



NIST

Analysis of Probable Collapse Sequence

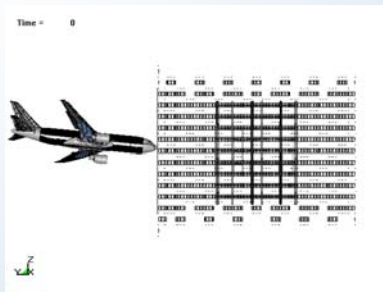
NIST developed and used a series of rigorous and comprehensive models to determine the probable collapse sequence for the WTC towers.

- Analyzed complete sequence of events:
 - aircraft impact damage to the buildings
 - spread of jet-fuel-ignited multi-floor fires
 - thermal weakening of structural components
 - progression of local structural failures until collapse initiation
- Combined:
 - mathematical modeling
 - well-established statistical and probability-based analysis methods
 - laboratory experiments
 - analysis of visual and physical evidence

Significantly advanced current state-of-the-art; tested the limits of current computational capabilities.

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WTC 1



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WTC 1 Damage: Composite Summary for Floors 93 to 98

Severe Floor Damage

Fireproofing and partitions

Floor system structural damage

Floor system removed

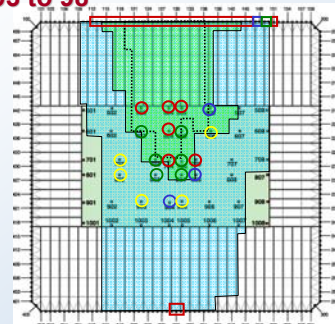
Column Damage

Severed

Heavy Damage

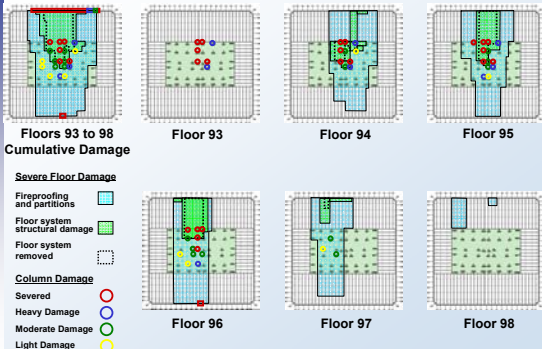
Moderate Damage

Light Damage



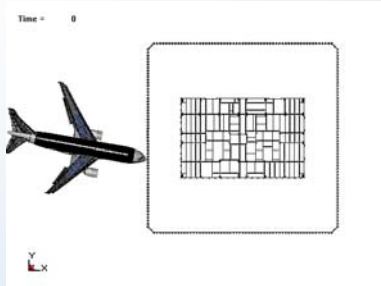
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WTC 1 Damage by Floor

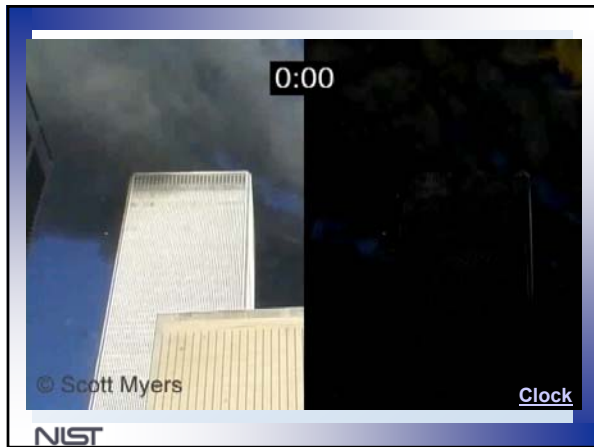
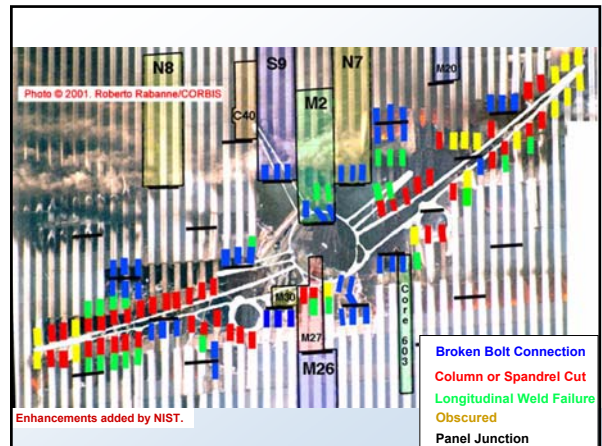
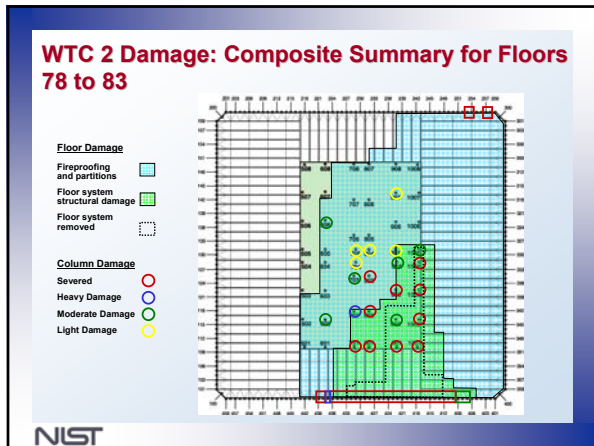


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WTC 2



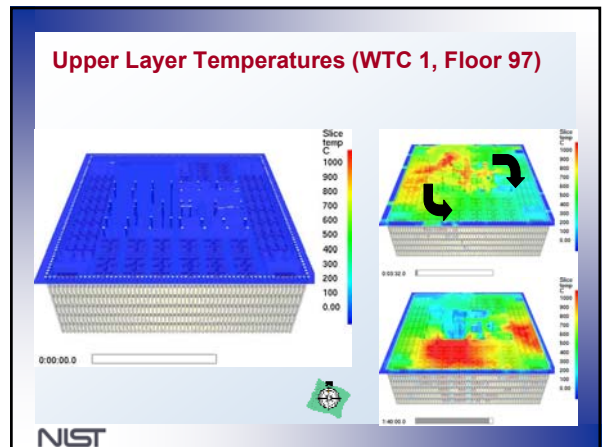
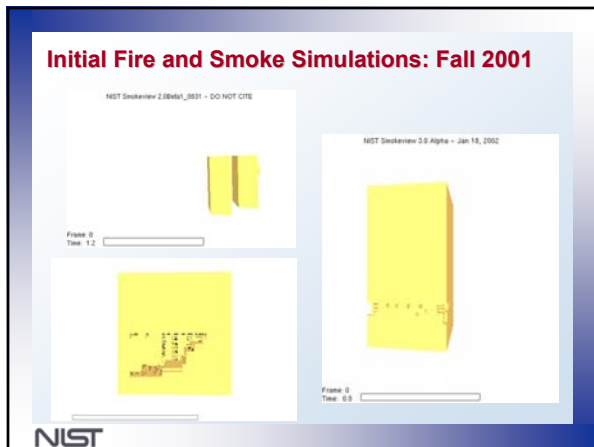
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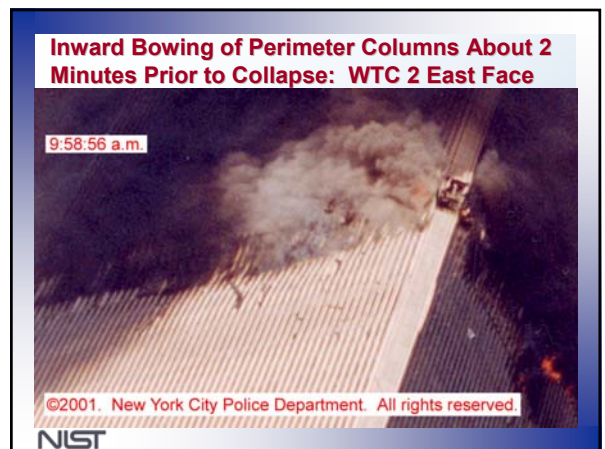
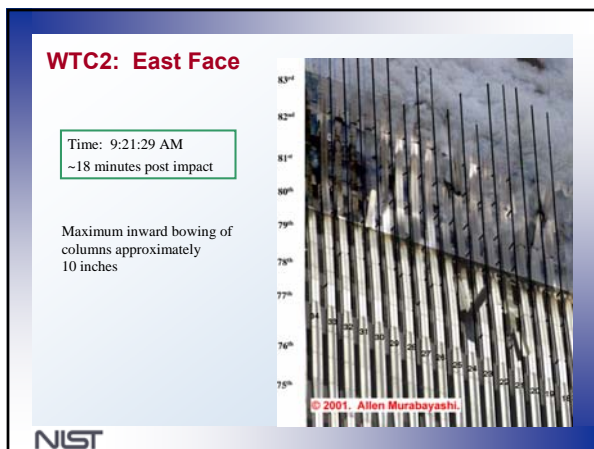
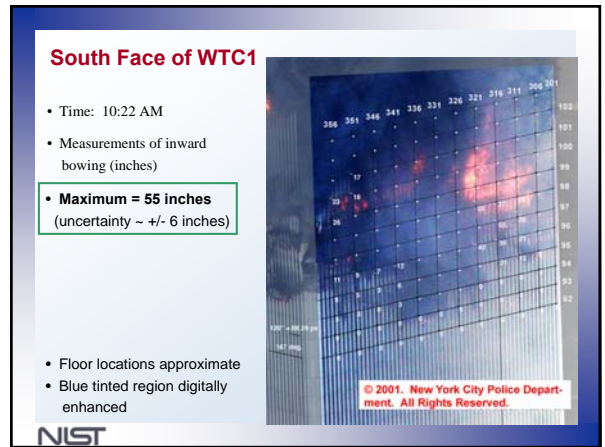
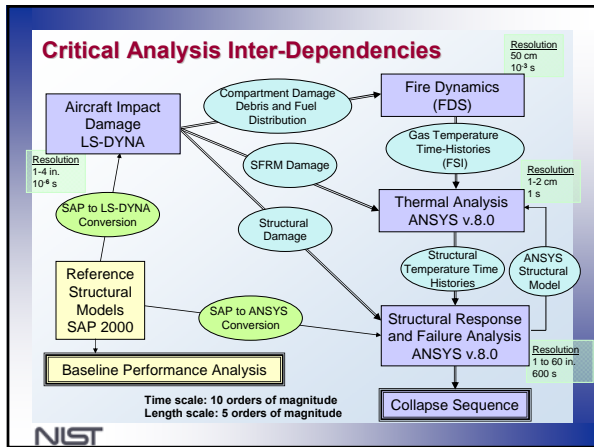
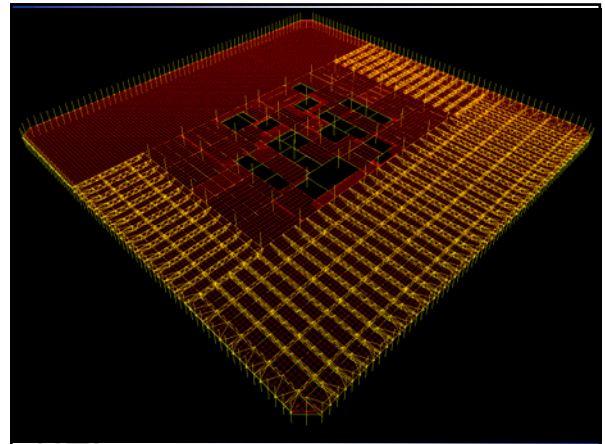
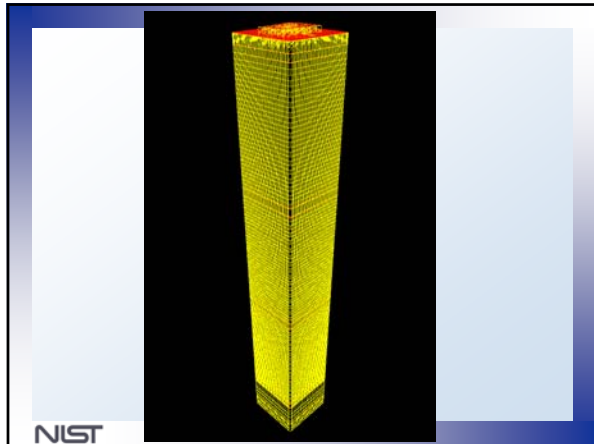


Relative Roles of Aircraft Impact and Fires

- Fires played a major role in further reducing structural capacity, initiating collapse.
- While aircraft impact did not initiate collapse, it contributed greatly to the subsequent fires and thermal response of the structures by:
 - Compromising 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 air supply into the damaged buildings, allowing fires to spread rapidly on multiple floors;
 - Damaging and dislodging fireproofing from structural components; and
 - Damaging ceilings that enabled "unabated" heat transport.

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Tilting of Building Sections

© 2001 Dean Riviere

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



Play
-0:00:02
SP



© Onno DeJong 2001

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

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Wind Load Estimates for WTC 2

Source	Year	Base Shear 10 ³ kips			Base Moment 10 ⁶ kips-ft		
		N-S	E-W	Resultant	About N-S	About E-W	Resultant
NYC Building Code	Prior to 1968	5.3	5.3		4.2	4.2	
NYC Building Code	1968 - 2001	9.3	9.3		7.6	7.6	
RWDI / NYC Building Code	2002	9.7	11.1	12.3	10.1	9.2	11.3
RWDI / ASCE 7-98	2002	10.6	12.2	13.5	11.1	10.1	12.4
CPP / NYC Building Code	2002	NA	NA	NA	NA	NA	NA
CPP / ASCE 7-98 ^a	2002	15.1	15.3	17.1	15.5	14.0	17.0
NIST / third-party SOM review / ASCE 7-02	2004	12.2	14.0	15.6	12.8	11.6	14.3
Original WTC Design (Clarified by designer in July 2004)	1960's	13.1	10.1	16.5	8.8	12.6	15.2

^a Using ASCE 7-98 sections 6.5.4.1 and 6.6

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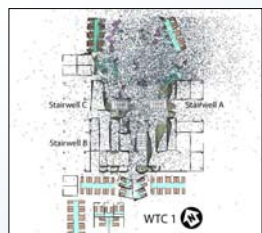
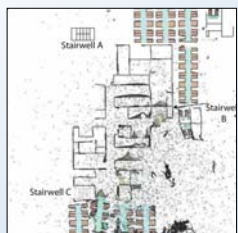
Results and Findings of Drift Analysis

Loading Case	WTC 1				WTC 2			
	E-W		N-S		E-W		N-S	
	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio
Original design case	56.6	H/304	55.7	H/309	51.2	H/335	65.3	H/263
SOP case	56.8	H/303	68.1	H/253	59.7	H/287	56.1	H/306
Refined NIST case	70.6	H/244	83.9	H/205	75.6	H/227	71.0	H/242

- The calculated drift ratios correspond to a **damping ratio of 2.5%** in estimated wind loads.
- Typical drift ratios considered in practice (not required by building codes):
 - H/500 (~ 32.9 in.)
- Limiting drift enhances structural stability and safety in tall buildings; this is already required to control damage in seismic regions.
- Acceleration limits used in current practice for occupant comfort (e.g., 15-20 mg) result in stricter control of drift.

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Condition of Stairwells

- The stairwells, with 2 h fire-rated enclosures and little structural integrity, were damaged in the region of the aircraft impacted floors.
- All 3 stairwells in WTC 1 and 2 stairwells in WTC 2 were rendered impassable.
- Stairwell A in WTC 2 was passable for some period of time.

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Context for Recommendations

- NIST's recommendations for improvements to codes, standards, and practices are applicable under the **hazards and conditions recognized in normal building design**.
- Public officials and building owners will need to determine appropriate performance requirements for **buildings that are at higher risk due to their iconic status, critical function, or design**.
- The recommendations are **performance-oriented**. They do not **prescribe** specific:
 - Systems, materials, or technologies.** NIST encourages competition among alternatives that can meet *performance requirements*.
 - Threshold levels.** This responsibility falls within the purview of the public policy and standards and codes development process.

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WTC Recommendations

- NIST has made **30 recommendations** for improvements to codes, standards, and practices which fall into **8 major groups**:
 - Increased Structural Integrity
 - Enhanced Fire Resistance of Structures
 - New Methods for Designing Structures to Resist Fires
 - Improved Active Fire Protection
 - Improved Building Evacuation
 - Improved Emergency Response
 - Improved Procedures and Practices
 - Education and Training Programs

Structural Design

Life Safety Systems

Practices & Development

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Increased Structural Integrity

Consensus standards and code provisions for **preventing progressive collapse** be developed and adopted nationwide – along with tools and guidelines for their use...and a standard methodology be developed to reliably **predict the potential for complex failures** in structural systems subjected to multiple hazards. Rec. #1

Nationally accepted performance standards be developed for:

- **wind tunnel testing** of prototype structures based on sound technical methods that result in **repeatable and reproducible results**; and
- **estimating wind loads** and their effects on tall buildings, based on wind tunnel testing data and directional wind speed data. Rec. #2

Appropriate criterion be developed and implemented to enhance performance of tall buildings by **limiting how much they sway** under lateral load design conditions (e.g., winds and earthquakes). Rec. #3

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Enhanced Fire Resistance of Structures

Improve the technical basis for century-old **standard for fire resistance testing** of components, assemblies, and systems and... develop **guidance for extrapolating results** of tested assemblies to prototypical building systems. A key step in fulfilling this recommendation is to establish a **capability for studying and testing** components, assemblies, and systems **under realistic fire and load conditions**. Rec. #5

Develop criteria, test methods, and standards:

- for **in-service performance of fireproofing** to protect structural components; and
- to ensure that **as-installed fireproofing** conforms to conditions in tests used to establish the fire resistance rating. Rec. #6

Adopt and use **"structural frame" approach** (structural members connected to the columns carry the high fire resistance rating of the columns). Rec. #7

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New Methods for Fire Resistance Design of Structures

Require that uncontrolled building fires result in **burnout without partial or global (total) collapse**. Rec. #8

Develop:

- **performance-based standards and code provisions** -- as an alternative to current prescriptive design methods -- to enable **design and retrofit of structures to resist real fire conditions**
- tools, guidelines, and test methods to **evaluate fire performance of the structure as a whole system**. Rec. #9

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New Methods for Fire Resistance Design of Structures (2)

Develop and evaluate **new fire resistive coating materials, systems, and technologies** with significantly enhanced performance and durability to provide protection following major events. Rec. #10

Evaluate performance and suitability of **advanced structural steel, reinforced and pre-stressed concrete, and other high-performance material systems** for use under conditions expected in building fires. Rec. #11

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Improved Building Evacuation

Design tall buildings to accommodate **timely full building evacuation of occupants when required** in building-specific or large-scale emergencies such as widespread power outages, major earthquakes, tornadoes, hurricanes, fires, explosions, and terrorist attack.

- Building size, population, function, and iconic status should be taken into account in designing the egress system.
- Stairwell capacity and stair discharge door width should be adequate to accommodate counterflow due to emergency access by responders. Rec. #17

Design egress systems:

- to **maximize remoteness of egress components** (i.e., stairs, elevators, exits) without negatively impacting the average travel distance;
- to maintain their functional **integrity and survivability** under foreseeable building-specific or large-scale emergencies; and
- with consistent layouts, standard signage, and guidance so that systems become **intuitive and obvious** to building occupants during evacuations. Rec. #18

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COLLAPSE OF WTC 7

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World Trade Center 7

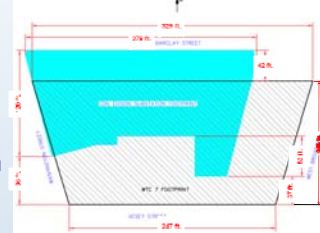
- WTC 7 was a 47 story office building located north of the WTC Complex.
 - Built over an existing Con Edison electric power substation, on land owned by The Port Authority of New York and New Jersey.
- On September 11, 2001, fires burned for almost seven hours, from the collapse of WTC 1 at 10:28:22 a.m. until 5:20:52 p.m., when WTC 7 collapsed.
 - The collapse of WTC 7 was the first known instance of the total collapse of a tall building primarily due to fires.



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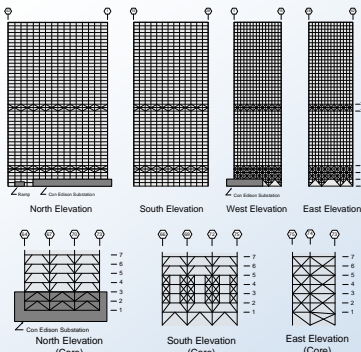
WTC 7 Structural Concept

- The 47 story building contained approximately 200,000 m² (2 million ft²) of floor area.
- Structurally, WTC 7 consisted of four "tiers":
 - The lowest four floors housed two 2-story lobbies. The north side of the 1st and 2nd stories was the Con Edison substation.
 - Floors 5 and 6 were mechanical spaces with transfer elements.
 - Floors 7 through 45 were tenant floors.
 - The 46th and 47th floors, while mainly tenant floors, were structurally reinforced to support special loads, such as cooling towers.



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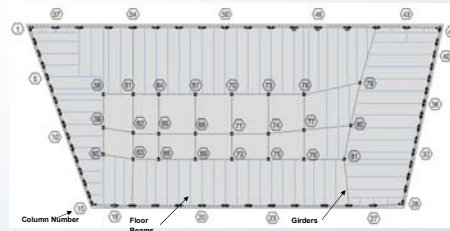
WTC 7 Framing



- The WTC 7 structural system was designed to distribute the weight of the building (gravity loads) and resist (lateral) wind loads.
- The frame included columns, floor assemblies, spandrel beams, girders, and transfer elements.
- The lateral loads were resisted by the exterior moment frame.
- The gravity loads were supported roughly equally by the 58 exterior columns and the 24 interior columns.

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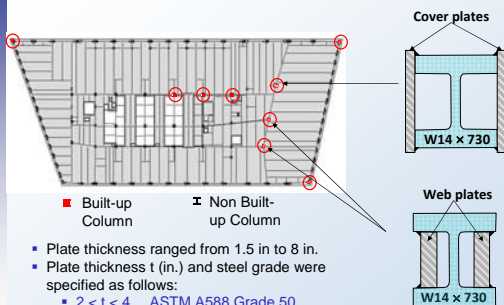
Typical WTC 7 Floor Framing



From the 7th floor to the 47th floor, WTC 7 was supported by 24 interior columns and 58 exterior columns. Columns 58 through 78 formed the building core. Columns 79, 80, and 81 were particularly large and supported long floor spans on the east side of the building.

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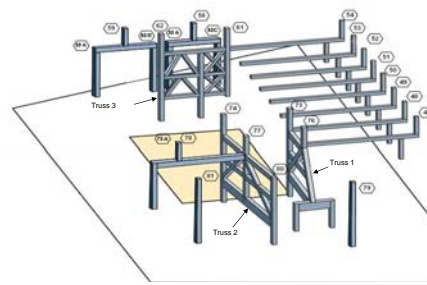
Built-up Columns on Lower Floors



- Built-up Column
 - Non Built-up Column
- Plate thickness ranged from 1.5 in to 8 in.
- Plate thickness t (in.) and steel grade were specified as follows:
 - $2 < t < 4$ ASTM A588 Grade 50
 - $4 < t < 6$ ASTM A572 Grade 42
 - $t > 6$ ASTM A588 Grade 42

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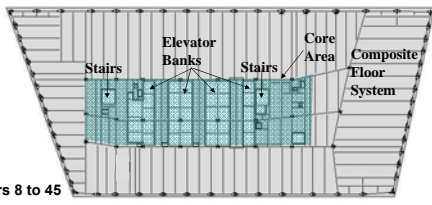
Transfer Trusses and Girders



The layout of the WTC 7 columns did not align with the building foundation and the Con Edison columns. Therefore, a set of column transfers were constructed between the 5th and 7th floor slabs.

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WTC 7 Floor System



Floors 8 to 45

- The floor slabs were reinforced concrete of varying thickness.
 - The concrete on most floors was poured on a 3 in. corrugated metal deck.
 - Floors 2, 3, 4, and 6 had a 6 in. total slab thickness.
 - On Floor 5, the concrete slab was 14 in. thick.
 - On Floor 7, had a 8 in. total slab thickness.
 - On Floors 8 through 47, the concrete slab was 5.5 in. thick.

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Analysis of Probable Collapse Sequence

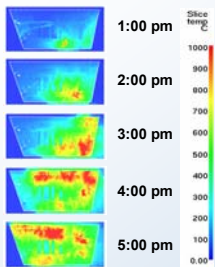
NIST developed and used a series of rigorous and comprehensive models to determine the probable collapse sequence for WTC 7

- Analyzed complete sequence of events:
 - Initial damage due to collapse of WTC 1
 - Growth and spread of fires
 - Thermal response of structural components
 - Thermally-induced initial local failure for collapse initiation
 - Collapse propagation, resulting in global collapse
- Combined:
 - Physics-based mathematical modeling
 - Analysis of visual evidence (photographs and videos)
 - Analysis of design, construction, and inspection documents

Significantly advanced current state-of-the-art;
Tested limits of current computational capabilities

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Fire Growth and Spread

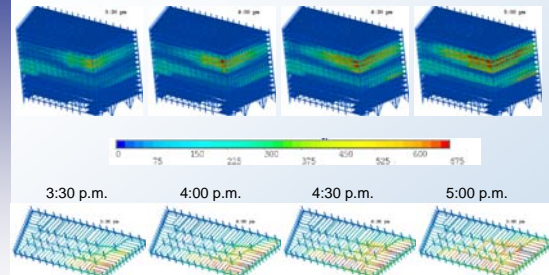


Progression of fires on Floor 12

- The major fires in WTC 7 were modeled using the Fire Dynamics Simulator (FDS).
 - There were far fewer photographs and videos of WTC 7 than of the towers.
 - The fire simulations for WTC 7 were conducted for each floor individually.
 - Sustained and/or late fires were observed only on Floors 7 through 9 and 11 through 13.
 - The actual fires on these floors were most likely initiated at the time of the collapsing towers.

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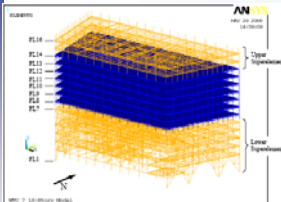
Thermal Response to Fire



Temperature distribution (°C) on the floor beams of Floor 13.

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ANSYS Structural Response Model

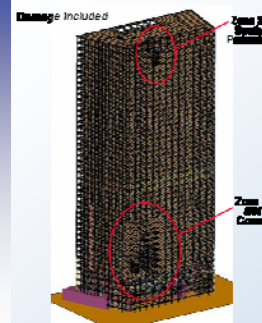


- Floor framing between Floors 8 and 14 and columns between Floors 7 and 14 were explicitly modeled while Floor 7 and below and Floors 15 and 16 were modeled using superelements.

- The 16-story ANSYS model was used to determine the sequence of events that led to fire-induced collapse initiation.
- Software: double precision version of ANSYS 11.0
- Model
 - 93,413 Nodes
 - 101,357 Elements
- Computer
 - 64-bit workstation
 - quad-core, 3.0 GHz processor
 - 64 GB of random access memory (RAM)
- Analysis Time
 - approximately 6 months

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LS-DYNA Structural Response Model



- The LS-DYNA model was used to determine the sequence of events that led to global collapse.
- Software: double precision version of LS-DYNA
- Model
 - 3,593,049 Nodes
 - 3,045,925 Elements
- Computer
 - High speed Linux computer cluster.
 - 1.5 terabytes of RAID 5 disk storage
 - 64-bit 2.6 GHz processors, with 8 GB to 16 GB of RAM
- Analysis Time
 - Up to 8 weeks

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Summary of Probable Collapse Sequence (1)



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

Aerial photograph shot $14 \text{ s} \pm 0.5 \text{ s}$ after WTC 1 began to collapse.

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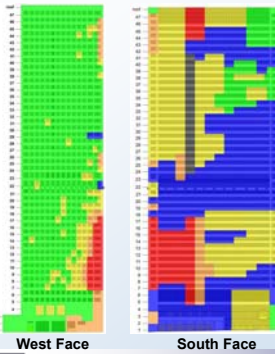
Debris Impact Damage to WTC 7



- Enlargement of a photograph showing part of the west face of WTC 7.
- Arrows and floor numbers have been added for the corresponding rows of windows.

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Observed Debris Impact Damage to WTC 7



- green (■) - no visible damage
- yellow (■) - window glass broken
- orange (■) - granite and underlying truss damage
- red (■) - damage to exterior structural steel
- gray (■) - vertical dark band
- blue (■) - not visible due to smoke, dust, and intervening buildings.

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Summary of Probable Collapse Sequence (2)



- **Growth and Spread of Fires.**
- Fires on Floors 7 to 9 and 11 to 13 grew and spread since they were not extinguished either by the automatic sprinkler system or by FDNY because water was not available.
- Fires were generally concentrated on the east and north sides beginning at about 3 p.m. to 4 p.m.
- The local fires on Floors 19, 22, 29, and 30 were not observed after ~ 1 p.m.

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Observed Fires



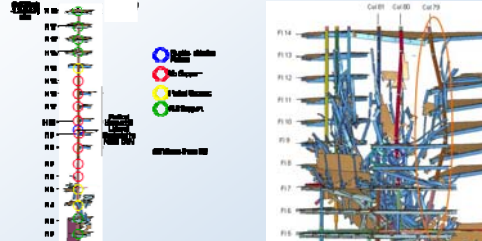
- Cropped photograph of north face taken between 3:11:15 p.m. and 3:16:51 p.m.

- Cropped photograph showing part of north face at 4:39 p.m. $\pm 120 \text{ s}$.

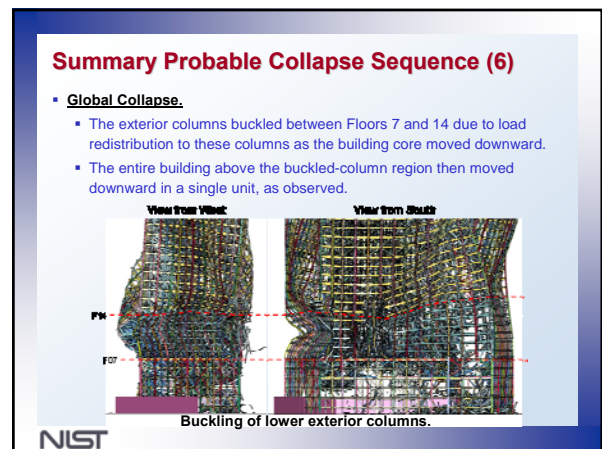
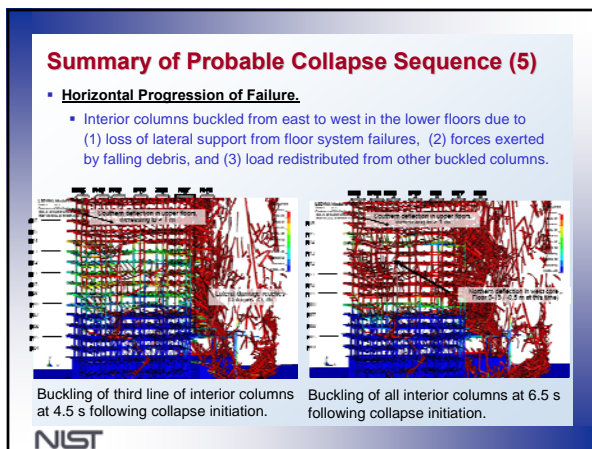
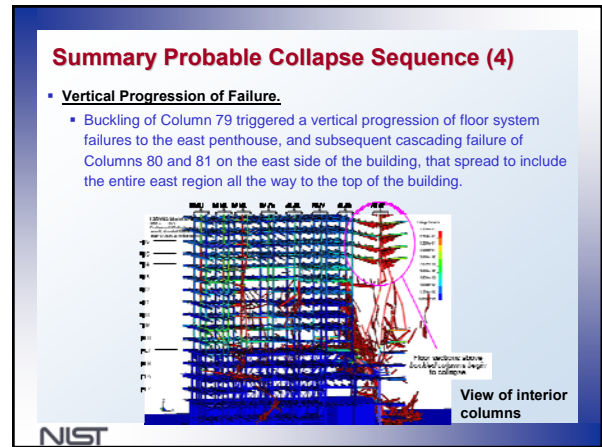
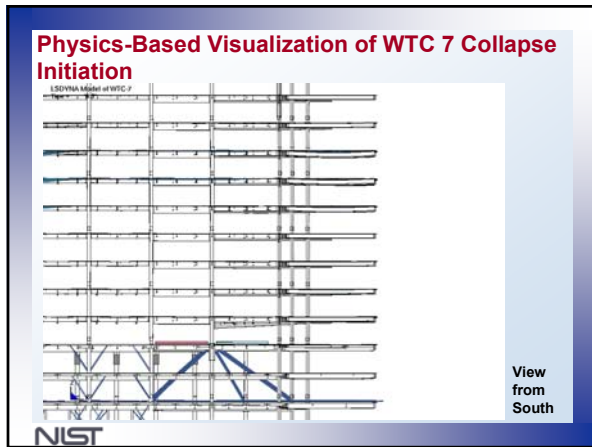
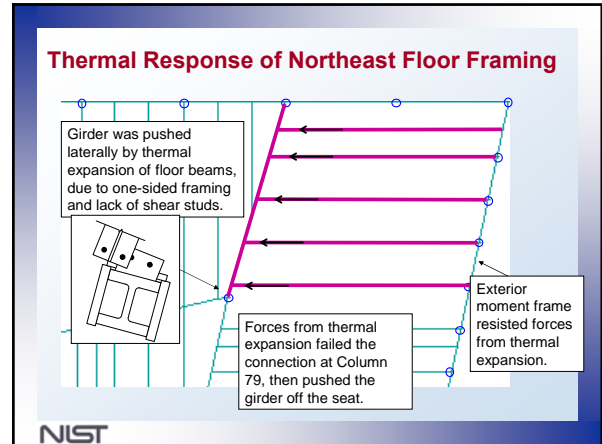
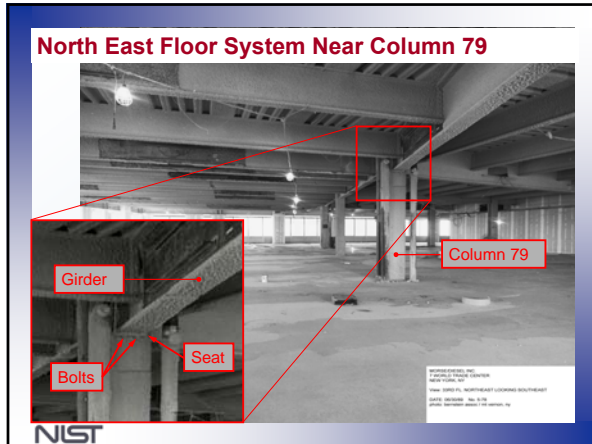
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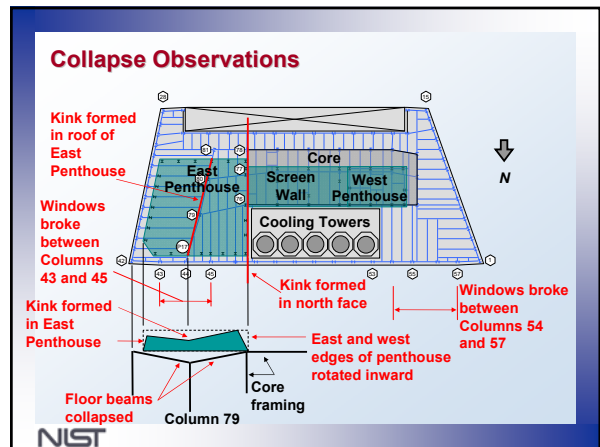
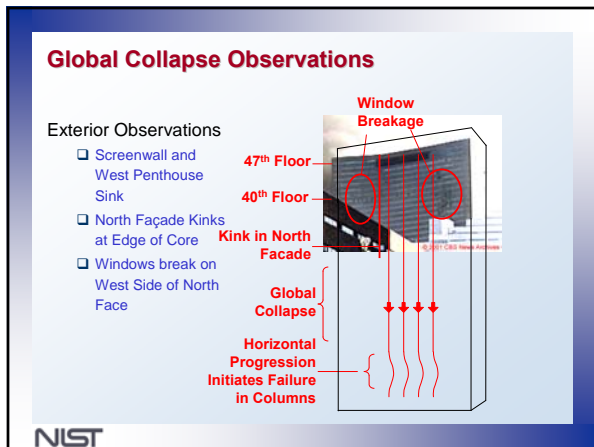
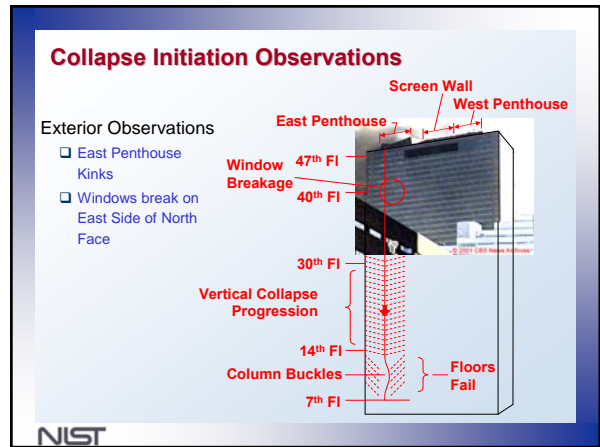
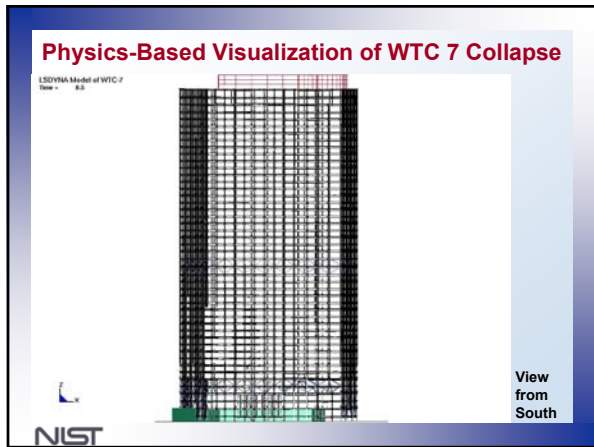
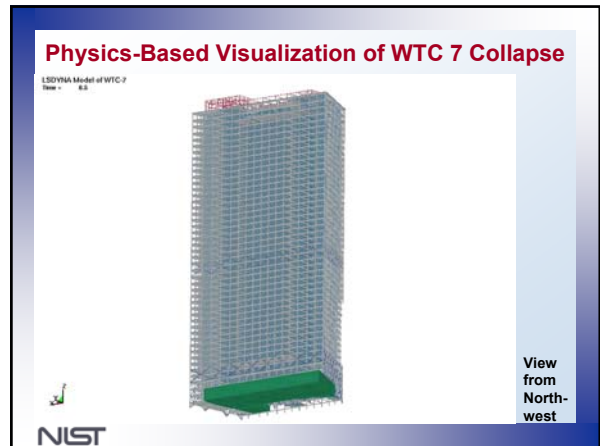
Summary Probable Collapse Sequence (3)

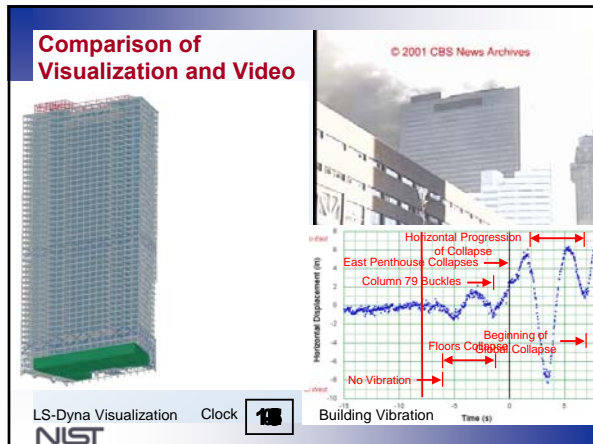
- **Initial Local Failure for Collapse Initiation.**
- Fire-induced thermal expansion of the floor system surrounding Column 79 led to the collapse of Floor 13 and triggered a cascade of floor failures.
- This, in turn, led to loss of lateral support to Column 79 over nine stories, resulting in the buckling failure of Column 79.



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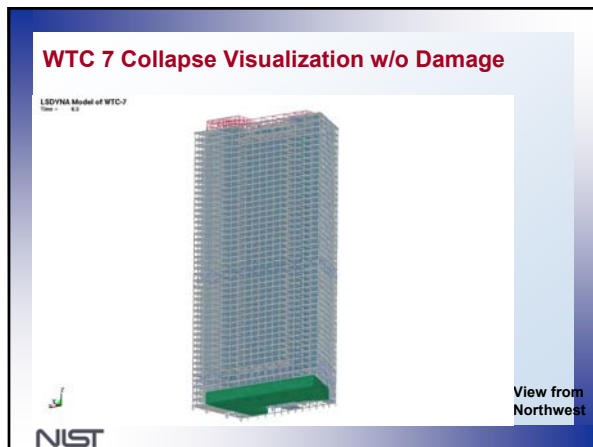


Accuracy of the Probable Collapse Sequence

Event	Observation Time (s)	Analysis w/Debris Damage (s)	Analysis w/o Debris Damage (s)
Cascading failure of floors surrounding Column 79	≈ -0 s	-6.6 s	-6.6 s
Buckling of Column 79, followed by Columns 80 and 81	Not observable	-1.3	-1.4
East penthouse starts to fall	0.0	0.0	0.0
East penthouse falls below roofline	2.0	2.4, 2.7	2.3, 2.6
Buckling of columns across core	Not observable	3.5, 6.1	3.2, 13.5
Initial downward motion of the north face roofline	6.9	6.3	9.8
East end of the screenwall falls below the roofline	8.5	7.3, 7.7	8.7, 9.2
West penthouse falls below the roofline	9.3	6.9, 7.3	10.6, 10.9

Agreement between observations and simulations is good; results with debris damage better match observations of overall global collapse sequence.

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- ### Principal Findings for Objective 1: Probable Collapse Sequence
- WTC 7 withstood debris impact damage that severed seven exterior columns and subsequent conventional fires on several floors for almost seven hours.
 - The collapse of WTC 7 represents the first known instance of the total collapse of a tall building primarily due to fires.
 - WTC 7 collapsed due to uncontrolled fires with characteristics similar to previous fires in tall buildings.**
 - The fires in WTC 7 were similar to those that have occurred previously in several tall buildings (One New York Plaza, 1970, First Interstate Bank, 1988, and One Meridian Plaza, 1991) where the automatic sprinklers did not function or were not present.
 - These three buildings, however, did not collapse because of differences between their structural designs and that of WTC 7.
 - Had a water supply for the automatic sprinkler system been available and had the sprinkler system operated as designed, it is likely that fires in WTC 7 would have been controlled and the collapse prevented.
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- ### Principal Findings for Objective 1: Probable Collapse Sequence (2)
- Observations support a single point of fire ignition on any given floor.**
 - In most instances, the fire on any given floor likely initiated near the damaged southwest region.
 - Unlike the WTC towers, there was no dispersion of jet fuel in WTC 7 causing simultaneous fire initiation over extensive areas of multiple floors.
 - The probable collapse sequence was initiated by the buckling of Column 79, which was unsupported over nine stories, after local fire-induced damage led to a cascade of floor failures.**
 - The buckling of Column 79 led to a vertical progression of floor failures up to the east penthouse and to the buckling of Columns 80 and 81.
 - An east-to-west horizontal progression of interior column buckling followed.
 - The exterior columns then buckled as the failed building core moved downward, redistributing its loads to the exterior columns.
 - Global collapse occurred as the entire building above the buckled region moved downward as a single unit.
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- ### Principal Findings for Objective 1: Probable Collapse Sequence (3)
- The collapse of WTC 7 was a progressive collapse.**
 - Progressive collapse—also known as disproportionate collapse—is defined as the spread of local damage, from an initiating event, from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it (ASCE 7-05).
 - Despite extensive thermal weakening of connections and buckled floor beams, **fire-induced damage in the floor framing surrounding Column 79 over multiple stories was the determining factor causing the buckling of Column 79 and, thereby, initiating progressive collapse.**
 - This is the **first known instance where fire-induced local damage** (i.e., buckling failure of Column 79; one of 82 columns in WTC 7) **led to the collapse of an entire tall building.**
 - The transfer elements (trusses, girders, and cantilever overhangs) did not play a significant role in the collapse of WTC 7. Likewise, the Con Edison substation did not play a significant role in the collapse of WTC 7.
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Principal Findings for Objective 1: Probable Collapse Sequence (4)

- Prior to the collapse, there was no damage to the SFRM that was applied to the steel columns, girders, and beams, except in the vicinity of the structural damage from the collapse of WTC 1.
- **Even without the initial structural damage caused by debris impact from the collapse of WTC 1, WTC 7 would have collapsed from fires having the same characteristics as those experienced on September 11, 2001.**
- Early stage fires in the southwest region did not play a role in the collapse of WTC 7. Unlike the northeast region where collapse initiated:
 - there were no columns supporting long span floors in the southwest region.
 - the fires in this region were not severe enough since they had not fully developed and there were few combustibles in the adjacent core area.
- **Collapse time of the north face of the upper 18 floors (the floors clearly visible in video evidence) was 40 percent greater than the computed free fall time.**
 - The actual time for the north face to fall 18 floors was ~ 5.4 s
 - The computed time for free fall (i.e., with no air friction) was 3.9 s.

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Principal Findings for Objective 1: Probable Collapse Sequence (5)

- **Diesel fuel fires did not play a role in the collapse of WTC 7.** The worst-case scenarios for fires being fed by ruptured fuel lines or day tanks:
 - could not have been sustained long enough, or generated sufficient heat, to cause significant loss of strength/stiffness in a critical column
 - would have produced large amounts of smoke from the exhaust louvers. No such smoke discharge was observed.
- **Hypothetical blast events did not play a role in the collapse of WTC 7.**
 - Based on visual and audio evidence and computer modeling, NIST concluded that blast events did not occur, and found no evidence of a blast.
 - Blast from the smallest charge capable of failing a critical column would have resulted in a sound level of 130 dB to 140 dB at approximately half a mile.
 - This sound level is consistent with a gunshot blast, standing next to a jet engine, and 10 times louder than being in front of speakers at a rock concert.
 - There were no witness reports of such a loud noise, nor was such a noise heard on the audio tracks of video recordings of the WTC 7 collapse.

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Principal Findings for Objective 3: Procedures and Practices (1)

- The design of WTC 7 was generally consistent with the NYCBC.
- **Current practice for the fire resistance design of structures, based on the use of ASTM E 119 standard test method, is deficient since the method was not designed to include key fire effects that are critical to structural safety. Specifically, current practice does not capture:**
 - *thermally-induced interactions between structural subsystems, elements, and connections—especially restraint conditions.*
 - *system-level interactions—especially those due to thermal expansion—since columns, girders, and floor subassemblies are tested separately.*
 - *the performance of connections under both gravity and thermal effects.*
 - *scale effects in buildings with long span floor systems.*

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Principal Findings for Objective 3: Procedures and Practices (2)

- **Current practice does not require design professionals to possess the qualifications necessary to ensure adequate passive fire resistance of the structural system.** In current practice,
 - Architects typically rely on catalogued ASTM E 119 test data to specify the required passive fire protection to comply with the building code.
 - Structural engineers are not required to consider fire as a load condition in structural design.
 - Fire protection engineers may or may not be called upon to assist the architect in specifying the required passive fire protection.

Thus, **none of the key professionals is assigned the responsibility to ensure the adequate fire performance of the structural system.**
- **There is a critical gap in knowledge about how structures perform in real fires,** particularly considering: the effects of the fire on the entire structural system; the interactions between the subsystems, elements, and connections; and scaling of fire test results to full-scale structures (especially for structures with long span floor systems).

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WTC 7 Recommendations

- Based on its findings, NIST identified **one new recommendation** and **reiterated 12 recommendations** from its Investigation of the WTC towers.
 - **The urgency of prior recommendations is significantly reinforced by their pertinence to the collapse of a tall building with a structural system design that is in widespread use.**
- The **13 recommendations** for improvements to codes, standards, and practices fall into **7 of the 8 major groups**:
 - ☐ Increased Structural Integrity
 - ☐ Enhanced Fire Resistance of Structures
 - ☐ New Methods for Designing Structures to Resist Fires
 - ☐ Improved Active Fire Protection
 - ☐ Improved Building Evacuation (not applicable for WTC 7)
 - ☐ Improved Emergency Response
 - ☐ Improved Procedures and Practices
 - ☐ Education and Training Programs

Structural Design
Life Safety Systems
Practices & Development

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Comparison of WTC 7 and WTC Towers

- WTC 7 was unlike the WTC towers in many respects:**
- It was a more typical tall building in the design of its structural system.
 - It was not struck by an aircraft.
 - The fires in WTC 7 were quite different from those in the towers. Since WTC 7 was not doused with thousands of gallons of jet fuel, large areas of any floor were not ignited simultaneously.
 - Instead, the fires in WTC 7 were similar to those that have occurred in several tall buildings where the automatic sprinklers did not function or were not present.
 - These other buildings did not collapse due to differences in structural design, while WTC 7 succumbed to its fires.

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Key Premise

- The partial or total collapse of a building due to fires is an infrequent event.
- This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system.
- A properly designed and operating automatic sprinkler system will contain fires while they are small and, in most instances, prevent them from growing and spreading to threaten structural integrity.
- The intent of current practice, based on prescriptive standards and codes, is to achieve life safety, not collapse prevention.
- **Buildings, however, should not collapse in infrequent (worst-case) fires that may occur when active fire protection systems are rendered ineffective (e.g., when sprinklers do not exist, are not functional, or are overwhelmed by the fire).**
- Fire scenarios for structural design based on single compartment or single floor fires are not appropriate representations of infrequent fire events. Such events occurred in several tall buildings resulting in unexpected substantial losses.

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Historic Tall Building Fires



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Characteristics of Infrequent (Worst-Case) Fire Events for Structural Design Based on Historical Data

- Ordinary combustibles and combustible load levels.
- Local fire origin on any given floor.
- No widespread use of accelerants.
- Consecutive fire spread from combustible to combustible.
- Fire-induced window breakage providing ventilation for continued fire spread and accelerated fire growth.
- Concurrent fires on multiple floors.
- Active fire protection systems rendered ineffective (e.g., sprinklers do not exist, are not functional, or are overwhelmed by fire).

The fires in WTC 7 had all of these characteristics.

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Recommendations for Group 2: Enhanced Fire Endurance of Structures

Recommendation B (New). NIST recommends that buildings be explicitly evaluated to ensure adequate performance of the structural system under worst-case design fires with active fire protection systems rendered ineffective. Of particular concern are buildings with one or more of the following features:

long-span floor systems, connection designs that cannot accommodate thermal effects, floor framing that induces asymmetric thermally-induced forces on girders, shear studs that could fail due to differential thermal expansion in composite floor systems, and lack of shear studs on girders.

Careful consideration should also be given to the possibility of other design features that may adversely affect the performance of the structural system under fire conditions.

Relevance to WTC 7: The effects of restraint of thermal expansion on steel framing systems, especially the long spans on the east side of WTC 7, were not considered in the structural design and led to the initiation of global collapse.

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Details of Recommendation B (New)

- Typical floor span length in tall office buildings is in the range of 40 ft to 50 ft; this range is considered to represent long-span floor systems.
- Thermal effects (e.g., thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.
- **Building owners, operators, and designers are strongly urged to act upon this recommendation.** Engineers should be able to design cost-effective fixes to address any areas of concern identified by the evaluations using existing, emerging, or anticipated future capabilities.
- Industry should partner with the research community to fill **critical gaps in knowledge about how structures perform in real fires**, particularly considering:
 - the effects of fire on the entire structural system;
 - the interactions between subsystems, elements, and connections;
 - scaling of fire test results to full-scale structures, especially for structures with long span floor systems.

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Implementing the WTC Recommendations

- NIST believes the WTC recommendations are realistic, appropriate, and achievable within a reasonable period of time.
- NIST strongly urges that immediate and serious consideration be given to these recommendations by the building and fire safety communities.
- Implementation of these recommendations will achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used—with the goal of making buildings safer in future emergencies.

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Implementing the WTC Recommendations (2)

- NIST has assigned **top priority to work vigorously with the building and fire safety communities** to assure that there is a *complete understanding* of the recommendations and to provide needed *technical assistance*.
- Key U.S. standards and codes development organizations are seriously considering the WTC recommendations and the **first comprehensive set of model building code changes have been adopted in the International Building Code**.
- The WTC recommendations already are having a significant impact on the construction of iconic high-rise buildings worldwide, including the **Freedom Tower**.
- NIST has implemented a web-based system so that the public can track progress on implementing the recommendations.

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Changes to Building Codes and Standards

- First comprehensive set of eight model building code changes based on recommendations from NIST's WTC investigation were adopted by the International Building Code in 2007.
- Second set of eight model building code changes based on NIST's WTC recommendations were approved by technical committees and are awaiting approval, along with potential appeals on several other code changes, at the Final Action Hearing for the 2009 edition of the International Building Code
- NIST's WTC Recommendations have spurred actions to develop new provisions/ guidelines within other standards, codes, and industry organizations, such as:
 - National Fire Protection Association, American Society of Mechanical Engineers, ASTM International, American Society of Civil Engineers, and the Council on Tall Buildings and Urban Habitat

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