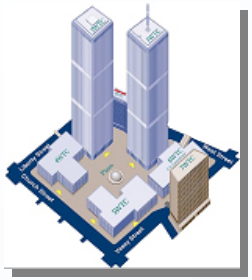

Technical Conference on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Session VI - Structural Fire Response and Collapse Analysis

Observations for Structural Response

Structural and Fire Protection Damage Due to Aircraft Impact

September 15, 2005

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National Institute of Standards and Technology
U.S. Department of Commerce

NIST

Observations

Development of probable collapse sequence for each tower was guided by evidence

- Photographs and videos
- Design and maintenance documents
- Eyewitness accounts

Changes in structural performance are not observable until significant deformation has occurred.

Observations of structural behavior from over 7000 photographs and 150 hours of video records include:

- Severed components
- Deflections and buckling (inward bowing of exterior walls)
- Disconnection and sagging of floors at exterior walls
- Relative alignment of columns (tilting of upper building section)

Observations

Visual evidence was used in three ways:

- Determine input information (exterior column damage, location of sagging floors, and failure of floor connections at the exterior wall)
- Impose time related constraints on analyses (time at which inward bowing was observed)
- Validate analysis results (global stability after impact and during structural response to fire)

Observations of structural behavior were broken into 2 groups:

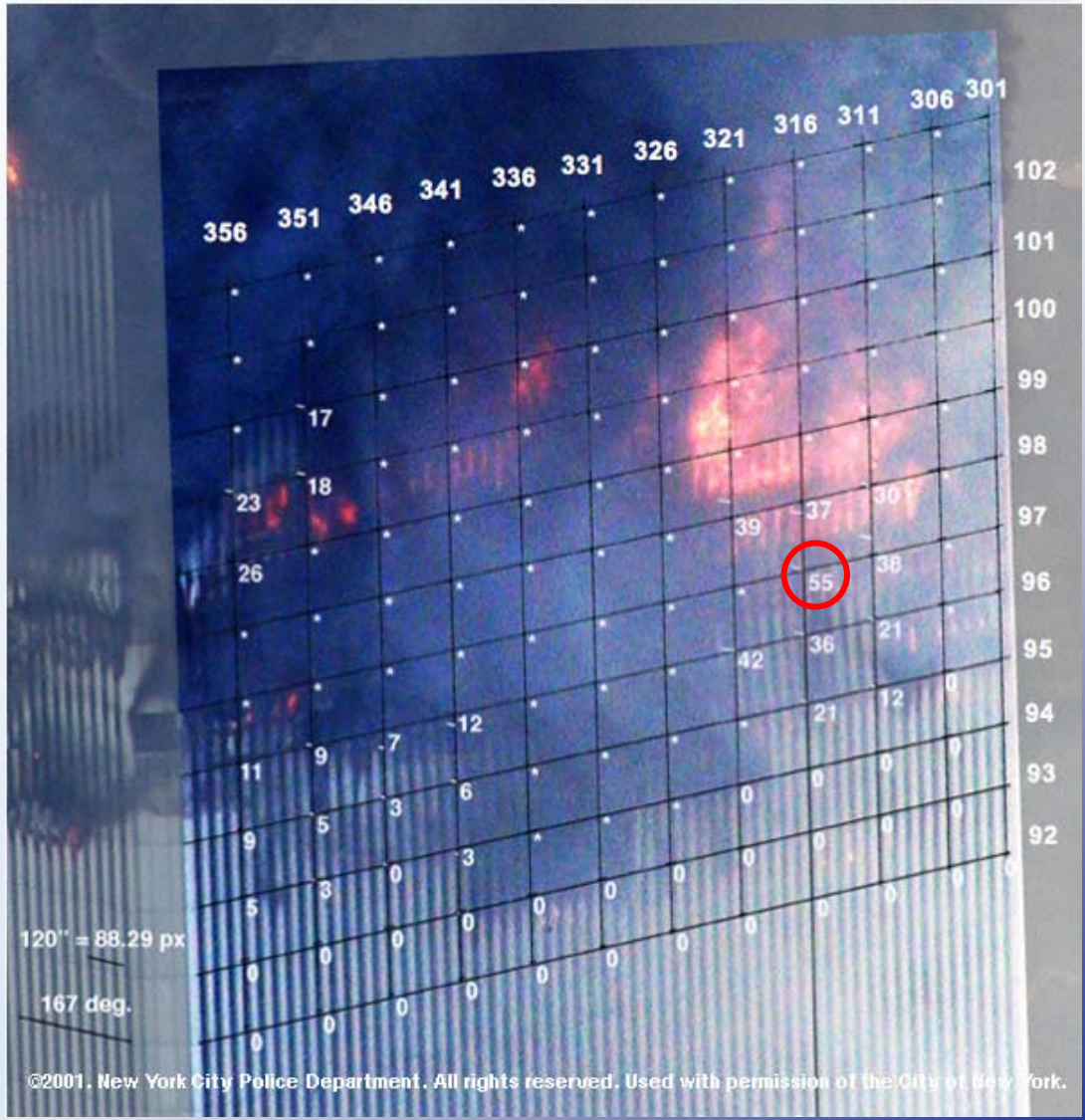
- *Key observations* - significant events used in analyses and to develop a timeline of structural events
- *Noted observations* – significance to structural response could not be conclusively identified

South Face of WTC 1 - 9:40 a.m. No inward bowing

South Face of WTC1 - 10:23 a.m. Inward bowing

- **Maximum = 55 inches**
  (uncertainty ~ +/- 6 inches)

- Floor locations approximate
- Blue tinted region digitally enhanced



South Face of WTC1 - 10:23 a.m. Inward bowing

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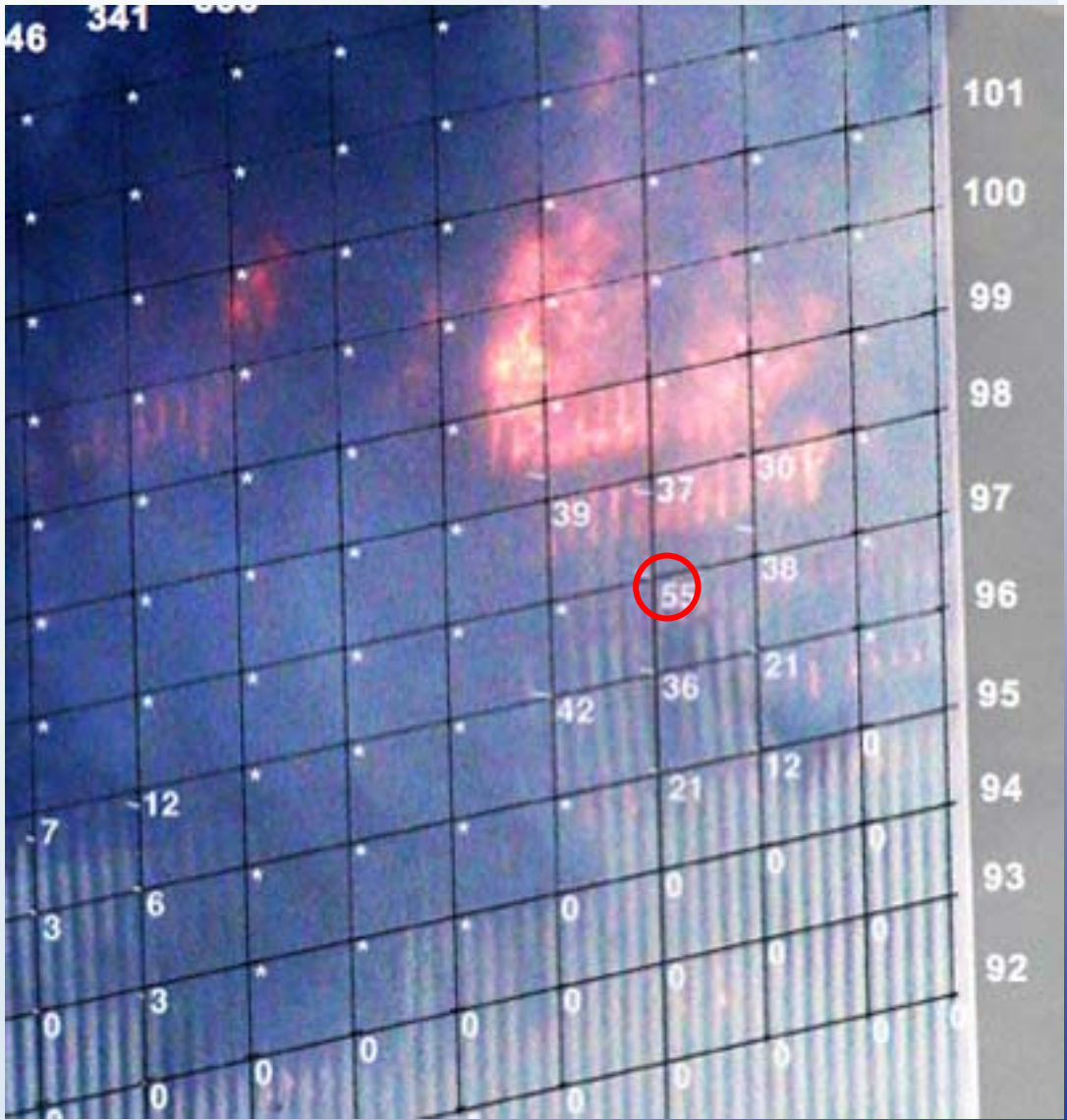
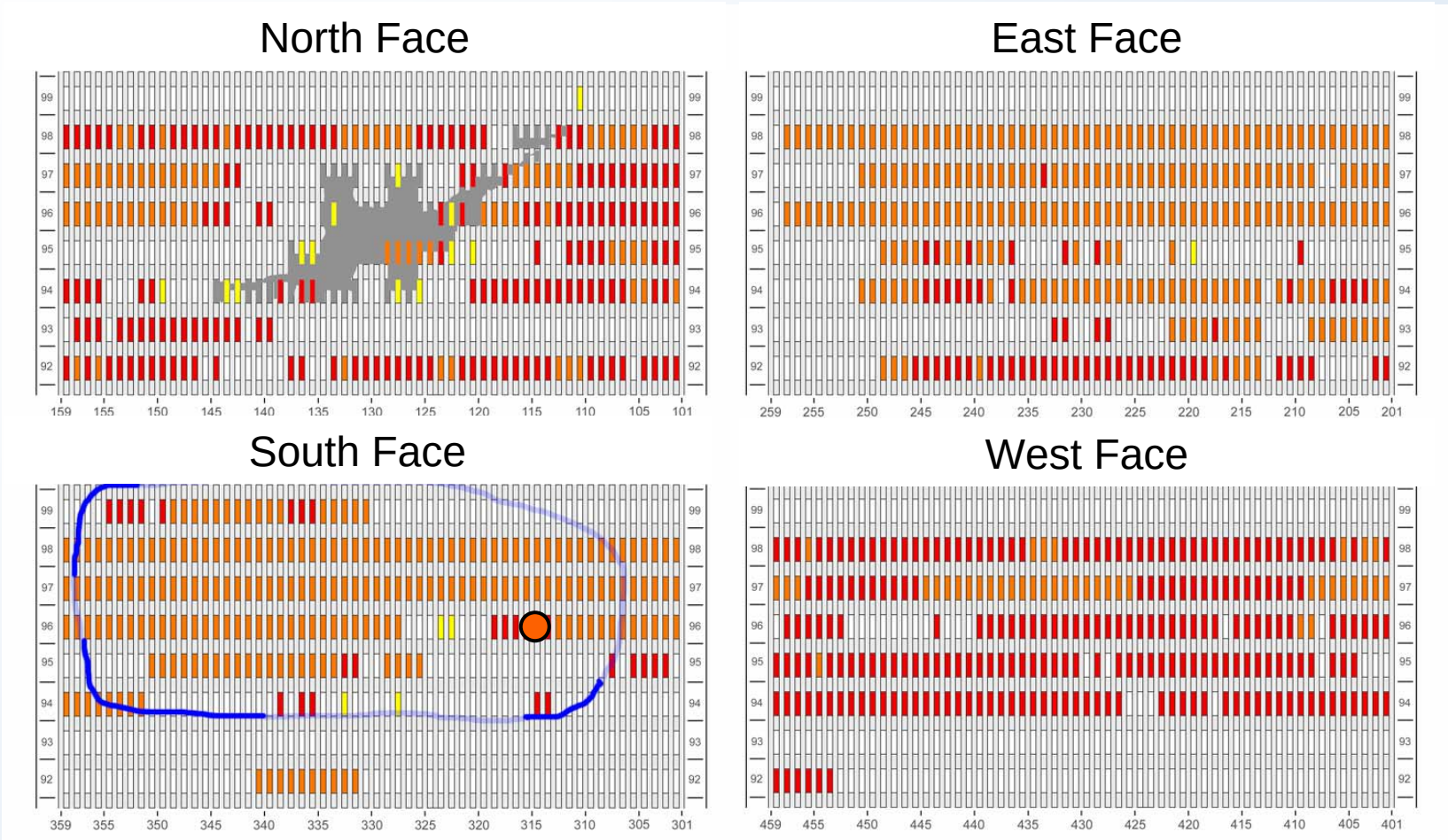
- Floor locations approximate
- Blue tinted region digitally enhanced



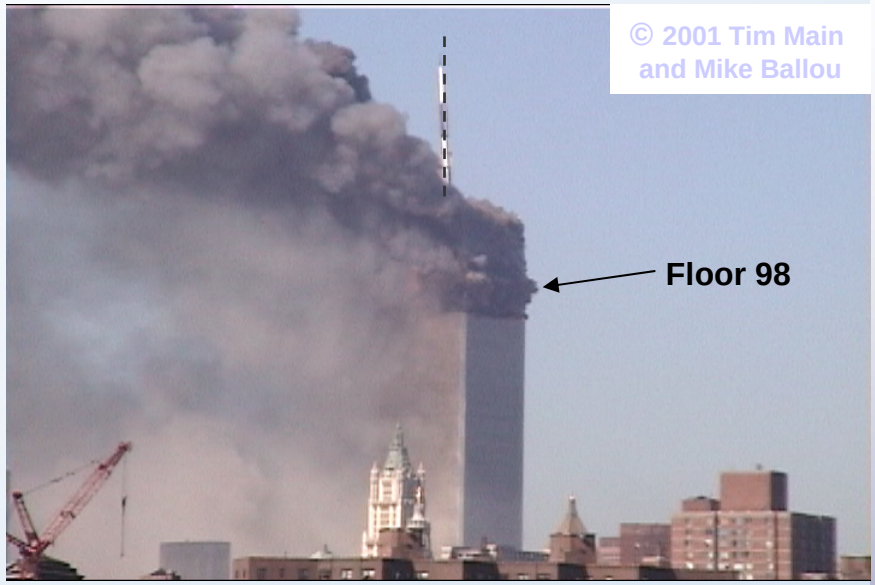
Visual Evidence of Fires in WTC 1, 8:47 a.m. to 10:28 a.m.



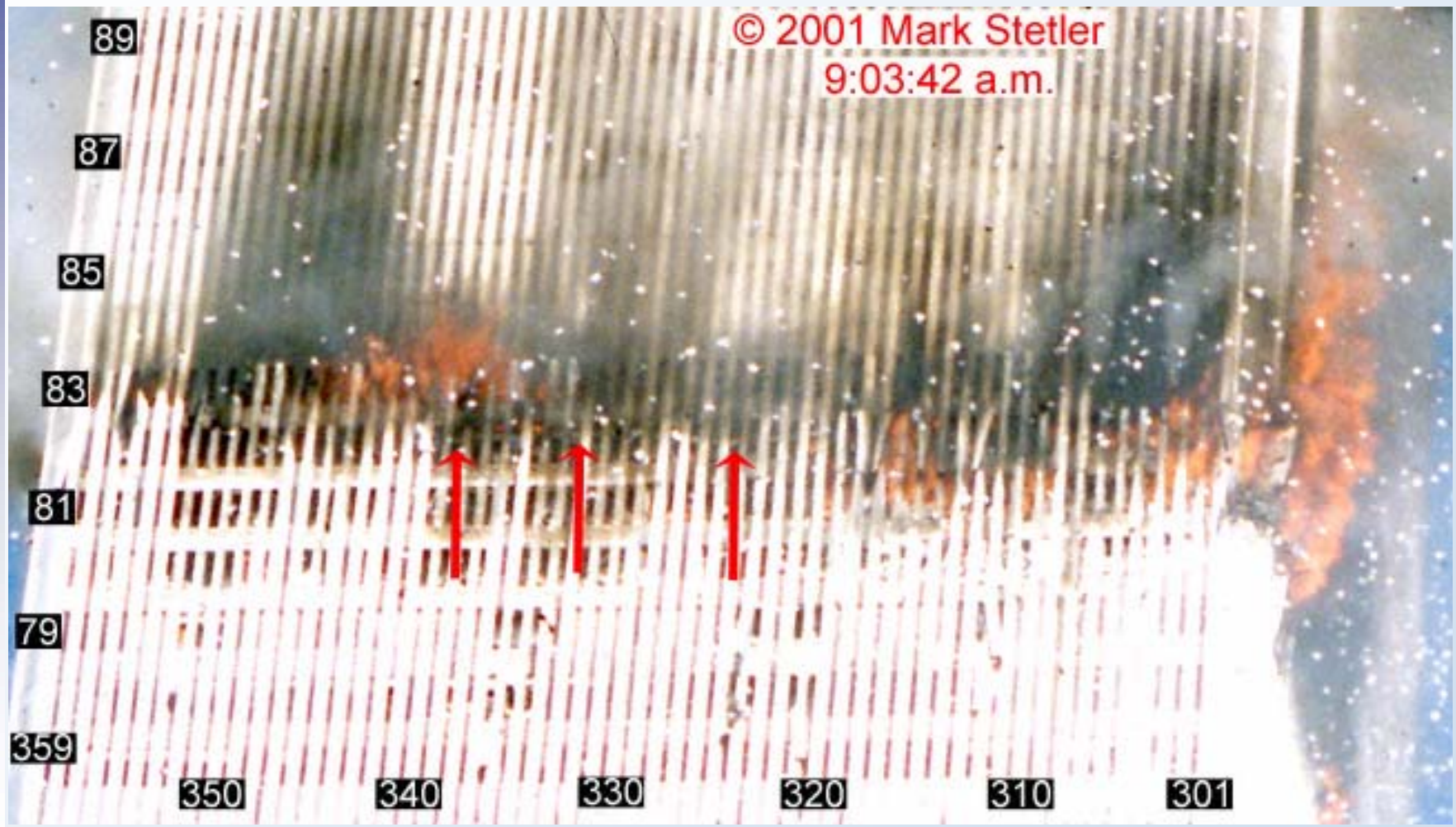
Dark blue line indicates extent of inward bowing observed in visual images.
Light blue line is estimated region of inward bowing where visual images were obscured.

WTC 1 Collapse Initiated at 10:28 a.m.

- WTC 1 tilted to the south (view from the northeast).
- Initiation of global collapse was first observed by the tilting of the building sections above the impact region.

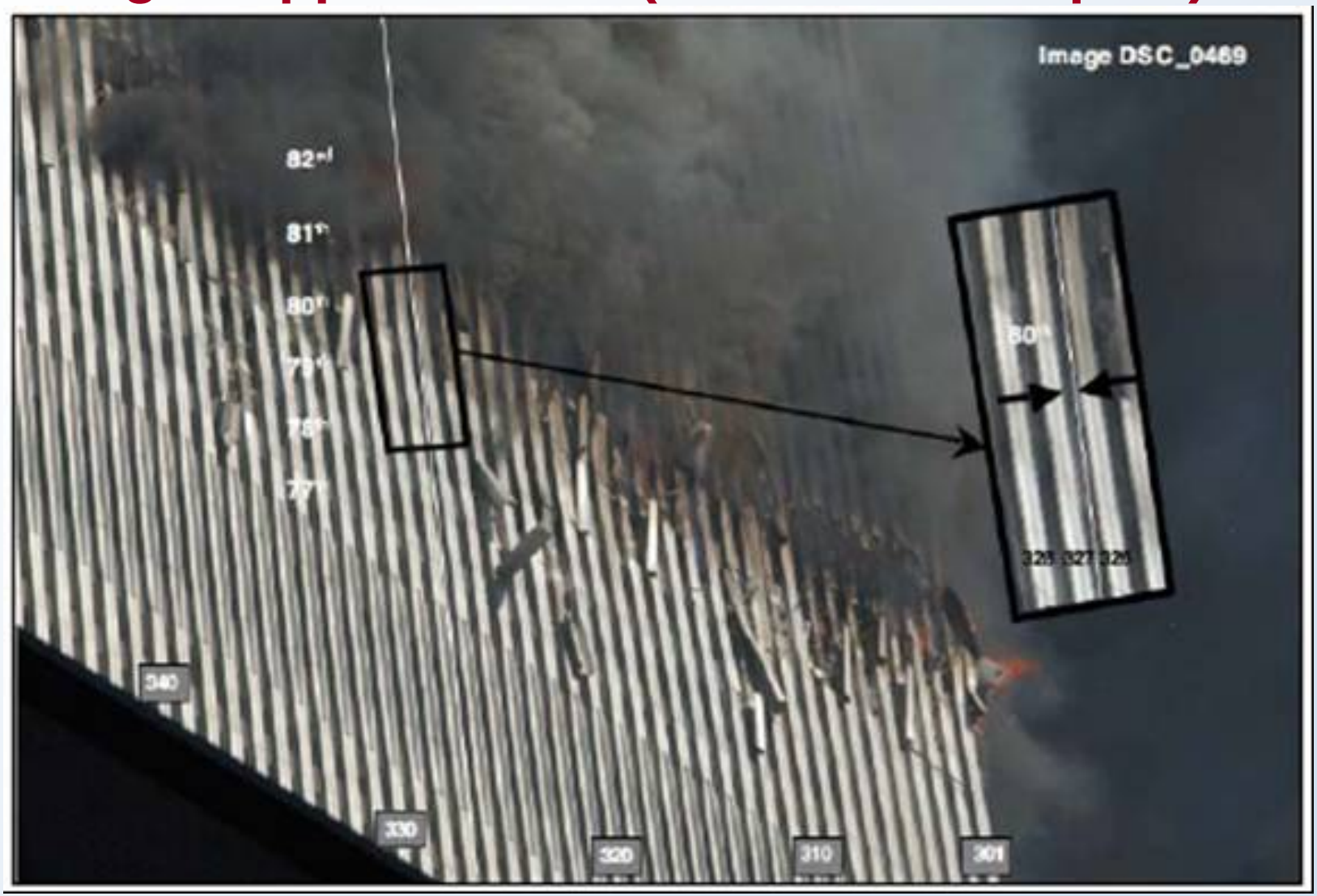


East Face of WTC 2 - 9:03 a.m. Hanging objects in east windows of Floor 82



East Face of WTC 2 - 9:10 a.m. Hanging objects in north window of Floor 80

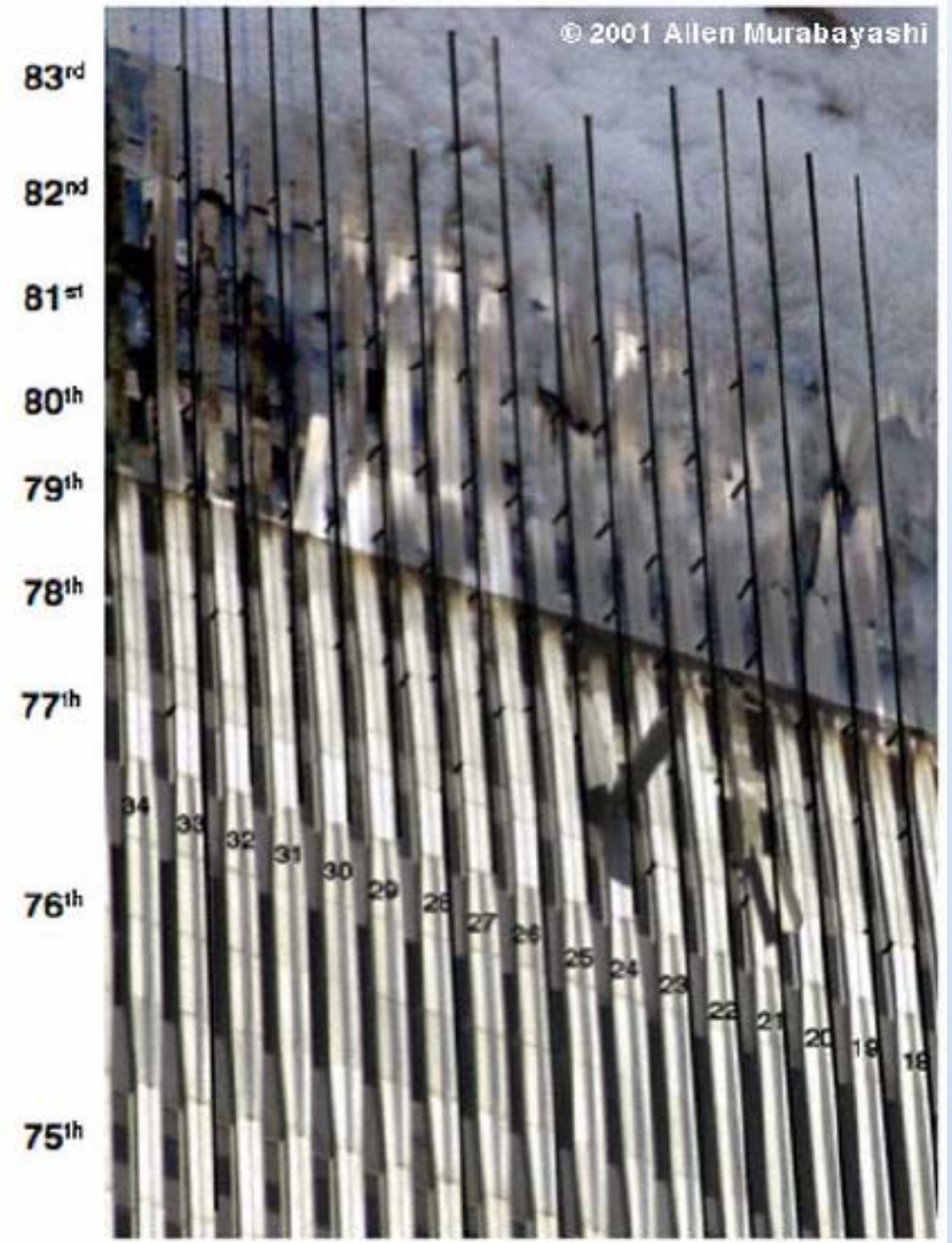
East Face of WTC 2 – 9:21 a.m. Maximum inward bowing of approx. 10 in. (18 min after impact)



East Face of WTC 2 – 9:47 a.m. Hanging Floor 83 Slab in Windows of Floor 82

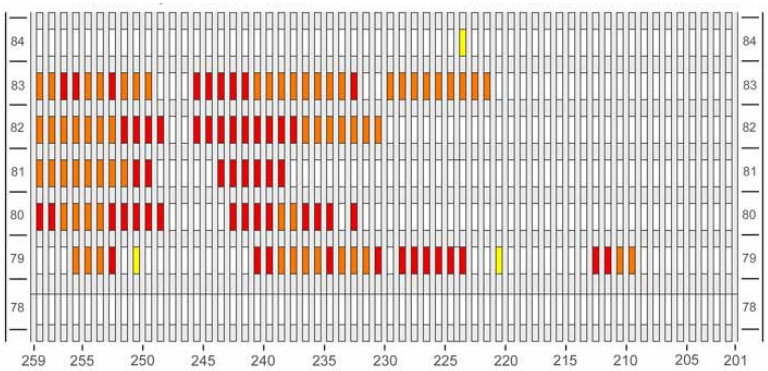
East Face of WTC 2 – 9:53 a.m.

Maximum inward bowing of approx. 20 in.

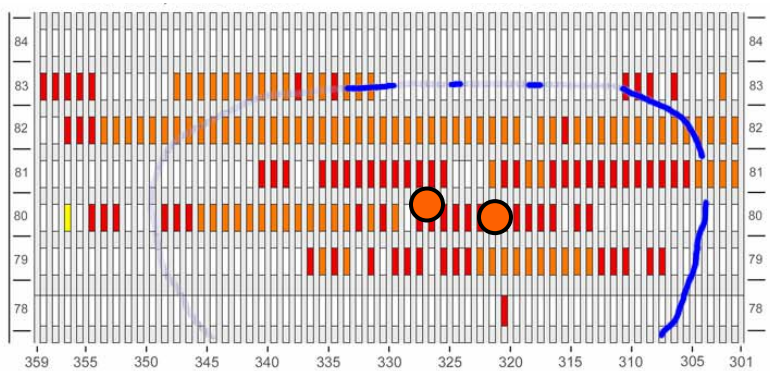


Visual Evidence of Fires in WTC 2, 9:04 a.m. to 9:58 a.m.

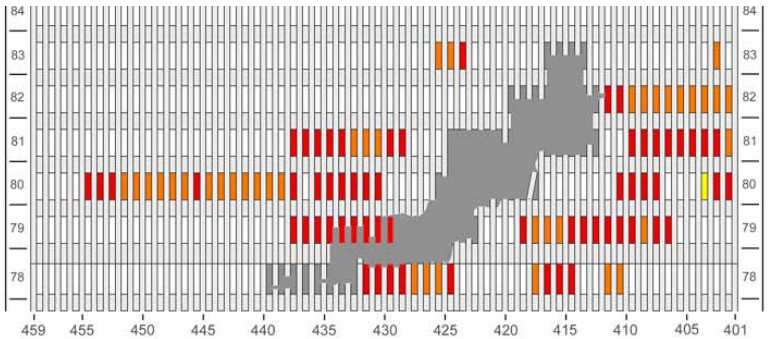
North Face



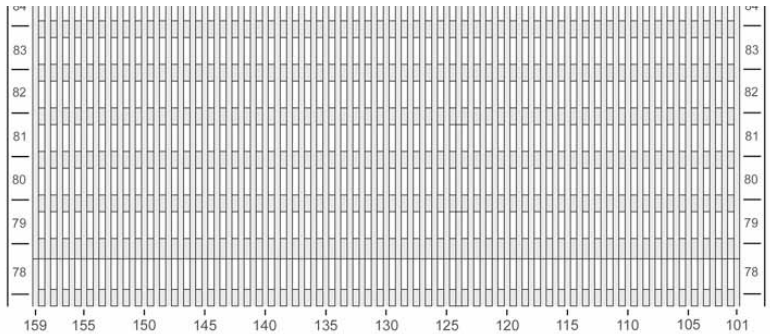
East Face



South Face



West Face



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

East Face of WTC 2 – 9:58 a.m. Inward Bowing of Perimeter Columns Seconds Before Collapse

NIST

9:03 9:58 9:59

WTC 2 Collapse at 9:59 a.m.

WTC 2 tilted to the east and south in this view from the northeast.

WTC 1 Observations and Timeline Findings

- Inward bowing of south face first seen at 10:23 a.m., 5 min before collapse initiated.
- Maximum inward bow was 55 in. ± 6 in. at Floor 97.
- Extent of fires on all WTC 1 exterior faces was similar.
- North face did not bow inward.
- Time to collapse was 102 min.
- Tilt of upper building section took place near Floor 98. Exterior column buckling progressed rapidly across the adjacent east and west faces.
- Upper building section tilted to the south with no discernable east or west component in the tilt.
- Tilt reached 8° before view was obscured by dust clouds.

WTC 2 Observations and Timeline Findings

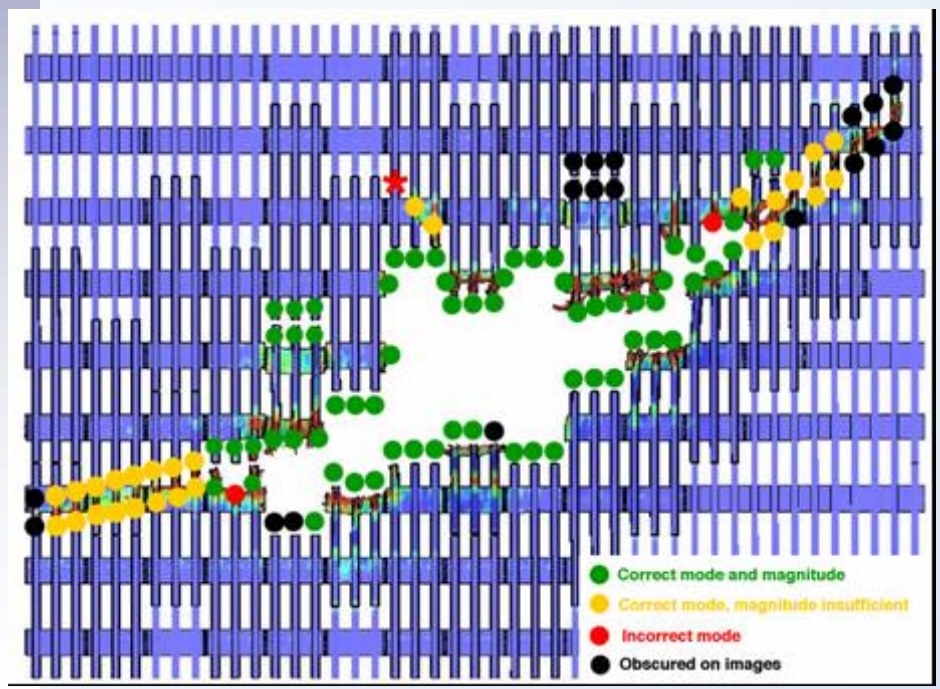
- Draped objects were observed in the windows of the east and north faces which appeared to be hanging floors. The drape increased with time and extended across approximately half of the east face.
- Maximum inward bow of the east face was 10 in. ± 1 in. at Floor 80, first seen at 9:21 a.m., 18 min after impact.
- Maximum inward bowing increased to 20 in. ± 1 in. at Floor 80, 6 min before collapse initiation.
- Fires were more extensive on the east side of the tower. No fires or inward bowing of the west wall were observed on the west face.
- Time to collapse was 56 min.
- Tilt of upper building section took place near Floor 82. Exterior column buckling progressed rapidly across the adjacent north and south faces.
- Upper building section tilted 3° to 4° south and 7° to 8° to the east.
- Tilt to the east reached 20° before view was obscured by dust clouds.

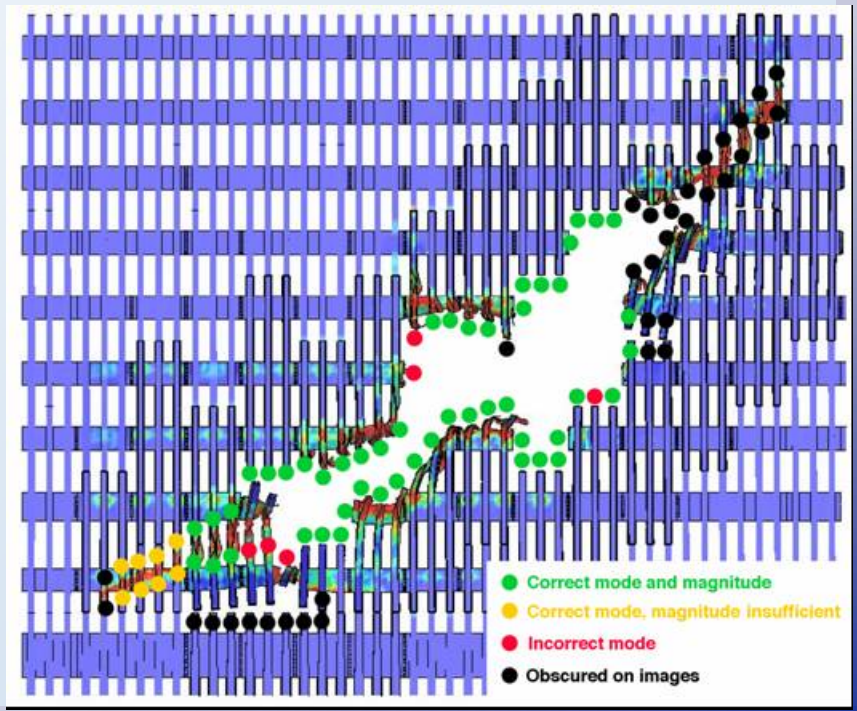
Aircraft Impact Damage to Structural Systems and Fire Protection

Aircraft Impact Damage for Structural Response Analysis

Damage to exterior columns was determined from photographs.

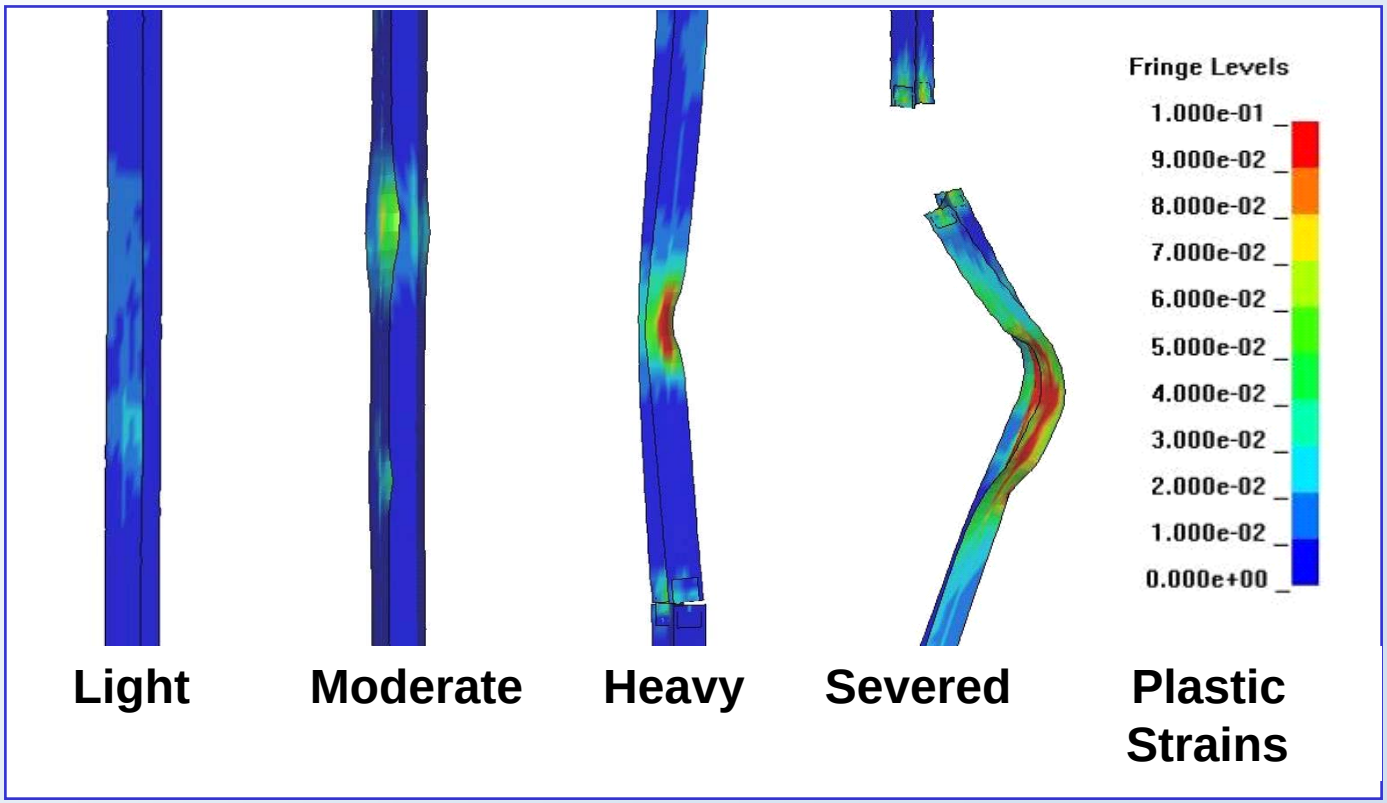
Damage to core columns, floor systems (slabs, core beams, trusses), and fire protection and partitions was determined from aircraft impact analysis results, which were validated with evidence from photographs and videos.





Core Column Damage

	WTC 1	WTC 2
Severed	6	10
Heavy	3	1
Moderate	6	6
Light	5	6

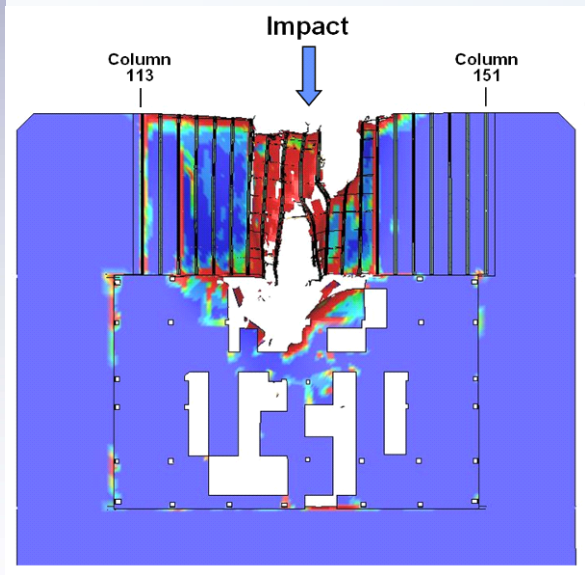


Structural Floor Damage

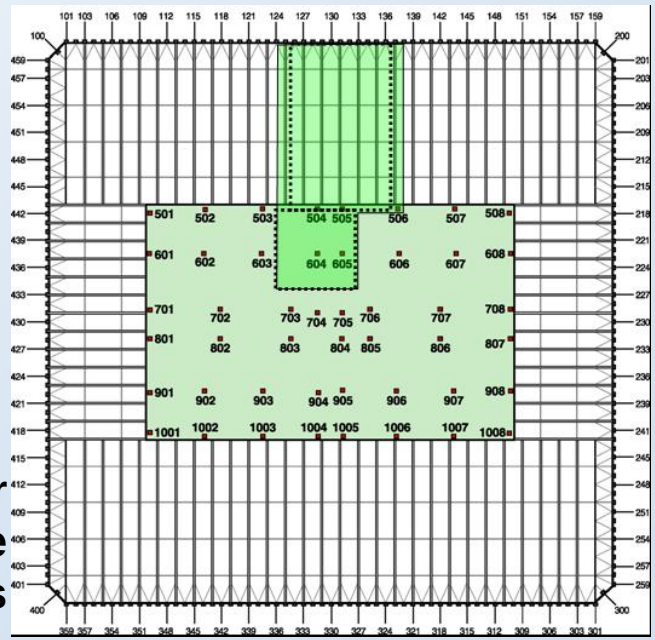
Severely damaged or missing areas incapable of supporting loads

- Severed trusses, beams, and connections
- Concrete damage

Floor areas were removed for both types of damage in structural analyses



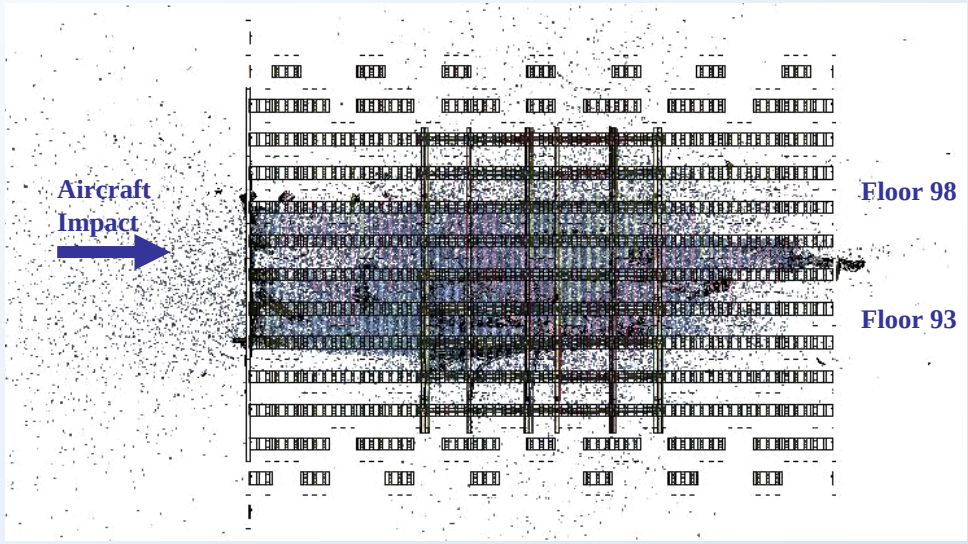
Floor slab damage from aircraft impact analysis



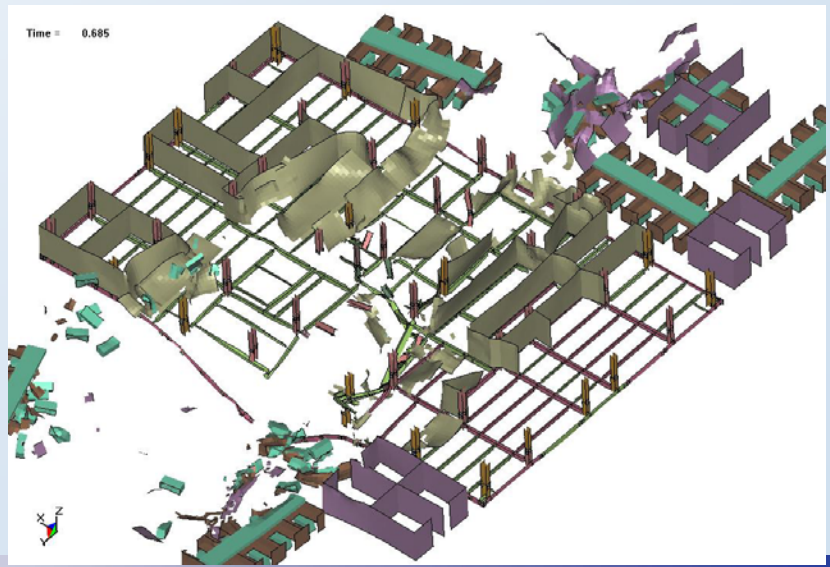
Floor slab damage for structural response analysis

Damage to Passive Fire Protection for Structural Steel

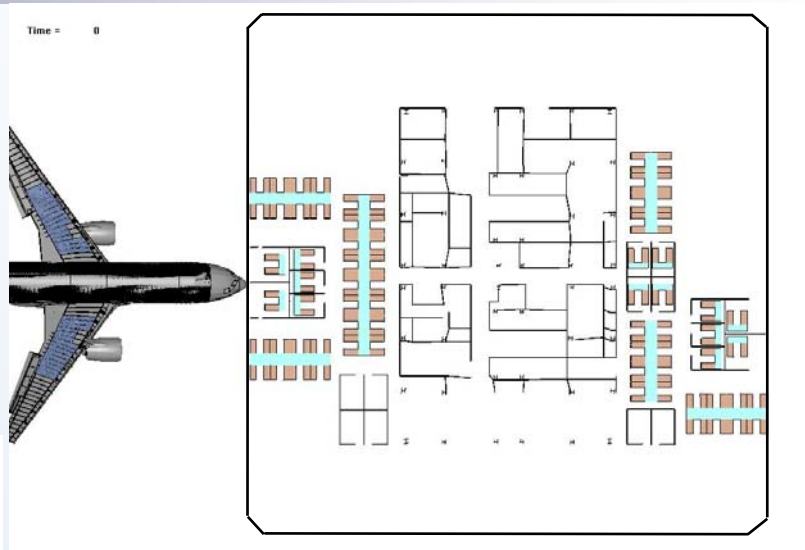
Debris and fuel field traveled across multiple floors and tended to fill floor spaces.

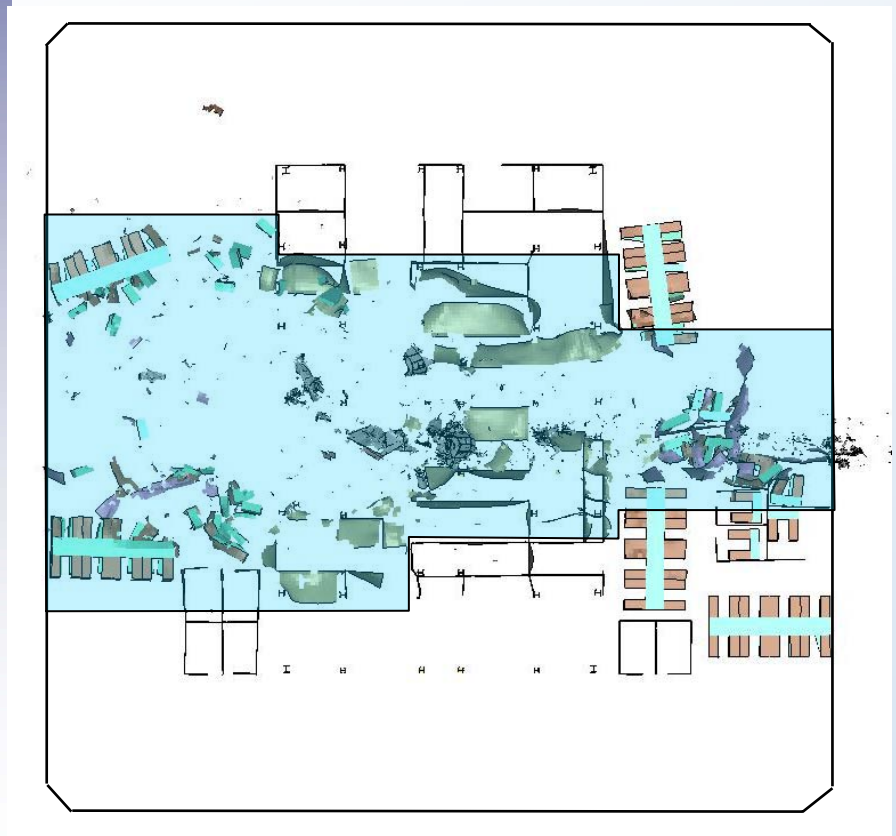


Damage to interior structural framing, partitions, and furnishings was calculated by the aircraft impact analysis.



Damage to Passive Fire Protection for Structural Steel



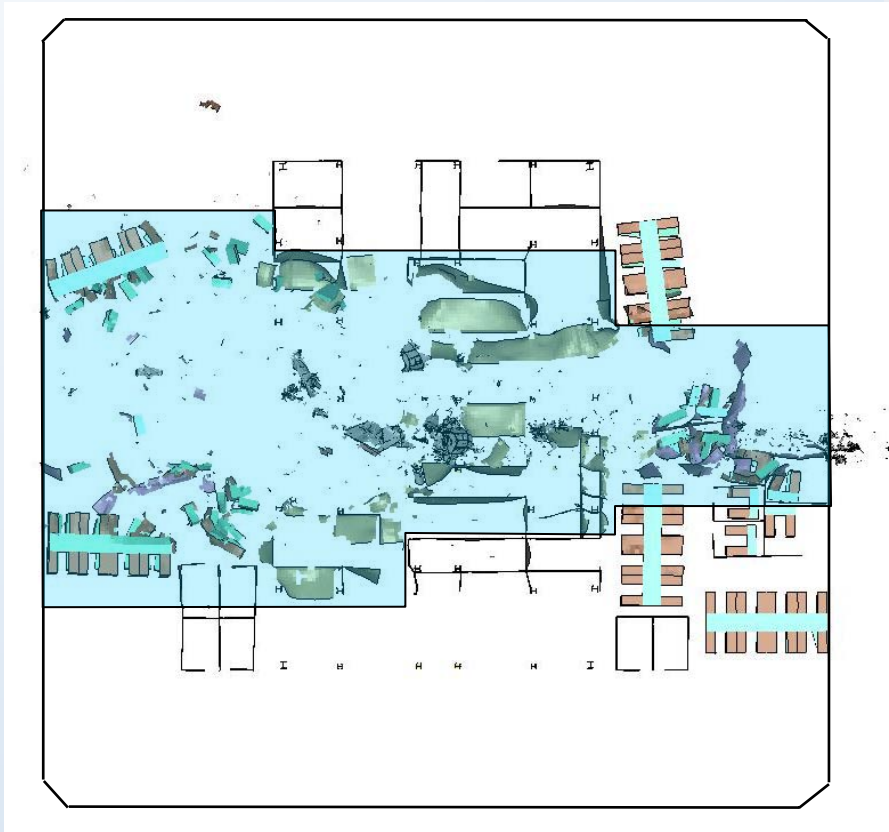


Criteria were established for estimating the extent of dislodged fire protection from direct debris impact.

Criteria for Dislodged Passive Fire Protection of Floor Trusses

If the debris impact damaged or destroyed room furnishings (modular office workstations), then the debris field was considered to extend high enough and be strong enough to dislodge the fire protection in the same floor area.

If the debris field did not damage room furnishings, then the fire protection in the same floor area was considered to be intact.



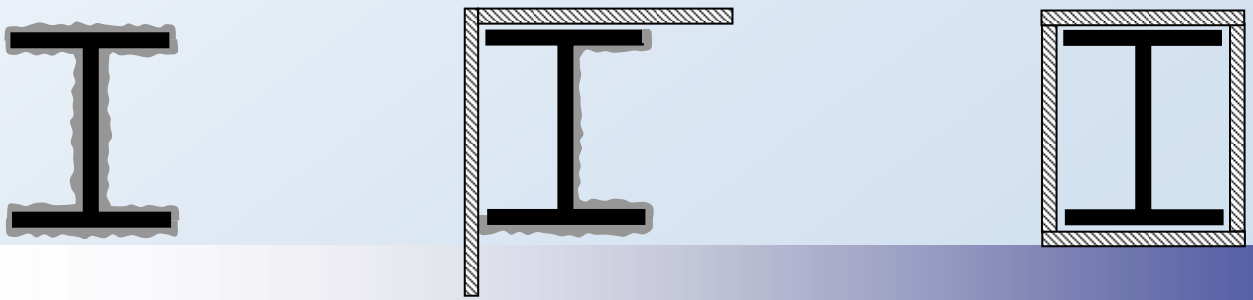
Criteria for Dislodged Passive Fire Protection of Core Columns

If debris impact failed partitions immediately in front of core columns, then the fire protection was assumed to be dislodged over the floor height on core columns behind failed partitions.

If the partitions remained intact, then the fire protection on core columns behind these partitions was assumed to remain intact.

The *representative* strength of building partitions was assumed to be 500 psi based on a survey of data for partition walls and modular workstations; while the *representative* laboratory cohesive and adhesive strengths of fire protection measured by NIST was generally less than 12 psi.

Passive fire protection for core columns included sprayed fire resistive material (SFRM), gypsum wallboard enclosures, or a combination.

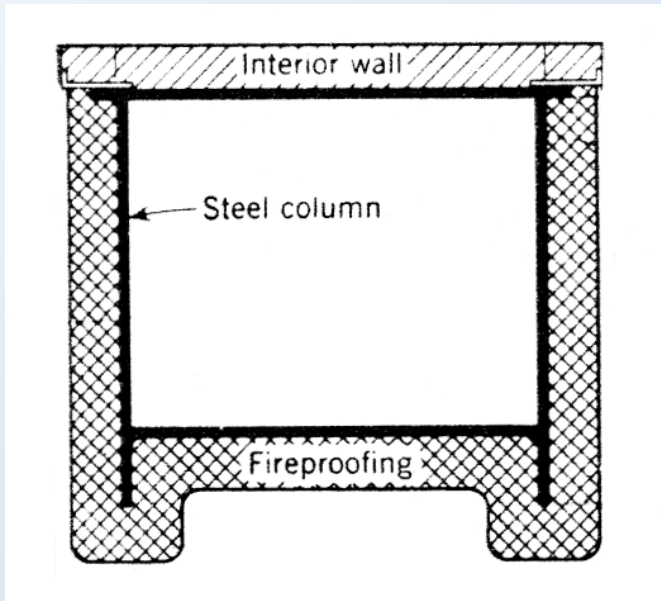


Criteria for Dislodged Passive Fire Protection of Exterior Columns

If debris impact damaged or destroyed room furnishings (modular office workstations) adjacent to the exterior columns, then the fire protection on the inside face of the exterior columns in the same vicinity was assumed to be dislodged over the floor height.

If furnishings remained intact adjacent to the exterior columns, then the fire protection on the inside face of the exterior columns behind the furnishings was assumed to remain intact.

The other three faces of the exterior columns were protected by the windows and/or aluminum cladding and were assumed to have no fire protection damage.

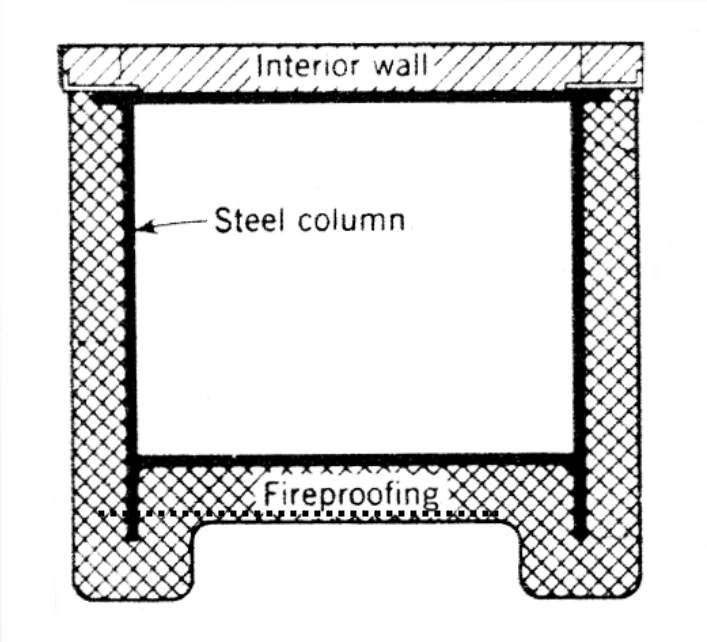


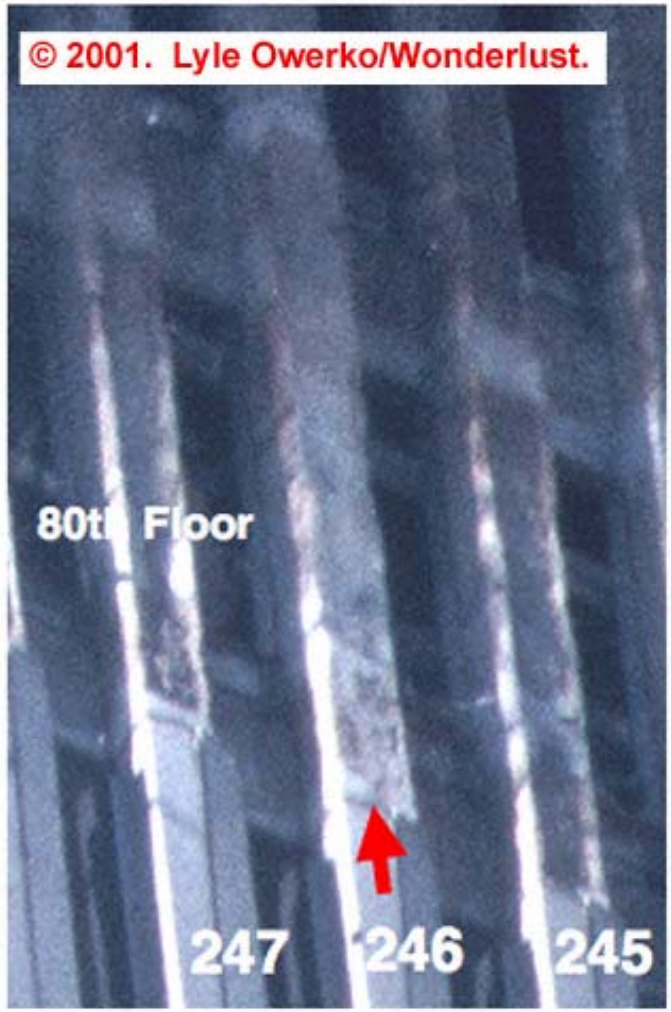
Estimate of Fire Protection Damage

Consistent with a conservative approach, NIST estimates ignored the possibility that passive fire protection on structural components over a much larger region than the direct path of the debris was dislodged by shock or strong vibrations.

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

Application of SFRM to External Columns





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

Thermal Analysis of Dislodged Passive Fire Protection

For intact fire protection:

- Floor trusses - a thermally equivalent uniform thickness
- Columns - the specified thickness determined from available documents.

For dislodged fire protection:

- Core columns and floor trusses - the fire protection was considered to be missing on the component. Separate analysis showed that significant regions of missing fireproofing is essentially equivalent to there being no fireproofing.
- Exterior columns - the fire protection was considered to be missing on the inner face.

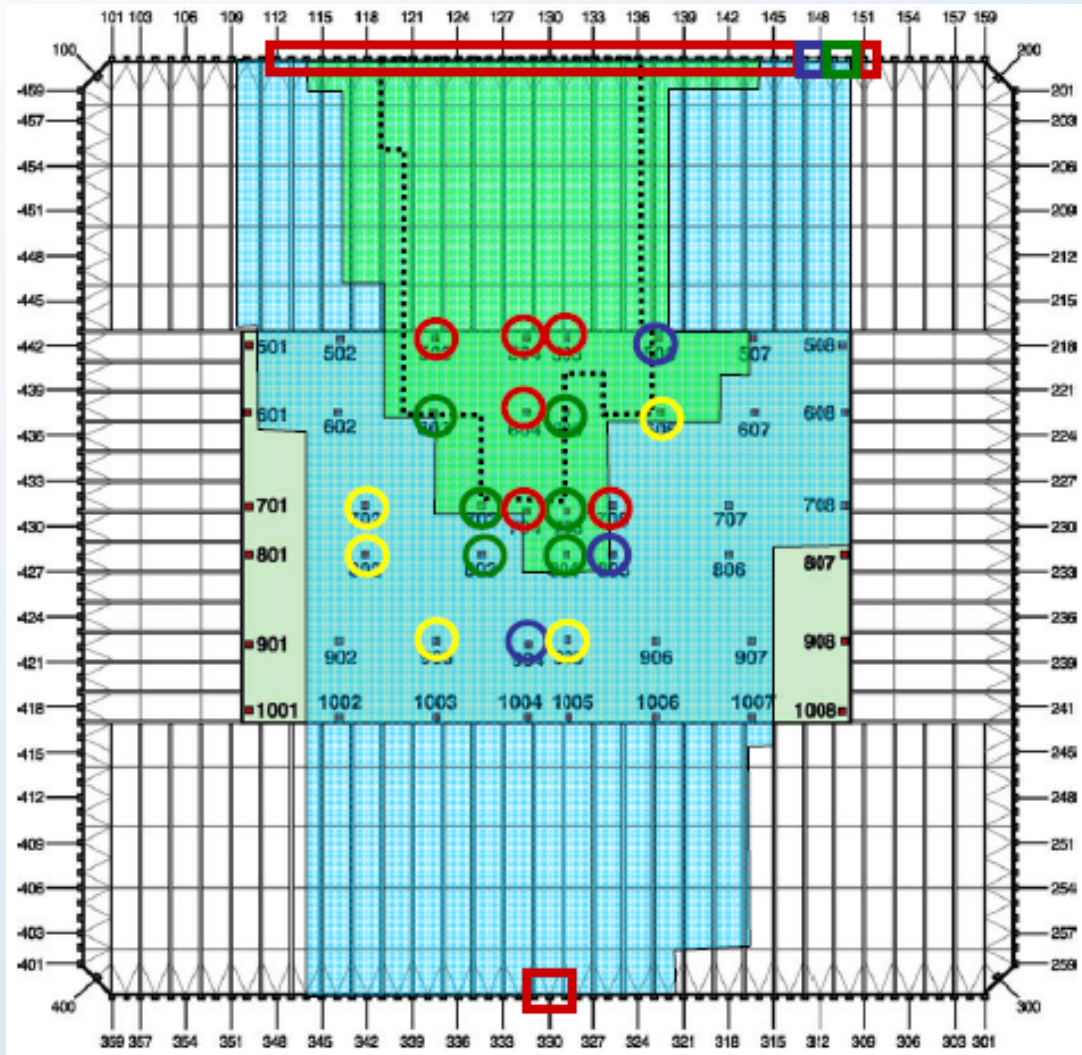
WTC 1 Damage: Composite Summary for Floors 93 to 98

Severe Floor Damage

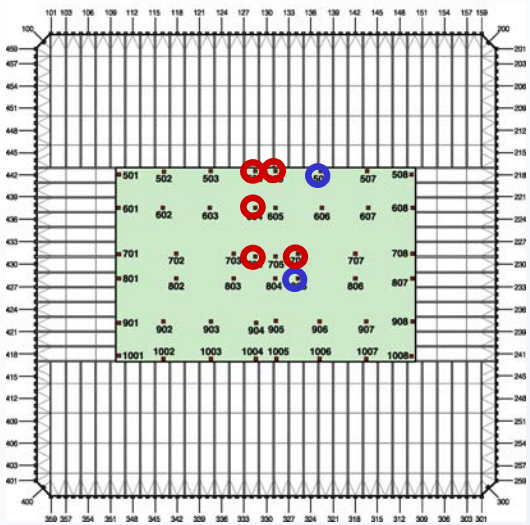
- Fireproofing and partitions
- Floor system structural damage
- Floor system removed

Column Damage

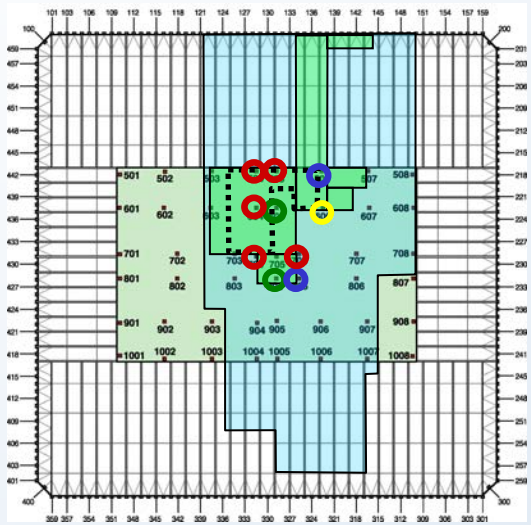
- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



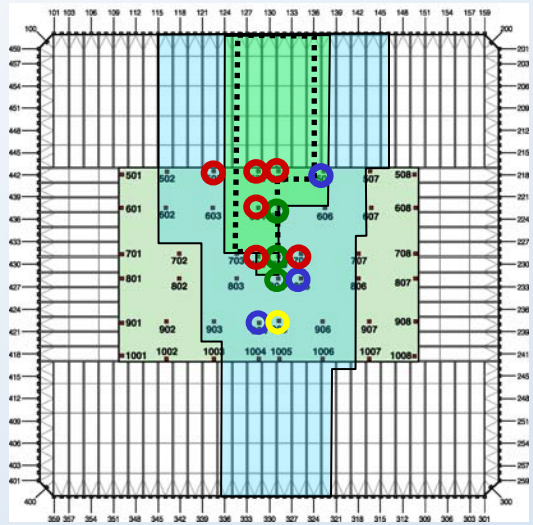
WTC 1 Damage by Floor



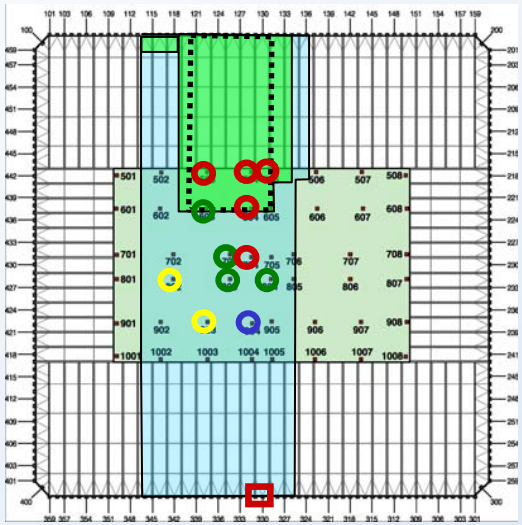
Floor 93



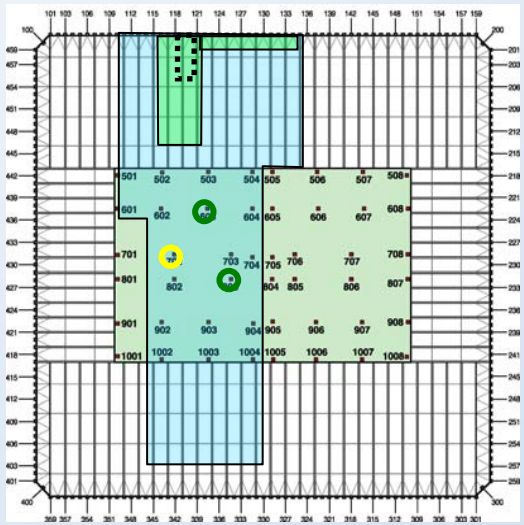
Floor 94



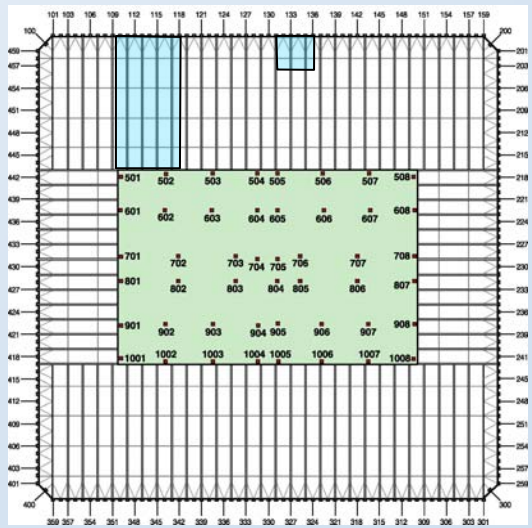
Floor 95



Floor 96



Floor 97



Floor 98

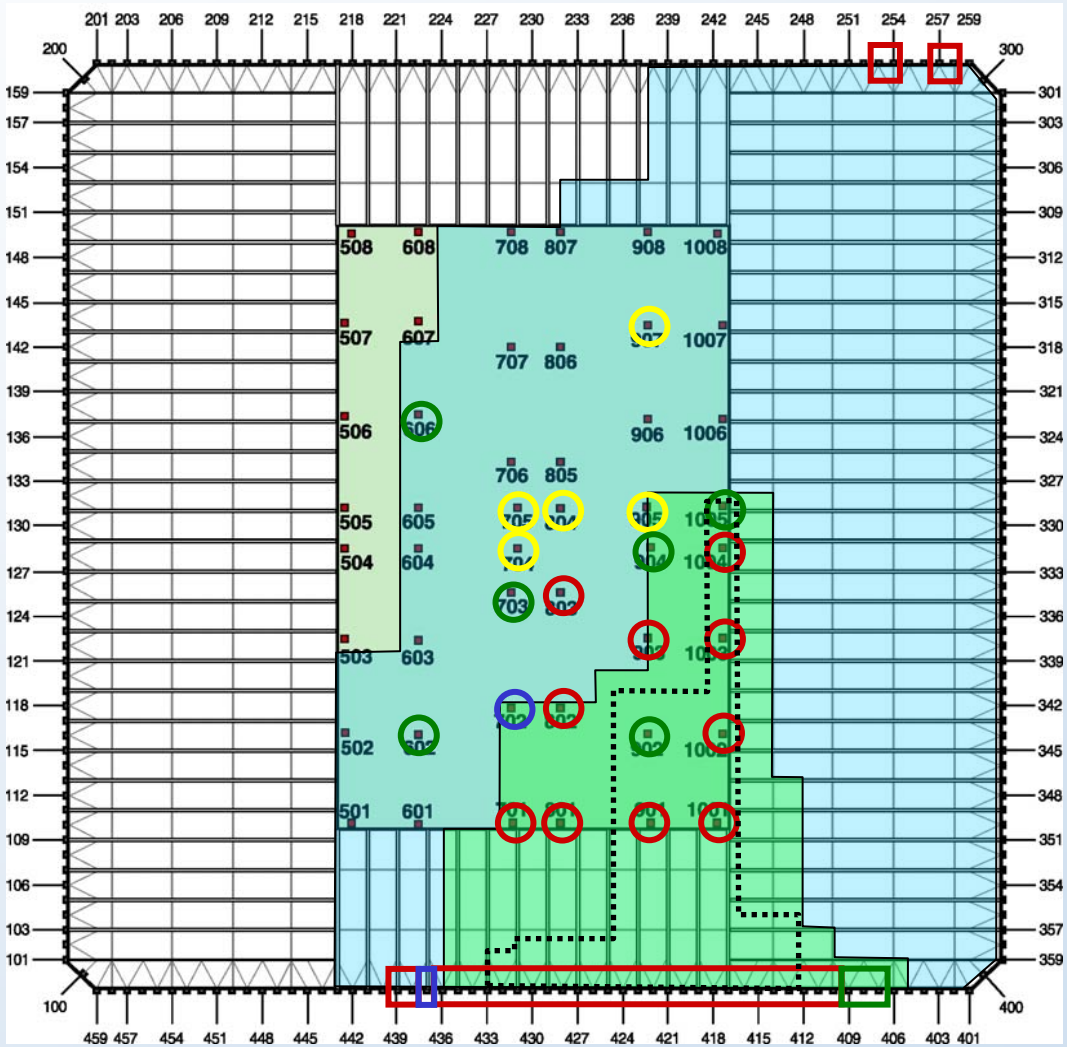
WTC 2 Damage: Composite Summary for Floors 78 to 83

Severe Floor Damage

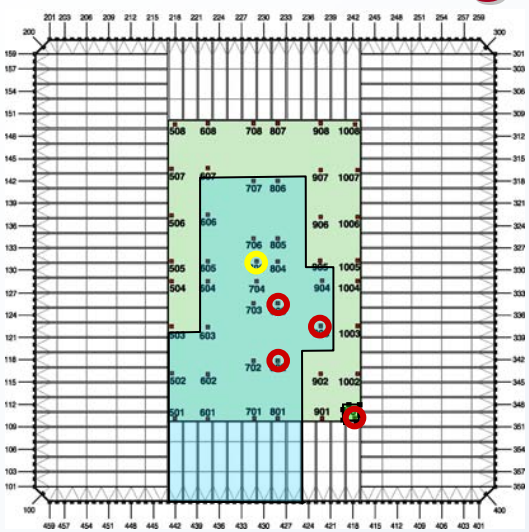
- Fireproofing and partitions
- Floor system structural damage
- Floor system removed

Column Damage

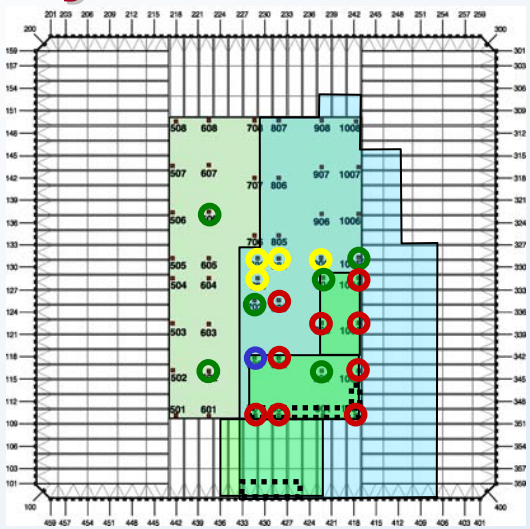
- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



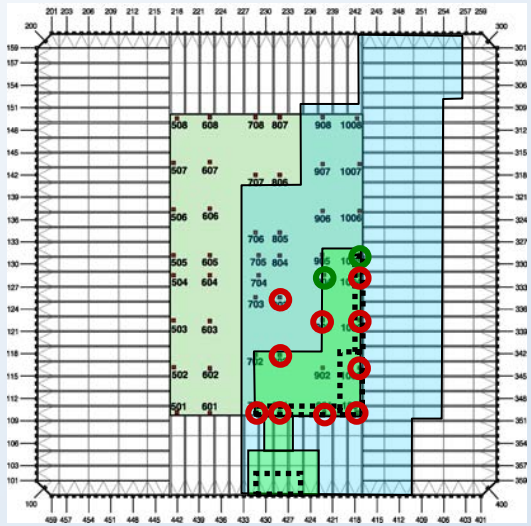
WTC 2 Damage by Floor



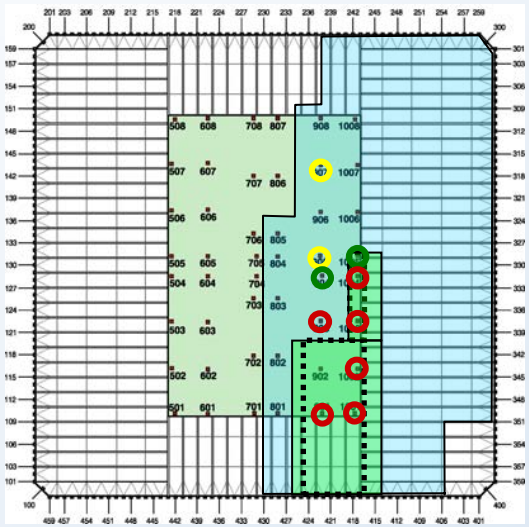
Floor 78



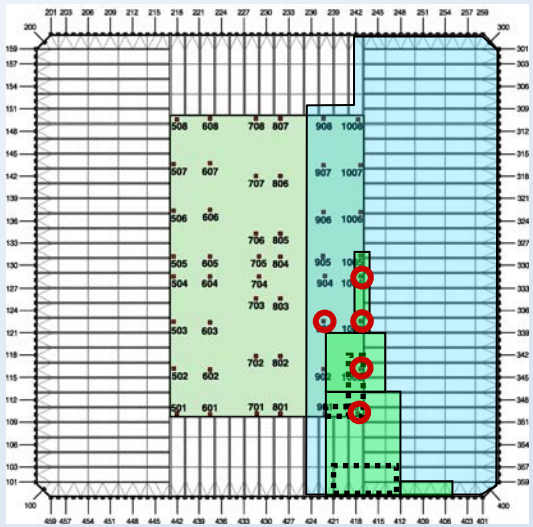
Floor 79



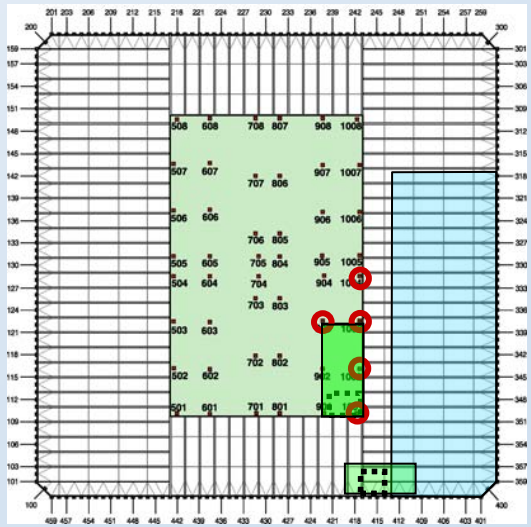
Floor 80



Floor 81



Floor 82



Floor 83

Aircraft Impact Damage to Structural Systems and Fire Protection

- In WTC 1, structural systems were damaged and fire protection was dislodged by direct debris impact over Floors 94 to 98, over most of the north floor areas, the core, and central regions of the south floor areas, extending to the south wall.

- In WTC 2, structural systems were damaged and fire protection was dislodged by direct debris impact over Floors 78 to 83, over the south floor area in front of the core, central and east regions of the core, and most of the east floor areas, extending to the north wall.

- Fire protection damage estimates were conservative. Possible damage outside area of direct debris impact was not included as a robust criteria to estimate vibration-induced dislodging could not be established.

The End