



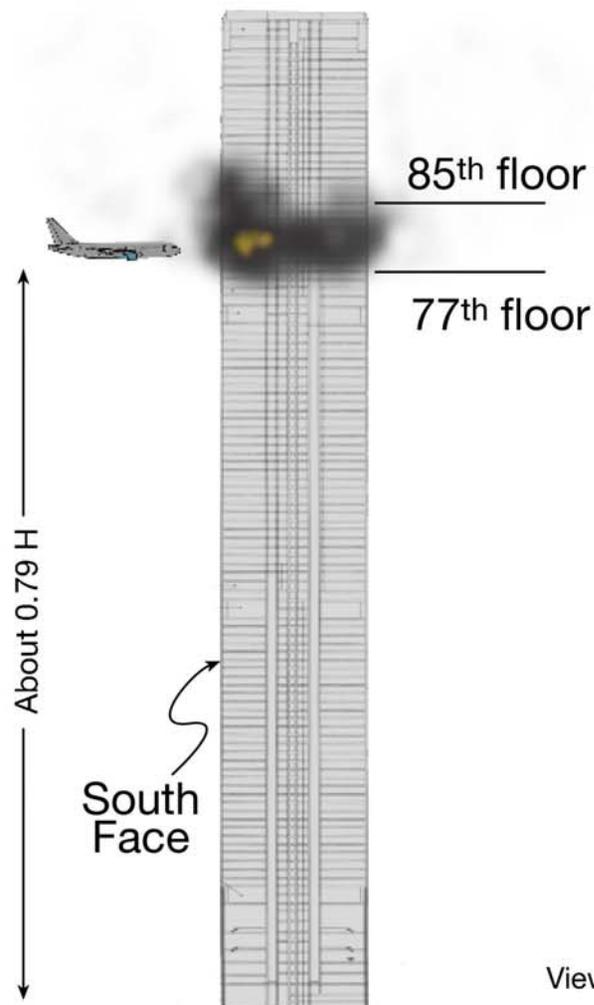
NIST Response to the World Trade Center Disaster

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

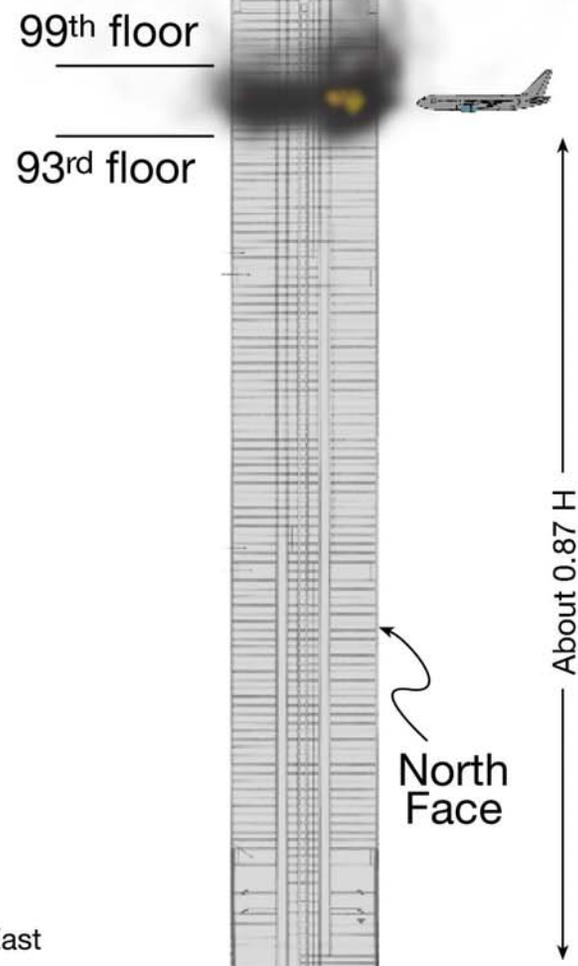
Part IIB – Collapse Sequence

April 5, 2005

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



WTC 2: Hit at 9:02:59 a.m.
Collapsed after 56 minutes

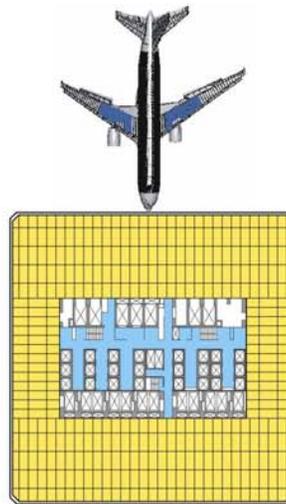


WTC 1: Hit at 8:46:30 a.m.
Collapsed after 102 minutes

View from the East

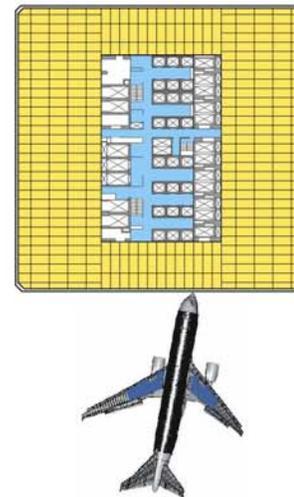
Point of impact:
Close to the center
and nearly normal
to the building

WTC 1



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

WTC 2



Determining the Probable Collapse Sequences

- Performed extensive sensitivity analyses to determine most influential factors for each analysis step.
- Determined three sets of values for the parameters most influential to the aircraft damage and the progress of the fires.
- Performed three aircraft impact and fire dynamics analyses by pairing the expected aircraft and fire parameter sets that provide different levels of damage.
- Conducted thermal and structural subsystem analyses for the cases that reasonably matched observed impact damage and fire progression.
- Completed global structural collapse analyses for the case that best matched observed structural collapse data.

Progress in Determining Collapse Sequences

- **Possible Collapse Hypotheses** (May 2003) – not building specific; key events not identified
- **Working Collapse Hypothesis** (June 2004) – single hypothesis for both WTC towers; identifies chronological sequence of major events
- **Leading Collapse Hypotheses** (October 2004) – separate hypothesis for each WTC tower; identifies building-specific load redistribution paths and damage scenarios in addition to chronological sequence of major events
- **Probable Collapse Sequences** (April 2005) – refined building specific collapse sequences with chronological sequence of major events, load redistribution paths, and damage scenarios.

Probable Collapse Sequence for WTC 1

1. Aircraft Impact Damage:

- Aircraft impact severed a number of exterior columns on the North wall from floors 93 to 98, and the wall section above the impact zone moved downward.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, severing floor framing and core columns at the North side of the core. Core columns were also damaged toward the center of the core and, to a limited extent on the South side of the core. Fireproofing was damaged from the impact area to the South perimeter wall, primarily through the center of WTC 1 and at least over a third to a half of the core width.
- Aircraft impact severed a single exterior panel at the center of the South wall between floors 94 and 96.
- The impact damage to the exterior walls and to the core resulted in redistribution of severed column loads, mostly to the columns adjacent to the impact zones. The hat truss resisted the downward movement of the North wall, and rotated about the East-West axis.
- As a result of the aircraft impact damage, the North and South walls each carried about 7 percent less gravity loads after impact, and the East and West walls each carried about 7 percent more loads. The core carried about 1 percent more gravity loads after impact.

Probable Collapse Sequence for WTC 1 (2)

2. Effects of Subsequent Fires and Impact Damaged Fireproofing:

A. Thermal Weakening of the Core:

- The undamaged core columns developed high plastic and creep strains over the duration the building stood, since both temperatures and stresses were high in the core area. The plastic and creep strains exceeded thermal expansion in the core columns.
- The shortening of the core columns (due to plasticity and creep) was resisted by the hat truss which unloaded the core over time and redistributed loads to perimeter walls.
- As a result of the thermal weakening (and subsequent to impact and prior to inward bowing of the South wall), the North and South walls each carried about 10 percent more gravity loads, and the East and West walls each carried about 25 percent more loads. The core carried about 20 percent less gravity loads after thermal weakening.

B. Thermal Weakening of the Floors:

- Floors 95 to 99 weakened with increasing temperatures over time on the long-span floors and sagged. The floors sagged first and then contracted due to cooling on the North side; fires reached the South side later, the floors sagged, and the seat connections weakened.
- Floor sagging induced inward pull forces on the South wall columns.
- About 20 percent of the connections to the South perimeter wall on floors 97 and 98 failed due to thermal weakening of the vertical supports.

C. Thermal Weakening of the South Wall:

- South wall columns bowed inward as they were subjected to high temperatures and inward pull forces in addition to axial loads.
- Inward bowing of the South wall columns increased with time.

Probable Collapse Sequence for WTC 1 (3)

3. Collapse Initiation

- The inward bowing of the South wall induced column instability, which progressed rapidly horizontally across the entire South face.
- The South wall unloaded and tried to redistribute the loads via the hat truss to the thermally weakened core and via the spandrels to the adjacent East and West walls.
- The entire section of the building above the impact zone began tilting as a rigid block (all four faces; not only the bowed and buckled South face) to the South (at least about 8°) as column instability progressed rapidly from the South wall along the adjacent East and West walls.
- The change in potential energy due to downward movement of building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued.

Probable Collapse Sequence for WTC 2

1. Aircraft Impact Damage:

- Aircraft impact severed a number of exterior columns on the South wall from floors 78 to 84, and the wall section above the impact zone moved downward.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, severing floor framing and core columns at the Southeast corner of the core. Fireproofing was damaged from the impact area through the East half of the core up to the North and East perimeter walls. The floor truss seat connections over about 1/4 to 1/2 of the East side of the core were severed on floors 80 and 81 and over about 1/3 of the East perimeter wall on floor 83.
- Aircraft impact severed a few columns near the East corner of the North wall between floors 80 and 82.
- The impact damage to the exterior walls resulted in redistribution of severed column loads, mostly to the columns adjacent to the impact zones. The impact damage to the core columns resulted in redistribution of severed column loads mostly to other intact core columns and the East exterior wall. The hat truss resisted the downward movement of the South wall, and rotated about the East-West axis.
- As a result of the aircraft impact damage, the core carried 6 percent less gravity loads after impact and the North face carried 10 percent less loads. The East face carried 24 percent more gravity load, while the West face and the South face carried 3 percent and 2 percent more gravity load, respectively.
- After impact, the core was leaning toward the East and South perimeter walls. The perimeter walls acted to restrain the core structure.

Probable Collapse Sequence for WTC 2 (2)

2. Effects of Subsequent Fires and Impact Damaged Fireproofing:

A. Thermal Weakening of the Core:

- Several of the undamaged core columns near the damaged and severed core columns developed high plastic and creep strains over the duration the building stood, since both temperatures and stresses were high in the core area. The plastic and creep strains exceeded thermal expansion in the core columns.
- The core continued to tilt toward the East and South due to the combination of column shortening (due to plasticity, creep, and buckling) and the failure of column splices at the hat truss in the Southeast corner.
- As a result of thermal weakening (and subsequent to impact), the East wall carried about 5 percent more gravity loads and the core carried about 2 percent less loads. The other three walls carried between 0 and 3 percent less loads.

B. Thermal Weakening of the Floors:

- Floors 79 to 83 weakened with increasing temperatures over time on the long-span floors on the East side and sagged.
- Floor sagging induced inward pull forces on the East wall columns.
- About an additional 1/3 of the connections to the East perimeter wall on floor 83 failed due to thermal weakening of the vertical supports.

C. Thermal Weakening of the East Wall:

- East wall columns bowed inward as they were subjected to high temperatures and inward pull forces in addition to axial loads.
- Inward bowing of the East wall columns increased with time.

Probable Collapse Sequence for WTC 2 (3)

3. Collapse Initiation

- The inward bowing of the East wall induced column instability, which progressed rapidly horizontally across the entire East face.
- The East wall unloaded and tried to redistribute the loads via the hat truss to the weakened core and via the spandrels to the adjacent North and South walls.
- The entire section of the building above the impact zone began tilting as a rigid block (all four faces; not only the bowed and buckled East face) to the East (about 7° to 8°) and South (about 3° to 4°) as column instability progressed rapidly from the East wall along the adjacent North and South walls. The building section above impact continued to rotate to the East as it began to fall downward, and rotated to at least 20 to 25 degrees.
- The change in potential energy due to downward movement of building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued.

Validation of Probable Collapse Sequence

- NIST evaluated the key factors related to:
 - Innovative structural system
 - Aircraft impact and subsequent fires: How safe was each building immediately after aircraft impact but before fire weakened the structures?
 - Post-impact condition of fireproofing
 - Quality and properties of structural steel
 - Relative roles of the perimeter and core columns and the composite floor system, including connections
 - Role of compartmentation (i.e. areas divided by fire-rated walls)
- NIST made concerted efforts to validate results with key observations obtained from its extensive collection of over 7,000 photographs and over 150 hours of videotape documenting the events at the World Trade Center on September 11, 2001
- The probable collapse sequences are supported by the evidence held by NIST, including photographs and videos, recovered steel, eyewitness accounts, and emergency communication records

Time to Collapse Initiation

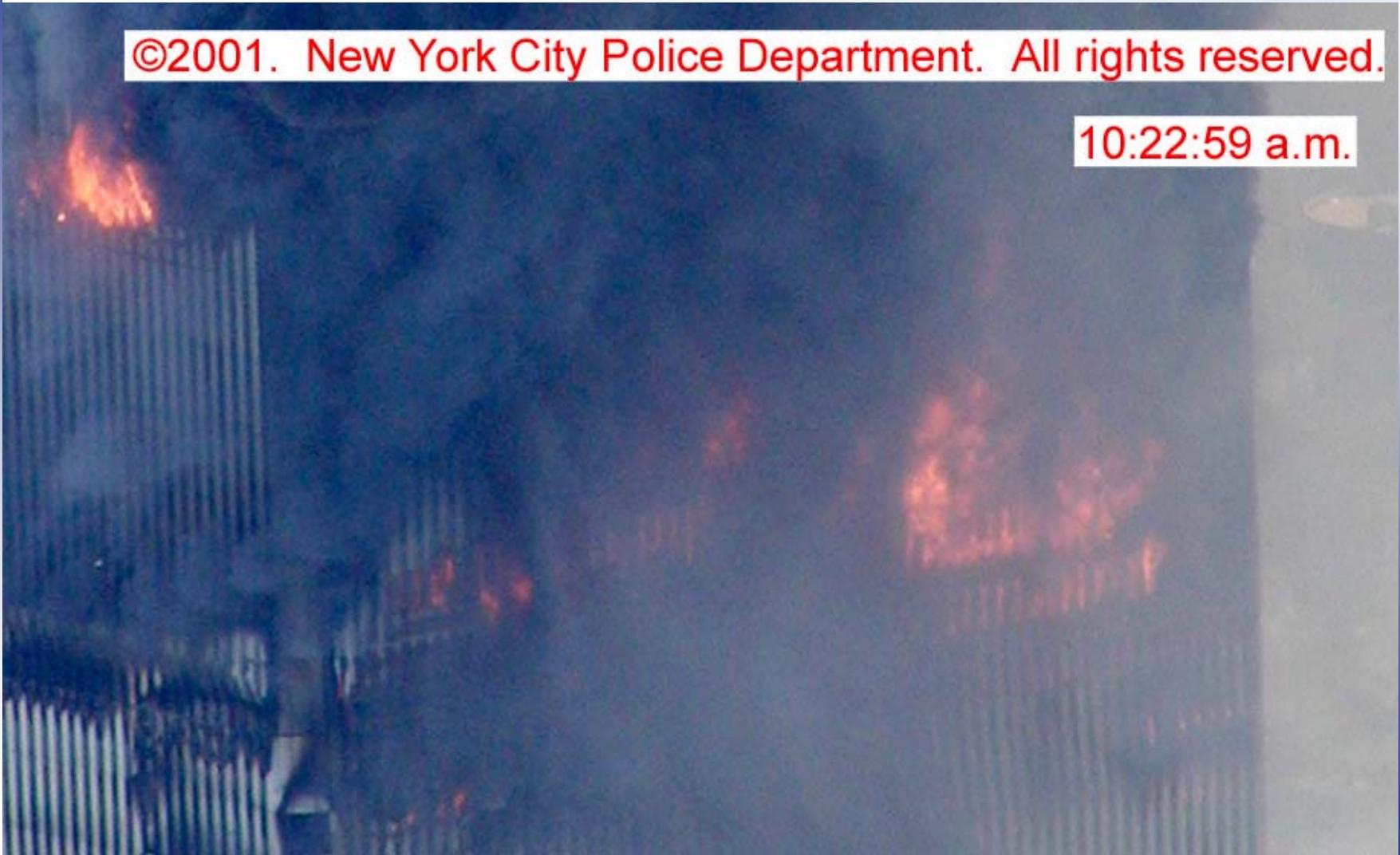
	WTC 1	WTC 2
Actual Time	102 min	56 min
Estimated Time*	100 min	42 min

* The exact times are sensitive to the factors that control the inward bowing of the exterior columns. The sequence of events leading to collapse is not sensitive to these factors.

Inward Bowing of Perimeter Columns About 5 Minutes Prior to Collapse: WTC 1 South Face

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10:22:59 a.m.



South Face of WTC 1, 9:25 am. No inward bowing



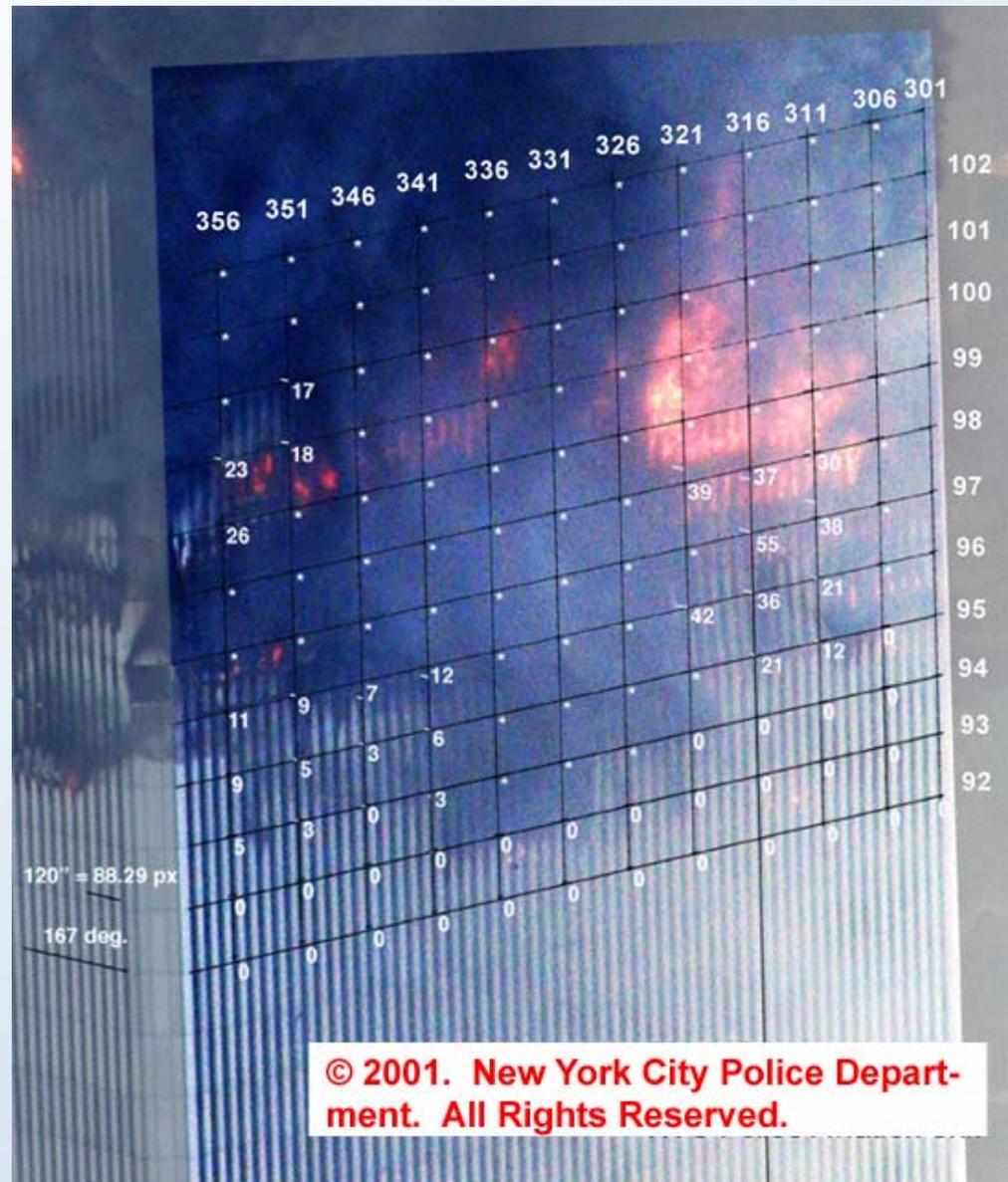
South Face of WTC 1, 9:40 am. No inward bowing



South Face of WTC1

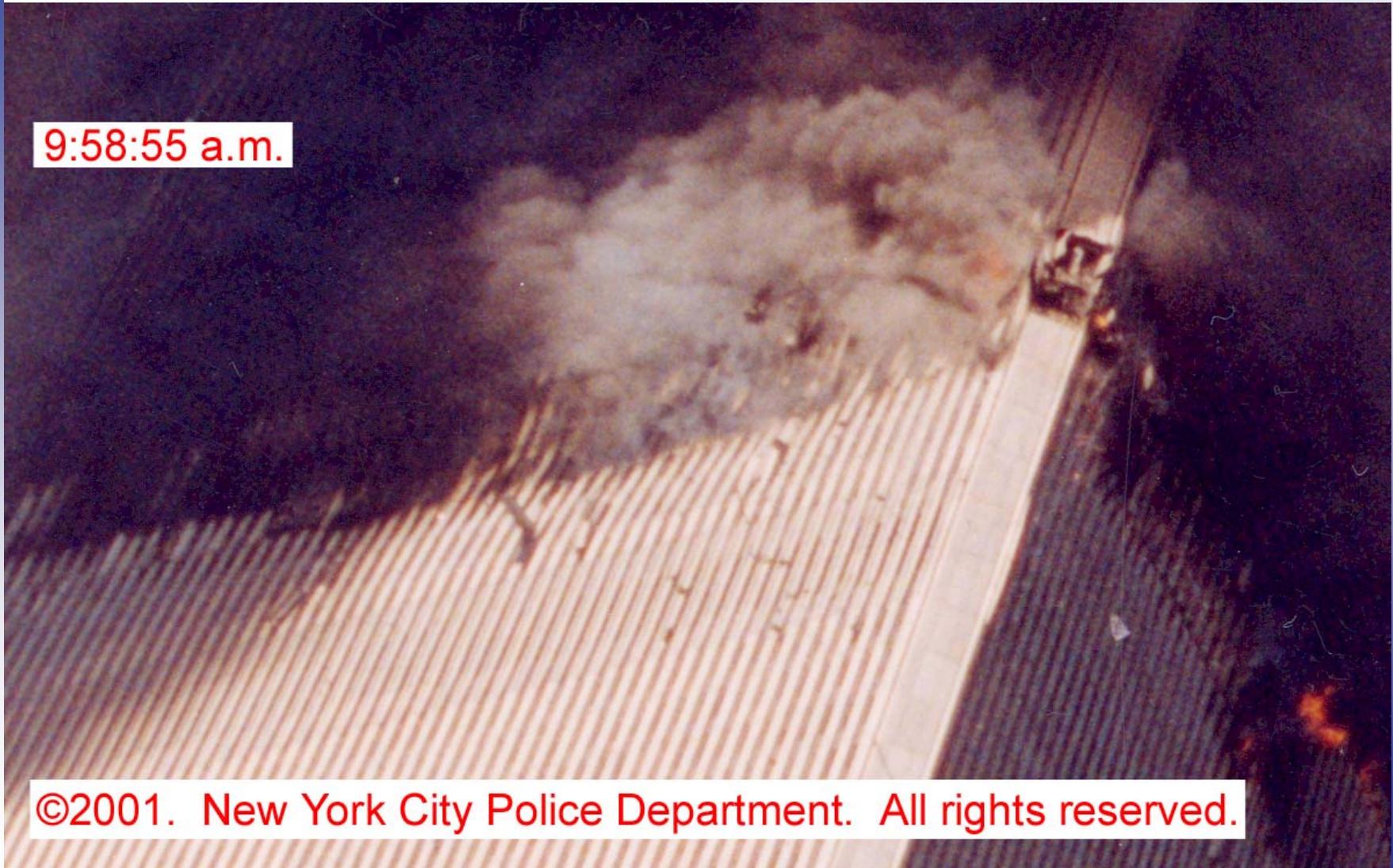
- Time: 10:22 AM
- Measurements of inward bowing (inches)
- **Maximum = 55 inches**
(uncertainty ~ +/- 6 inches)

- Floor locations approximate
- Blue tinted region digitally enhanced



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

9:58:55 a.m.

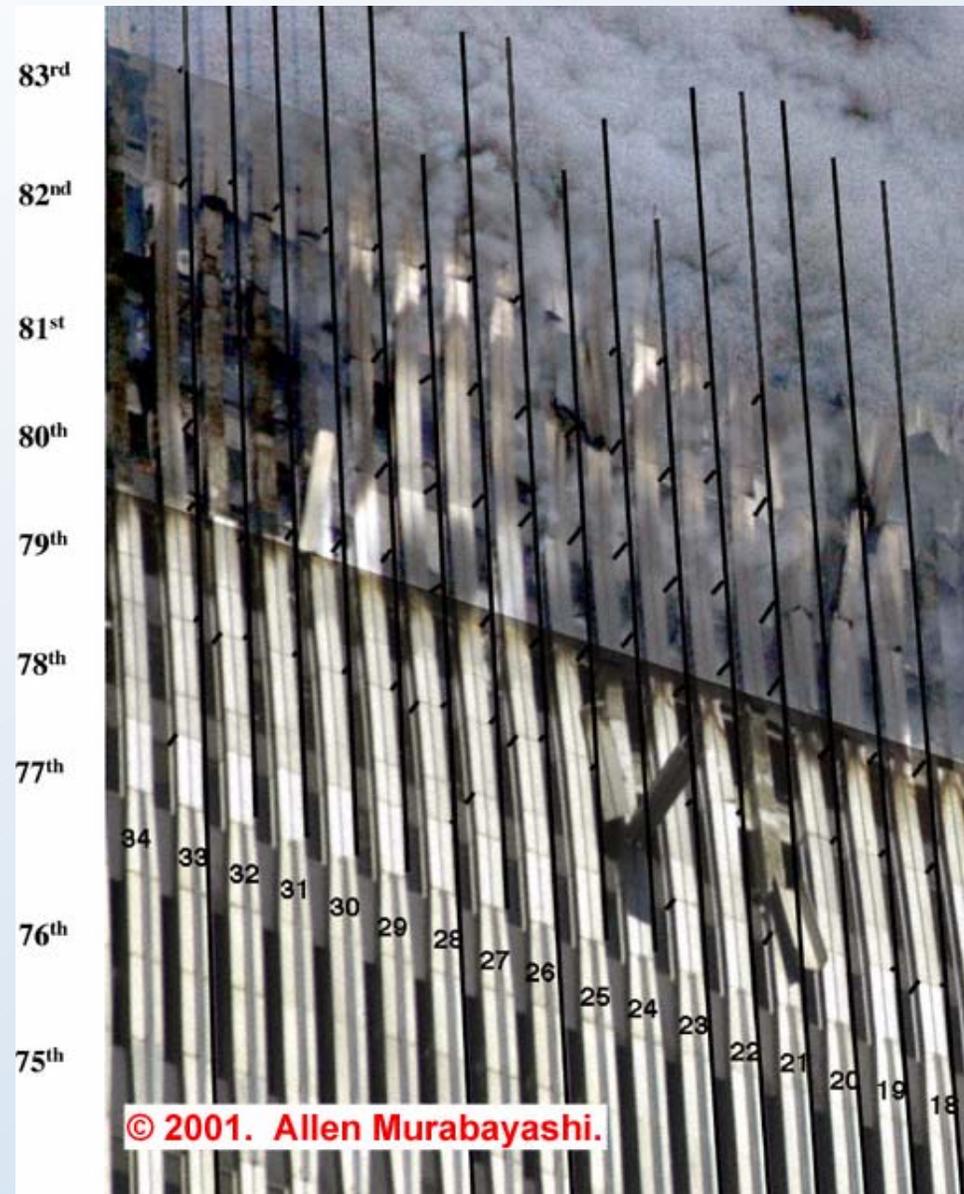


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WTC2: East Face

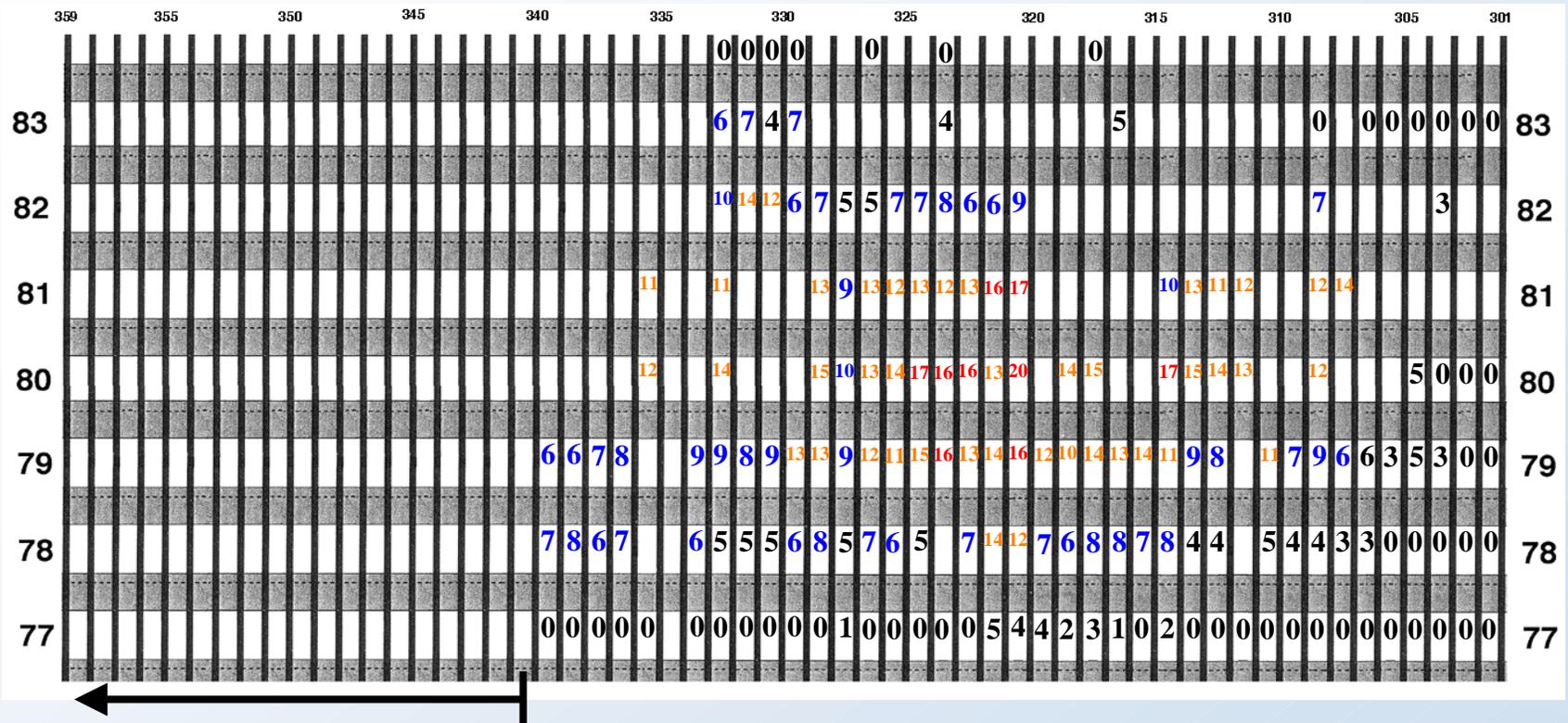
Time: 9:21:29 AM
~18 minutes post impact

Maximum inward bowing of
columns approximately
10 inches



Map of Inward Bowing: East Face of WTC 2

Time: 9:52:54 AM to 9:53:04 AM



Obscured in Photos

Pull-in (inches)

Estimated uncertainty: +/- 1 inch

Empty regions have no data (smoke, damaged aluminum, could not establish true vertical, etc.)

Photographic Evidence of Hanging Floor Slab

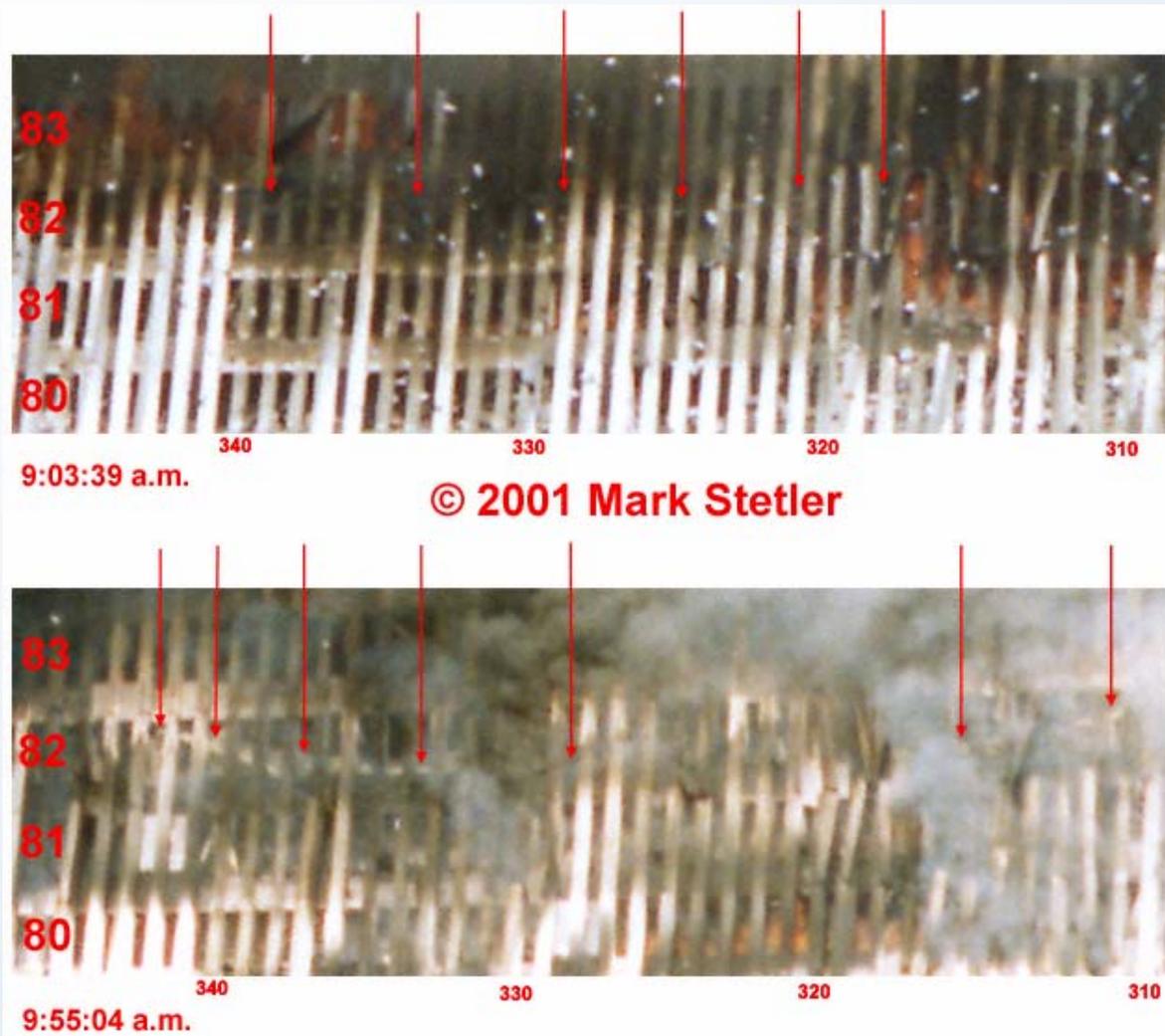


© 2001 Allen Murabayashi

9:47:10 a.m.

East Face of WTC 2. Image shows what appear to be a floor slab from the 83rd floor hanging across window opening over a large portion of the 82nd floor.

Photographic Evidence of Hanging Floor Slab



Amount and extent of floor sag increased over the 51 minute period.

Photographic Evidence of Hanging Floor Slab

© 2001 Shannon Stapleton/Reuters



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

Tilting of Building Sections

WTC 1 tilted to the south; WTC 2 tilted to the east and south.

© 2001 Dean Riviere



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

WTC 1: First Responder Communications

- 10:06 am NYPD aviation unit advises everybody to evacuate the area in the vicinity of Battery Park City and states that, about 15 floors from the top, it is totally glowing red on the inside and collapse was inevitable.

NYPD officer advises that it is isn't going to take much longer before the North tower comes down and to pull emergency vehicles back from the building.
- 10:21 am NYPD aviation unit first reports that the top of the tower might be leaning, then confirms that it is buckling and leaning to the South.

NYPD aviation unit reports that the North tower is leaning to the Southwest and appears to be buckling in the Southwest corner.

NYPD officer advises that all personnel close to the building pull back three blocks in every direction.
- 10:28 am NYPD aviation unit reports that the roof is going to come down very shortly.

NYPD officer reports that the tower is collapsing.

WTC 2: First Responder Communications

- 9:36 am New York City 9-1-1 telephone operator receives a message from an occupant of WTC 2 that a floor had collapsed below them in the 90s level.
- 9:41 am NYPD dispatcher advises units that floor 106* in WTC 2 is collapsing and that the message comes from someone on that floor.
- 9:52 am NYPD aviation unit gives a radio report stating that “large pieces” are falling from WTC 2.

NYPD dispatcher advises that floor 106 of WTC 2 is crumbling per communications with victims trapped on the floor.
- 9:58 am NYPD aviation unit advises that the whole building is coming down.

* The 9/11 Commission report suggests that the source of this message appears to be the previously cited 911 call from a floor in the 90s.

WTC 1 Timeline

Time	Floors	Face	Columns	Event Description
8:46:26	93-99	N	109-152	WTC1 Aircraft Impact between floors 93 to 99, columns 109 to 152.
	94-96	S	329	Panel knocked out by nose or landing gear in window 95-329.
~9:55		S	301-323	No bowing of South face columns.
10:22:59	95-99	S	308-326+	South face columns are bowing inward.
10:28:20				Tower begins to collapse – First exterior movement is at floor 98. Rotation of at least 8 degrees to the south occurs before the building section begins to fall vertically.

WTC 2 Timeline

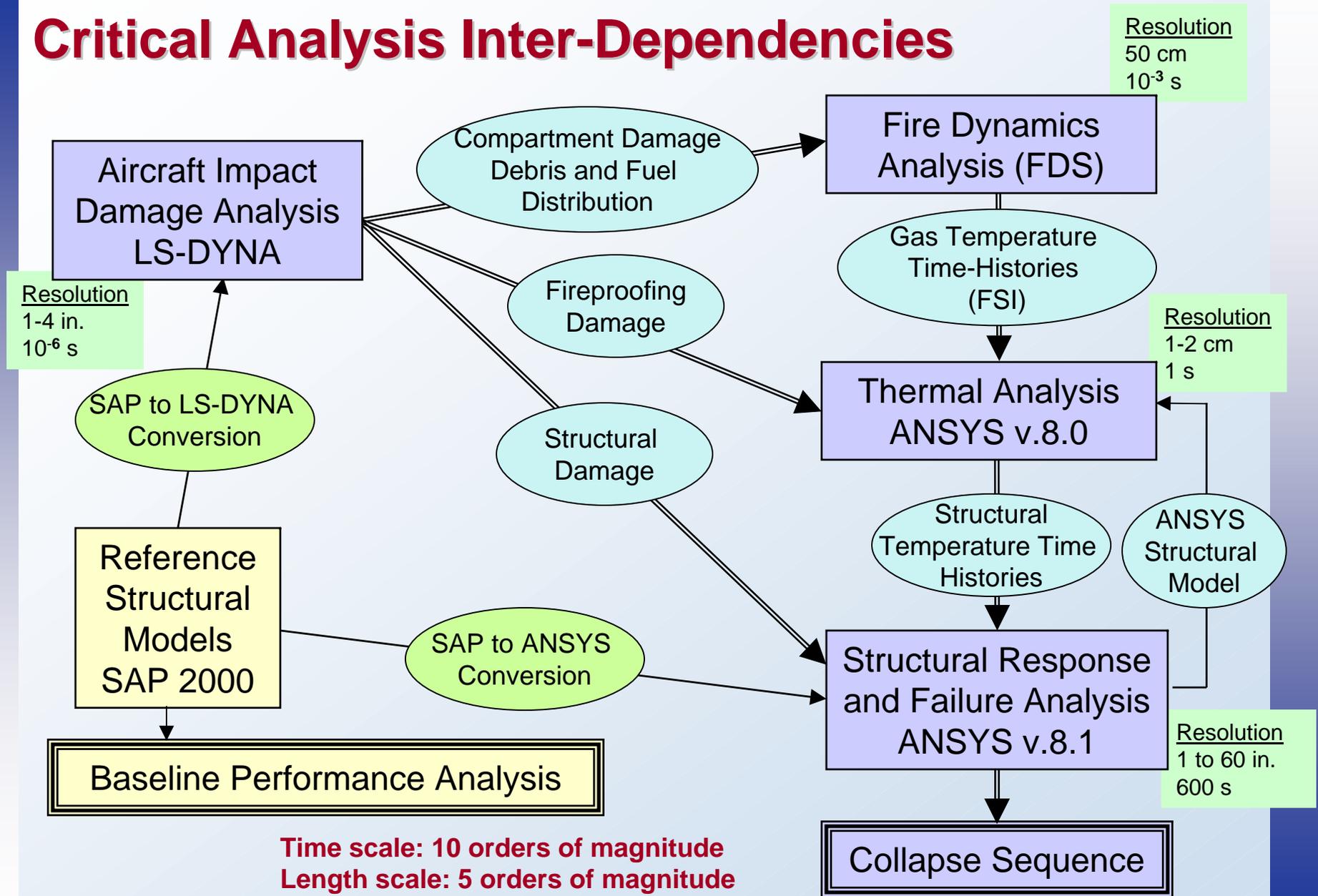
Time	Floors	Face	Columns	Event Description
9:02:59	77-85	S	404-443	Airplane strikes WTC 2 between floors 77 to 85, columns 404 to 443.
				Impact followed by fireballs on N, E, S faces with brief period of intense burning.
9:03:42	83	E	310-342	Floor 83 edge appears to be draped in floor 82 windows between columns 310 to 342.
9:10:01	79-82	N		Floor edge appears to be draped through windows in 'cold spot' toward floor 79 debris pile. Column 81-253 is severed.
9:21:29	~78-82	E	~318-338	East face columns are bowing inward.
9:53:04	~78-82	E	-318-334+	East face columns are bowing inward.
9:58:59				WTC2 begins to collapse.

Tilting of WTC 2 at Collapse Initiation



© Mark Stetler 2001

Critical Analysis Inter-Dependencies



WTC 1 Damage: Composite Summary for Floors 93 to 98

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

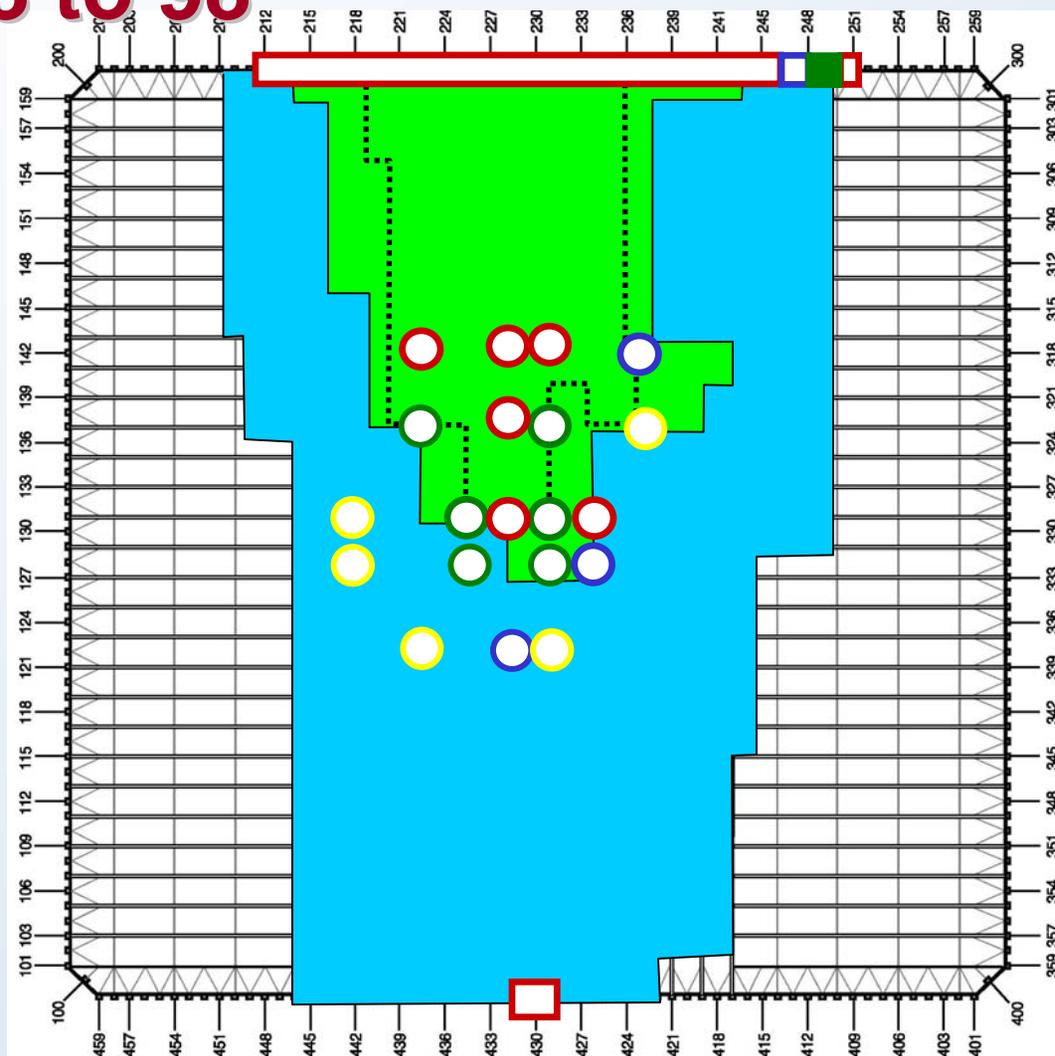
Column Damage

Severed 

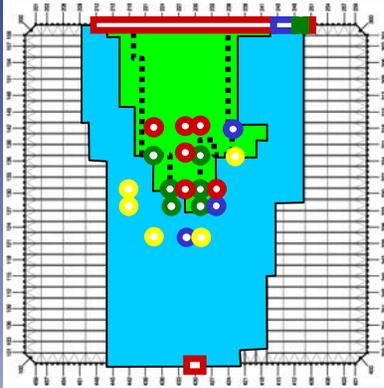
Heavy Damage 

Moderate Damage 

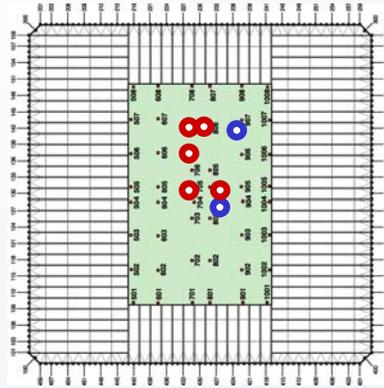
Light Damage 



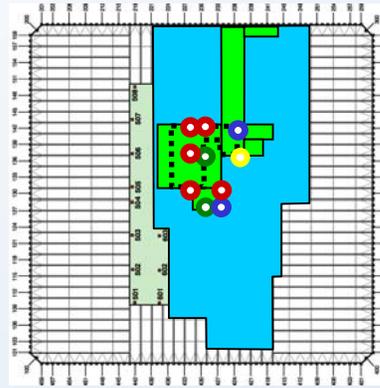
WTC 1 Damage by Floor



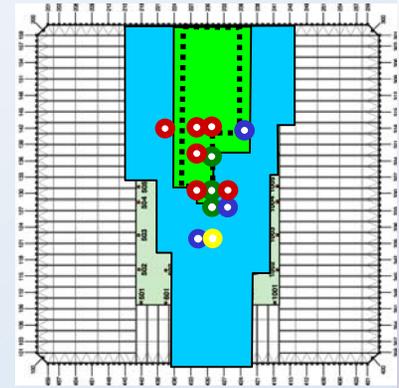
Floors 93 to 98
Cumulative Damage



Floor 93



Floor 94



Floor 95

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

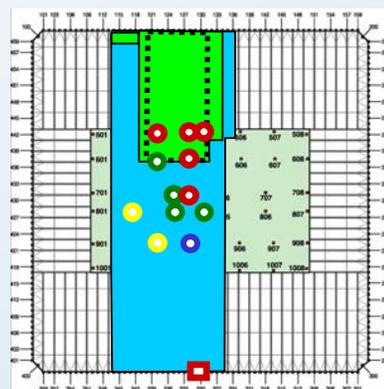
Column Damage

Severed 

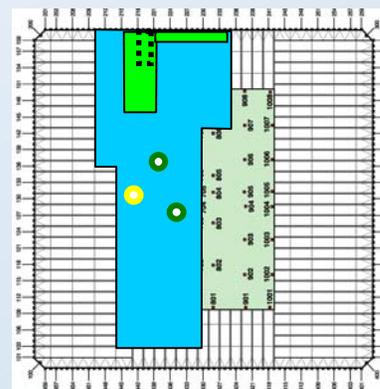
Heavy Damage 

Moderate Damage 

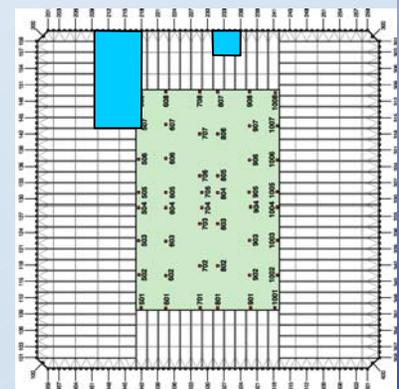
Light Damage 



Floor 96



Floor 97



Floor 98

WTC 2 Damage for Severe Case

Composite Summary for Floors 78 to 83

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

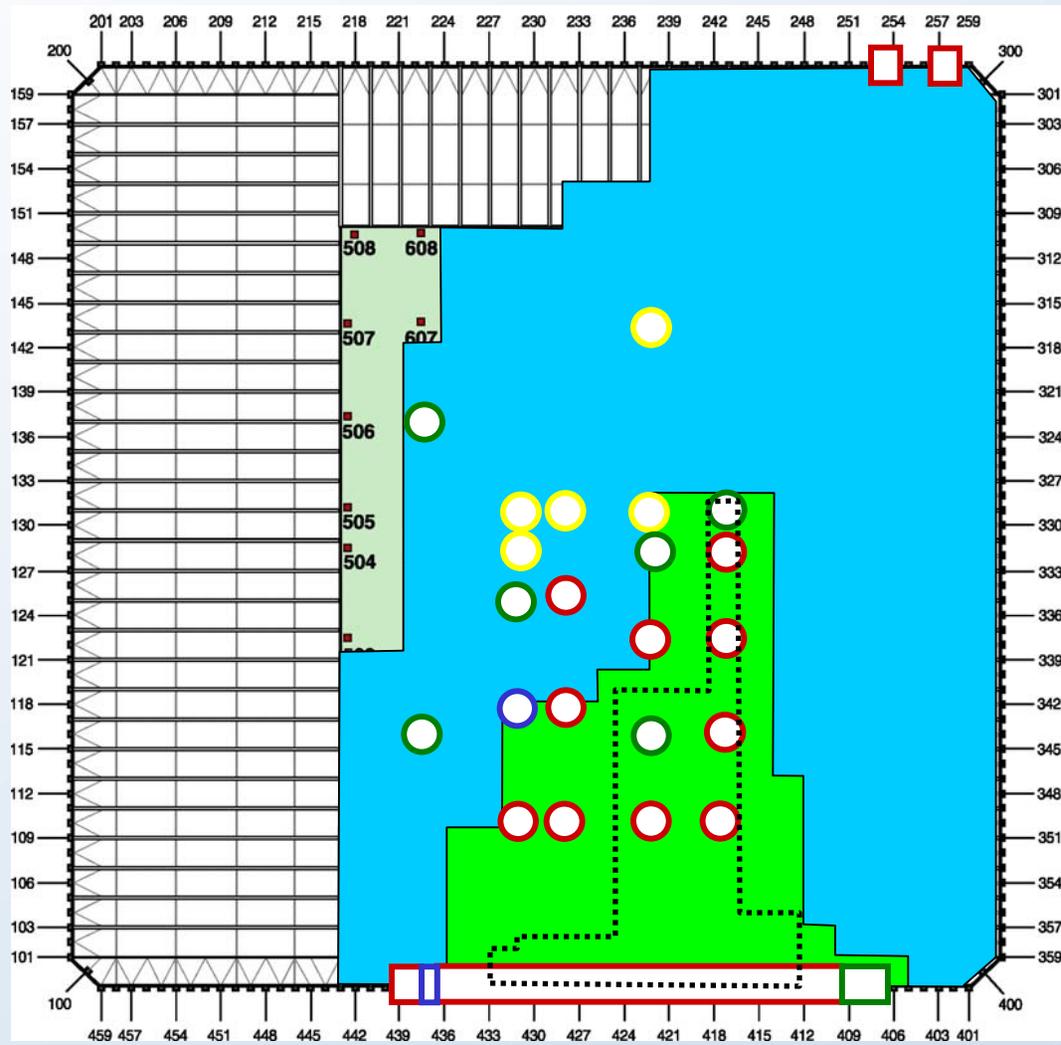
Column Damage

Severed 

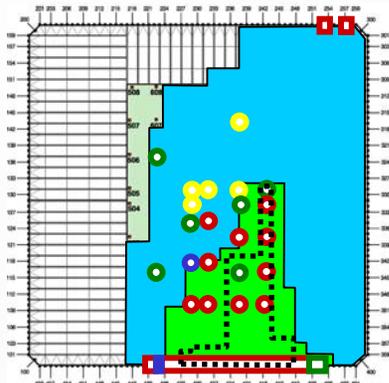
Heavy Damage 

Moderate Damage 

Light Damage 

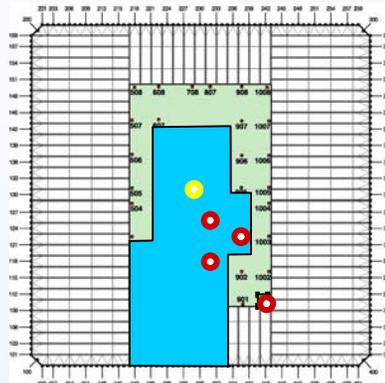


WTC 2 Severe Damage

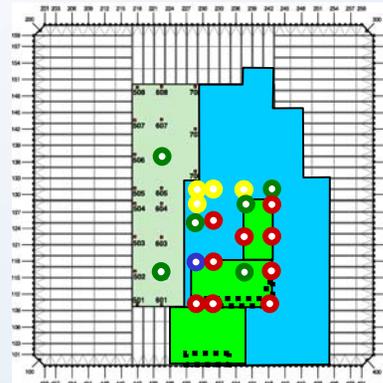


Floors 78-83

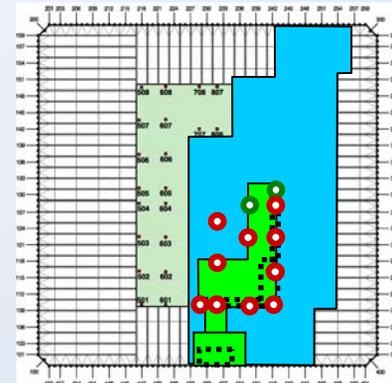
Cumulative Damage



Floor 78



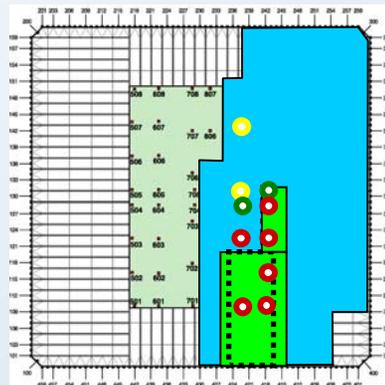
Floor 79



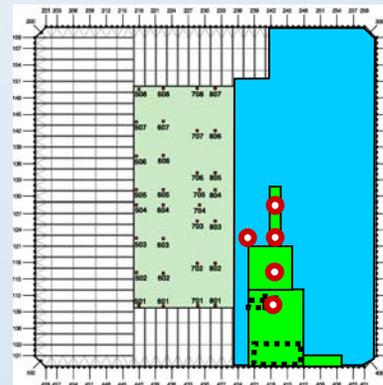
Floor 80

Severe Floor Damage

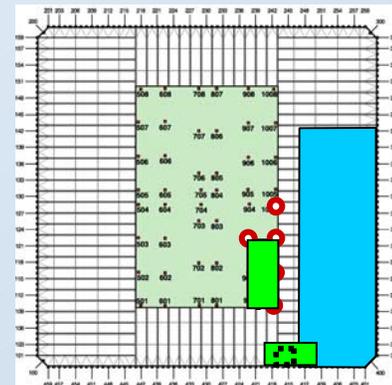
- Fireproofing and partitions ■
- Floor system structural damage ■
- Floor system removed
- Column Damage**
- Severed ○
- Heavy Damage ○
- Moderate Damage ○
- Light Damage ○



Floor 81



Floor 82



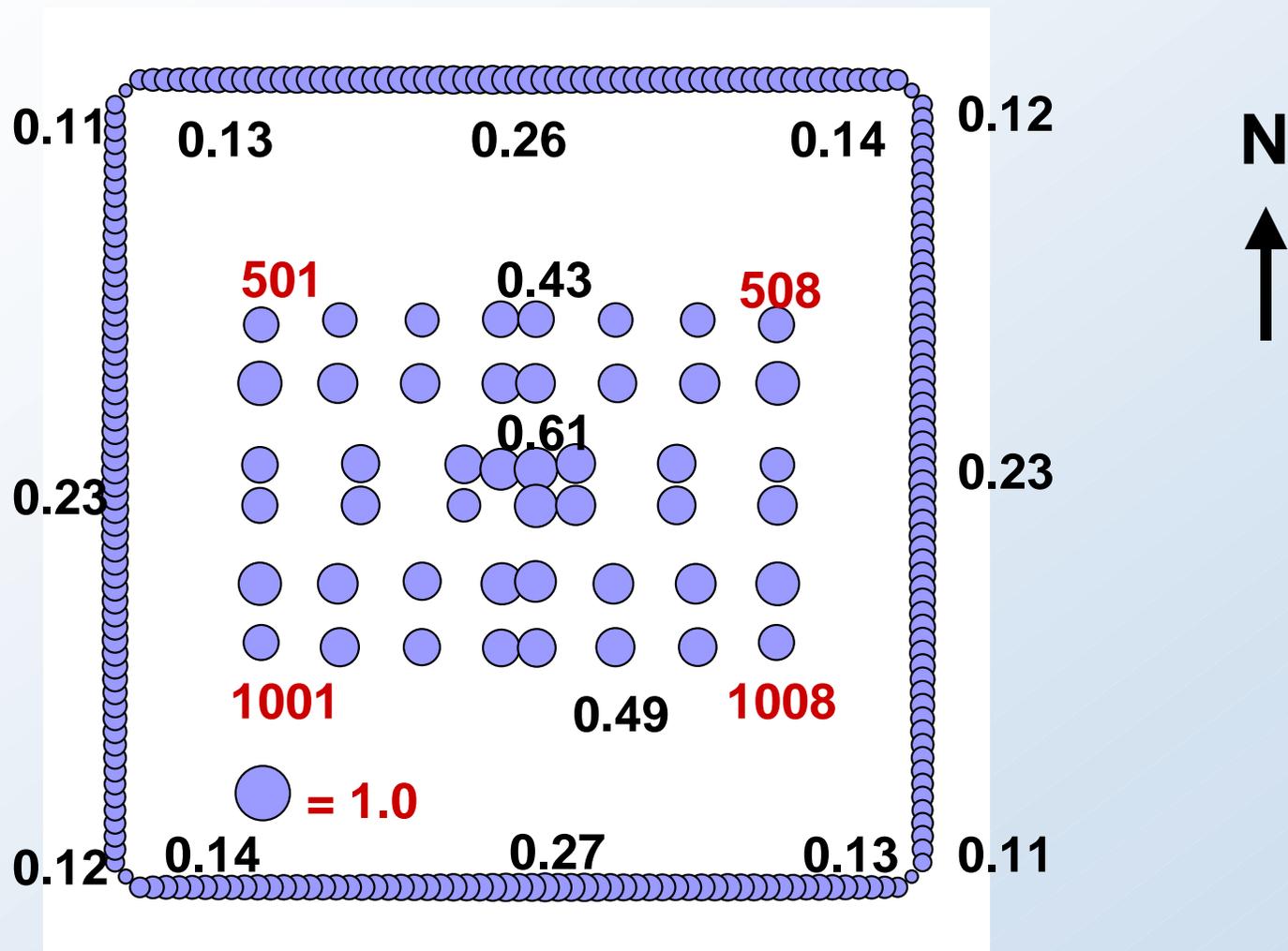
Floor 83

Comparison of Aircraft Damage to Core Columns with Prior Studies

WTC Impact Study	WTC 1 Core Column Damage	WTC 2 Core Column Damage
MIT Impact Analysis	4-12 Failed	7-20 Failed
WAI Impact Analysis	23 failed & significantly damaged Plus 5 Damaged	14 failed and significantly damaged Plus 10 damaged
WAI Collapse Analysis	20 Failed	5 Failed
NIST Base Case Impact Analysis	3 Failed Plus 4 Heavily Damaged	5 Failed Plus 4 Heavily Damaged
NIST More Severe Impact Analysis	6 Failed Plus 3 Heavily Damaged	10 Failed Plus 1 Heavily Damaged
NIST Less Severe Impact Analysis	1 Failed Plus 2 Heavily Damaged	3 Failed Plus 2 Heavily Damaged

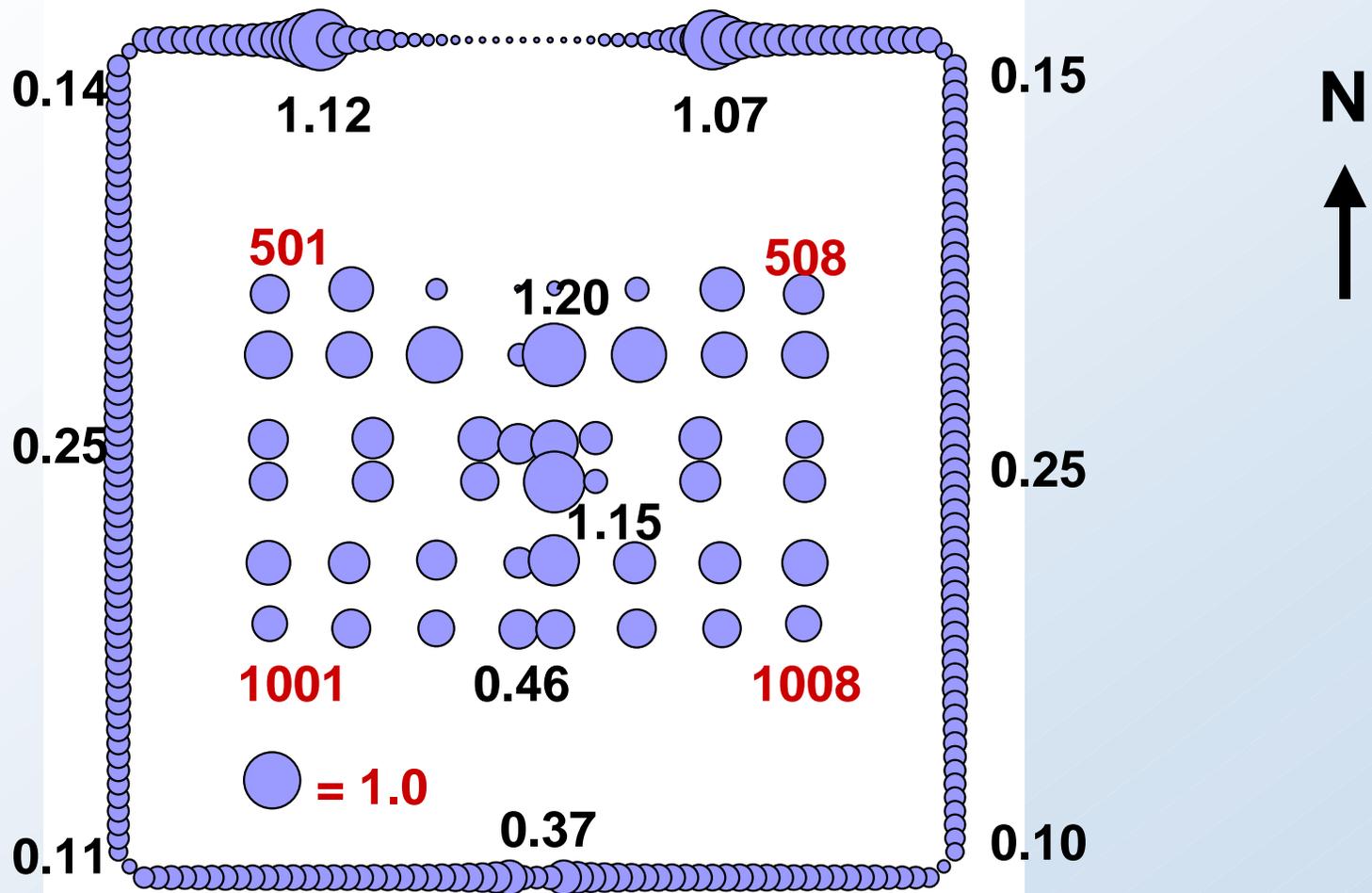
MIT study reported in Chapter 4 of a collection of essays by MIT researchers "The Towers Lost and Beyond," 2002.
Weidinger study prepared for Silverstein Associates as part of insurance litigation involving the WTC towers, 2002.

WTC 1 Column Demand to Capacity Ratio Before Aircraft Impact (Maximum over Floors 93 to 98)



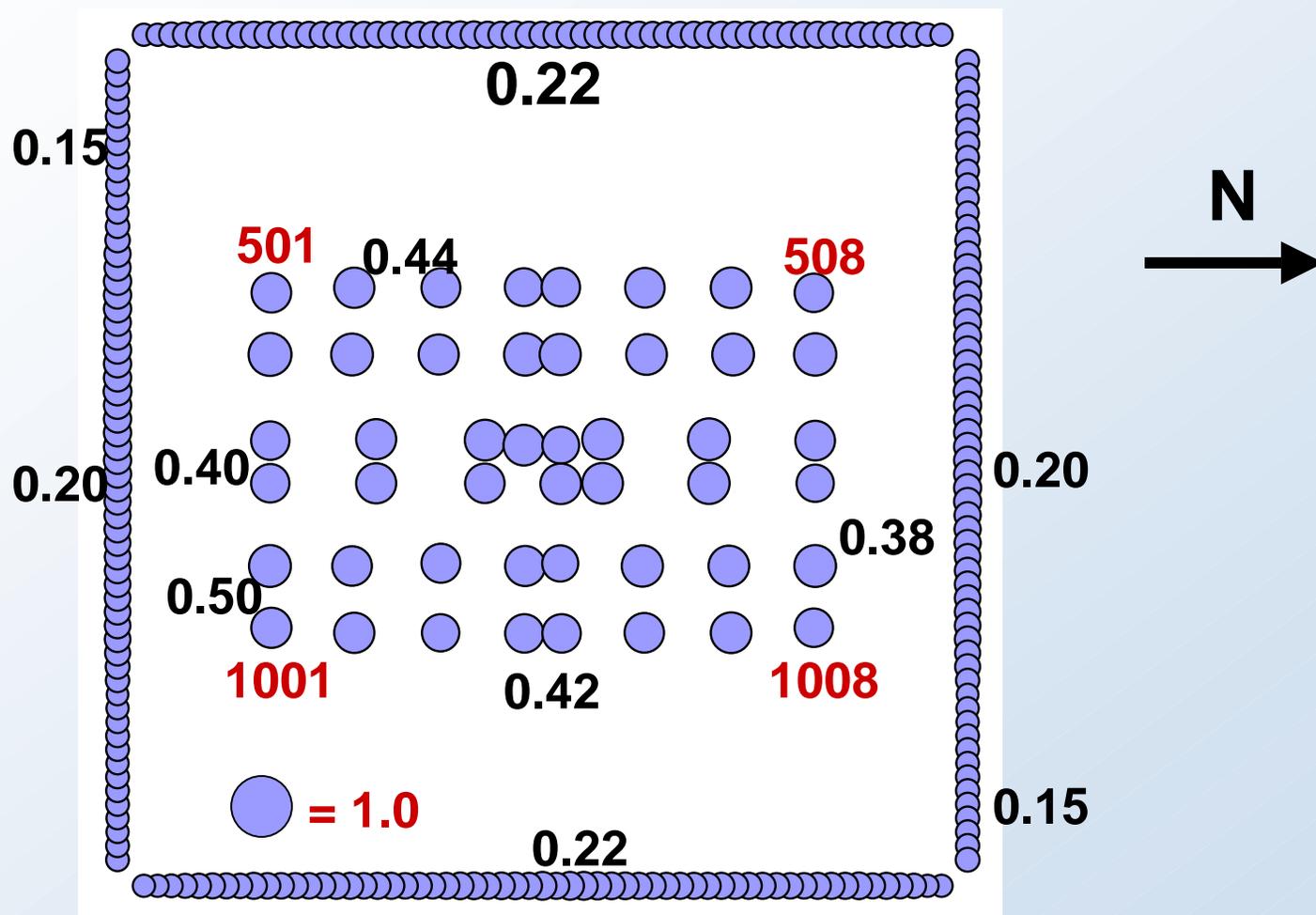
Demand to Capacity Ratio (DCR) = (Dead + Service Live Loads)/Load at Yield

WTC 1 Column Demand to Capacity Ratios After Aircraft Impact (Maximum over Floors 93 to 98)



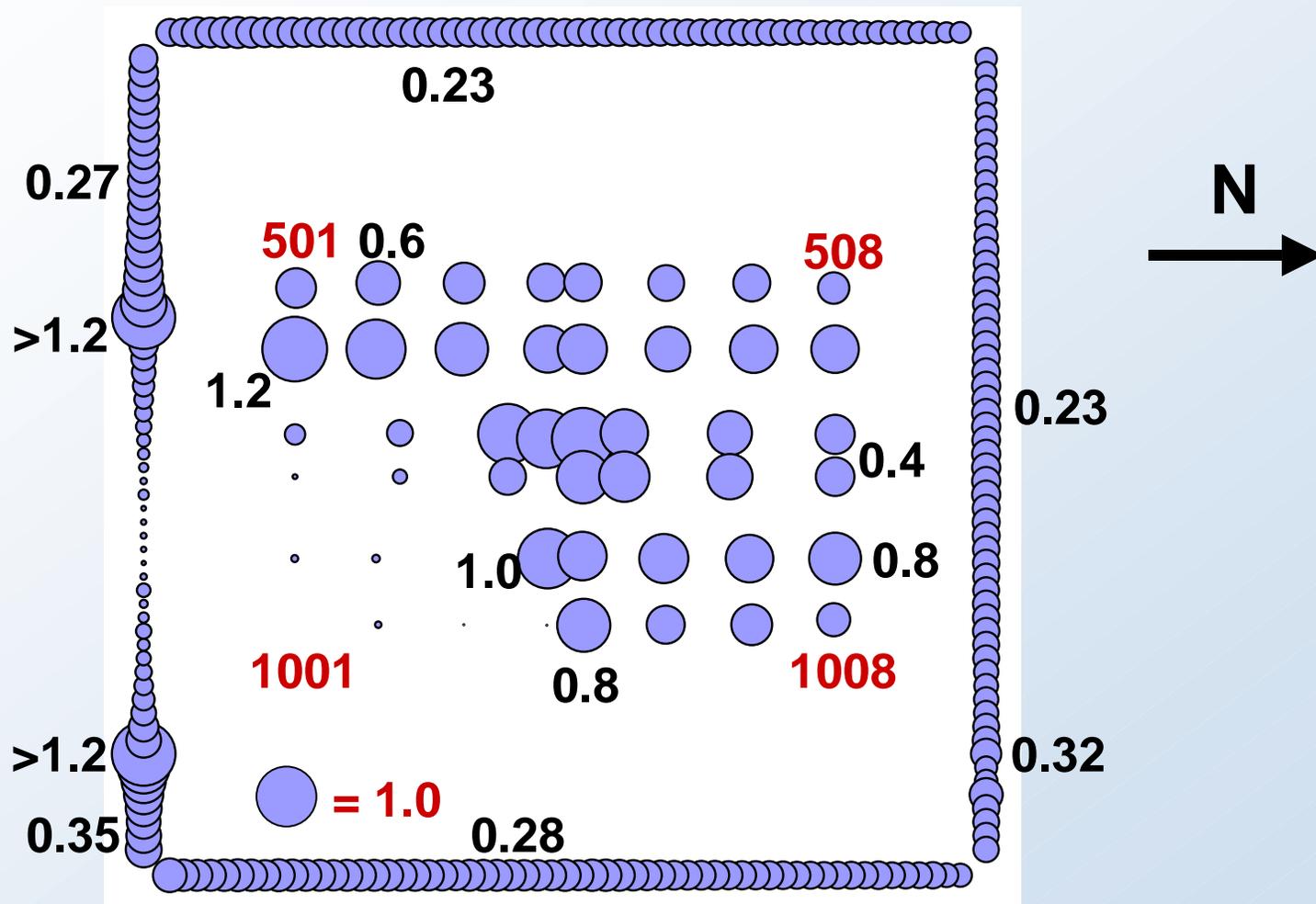
Demand to Capacity Ratio (DCR) = (Dead + Service Live Loads)/Load at Yield

WTC 2 Column Demand to Capacity Ratio Before Aircraft Impact (Maximum over Floors 78 to 84)



Demand to Capacity Ratio (DCR) = (Dead + Service Live Loads)/Load at Yield

WTC 2 Column Demand to Capacity Ratio After Aircraft Impact (Maximum over Floors 78 to 84)



Demand to Capacity Ratio (DCR) = (Dead + Service Live Loads)/Load at Yield

0:00

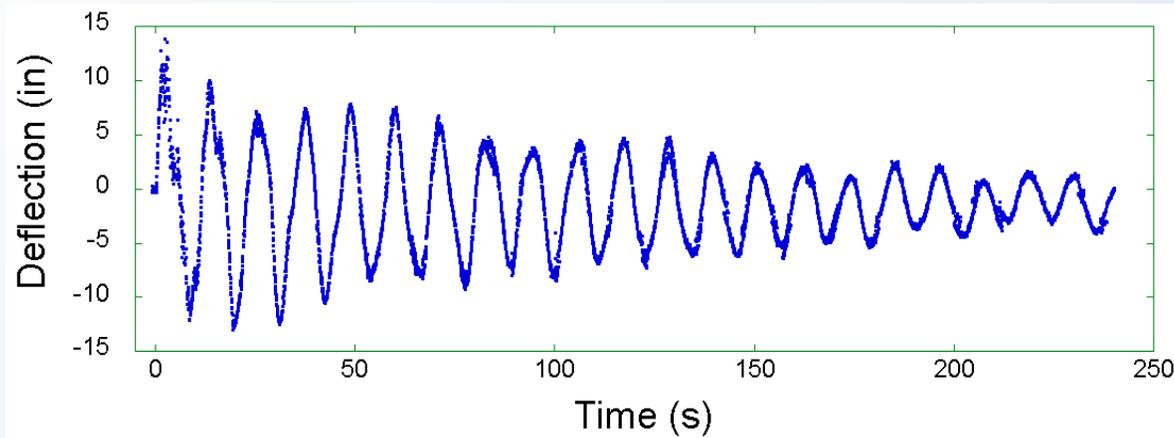
© Scott Myers

Clock

NIST

Aircraft Impact Damage to WTC Tower Structures

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



- The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were more than about 1/3 of the design wind sway from the baseline analysis and an oscillation period nearly equal to the average measured for the undamaged building.
- **Calculations of demand to capacity ratios due to aircraft impact damage showed that for the floors affected by the aircraft impacts, the majority of the core and perimeter columns in both towers continued to carry their loads after the impact. The loads from damaged and severed columns were redistributed to nearby undamaged columns.**
- **The above finding supports the fact that the WTC towers withstood the initial aircraft impact and the finding that they would have continued to remain standing indefinitely but for another significant event such as the subsequent fires.**

Relative Roles of Aircraft Impact and Fires

- **Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires and the thermal response of the structures by:**
 - Compromising the sprinkler and water supply systems;
 - Dispersing jet fuel and igniting building contents over large areas;
 - Creating large accumulations of combustible matter containing aircraft debris and building contents;
 - Increasing the air supply into the damaged buildings that permitted significantly higher energy release rates than would normally be seen in ventilation limited building fires, allowing the fires to spread rapidly on multiple floors;
 - Damaging and dislodging fireproofing from structural components in the direct path of the debris and due to the strong vibrations generated by aircraft impact; and
 - Damaging ceilings that enabled “unabated” heat transport over the floor-to-ceiling partition walls and to structural components.

Relative Roles of Aircraft Impact and Fires (2)

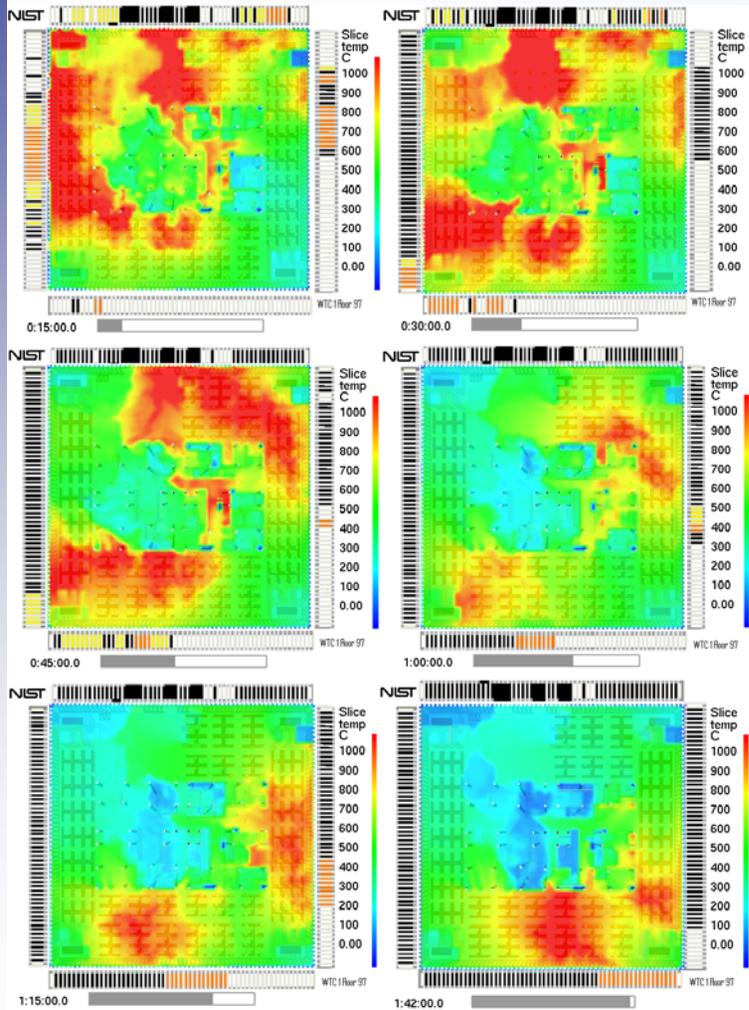
- **The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.**
- **Typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor.** No structural component, however, was subject to intense fires for the entire period of burning. The duration of intense burning impacting any specific component was controlled by:
 - **The availability of combustible materials**
 - **Fuel gases released by those combustibles**
 - **Combustion air in the specific area**
- **The typical floor had on average about 4 psf of combustible materials on floors.** Mass of aircraft solid combustibles was significant in the immediate impact region of both WTC towers.

Effect of Initial Fire Ball

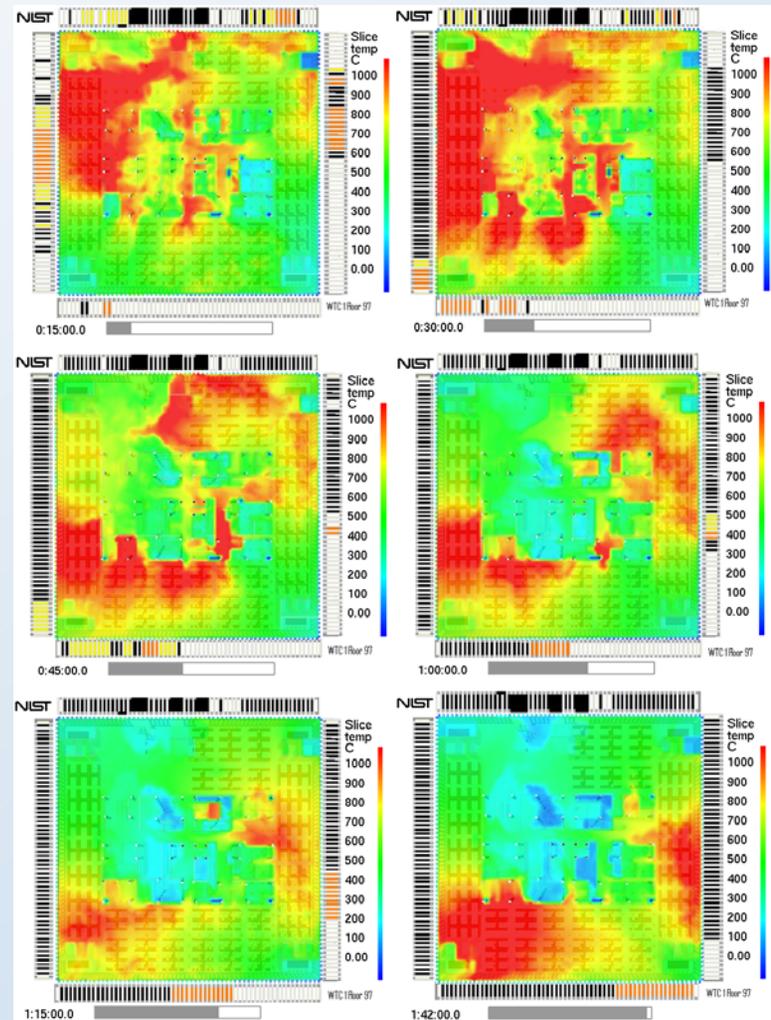
- ❑ The overpressure on WTC floors associated with initial internal fire ball (deflagration) is estimated to be
 - maximum pressure roughly 2 psi to 3 psi
 - duration roughly 0.5 sec to 2 sec
- ❑ The natural frequency of the composite floor system is approximately 3.7 Hz (period approx. 0.27 sec)
- ❑ The pressure pulse duration is sufficiently greater than the natural frequency of the floor such that dynamic effects can be neglected
- ❑ Based on failure of the truss seat connections, the static capacity of the floor is calculated to be
 - 4.8 psi against uplift pressure
 - 4.4 psi against downward pressure

Reconstruction of Fires (WTC 1, 97th Floor)

Base Case



More Severe

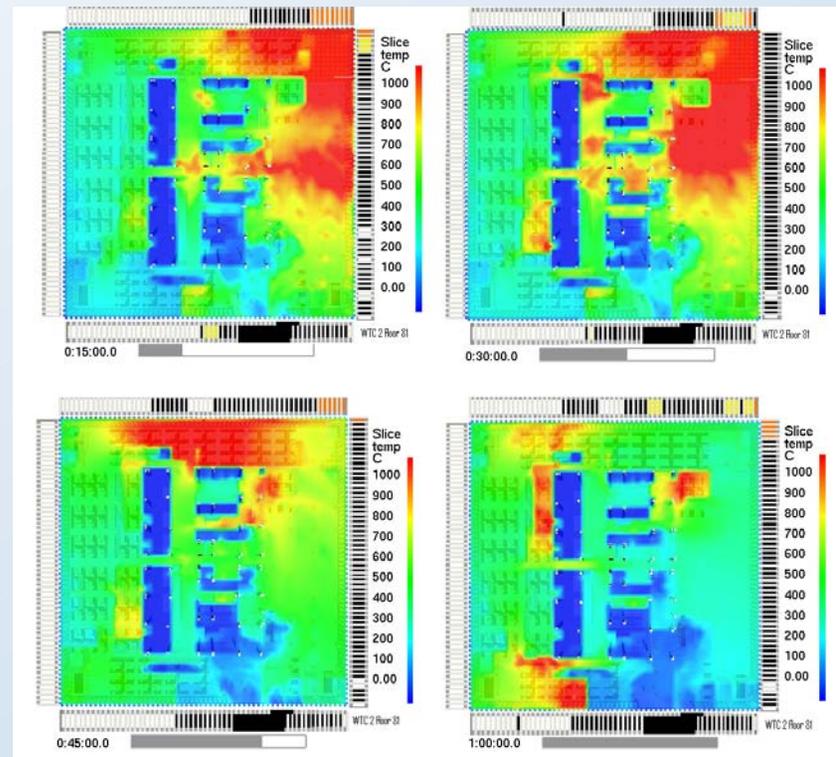
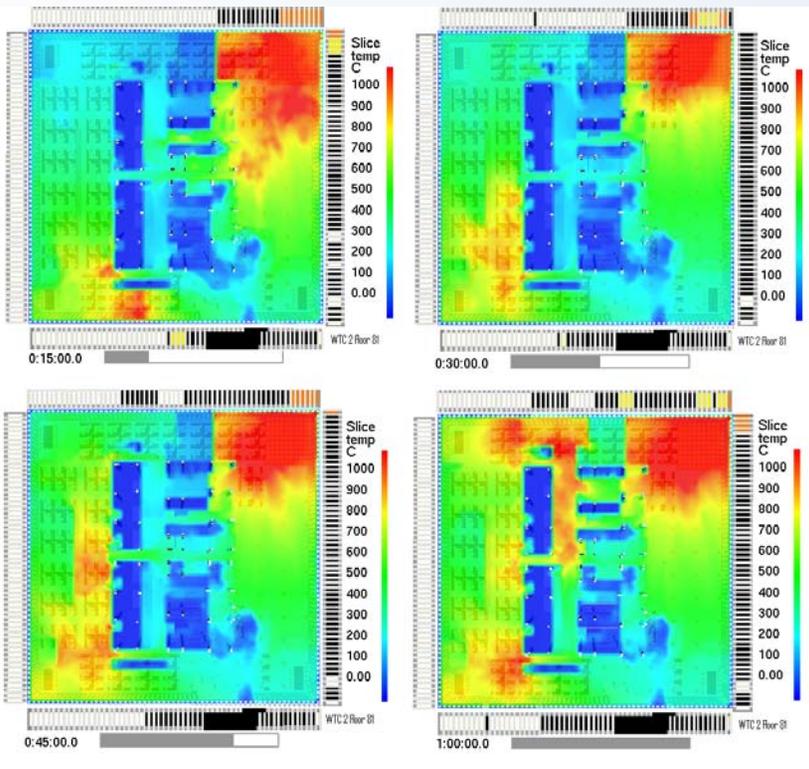


Reconstruction of Fires (WTC 2, 81st Floor)

Combustible load more critical in WTC 2

Base Case

More Severe

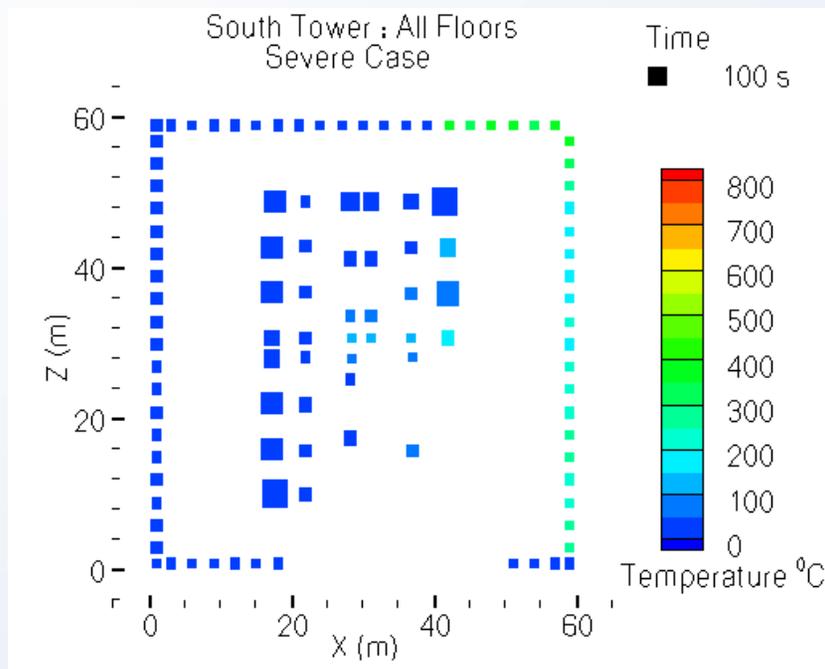


Spread of Jet-Fuel Ignited Multi-Floor Fires

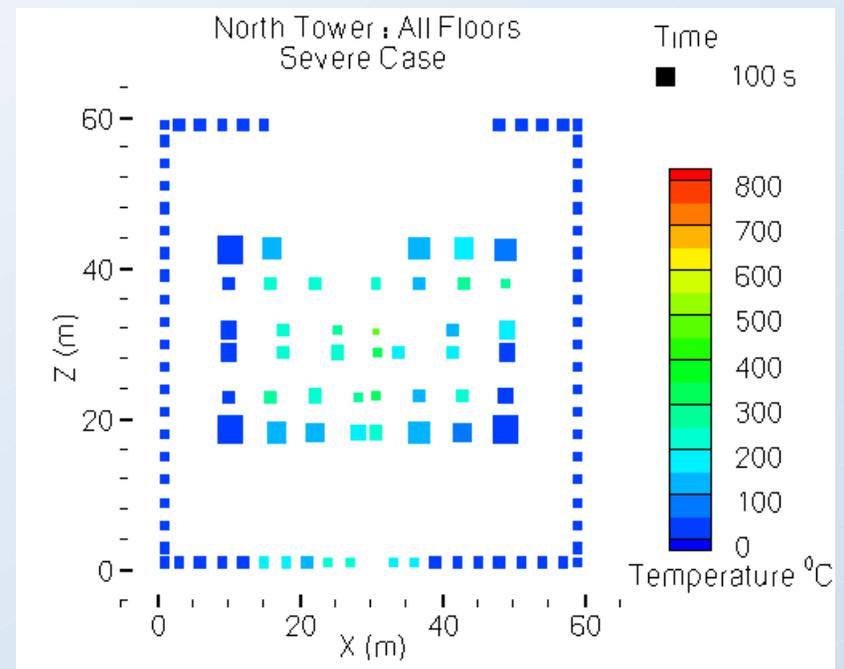
- Consistent with available photographic and videographic evidence, NIST computer simulations capture the broad patterns of fire movement around the floors, with **flames in a given location lasting for about 20 min before spreading to adjacent, yet unburned combustibles**; some observed instances where fires persisted longer in regions with accumulated combustible debris; other instances of sudden or interrupted fire spread.
- The **affected floors in the WTC towers had an open floor plan**—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants, and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space **partitions** (such as those that divided spaces to provide corner conference rooms) **provided substantial resistance to fire spread in the affected floors**.
- For the time that the fires were active prior to building collapse, **the presence of undamaged 1 h fire-rated compartments may have assisted in mitigating fire spread and consequent thermal weakening of structural components**.
- The 1968 NYC Building Code required buildings like the WTC towers to have 1 h fire-rated tenant separations, but the code did not impose any minimum compartmentation requirements (e.g., 12,000 ft²) to mitigate the spread of fire in large open floor plan buildings.

Results of Thermal Analysis for WTC 1 Columns

Base Case



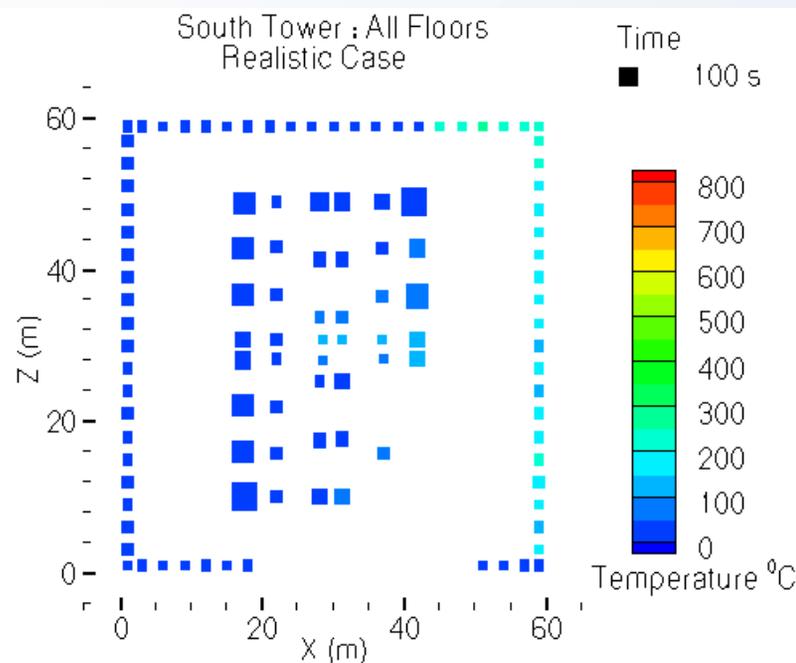
Severe Case



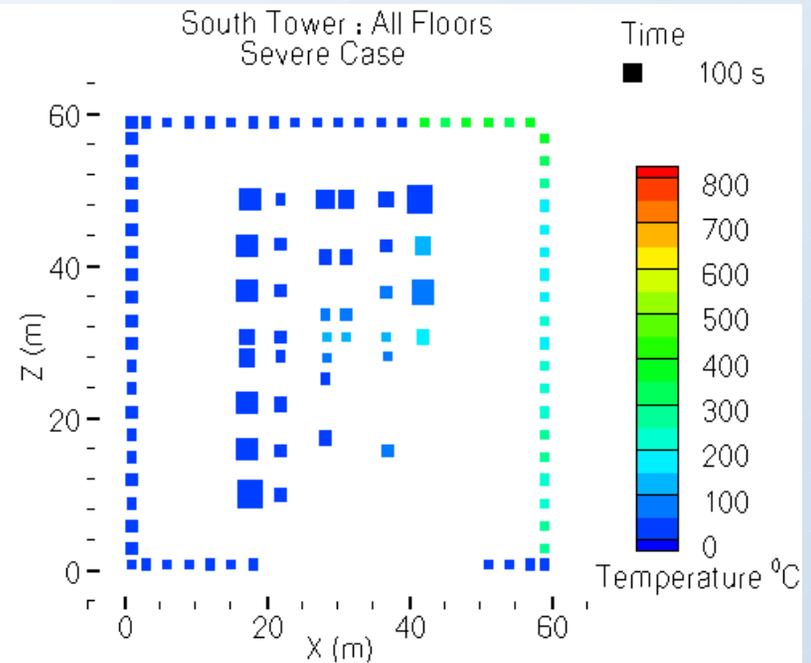
Shows maximum temperature reached by each column.

Results of Thermal Analysis for WTC 2 Columns

Base Case

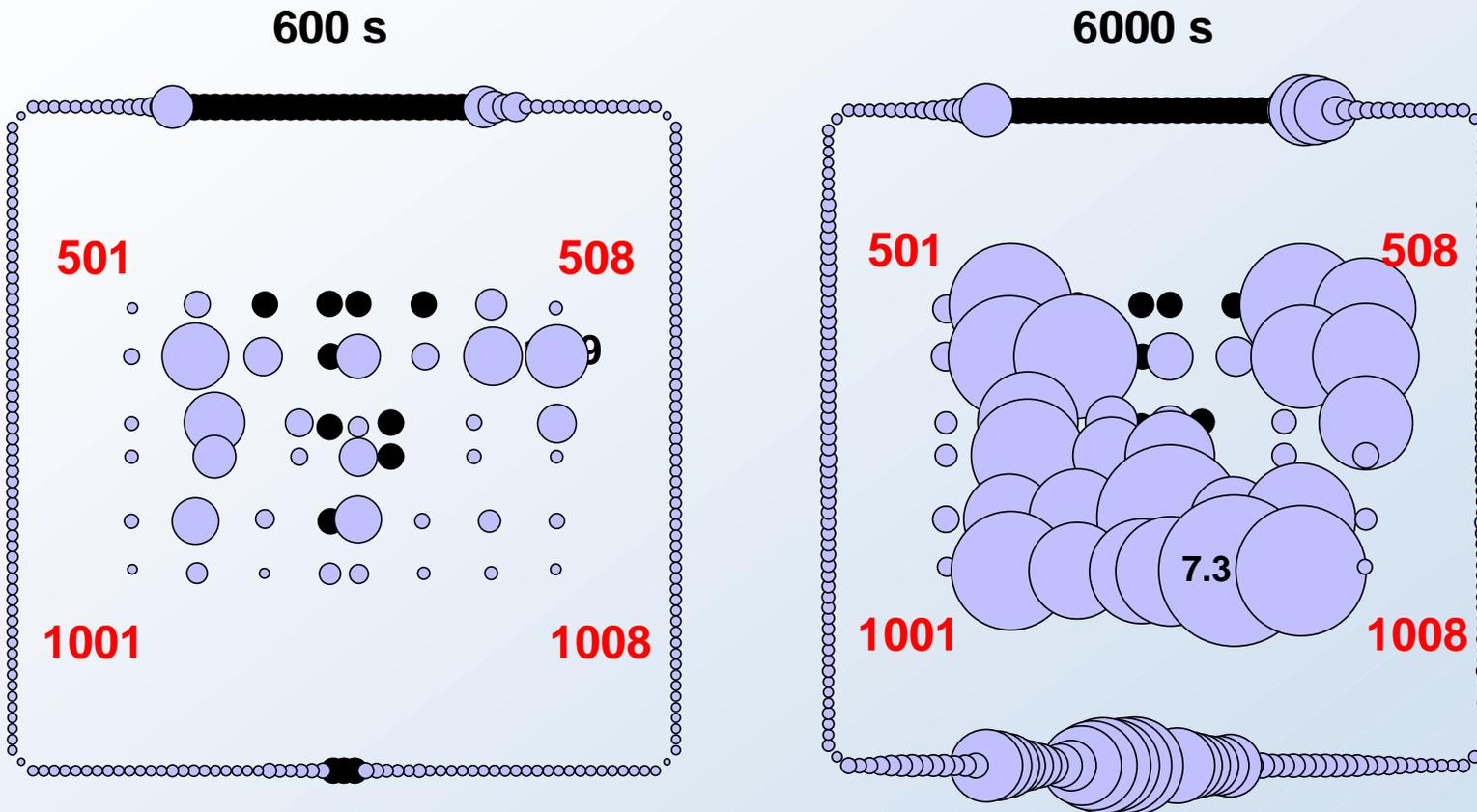


Severe Case



Shows maximum temperature reached by each column.

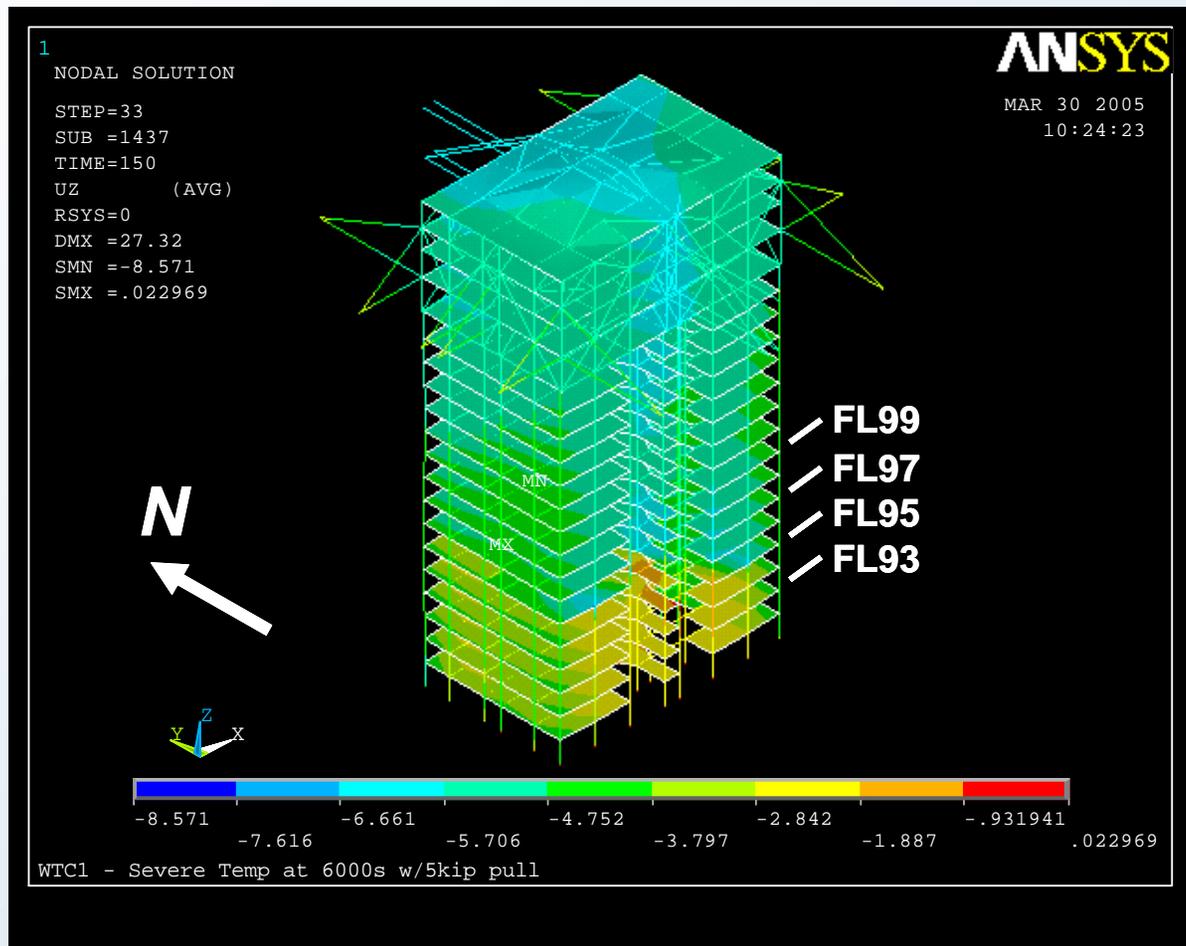
WTC 1 Severe Case: Maximum Elastic, Plastic, and Creep Strain in Columns between Floors 93 and 99



- Severed or Heavily Damaged
- Elastic + Plastic + Creep Strain

Maximum strain is given in %.

Vertical Displacement of WTC 1 Core at 6000 s



Summary of Column Loads at Floor 98 of WTC 1

	North	East	South	West	Core
Before Impact	10,974	8,545	11,025	8,572	34,029
After Impact	10,137	9,071	10,356	9,146	34,429
10 min	9,796	8,490	9,848	8,536	36,473
20 min	10,437	9,108	9,900	9,202	34,495
30 min	10,913	10,034	10,420	9,715	32,060
40 min	11,068	10,599	11,004	10,178	30,294
50 min	11,149	10,908	11,192	10,458	29,435
60 min	11,205	11,168	11,285	10,716	28,766
70 min	11,286	11,366	11,343	10,939	28,205
80 min	11,376	11,555	11,409	11,119	27,681
90 min	10,916	11,991	9,949	11,657	28,587
100 min	10,828	12,249	9,638	11,905	28,478

Summary of Column Loads at Floor 105 of WTC 1

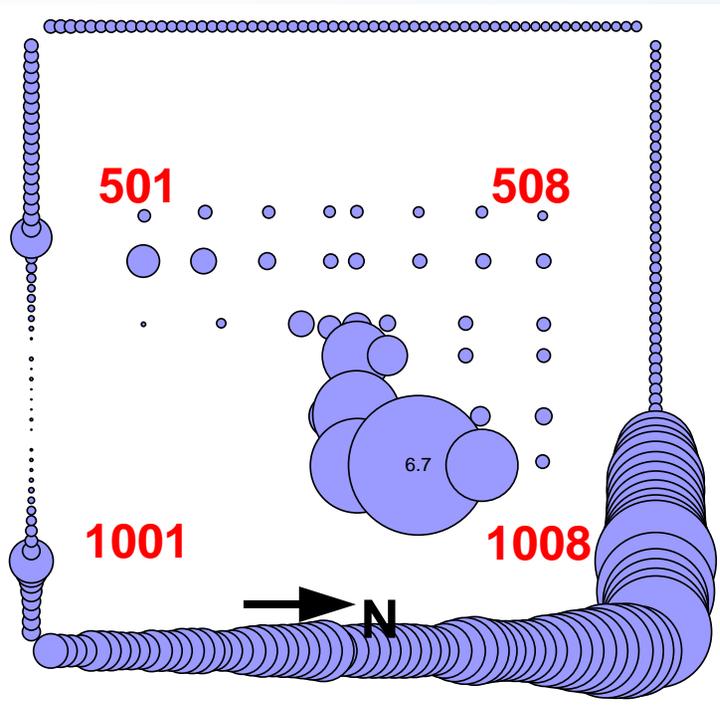
	North	East	South	West	Core
Before Impact	8,026	6,562	8,092	6,604	20,361
After Impact	7,294	7,028	7,488	7,076	20,761
10 min	6,944	6,461	6,981	6,469	22,790
20 min	7,551	7,075	7,057	7,158	20,806
30 min	8,020	7,998	7,569	7,685	18,377
40 min	8,193	8,571	8,129	8,147	16,608
50 min	8,285	8,878	8,315	8,428	15,743
60 min	8,351	9,130	8,414	8,687	15,069
70 min	8,435	9,319	8,481	8,914	14,502
80 min	8,528	9,497	8,551	9,097	13,978
90 min	8,096	9,847	7,327	9,506	14,876
100 min	8,023	10,076	7,066	9,720	14,767

Changes in Total Load in WTC 1 Subsystems between 80 min and 100 min

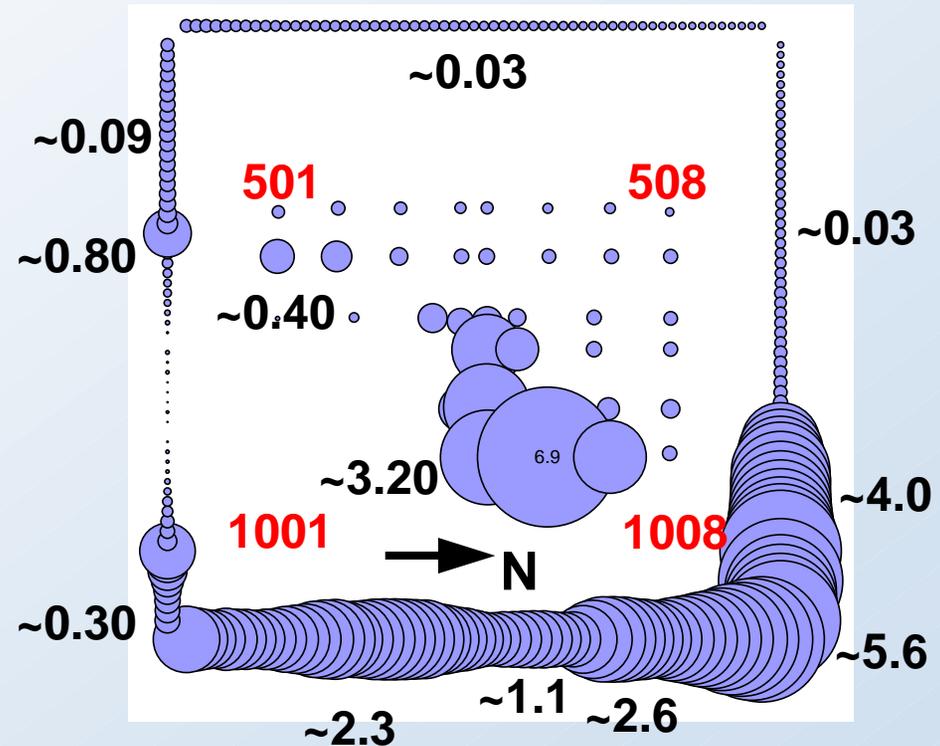
Floor No.	North Wall (kip)	East Wall (kip)	South Wall (kip)	West Wall (kip)	Core (kip)
98	-548	+694	-1,771	+786	+797
105	-504	+579	-1,485	+623	+790
Change between Floor 98 and Floor 105	-44	+115	-285	+163	+7

WTC 2 Severe Case: Maximum Elastic, Plastic, and Creep Strain in Columns between Floors 78 and 84

2400 s

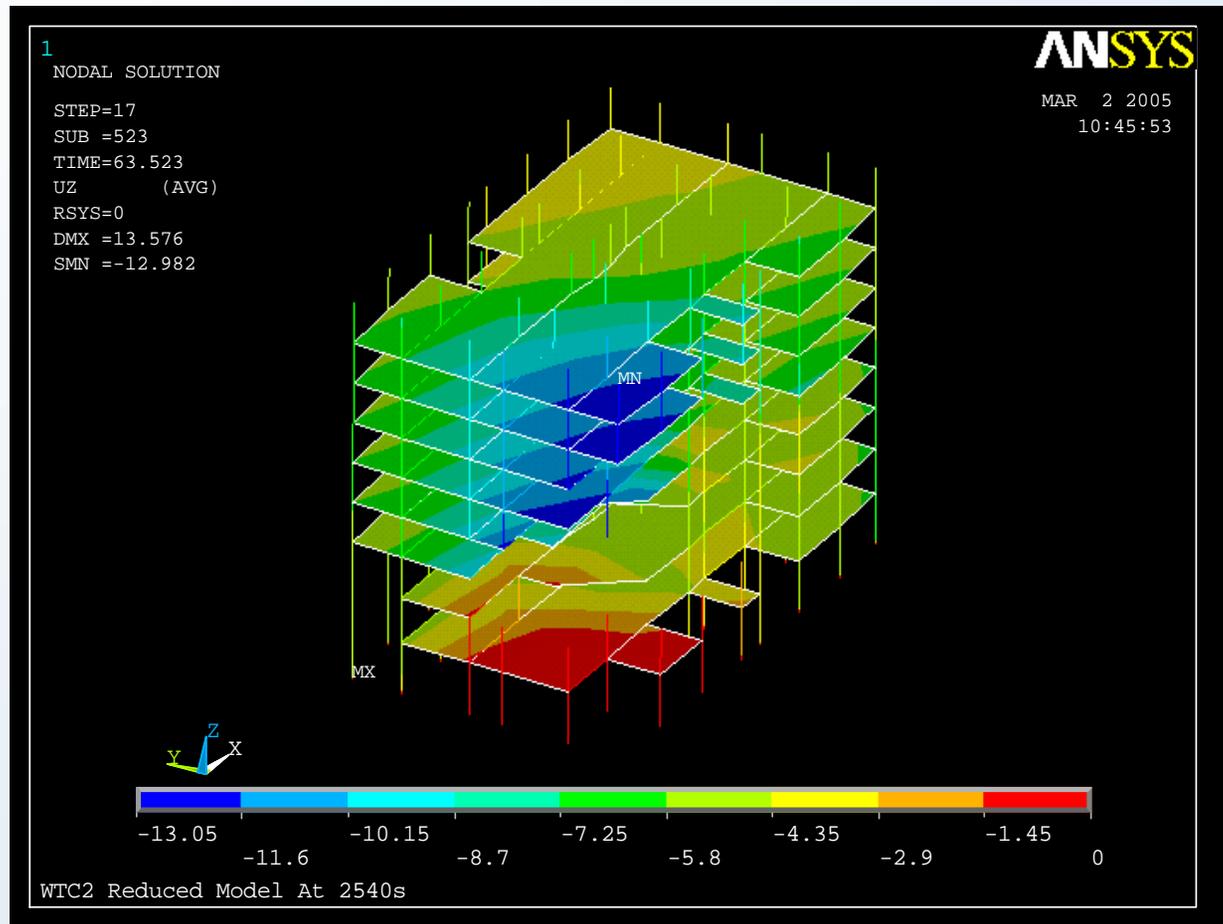


2540 s



Compression is taken as positive, strain values are in %

Vertical Displacement of WTC 2 Core from Floor 77 to Floor 86 at 2,540 s



Summary of Column Loads between Floors 105 and 106 of WTC 2

	West	East	North	South	Core	Sum
(1) Before Impact	8497	8572	7382	7169	17123	48742
(2) After Impact	9170	11272	6488	8432	13380	48742
(3) 600 s	9181	11062	6250	8274	13975	48742
(4) 1,200 s	9279	11121	6310	8350	13683	48742
(5) 1,800 s	9369	11860	6416	8553	12544	48742
(6) 2,400 s	9199	11928	6525	8691	12400	48742
(7) 2,540 s	7092	8026	6551	9173	17900	48742
(8) (2)-(1)	674	2700	-894	1263	-3743	0
(9) (3)-(2)	11	-211	-238	-157	595	0
(10) (4)-(3)	97	59	60	76	-292	0
(11) (5)-(4)	91	739	106	203	-1139	0
(12) (6)-(5)	-170	68	108	138	-144	0
(13) (7)-(6)	-2107	-3902	27	482	5501	0

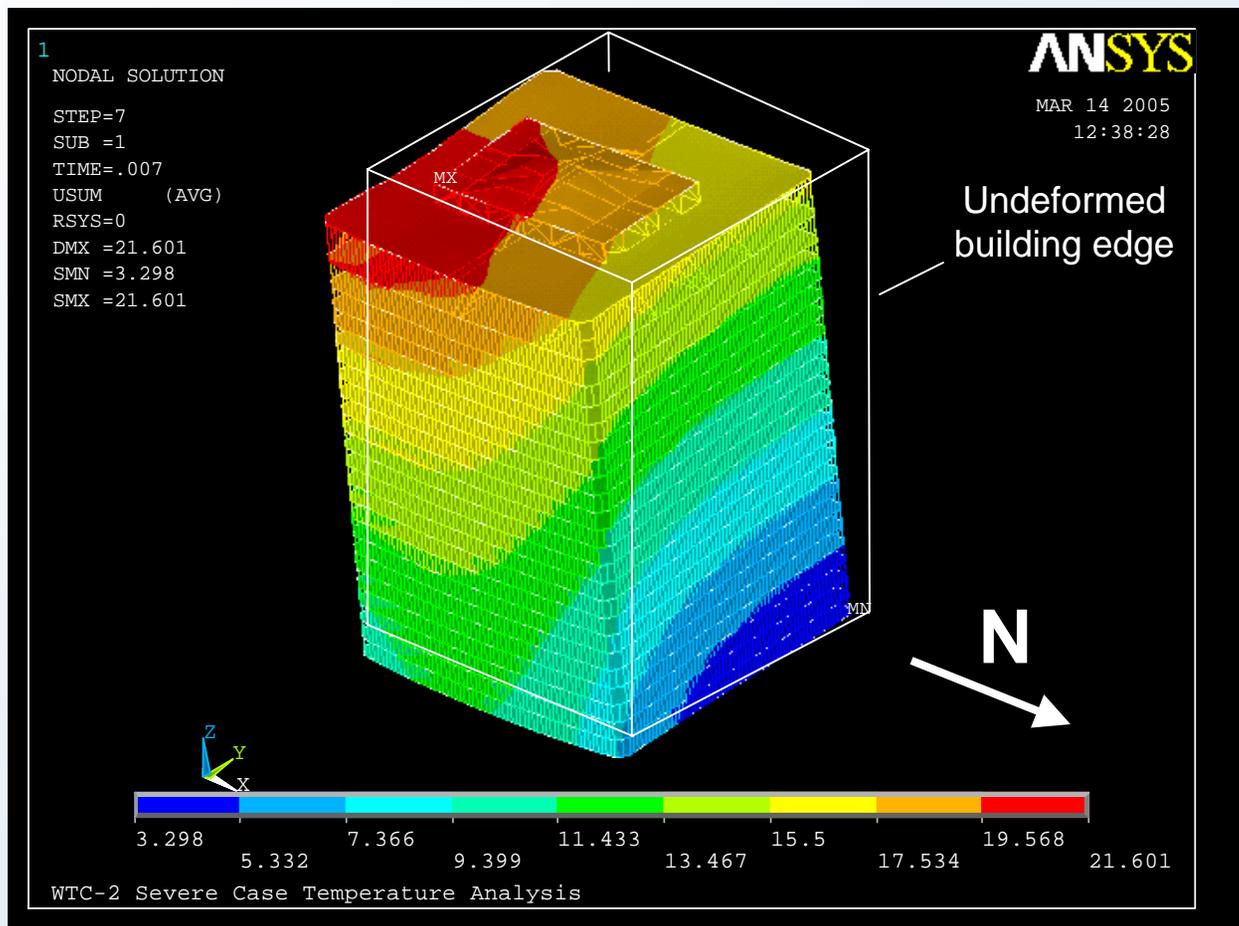
- Compression is taken as positive

Summary of Column Loads at Floor 83 of WTC 2

	West	East	North	South	Core	Sum
(1) Before Impact	18065	18114	13567	13284	61828	124857
(2) After Impact	18670	22481	12193	13511	57821	124676
(3) 600 s	18728	22226	11896	13358	58413	124621
(4) 1,200 s	18914	22208	12052	13318	58124	124616
(5) 1,800 s	18876	23681	11770	13365	56967	124659
(6) 2,400 s	18531	23682	11906	13473	56825	124418
(7) 2,540 s	15667	15143	14215	16292	62422	123738
(8) (2)-(1)	604	4368	-1374	227	-4007	-181
(9) (3)-(2)	58	-255	-296	-153	592	-55
(10) (4)-(3)	186	-18	156	-40	-289	-5
(11) (5)-(4)	-38	1473	-282	47	-1157	43
(12) (6)-(5)	-345	1	136	108	-142	-241
(13) (7)-(6)	-2864	-8539	2309	2819	5596	-679

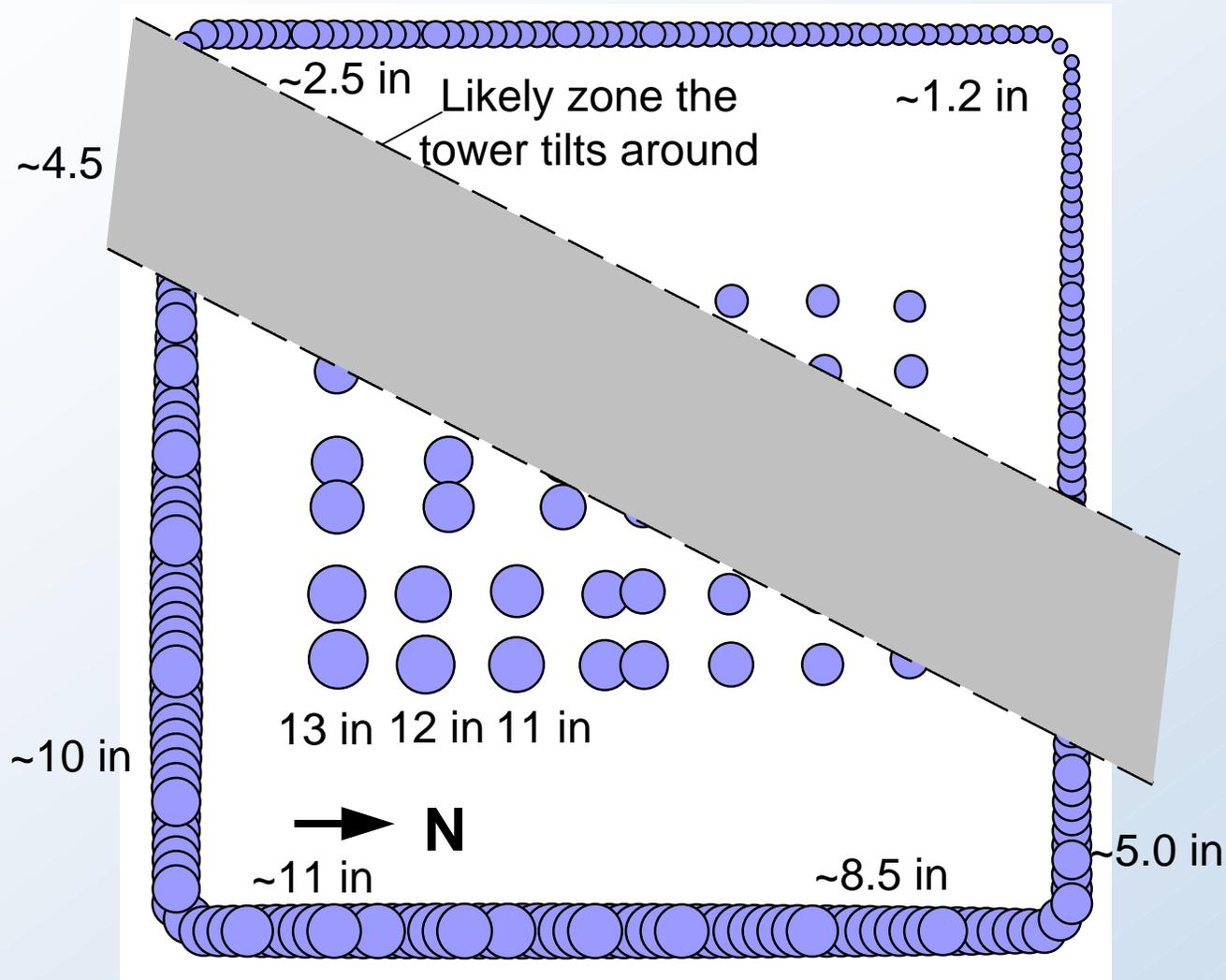
- Compression is taken as positive

WTC 2 Tilt at 2,540 s (Total Displacement Contours)

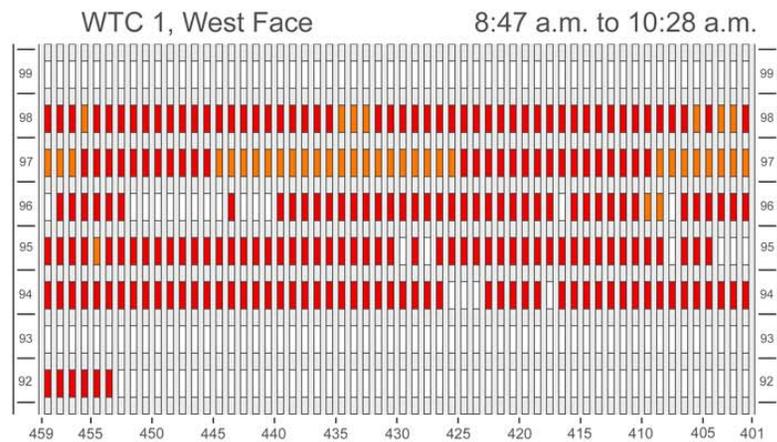
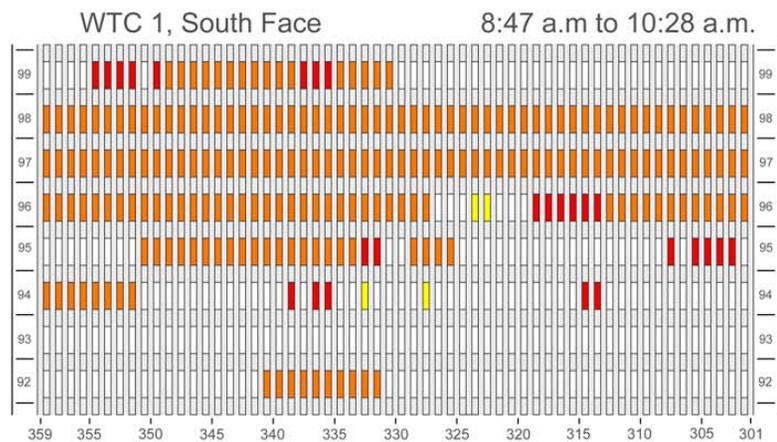
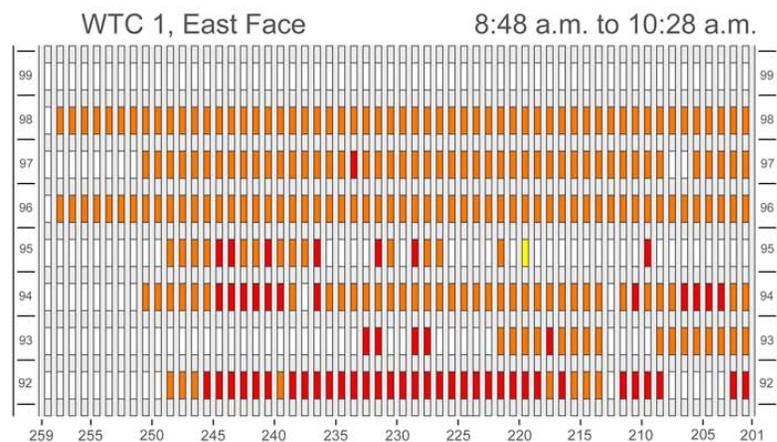
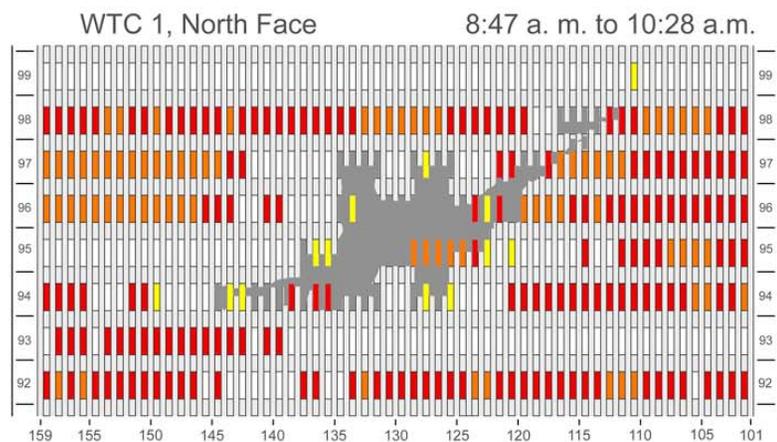


X20 Magnification

Variation of Vertical Displacements at Floor 86 at 2,540 s

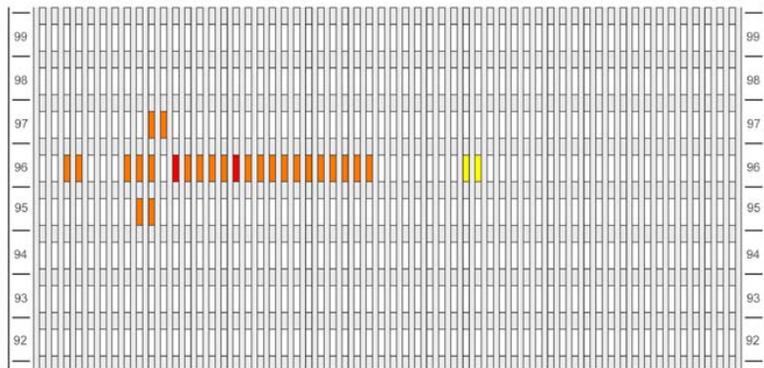


Visual Evidence of Fires in WTC 1



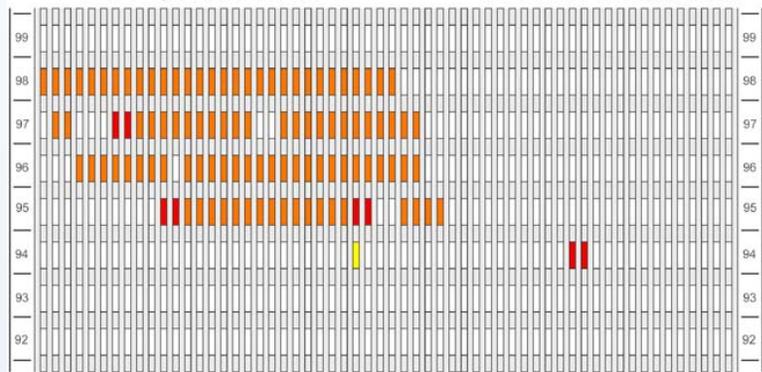
WTC 1, South Face

8:47 a.m. to 9:02 a.m.



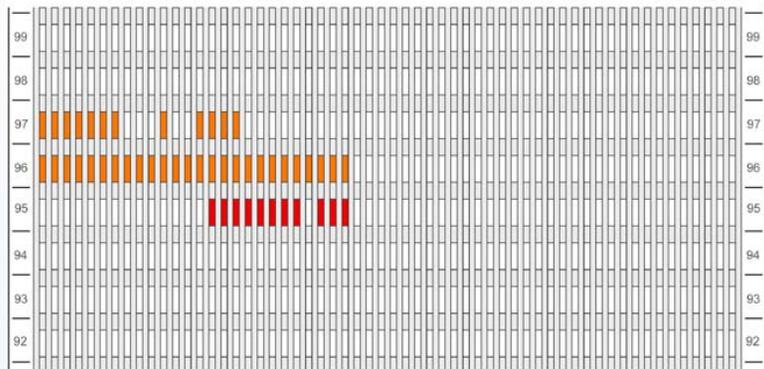
WTC 1, South Face

9:38 a.m. to 9:58 a.m.



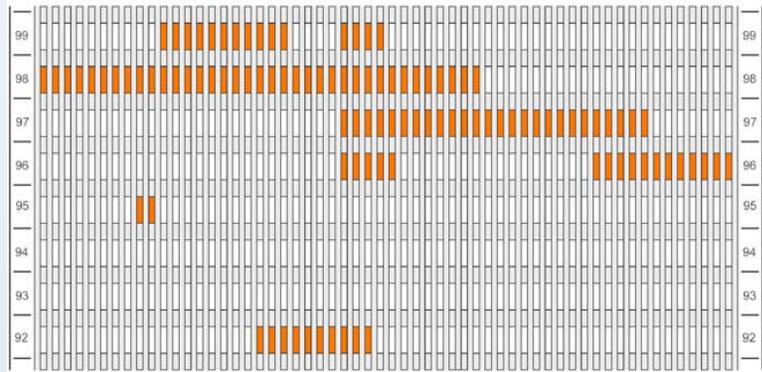
WTC 1, South Face

9:08 a.m. to 9:16 a.m.



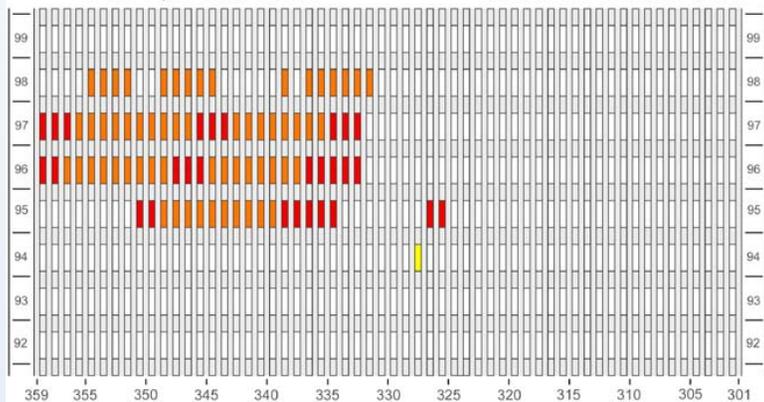
WTC 1, South Face

10:00 a.m. to 10:18 a.m.



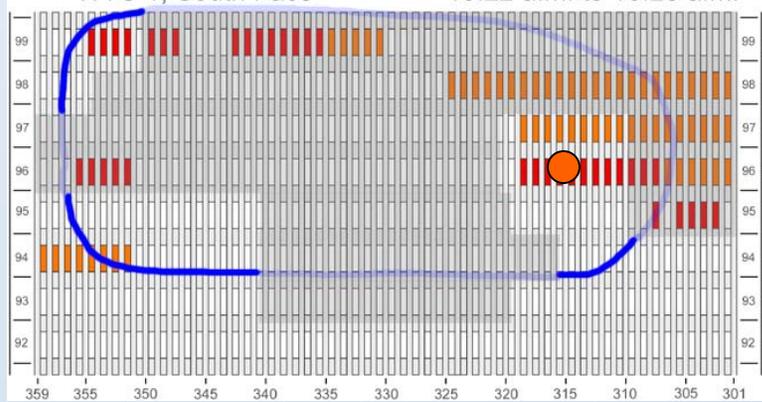
WTC 1, South Face

9:20 a.m. to 9:34 a.m.

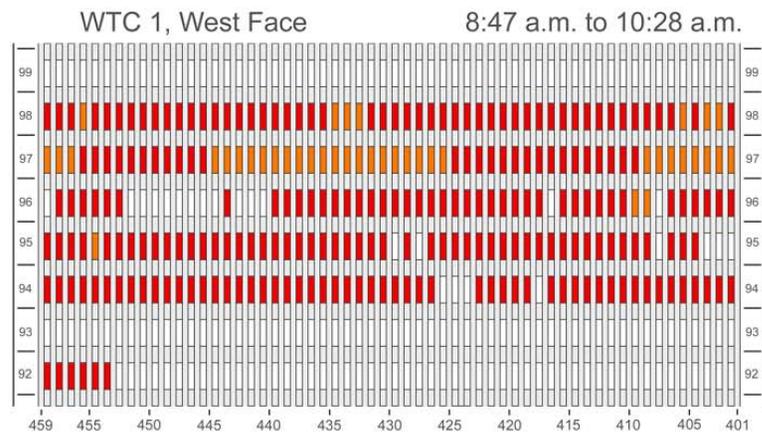
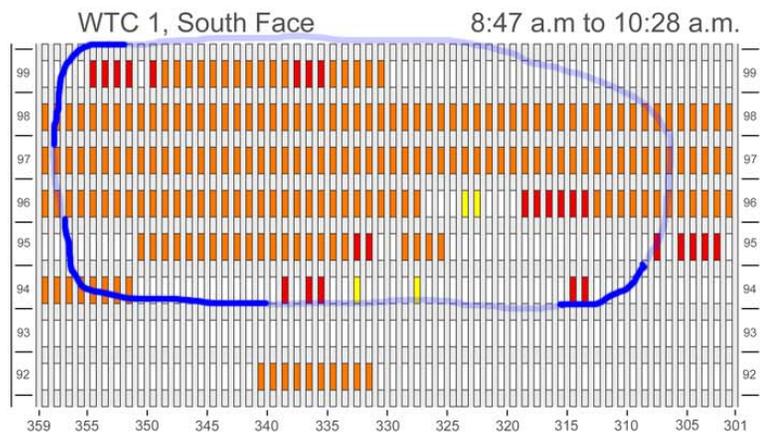
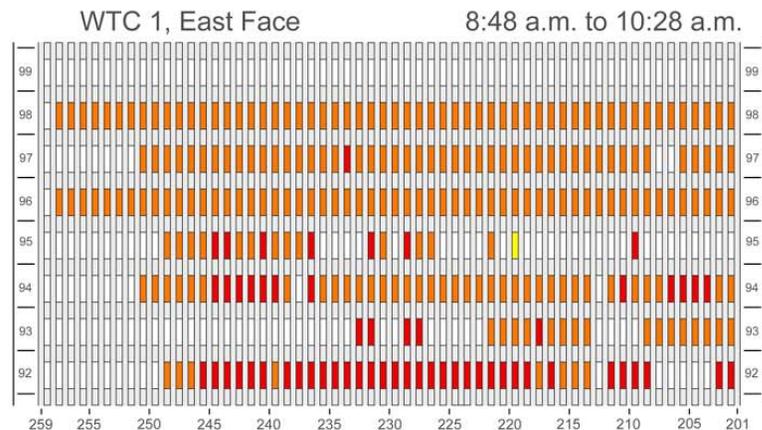
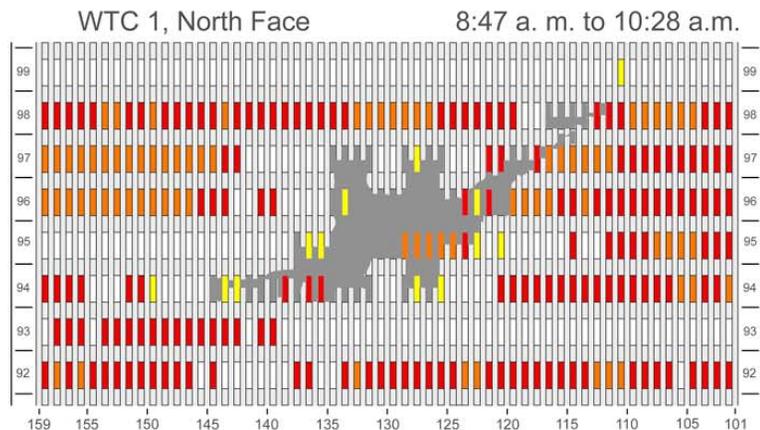


WTC 1, South Face

10:22 a.m. to 10:28 a.m.

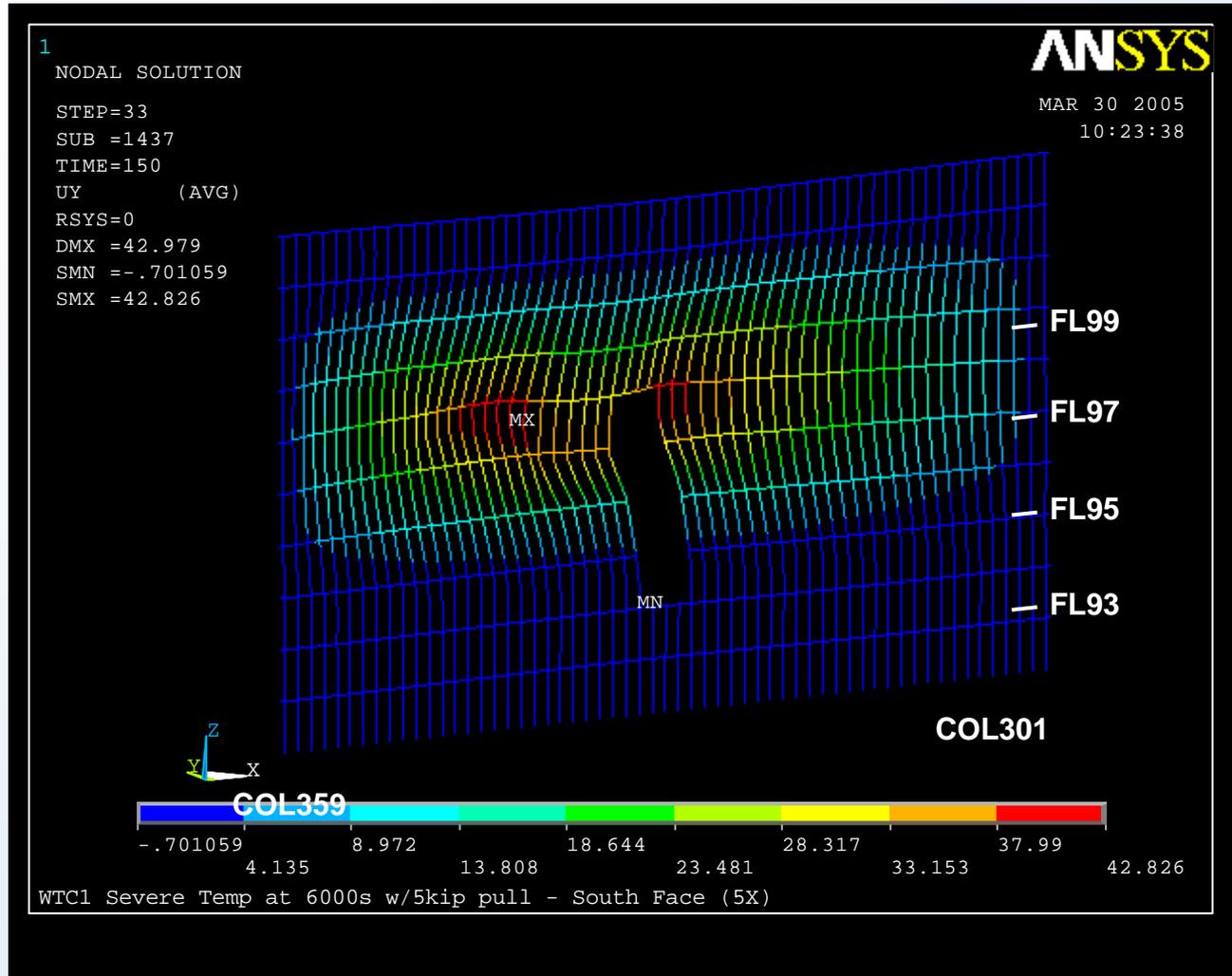


Visual Evidence of Fires in WTC 1



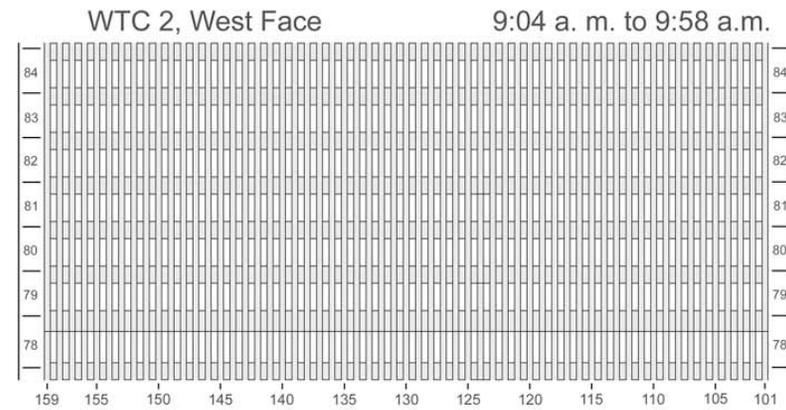
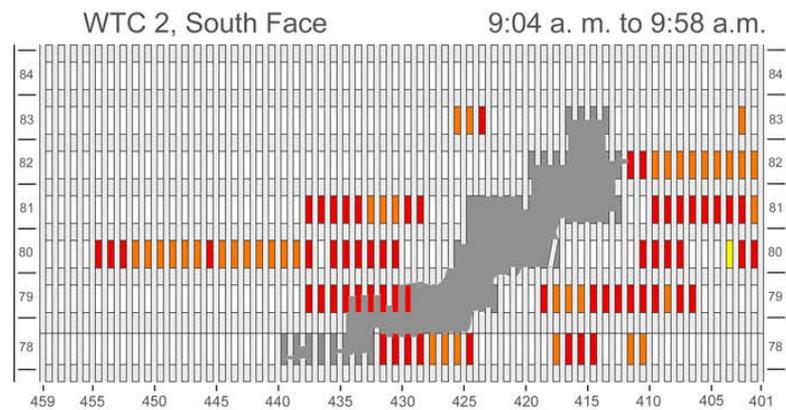
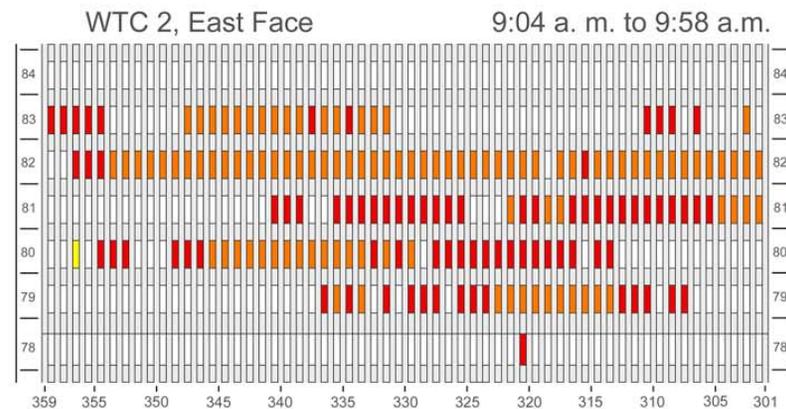
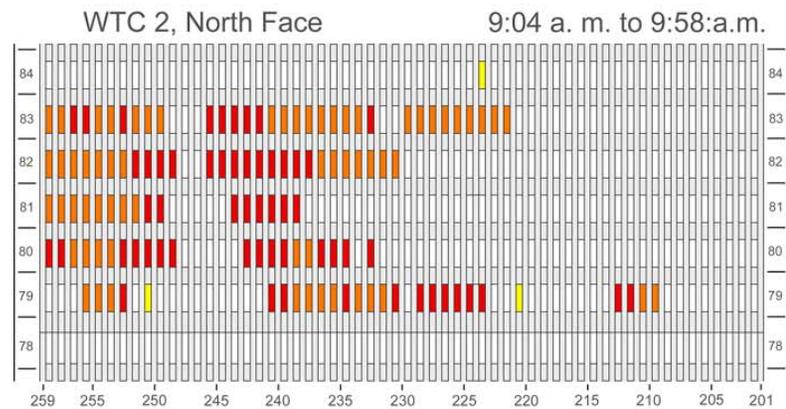
Dark blue line indicates extent of inward bowing observed in visual images.
Light blue line is estimated region of inward bowing where visual images were obscured.

Inward Bowing of the WTC 1 South Face at 6000 s

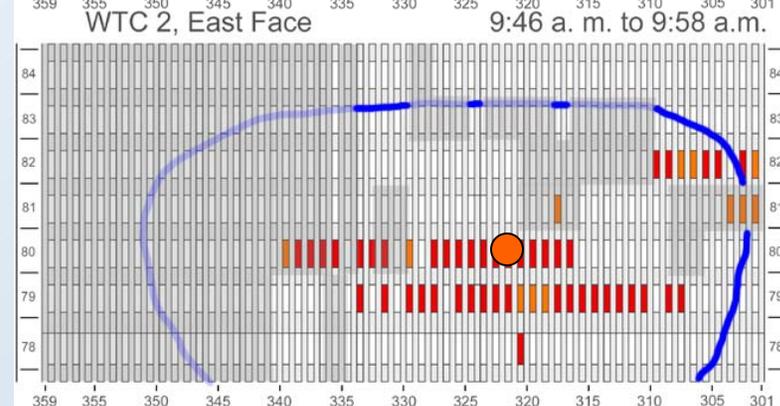
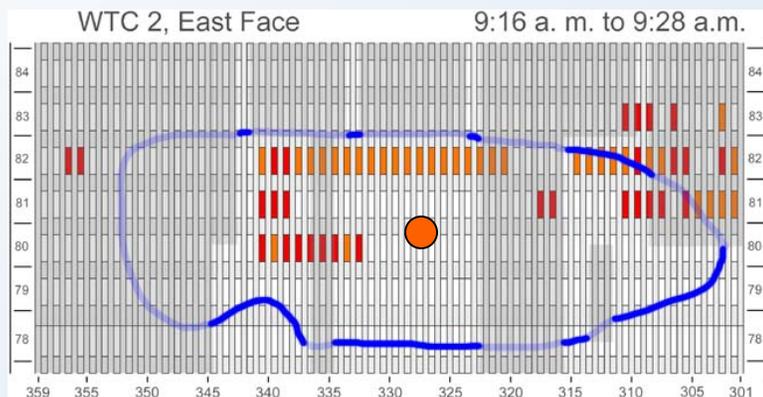
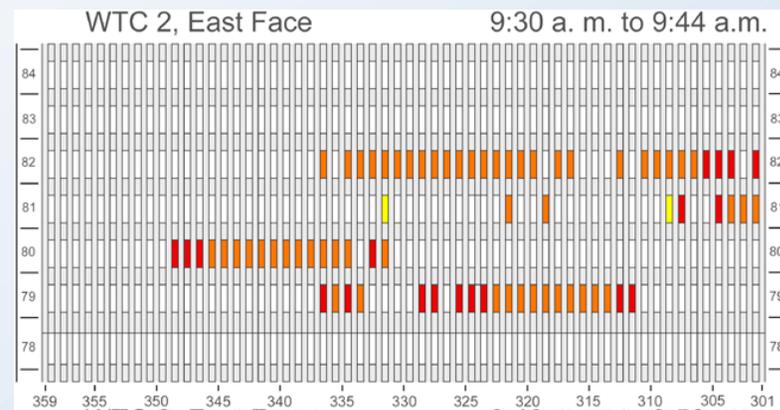
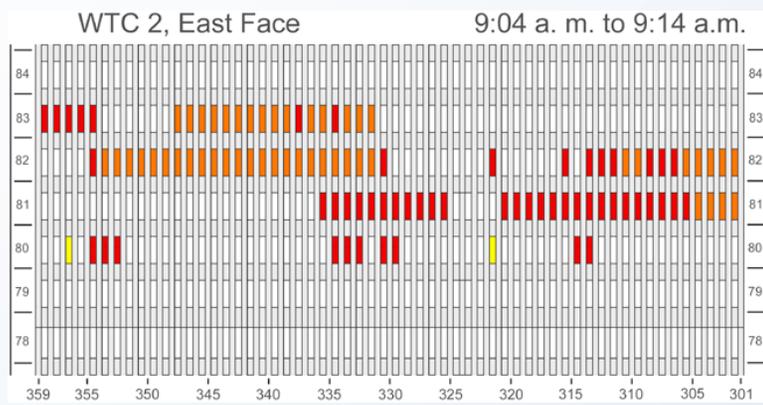


Maximum Inward Displacement = 43 in.
Looking from the outside of the building
Inward displacement is shown as positive displacement

Visual Evidence of Fires in WTC 2



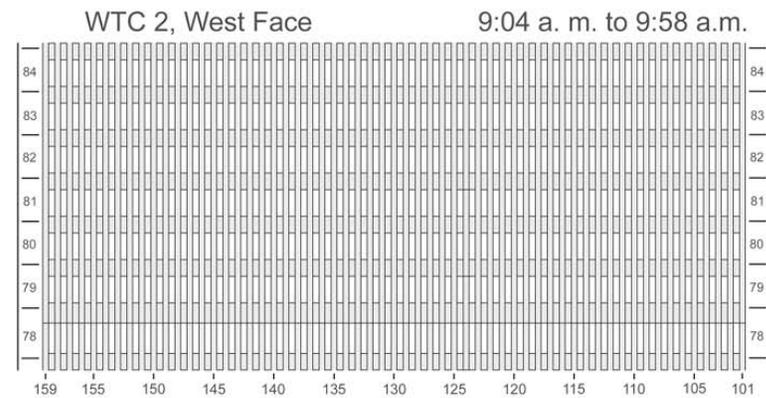
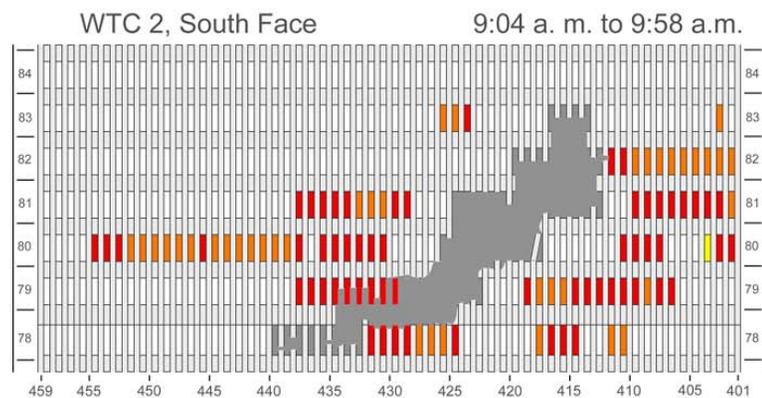
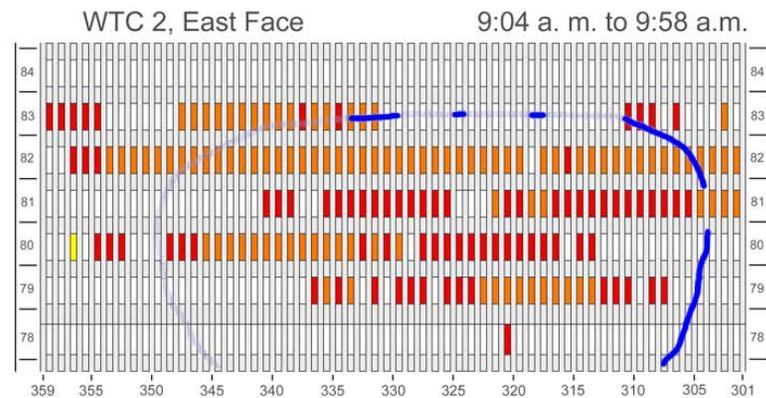
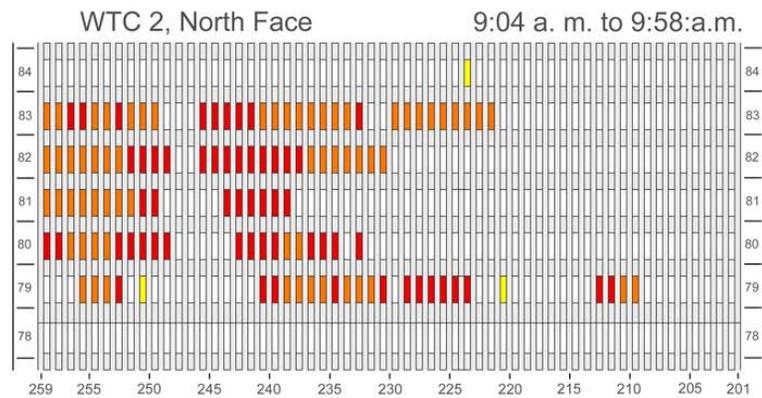
Visual Evidence of Fires in WTC 2



Dark blue line indicates extent of inward bowing observed in visual images.

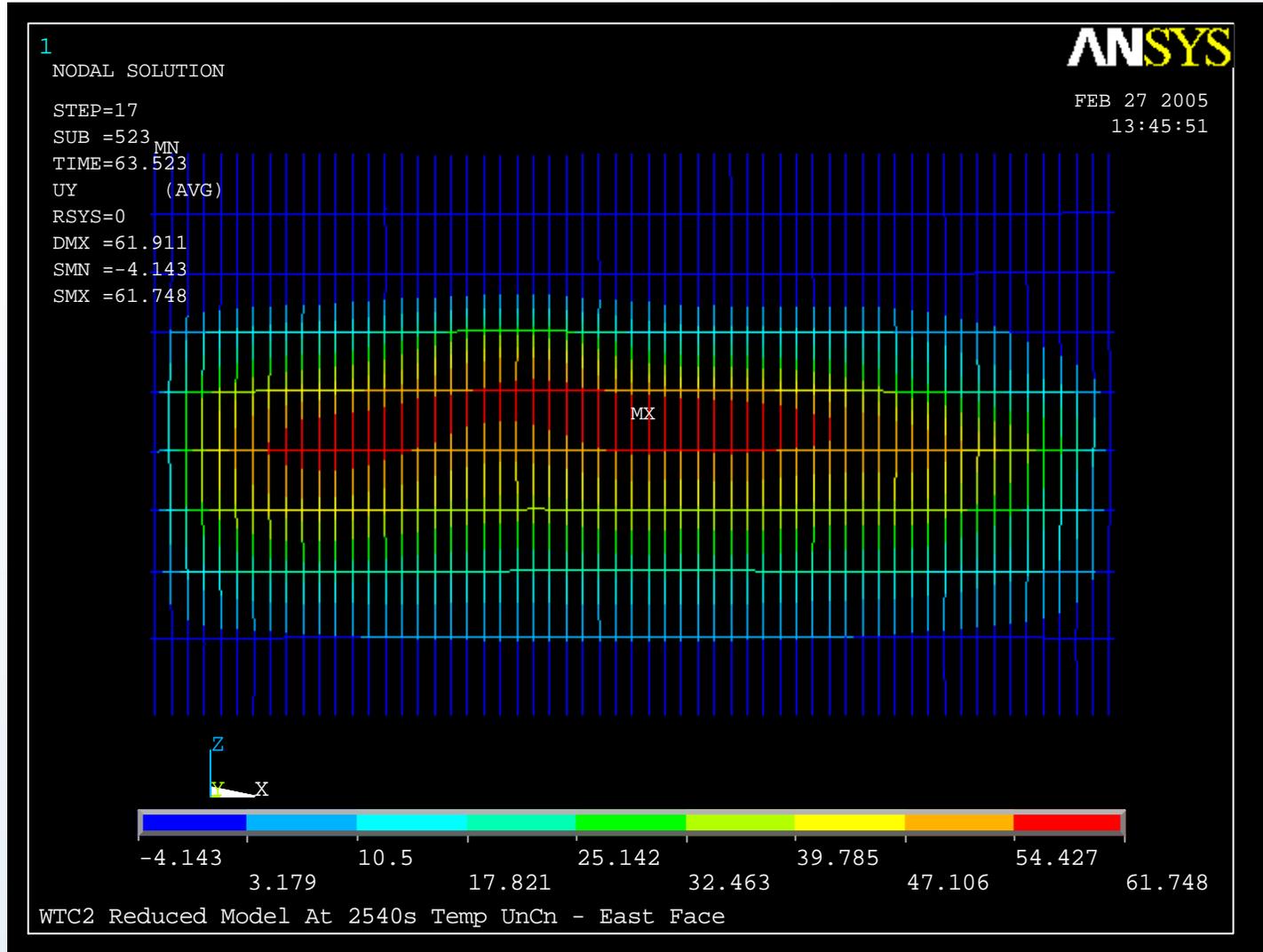
Light blue line is estimated region of inward bowing where visual images were obscured.

Visual Evidence of Fires in WTC 2



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.

Inward Bowing of the WTC 2 East Face at 2,540 s



Maximum inward displacement = 60 in.

Fireproofing Conditions

- In general, the affected floor systems in WTC 1 had upgraded or thicker fireproofing (1.5 in. specified); affected floors in WTC 2 had the original fireproofing (0.5 in. specified).
- **Structural response is sensitive to variability in fireproofing thickness along the length of components; it is possible to determine a thermally equivalent uniform thickness that should be greater than the specified thickness. The thermally equivalent thicknesses were used in the analysis.**

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

* Coefficient of Variation

- **In the analysis under the original condition, the fireproofing thickness on the bridging trusses was considered to be *one-half* the thickness for the primary trusses from interpretation of photographic evidence. For the upgraded condition, the fireproofing thickness on the bridging trusses was considered to be *equal* to the thickness for the primary trusses.**

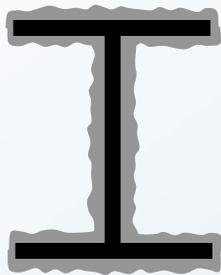
Analysis of Fireproofing Damage

- NIST developed and used a rigorous technical approach to evaluate the role of the post-impact condition of the fireproofing in the collapse of the WTC towers.
- The technical approach was based on a **comprehensive aircraft impact analysis that predicted in detail (1) the damage to structural components and building partitions and furnishings (the partitions and modular office workstations were modeled explicitly in the impact region), (2) the path of the debris field that was generated by aircraft impact, and (3) the dispersion of jet fuel.**
- NIST determined the most influential parameters that governed the results of the aircraft impact damage analysis based on formal statistically-based methods. **NIST then conducted analyses for two sets of values for the most influential parameters for each WTC tower to estimate the range of damage caused by aircraft impact.**
- NIST determined conservative estimates for the extent of dislodged fireproofing by considering fireproofing damage only to structural components in the direct path of debris.

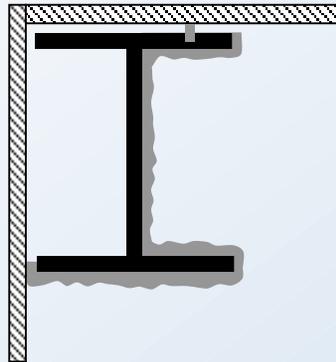
Analysis of Fireproofing Damage (2)

- **Consistent with a conservative approach, NIST estimates ignored the possibility that fireproofing on structural components in a much larger region that was not in 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 perimeter 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.

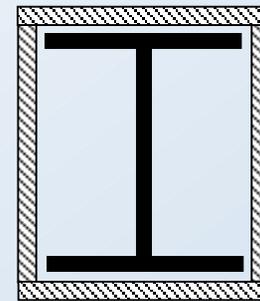
Examples of Types of Core Column Fireproofing



SFRM Only



SFRM +
Wallboard



Wallboard
Only

SFRM – Sprayed fire resistive material

Wallboard – Gypsum wallboard enclosure

Types of Fireproofing on Core Columns in Fire-Affected Floors

WTC 1

Floor	% SFRM only	% SFRM + Wallboard	% Wallboard only
94	13%	49%	38%
95	9%	49%	43%
96	11%	45%	45%
97	11%	45%	45%
98	11%	45%	45%
All	11%	46%	43%

Information from original design drawings

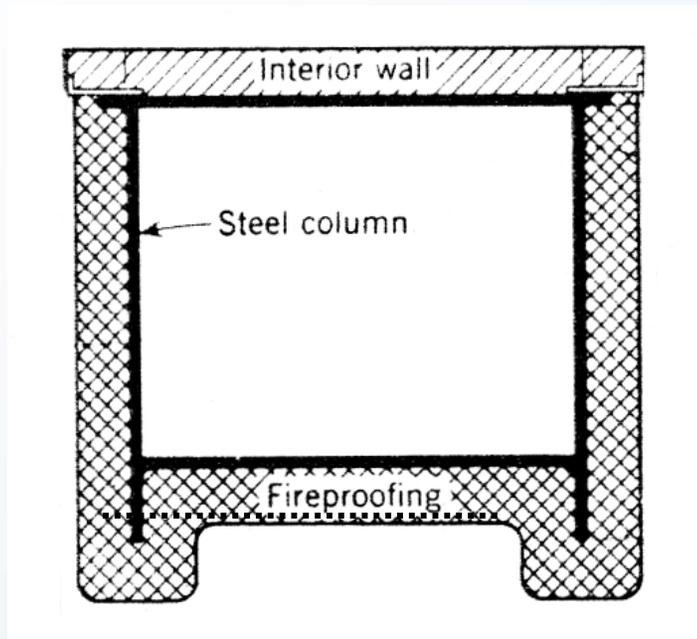
SFRM – Sprayed fire resistive material

Wallboard – Gypsum wallboard enclosure

WTC 2

Floor	% SFRM only	% SFRM + Wallboard	% Wallboard only
78	38%	49%	13%
79	19%	68%	13%
80	17%	51%	32%
81	17%	51%	32%
82	23%	55%	21%
83	15%	57%	28%
All	22%	55%	23%

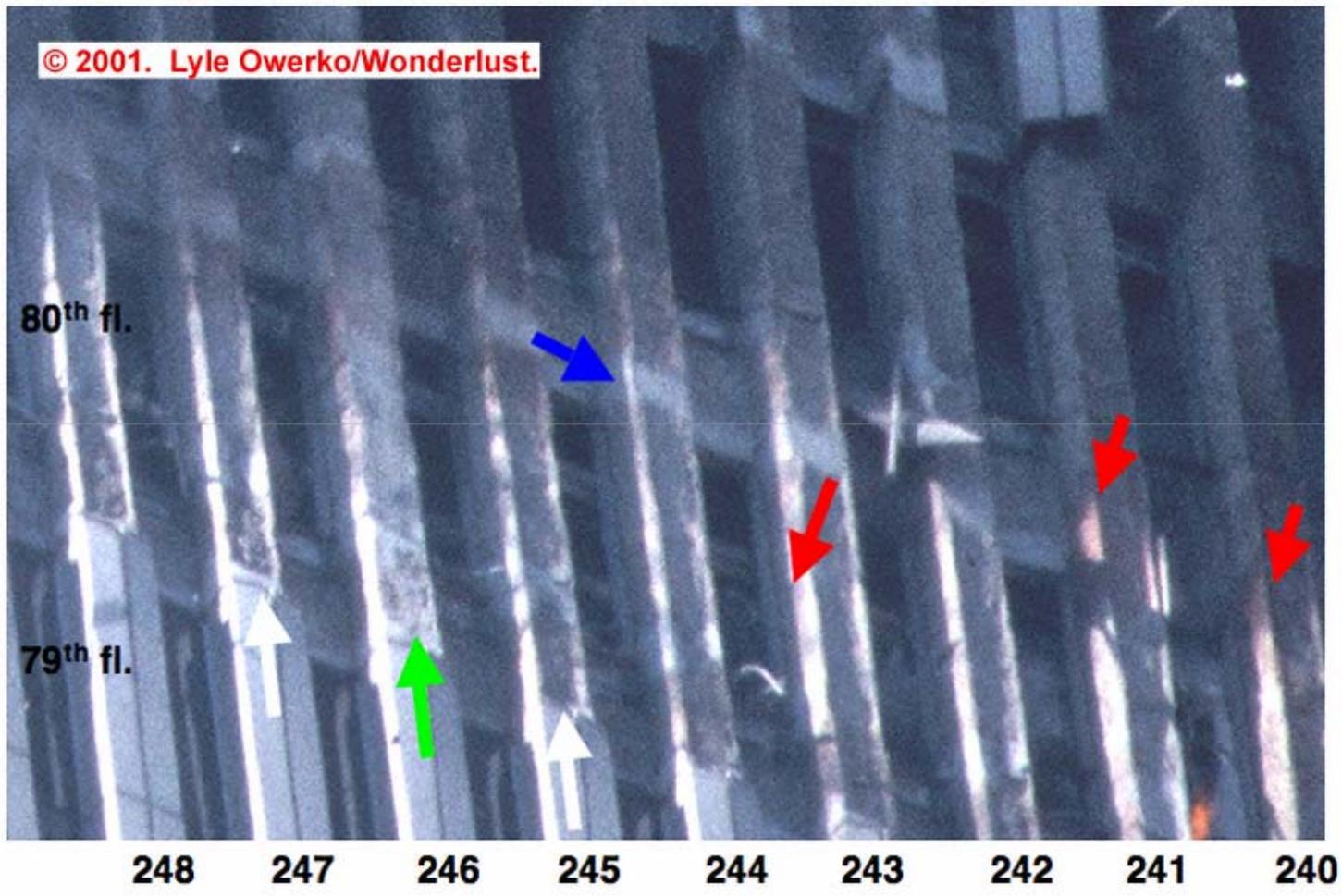
Application of SFRM to External Columns



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



Damaged SFRM - North Face of WTC 2



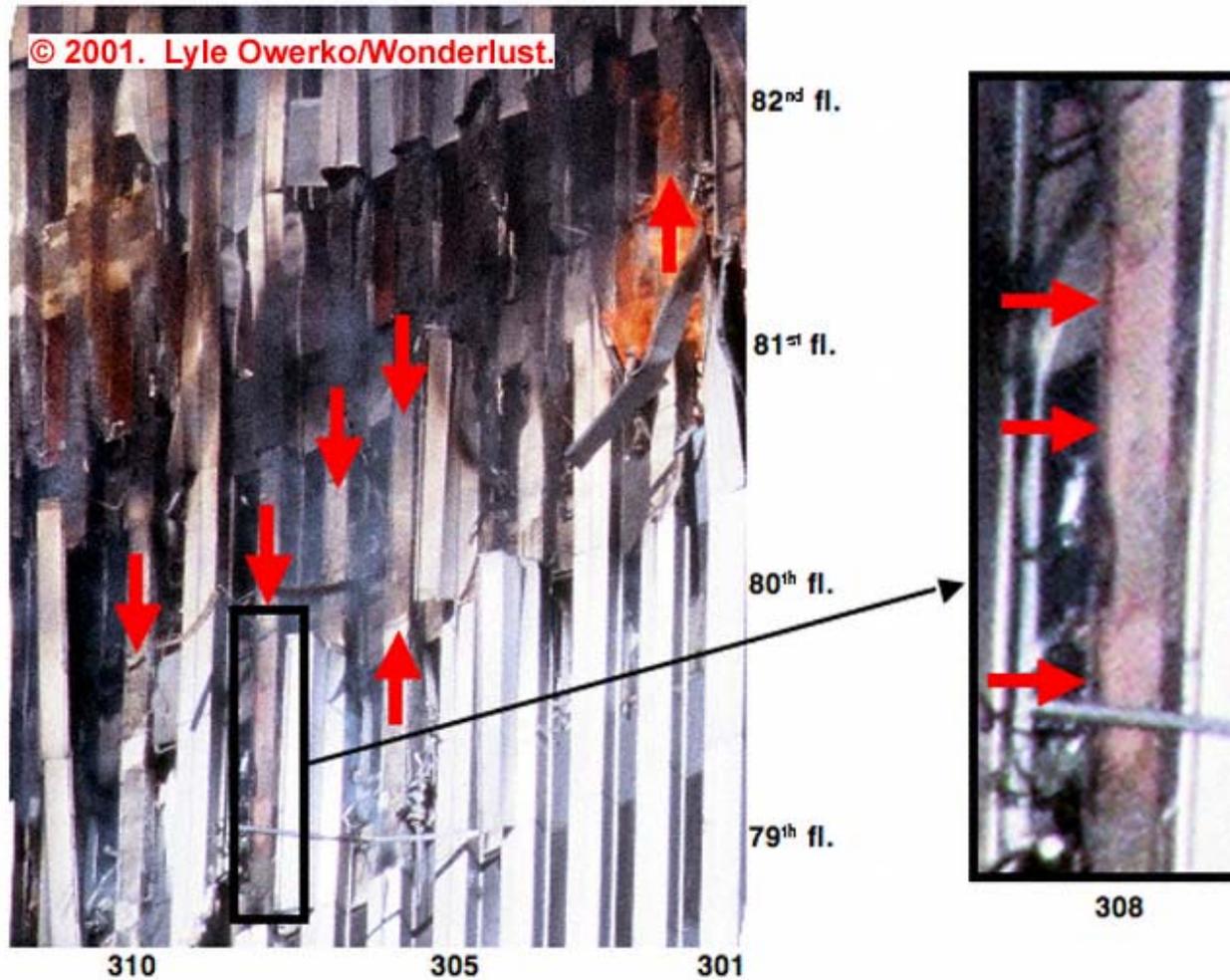
Removed from flanges (red)

Intact (green)

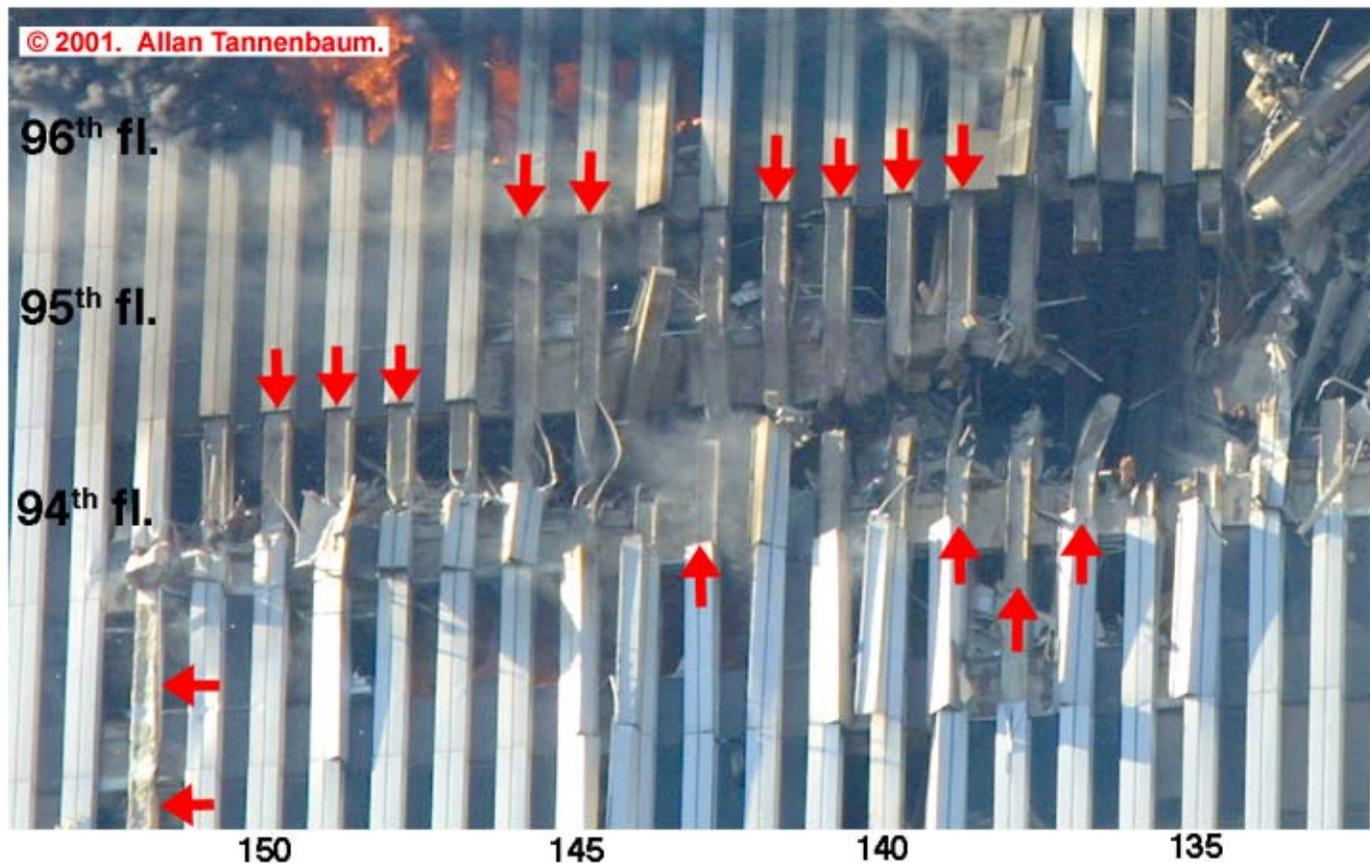
Removed from outer web (white)

Covered by weatherproofing coating (blue)

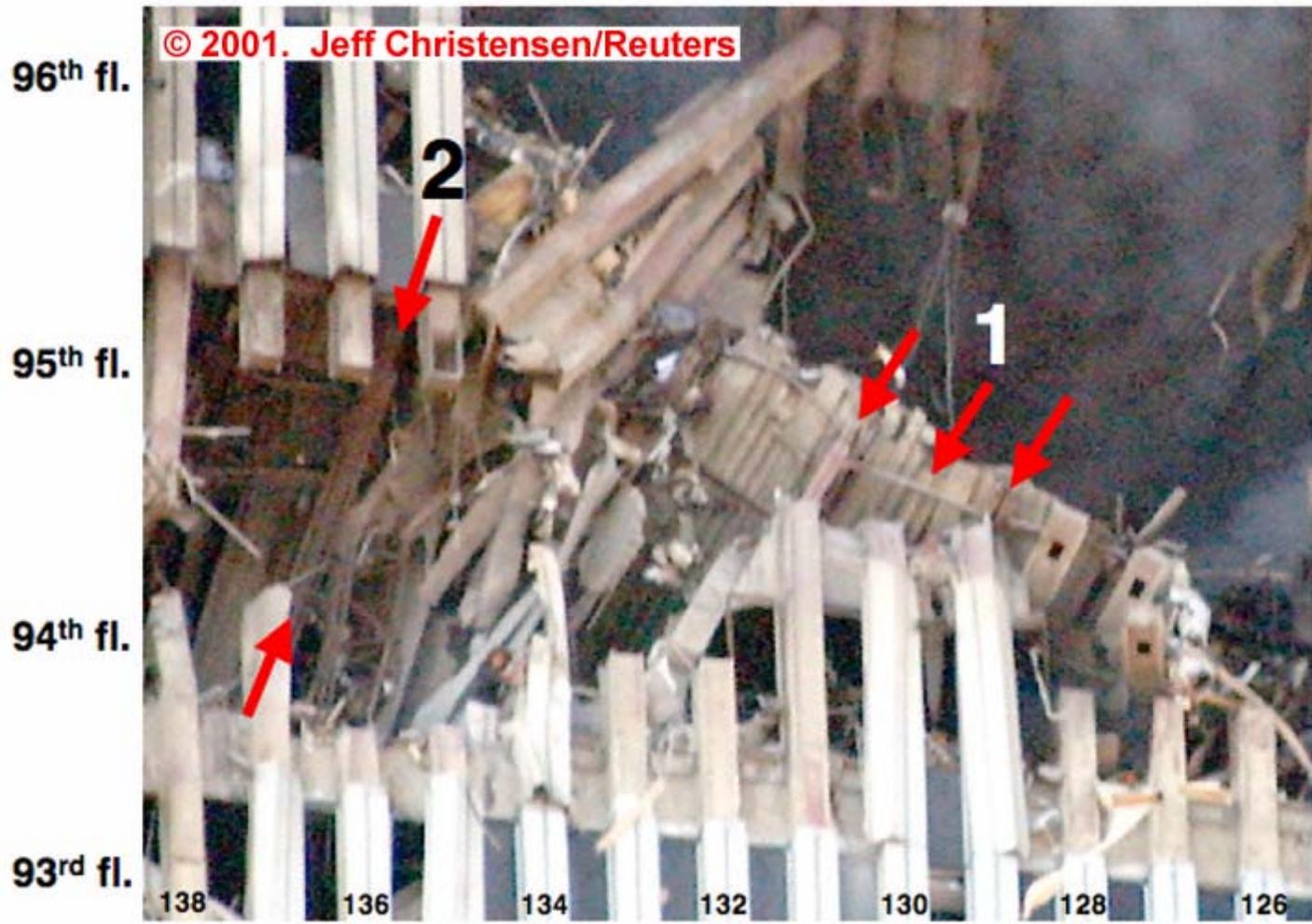
Damaged SFRM - East Face of WTC2



Damaged SFRM - North Face of WTC 1: Left Side of Impact Hole



Damaged SFRM - North Face of WTC 1: Missing from Trusses



Analysis of Fireproofing Damage (3)

- In the case of core columns, the analysis required the debris impact to be strong enough to fail building partitions immediately in front of the columns.
 - If the wall partitions remained intact in the core area after interaction with the debris field, then the fireproofing on core columns behind these partitions was assumed to remain intact.
 - If wall partitions were damaged or destroyed by the debris field, then fireproofing on core columns behind these partitions was assumed to be dislodged over that floor height.
 - For aircraft impact damaged core columns, fireproofing was assumed to be dislodged only if the columns were subject to direct debris impact that could fail wall partitions.
 - **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 fireproofing measured by NIST was generally less than 12 psi (1728 psf).**
 - Core columns had spray-on fireproofing, gypsum wallboard enclosures, or a combination.

Analysis of Fireproofing Damage (4)

- In the case of perimeter columns, the analysis required the debris impact to be strong enough to damage or destroy room furnishings (modular office workstations) adjacent to the columns.
 - If the room furnishings remained intact after interaction with the debris field, then the fireproofing on the inside face of the perimeter columns behind these furnishings was assumed to remain intact.
 - If the room furnishings were damaged or destroyed after interaction with the debris field, then the fireproofing on the inside face of the perimeter columns in the same vicinity was assumed to be dislodged over that floor height.
 - The other three faces of the perimeter columns were protected by the windows and/or aluminum cladding and were assumed to have no fireproofing damage.

Analysis of Fireproofing Damage (5)

- In the case of floor trusses, the analysis required debris impact to be strong enough to damage or destroy room furnishings (modular office workstations) in the same area of the affected floor.
 - If the debris field momentum was not strong enough to damage the furnishings, then the debris field was also considered not to extend high enough or be strong enough to dislodge the fireproofing.
 - If the debris field momentum was strong enough to damage the furnishings, then the debris field was also considered to extend high enough or be strong enough to dislodge the fireproofing.

Analysis of Fireproofing Damage (6)

- **The thermal analysis of the WTC towers was conducted with rigor and care, properly taking into account the estimated post-impact condition of the fireproofing on each structural component.**
 - For floor trusses without dislodged fireproofing, a thermally equivalent uniform thickness was considered to appropriately account for the average application thickness and its variability (floor trusses had original fireproofing thickness in the affected floors of WTC 2 and upgraded fireproofing thickness in the affected floors of WTC 1).
 - For columns without dislodged fireproofing, the specified thickness as determined from available documents was used. No information was available on the in-place conditions of the fireproofing on the perimeter columns, and little information was available on core columns.
 - For structural components with significantly dislodged fireproofing, the fireproofing was considered to be missing on each such component. Separate analysis showed that significant regions of missing fireproofing in a component is essentially equivalent to there being no fireproofing.
 - For structural components with partially dislodged fireproofing, the fireproofing was considered to be missing on specifically identified faces for each such component (e.g., on inner face of perimeter columns that bowed inwards minutes prior to collapse of each WTC tower).

Estimation of Floor Effects in Global Model

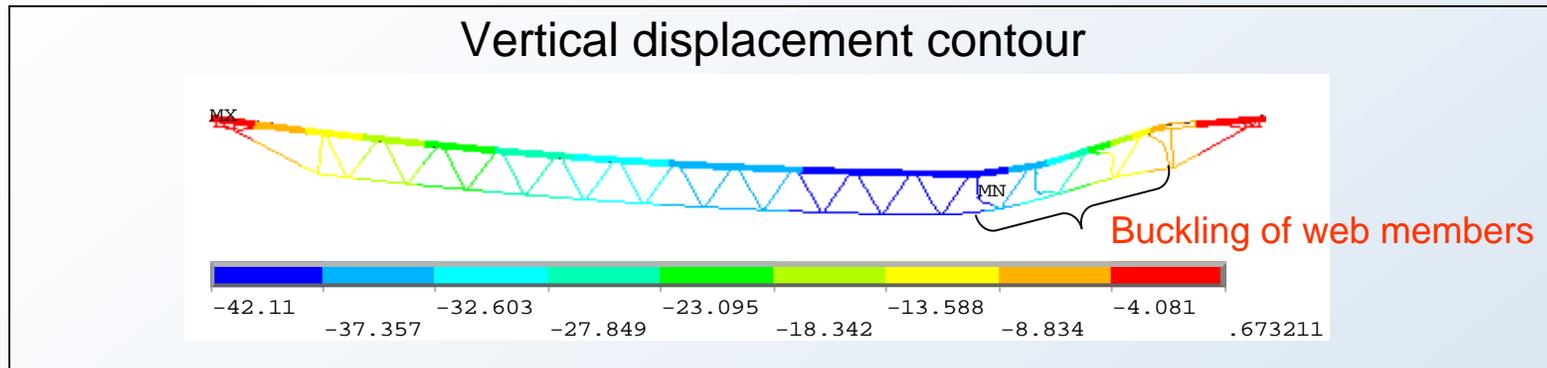
- Floor Subsystem Models

- Analyzed structural response of single truss-with-slab-section model to thermal effects; estimated *magnitude* of inward pull forces from exterior connections.
- Analyzed structural response of full floor model to thermal effects; estimated regions where floor sags and *extent* of disconnections from columns.

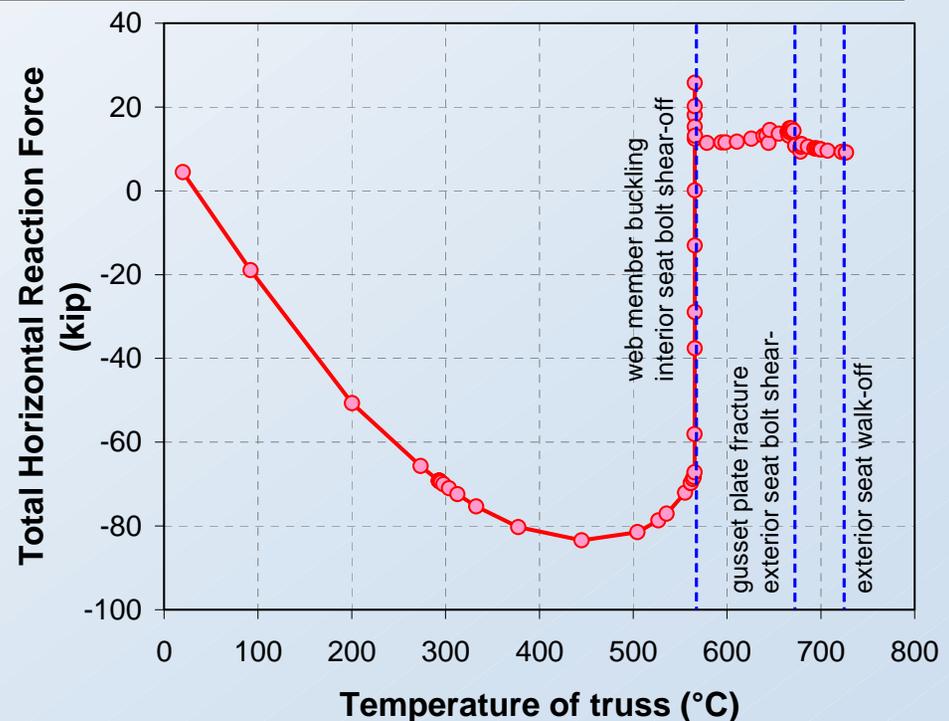
- Wall Subsystem Model

- Analyzed structural response of wall model to thermal effects (South face of WTC 1; East face of WTC 2).
- Imposed floor disconnections due to aircraft impact damage; made adjustments to match observations (e.g., floor 83 of WTC 2).
- Imposed floor disconnections from full floor thermal model.
- Imposed inward pull forces estimated from single truss with slab section model.
- Compared results with observed inward bowing.
- Estimated magnitude and extent of inward *pull forces* required to match observed inward bowing.

Sagging in Detailed Truss Model



- After web members buckled, the truss pulled exterior columns in.
- The tension force ranged from 9 kip to 14 kip per column in this model at the exterior column.

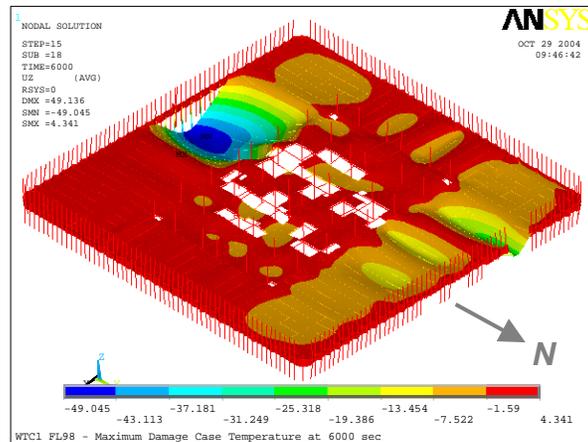


Floor Sagging and Inward Pull Forces

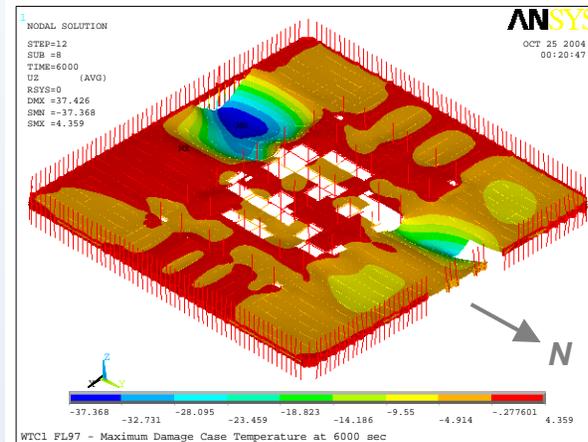
	Floor Model	Perimeter Column Model	Maximum Temperature Tmax	Floor Sag	Tensile Forces	Column Inward Displacement
Usmani, et al ¹	<ul style="list-style-type: none"> • 12 floors • fire on 3 floors 	<ul style="list-style-type: none"> • 13 story single perimeter column • column area doubled to account for adjacent column participation • pinned at end supports 	500 °C	16 to 17 in.	16 to 20 kips	8 to 14 in.
Duthinh ²	<ul style="list-style-type: none"> • 5 floors • fire on 4 floors 	<ul style="list-style-type: none"> • 6 story perimeter column • pinned at end supports 	925 °C	18 to 24 in.	16 to 27 kips	1 in.
NIST ³	<ul style="list-style-type: none"> • 1 floor • fire on floor below • creep included 	<ul style="list-style-type: none"> • 2 story perimeter column • fixed at end supports 	650 °C	25 to 27 in.	9 to 14 kips	0.1 in.

1. *Fire Safety Journal*, v 38, n 6, October, 2003, p 501-533; Temperature profile assumed for floors with Tmax near perimeter column and a linear reduction toward the core
2. *NIST Special Publication 1000-5*, June 2004 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster, v 5, App. M; Temperature profile developed from NIST Fire Dynamics Similar (FDS)
3. A uniform temperature profile was assumed

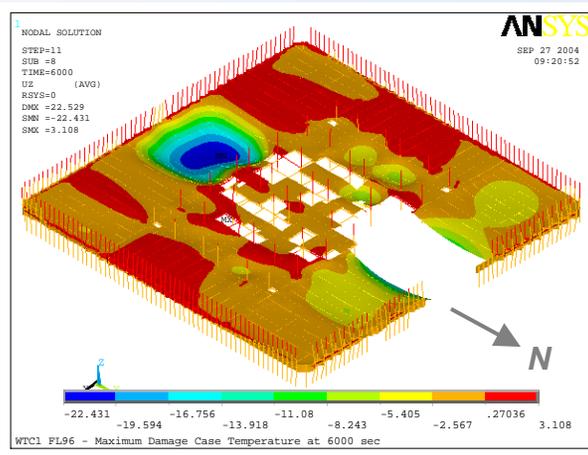
WTC 1 - Vertical Displacement of Floors 95 to 98 at 6,000 s



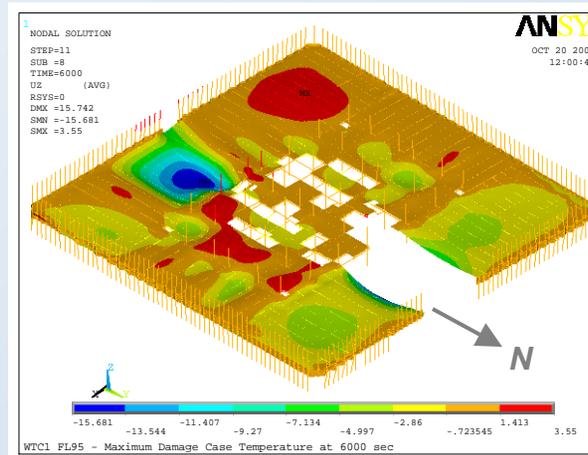
Floor 98, max sag = 49 in.



Floor 97, max sag = 37 in.

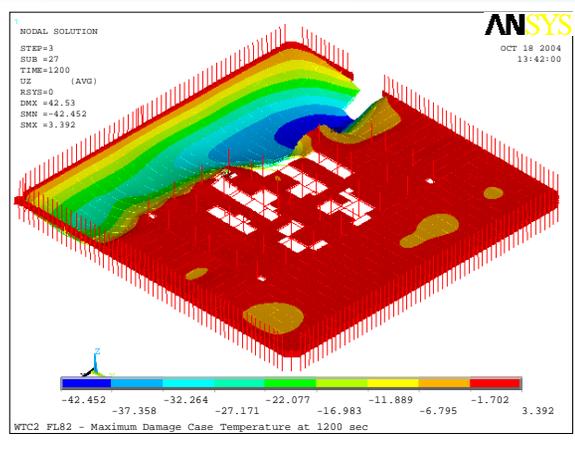


Floor 96, max sag = 22 in.

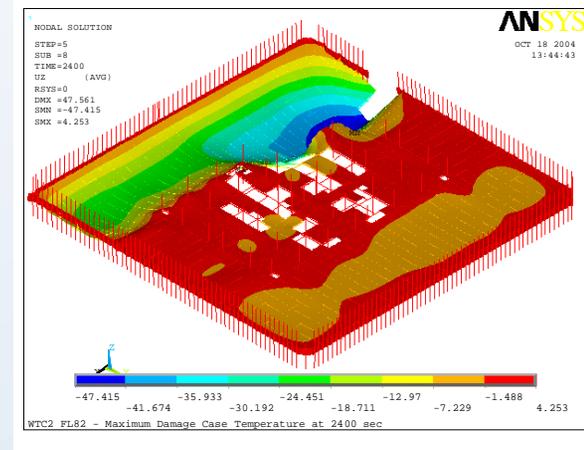


Floor 95, max sag = 15 in.

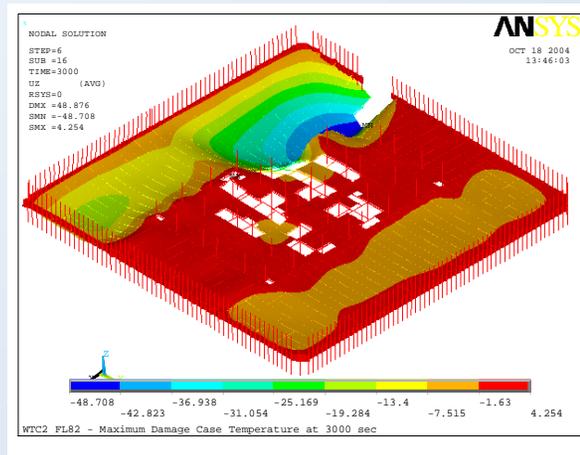
WTC 2 - Vertical Displacements of Floor 82



1,200 s max sag = 42 in.

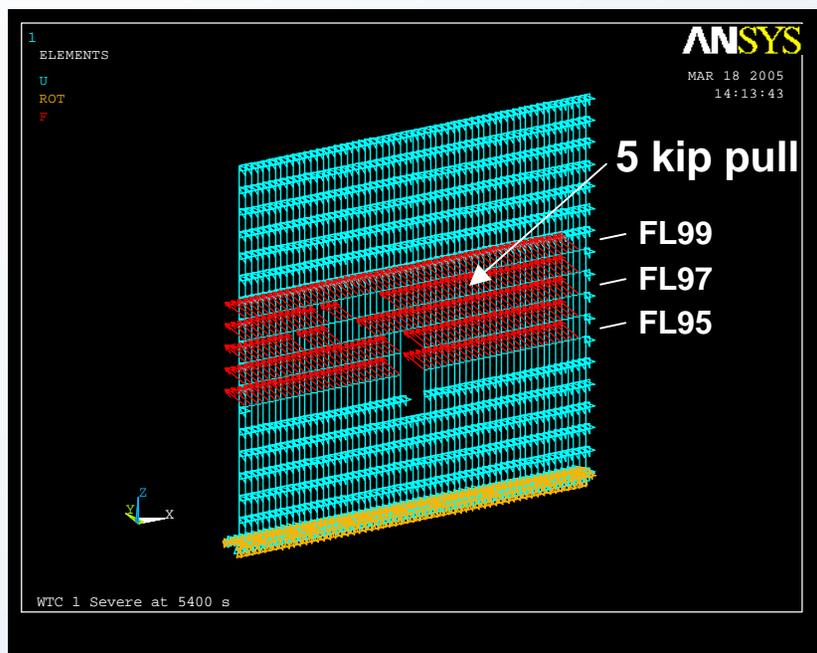


2,400 s max sag = 47 in.

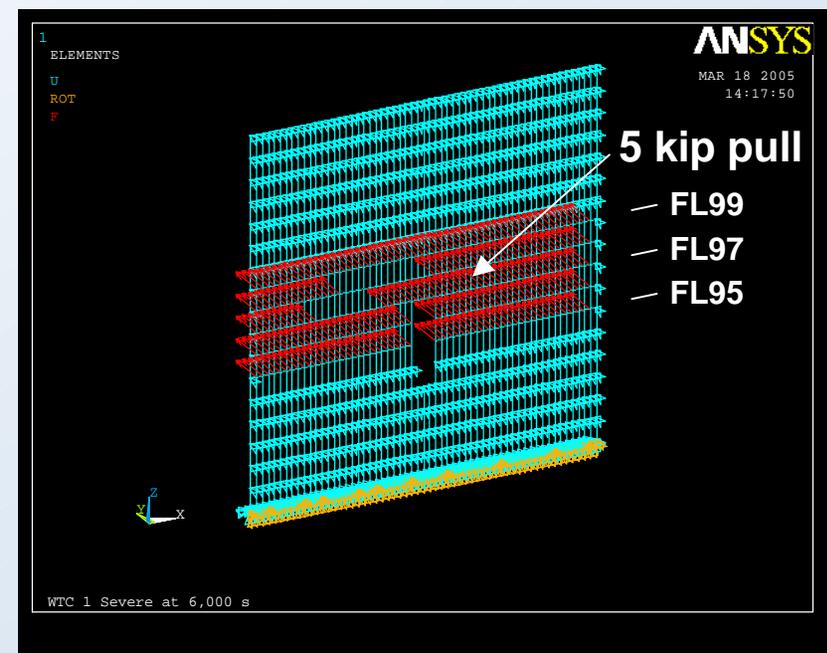


3,000 s max sag = 48 in.

Pull-in Forces on the WTC 1 South Wall

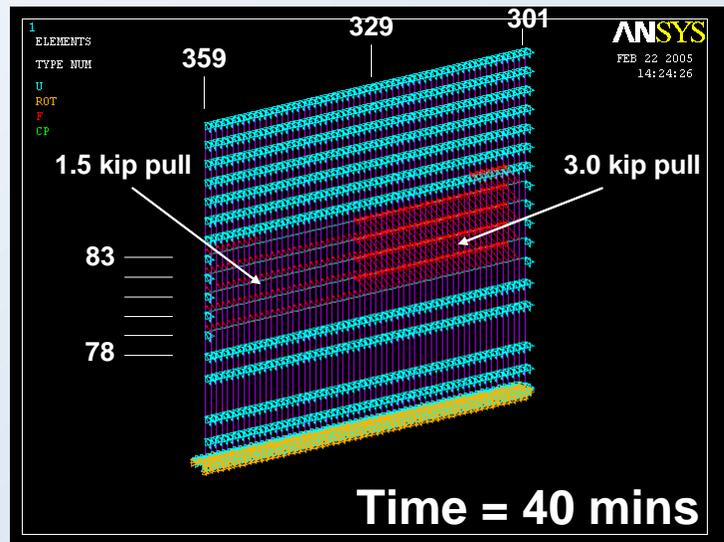
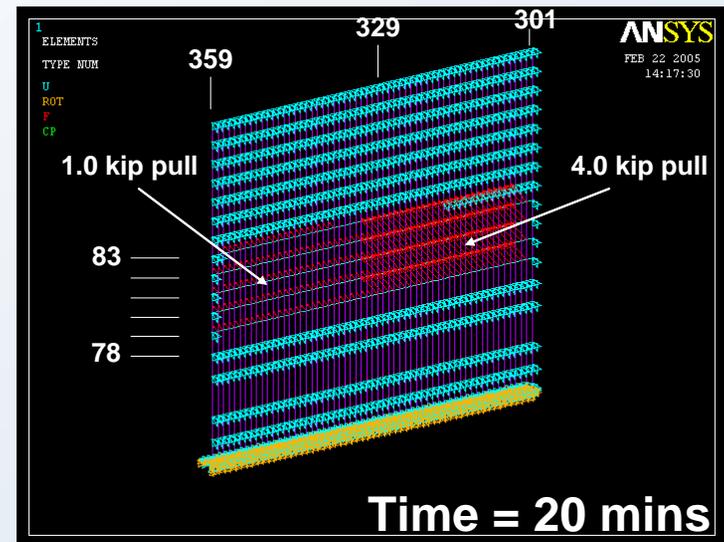
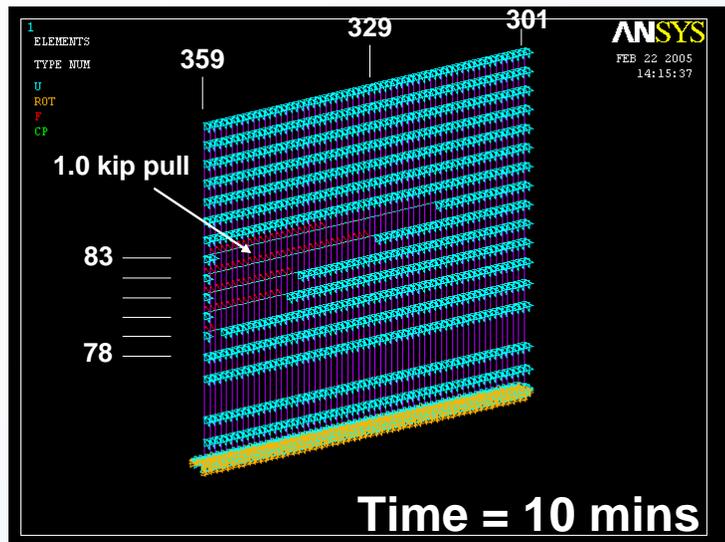


Between 4,800 s and 5,400 s



Between 5,400 s and 6,000 s

Pull-in Forces on the WTC 2 East Wall



Estimation of Floor Effects in Global Model (2)

- Global Model with Creep
 - Analyzed structural response of global model with thermal effects.
 - Imposed floor disconnections and inward pull forces estimated from wall model (South face of WTC 1; East face of WTC 2).
 - Compared results with observed inward bowing.
 - Adjusted magnitude of inward bowing forces to match observations.

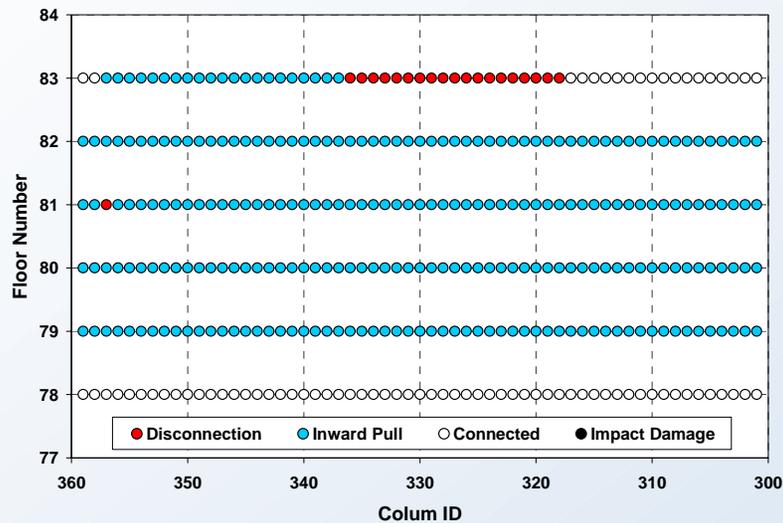
WTC 1 (South Face of Floors 95 to 99)	
Time Interval (s)	Inward Pull (kip)
0 – 4,800	0
4,800 – 6,000	5

WTC 2 (East Face of Floors 79 to 83)	
Time Interval (s)	Inward Pull* (kip)
0 – 1,800	1, 4
1,800 – 2,540	1.5, 3.0

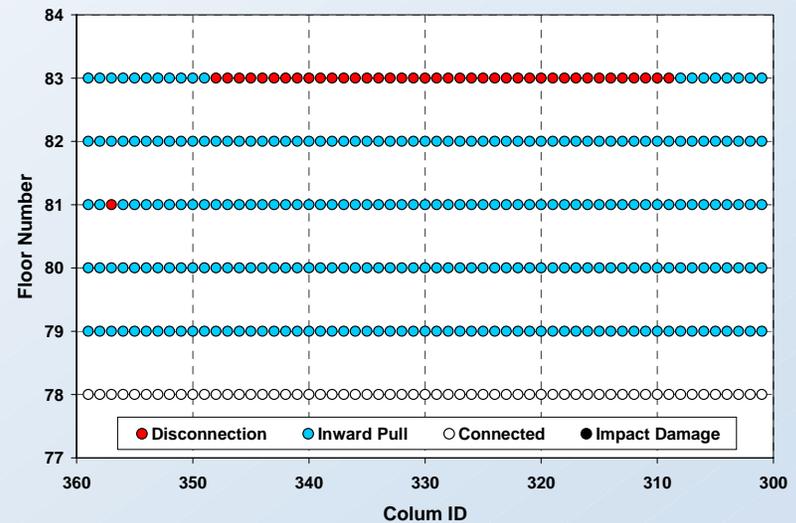
* Pull forces applied to each of two regions

WTC 2 Floor Disconnection and Pull-In Locations for the East Face

1200 s



2400 s



Estimation of Floor Effects in Global Model (3)

- *Magnitude* of Inward Pull Forces
 - Represent small fraction (0.3 to 2.5%) of column axial loads (average column axial load of about 200 kip for WTC 1 and 300 kip for WTC 2).
 - Consistent with magnitudes estimated from single truss-with-slab section model. Related studies by Usmani (U. Edinburgh) and Duthinh (NIST) with simplified subsystem models of single trusses over multiple floors found similar magnitudes of pull-in forces.
- *Extent* of Inward Pull Forces
 - Greater than estimates obtained from thermal analysis of full floor model.
 - Fireproofing dislodged from floor trusses over a larger region (estimates used were conservative).
 - Additional floor sag over large region due to effects of thermally-induced concrete spalling/delamination.
- Additional factors that may influence *Magnitude* and *Extent* of Inward Pull Forces:
 - Boundary conditions on full floor model were too rigid (far end of top and bottom columns at floor supports were fixed)
 - Full floor model included large deflections, nonlinear buckling, and temperature-dependent plasticity but did not include creep.

Findings on Probable Collapse Sequences (1)

- Inward bowing and primary tilting direction at collapse initiation in WTC 1 and WTC 2:
 - Not observed on face where aircraft impact occurred.
 - Observed on face parallel to the longer dimension of the building core.
 - Observed on face associated with less stiff (longer period) direction of the building.
 - Occurred on face associated with long span direction of floor system; truss chord demand-to-capacity higher in long span direction.
- Inward bowing on South face and Southward tilting for WTC 1:
 - Extent of fires similar on all faces; somewhat more extensive on East and West faces; similar in extent on North and South faces.
 - Although North face had extensive impact damage, inward bowing occurred on South face and building tilted to South at collapse initiation.
 - Thermal weakening of perimeter columns with floor sagging (which induced inward pull and occurred on South side) caused inward bowing on South face and tilting in that direction.
- Inward bowing on East face and primary tilting towards East for WTC 2:
 - Fires more extensive on East face; less extensive on North face and South face, though significant on East side of both faces; no observed fires on West face.
 - Although South face had extensive impact damage, inward bowing occurred on East face and building tilted more to the East and less to the South at collapse initiation.
 - Thermal weakening of perimeter columns with floor sagging caused inward bowing on East face and primary tilting in that direction (with additional Southward tilting due to the aircraft impact damage).

Findings on Probable Collapse Sequences (2)

- The time it took for each WTC tower to collapse was due primarily to:
 - Asymmetric structural damage resulting from aircraft impact in WTC 2 compared to WTC 1; and greater damage (severed or heavy damage) to core columns in WTC 2 than in WTC 1; higher aircraft speed/impact energy and impact location (shorter floor span resistance and off center position) caused greater WTC 2 core damage.
 - Time it took for the fires, in combination with aircraft impact damage, to weaken the core.
 - Time it took for fires to traverse from their initial location to the critical side of the towers, and:
 - time it took for heat to weaken and sag floor system, resulting in inward pull on adjacent face;
 - time it took for heat to weaken perimeter columns observed to be bowing inward prior to collapse of each tower (traverse time of fires to South face of WTC 1 was much longer than on East face of WTC 2 where fires already existed).
 - Time it took for heat to weaken and buckle those perimeter columns that were simultaneously subject to inward pull forces and, to a lesser extent in WTC 2, additional vertical loads redistributed from core.

Findings on Probable Collapse Sequences (3)

- **The time to destructive heating was determined by the fires**, whose extent and intensity was determined by the large mass and wide distribution of the jet fuel, the nature and (rather low) loading of combustibles, **the sparseness of initial or surviving building partitions, and the ease with which windows were broken allowing oxygen to feed the fires.**
- **Separate analyses showed that heating of structural members was more sensitive to effect of dislodged fireproofing due to debris from aircraft impact than to episodic regions of missing fireproofing or thinness of fireproofing in fire-affected region. As-built fireproofing conditions elsewhere did not play a role in fire-induced collapse.**
- Debris field generated by aircraft impact removed significant fireproofing and gypsum board enclosures, as well as some of the walls. Structural components that became thermally weakened were generally determined by impact of the debris field. **Had fireproofing not been dislodged by debris field, temperature rise of structural components would likely have been insufficient to induce global collapse.**

Findings on Probable Collapse Sequences (4)

- **Role of the Building Core**

- Core weakened significantly due to aircraft impact damage and thermal effects (thermal effects dominated WTC 1; aircraft impact damage dominated WTC 2).
- Loads redistributed to perimeter faces; additional axial loads on perimeter columns not significant (only about 20-25 percent on average)

- **Role of the Building Floors**

- Primary role was to provide inward pull forces that induced inward bowing of columns on exterior face (South face of WTC 1; East face of WTC 2).
- Sagging floors continued to support floor loads despite extensive fires and dislodged fireproofing; there would be no inward pull forces if floors had failed/disconnected.

- **Role of Exterior Frame-Tube**

- Column instability over an extended region of the exterior face ultimately triggered system failure (loads could not be redistributed via hat truss to already weakened building core; load transfer via spandrels propagated column instability to adjacent faces) causing initiation of building collapse.
- Column instability induced by thermal weakening of columns, inward pull forces from sagging floors, and to a much lesser degree, additional axial loads from the core.

Findings on Probable Collapse Sequences (5)

- **Performance of WTC floor system with *intact* fireproofing:**
 - **WTC 1 did not collapse during the major 1975 fire which engulfed about 9,000 ft² on the Southeast quadrant of the 11th floor** and spread mostly via utility closets to 10 floors. At the time, office spaces in the WTC towers were unsprinklered. **The fire caused minimal damage to the floor system, and at no time was the load carrying capacity of the floor system compromised.** The fire “did not damage a single primary, fireproofed element. Some top chord members (not needed for structural integrity), some bridging members (used to reduce floor tremor and the like) and some deck support angles (used only as construction devices) were buckled in the fire—all were unfireproofed steel.” (SCHR Letter Report 1975).
 - **The load carrying capacity of the floor system was not compromised by the furnace temperatures in any of the four fire resistance (ASTM E 119) tests** conducted in August 2004 up until the time they were stopped which was approximately 2 hours. **The applied loads were about twice those on September 11, 2001.** The high temperature conditions in the tests were at least as severe and lasting as the WTC fires (although the top of the slab was not heated)
 - **A detailed thermal-structural analysis, which did not include slab delamination/spalling effects, showed that a full collapse of the WTC floor system would not occur even with a number of failed trusses or connections.**
 - The horizontal and vertical capacity of the floor connections to the perimeter and core columns exceeded the demand under design load conditions.

Role of Fire Resistance Tests

- The fire resistance tests cannot be used to determine the actual performance of the floor systems in the collapse of the WTC towers, nor can the tests determine whether or not the actual floor systems *as built* met code requirements. Further, the PANYNJ could have taken the highly unusual step of reclassifying the structure to Class 1-C, with a 1-1/2 hour required rating for floors and a 2 hour rating for columns, when installation of the sprinkler system was completed just prior to September 11, 2001.
- The fire resistance tests provided valuable insights into the behavior of the floor systems for use in analyzing the thermal response and collapse of the WTC tower structures.
- The occurrence and spread of jet-fuel due to the terrorist attacks on September 11, 2001 ignited multi-floor fires in the WTC towers. These fires were significantly different from the fires to which floor systems in standard U.S. fire rating tests are subjected. Consider, for example:
 - Combustible fuel load of the hijacked jets.
 - Extent and number of floors involved in fires.
 - Rate of fire spread across and between floors.
 - Ventilation conditions in the fire-affected floors.
- The probable collapse sequence for the WTC towers are based on the behavior of thermally weakened structural components that had extensive damage to fireproofing or gypsum board fire protection induced by the debris field generated by aircraft impact.

Factors that Enhanced Building Performance on September 11, 2001

- The unusually dense spacing of perimeter columns, coupled with deep spandrels, that was an inherent part of both the architectural and structural design of the exterior walls, resulted in a robust building that was able to redistribute loads from severed perimeter columns to adjacent intact columns.
- The wind loads used for the WTC towers, which governed the design of the perimeter frame-tube system, significantly exceeded the prescriptive requirements of the New York City building code and selected other building codes of the era (Chicago, New York State), including the relevant national model building code (BOCA).
- The robustness of the perimeter frame-tube system and the large dimensional size of the WTC towers helped the buildings withstand the aircraft impact.
- The composite floor system with open-web bar joist elements, framed to provide two-way flat plate action, enabled the floors to redistribute loads without collapse from places of aircraft impact damage to other locations, avoiding larger scale collapse upon impact.

Factors that Enhanced Building Performance on September 11, 2001 (2)

- The hat truss resisted the significant weakening of the core, due to aircraft impact damage and subsequent thermal effects, by redistributing loads from the damaged core columns to adjacent intact columns and, ultimately, by redistributing loads to the perimeter walls from the thermally weakened core columns that lost their ability to support the buildings' weight.
- As a result of the above factors, the buildings would likely not have collapsed under the combined effects of aircraft impact and the subsequent jet-fuel ignited multi-floor fires, if the fireproofing had not been dislodged or had been only minimally dislodged by aircraft impact. The existing condition of the fireproofing prior to aircraft impact and the fireproofing thickness on the WTC floor system did not play a significant role in initiating collapse on September 11, 2001.

Future Technologies and Practices that Potentially Could Have Improved Performance on September 11, 2001 (Requires Analysis)

- Fireproofing not dislodged or only minimally dislodged by aircraft impact.
- Perimeter columns and floor framing with greater mass to enhance thermal and buckling performance.
- Other passive and active fire protection features (e.g., compartmentation to retard spread of building fires; thermally-resistant window assemblies to limit air supply and retard the spread of fires; fire-protected and structurally-hardened elevators for firefighter access with continuous, redundant water supply for standpipes).
- Steels with improved high-temperature properties (e.g., yield strength and stiffness) and creep behavior.

There is far greater knowledge of how fires influence structures in 2005 than was the case in the 1960s. The analysis tools available to calculate the response of structures to fires are also far better now than they were when the WTC towers were built.

Limitations and Uncertainties in Determining Probable Collapse Sequences

- NIST recognized the inherent limitations and uncertainties in the analyses performed for determining the probable collapse sequences:
 - As-built condition of the WTC towers, as well as occupancy and use.
 - Estimated aircraft impact damage to WTC towers (structure, partitions, debris, fireproofing, jet fuel dispersion, material failure criteria, model size limitations and uncertainties) not observable from exterior of buildings
 - Estimated growth and spread of building fires (fuel load from building and aircraft contents, ventilation within the core, compartmentation, fire dynamics model size limitations and uncertainties), especially interior building fires
 - Estimated response of the aircraft-impact damaged WTC tower structures to the fires (extent of fireproofing damage, material and structural failure criteria, thermal and structural model size limitations and uncertainties)
- **NIST validated the probable collapse sequences with available factual evidence, carefully considering the sensitivity of its results to these uncertainties.**

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Regular mail:

**WTC Technical Information Repository, Stop 8610,
100 Bureau Drive, Gaithersburg, MD 20899-8610.**

Background Slides

WTC 1 Damage for Base Case

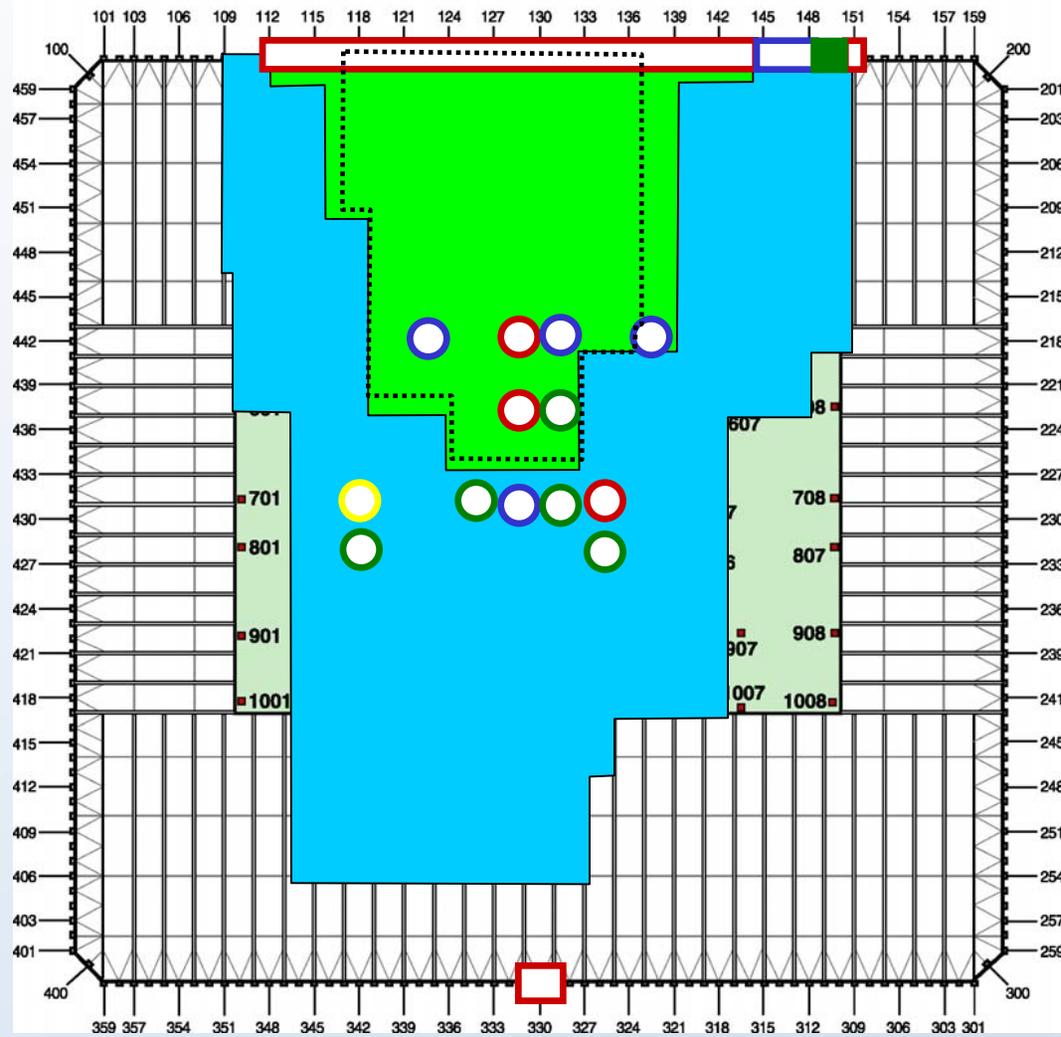
Composite Summary for Floors 94 to 98

Severe Floor Damage

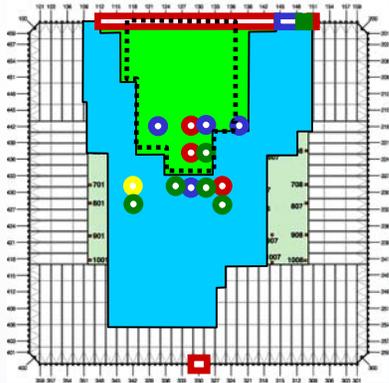
- Fireproofing and partitions ■
- Floor system structural damage ■
- Floor system removed

Column Damage

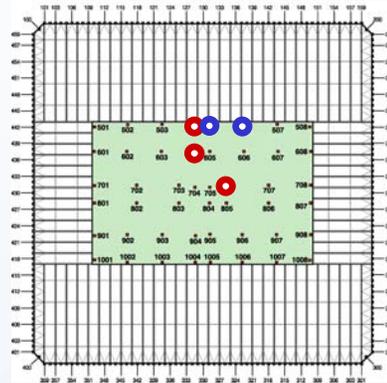
- Severed ○
- Heavy Damage ○
- Moderate Damage ○
- Light Damage ○



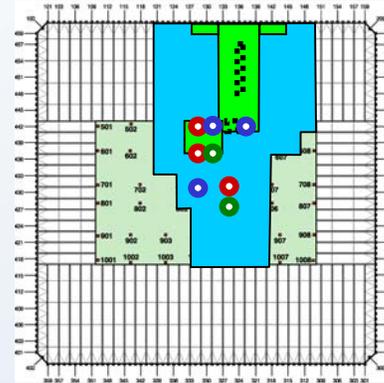
WTC 1 Base Case Damage



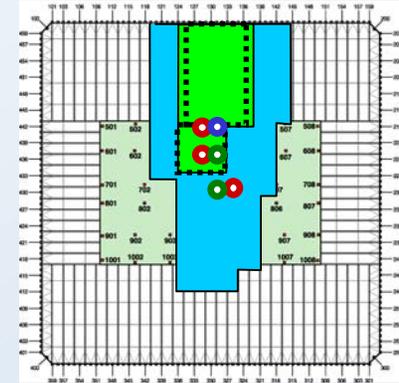
Floors 93 to 98
Cumulative Damage



Floor 93



Floor 94



Floor 95

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

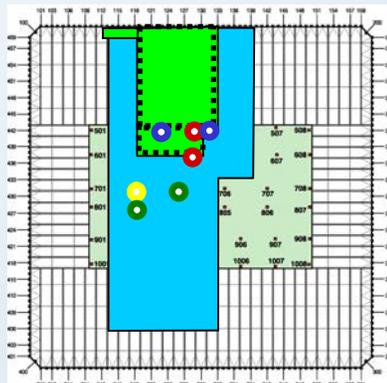
Column Damage

Severed 

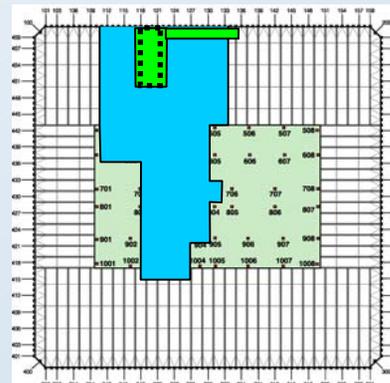
Heavy Damage 

Moderate Damage 

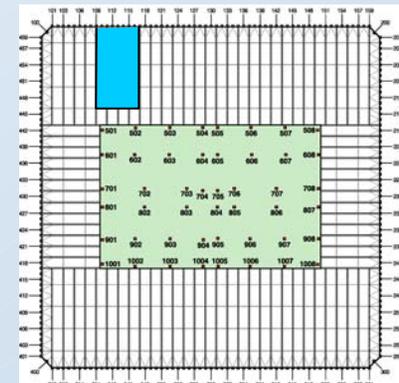
Light Damage 



Floor 96



Floor 97



Floor 98

WTC 1 Floor 93 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

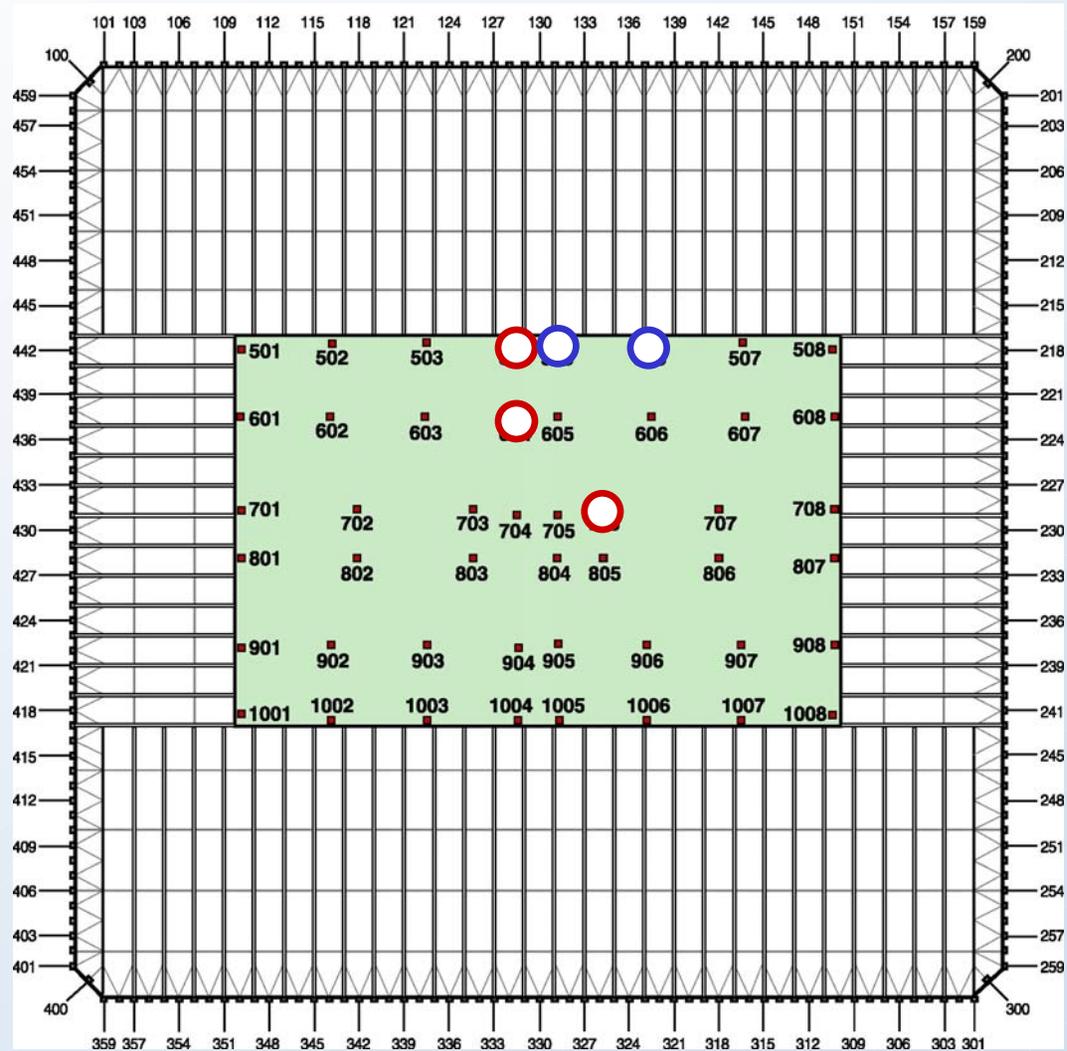
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 94 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

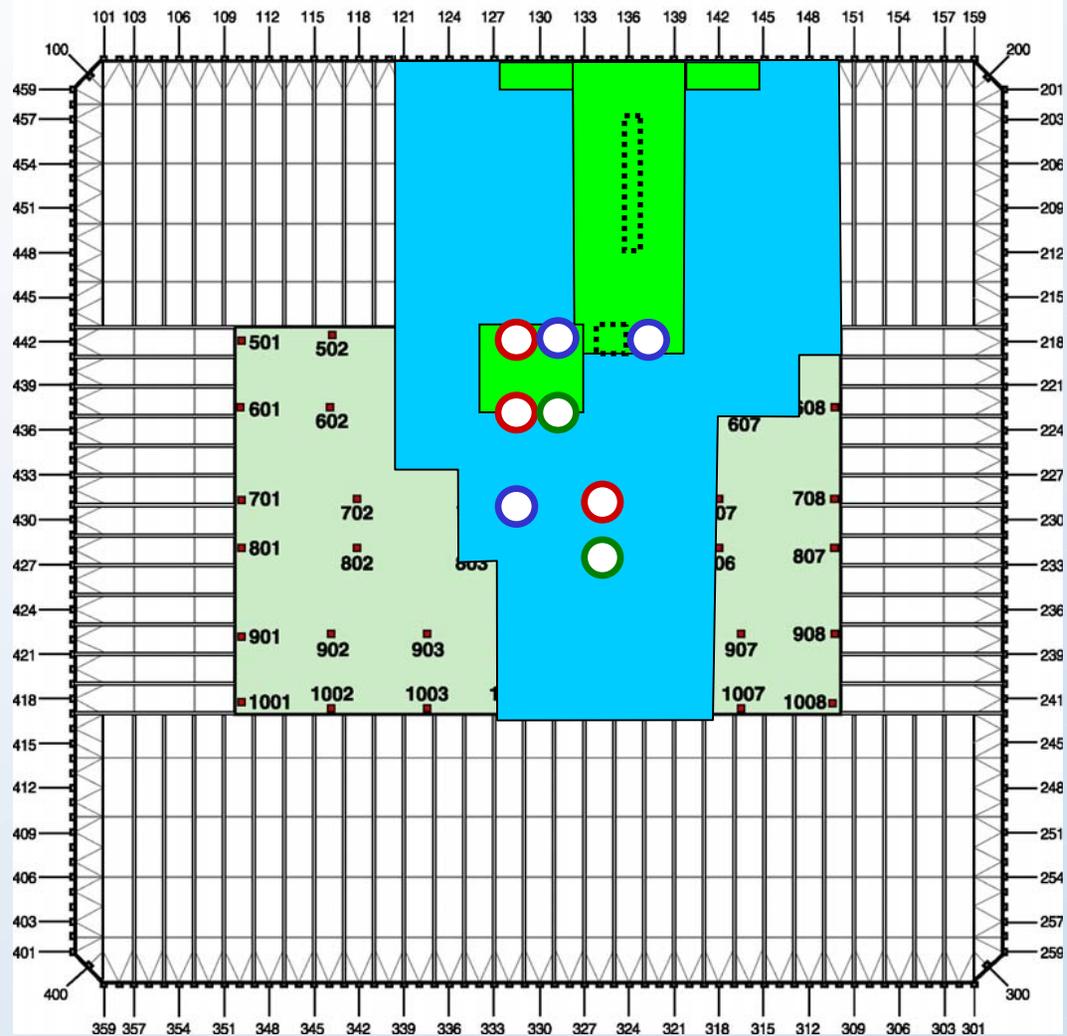
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 95 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

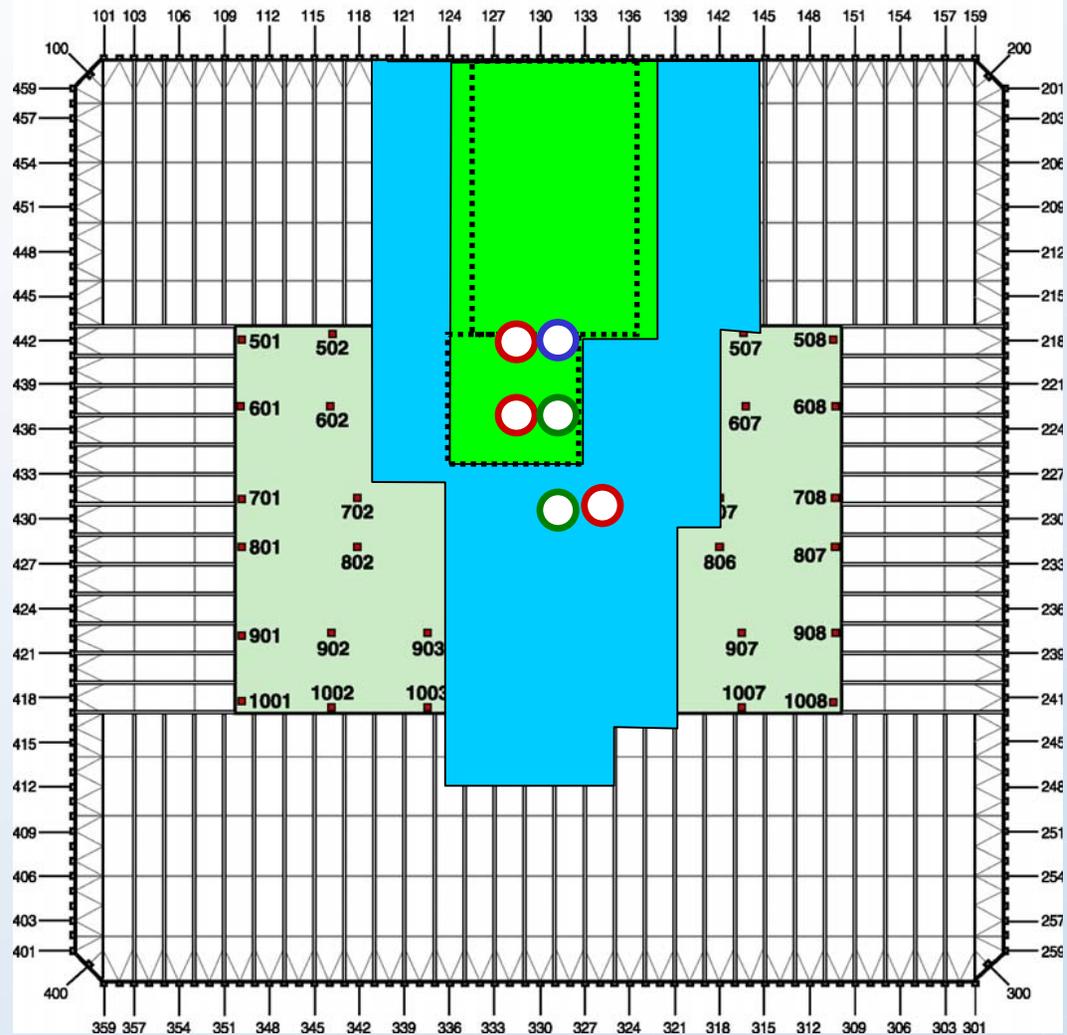
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 96 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

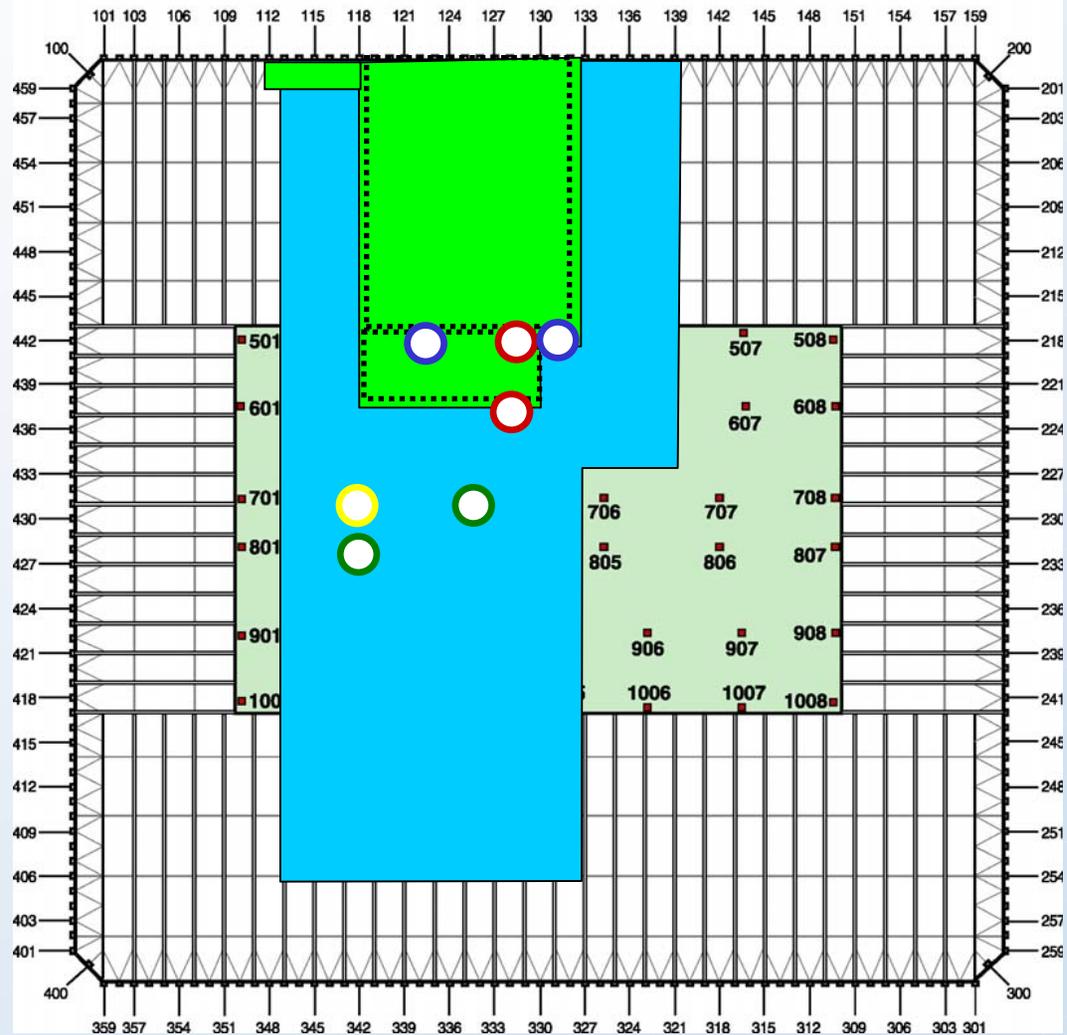
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 97 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions ■

Floor system structural damage ■

Floor system removed

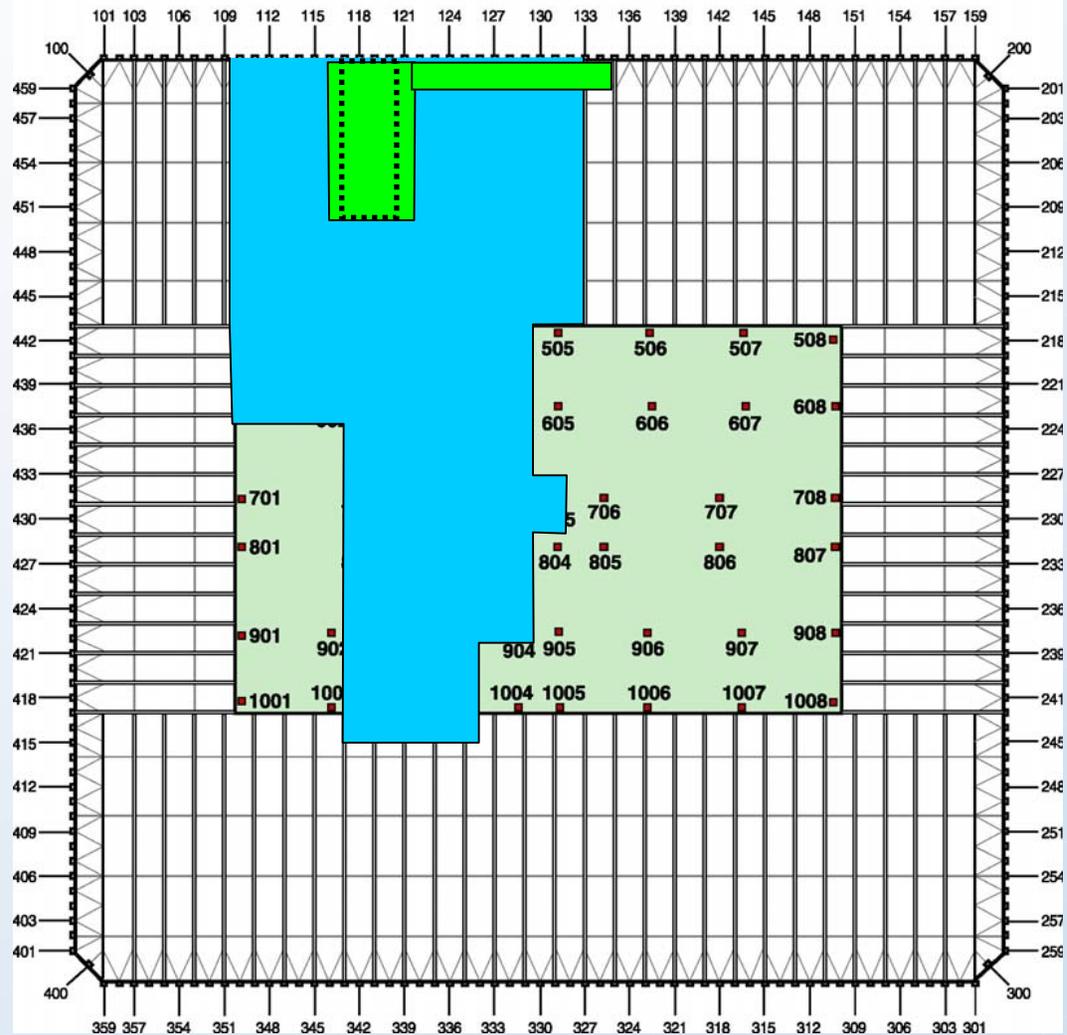
Column Damage

Severed ○

Heavy Damage ○

Moderate Damage ○

Light Damage ○



WTC 1 Floor 98 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

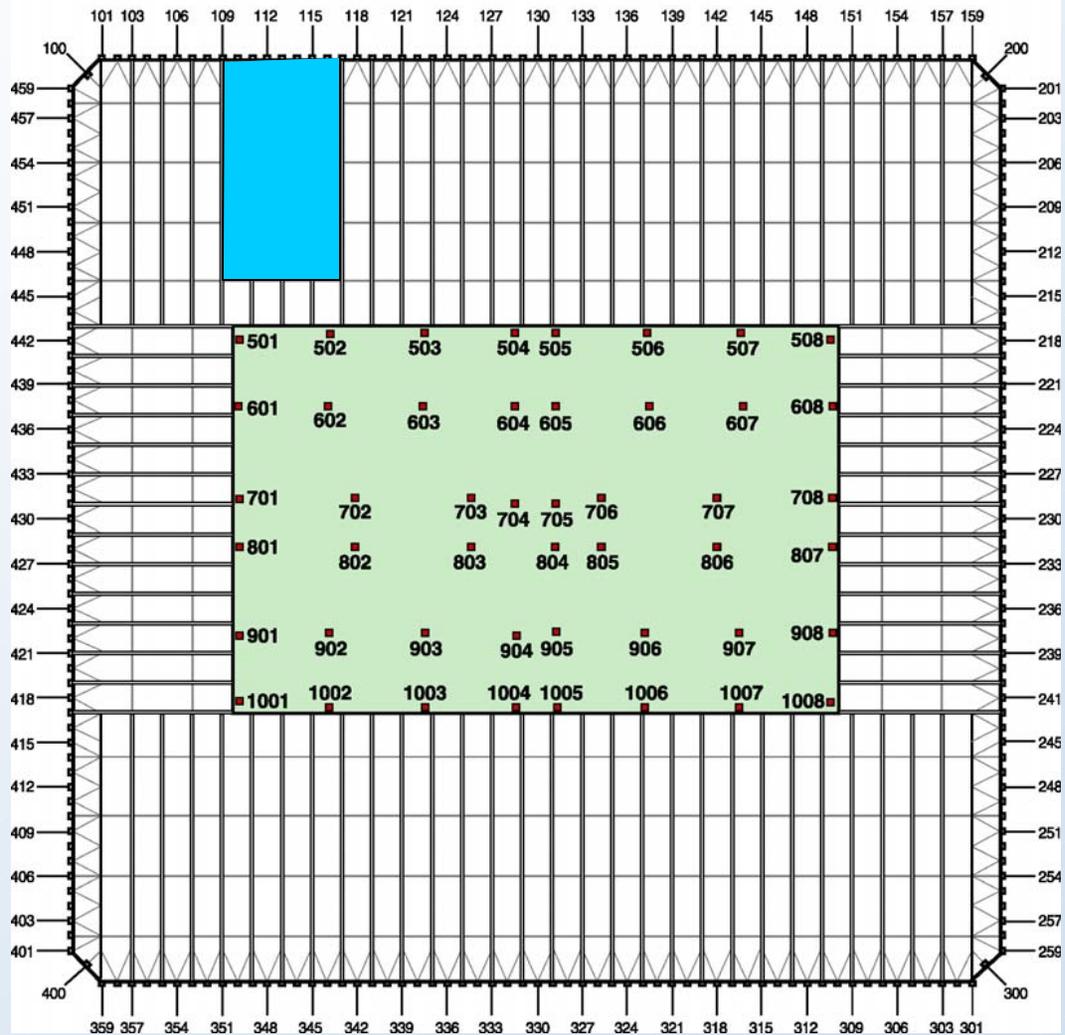
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 93 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

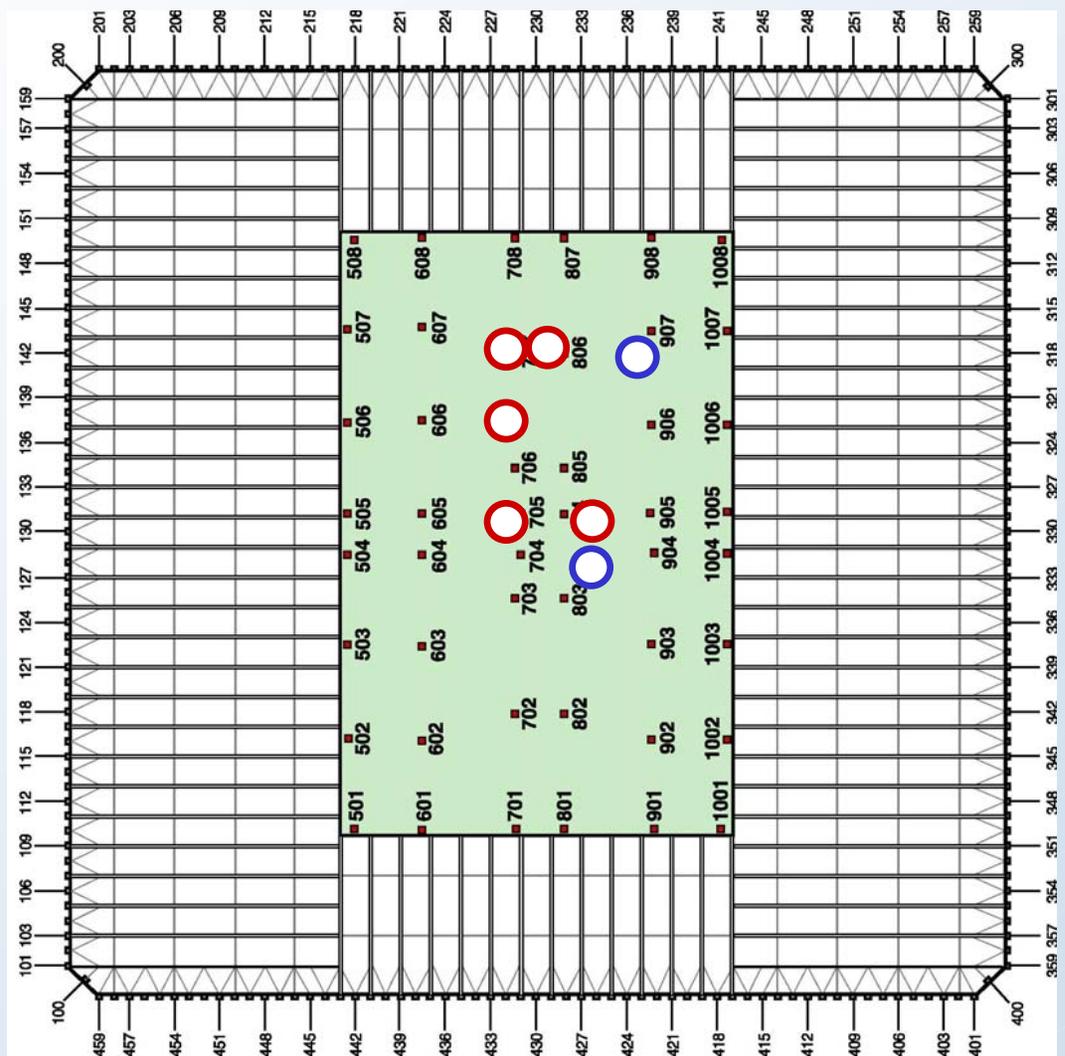
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 94 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

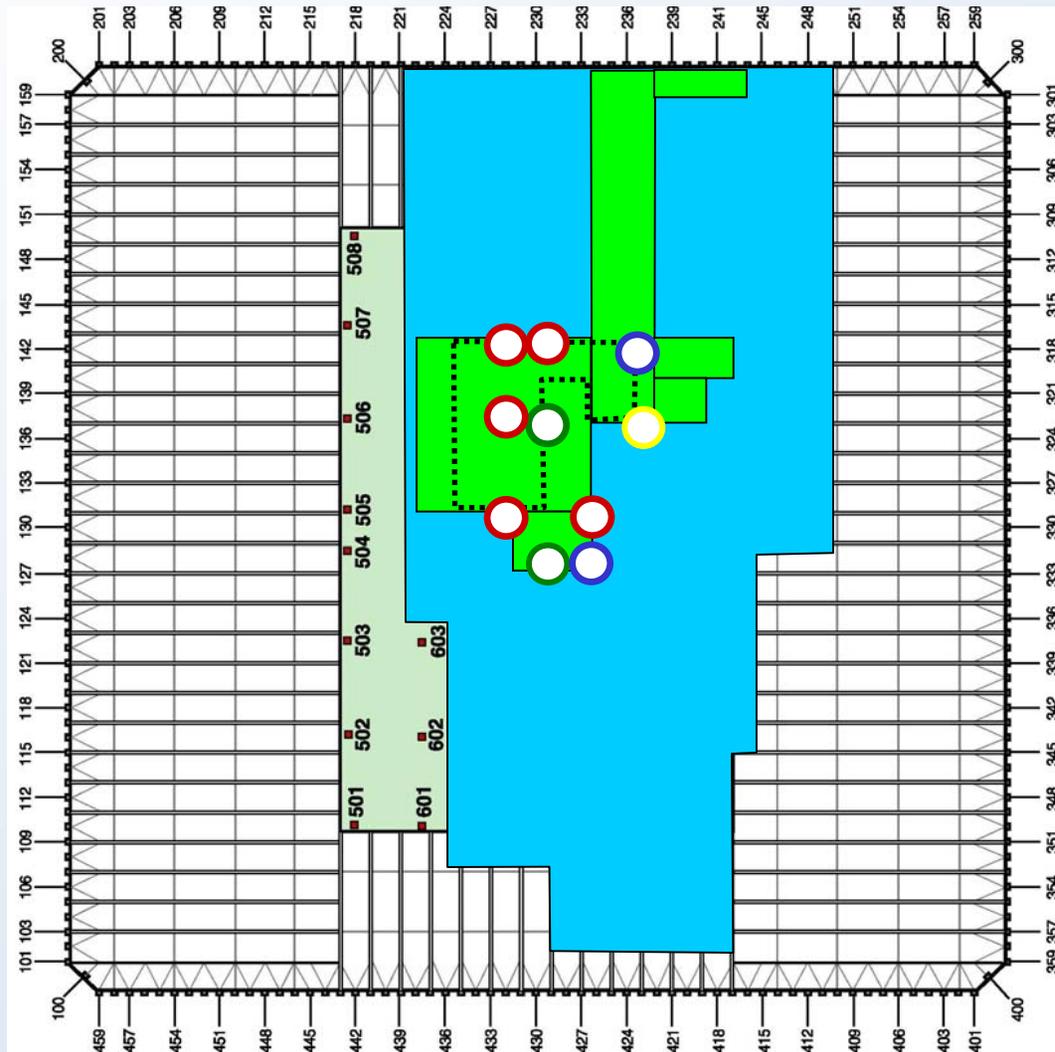
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 95 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

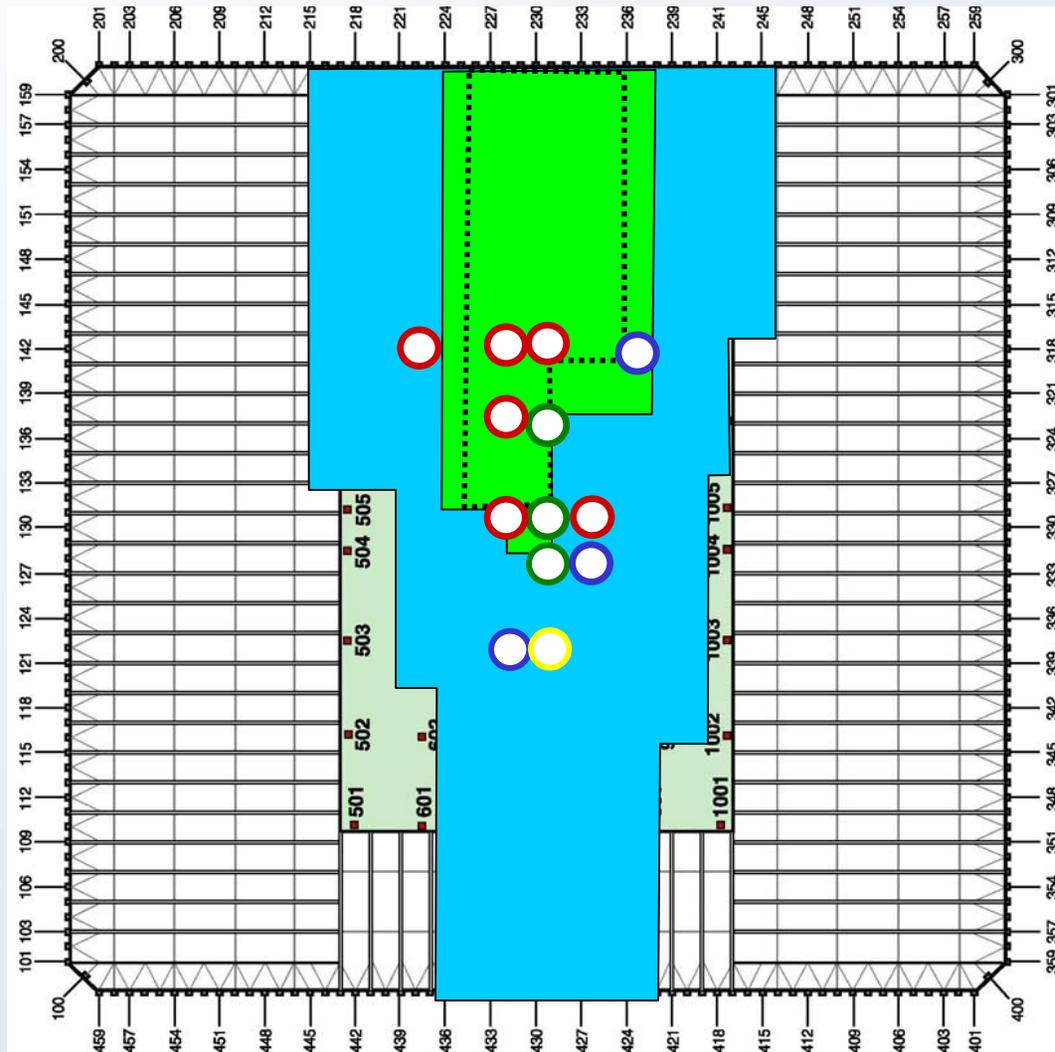
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



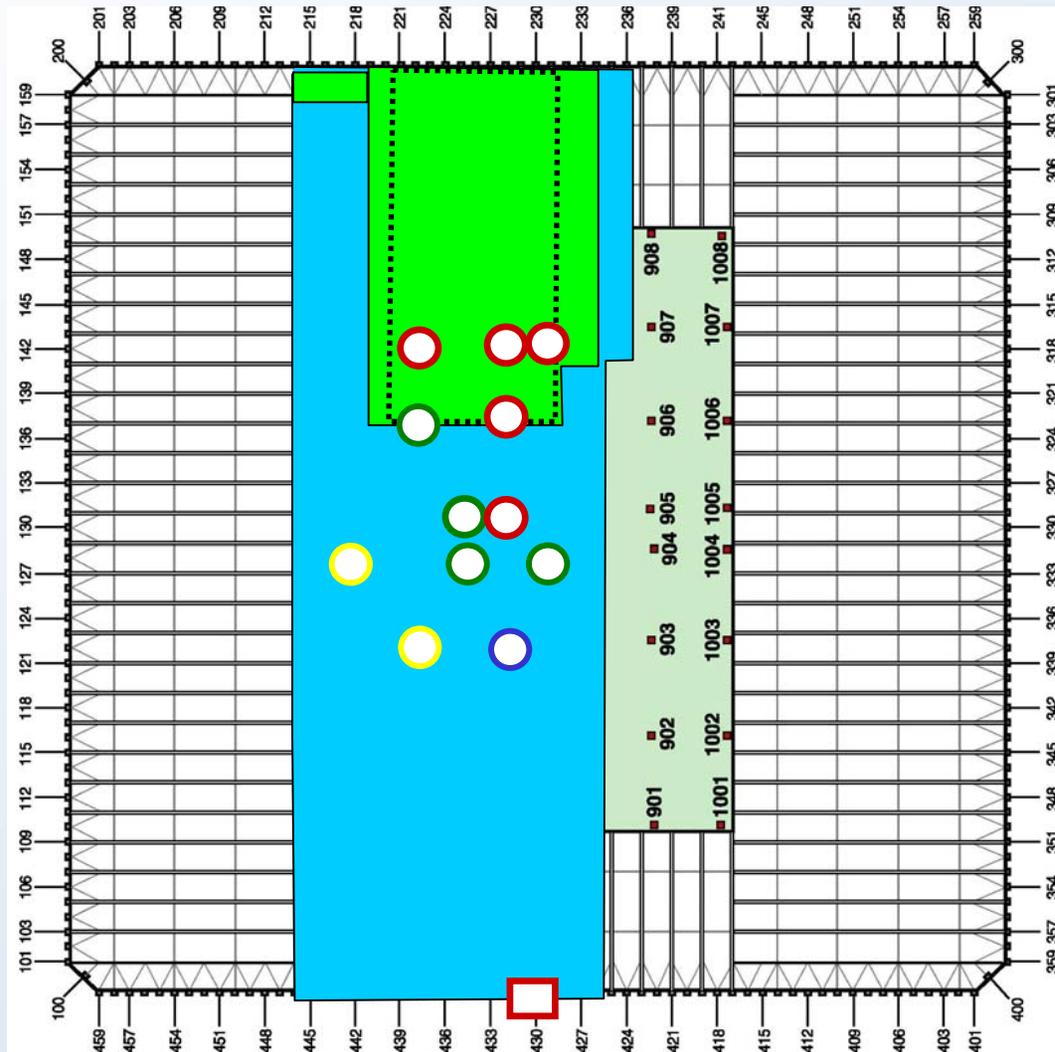
WTC 1 Floor 96 Damage for Severe Case

Severe Floor Damage

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

Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



WTC 1 Floor 97 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

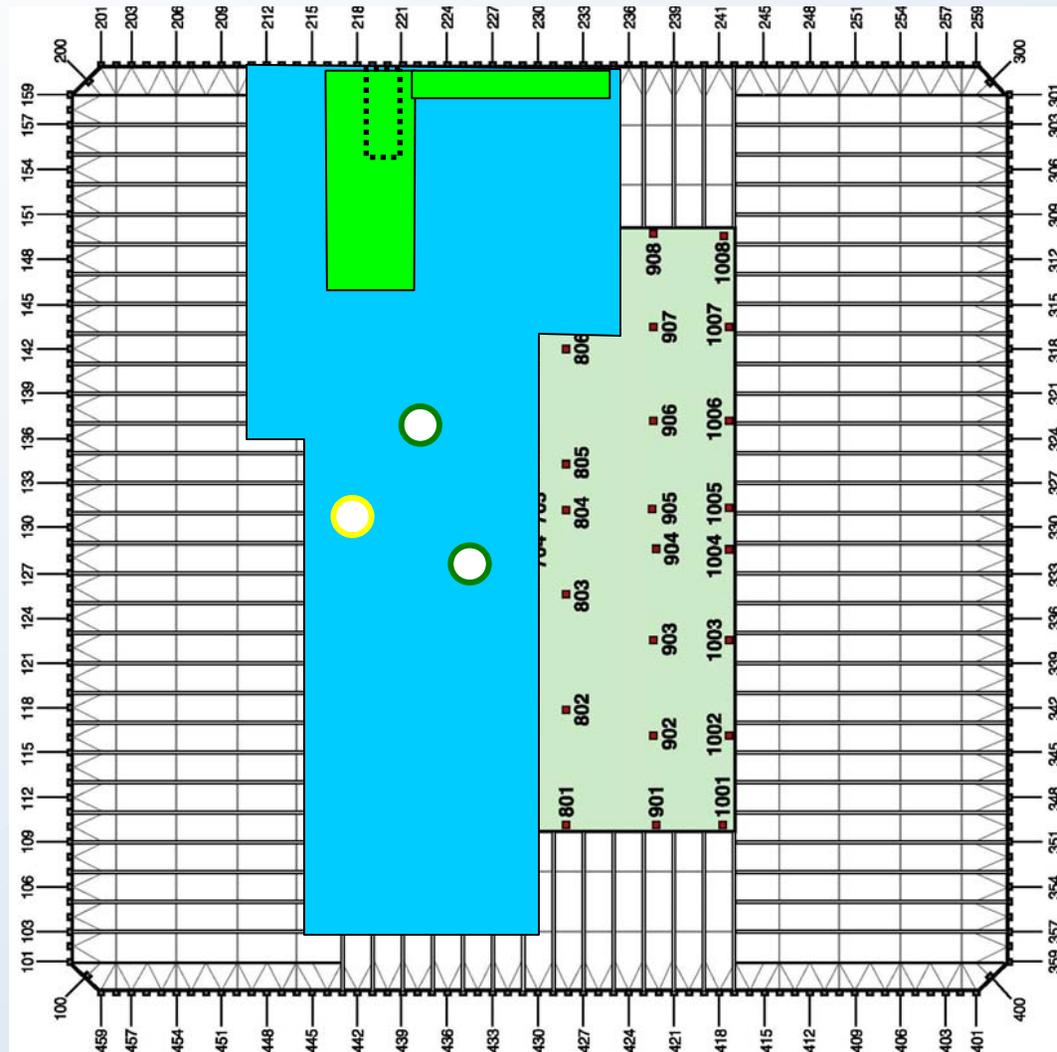
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 1 Floor 98 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

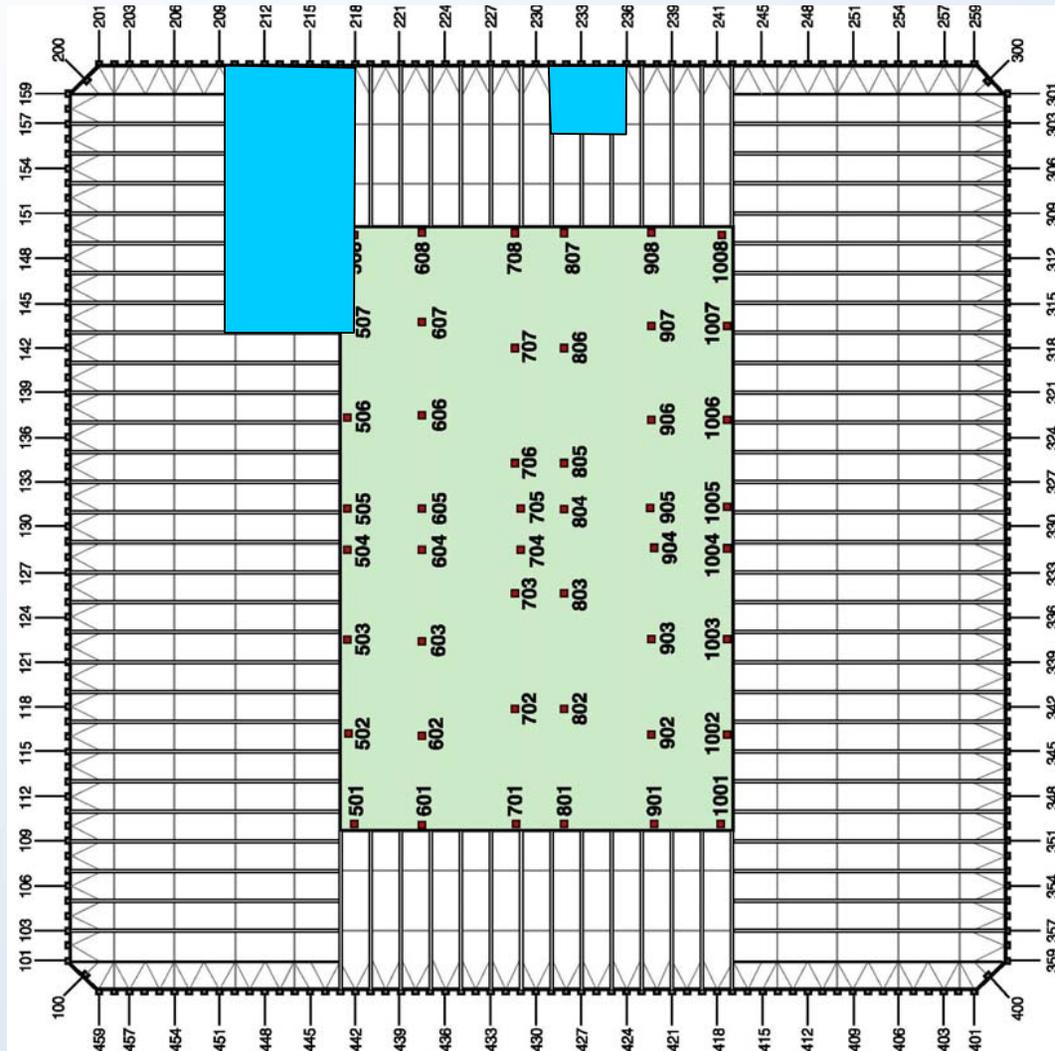
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Damage for Base Case Composite Summary for Floors 78 to 83

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

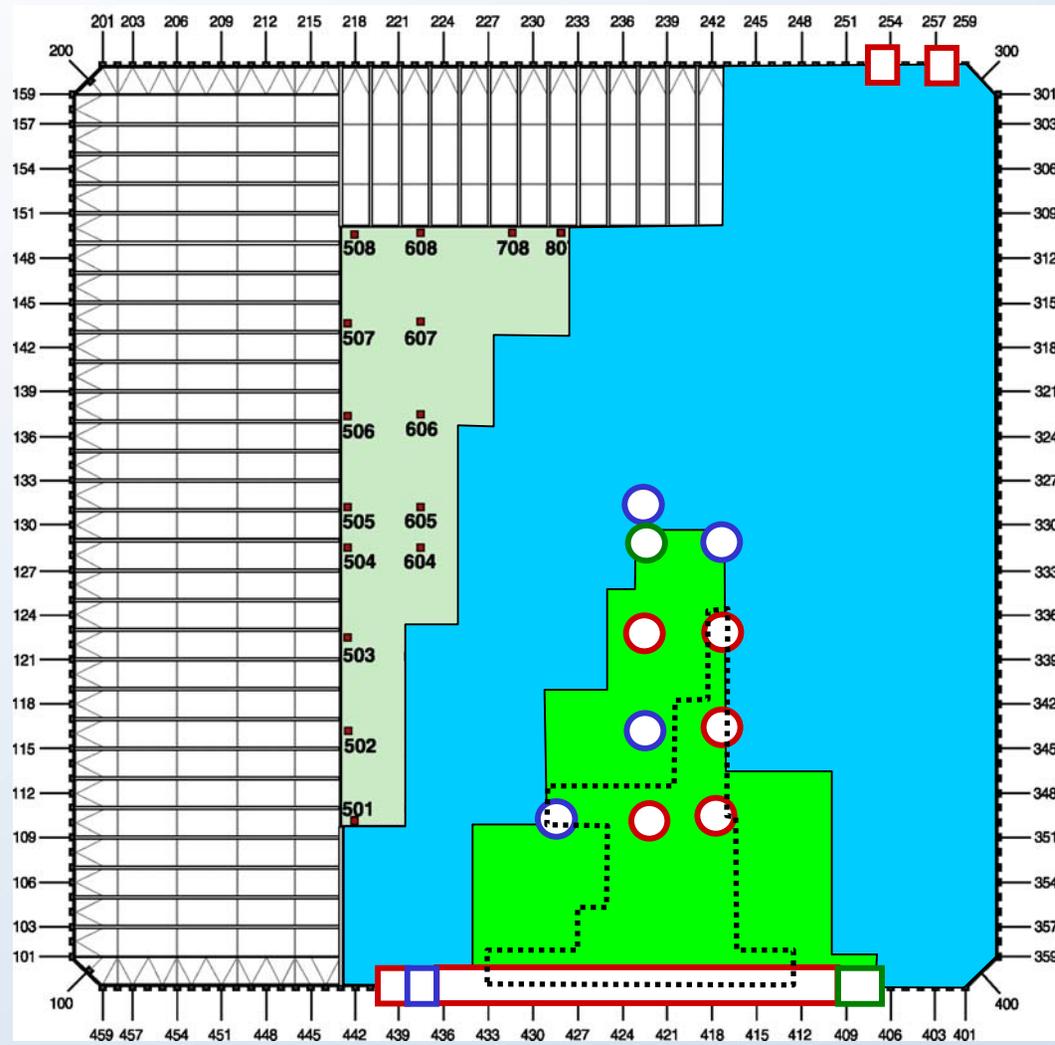
Column Damage

Severed 

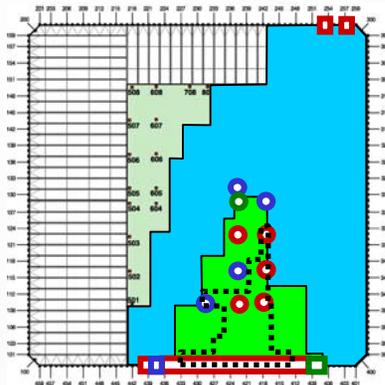
Heavy Damage 

Moderate Damage 

Light Damage 

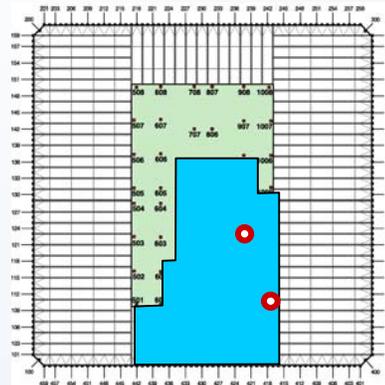


WTC 2 Base Case Damage

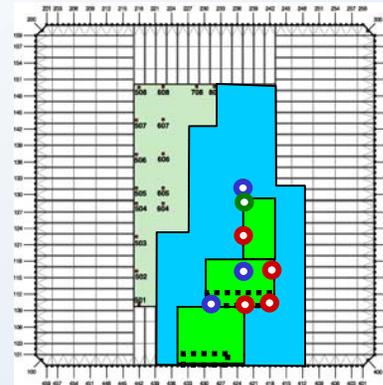


Floors 78-83

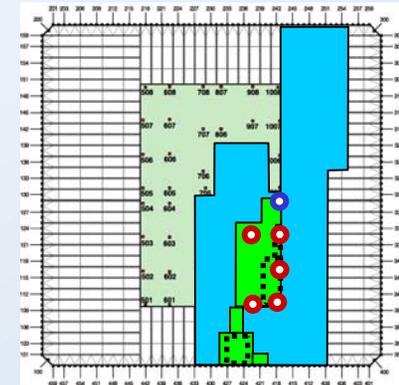
Cumulative Damage



Floor 78



Floor 79



Floor 80

Severe Floor Damage

Fireproofing and partitions ■

Floor system structural damage ■

Floor system removed

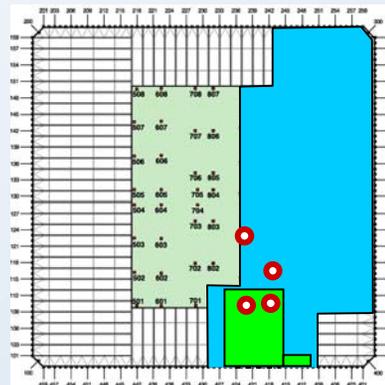
Column Damage

Severed ○

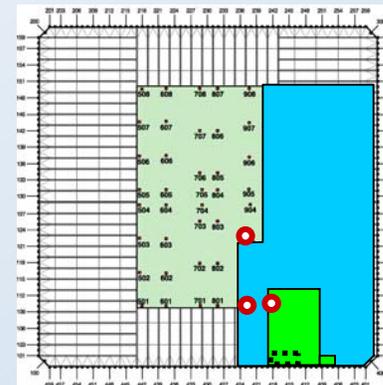
Heavy Damage ○

Moderate Damage ○

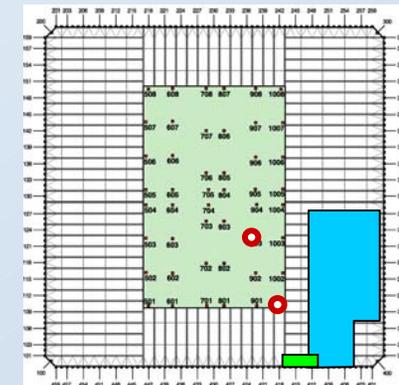
Light Damage ○



Floor 81



Floor 82



Floor 83

WTC 2 Floor 77 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

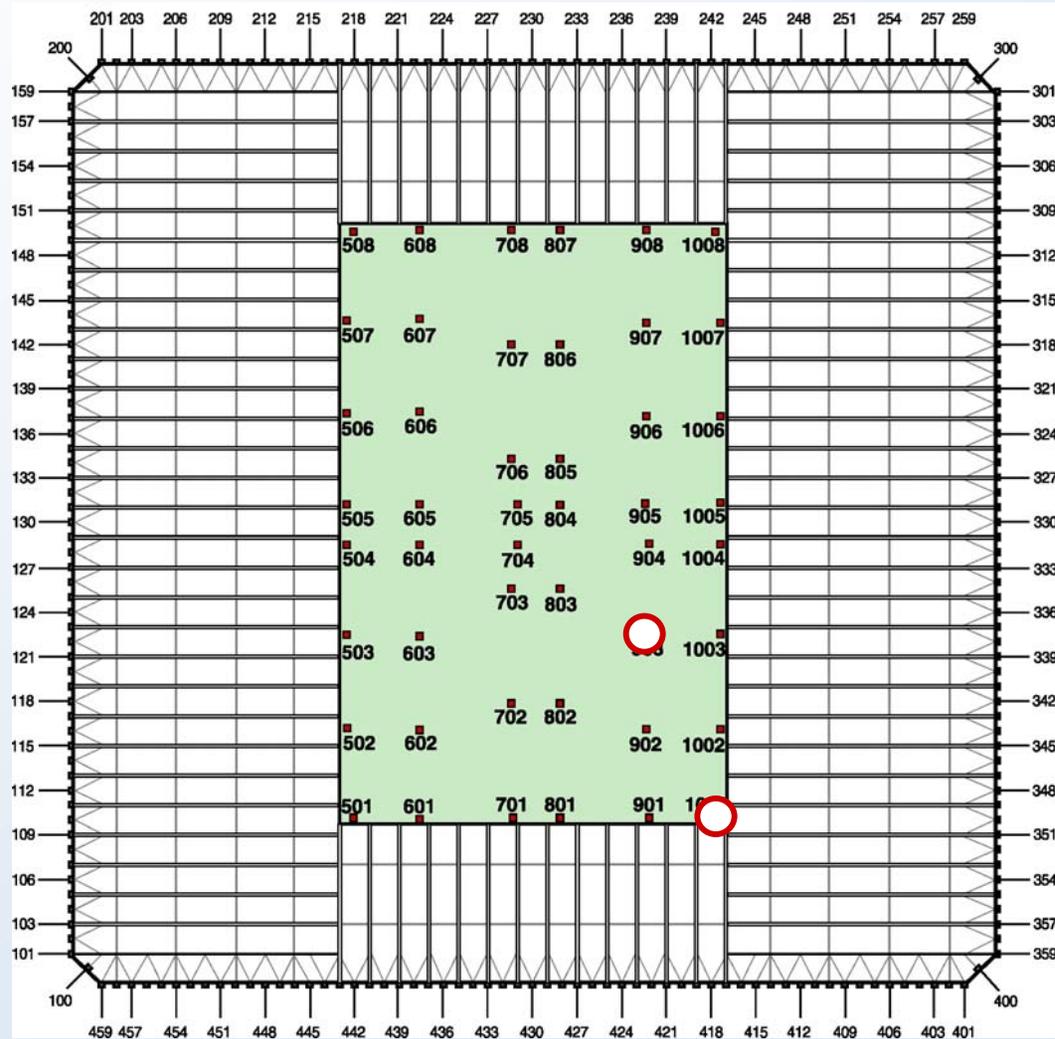
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 78 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

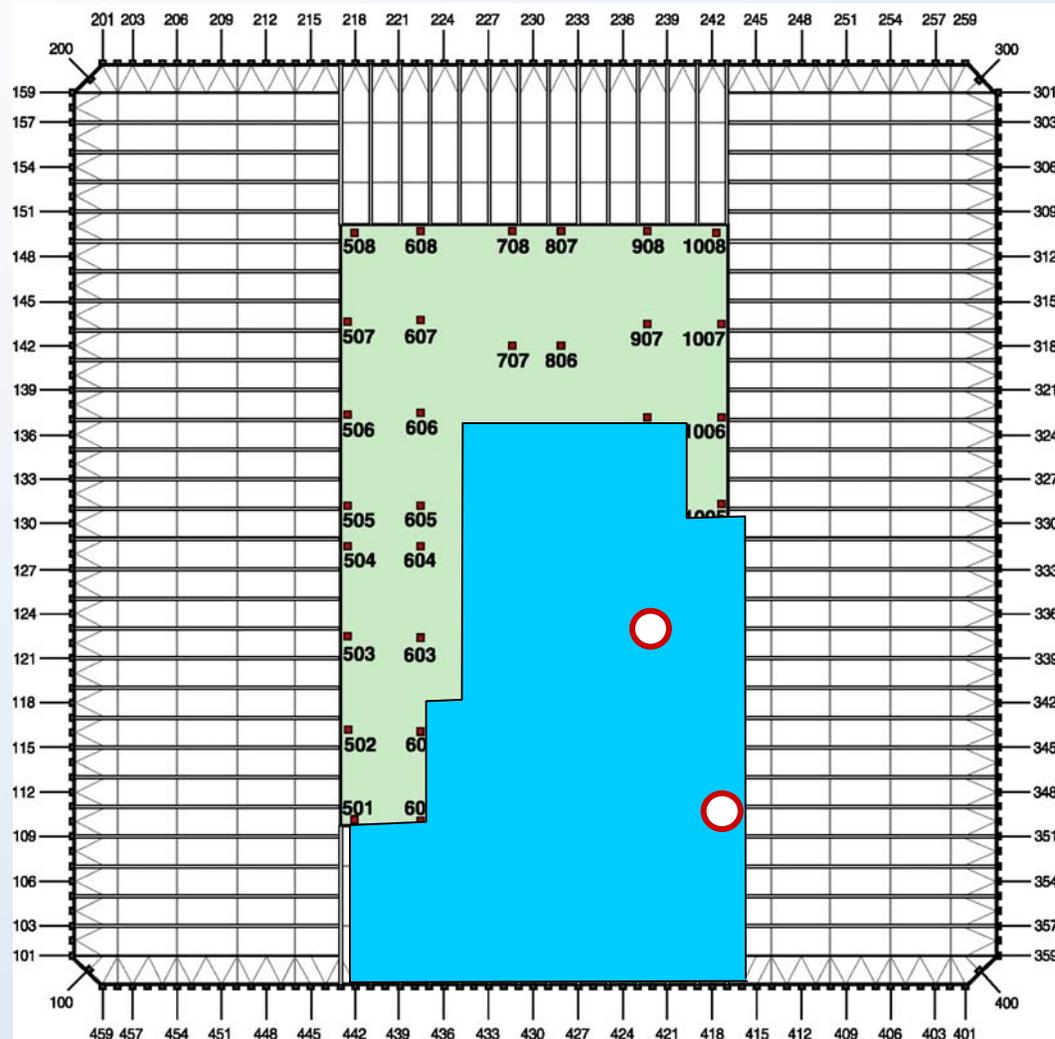
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



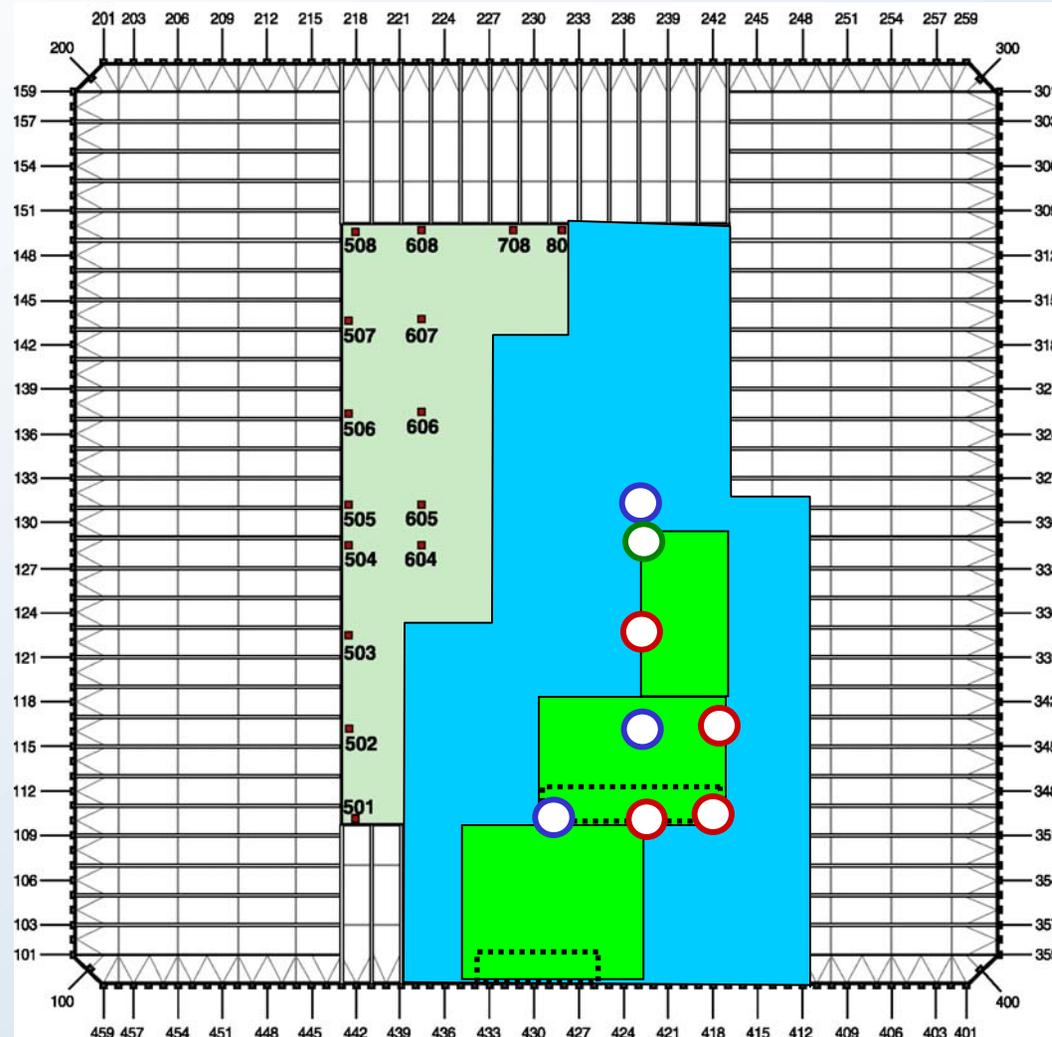
WTC 2 Floor 79 Damage for Base Case

Severe Floor Damage

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

Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



WTC 2 Floor 80 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

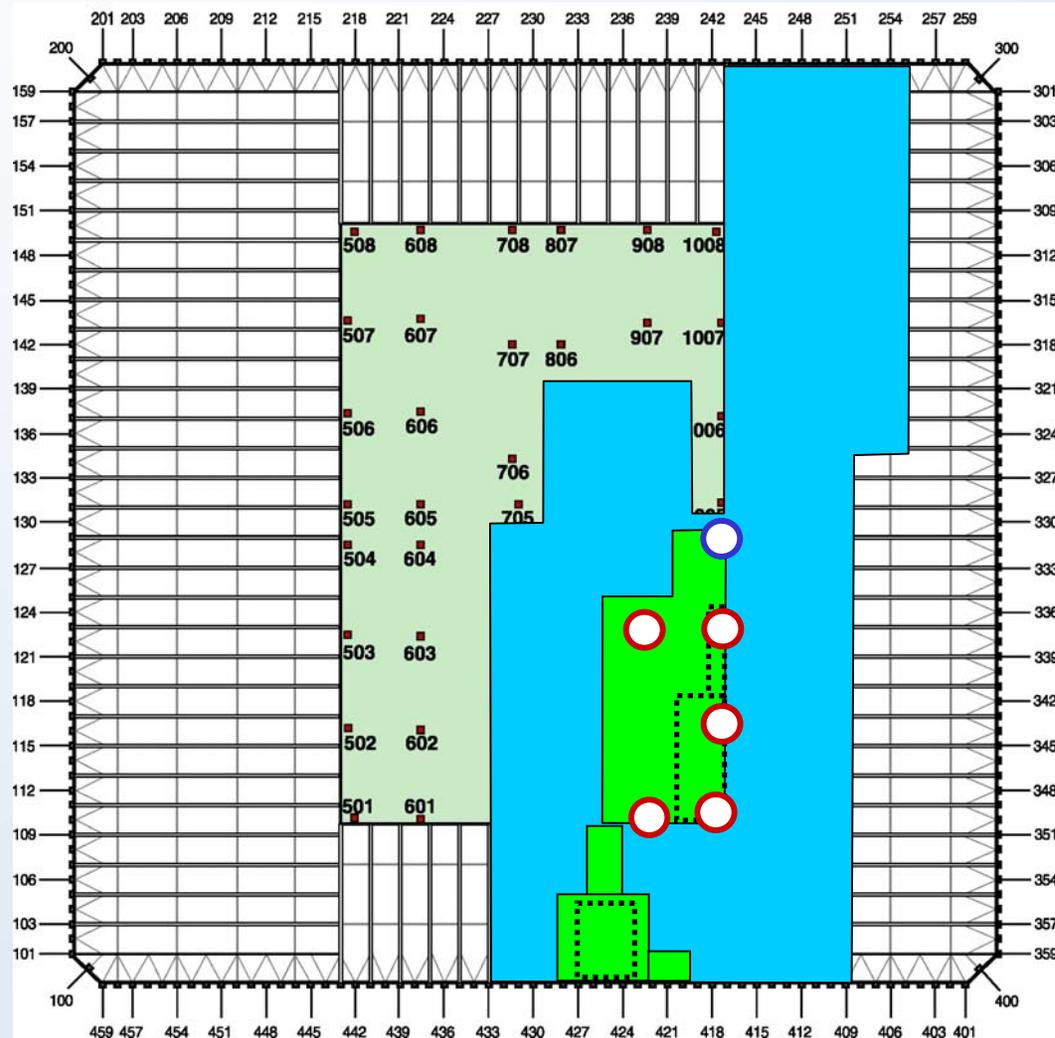
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 81 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

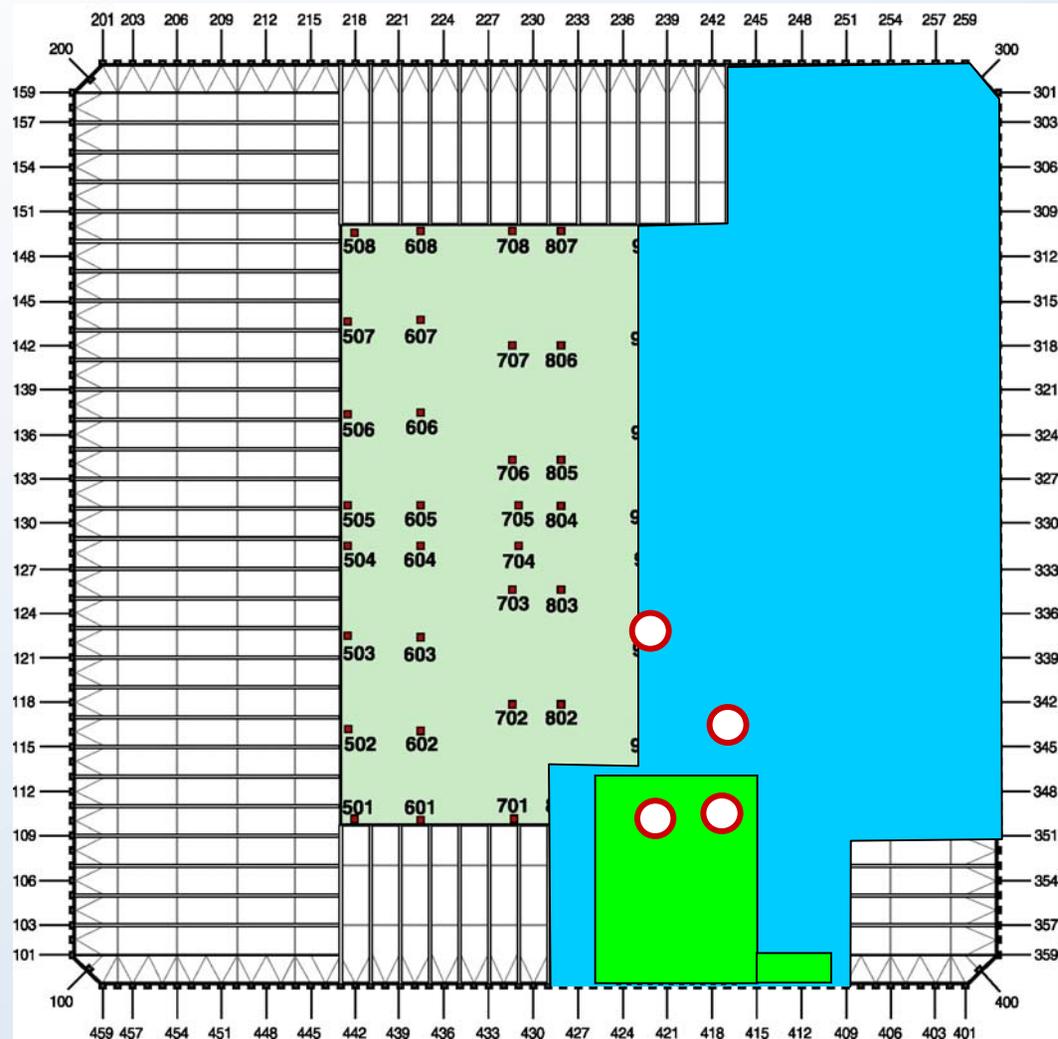
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 82 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

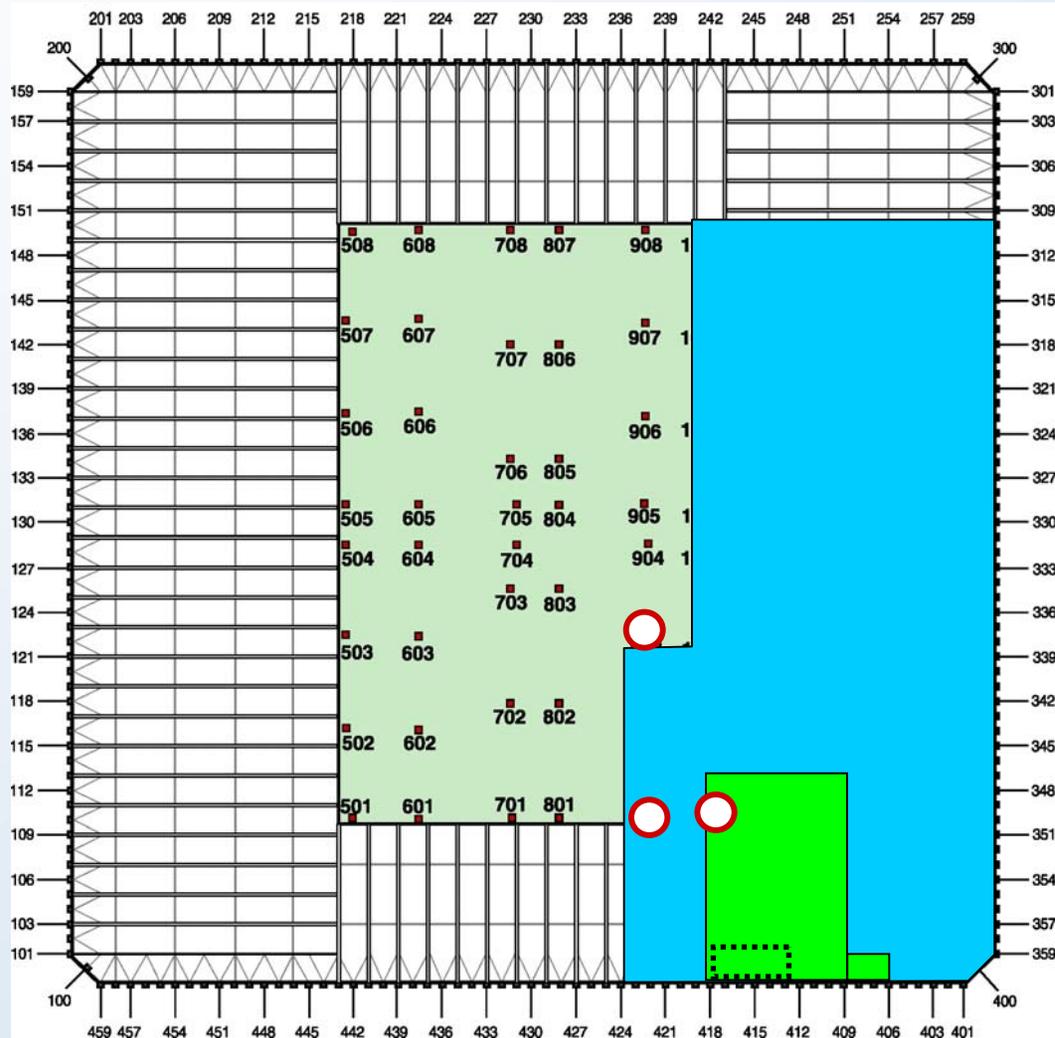
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 83 Damage for Base Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

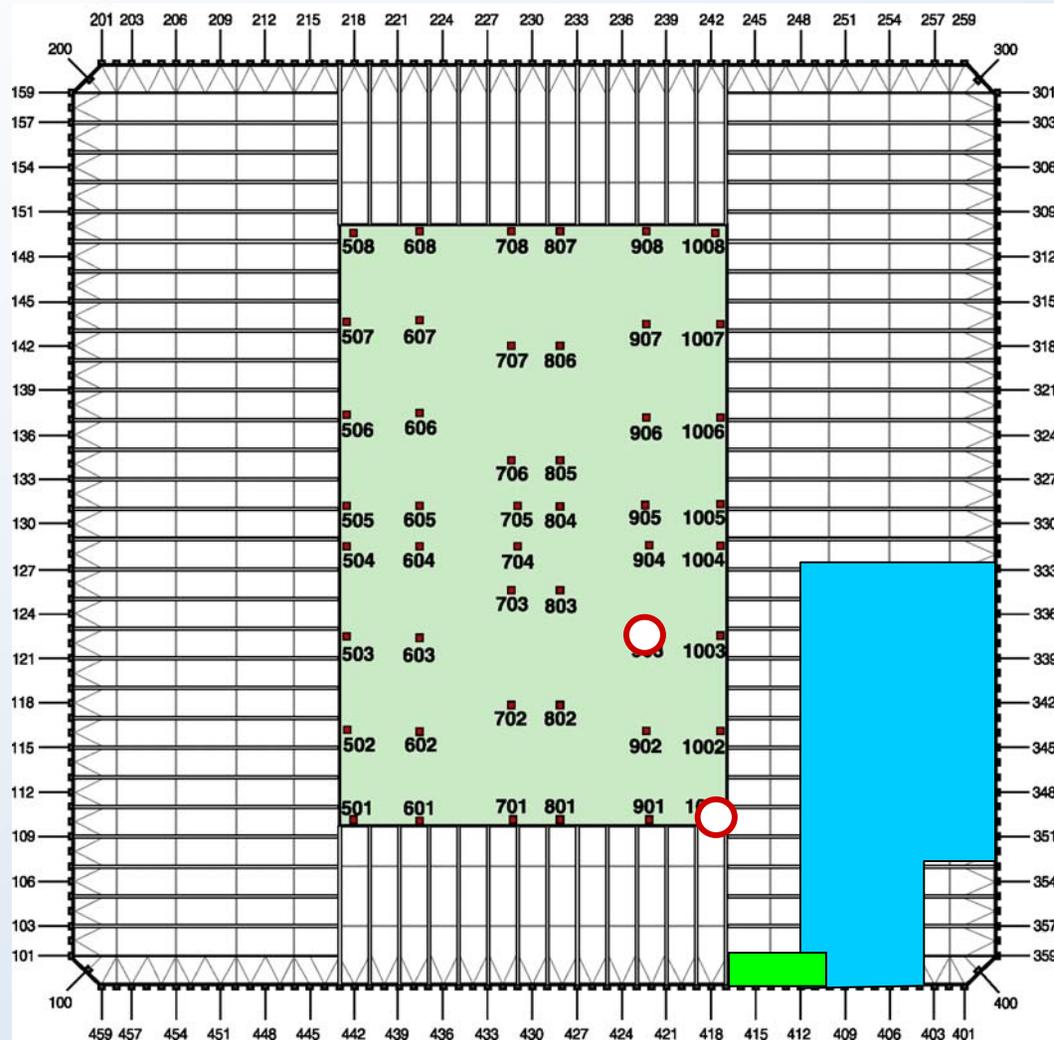
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 77 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

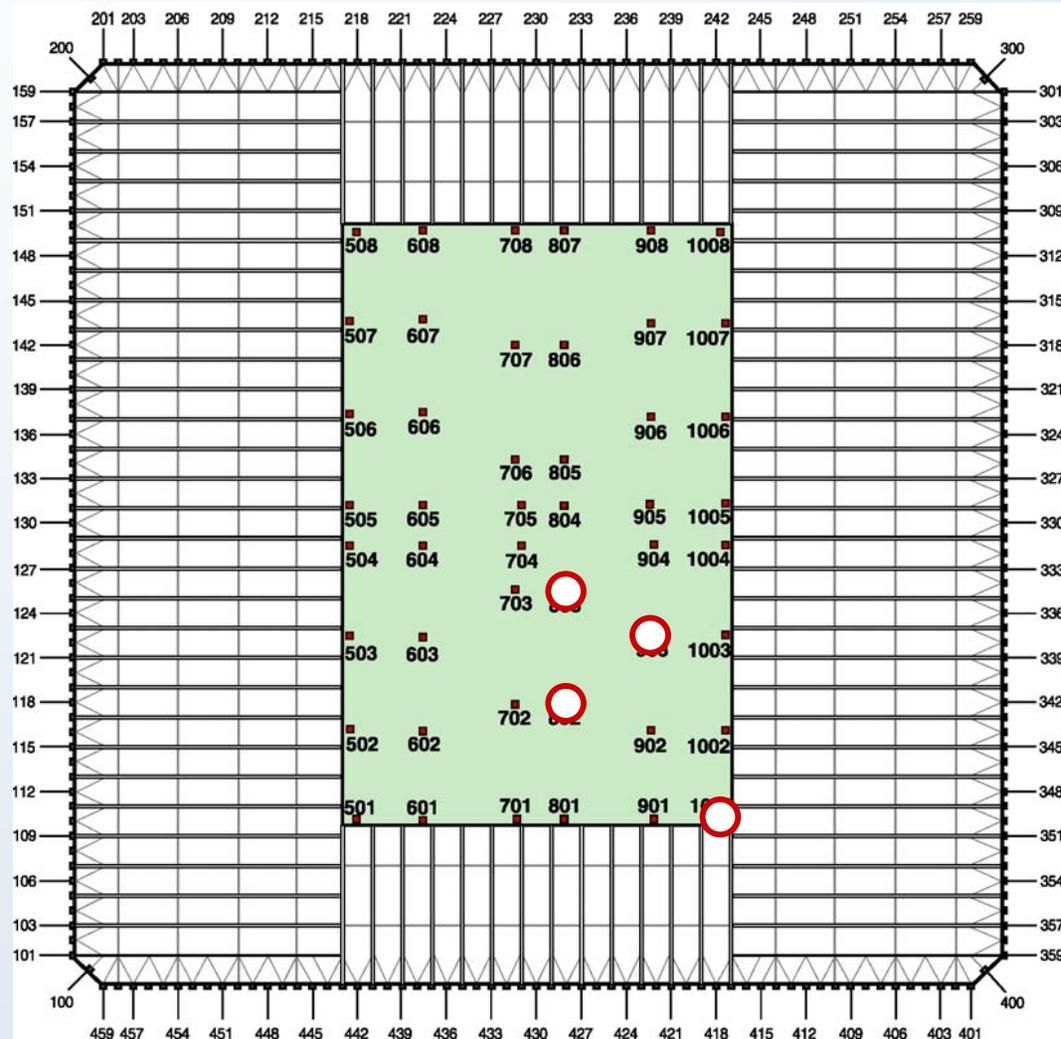
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



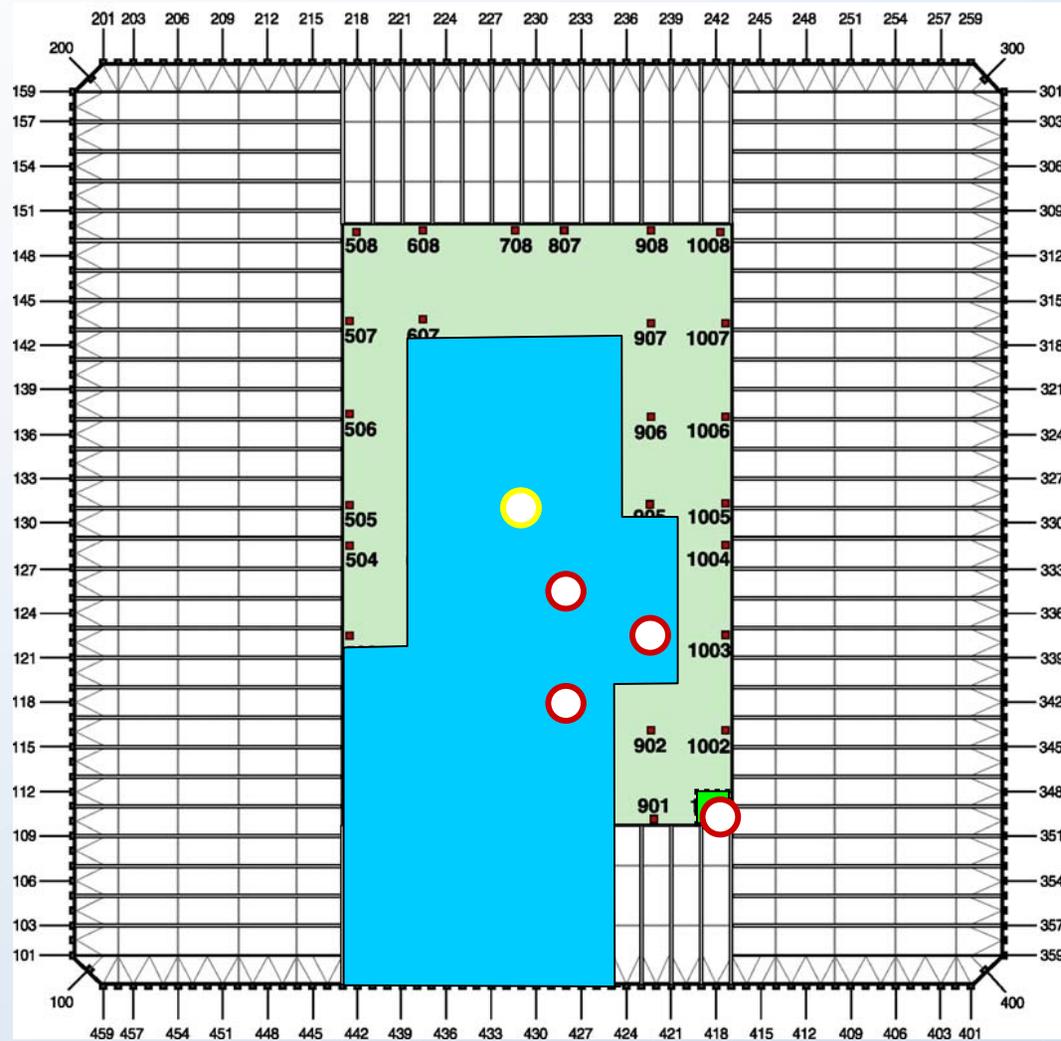
WTC 2 Floor 78 Damage for Severe Case

Severe Floor Damage

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

Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



WTC 2 Floor 79 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

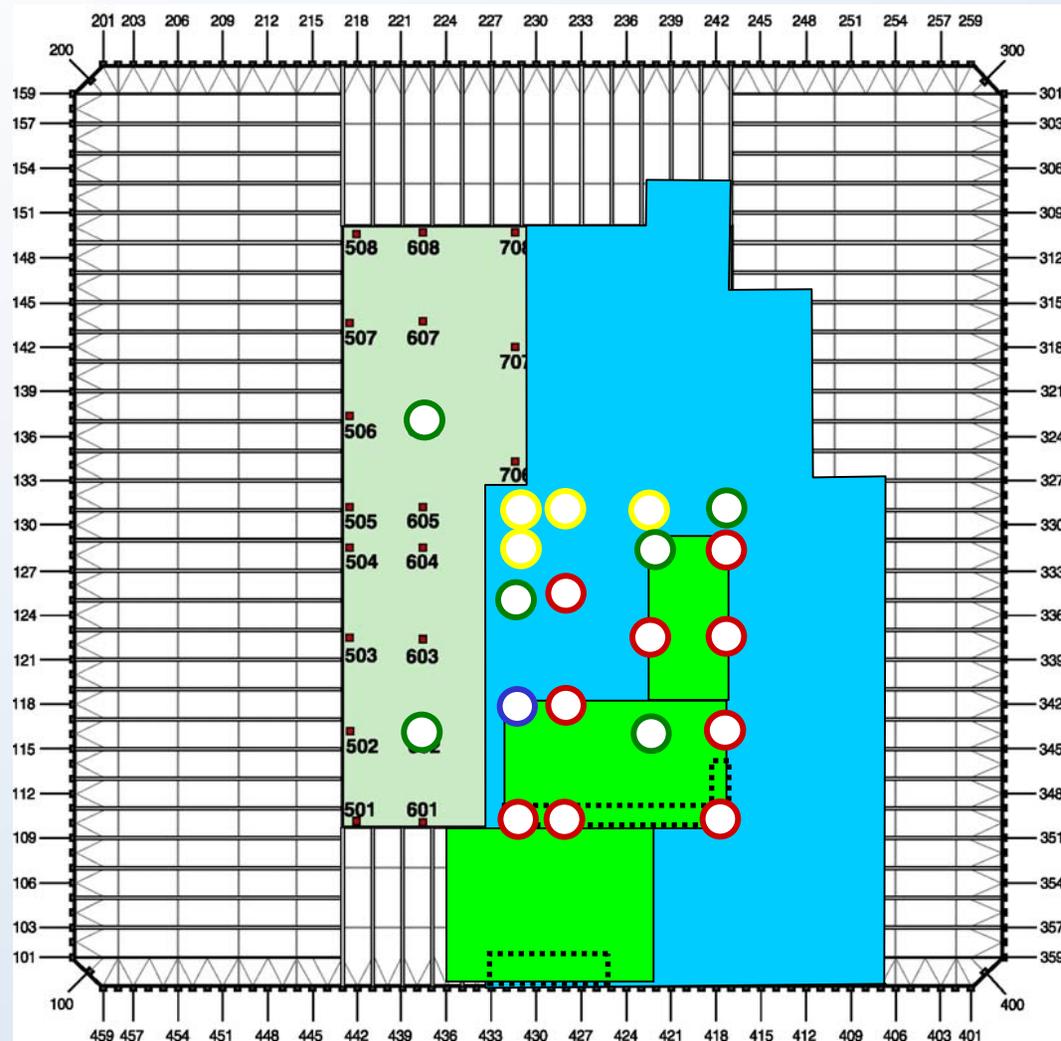
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 80 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

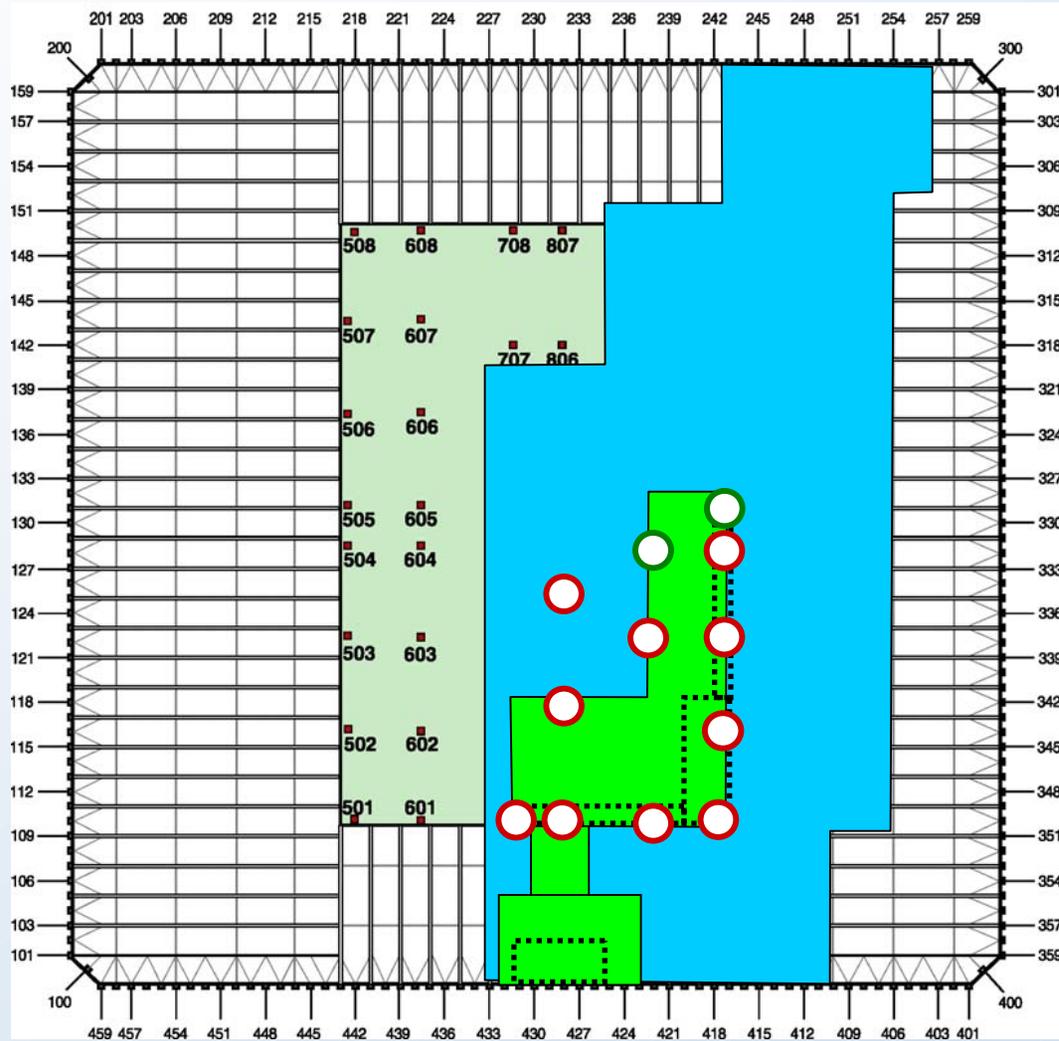
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 81 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

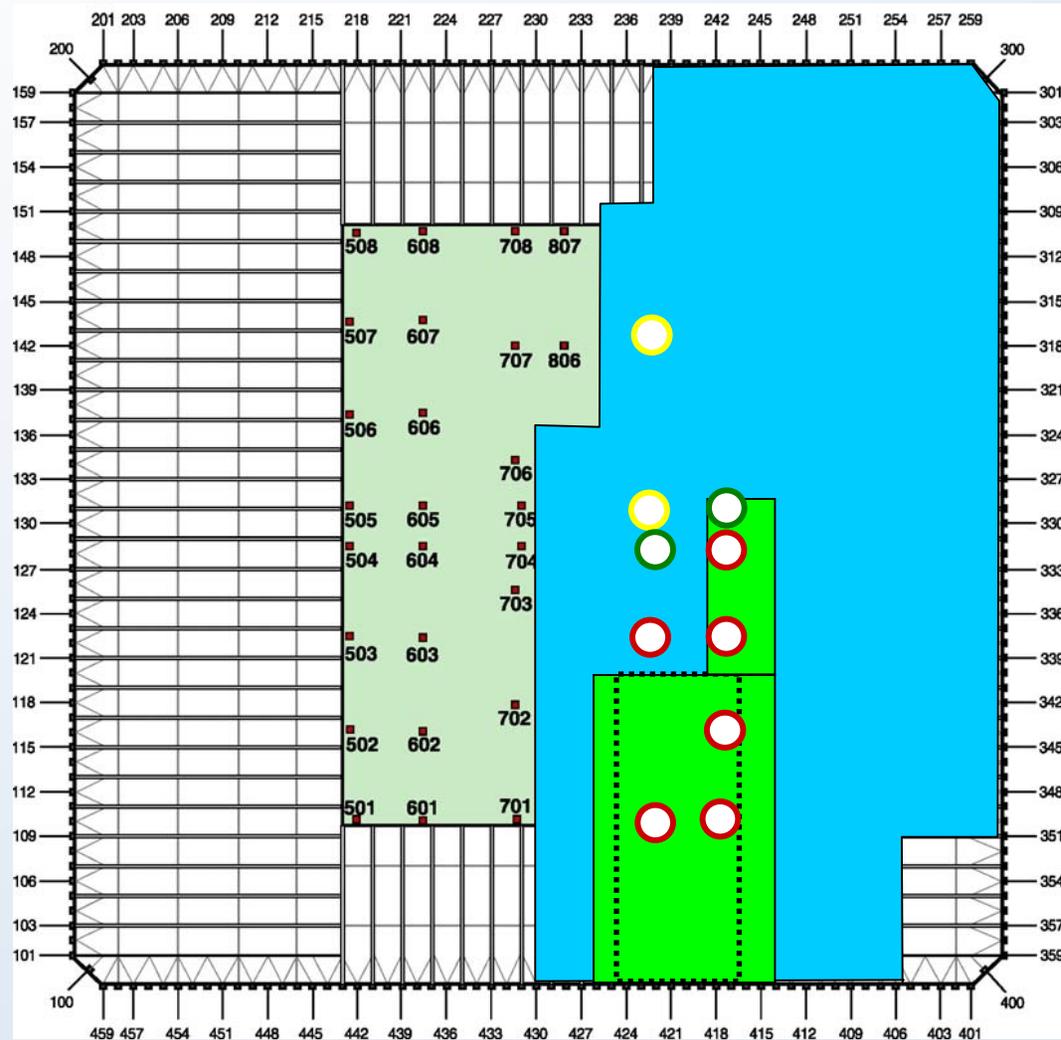
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 82 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

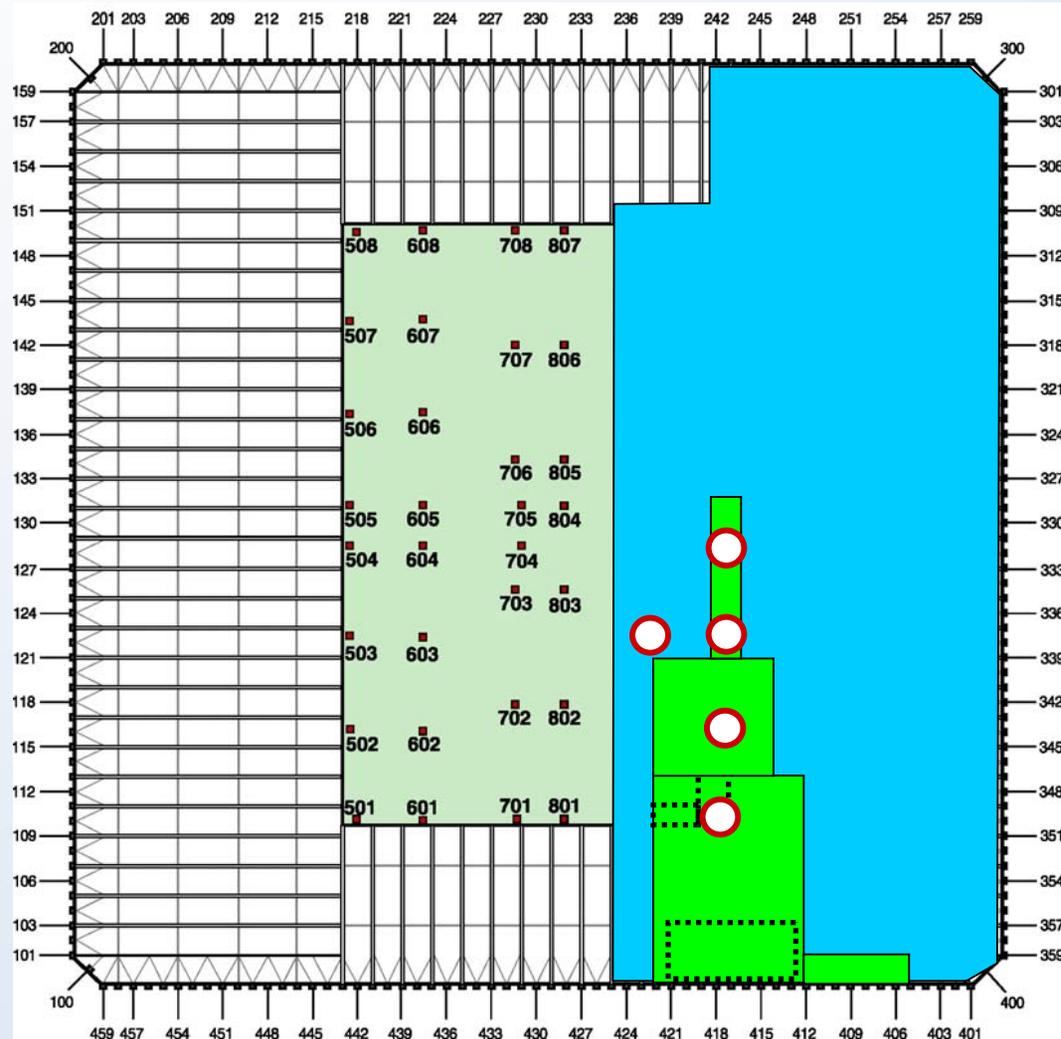
Column Damage

Severed 

Heavy Damage 

Moderate Damage 

Light Damage 



WTC 2 Floor 83 Damage for Severe Case

Severe Floor Damage

Fireproofing and partitions 

Floor system structural damage 

Floor system removed 

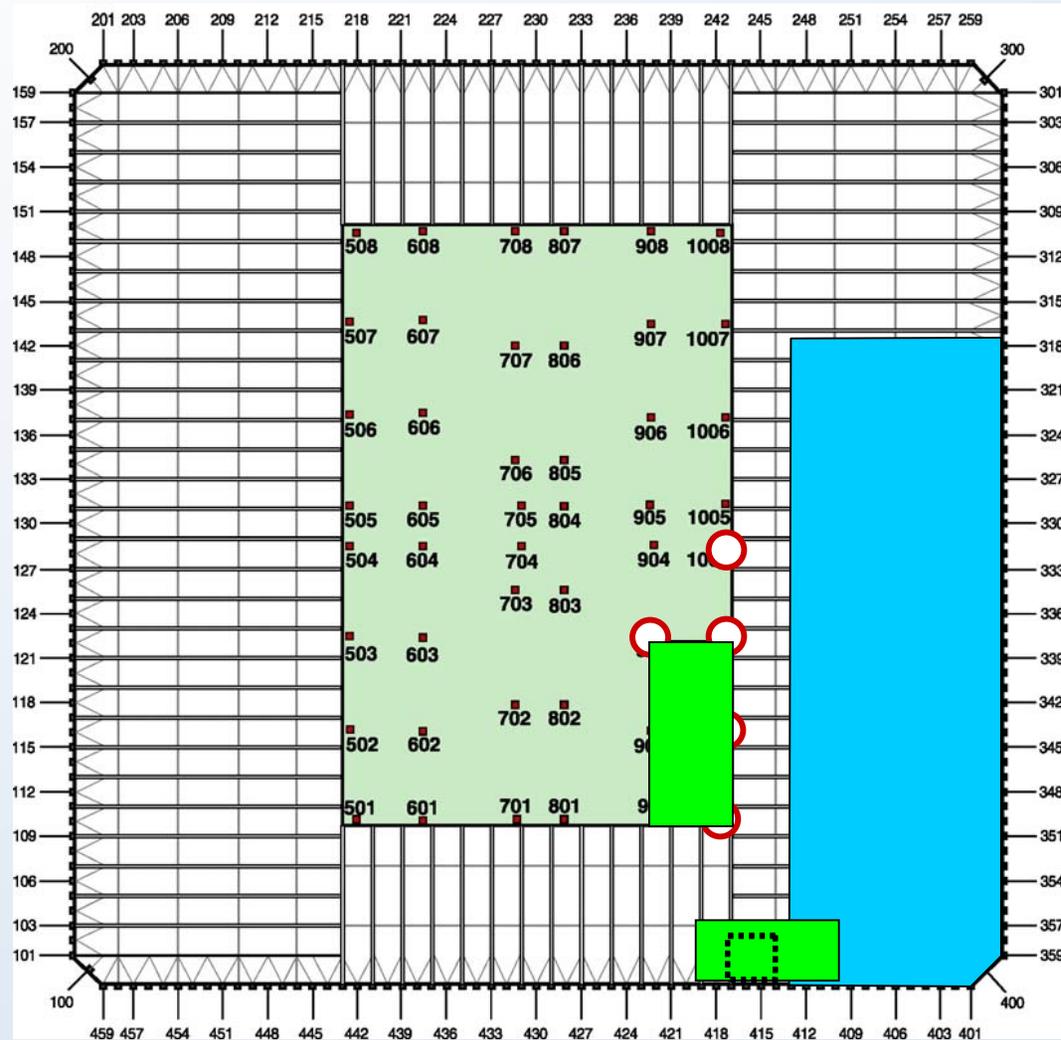
Column Damage

Severed 

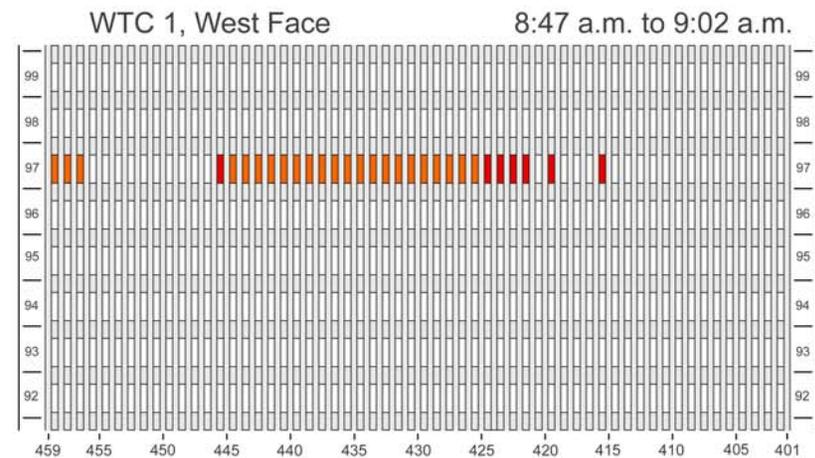
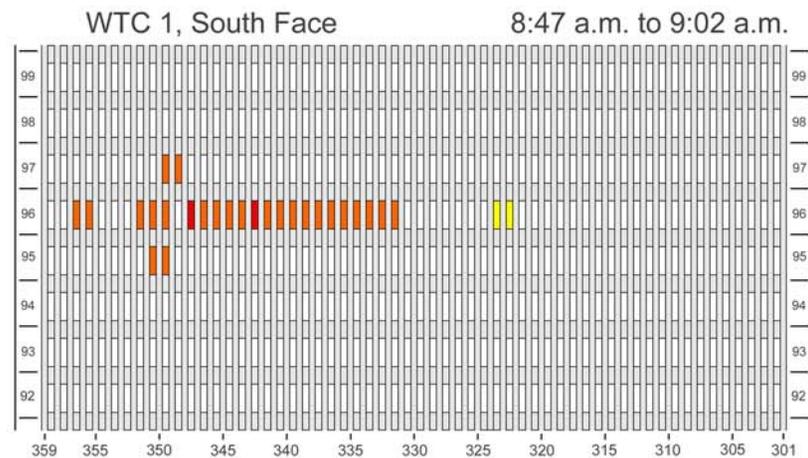
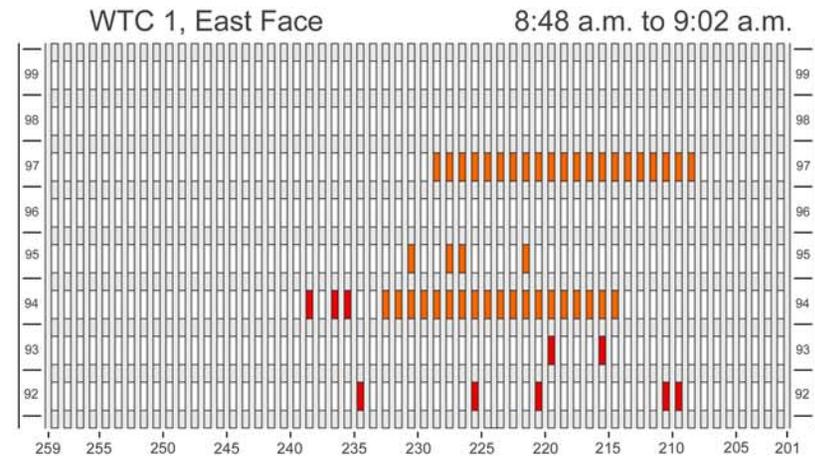
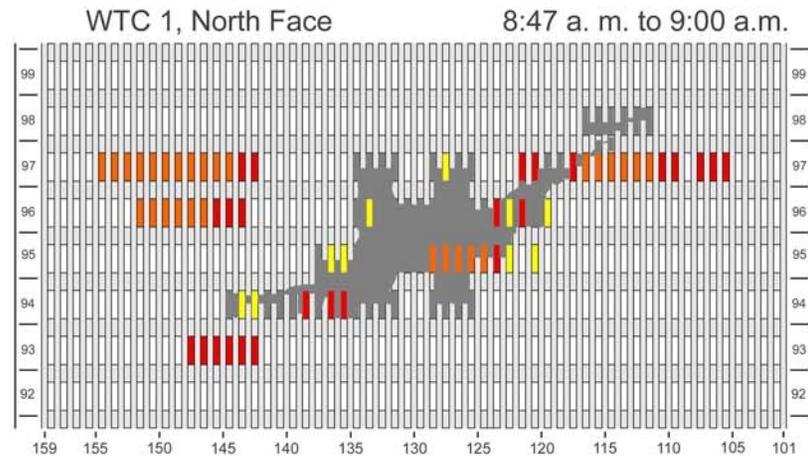
Heavy Damage 

Moderate Damage 

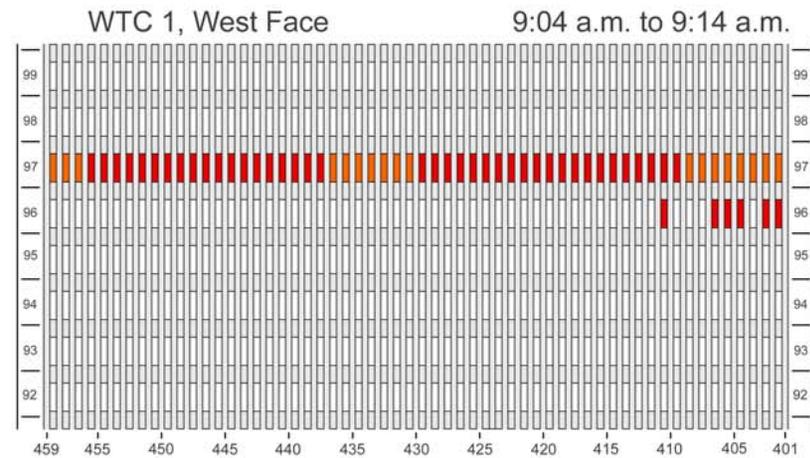
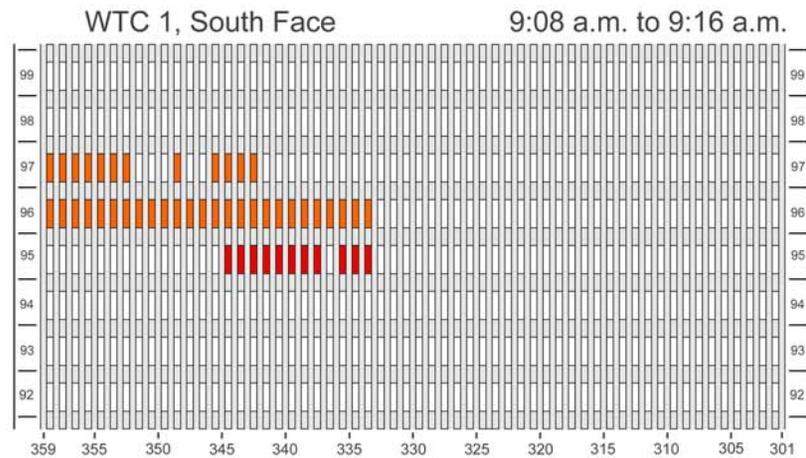
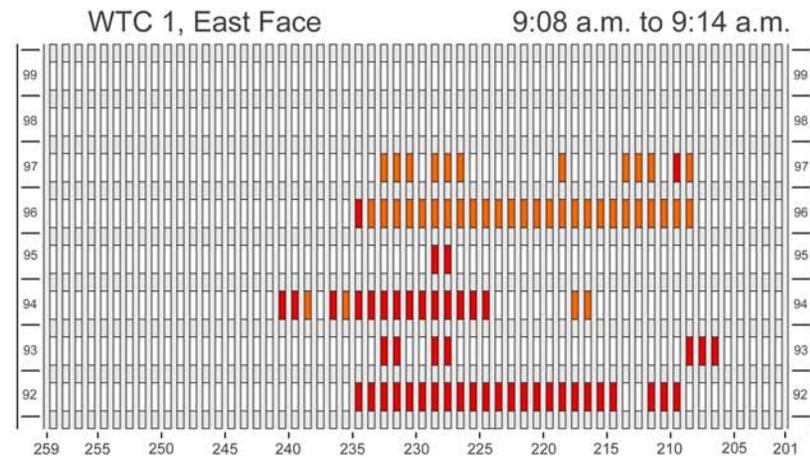
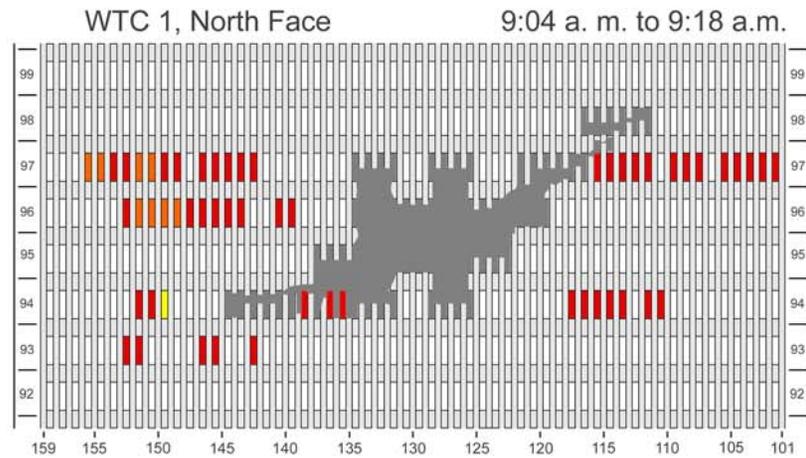
Light Damage 



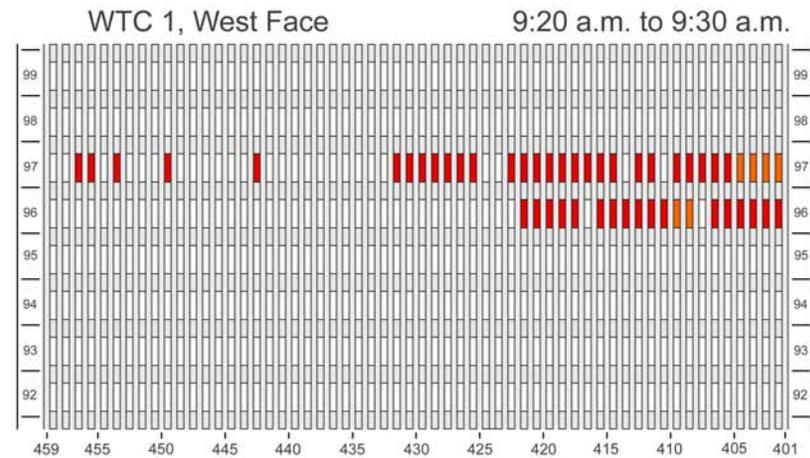
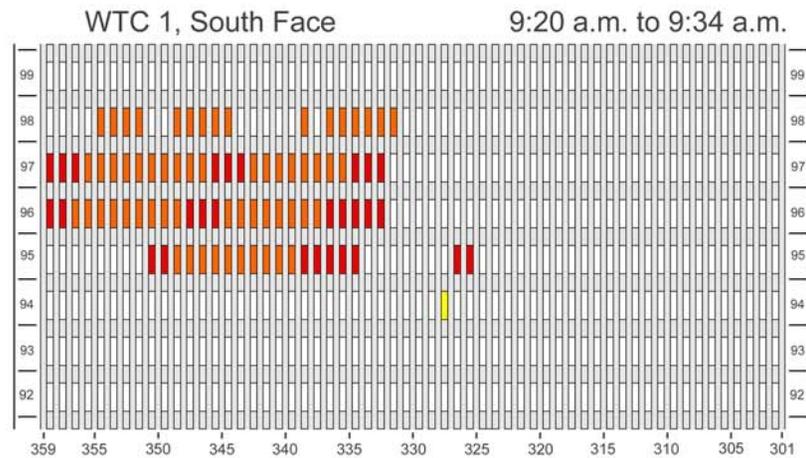
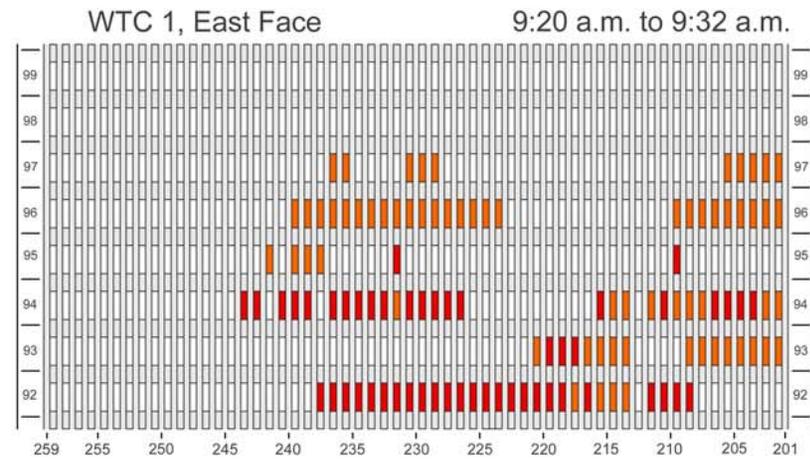
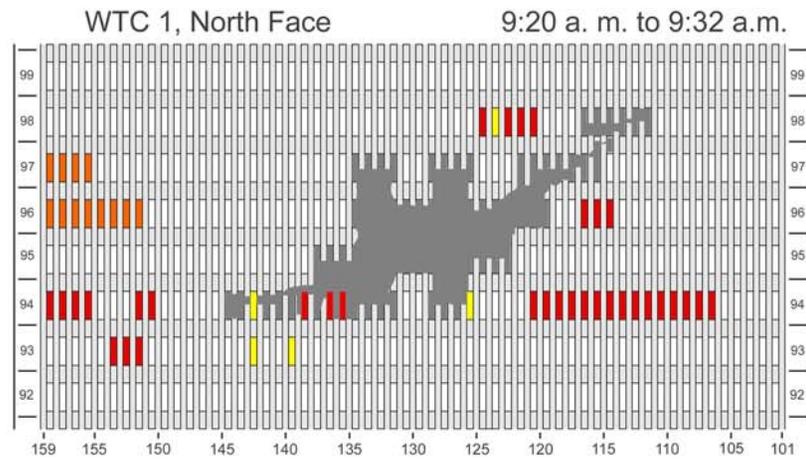
Visual Evidence of Fires in WTC 1: 8:48 to 9:02



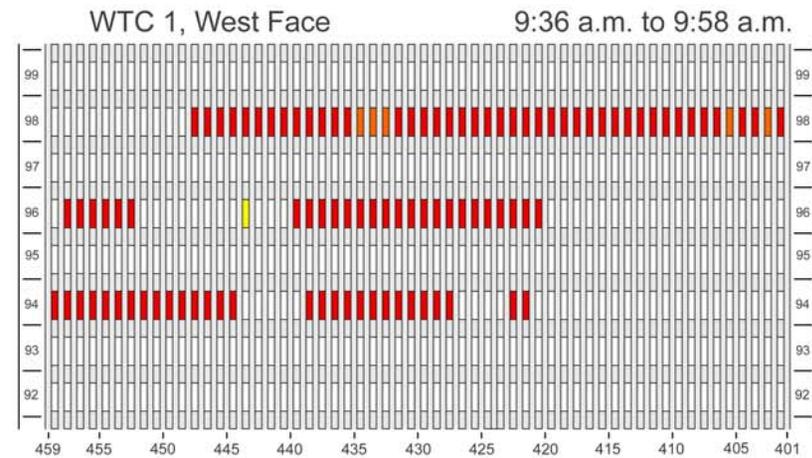
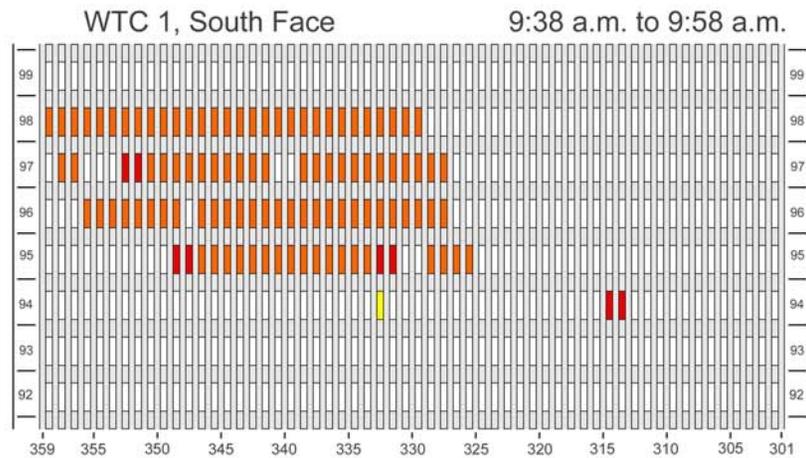
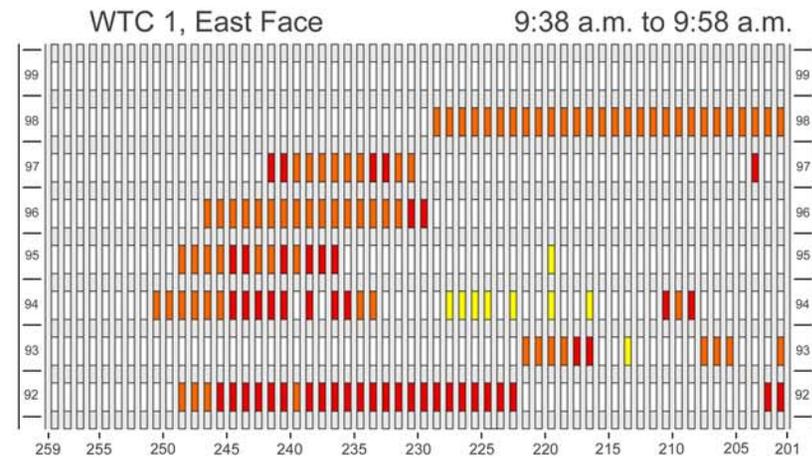
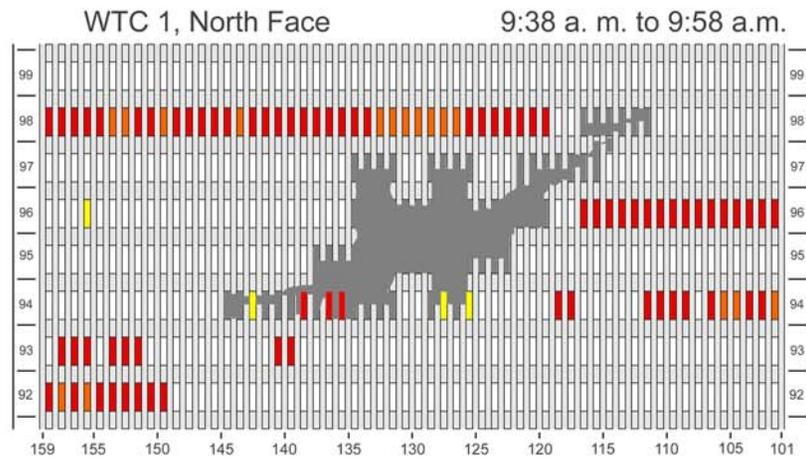
Visual Evidence of Fires in WTC 1: 9:04 to 9:18



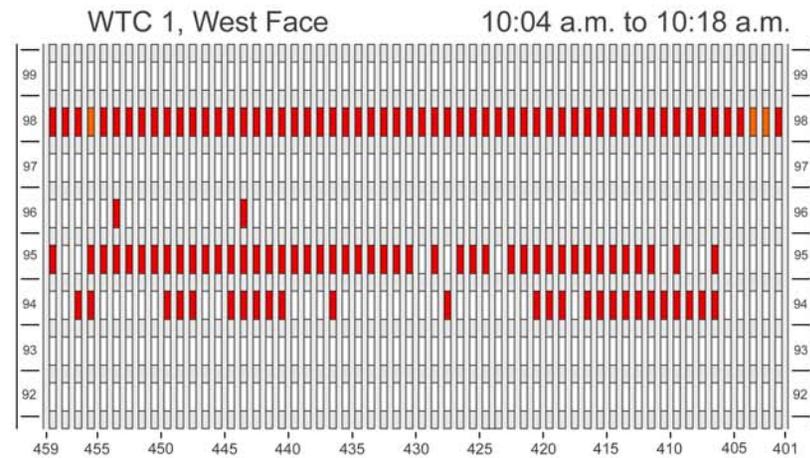
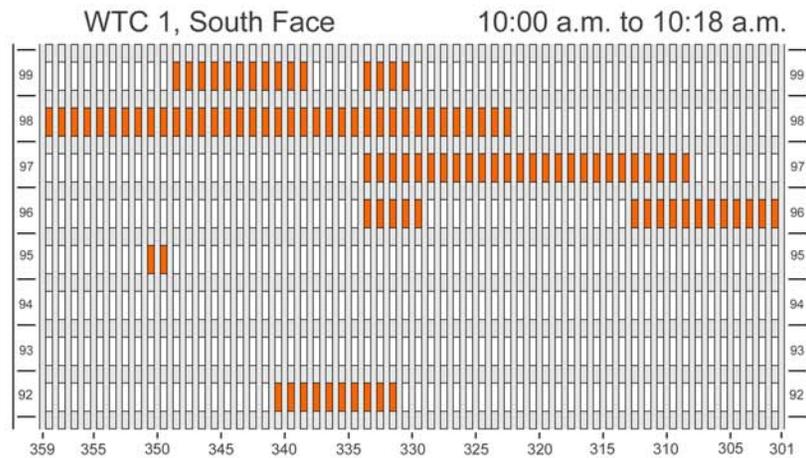
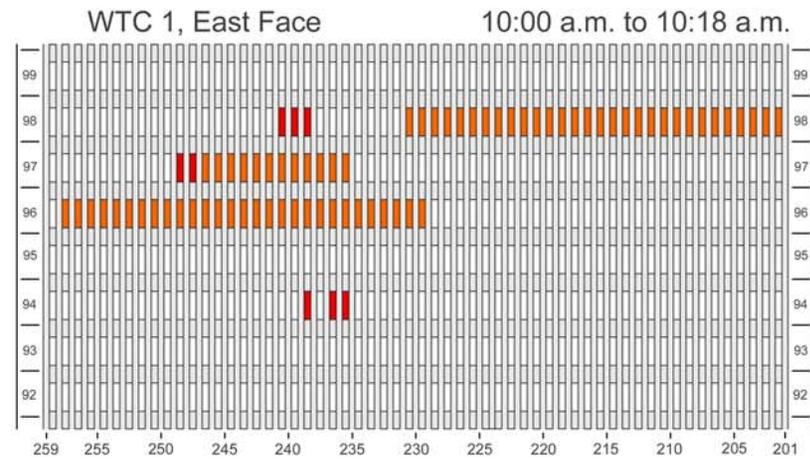
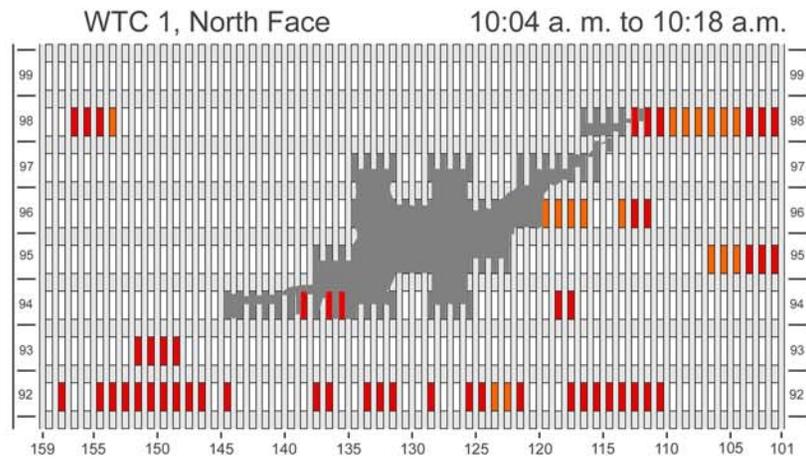
Visual Evidence of Fires in WTC 1: 9:20 to 9:32



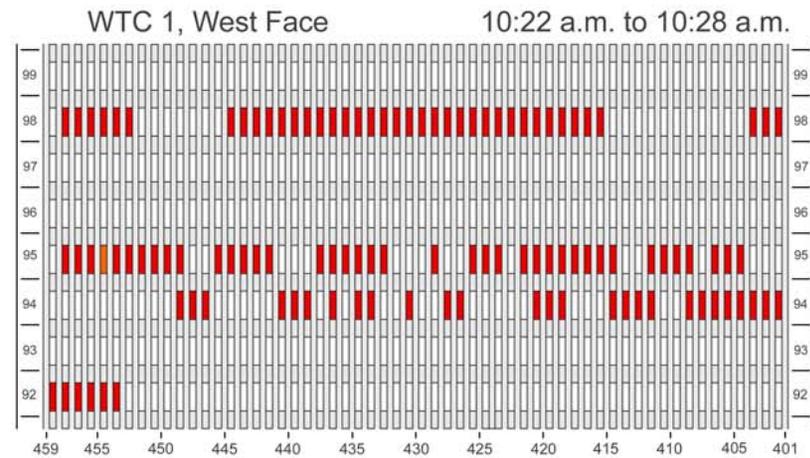
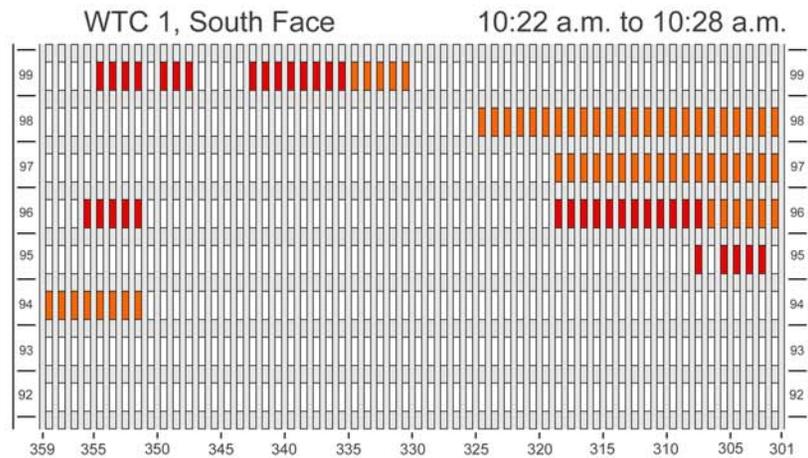
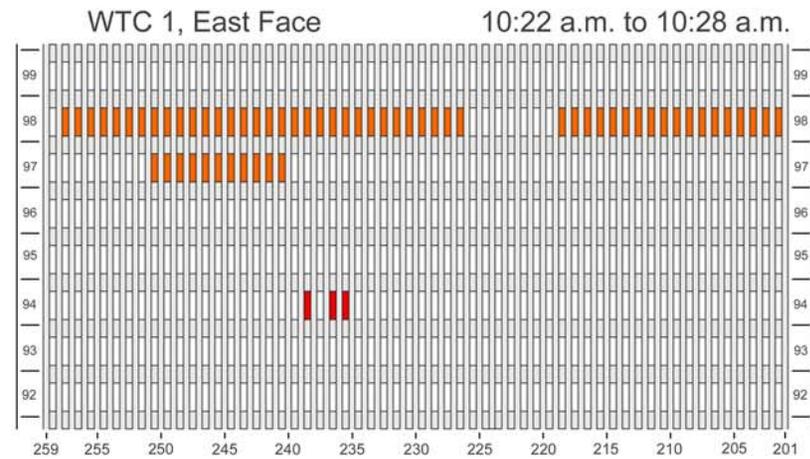
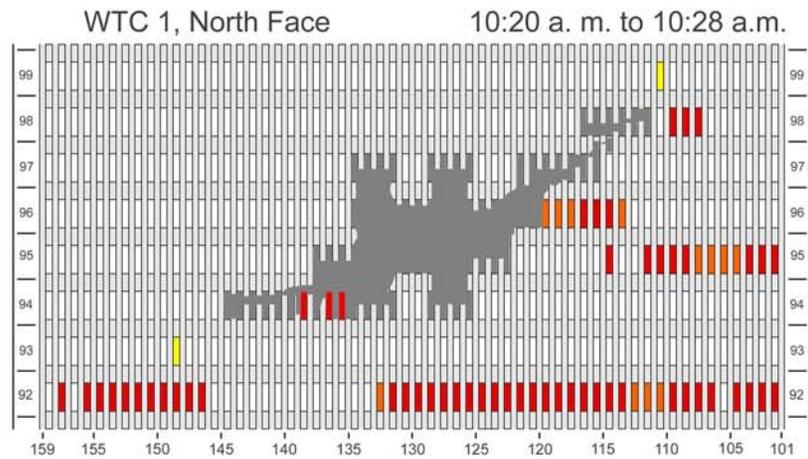
Visual Evidence of Fires in WTC 1: 9:38 to 9:58



Visual Evidence of Fires in WTC 1: 10:04 to 10:18

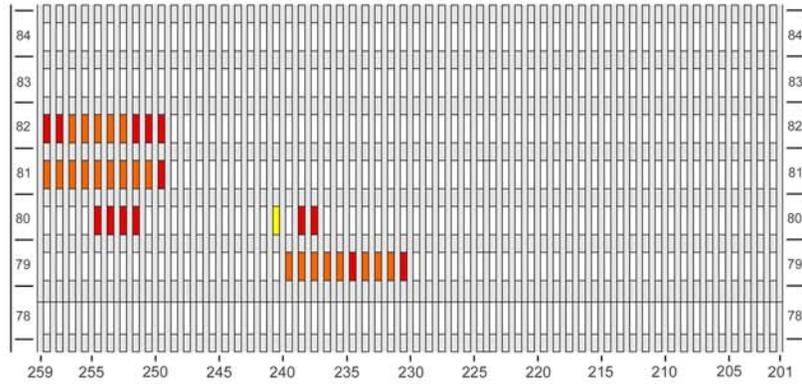


Visual Evidence of Fires in WTC 1: 10:22 to 10:28



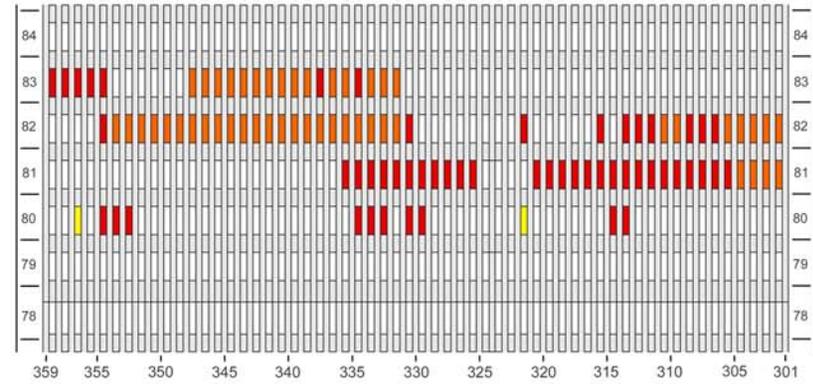
WTC 2, North Face

9:04 a. m. to 9:14 a.m.



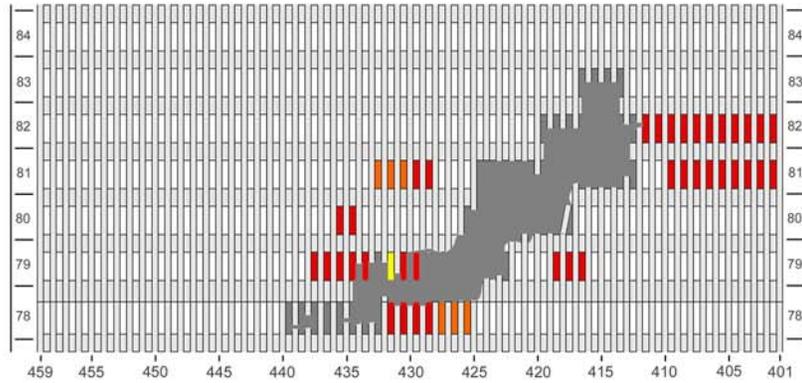
WTC 2, East Face

9:04 a. m. to 9:14 a.m.



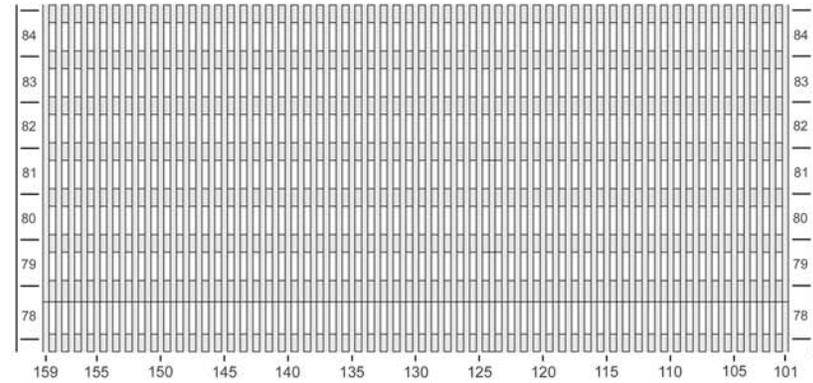
WTC 2, South Face

9:04 a. m. to 9:14 a.m.



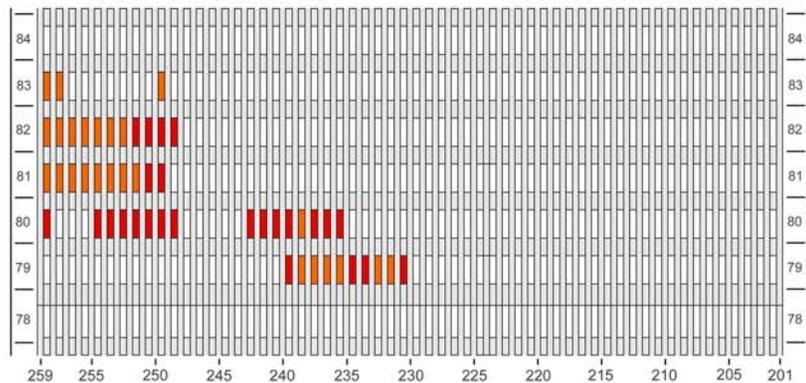
WTC 2, West Face

9:04 a. m. to 9:14 a.m.



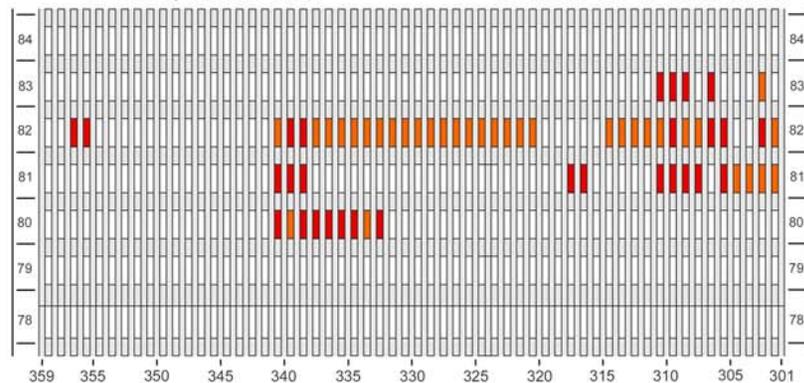
WTC 2, North Face

9:16 a. m. to 9:28 a.m.



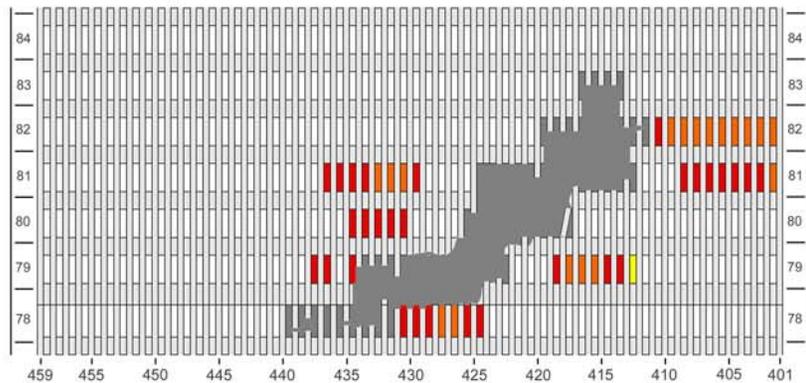
WTC 2, East Face

9:16 a. m. to 9:28 a.m.



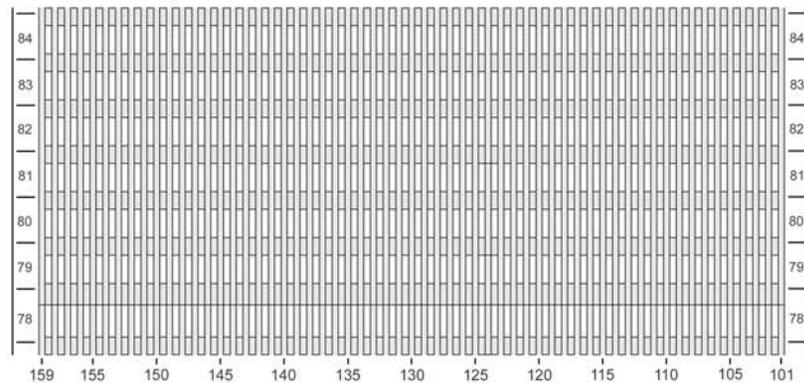
WTC 2, South Face

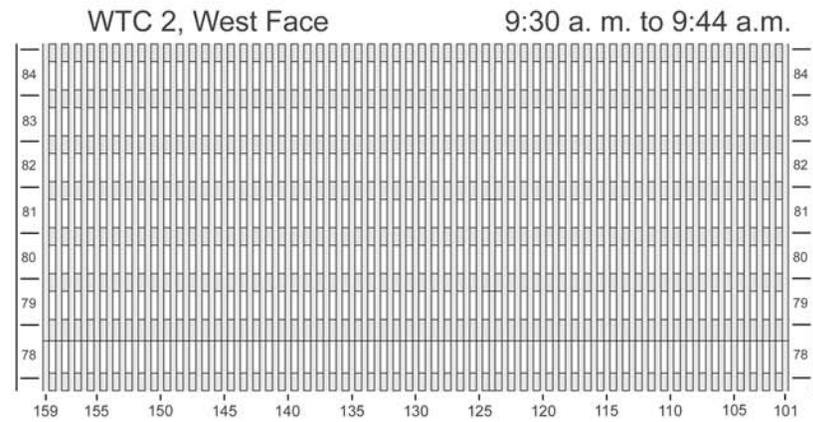
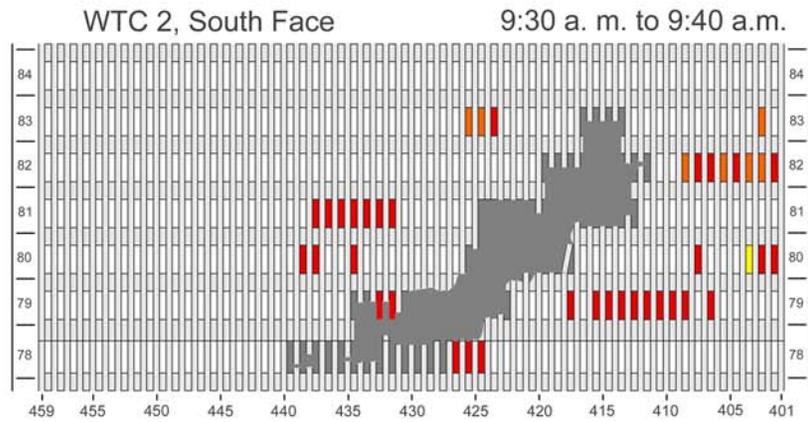
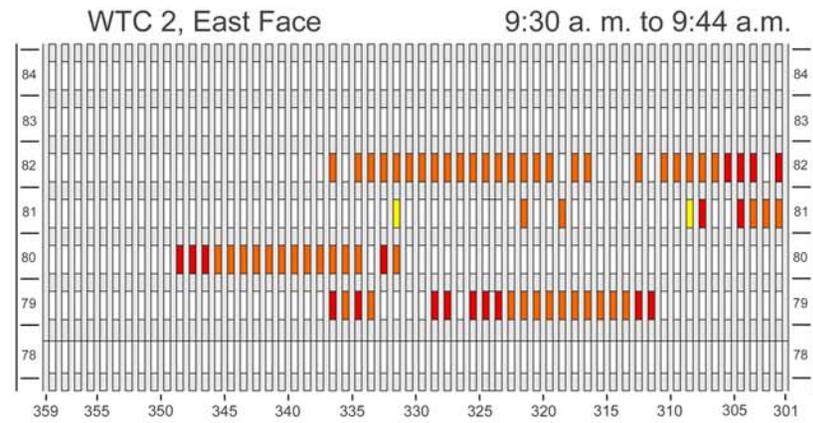
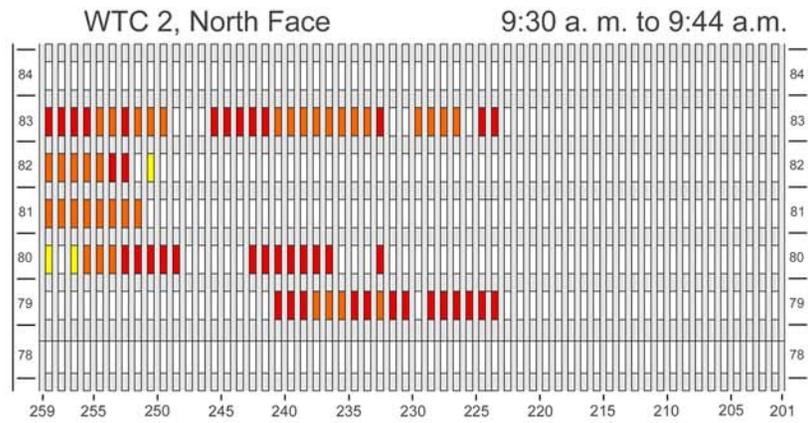
9:16 a. m. to 9:28 a.m.



WTC 2, West Face

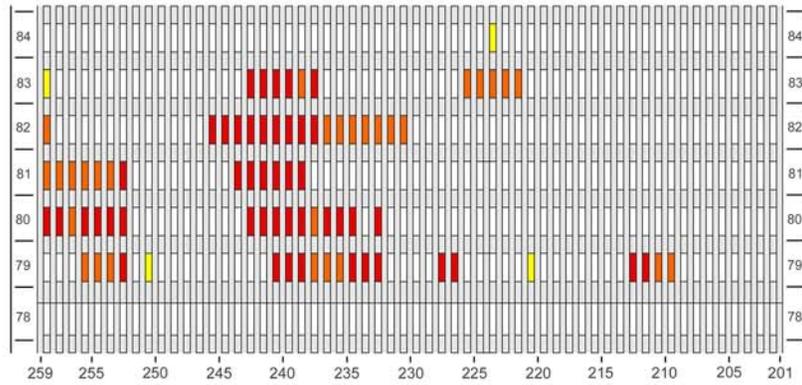
9:16 a. m. to 9:28 a.m.





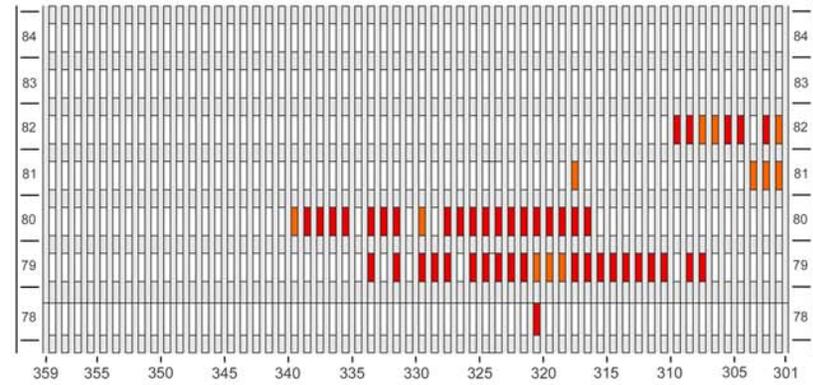
WTC 2, North Face

9:46 a. m. to 9:58 a.m.



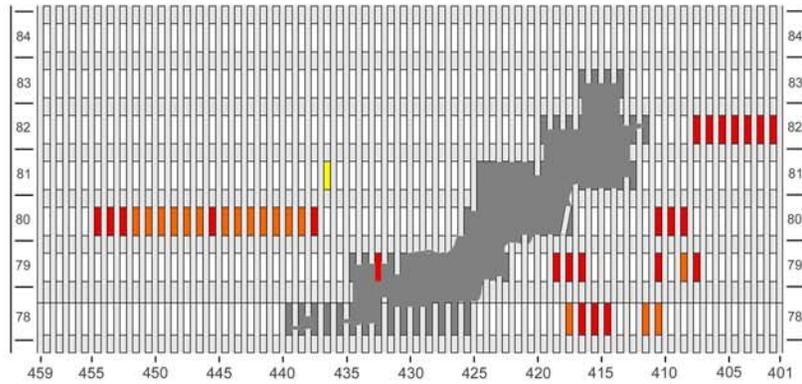
WTC 2, East Face

9:46 a. m. to 9:58 a.m.



WTC 2, South Face

9:46 a. m. to 9:58 a.m.



WTC 2, West Face

9:46 a. m. to 9:58 a.m.

