

**November 6, 2008**

# 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.**

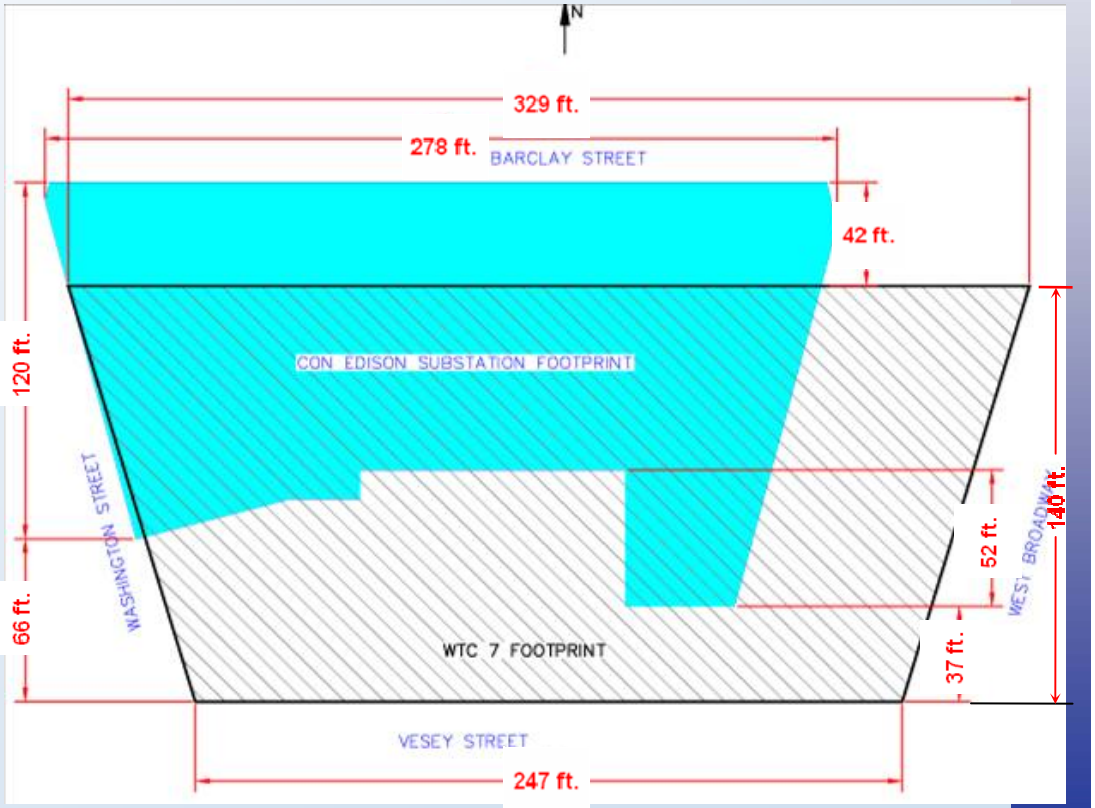


# Con Edison Substation

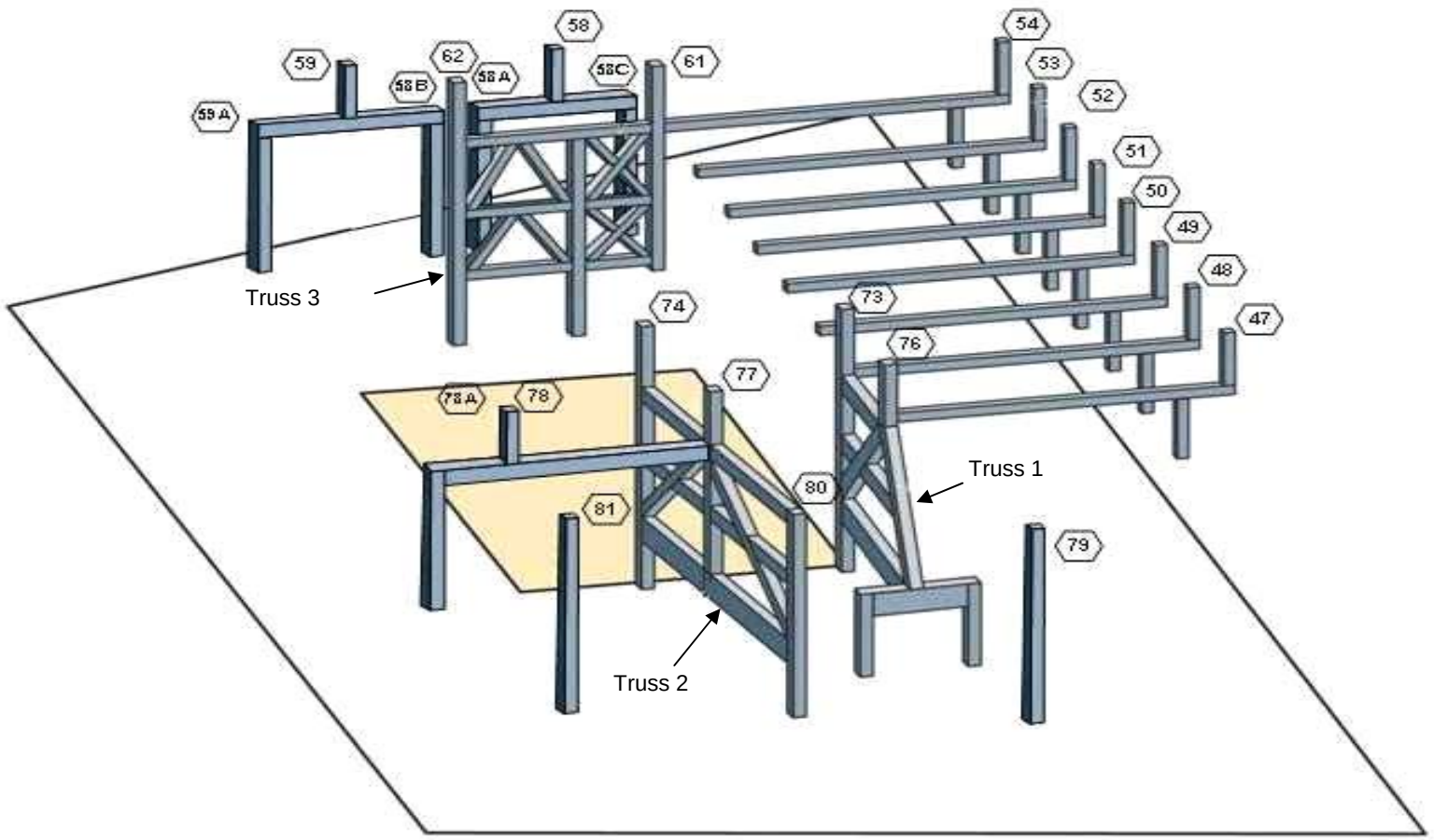
# WTC 7 Structural Concept

**Building contained approximately 2 million ft² of floor area, four "tiers"**

- **Lowest four floors:** two two-story lobbies; Con Edison substation on north side, 1st and 2nd stories.
- **Floors 5 & 6:** mechanical spaces; 3 transfer trusses, 8 cantilever transfer girders, floors 5 and 7.
- **Floors 7 – 45:** tenant floors, all structurally similar to each other.
- **46th and 47th floors**: mainly tenant floors, structurally reinforced to support cooling towers and water tanks for fire suppression.

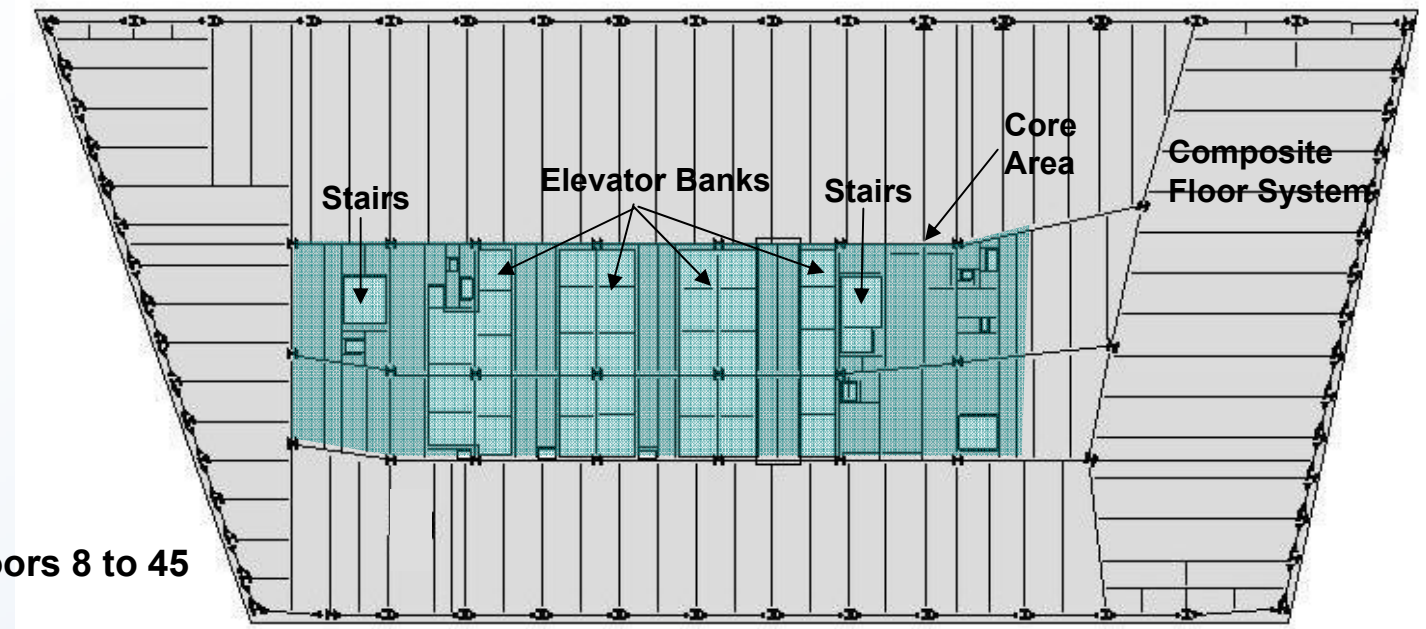


# Transfer Trusses and Girders




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

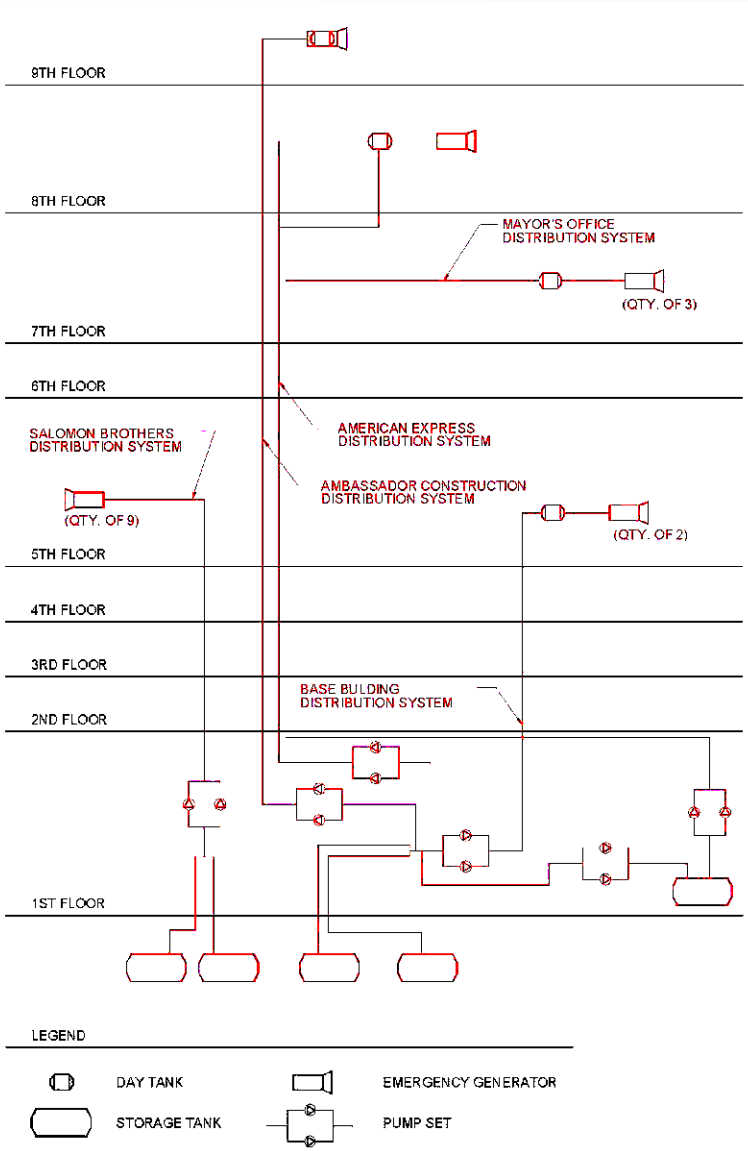


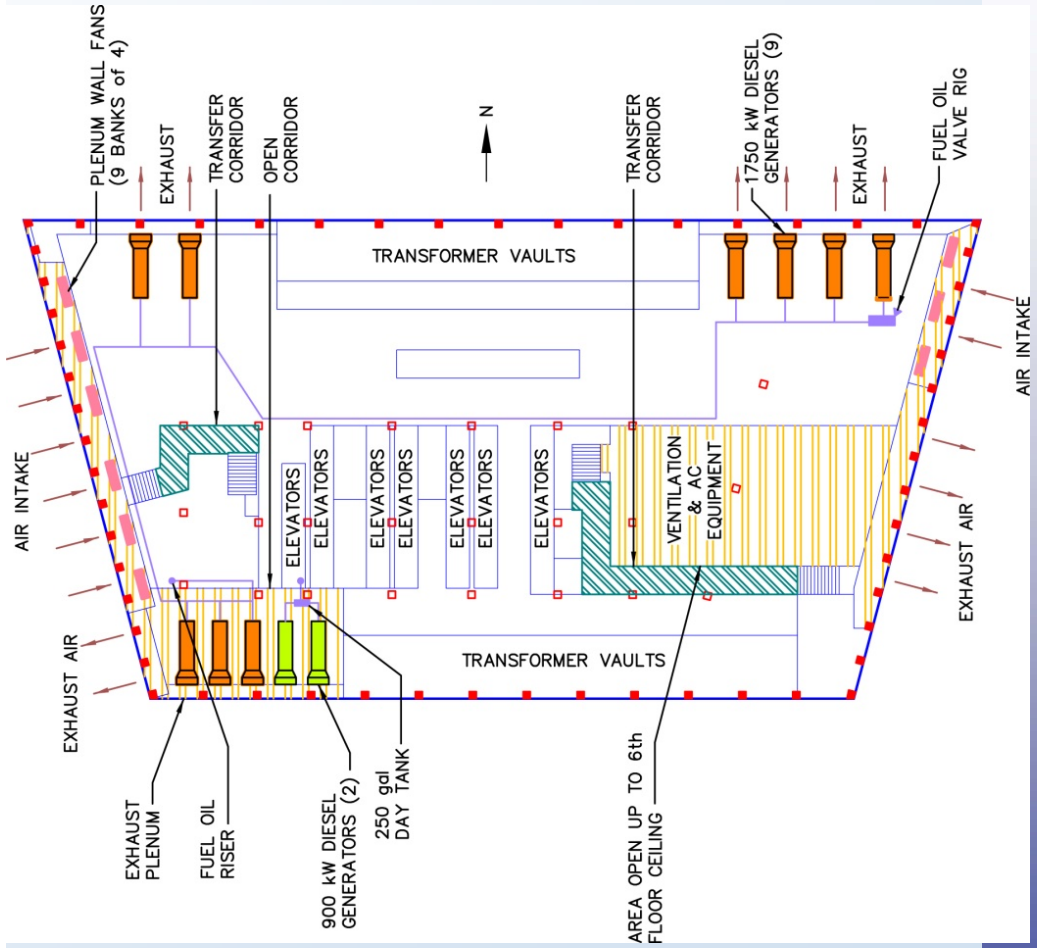

Floors 8 to 45

**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.

# 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?

# 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**

Combined:

- Analysis of visual evidence (photographs and videos)
- Analysis of design, construction, and inspection documents

Complete sequence of events:

1. Initial damage due to collapse of WTC 1
2. Growth and spread of fires
3. Thermal response of structural components
4. Thermally-induced initial local failure for collapse initiation
5. Collapse propagation, resulting in global collapse

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**

# 1. Initial Damage Due to Collapse of Towers

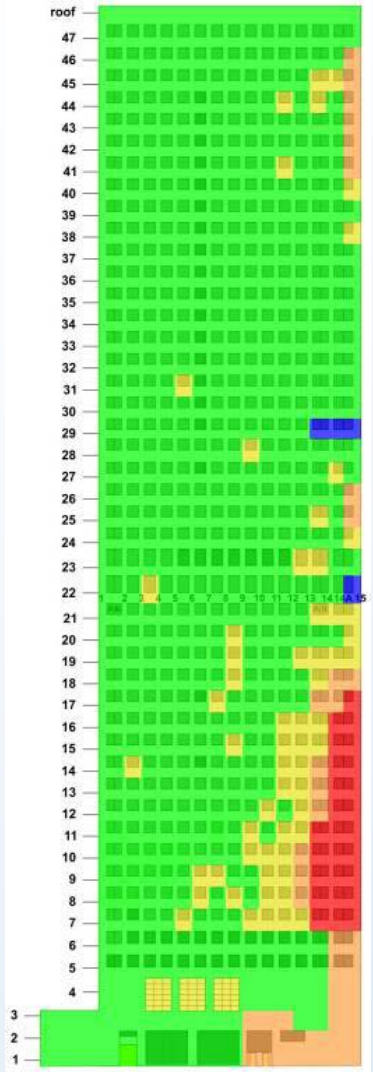

- Collapse of WTC 2 did not cause any structural damage or start any fires in WTC 7.
- Collapse of WTC 1 damaged seven exterior columns on the lower floors of the south and west faces and initiated fires on 10 floors between Floors 7 and 30.

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

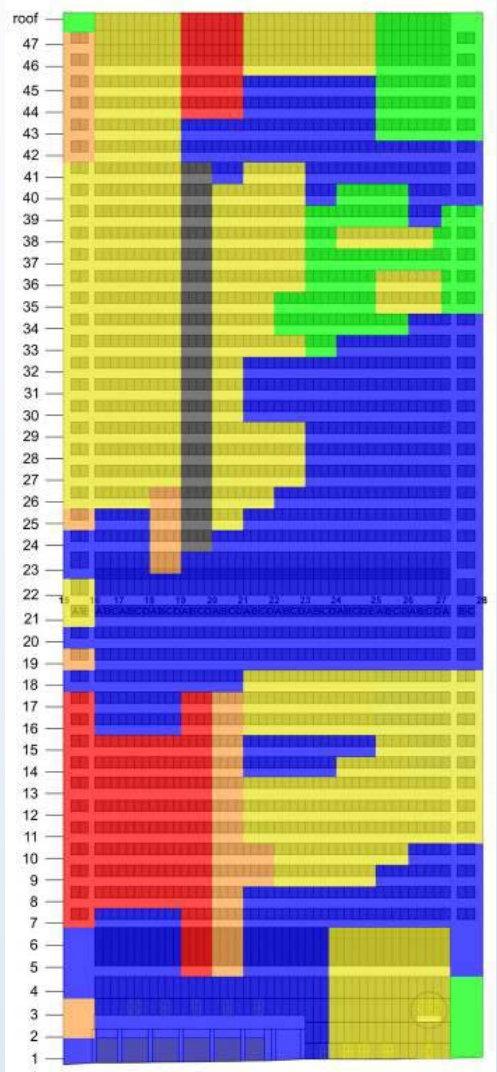
# Debris Impact Damage to WTC 7


- 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

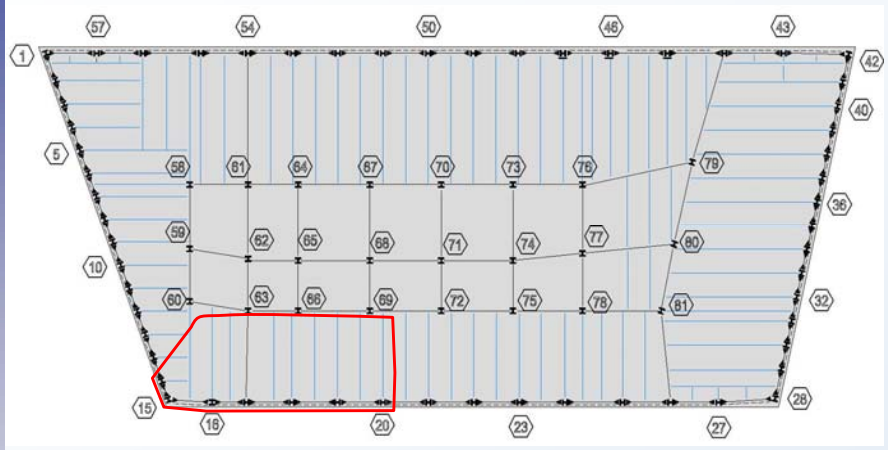
orange (■) – granite and underlying truss damage

red (■) – damage to *exterior* structural steel

gray (■) – vertical dark band

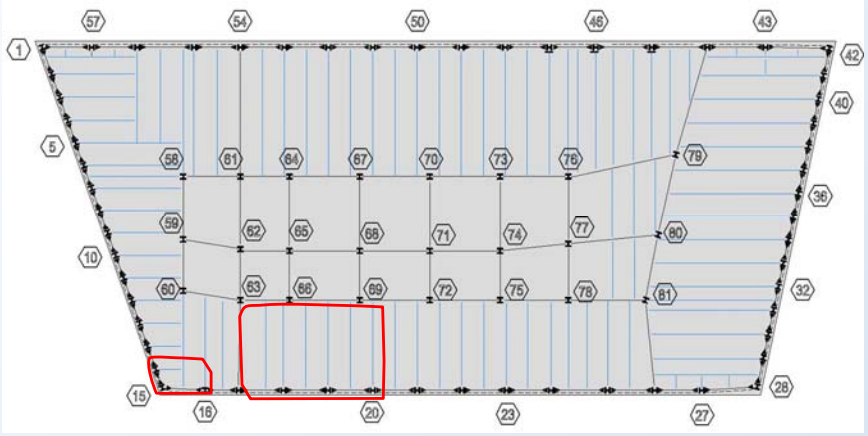
blue (■) – not visible due to smoke, dust, and intervening buildings.

# Estimated Debris Impact Damage by Floor

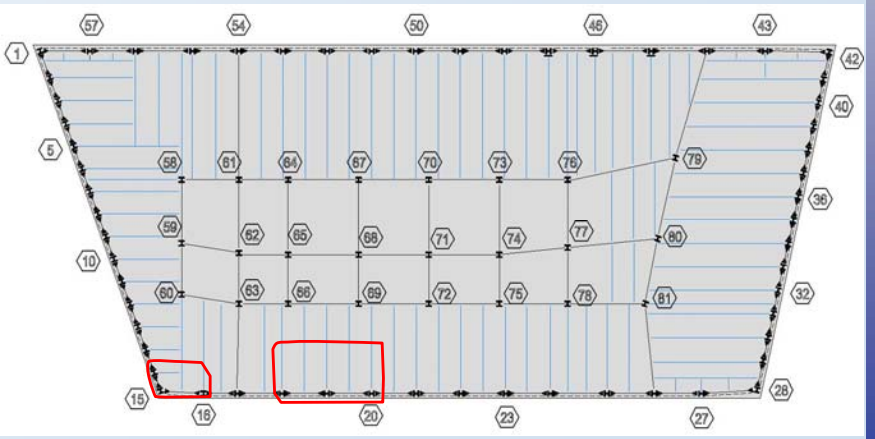


Floor 8

Floor 9



Floors 10 and 11

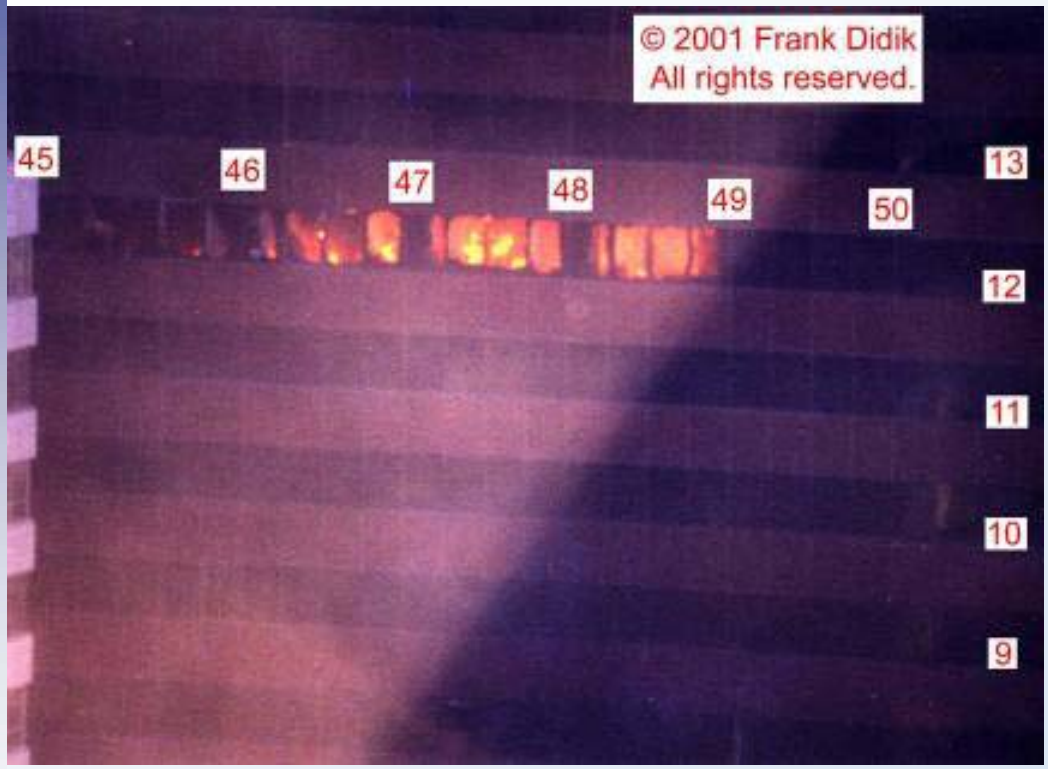


Floors 12 to 14

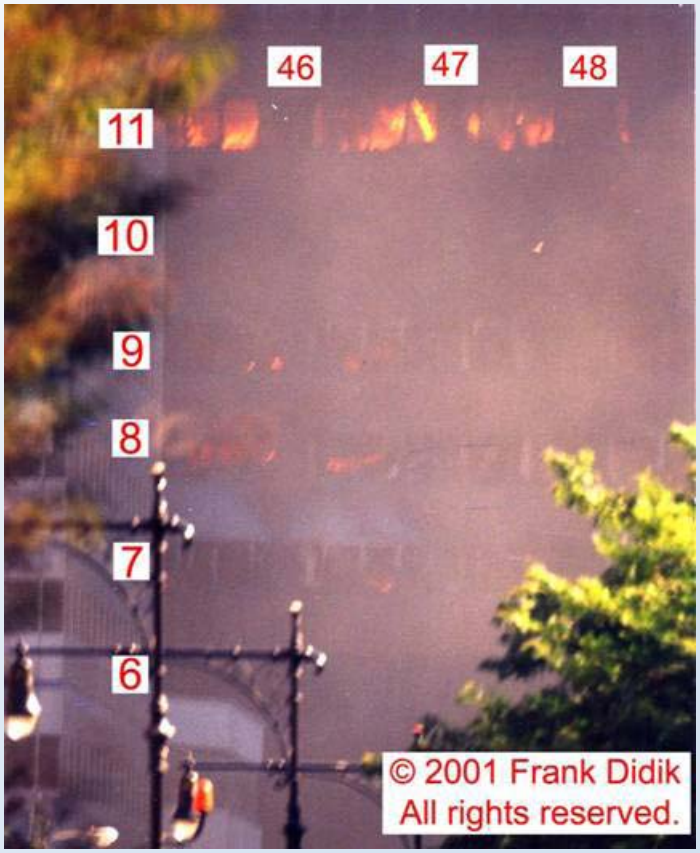
# 2. Fire Growth and Spread


- 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

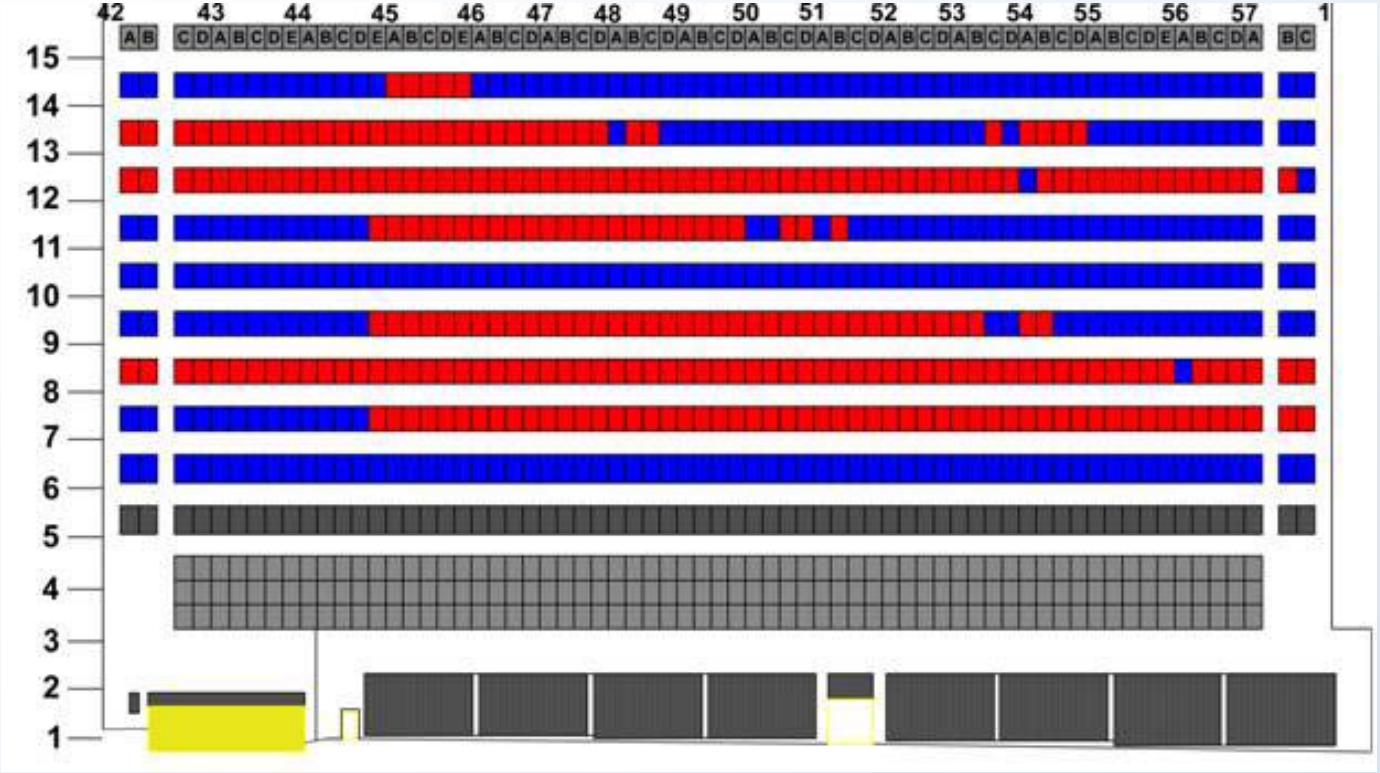



- Cropped photograph of north face of WTC 7 taken between 3:11:15 p.m. and 3:16:51 p.m.



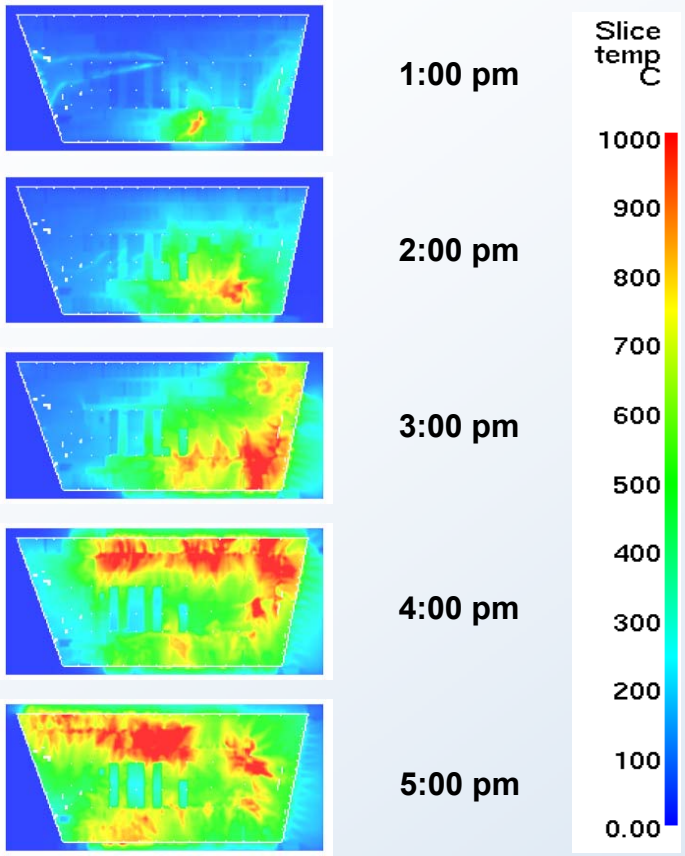

- Cropped photograph showing part of north face of WTC 7 at 4:39 p.m. ± 120 s.

# Summary of Fires on North Façade of WTC 7




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

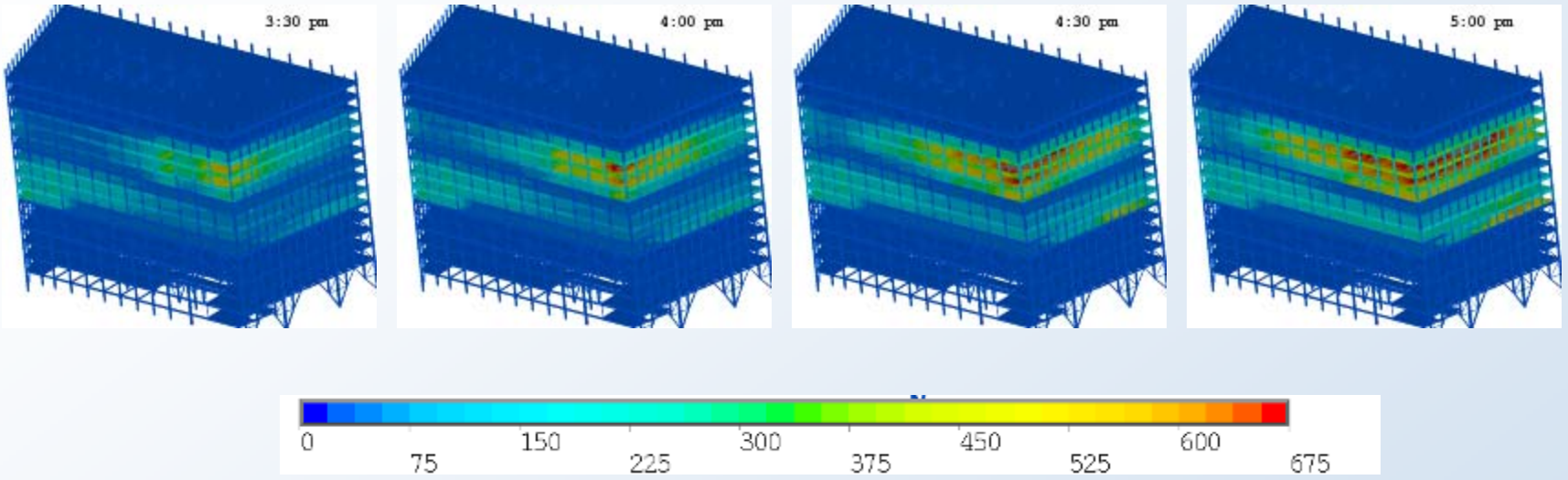
# Modeling Fire Growth and Spread




Progression of fires on Floor 12

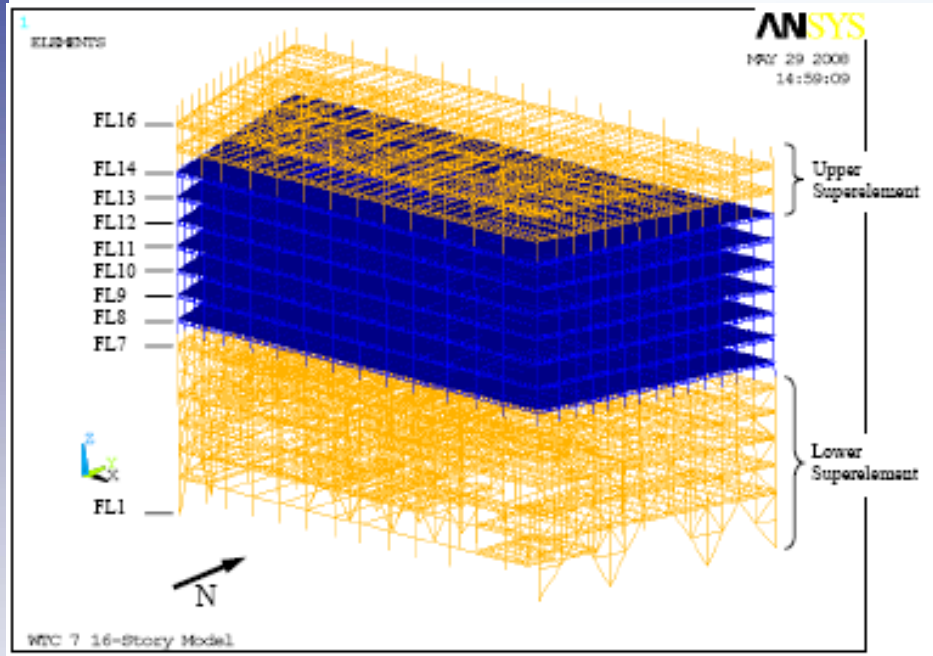
- The major fires in WTC 7 were modeled using the Fire Dynamics Simulator (FDS) in a manner similar to those for the WTC towers.
- There were far fewer photographs and videos of WTC 7 than of the towers; thus, details of the WTC 7 fires were not as precise as for the towers.
- The fire simulations for 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.

# 3. Modeling Thermal Response to Fire (FSI/ANSYS)




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

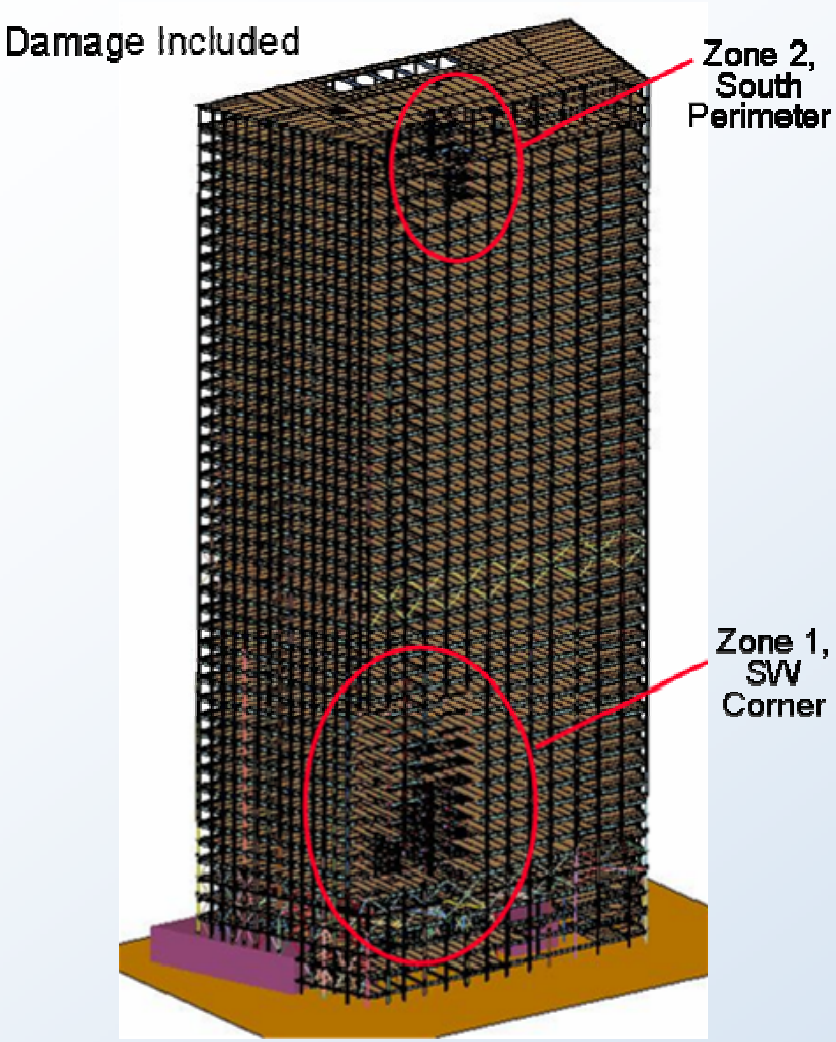
# 4. Modeling Quasi-static Structural Response to Heating (ANSYS)




- 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 super-elements.

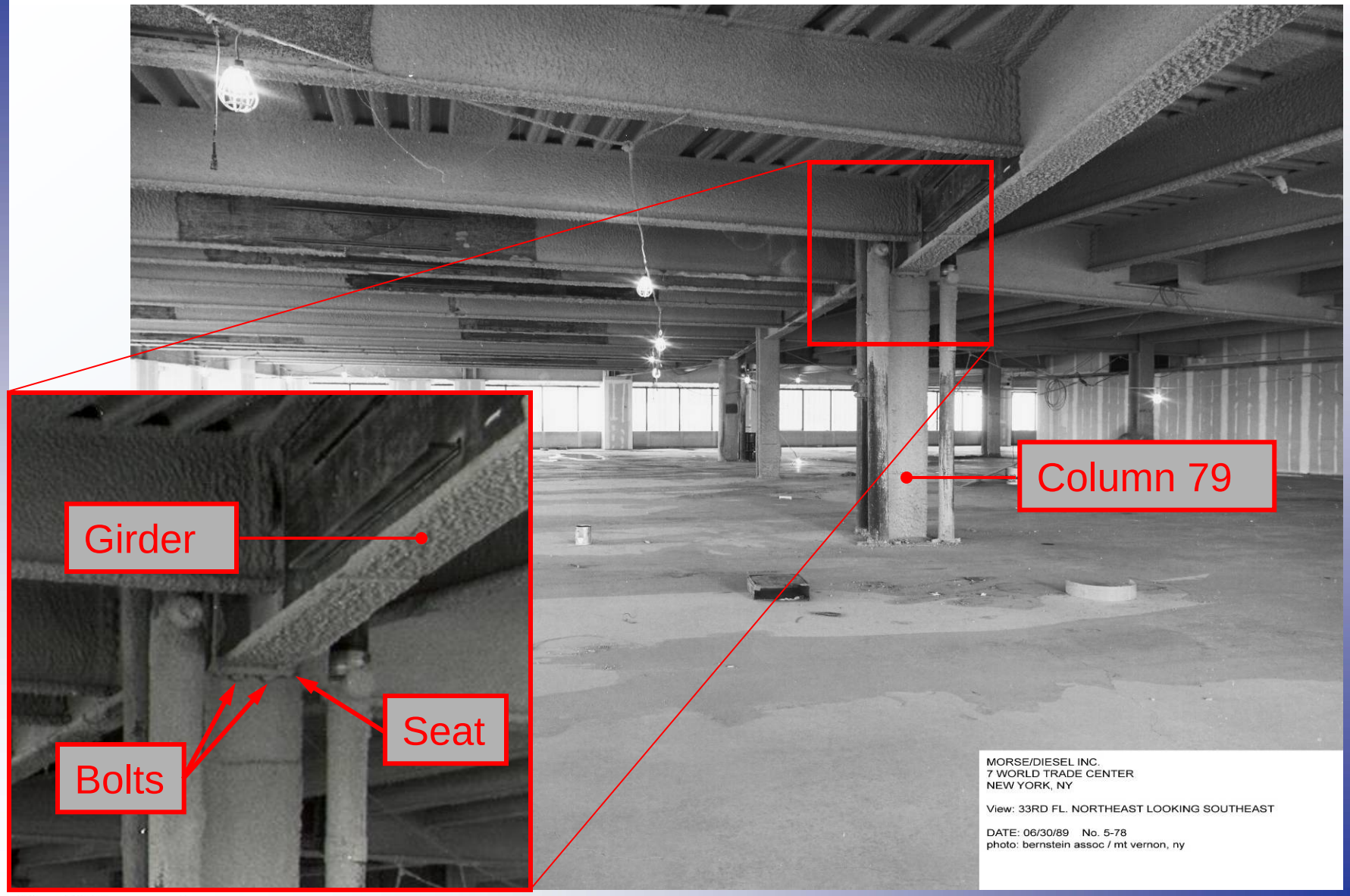
- The 16-story ANSYS model was used to determine the sequence of events that led to fire-induced collapse initiation.
- Software: double precision version of ANSYS 11.0
- Model
  - 93,413 Nodes
  - 101,357 Elements
    - 21,095 beam elements
    - 28,182 rigid beam elements
    - 34,461 shell elements
    - 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

# 5. Modeling Collapse Dynamics (LS-DYNA)

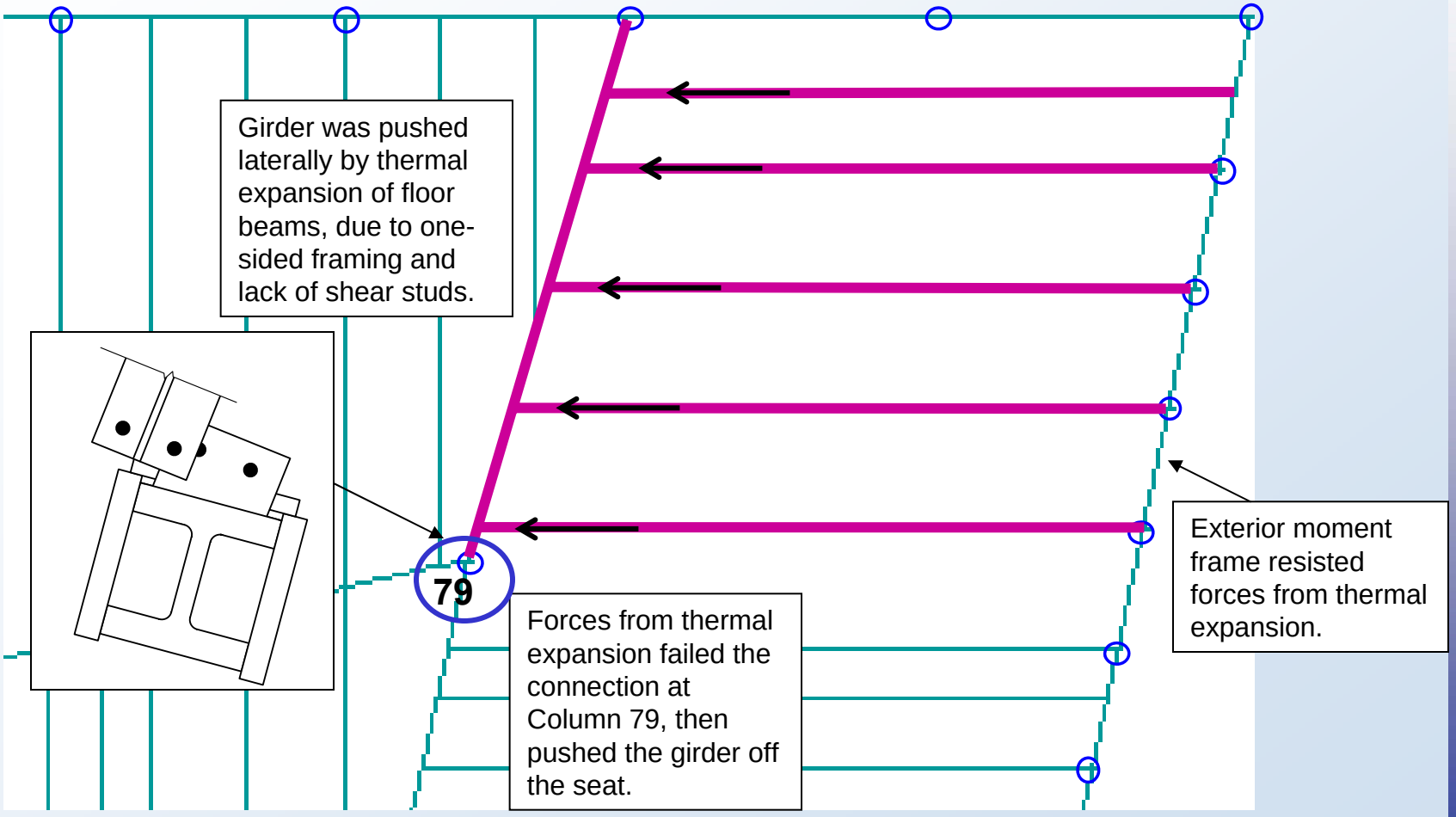



- The LS-DYNA model was used to determine the sequence of events that led to collapse propagation and, ultimately, global collapse.
- Software: double precision version of LS-DYNA
- Model
  - 3,593,049 Nodes
  - 3,045,925 Elements
    - 3,006,910 shell elements
    - 33,364 discrete spring elements
    - 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

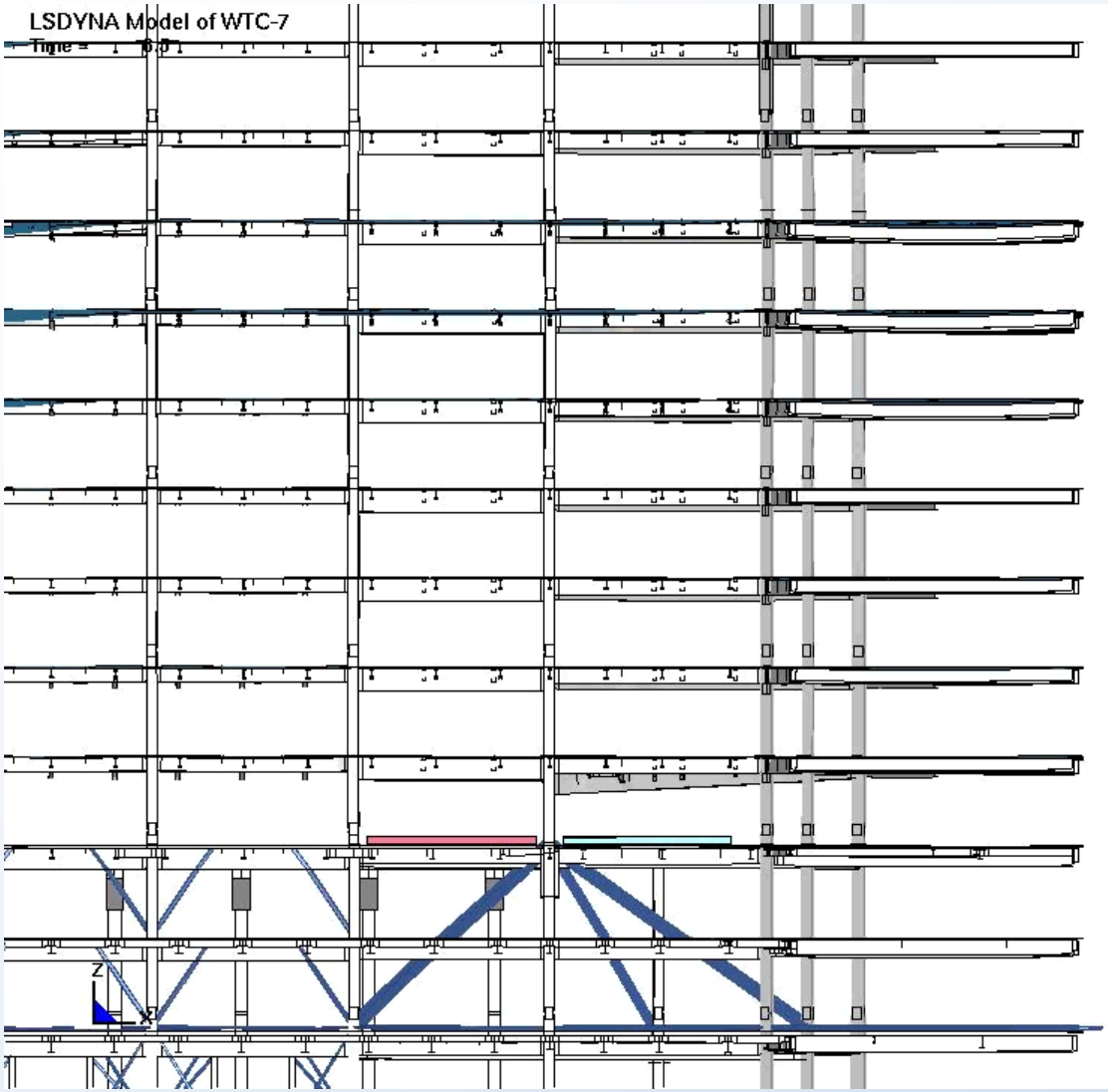
# Focus on Northeast Floor System Near Column 79



# Thermal Response of Northeast Floor Framing



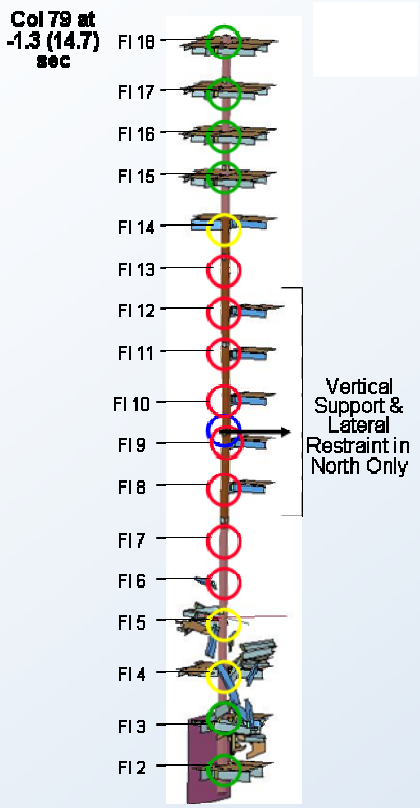
# Physics-Based Visualization of WTC 7 Collapse Initiation

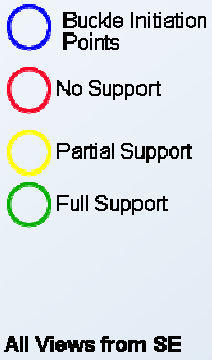


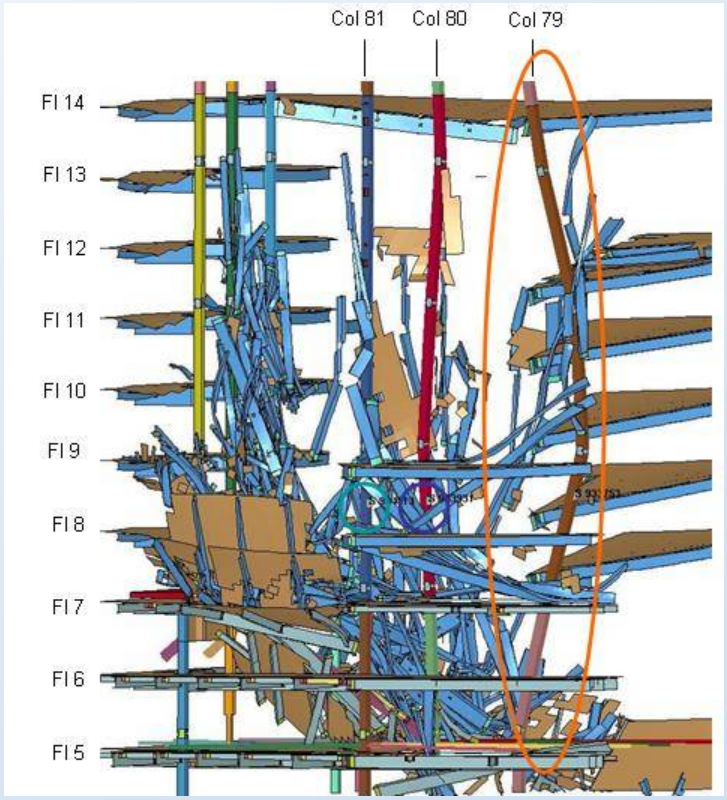

View from South

# 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.

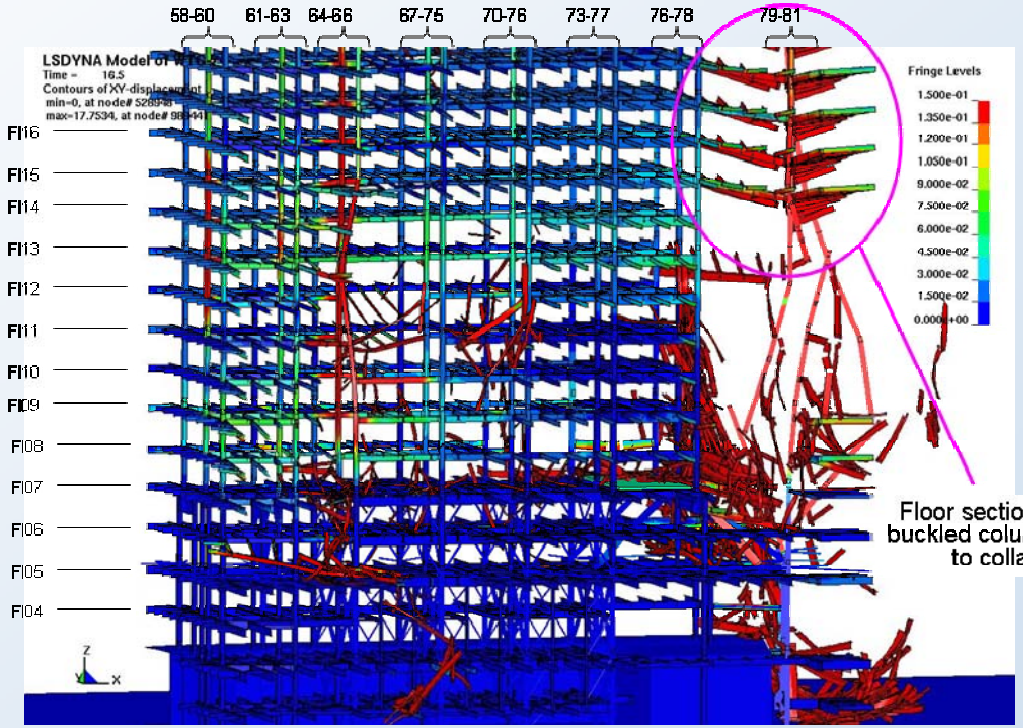


# Vertical Progression of Failure

- 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.

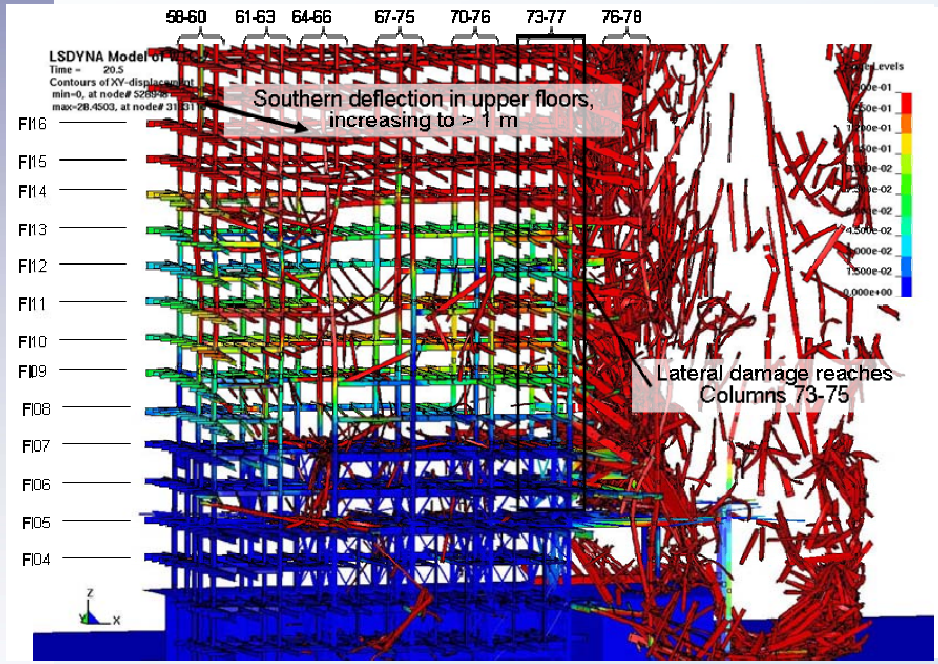



**View of interior columns**

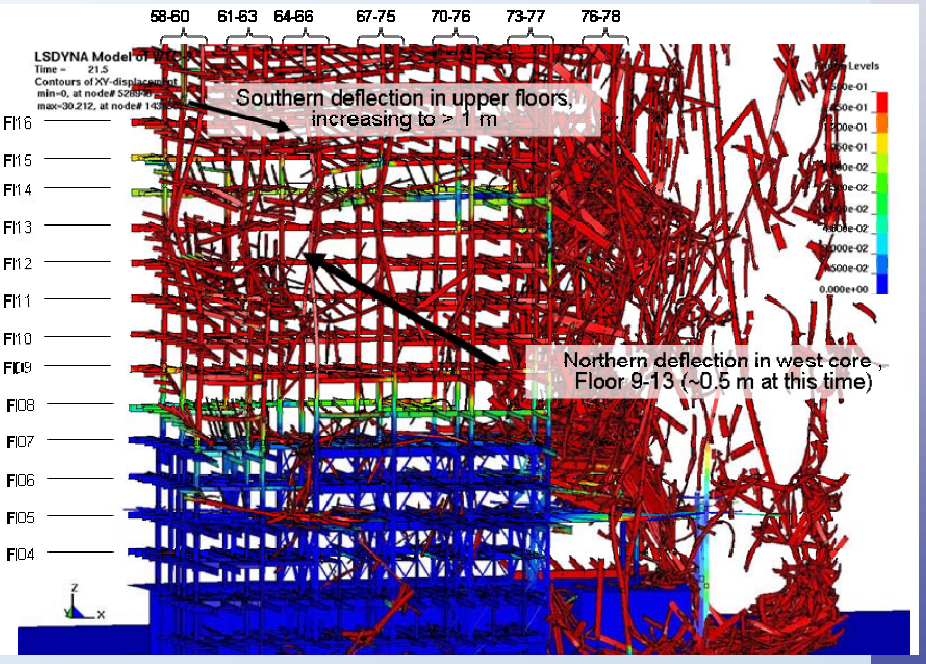
# Horizontal Progression of Failure

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.



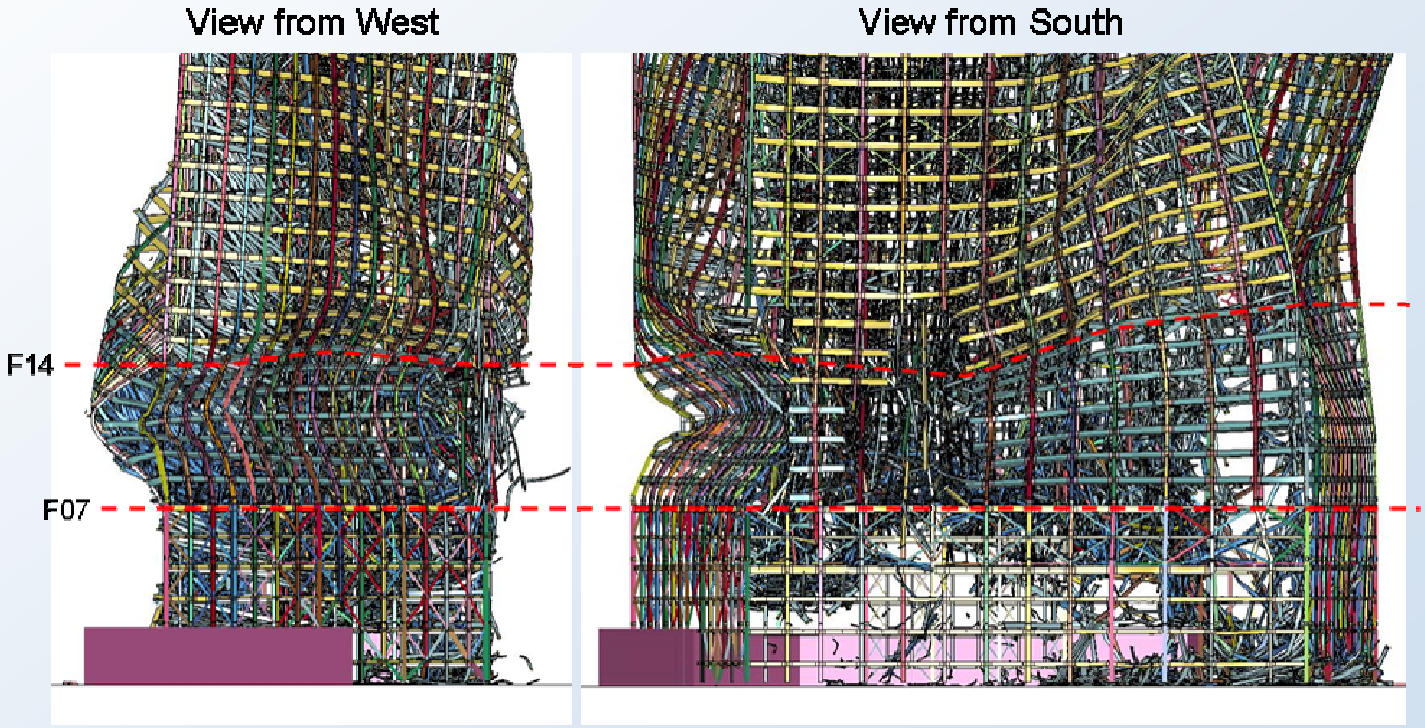

Failure progresses to the third line of interior columns from the east at 4.5 s following collapse initiation.




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

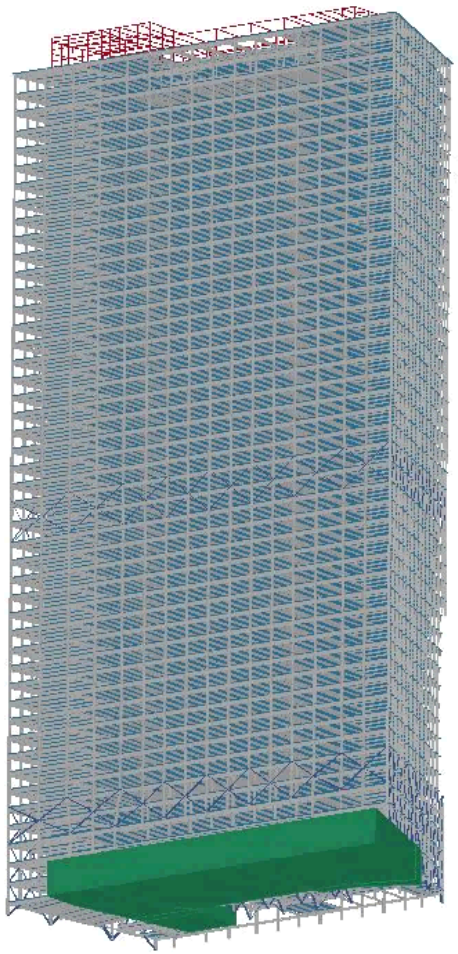
# Global Collapse

- 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.

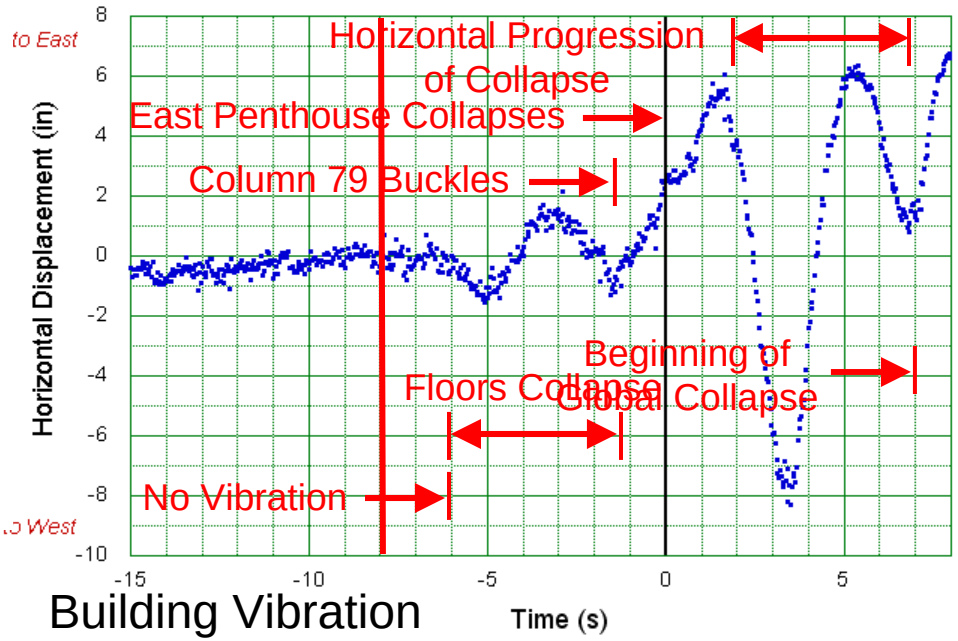



**Buckling of lower exterior columns.**

# Comparison of Visualization and Video



LS-Dyna Visualization Clock 19


Building Vibration

# Principle Findings (1/2)

- WTC 7 withstood debris impact damage that resulted in 7 exterior columns being severed and subsequently withstood conventional fires on several floors for almost 7 hrs.
- Observations support a single point of fire ignition on any given floor in WTC 7.
- **WTC 7 collapsed due to uncontrolled fires with characteristics similar to previous fires in tall buildings.**
- 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.
- **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 collapse of WTC 7 was a progressive collapse.**
- **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.**

# Principle Findings (2/2)

- Prior to the collapse, there had been 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, which was near the west side of the south face of the building.
- **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:
- Collapse time of the north face of the upper 18 floors (the floors clearly visible in video evidence) was similar to the computed free fall time.
- Diesel fuel fires did not play a role in the collapse of WTC 7.
- Hypothetical blast events did not play a role in the collapse of WTC 7.

# 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.

# WTC 7 Recommendations

- Based on its findings, NIST ***reiterated 12 recommendations*** from its Investigation of the WTC towers and identified ***one new recommendation***.
- **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.
- ***Relevance of new recommendation 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.

# New Recommendation: Enhanced Fire Endurance of Structures

**NIST recommends that buildings be explicitly evaluated to ensure the adequate performance of the structural system under worst-case 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.**

# 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.

# 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 2007
- Second set of eight model building code changes based on NIST's WTC recommendations approved 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
  - Council on Tall Buildings and Urban Habitat

# QUESTIONS?