

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

## Session VI - Structural Fire Response and Collapse Analysis

# Probable Collapse Sequence and Key Findings

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# Probable Collapse Sequences

NIST adopted an approach that combined mathematical modeling, statistical analysis, laboratory experiments, and analysis of photographs and videos, and accounted for uncertainty in input parameters, analyses, and observed events, to address:

- ❑ The probable sequence of events from the moment of aircraft impact until the initiation of global building collapse.
- ❑ How and why WTC 1 stood nearly twice as long as WTC 2 before collapsing (102 min vs 56 min).
- ❑ What factors, if any, could have delayed or prevented the collapse of the WTC towers?

# Methodology for Determining the Probable Collapse Sequence

Identified key observables from evidence held by NIST.

- ❑ Over 7,000 photographs and 150 hours of video records, 236 recovered steel pieces, eyewitness accounts, and emergency communication records.

Developed hypotheses and refined through course of investigation.

Developed and refined mathematical models (finite element and computational fluid dynamic analyses) for:

- ❑ Aircraft Impact
- ❑ Fire spread and growth
- ❑ Temperature histories
- ❑ Structural response

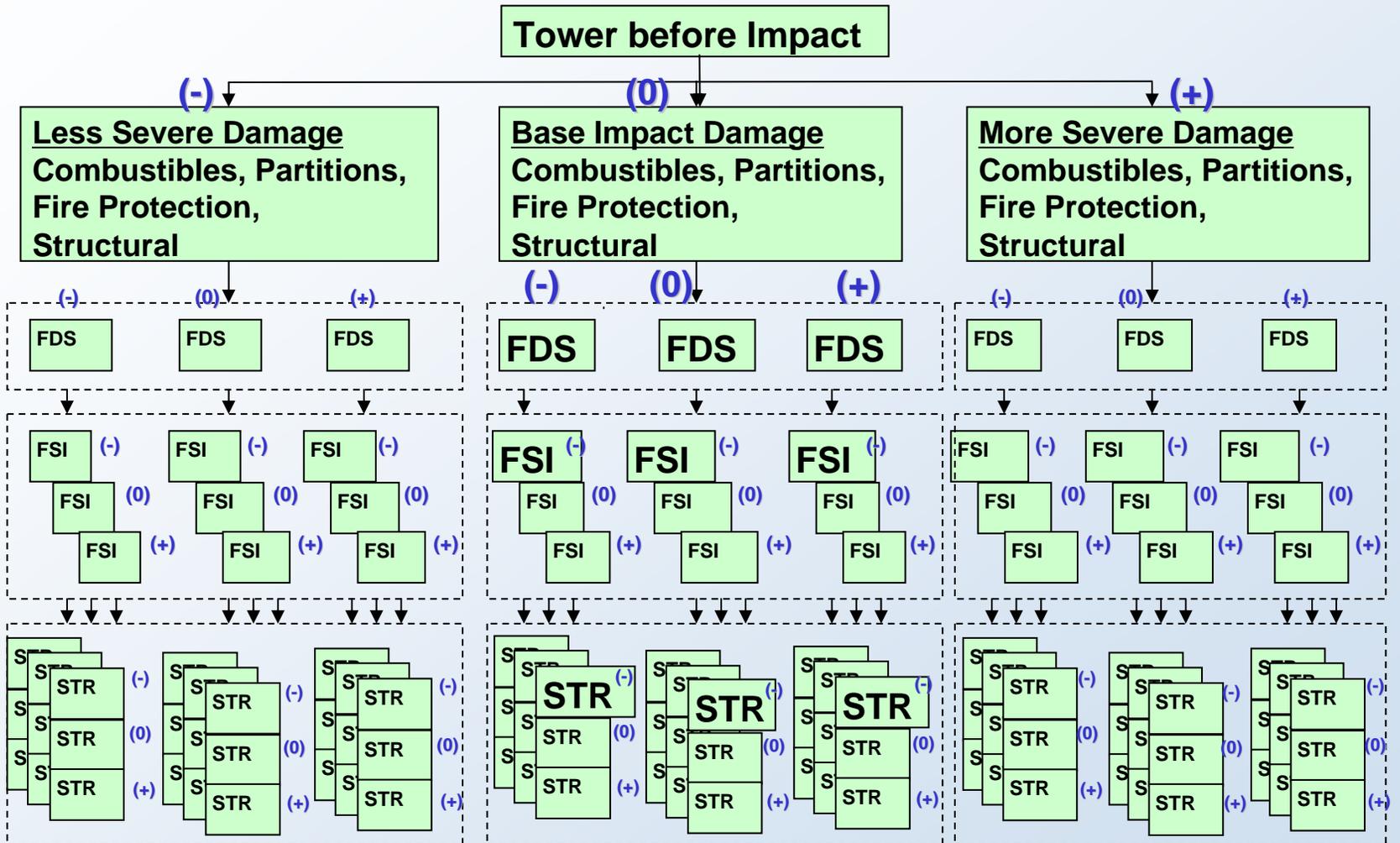
Performed sensitivity studies to determine the influential parameters at component and subsystem levels to determine 3 sets of values for influential parameters – lower, central, and upper bound likely values.

# Methodology for Determining the Probable Collapse Sequence (cont)

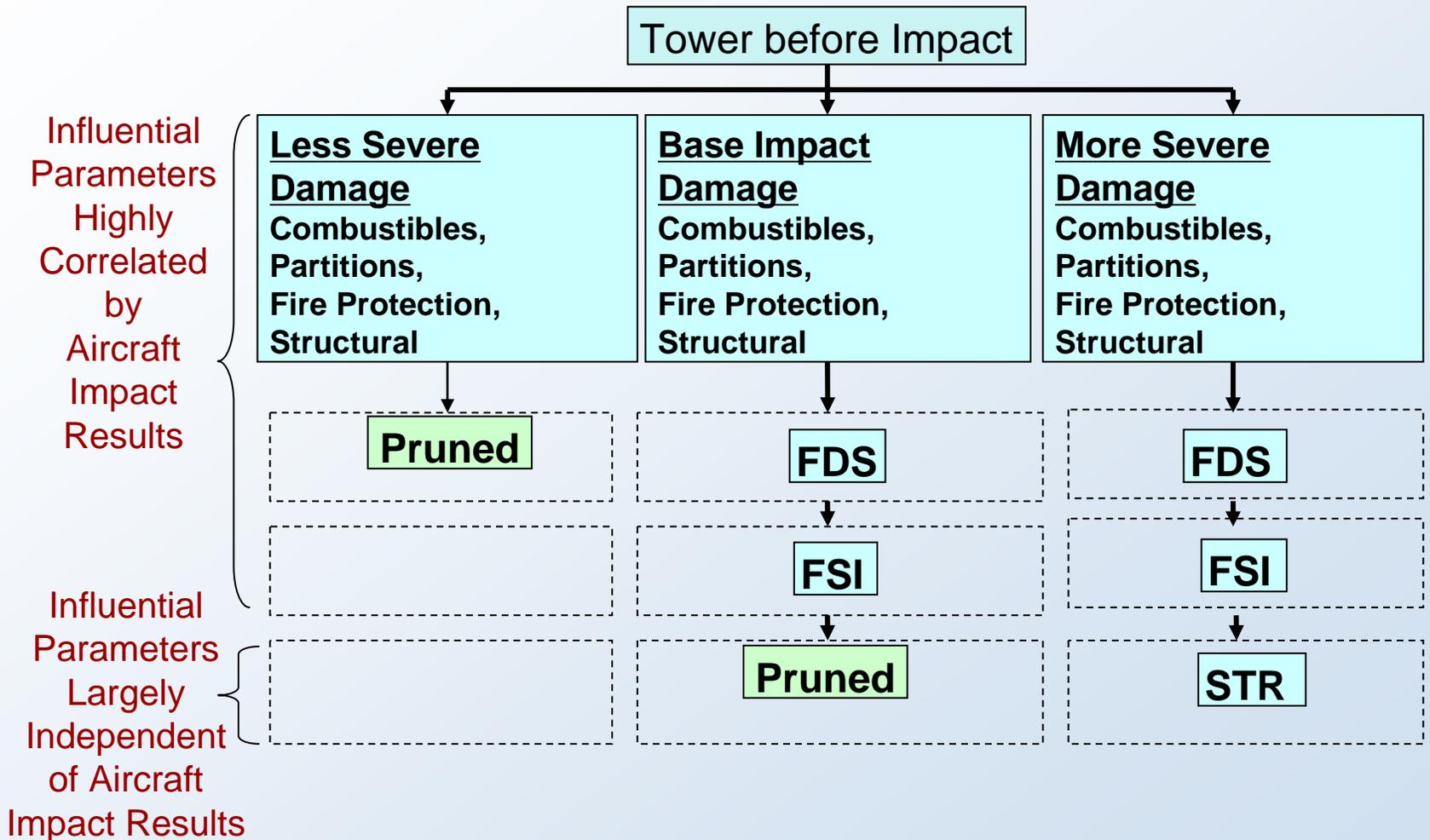
Evaluated analysis results for each data set against observed structural behavior, with adoption of event tree techniques, pruning, and updating of tree branches.

- ❑ Perform analyses for parameter sets that provide different levels of damage.
- ❑ Compare results to observations.
- ❑ Discard (prune) branches that do not reasonably match.
- ❑ Use observations to constrain model parameters and analysis results.

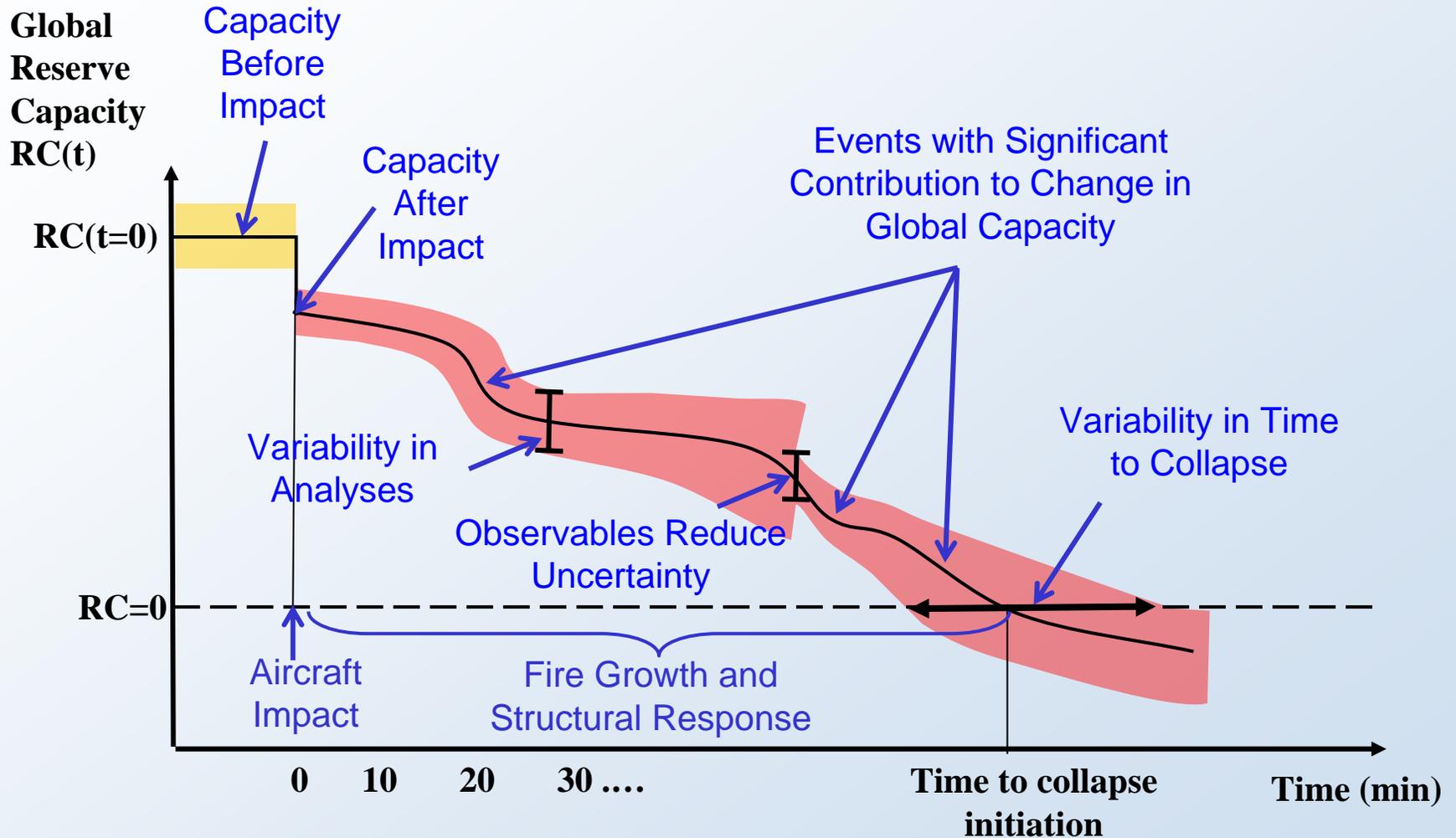
# Analysis Tree for All Influential Parameter Combinations



# Pruned Analysis Tree



# Variability in Sequential Analyses Due to Imperfect Information



# 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.

# Structural Events Leading to Collapse

Four structural events were common to both towers :

## Floor sagging

- ❑ Caused by elevated steel and concrete temperatures and either
  - buckling of the truss web diagonals with dislodged fireproofing or
  - disconnection of floor connections to the exterior wall.
- ❑ Substantial sagging resulted in pull-in forces at intact column connections, and led to inward bowing of the exterior wall.

## Bowing and inelastic buckling of an exterior wall

- ❑ Caused by pull-in forces from sagging floors, elevated temperatures, and redistributed gravity loads.

# Structural Events Leading to Collapse (cont.)

## Core weakening

- ❑ Caused by structural impact damage, redistributed loads, elevated temperatures, plastic and creep strains, and inelastic buckling of core columns.
- ❑ Downward displacement or shortening of the core was resisted by the hat truss.

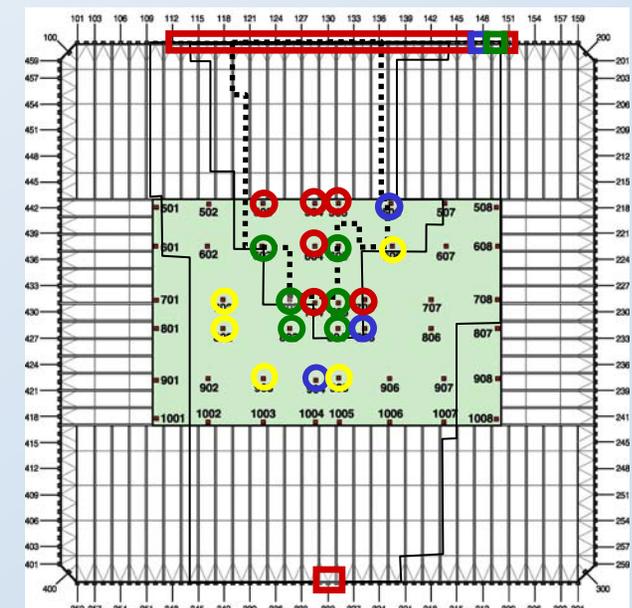
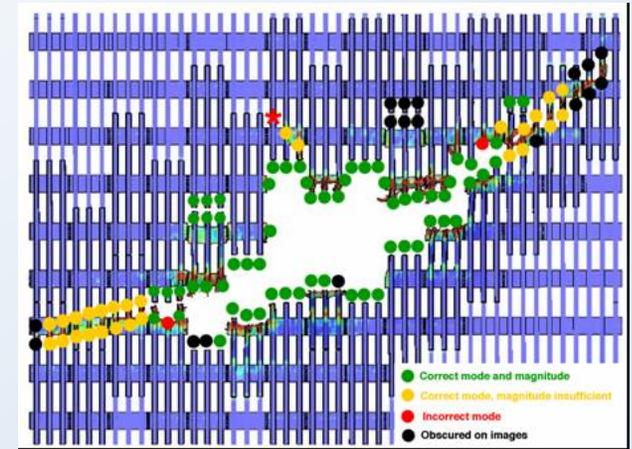
## Redistribution of gravity loads

- ❑ Resulted from impact damage, restrained thermal expansion, core weakening, leaning of the tower section above the impact damage, and bowing of exterior walls.
- ❑ Load redistribution between the core and exterior walls occurred primarily through the hat truss.
- ❑ Load redistribution between adjacent exterior walls occurred primarily through the spandrels.
- ❑ The hat truss restrained thermal expansion in the core columns relative to the exterior wall and transferred loads between the exterior wall and the core.

# WTC 1 Probable Collapse Sequence

## Aircraft Impact Damage

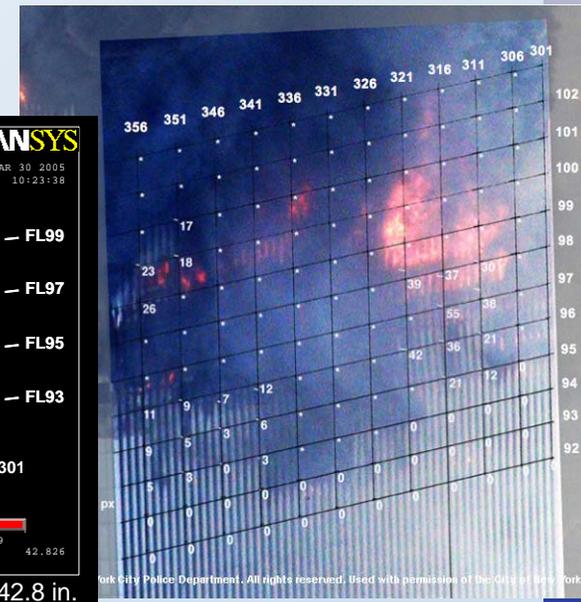
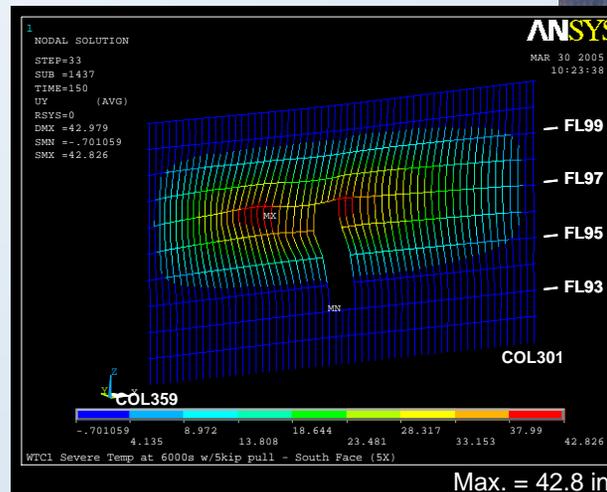
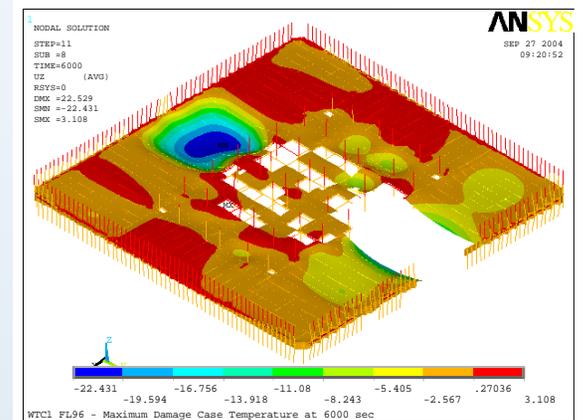
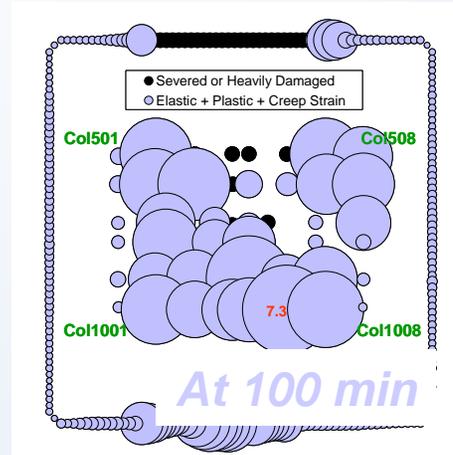
- ❑ Exterior columns, floor sections, and core columns were severed through the building center. An exterior panel was severed at the south wall.
- ❑ Fire protection was damaged through the building center to the south exterior wall.
- ❑ Loads were redistributed mostly to adjacent columns and the hat truss resisted downward movement of the north wall.
- ❑ North and south walls carried 7% less load, east and west wall carried 7% more load, core carried 1% more load.



# WTC 1 Probable Collapse Sequence (cont.)

## Thermal Weakening

- ❑ Core columns developed high plastic and creep strains, after initial thermal expansion. Hat truss resisted core column shortening.
- ❑ Long span south floors sagged and pulled inward on the south exterior wall after the fires reached the south side.
- ❑ The south wall bowed inward due to inward pull by intact sagging floors.



# WTC 1 Probable Collapse Sequence (cont.)

## Collapse Initiation

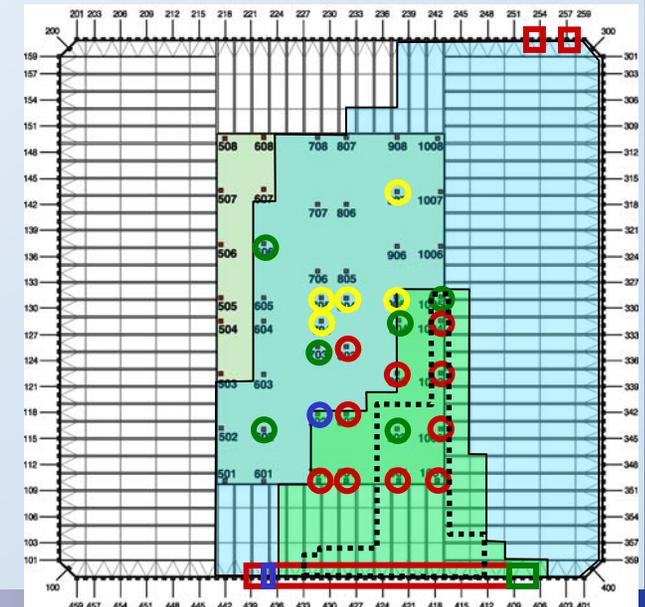
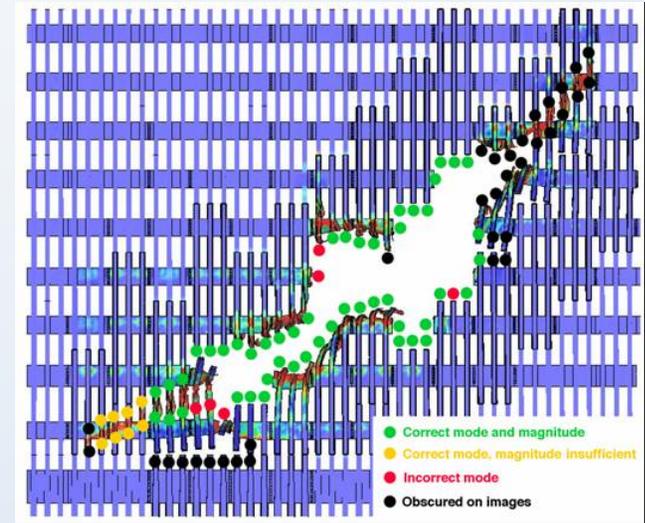
- ❑ The south wall buckled and transferred its loads to the weakened core through the hat truss and to the adjacent exterior walls through the spandrels.
- ❑ The upper building sections began to tilt to the south as a rigid block.
- ❑ Instability progressed along the east and west exterior walls.
- ❑ Collapse ensued as the released potential energy could not be resisted by the structure.



# WTC 2 Probable Collapse Sequence

## Aircraft Impact Damage

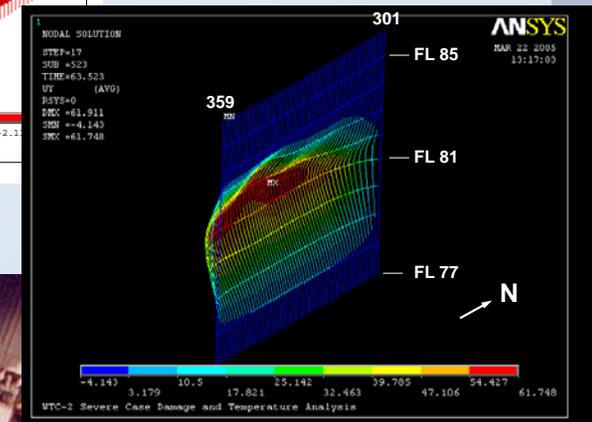
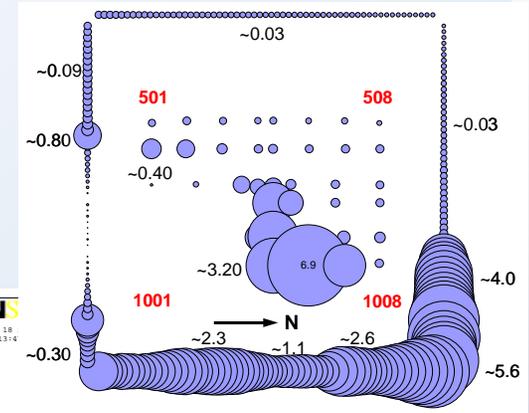
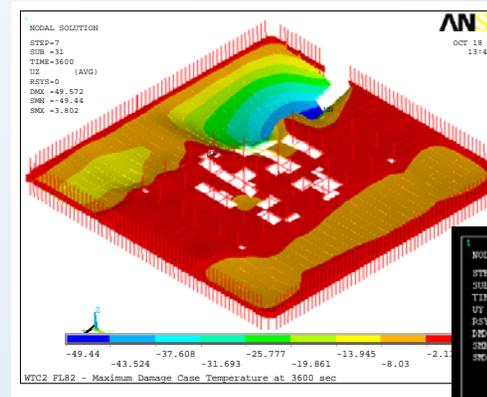
- ❑ Exterior columns, floor sections, and core columns were severed through the southeast corner and east side of the building.
- ❑ Loads were redistributed mostly to adjacent columns and the east exterior wall.
- ❑ Fire protection was damaged in the east side of the building.
- ❑ After impact, the core was leaning slightly toward the east and south walls. The exterior walls restrained the tendency of the core to lean through the hat truss and intact floors.
- ❑ East wall carried 24% more load, south and west wall carried 2-3% more load, north wall carried 10% less load, and the core carried 6% less load.



# WTC 2 Probable Collapse Sequence (cont.)

## Thermal Weakening

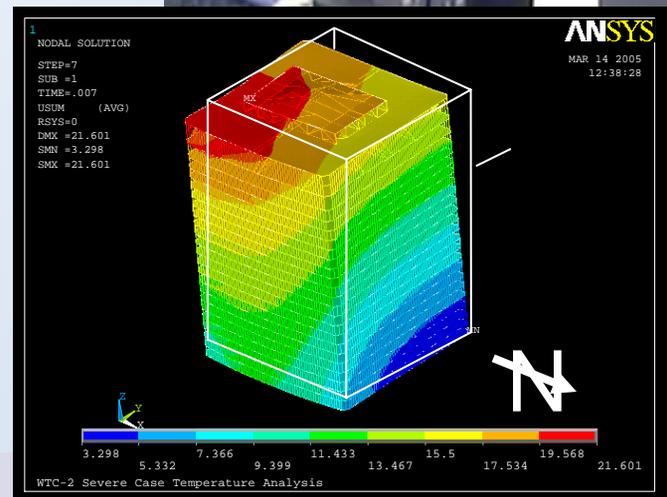
- ❑ Several core columns on the east side developed high plastic and creep strains, after initial thermal expansion.
- ❑ The long-span east floors sagged and pulled inward on the east exterior wall shortly after impact, due to the damage and fires on the east side.
- ❑ About 1/3 of the remaining Floor 83 connections to the exterior wall failed.
- ❑ The east wall bowed inward due to inward pull by intact sagging floors.



# WTC 2 Probable Collapse Sequence (cont.)

## Collapse Initiation

- ❑ The east wall buckled and transferred its loads to the weakened core through the hat truss and to the adjacent exterior walls through the spandrels.
- ❑ The upper building sections began to tilt to the east and south as a rigid block.
- ❑ Instability progressed along the north and south exterior walls.
- ❑ Collapse ensued as the released potential energy could not be resisted by the structure.



# Findings: Structural Response and Collapse Analysis

- ❑ The core columns were weakened significantly by the aircraft impact damage and thermal effects.
- ❑ Thermal effects dominated the weakening of WTC 1. As the fires moved from the north to the south side of the core, the core was weakened over time by significant creep strains on the south side of the core.
- ❑ Aircraft impact damage dominated the weakening of WTC 2. With the impact damage, the core subsystem leaned to the southeast and was supported by the south and east perimeter walls via the hat truss and floors.
- ❑ The primary role of the floors in the collapse of the towers was to provide inward pull forces that induced inward bowing of exterior columns. There would have been no inward pull forces if the floors connections had failed and disconnected.
- ❑ Column buckling over an extended region of the exterior face ultimately triggered the global system collapse as the loads could not be redistributed through the hat truss to the already weakened building core.

# Principal Findings

Objective 1: Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft.

- ❑ The two aircraft hit the towers at high speed and did considerable damage to principal structural components (core columns, perimeter columns, and floors) that were directly impacted by the aircraft or associated debris.
- ❑ However, the towers withstood the impacts and would have remained standing were it not for the dislodged fire protection and the subsequent multi-floor fires.
- ❑ The robustness of the exterior frame-tube system and the large size of the buildings helped the towers withstand the impact. The structural system redistributed loads in places of aircraft impact, avoiding larger scale damage upon impact. The hat truss, which was intended to support a television antenna atop each tower, prevented earlier collapse of the building core.
- ❑ In each tower, a different combination of impact damage and heat-weakened structural components contributed to the abrupt structural collapse.

# Principal Findings (cont.)

## For WTC 1:

- ❑ In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag.
- ❑ The floors pulled the heated south perimeter columns inward, reducing their capacity to support the building above.
- ❑ Their neighboring columns quickly became overloaded as the south wall buckled.
- ❑ The top section of the building tilted to the south and began its descent.
- ❑ The time from aircraft impact to collapse initiation was largely determined by how long it took for the fires to weaken the building core and to reach the south side of the building and weaken the perimeter columns and floors.

# Principal Findings (cont.)

For WTC 2:

- ❑ In WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors.
- ❑ The steady burning fires on the east side of the building caused the floors there to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as the east wall buckled.
- ❑ The top section of the building tilted to the east and to the south and began its descent.
- ❑ The time from aircraft impact to collapse initiation was largely determined by the time for the fires to weaken the perimeter columns and floor assemblies on the east and south sides of the building.
- ❑ WTC 2 collapsed more quickly than WTC 1 because there was more aircraft damage to the building core and there were early and persistent fires on the east side of the building, where the aircraft had extensively dislodged insulation from the structural steel.

# Principal Findings (cont.)

## Role of thermal insulation:

- ❑ The WTC towers would likely not have collapsed under the combined effects of aircraft impact damage and the extensive, multifloor fires if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

## Alternative hypotheses:

- ❑ NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photos and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

**The End**