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

Aircraft Impact Damage Analysis: Comparisons and Findings

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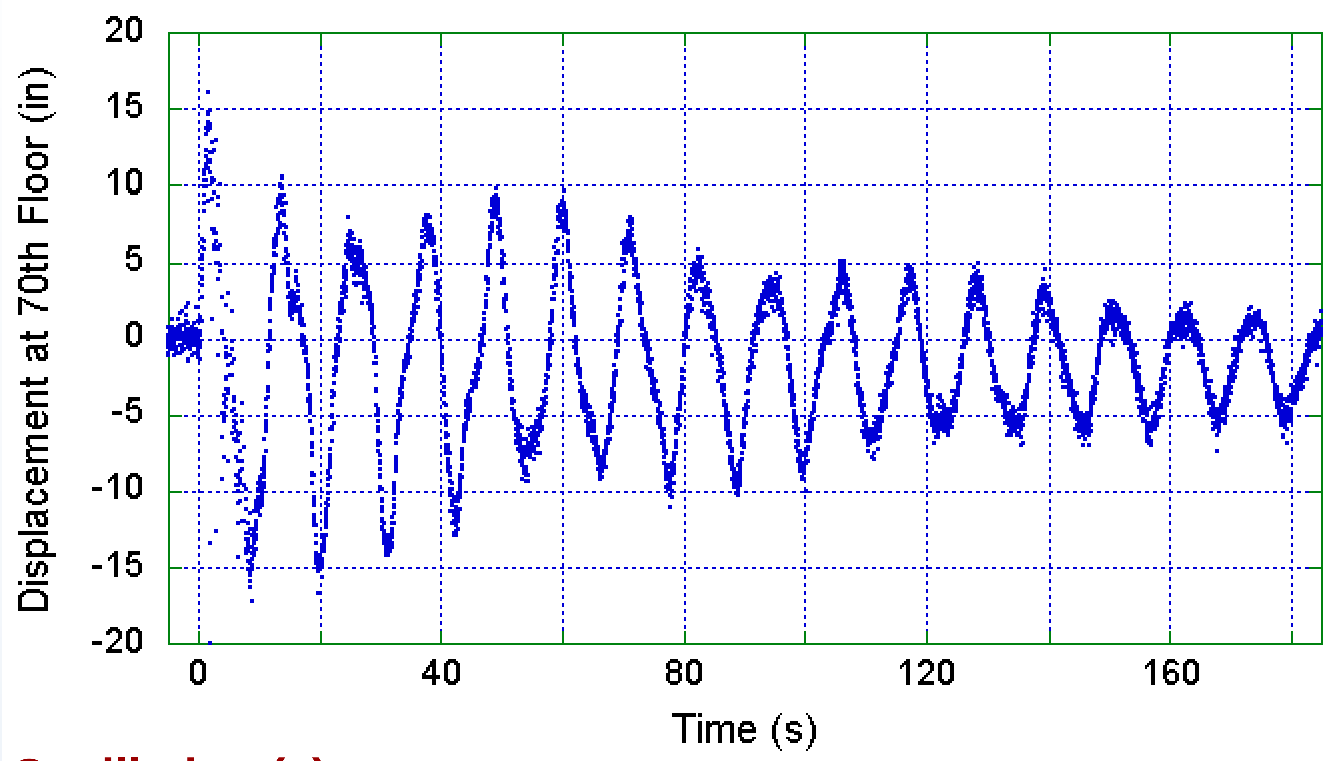
Motion Analysis of WTC 2 after Impact



Periods of Oscillation (s)

	Video Analysis	Model (with P-Δ effects)
Fundamental Mode (N-S)	11.4	11.2
Higher Mode (N-S)	3.9	4.0
Torsion	5.3	5.2

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Motion Analysis of WTC 2 after Impact

- The estimated period of oscillation was nearly equal to the calculated first mode period of the undamaged structure, indicating that the overall lateral stiffness of the tower was not affected appreciably by the impact damage.
- The maximum deflection at the top of the tower was estimated to be more than 1/3 of the drift resulting from the original design wind loads (about 65 in. in the N–S direction). Since the lateral stiffness of the building before and after impact was essentially the same, it can be concluded that the additional stresses in the columns due to this oscillation were roughly 1/3 of the column stresses resulting from the original design wind loads. The building demonstrated an ability to carry this additional load and therefore, still had reserve capacity.

Comparison between Impact Response of WTC 1 and WTC 2

WTC 1

- Impact Speed: 443 mph
- A downward impact trajectory angle of 10.6 degrees
- Long span trusses between the impact point and the core
- Impact close to centered and perpendicular on the face of the tower
- Almost all of the aircraft debris passed through the core
- Impact at floors 93-99

WTC 2

- Impact Speed: 546 mph
- A downward impact trajectory angle of 6 degrees
- Short span trusses between the impact point and the core
- Impact off center and angled away from the core
- Significant fraction of aircraft debris outside of core
- Impact at floors 77-85 (larger column sizes)

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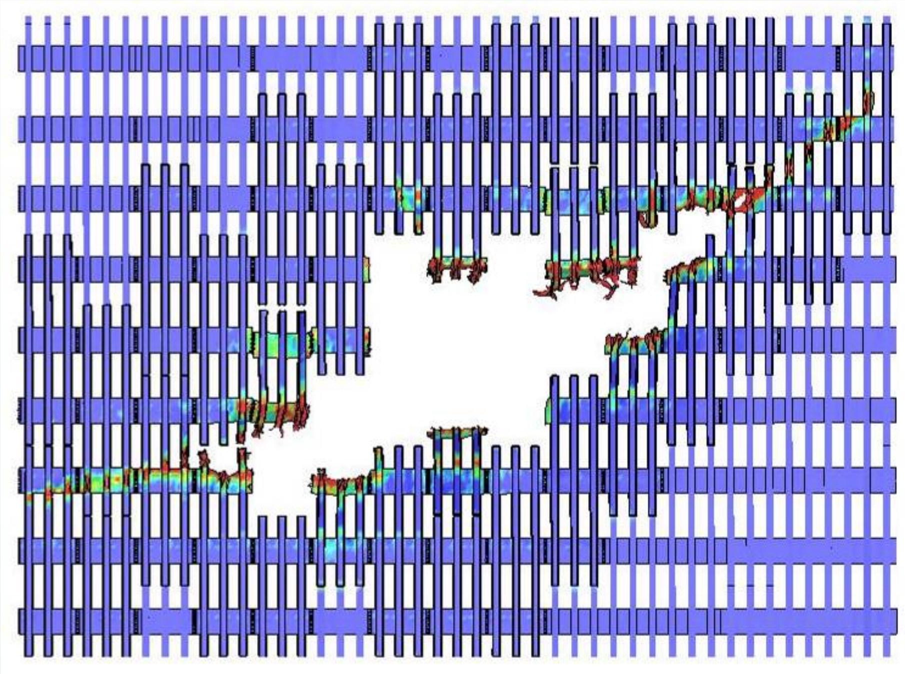
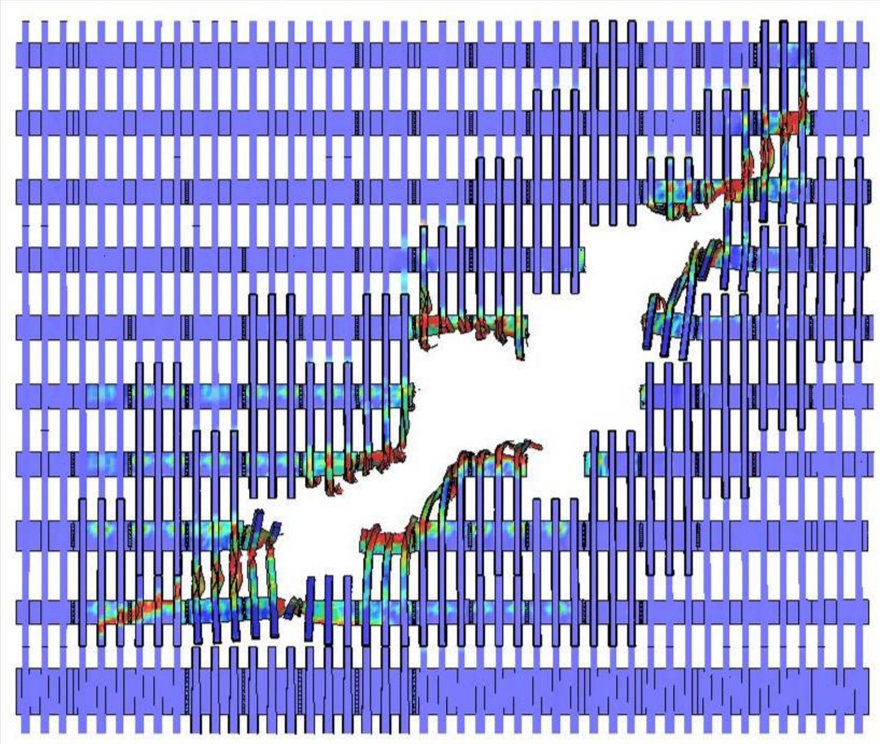
Comparison between WTC 1 and WTC 2: Exterior Damage



WTC 1

WTC 2



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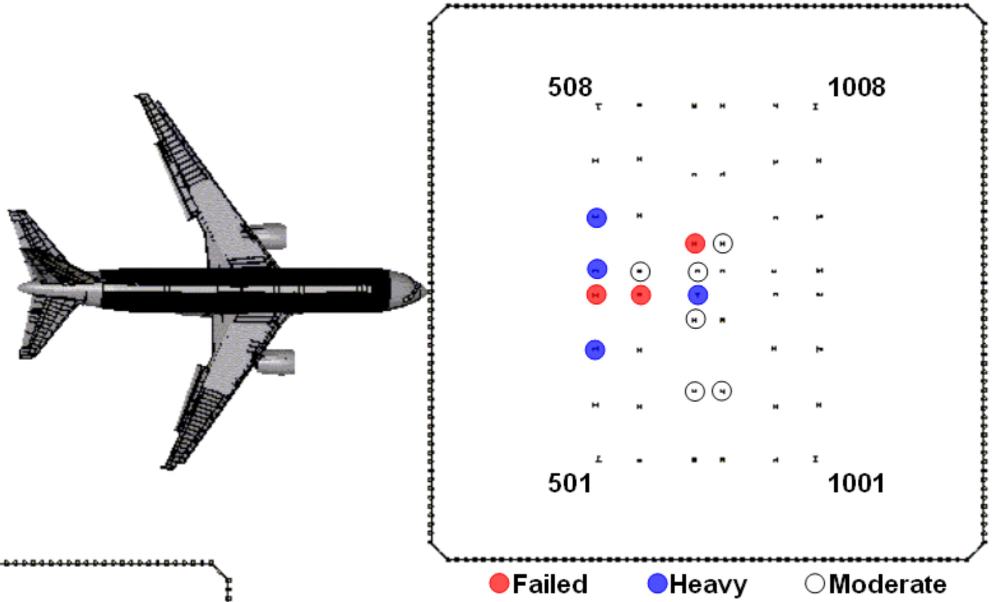
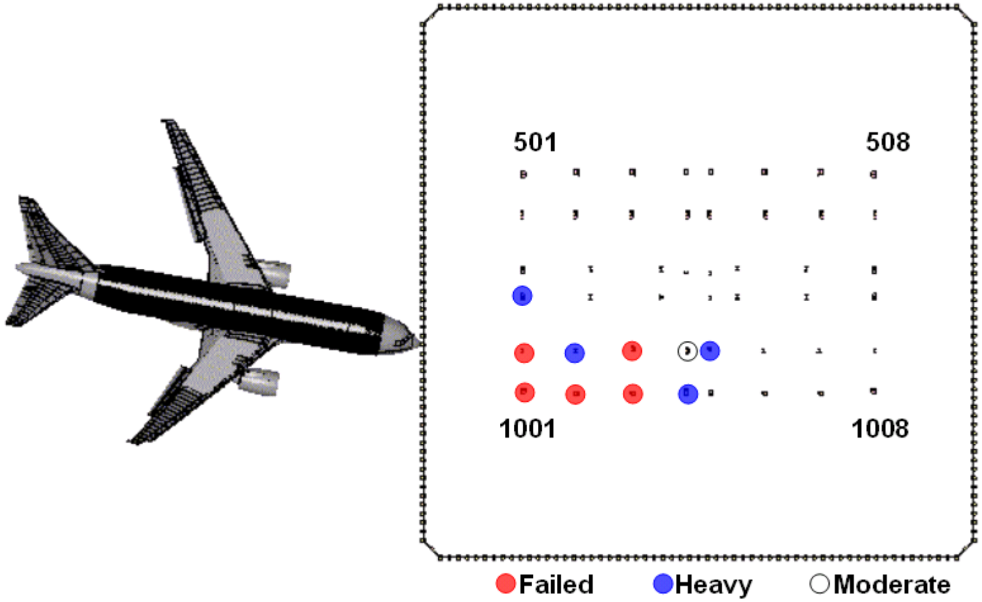
Comparison between WTC 1 and WTC 2: Core Columns



WTC 1

WTC 2



Comparisons with Observables: WTC 1

Observable	Importance	Agreement
Damage to the north exterior wall	Very significant	Very good
Damage to the south exterior wall	Slightly significant	Fair
Landing gear trajectory	Slightly significant	Poor
Stairwell disruption	Significant	Good
Floor damage visible on the north face	Significant	Unclear

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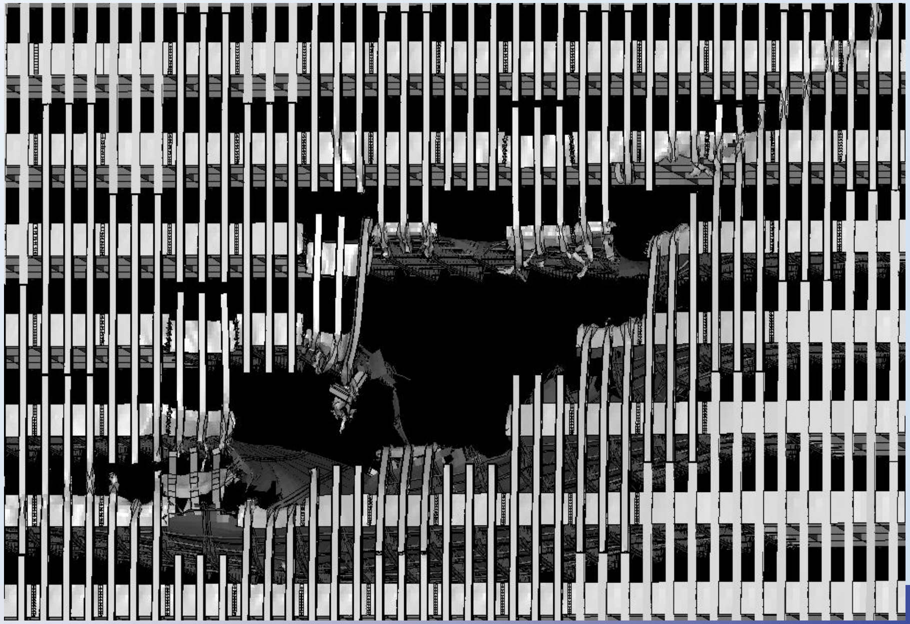
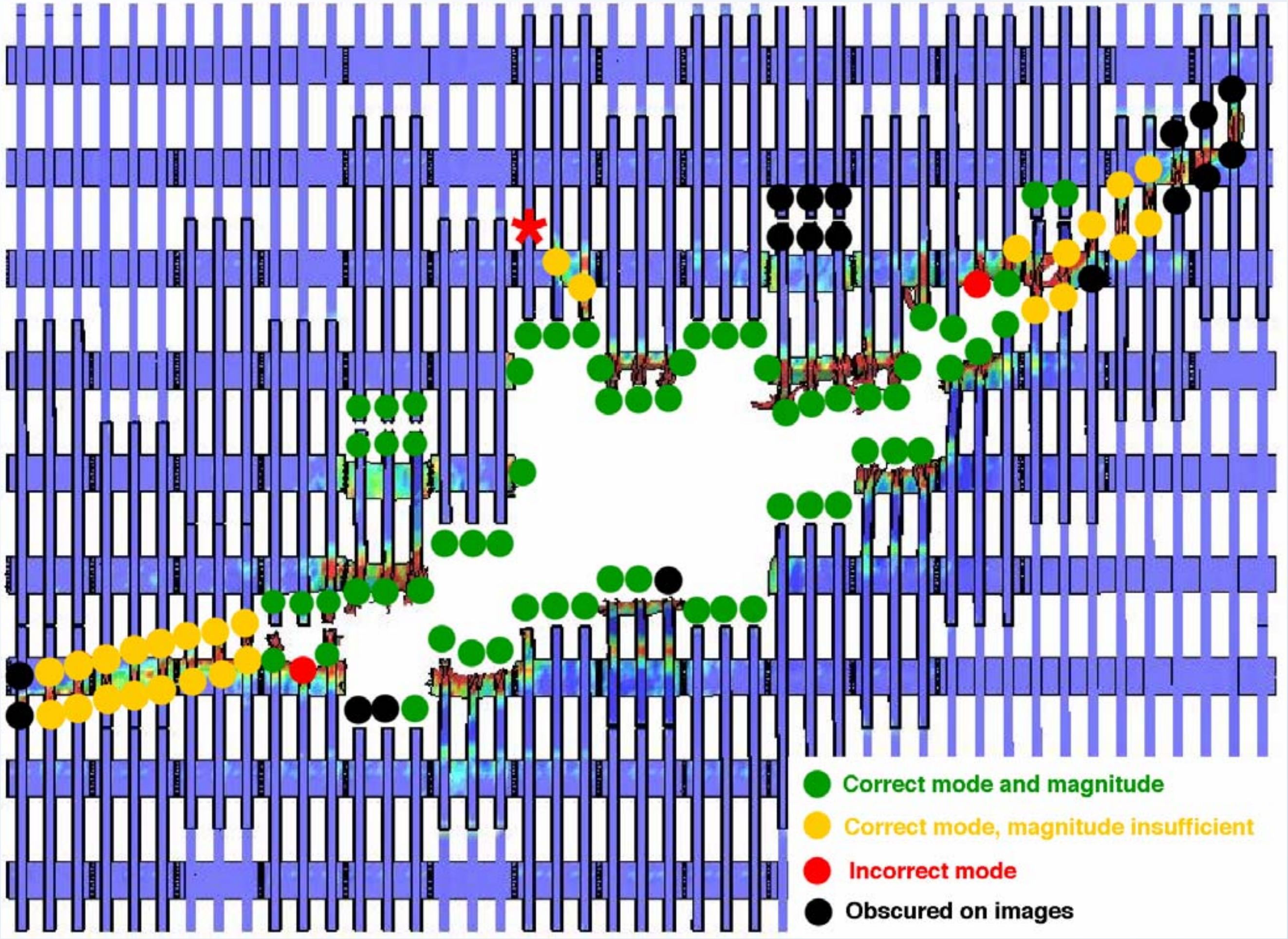
Comparisons with Observables: WTC 1

Exterior and floor damage

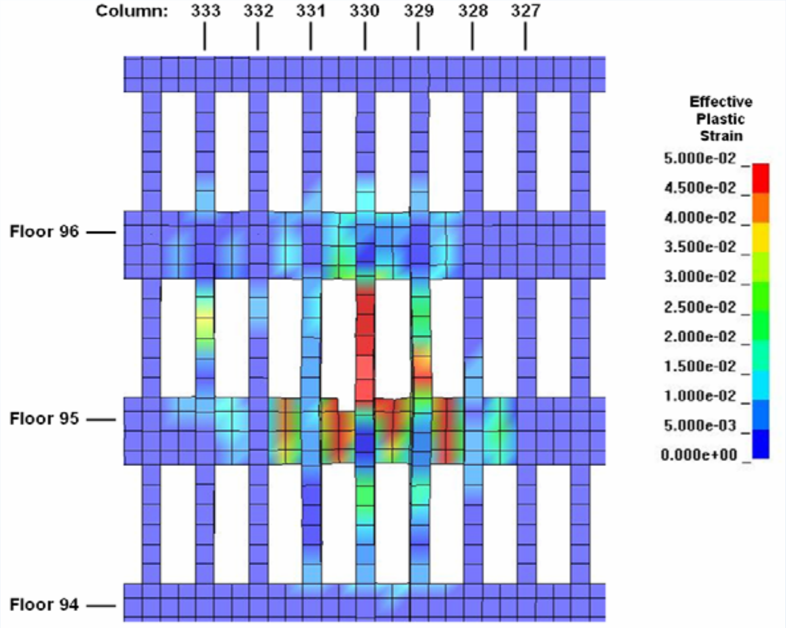


Comparisons with Observables: WTC 1



Comparison of observed and calculated base case impact damage to the north wall of WTC 1

Comparisons with Observables: WTC 1



Calculated damage to the south wall of WTC 1

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Comparisons with Observables: WTC 1

Landing gears were stopped in the core in the WTC 1 simulations

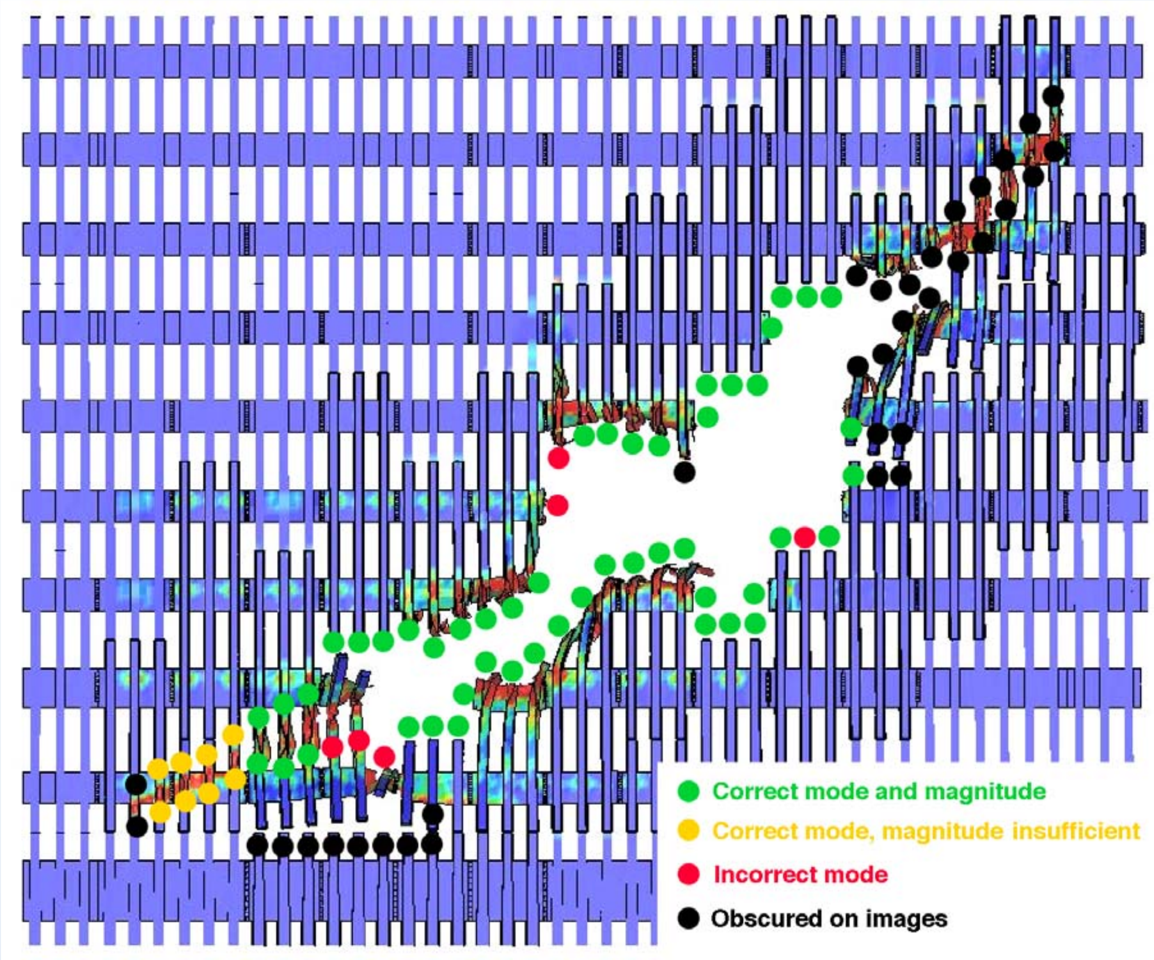
Comparisons with Observables: WTC 1

Stairwell Disruption in WTC 1

Comparisons with Observables: WTC 2

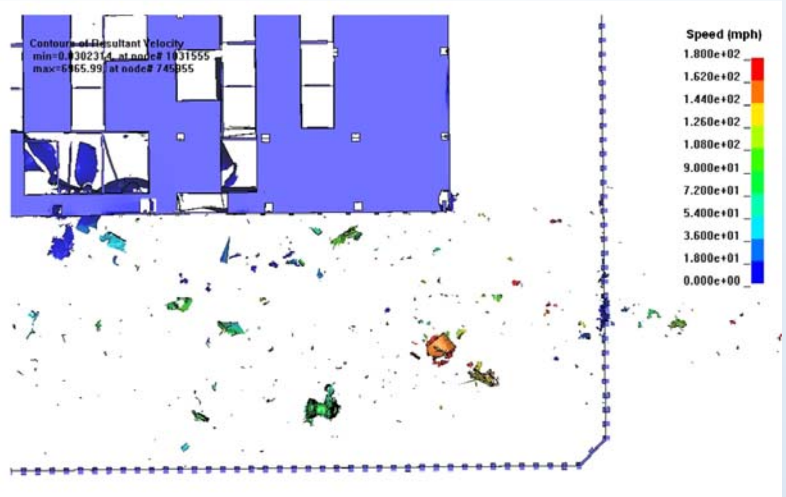
Observable	Importance	Agreement
damage to the south exterior wall	Very significant	Very good
damage to the north exterior wall	Slightly significant	Good
Stairwell disruption	Significant	Good
Landing gear trajectory	Not significant	Fair
Engine trajectory	Slightly significant	Good
Floor damage visible on the south face	Significant	Unclear
The ‘cold spot’ on the north face	Slightly significant	Unclear

Comparisons with Observables: WTC 2



Comparison of observed and calculated base case impact damage to the south wall of WTC 2

Comparisons with Observables: WTC 2



Calculated response to the north wall of WTC 2

Comparisons with Observables: WTC 2

Stairwell Disruption in WTC 2

Comparison with Previous Studies

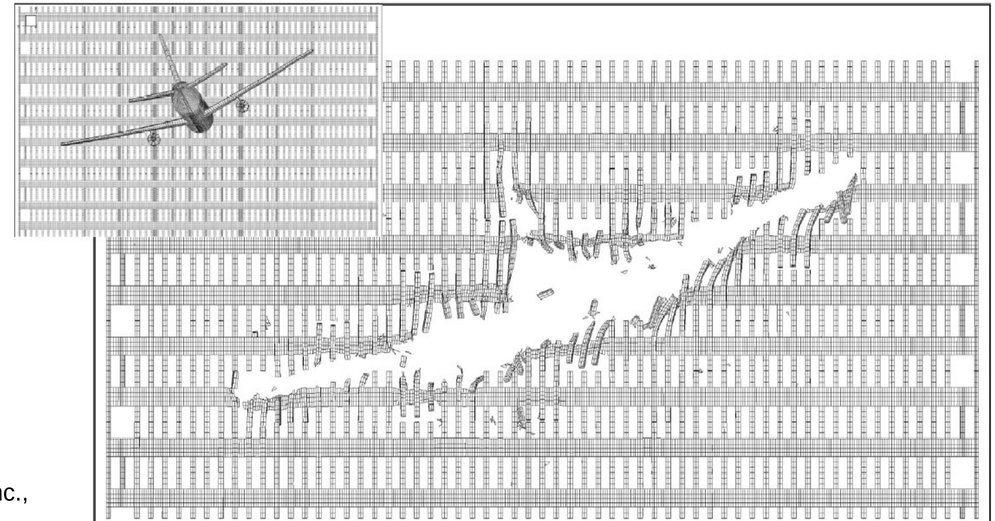
- MIT:

  Used an energy approach to estimate damage to core columns

$$E_{kinetic} = E_{plane} + E_{ext.\ Col.} + E_{floor} + E_{core}$$

- Weidlinger Associates, Inc.

  Used a finite element analysis to estimate damage to both towers



(a) FLEX simulation

Source: Levy, M., and N. Abboud. *WTC Structural Engineering Investigation*. Weidlinger Associates, Inc., Hart-Weidlinger, August 2002.

Comparison with Previous Studies

Summary Comparison of Damage to Core Columns from Various 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

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Key Findings: Aircraft Impact on WTC 1

- The aircraft had a speed of 443±30 mph with a roll angle of 25±2 degrees (port wing downward). The vertical approach downward angle was 10.6±3 degrees, and the lateral approach angle was close to being normal to the north wall of the tower.

- The aircraft impact resulted in extensive damage to the north wall of the tower, which failed in the regions of the fuselage, engine, and fuel-filled wing section impacts. Damage to the exterior wall extended to the wing tips, but the exterior columns were not completely severed in the outer wing and vertical stabilizer impact regions. 34 columns were completely severed, 4 columns were heavily damaged, and 2 columns were moderately damaged. The results of the impact analyses matched well with this damage pattern to the north wall. An exterior panel on the south wall between floors 94 to 96 was dislodged.

Key Findings: Aircraft Impact on WTC 1

- Subject to the uncertainties inherent in the models, the global impact simulations indicated that:
  - 3 core columns were severed and 4 columns were heavily damaged in the base case
  - 6 core columns were severed and 3 columns heavily damaged in the more severe case
  - 1 core column was severed and 2 columns heavily damaged in the less severe case.

  Floor trusses, core beams, and floor slabs experienced significant impact-induced damage on floors 94 to 96, particularly in the path of the fuselage.

- The wing structures were completely fragmented due to the interaction with the exterior wall and as a result, aircraft fuel was dispersed on multiple floors. The bulk of the fuel was deposited in floors 93 through 97, with the largest concentration on floor 94.

- Aircraft debris resulted in substantial damage to the nonstructural buildings contents (partitions and workstations) and also in dislodging of fireproofing. The bulk of the aircraft debris was deposited in floors 93 through 97, with the largest concentration on floor 94.

Key Findings: Aircraft Impact on WTC 2

- The impacting aircraft had a speed of 542±24 mph, with a roll angle of 38±2 degrees (port wing downward). The vertical approach downward angle was 6±2 degrees, and the lateral approach angle was 13±2 degrees clockwise from the south wall of the tower.

- The aircraft impact resulted in extensive damage to the south wall of the tower, which failed in the regions of the fuselage, engine, and fuel-filled wing section impacts. Damage to the exterior wall extended to the wing tips, but the exterior columns were not completely failed in the outer wing and vertical stabilizer impact regions. 29 columns were completely severed, and 1 column was heavily damaged. The 2 columns were obscured by smoke, but the analysis results showed that these columns were moderately damaged. results of the impact analyses matched the damage pattern to the south wall well. 4 columns on the north wall were failed.

Key Findings: Aircraft Impact on WTC 2

- Subject to the uncertainties inherent in the models, the global impact simulations indicated that
  - 5 core columns were severed, and 4 columns were heavily damaged in the base case
  - 10 core columns were severed and 1 column heavily damaged in the more severe case
  - 3 core columns were severed and 2 columns heavily damaged in the less severe case.

  Failure of the column splices located on floors 77, 80, and 83 contributed significantly to the failure of the core columns. Floor trusses, core beams, and floor slabs experienced significant impact-induced damage on floors 79 to 81, particularly in the path of the fuselage.
- The wing structures were completely fragmented due to the interaction with the exterior wall and as a result, aircraft fuel was dispersed on multiple floors. The bulk of the fuel was concentrated on floors 79, 81, and 82.
- Aircraft debris resulted in substantial damage to the nonstructural buildings contents (partitions and workstations) and also in dislodging of fireproofing. The bulk of the aircraft debris was deposited in floors 78 through 80, with the largest concentration on floor 80.

Key Findings: Aircraft Impact

- The towers sustained significant structural damage to the exterior walls, core columns, and floor systems due to aircraft impact. This structural damage contributed to the weakening of the tower structures, but did not, by itself, initiate building collapse. However, the aircraft impact damage contributed greatly to the subsequent fires and the thermal response of the tower structures that led ultimately to the collapse of the towers by:
    - dispersing jet fuel and igniting building contents over large areas,
    - creating large accumulations of combustible materials containing aircraft 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 building fires,
    - dislodging of fireproofing.

Key Findings: Aircraft Impact

- In general, the results of the simulations matched the observables reasonably well. Not all of the observables, however, were perfectly matched by the impact simulations due to the uncertainties in exact impact conditions, the imperfect knowledge of the interior tower contents, the chaotic behavior of the aircraft breakup and subsequent debris motion, and the limitations of the models.
- The less severe damage case did not meet two key observables:
  - No aircraft debris was calculated to exit the side opposite to impact and most of the debris was stopped prior to reaching that side, in contradiction to what was observed in photographs and videos of the impact event.
  - The fire-structural and collapse initiation analyses of the damaged towers (NIST NCSTAR 1-6) indicated that the towers would not have collapsed had the less severe damage results been used.