NIST's Findings On The World Trade Center Fire and Collapse

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National Context

- The collapse of the World Trade Center structures following the terrorist attacks of September 11, 2001 was one of the worst-ever building disasters in recorded history – killing 2749 people.
- More than 400 fire and emergency responders were among those killed, the largest loss of life for this group in a single incident.
- Strong private sector, public, and Congressional demand for a comprehensive response to the World Trade Center disaster.
- Congress passed and the President signed into law on October 1, 2002, the National Construction Safety Team (NCST) Act.
    - Gives NIST authorities to investigate building failures.
    - Modeled after the NTSB, with some differences.

NCST Advisory Committee

- Appointed by the NIST Director.
- Functions…
  - Review procedures and reports
  - Evaluate activities of teams
  - Assess implementation of recommendations
  - Annual report to Congress
- Reviewed WTC Investigation plan, progress, findings, draft recommendations at 6 meetings.
- Reviewed all WTC progress & final reports
- Membership balances broad scope of disciplines and interests

Members

Dr. Charles Thornton, Co-Chairman, Thornton-Tomasetti.

Dr. Robert Hanson, Professor Emeritus, University of Michigan.

Mr. Philip DiNenno, President, Hughes Associates.

Professor Glenn Corbett, John-Jay College, NYC.

Dr. Kathleen Tierney, University of Colorado, Boulder.

Mr. Paul Fitzgerald, FM Global, (ret.)

Mr. David Collins, The Preview Group.

Professor Forman Williams, University of California at San Diego.

Dr. John Barsom, President, Barsom Consulting.

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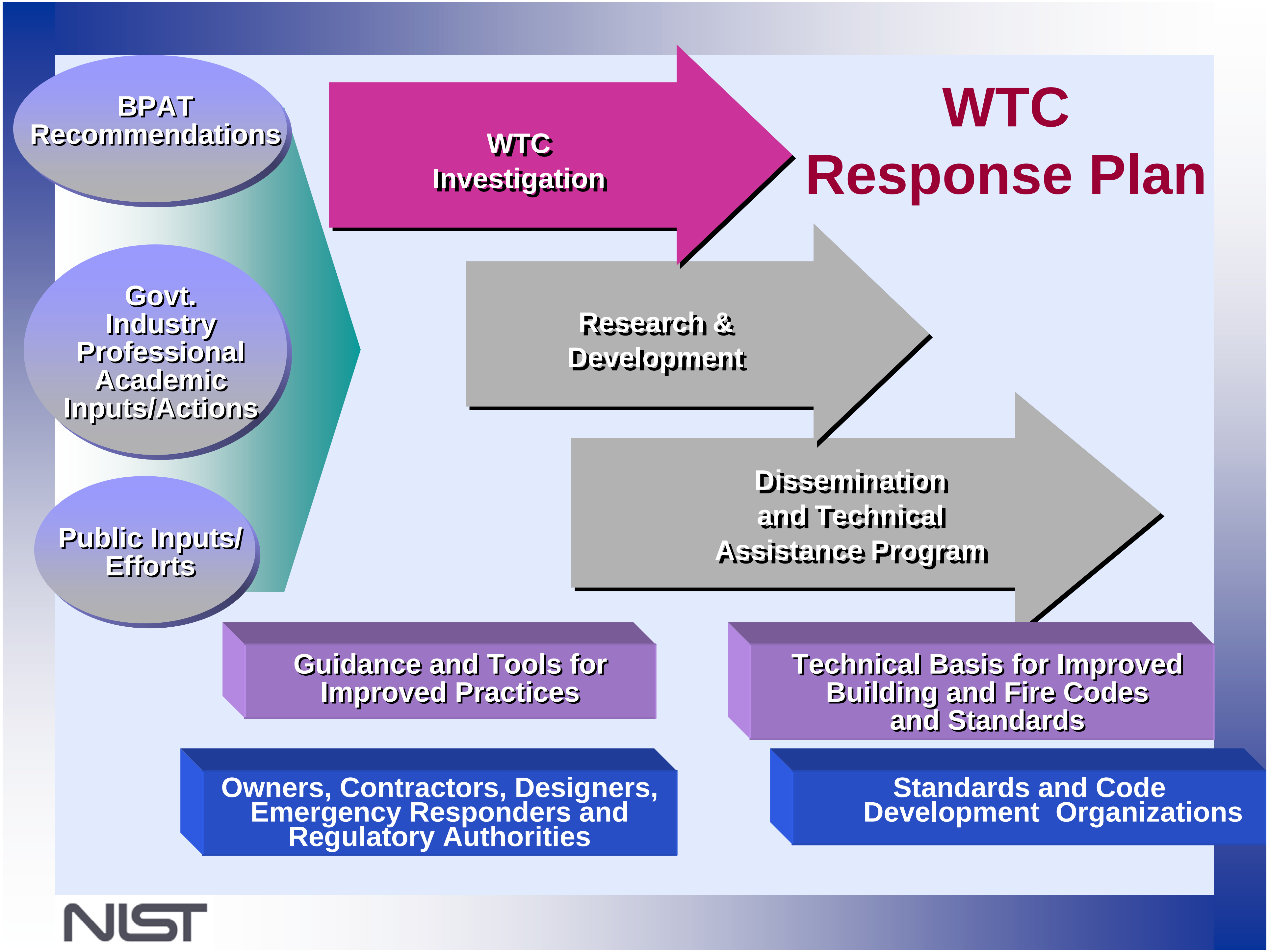
WTC Response Plan
BPAT Recommendations
Govt. Industry Professional Academic Inputs/Actions
Public Inputs/ Efforts
WTC Investigation
Research & Development
Dissemination and Technical Assistance Program
Guidance and Tools for Improved Practices
Technical Basis for Improved Building and Fire Codes and Standards
Owners, Contractors, Designers, Emergency Responders and Regulatory Authorities
Standards and Code Development Organizations
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NIST WTC Investigation Objectives

- Determine:
  - why and how the WTC Towers collapsed following the initial impact of the aircraft, and
  - why and how the 47-story WTC 7 collapsed
- Determine why the numbers of injuries and fatalities were so low or high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response
- Determine the procedures and practices that were used in the design, construction, operation, and maintenance of the WTC buildings
- **Identify, as specifically as possible, areas in current national building and fire model codes, standards, and practices that warrant revision**

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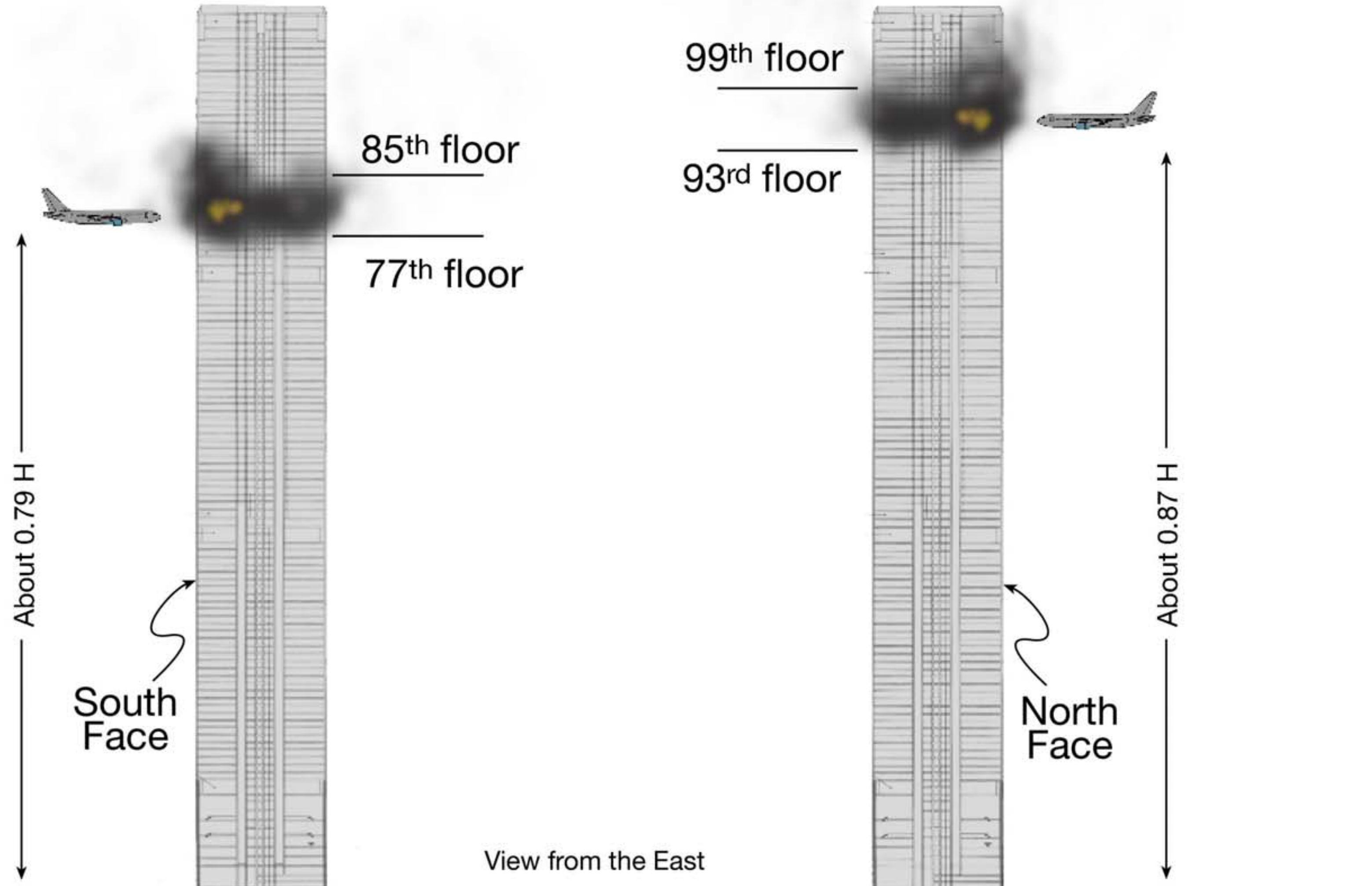
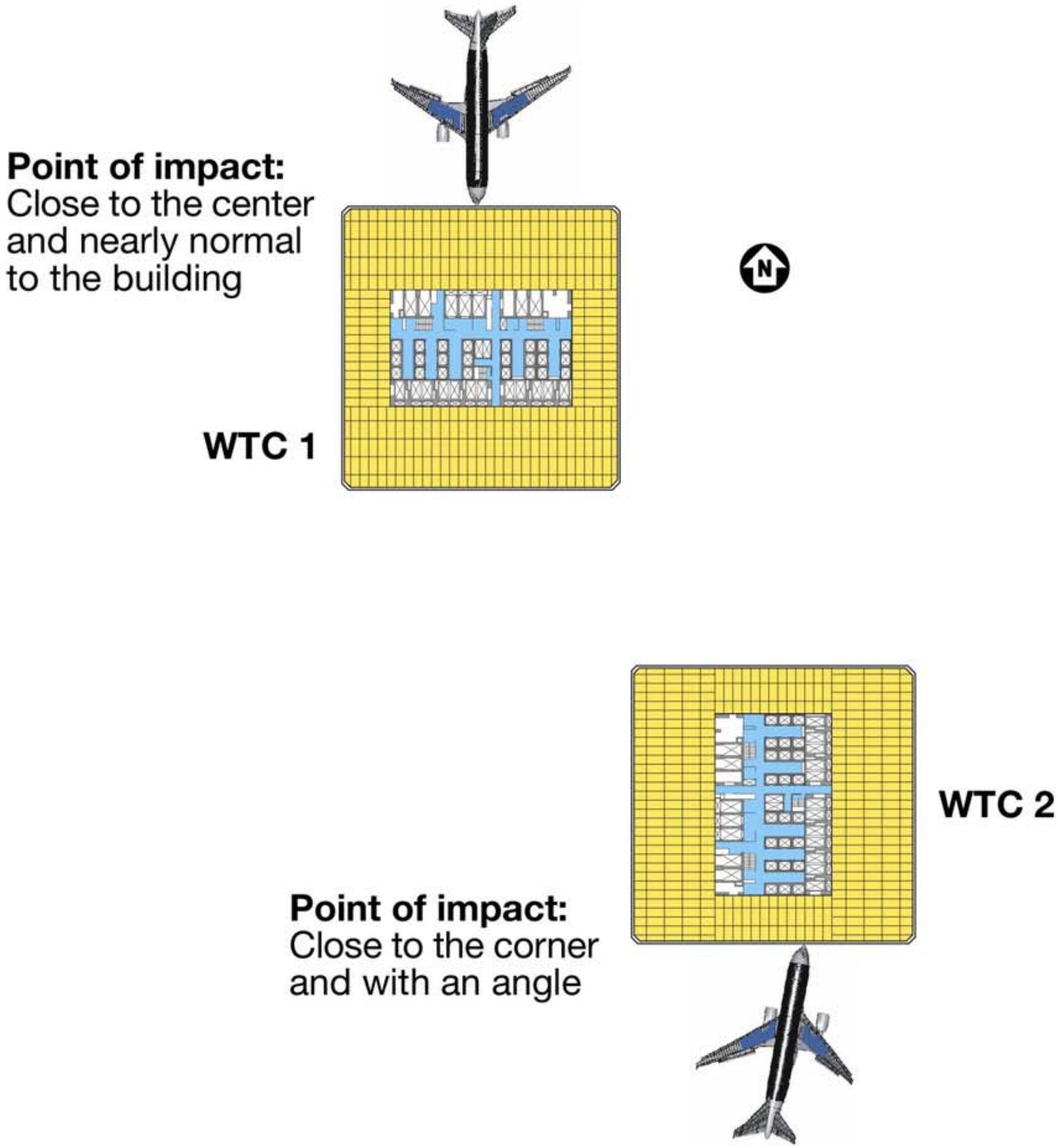


WTC 2: Hit at 9:02:59 a.m.
Collapsed after 56 minutes

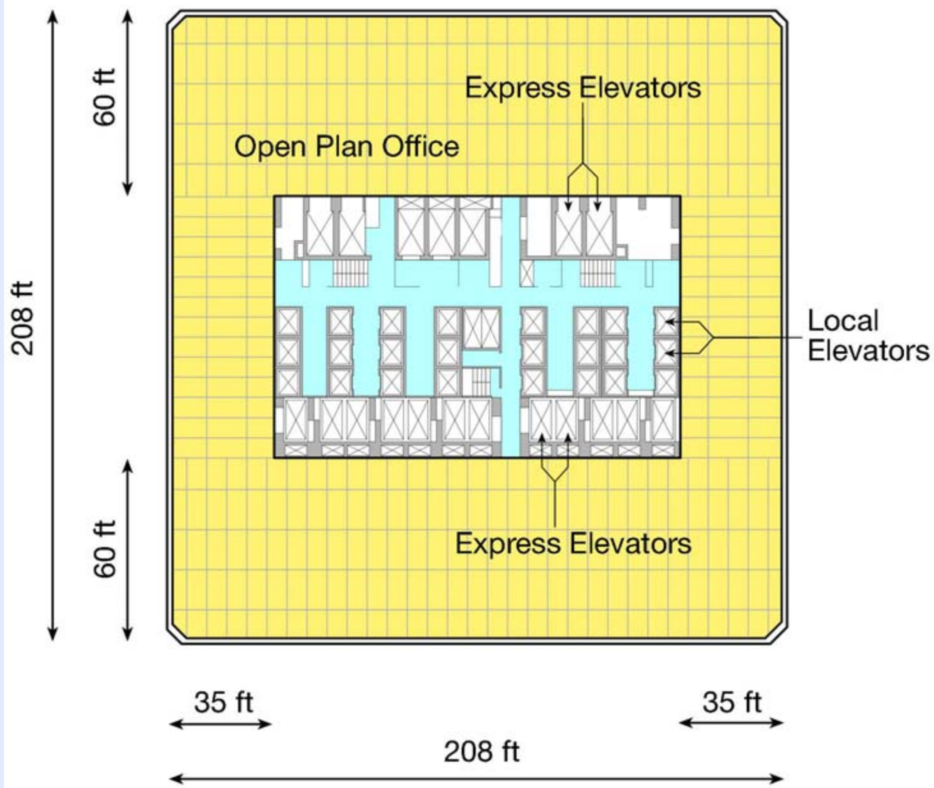
WTC 1: Hit at 8:46:30 a.m.
Collapsed after 102 minutes

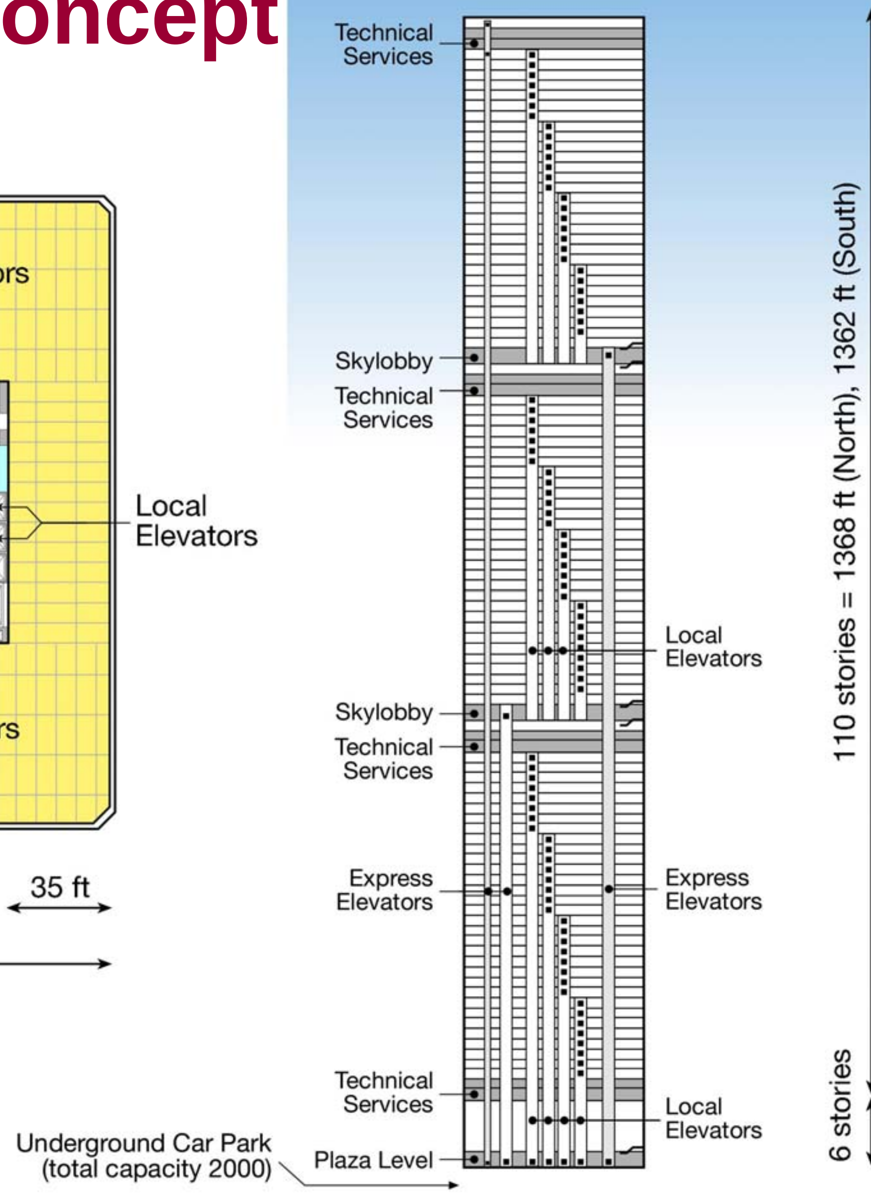

Point of impact:
Close to the center
and nearly normal
to the building
WTC 1
N
WTC 2
Point of impact:
Close to the corner
and with an angle

Some Specific Questions

- How and why did WTC 1 stand nearly **twice** as long as WTC 2 before collapsing (102 min. vs. 56 min.) though they were hit by virtually identical aircraft?
- What factors related to **normal** building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?
- Would the undamaged WTC towers have remained standing in a **conventional** large building fire scenario?
- What factors related to **normal** building and fire safety considerations, if any, could have saved additional WTC occupant lives or could have minimized the loss of life among the ranks of first responders?
- How well did the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings **conform** to accepted national practices, standards, and codes?

System Design Concept





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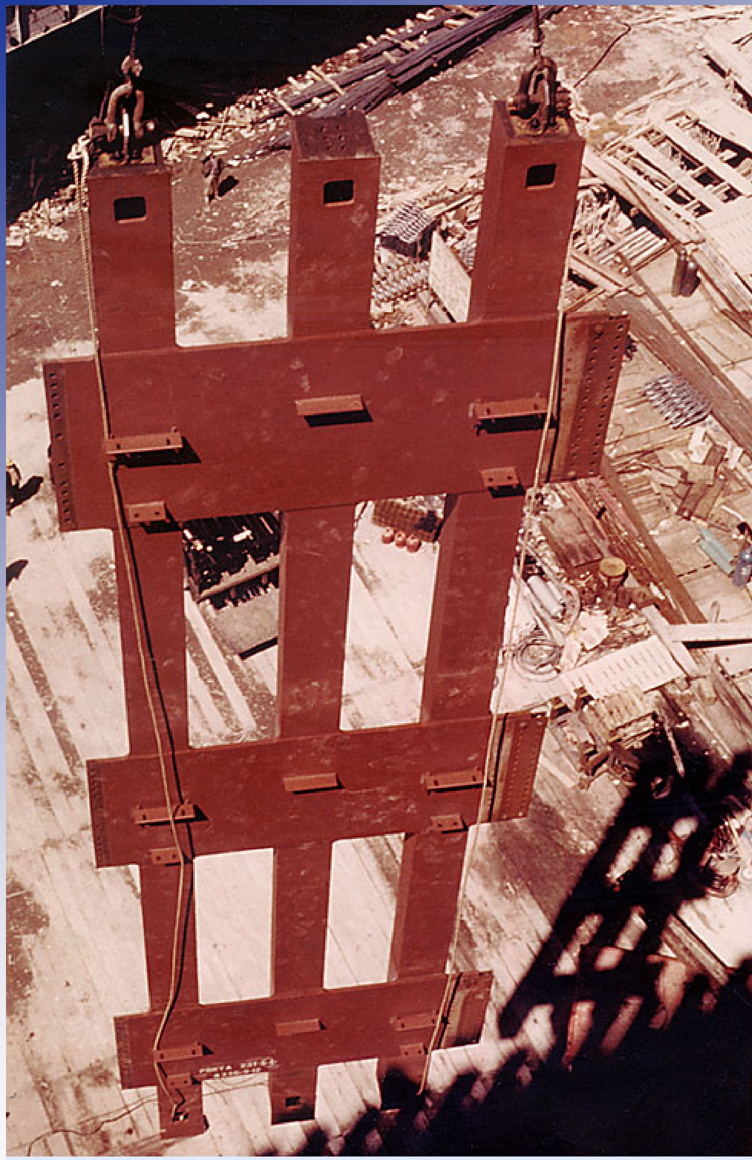

Available Information on Safety of WTC Towers in Aircraft Collision (1)

Type of Aircraft:	Boeing 707 (largest jet aircraft in the air at that time) DC-8
Speed of Aircraft:	600 mph (Port Authority, February 1964) 180 mph (FEMA 403, 2002)
Location of Impact:	80th floor (Port Authority, March 1964)
Structural design:	It appears that the design of the WTC towers considered the impact of 707 aircraft and **analysis** indicated that such collision would result in only local damage which could not cause collapse or substantial damage to the building ***NIST found no documentary evidence of any analysis supporting this conclusion.***

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Available Information on Safety of WTC Towers in Aircraft Collision (2)

Fire safety: There are two views on whether the effect of jet fuel and aircraft contents was a consideration in the original building design:

- One view suggests that an analysis was done indicating the biggest problem would be the fact that all the fuel would dump into the building and there would be a horrendous fire.
- Another view suggests that the fuel load, and the fire damage that it would cause, may not have been considered.

Life safety: There are two views on what would be the effect of aircraft impact on occupant life safety.

- One view, which did not consider the fires, suggests that the aircraft impact would not have endangered the lives and safety of occupants not in the immediate area of impact
- Another view, which considered the fires, recognized that many people would not survive even though the building structure would remain.

Context of Findings

- **Buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners.** While documents from the Port Authority of New York and New Jersey (PANYNJ) indicate that the impact of a Boeing 707 flying at 600 mph, possibly crashing into the 80^{th} floor, was analyzed during the design of the WTC towers in February/March 1964, the effect of the subsequent fires was not considered. **Building codes do not require building designs to consider aircraft impact.**

- **Buildings are not designed for fire protection and evacuation under the magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001.**

- **The load conditions induced by aircraft impacts and the extensive fires** on September 11, 2001, which triggered the collapse of the WTC towers, **fall outside the norm of design loads considered in building codes.**

- **Prior evacuation and emergency response experience in major events did not include the total collapse of tall buildings** such as the WTC Towers and WTC 7 that were occupied and in everyday use; instead, that experience suggests that major tall building fires result in burnout conditions, not overall building collapse.

- The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the building and fire codes of any local, state, or federal jurisdiction. The PANYNJ's longstanding stated policy is to meet and, where appropriate, exceed requirements of local building and fire codes.

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Applicable Building Codes and Policies

- Although not required to conform to NYC codes, the PANYNJ elected to adopt the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect.

- **The 1968 edition had less restrictive provisions** compared with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:
  - Eliminated a fire tower as a required means of egress;
  - Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
  - Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
  - Changed partition loads from 20 psf to loads based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings);
  - Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).

- **The NYC Department of Buildings reviewed the WTC tower drawings** in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code. All of the issues identified in the NYC review appear to deal with egress issues, not with any of the innovative features of the buildings.

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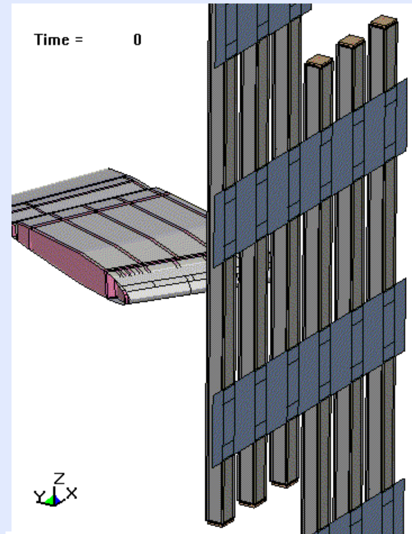
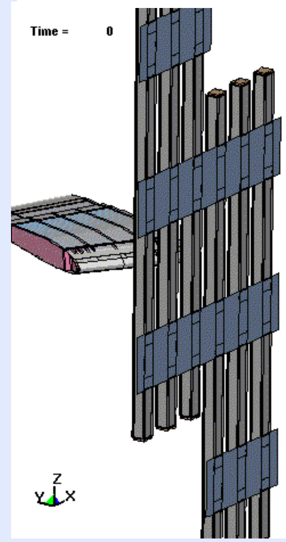
Preliminary Aircraft Impact Damage Analysis

- The impact of the exterior wall by an empty wing segment produces significant damage to the perimeter columns, not necessarily complete failure.

- The impact of a fuel-filled wing section results in extensive damage to the exterior wall panel, including complete failure of the perimeter columns.





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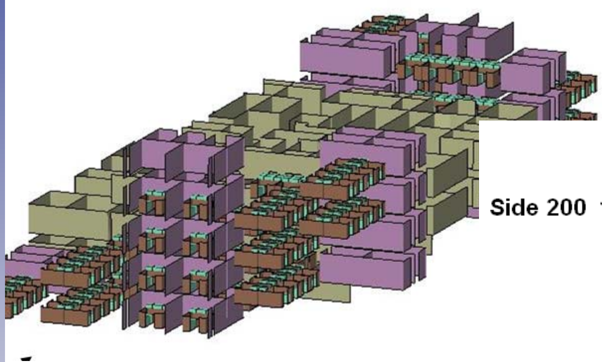
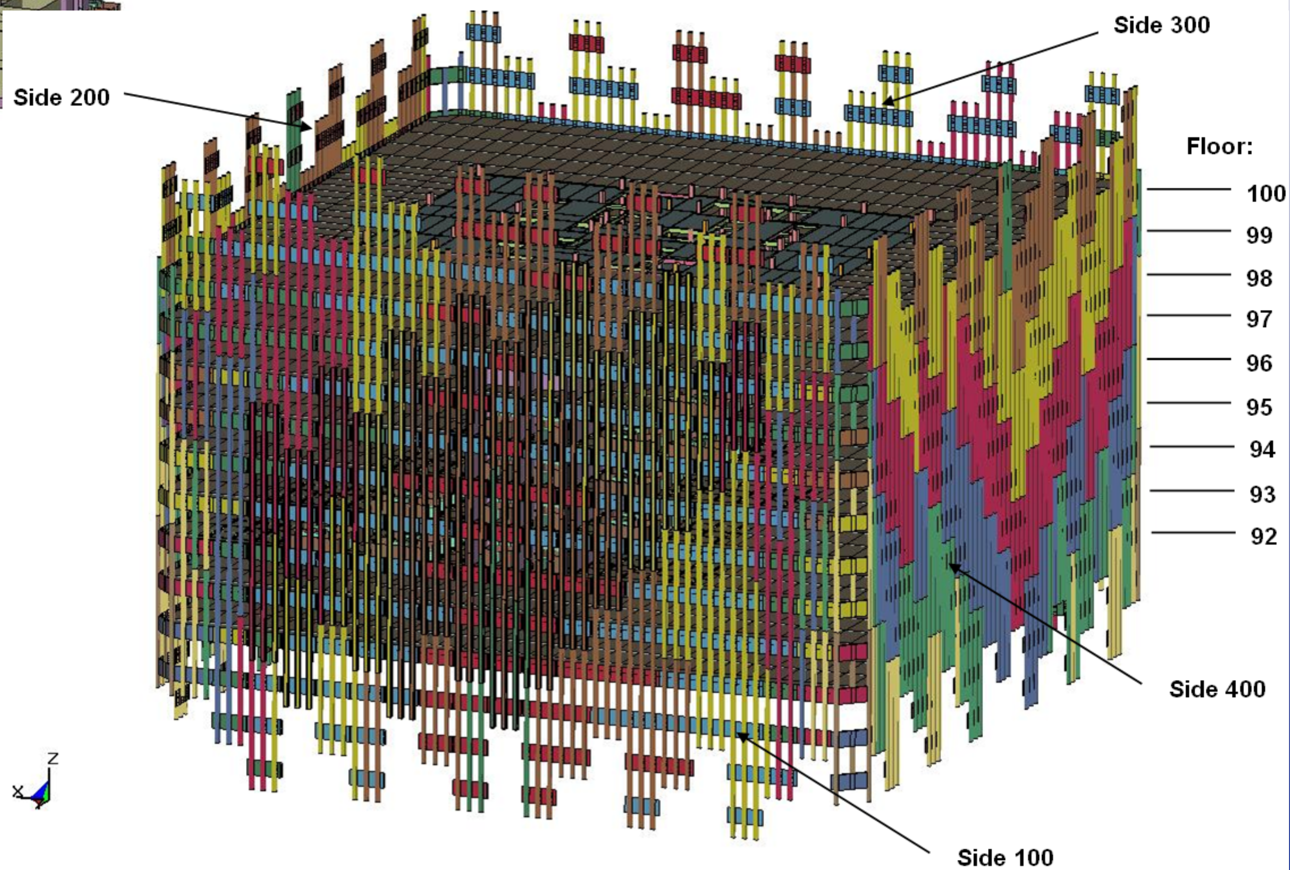
WTC 1 Tower Model for Aircraft Impact Analysis





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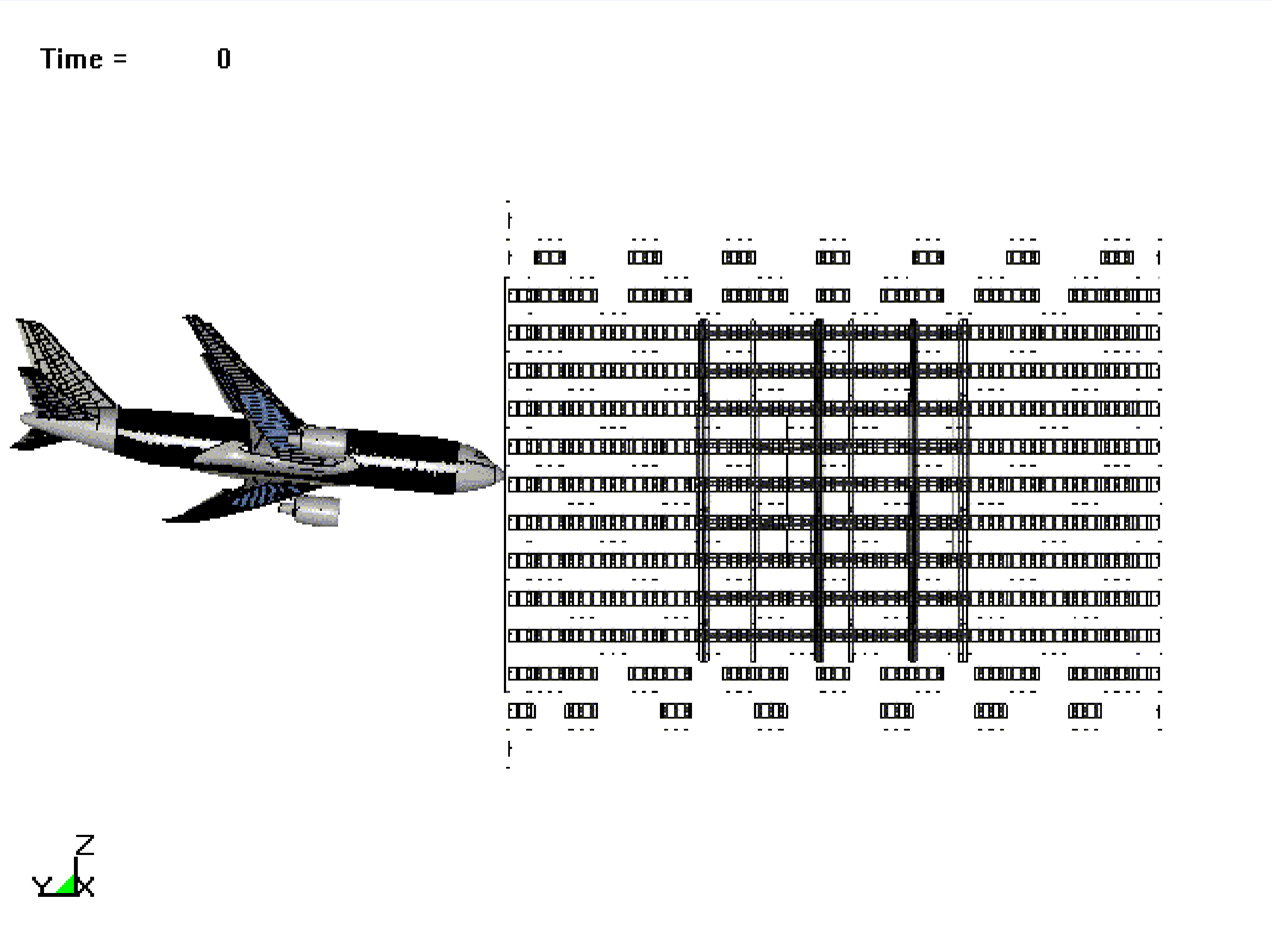
WTC 1



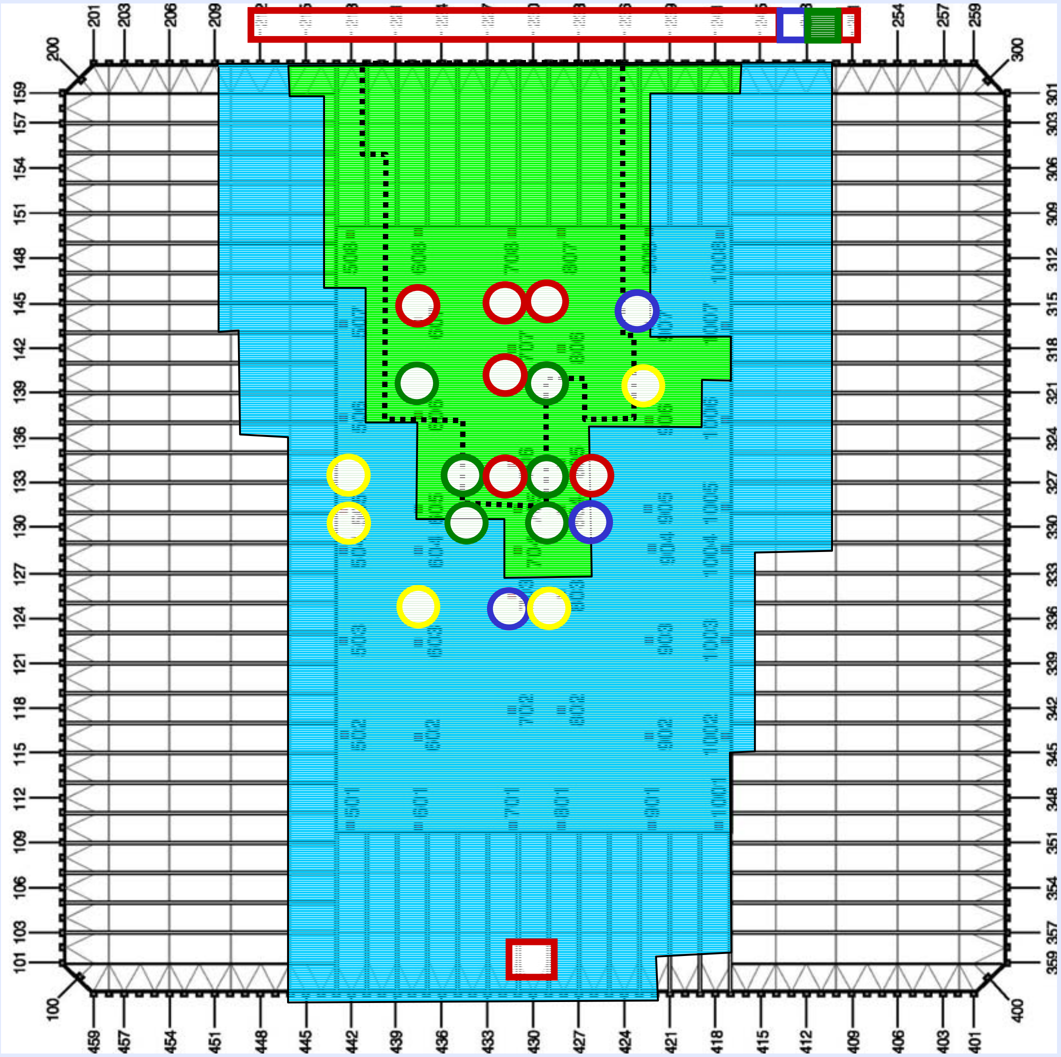
WTC 1 Damage: Composite Summary for Floors 93 to 98

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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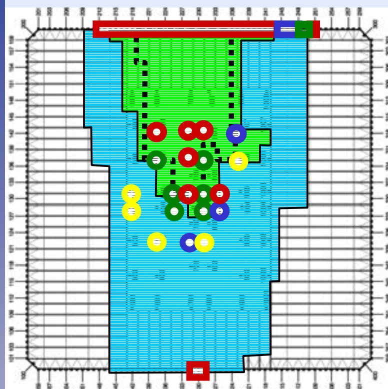
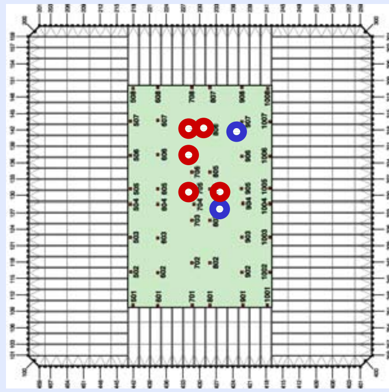
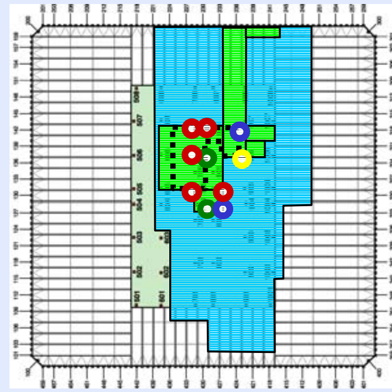
WTC 1 Damage by Floor



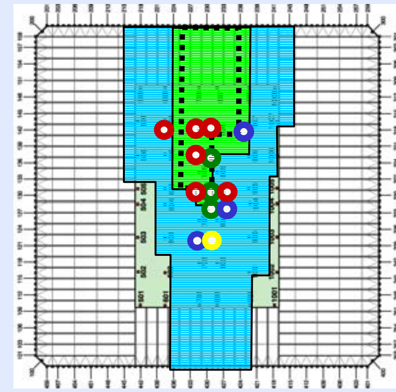
Floors 93 to 98
Cumulative Damage



Floor 93



Floor 94



Floor 95

Severe Floor Damage

Fireproofing and partitions

Floor system structural damage

Floor system removed

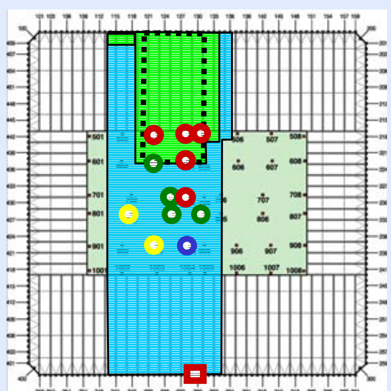
Column Damage

Severed

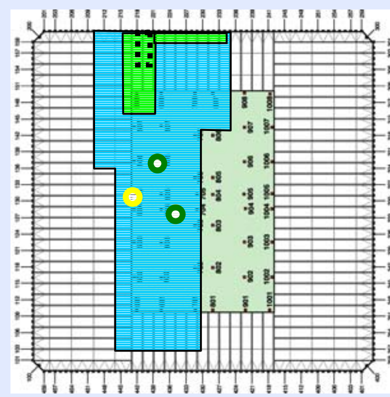
Heavy Damage

Moderate Damage

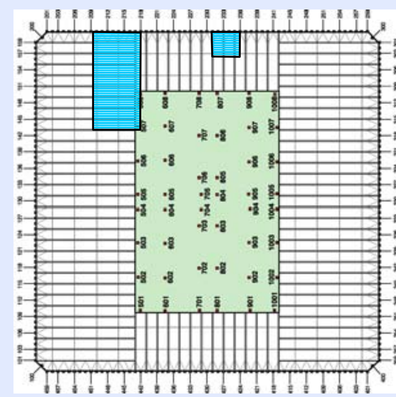
Light Damage



Floor 96

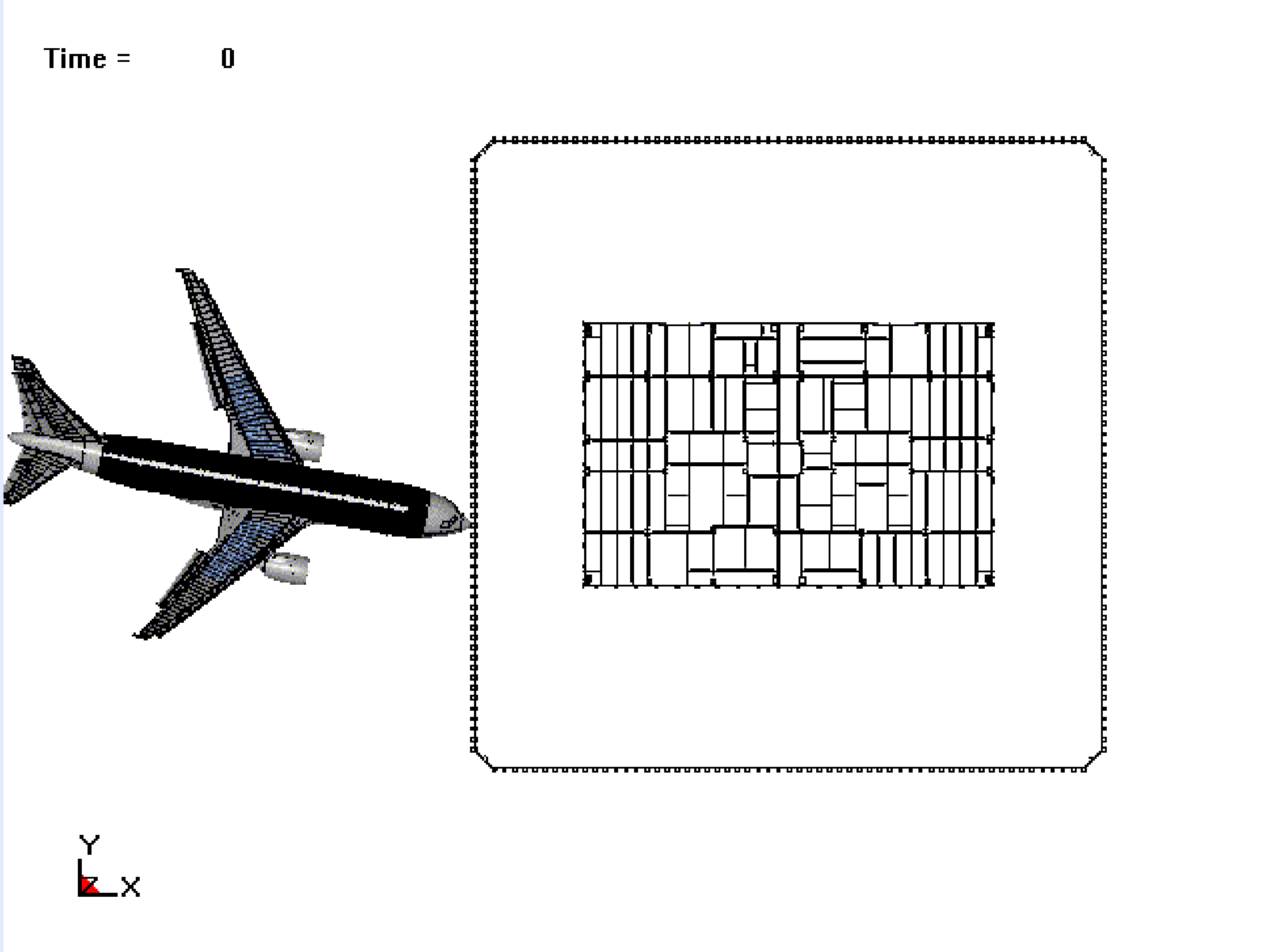


Floor 97



Floor 98

WTC 2



WTC 2 Damage: Composite Summary for Floors 78 to 83

Floor Damage

Fireproofing and partitions

Floor system structural damage

Floor system removed

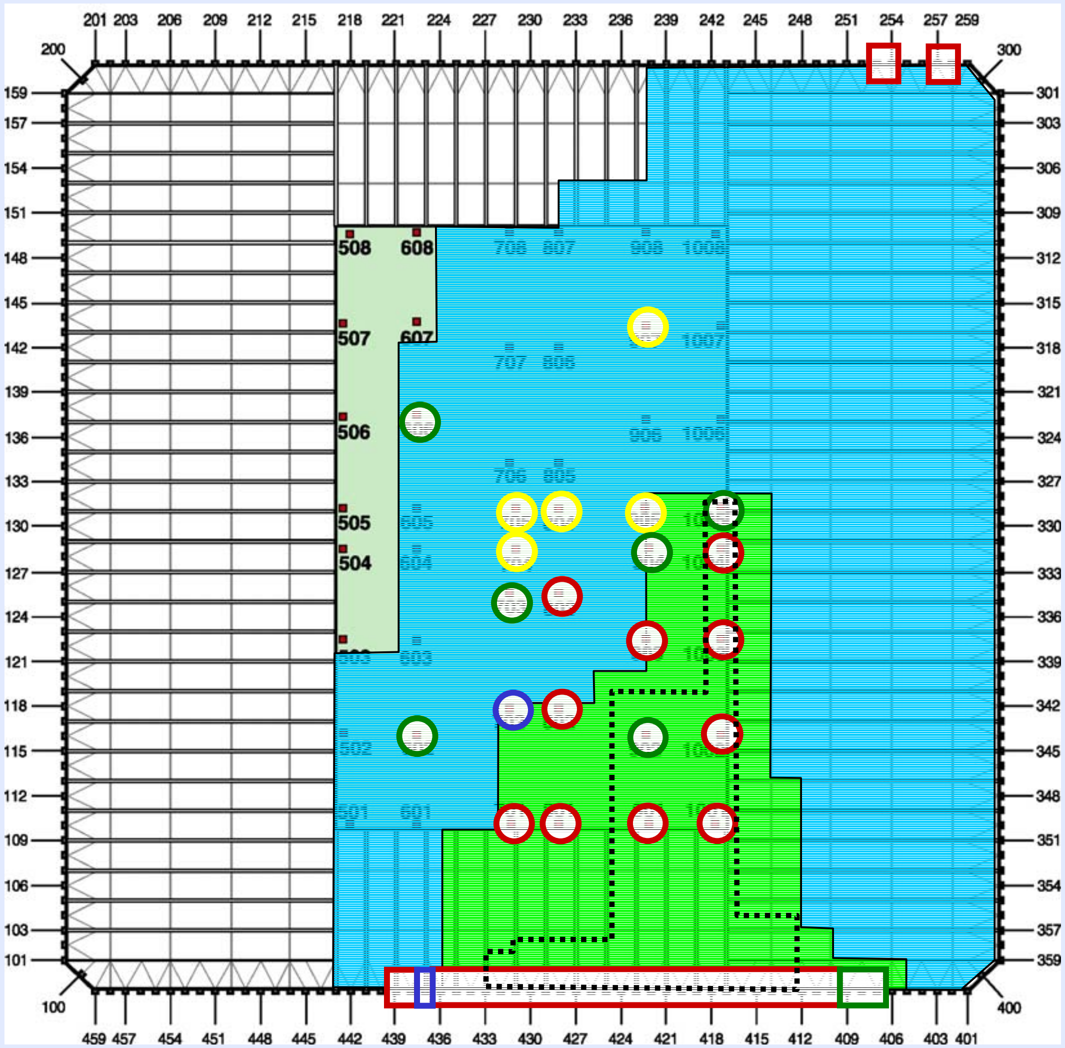
Column Damage

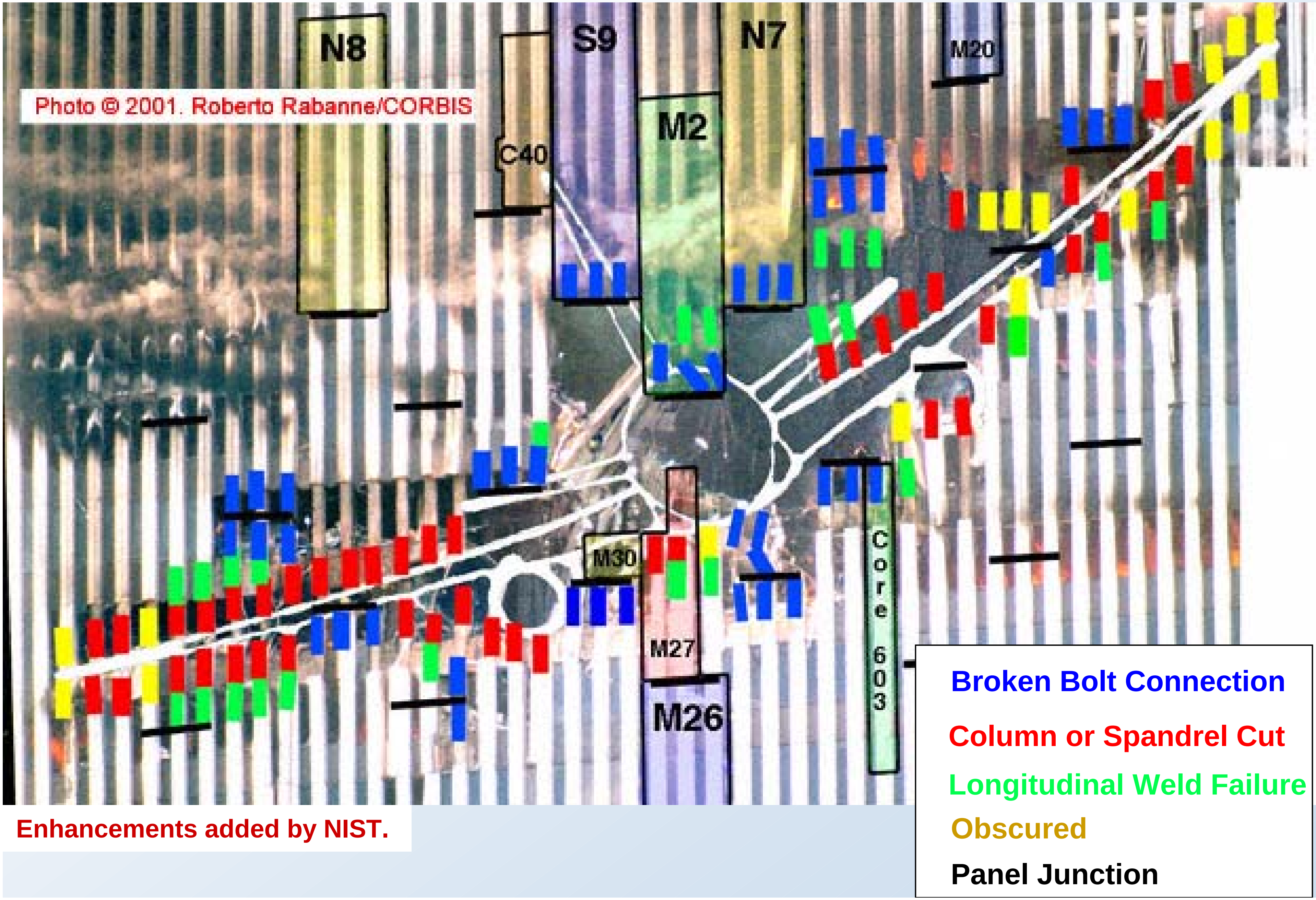
Severed

Heavy Damage

Moderate Damage

Light Damage





Enhancements added by NIST.

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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.

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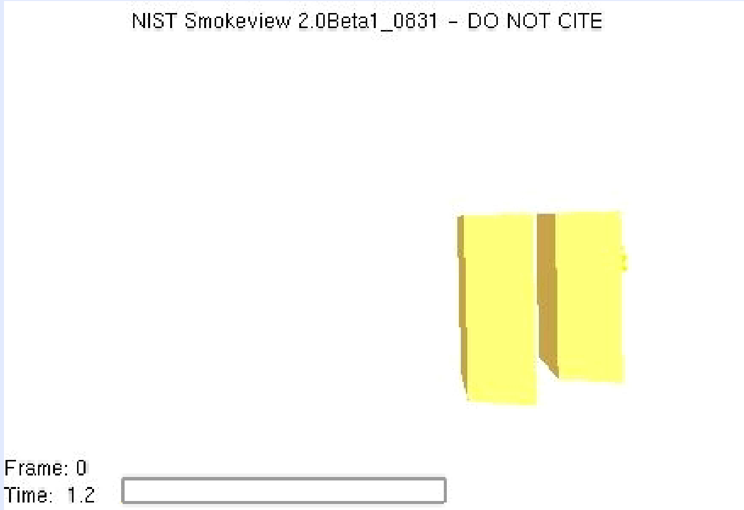
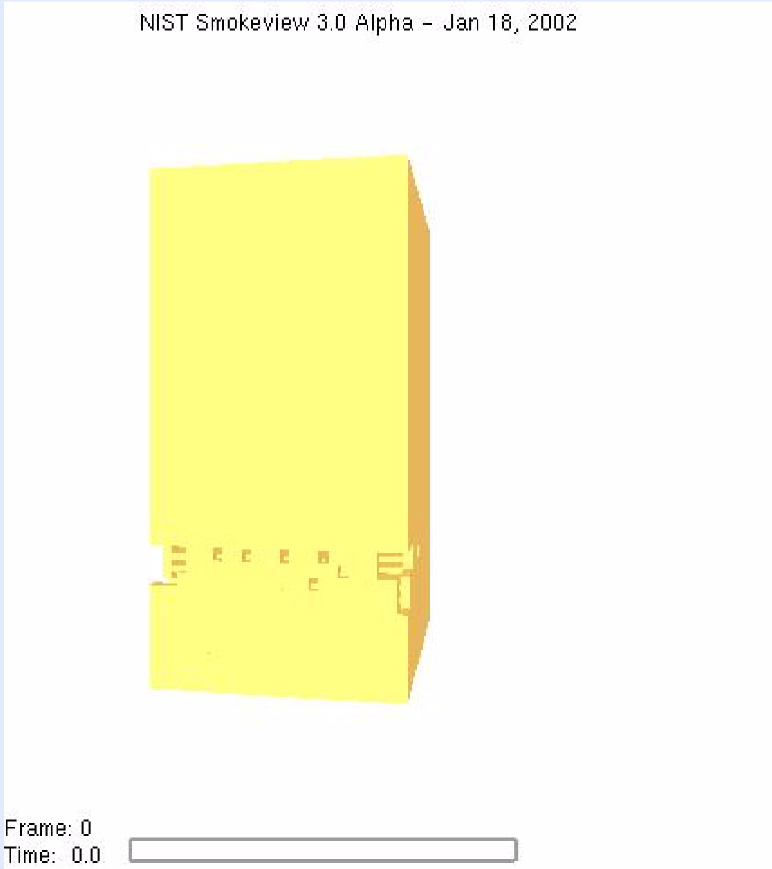
Initial Fire and Smoke Simulations: Fall 2001





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 ft^2) to mitigate the spread of fire in large open floor plan buildings.

Compartmentation Requirements

- The NYC Building Code and PANYNJ practice **required partitions to separate tenant spaces from each other and from common spaces** such as the corridors that served the elevators, stairs and other common spaces in the building core.
- Local Law 5 (1973) required compartmentation of unsprinklered spaces in existing office buildings over 100 ft in height “having air-conditioning and/or mechanical ventilation systems that serve more than the floor on which the equipment is located,” to be **subdivided by 1 hour fire separations into spaces or compartments not to exceed 7,500 ft^2. Floor areas could be increased up to 15,000 ft^2 if protected by 2 hour fire resistive construction and smoke detectors.**
- Shortly after the adoption of LL 5 (1973), the PANYNJ began to add the required compartmentation as a part of new tenant layouts as evidenced by several tenant alteration contracts at this time.
- **Following the 1975 fire** a fire safety consultant report recommended to PANYNJ that the buildings be **retrofit with sprinklers to address possible smoke problems**, and the PANYNJ realized that this would also **obviate the need for compartmentation** and permit the unobstructed views for which the buildings were known. The decision to sprinkler the buildings left the arrangement again with **only partitions separating tenant spaces from each other and from exit access corridors or common spaces in the core, and with shaft enclosures.**

Structural Analysis Progression

Component Analyses

- Knuckle
- Truss seat connections
- Single truss and concrete slab
- Full floor
- Column splice connection
- Single story column
- Nine story column
- Nine story-nine column exterior wall panel

Detailed nonlinear analyses to determine component behaviors and failure mechanisms

Subsystem Analyses

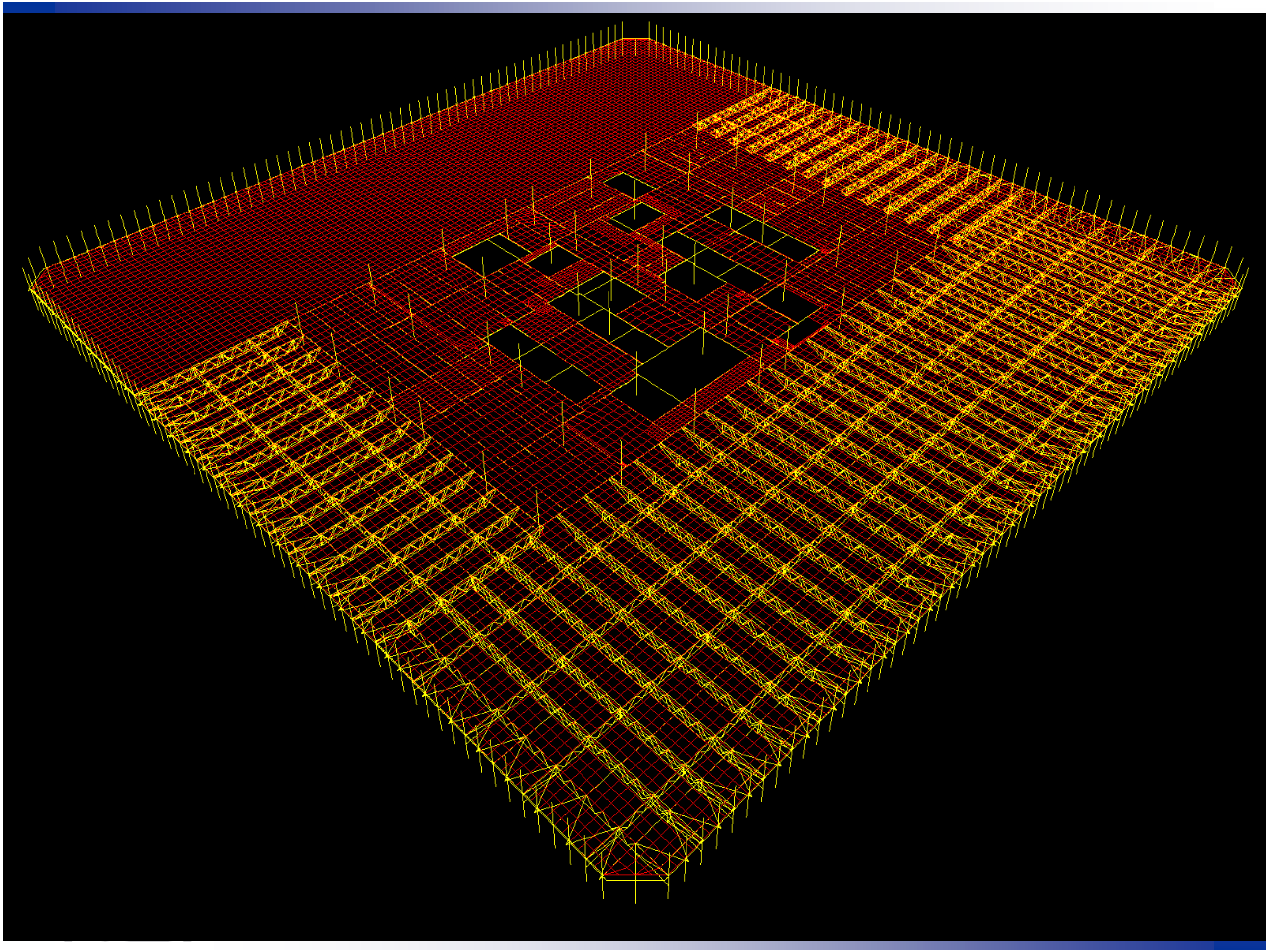
- WTC 1
  - Isolated Core
  - South Exterior Face
  - Floors 93 to 99
- WTC 2
  - Isolated Core
  - East Exterior Face
  - Floors 79 to 83

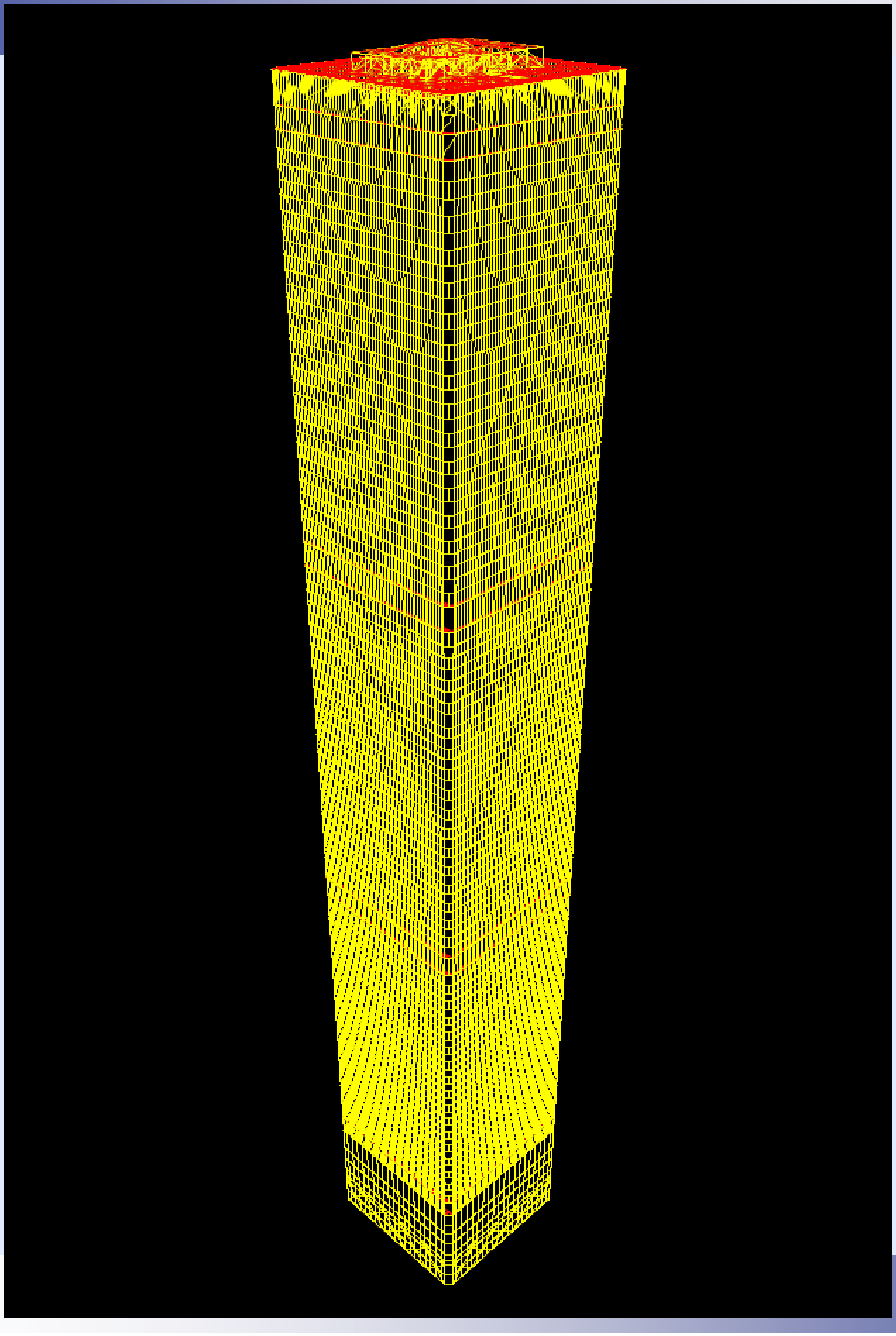
Nonlinear analyses with component simplifications and failure mechanism simplifications to determine major subsystem behavior and sequential failure mechanisms.

Global Analyses

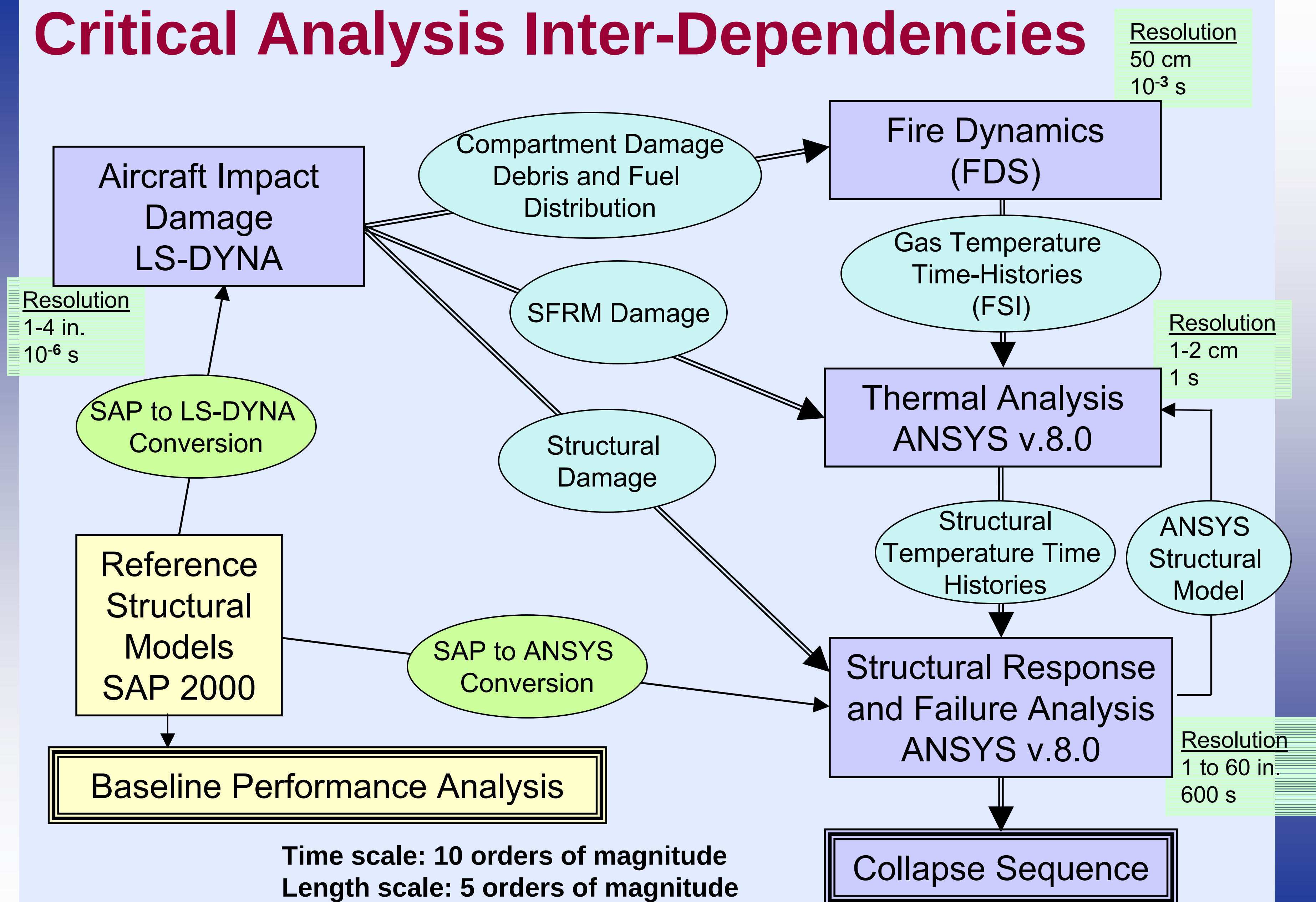
- WTC 1
- WTC 2

Nonlinear analyses to determine global behavior and sequential failure mechanisms.





Critical Analysis Inter-Dependencies



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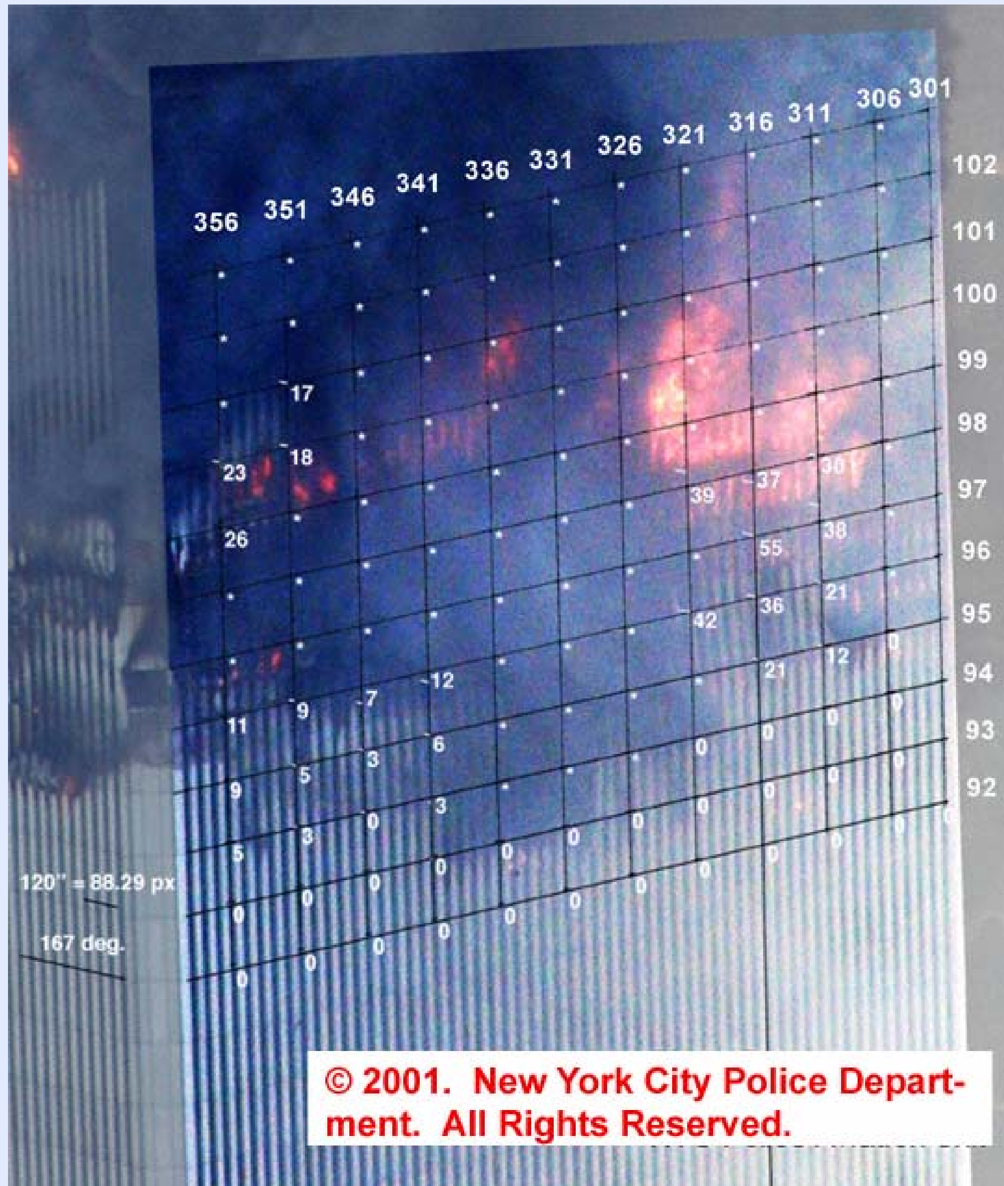
South Face of WTC1

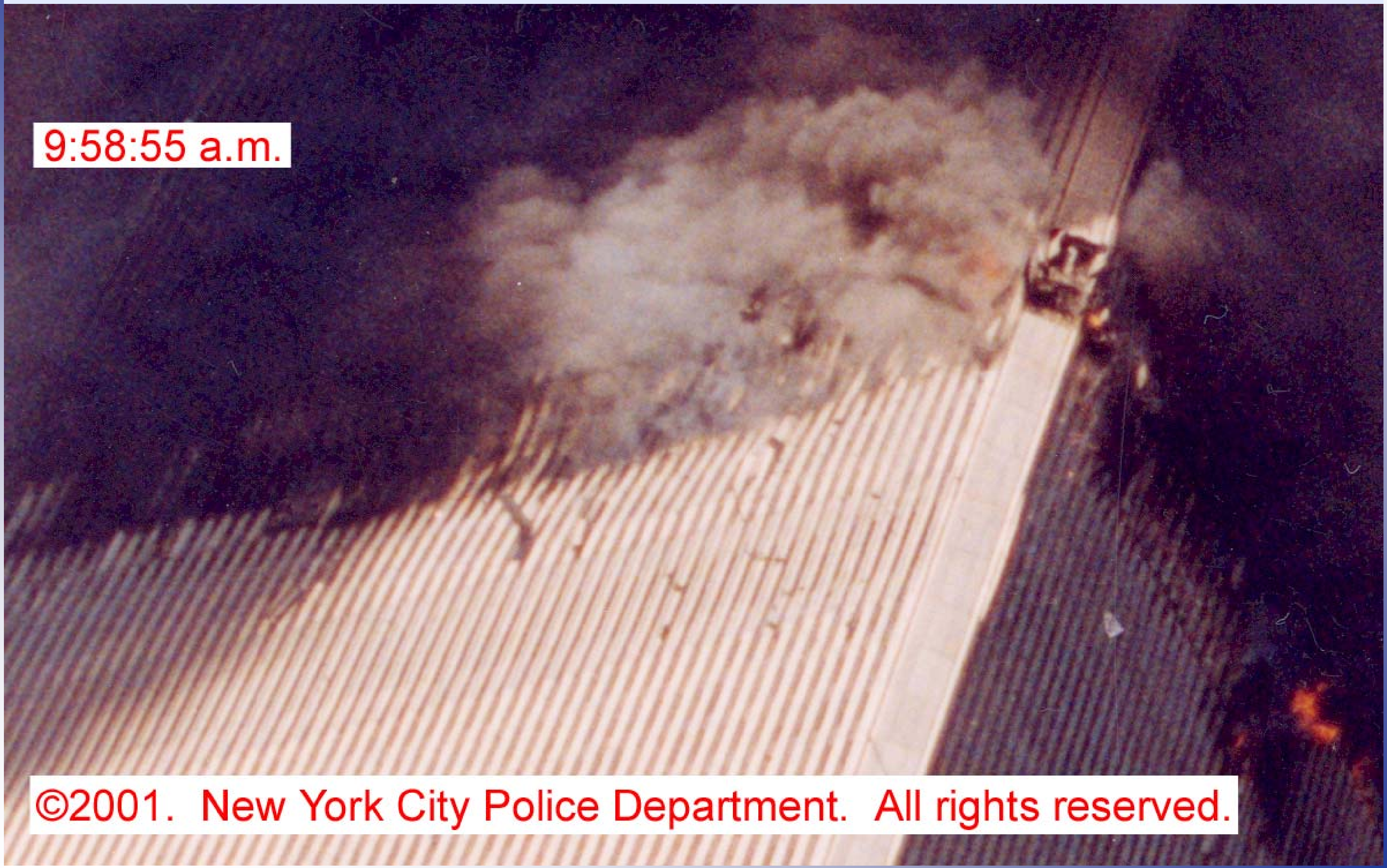
- Time: 10:22 AM
- Measurements of inward bowing (inches)

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

- Floor locations approximate
- Blue tinted region digitally enhanced



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



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Tilting of Building Sections

WTC 1 tilted to the south; WTC 2 tilted to the east and south and twisted in a counterclockwise motion

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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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.**

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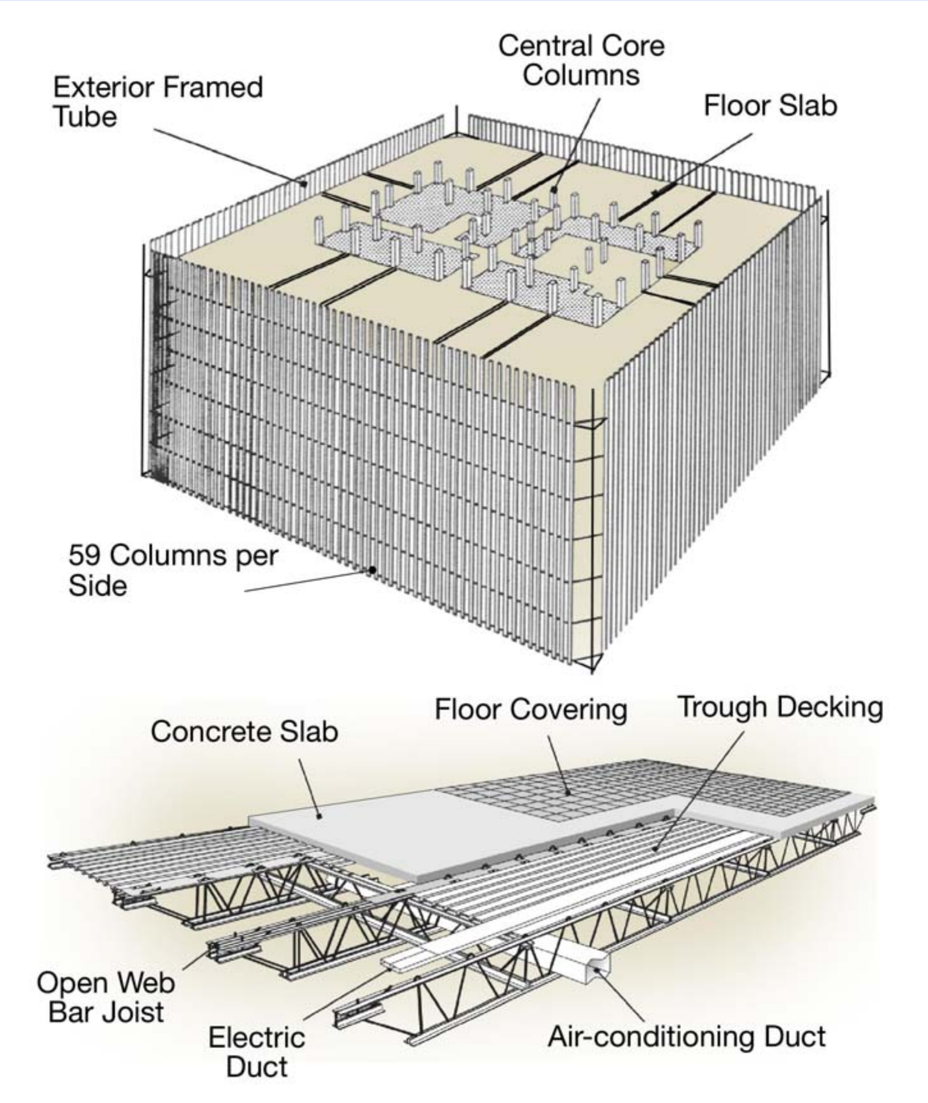
Innovative WTC Tower Structural System



- Innovative structural system when built; incorporated many new and unusual features
- Two features require additional consideration:
    - Composite floor truss system using long span open-web bar joists and spray-applied fireproofing
    - Design for wind loads and control of wind-induced vibrations

Fire Performance of Composite Floor System

- Fire-protection of a truss-supported floor system with spray-on fireproofing was innovative and not consistent with then-prevailing practice.

- **No evidence found of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
  - 1/2 in. specified when WTC towers were built to maintain Class 1-A (not 1-B) fire rating requirement of the NYC Building Code
  - 1-1/2 in. specified for upgrades some years prior to 2001
  - 2 in. for similar floor system in an unrestrained test (model code evaluation service recommendation in June 2001, unrelated to WTC buildings)

- **No evidence that full-scale fire resistance test of the WTC floor system was conducted** to determine the required fireproofing thickness; in 1966, the Architect of Record and, in 1975, the Structural Engineer of Record stated that the fire rating of the WTC floor system could not be determined without testing.

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Results From NIST-Sponsored Tests at UL

Test	Description	Times to Reach End-Point Criteria (min)					Test Termin-ated (min)	Standard Fire Test Rating		
		Temperature on Unexposed Surface		Steel Temperatures		Failure to Support Load		ASTM E 119-61	ASTM E 119-00	
		Average (Ambient +250ºF)	Maximum (Ambient +325ºF)	Average (1100ºF)	Maxi-mum (1300ºF)			Rating (hr)	Restr-ained Rating (hr)	Unrestr-ained Rating (hr)
1	35 ft, restrained, ¾ in fireproofing	---	111	66	62	(3)	116(1)	1½	1½	1
2	35 ft, unrestrained, ¾ in fireproofing	---	---	76	62	(3)	146(2)	2	---	2
3	17 ft, restrained, ¾ in fireproofing	180	157	86	76	(3)	210(2)	2	2	1
4	17 ft, restrained, ½ in fireproofing	---	58	66	58	(3)	120(1)	¾	¾	¾

(1) Imminent collapse
(2) Vertical displacement exceeded capability to measure accurately
(3) Did not occur

The end-point criterion that determined the rating is shown in matching color.

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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*	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

* 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.)
- **Under the original design wind loads, the WTC towers would need to have been between 1.5 to 1.9 times stiffer to achieve a H/500 drift limit; this can be efficiently achieved by increasing exterior column areas in the lower stories and/or significant additional damping.**

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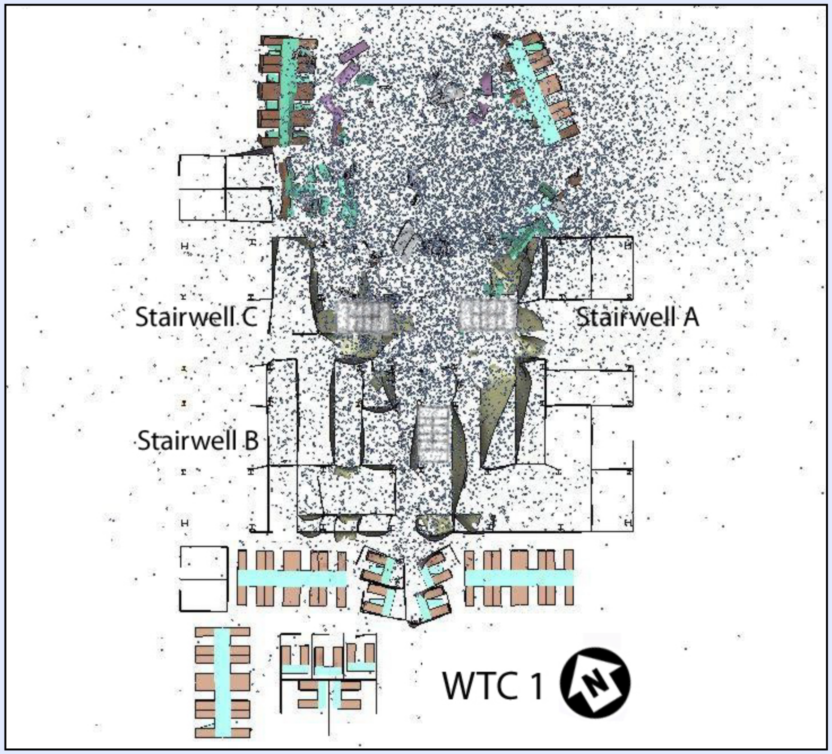
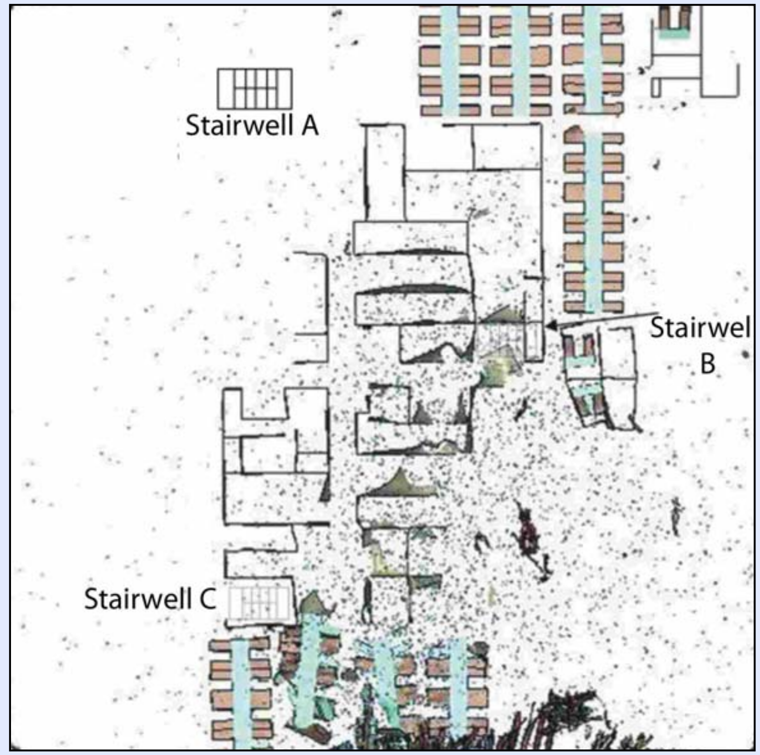
Summary of Evacuation Findings

- **It is estimated that 17,400 occupants (± 1,200) were present in the WTC towers on the morning of September 11, 2001; about 6 percent of the surviving occupants reported a pre-existing limitation to their mobility.**
- Approximately **87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully**.
- **Functioning elevators allowed many (roughly 3,000) survivors to self-evacuate WTC 2 during the 16 minutes prior to aircraft impact.**
- **The egress capacity (number and width of exits and stairways) was adequate to accommodate survivors who were seeking and able to reach and use undamaged exits and stairways.**
- **A full capacity evacuation of each WTC tower with 25,000 people—three times the number present on September 11, 2001—would have required about 4 hours and likely resulted in loss of 14,000 lives.**
- **The average surviving occupants moved down stairs at about half the slowest speed previously reported for non-emergency evacuations.**
- **Occupants were often unprepared for the physical challenge of full building evacuation.**

Condition of Stairwells





- The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.
- **One of the stairwells in WTC 2 (Stairwell A on the Northwest side) was passable in the region of aircraft impact for some period of time after WTC 2 was attacked.**
- All three stairwells in WTC 1 and the two other stairwells in WTC 2 were rendered impassable in the region of aircraft impact.

Selected Emergency Response Findings

- Radio communications in high-rise buildings
- Emergency response operations in high-rise buildings
- Evacuation of mobility impaired occupants
- Feasibility of roof evacuation
- Situational awareness
- Command and control for large-scale incidents

Issues Related to Practice, Standards, Codes

- Based on the Investigation findings, NIST identified a broad set of issues related to practice, standards, and codes that will provide the basis for formulating the Investigation's recommendations.

- Issues arising from the investigation are grouped under the following major categories:

  - Increased Structural Integrity
  - Enhanced Fire Resistance of Structures
  - New Methods for Designing Structures to Resist Fires
  - Enhanced Active Fire Protection
  - Improved Building Evacuation
  - Improved Emergency Response
  - Improved Procedures and Practices
  - Education and Training Programs

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Categories of Issues

Category: Responsible Community

- Professional Practices
- Provisions in standards, codes and regulations
- Adoption and enforcement of the provisions
- R&D or requiring further study
- Education and training

Category: Affected Building Population

- All tall buildings (buildings over 20 stories in height)
- Selected tall buildings (buildings over 20 stories in height that are at risk due to design, location, use, iconic status, nature of occupancy, etc.)
- Selected other buildings (buildings less than 20 stories in height that are at risk due to design, location, use, historic/iconic status, nature of occupancy, etc.)

Category: Relation to the outcome on 9/11

- If in place, could have changed the outcome on 9/11
- Would not have changed the outcome on 9/11, yet is an important building and fire safety issue that was identified during the course of the investigation

WTC Investigation Reports

- **WTC Towers Investigation Report**
  - **Building and Fire Codes**
    - 1A Design and Construction
    - 1B Structural Code Comparison
    - 1C Structural Modifications
    - 1D Fire Protection & Life Safety Provisions
    - 1E Fire Code Comparison
    - 1F Comparison of NYC Codes
    - 1G Fire Protection & Life Safety Amend.
    - 1H Post-Const. Modifications WTC1&2
    - 1I Post-Const. Modifications WTC 7
    - 1J WTC 7 Fuel System
  - **Baseline Performance & Aircraft Impact**
    - 2A Baseline Performance
    - 2B Aircraft Impact
  - **Steel Analysis**
    - 3A Contemp. Steel Specs.
    - 3B Steel Inventory
    - 3C Steel Damage
    - 3D Mechanical Steel
    - 3E Physical Properties
  - **Active Fire Protection**
    - 4A Fire History
    - 4B Fire Sprinklers
    - 4C Fire Alarms
    - 4D Smoke Management
  - **Thermal Reconstruction**
    - 5A Visual Evidence
    - 5B Steel Experiments
    - 5C Single Workstation
    - 5D Ceiling Tile
    - 5E Multiple Workstation
    - 5F Fire Simulation
    - 5G Fire Structure Interface
  - **WTC Towers: Structural Collapse**
    - 6A Passive Fire Protection
    - 6B Fire Resistance Test
    - 6C Component Analysis
    - 6D Global Analysis
  - **Occupant Behavior & Egress**
    - 7A Published Accounts
    - 7B Survey Instruments
  - **Emergency Response**
- **WTC 7 Investigation Report**
  - **WTC 7: Structural Collapse**
    - 6E Component & Sequence Analysis
    - 6F Seismic Study
    - 6G ConEd Substation

9 reports totaling about 1,500 pages

34 reports totaling about 8,000 pages

43 reports for WTC Towers; 5 reports for WTC 7

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Summary

- Draft WTC reports to be released June 23, 2005 at media and public briefings in New York City.
- Six-week public comment period closes 5 pm EDT August 4, 2005.
- WTC Conference: Putting Recommendations into Practice, September 13-15, 2005, to be held at NIST.
- Details available at http://wtc.nist.gov

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WTC INVESTIGATION DETAILS

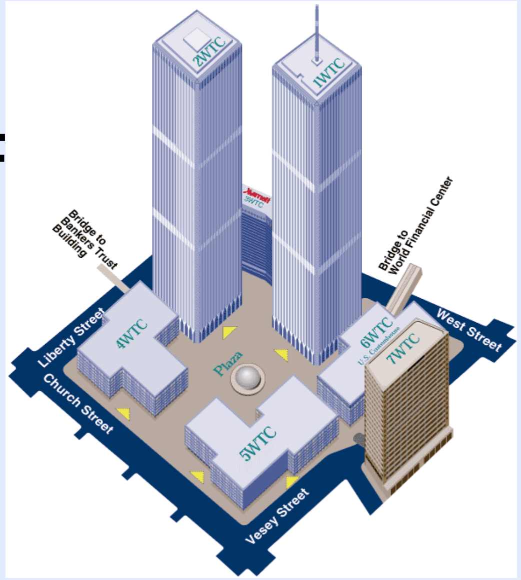
I. ACTIVE FIRE PROTECTION SYSTEMS

II. RECREATION OF BUILDING FIRES LEADING TO STRUCTURAL HEATING

III. EGRESS ISSUES AND EVACUATION MODELING

IV. EMERGENCY RESPONSE

V. RESEARCH, IMPLEMENTATION OF RECOMMENDATIONS



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I. ACTIVE FIRE PROTECTION SYSTEMS

A. Sprinklers and Standpipe Systems

B. Fire Alarm Systems

C. Smoke Management Systems

A. Sprinkler and Standpipe Systems

- Sprinklers were installed throughout WTC 1 & 2 on Sept. 11, 2001 (except where exempted).
- Storage tanks directly connected to NYC water distribution system supplied water to towers; sprinklers supplied automatically from tanks.
- Supply piping from the 100th floor resulted in restricted water supply to several floors; however, this inconsistency with current best practice had no impact on outcome.
- Manual initiation of electrical fire pumps was required to provide supplemental water; automatic initiation is required by NFPA 14, however, unlikely that it made a difference.
- Water supply risers were configured to provide redundancy; sprinkler floor level controls were vulnerable to single point failures at riser connection.

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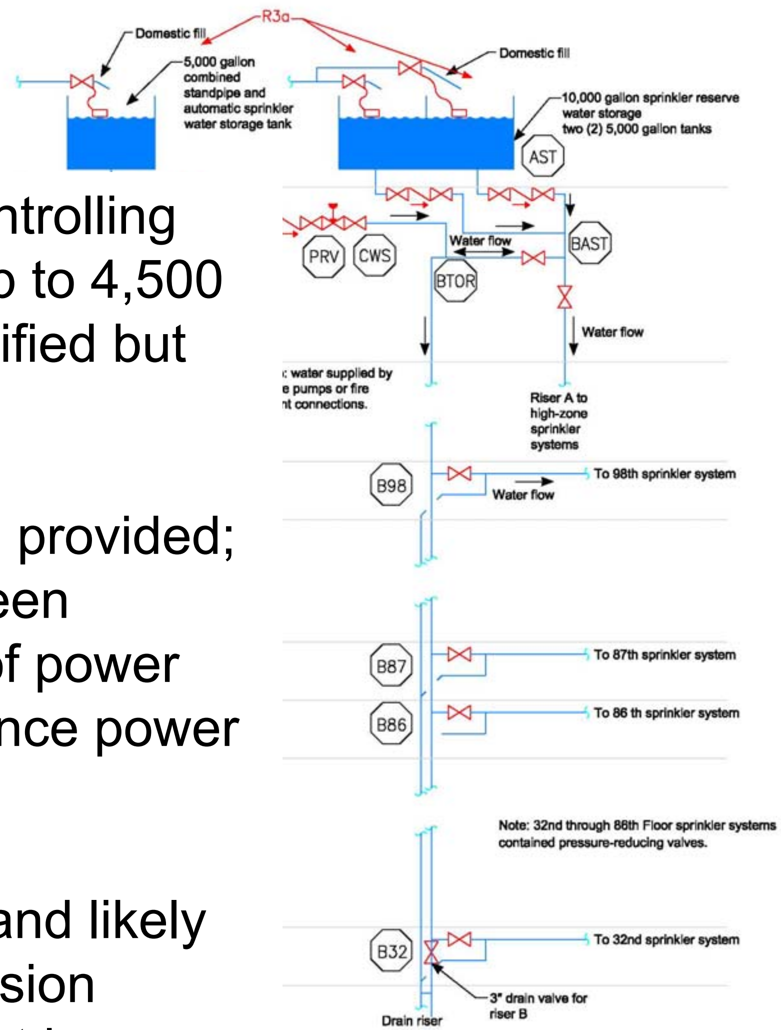
Sprinkler and Standpipe Systems (2)



- Sprinkler systems capable of controlling typical fire with coverage area up to 4,500 ft^2, three times design area specified but less than 15 % of single floor.
- Primary and backup power were provided; system operability could have been affected by lack of redundancy of power lines to emergency fire pumps once power was lost.
- Due to magnitude of initial fires and likely aircraft impact damage, suppression systems in WTC towers could not have been expected to control the fires.

B. Fire Alarm Systems

- Provided for automatic fire detection, but required manual activation of notification devices.
- Capable of determining and displaying (1) areas that had at some time reached alarm point conditions, and (2) areas that had not.
- System in WTC 1 & 2 had extensive back-up command capabilities and hardware that provided multiple places where some alarm history data were stored; up to 13 storage locations were identified.
- Monitored by PANYNJ; in WTC 1, overwhelming number of alarms registered and displayed at FCS, however, information at FCS was not used to manage evacuation; there was no means at FCS to determine whether or not announcements could be heard on intended floors.

Fire Alarm Systems (2)

- Manual activation of system was required in WTC towers to notify building occupants, delaying alarm for 12 minutes in WTC 1.
- Notification appliance circuit and warden/standpipe telephone circuit were not required to have the same high level of performance of signaling line circuits.
- Firefighter telephone systems in WTC towers were not used on Sept. 11; not uncommon since firefighters are trained to use their radios as preferred means of communications.
- Although fire alarm systems in WTC towers used multiple communication path risers, systems experienced performance degradation, especially in WTC 1 where all notification and communication functions were lost above impact floors.

C. Smoke Management Systems

- Smoke purge systems in WTC 1 & 2 were designed to remove smoke from fire area after suppression operations, to be activated manually at direction FDNY.
- Systems were not initiated on September 11; if they had been, it is unlikely that system would have functioned as designed due to loss of electrical power and damage to the HVAC shafts and other structural elements in the impact zone.
- WTC towers not required to have active smoke management systems or combination fire/smoke dampers because buildings were sprinklered throughout.
- PANYNJ commissioned a study in 1996 which cited lack of vents in stairs that were required in lieu of stair pressurization by Local Law 5 (1973), but that, due to height of stair shafts, required vents would be ineffective. PANYNJ pressurized corridors with outside air as alternative.

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Example of Vertical Smoke Spread

North Face – WTC 1

Smoke Exits NW Interior
Ventilation Zone Supply Inlet

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Smoke Management Systems (2)

- Alternative smoke management systems were evaluated:
  - Core pressurization
  - Building pressurization
  - Sandwich pressurization
  - Zoned smoke control with stair pressurization
- None would have prevented smoke spread for aircraft impact damage scenarios
- Stair pressurization would have been ineffective in improving conditions for occupants trying to exit the buildings.
- Installation of combination fire/smoke dampers in HVAC ductwork would have acted to slow development of hazardous conditions on uppermost floors of the building, but would likely not have had a significant effect on ability of occupants to egress buildings due to impassability of the exit stairways.

II. RECREATION OF BUILDING FIRES & STRUCTURE TEMPERATURES

A. Collection and analysis of photographic and video evidence

B. Identification of suitable computer simulation software

C. Supporting experimental effort

D. Predicted fire spread and structure temperatures

A. Collection and Analysis of Photographic and Video Images

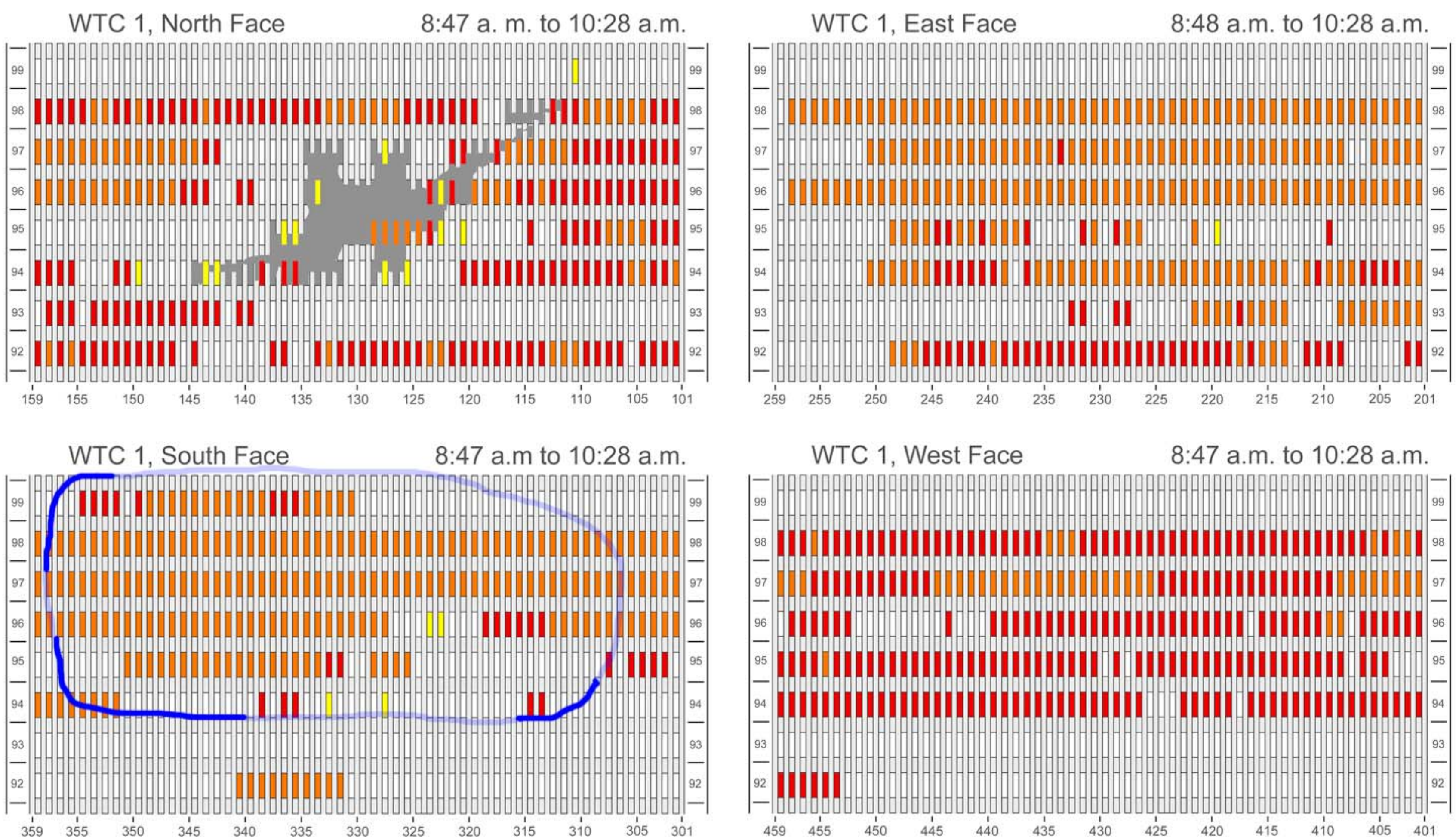
Visual database contains:

- Well in excess of 7,000 photographs taken by more than 185 photographers
- 150 hours of videotape from major media outlets, more than 20 individuals

From analysis of images, NIST has identified significant events for WTC 1 and 2 related to aircraft impact, fire development, and building damage

NIST has developed detailed mappings for fire, smoke, and condition of windows at several specific times for each tower.

Visual Evidence of Fires in WTC 1



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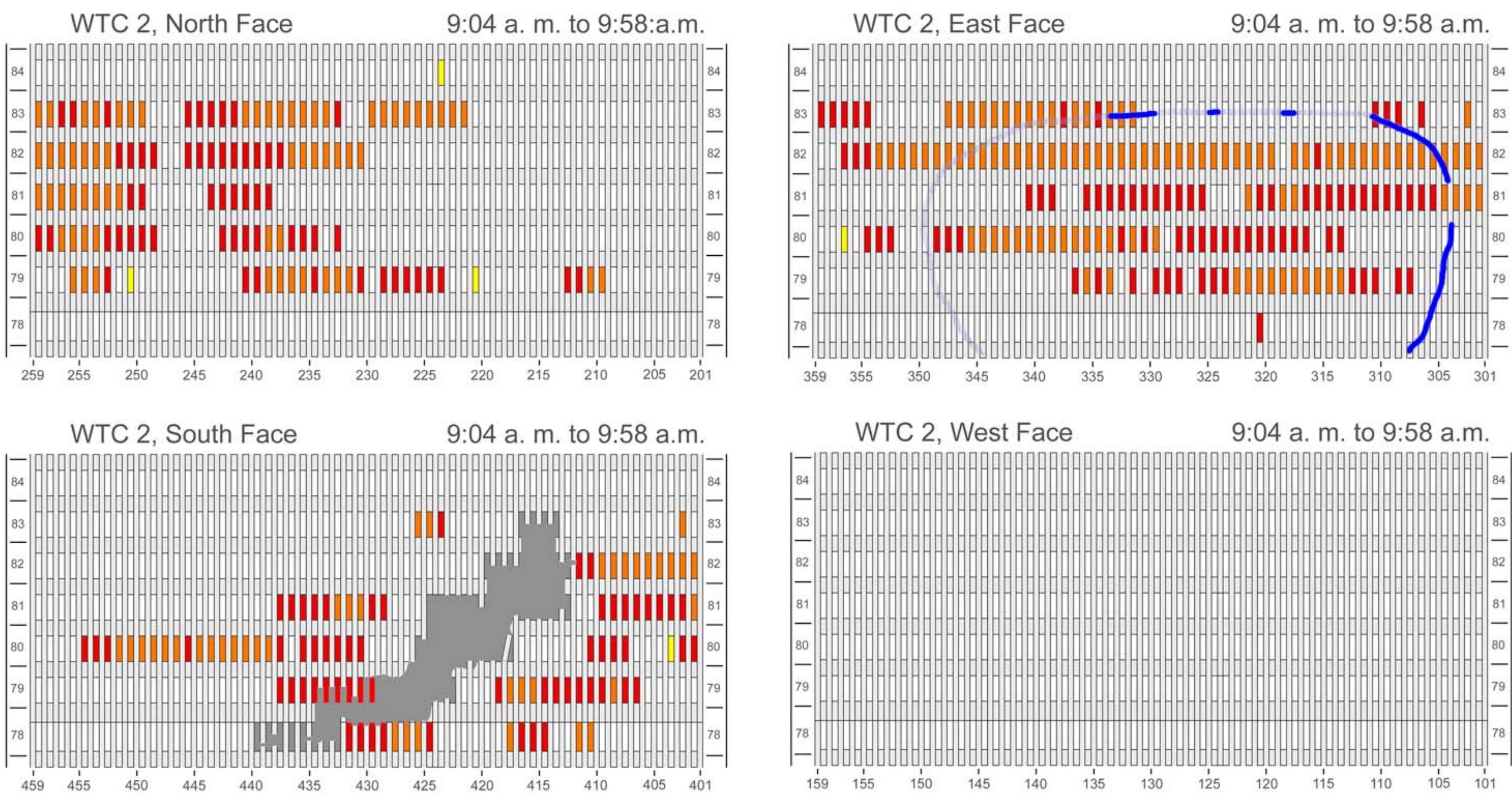
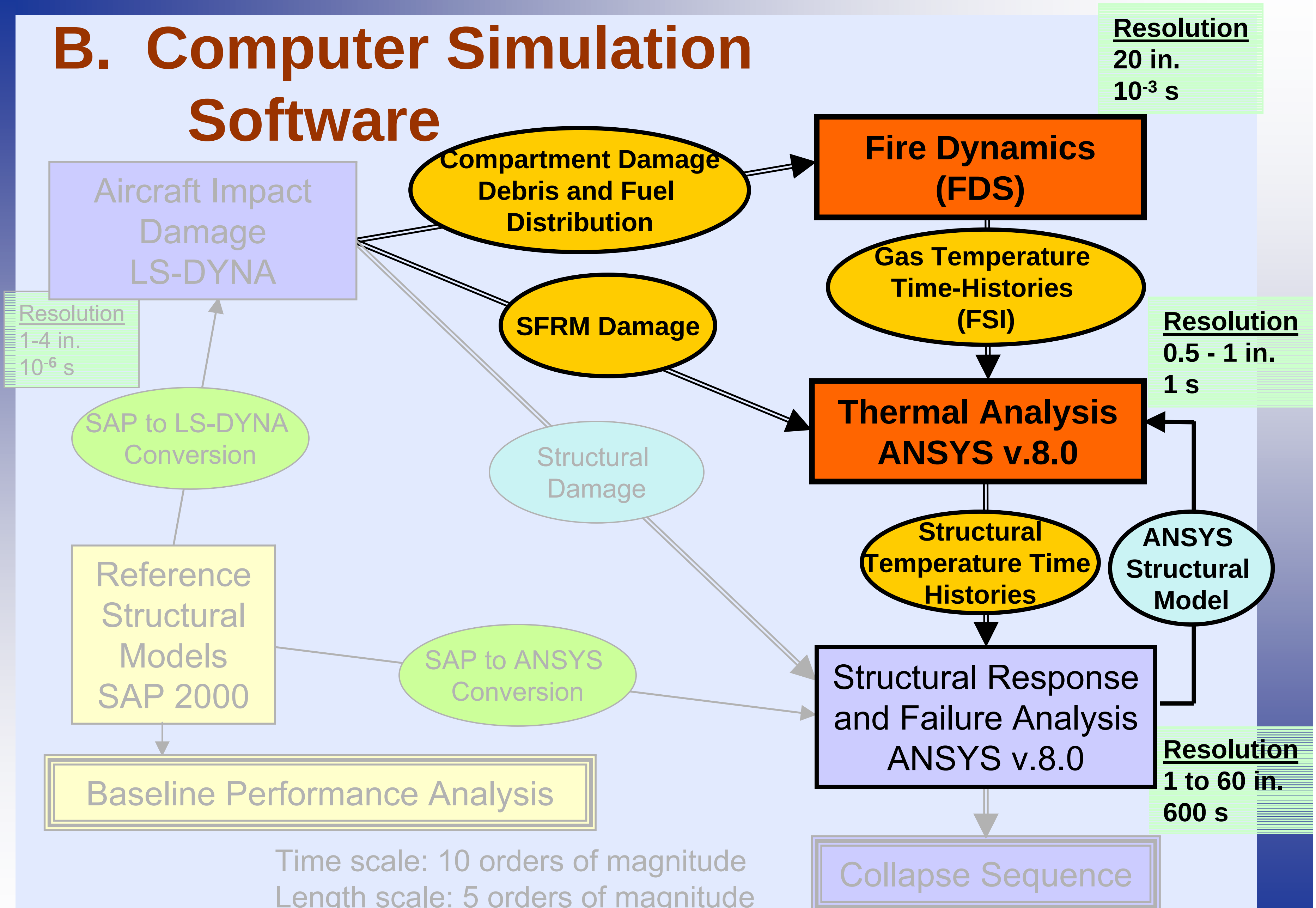
Visual Evidence of Fires in WTC 2



B. Computer Simulation Software



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C. Supporting Experimental Effort

Need to demonstrate capability to predict:

- Heat transfer from controlled fire to steel structural members through spray-on fire resistant material (SFRM) and gypsum board
- Heat release rate of representative work station
- Fire spread from one work station to another
- The influence of jet fuel on carpet and furnishings
- The impact of ruble on heat release rate

ASTM E119 testing of composite floor system

- To evaluate impact of scale, restraint, and SFRM thickness
- To characterize thermal environment and temperatures of floor system

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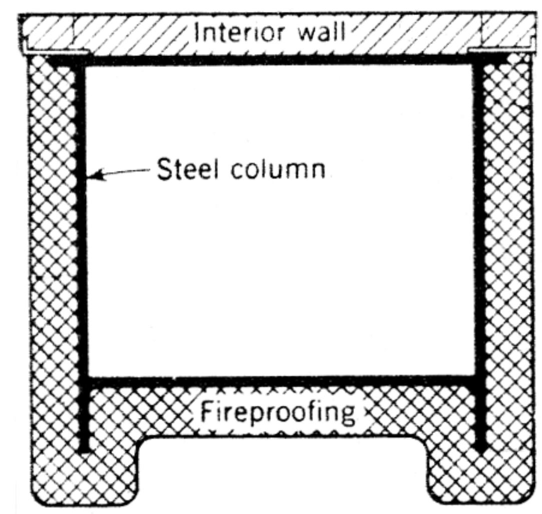
SFRM used in Towers



Structural Component	Member size	Location	Material	Thickness, inches
Floor Trusses	All	All	Cafco DC/F	1/2
Interior columns	< 14WF228	All	Cafco DC/F	2-3/16
	≥ 14WF228	All	Cafco DC/F	1-3/16
Exterior Columns	"heavy"	Ext. Faces	Cafco DC/F	1-3/16
	"heavy"	Int. Faces	Vermiculite Aggregate	7/8
Spandrel Beams	All	Ext. Face	Cafco DC/F	1/2
	All	Int. Face	Vermiculite Aggregate	1/2

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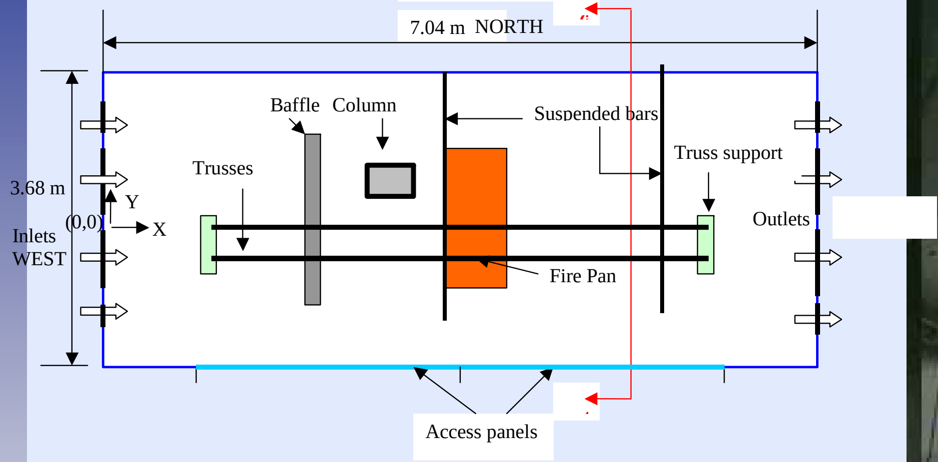
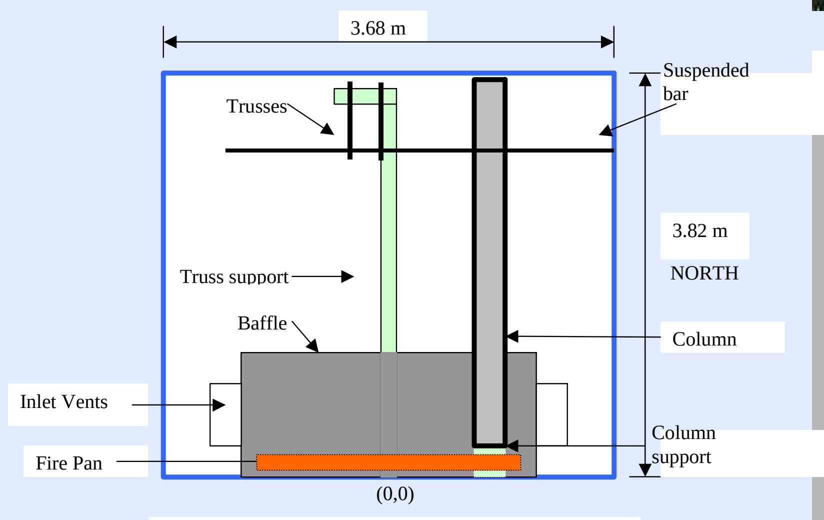
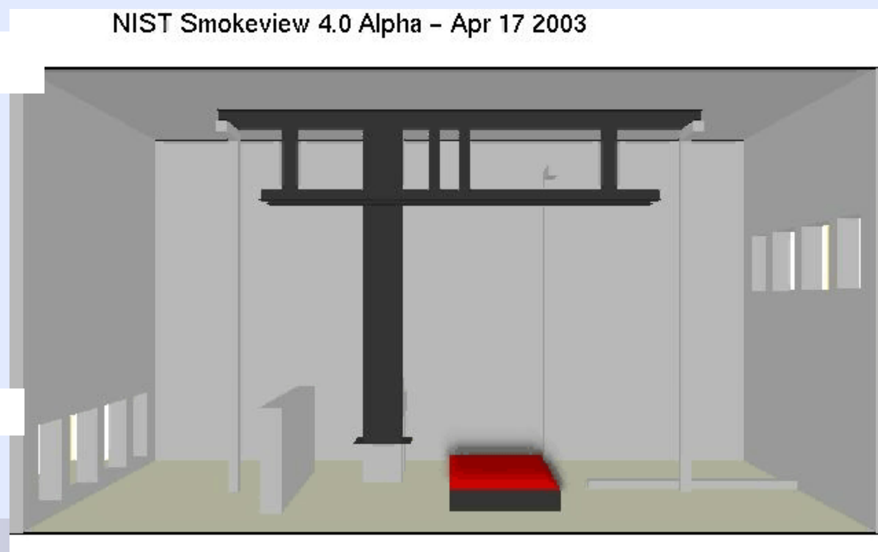
Heat Transfer Experiments

PLAN VIEW

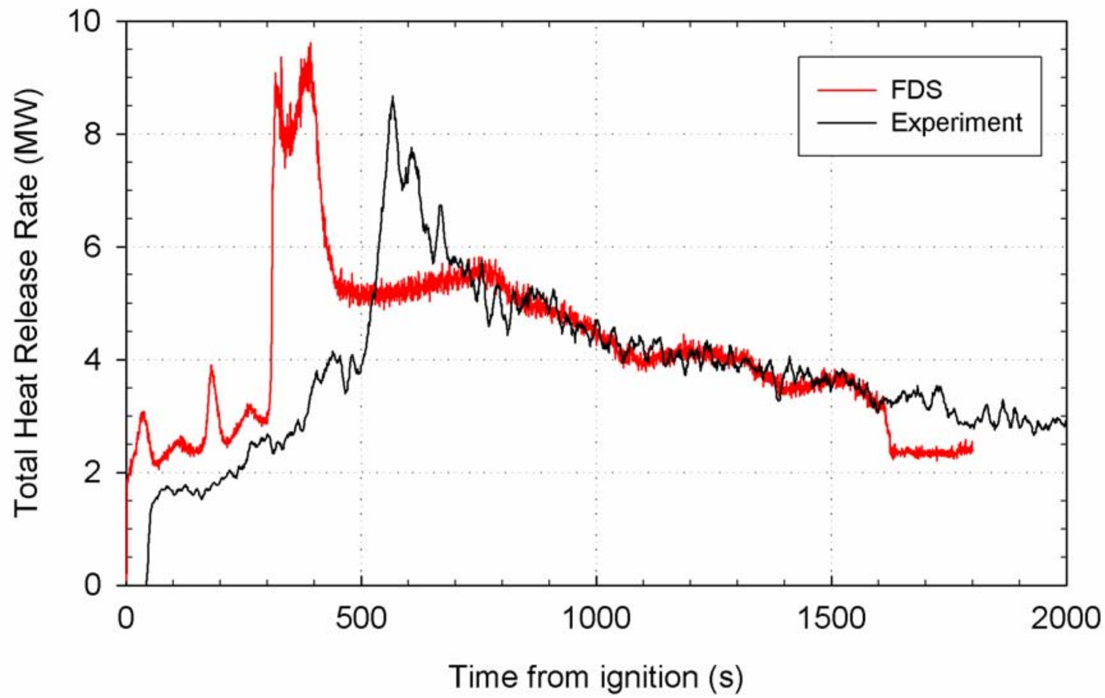


1.2 SECTION A-A





Heat Release Rate, Single Workstation



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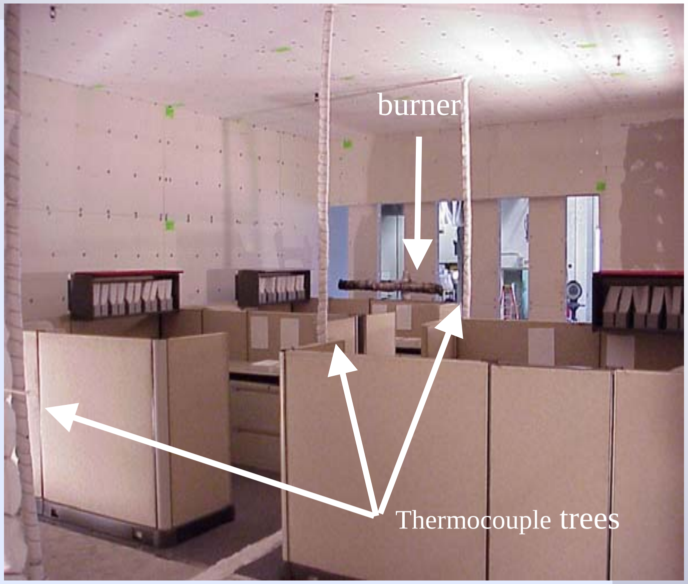
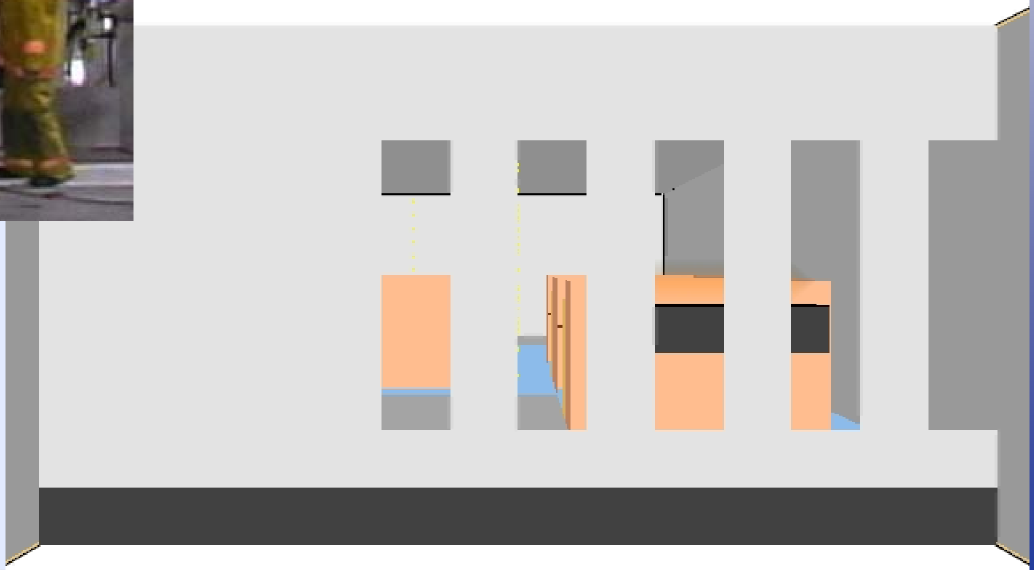
Workstation-to-workstation Fire Spread





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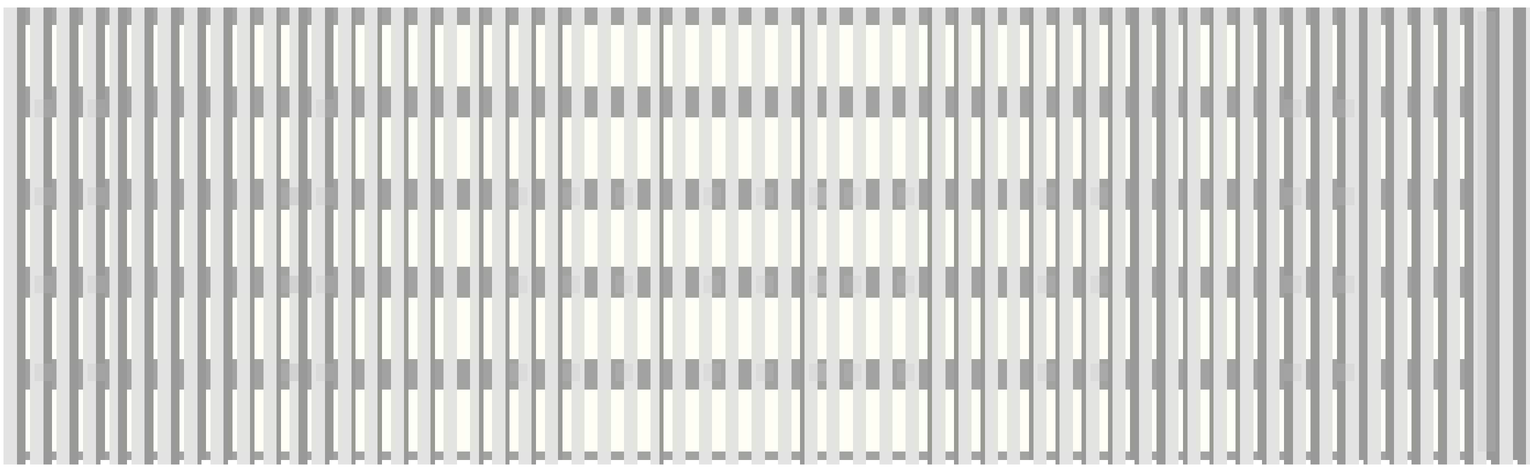
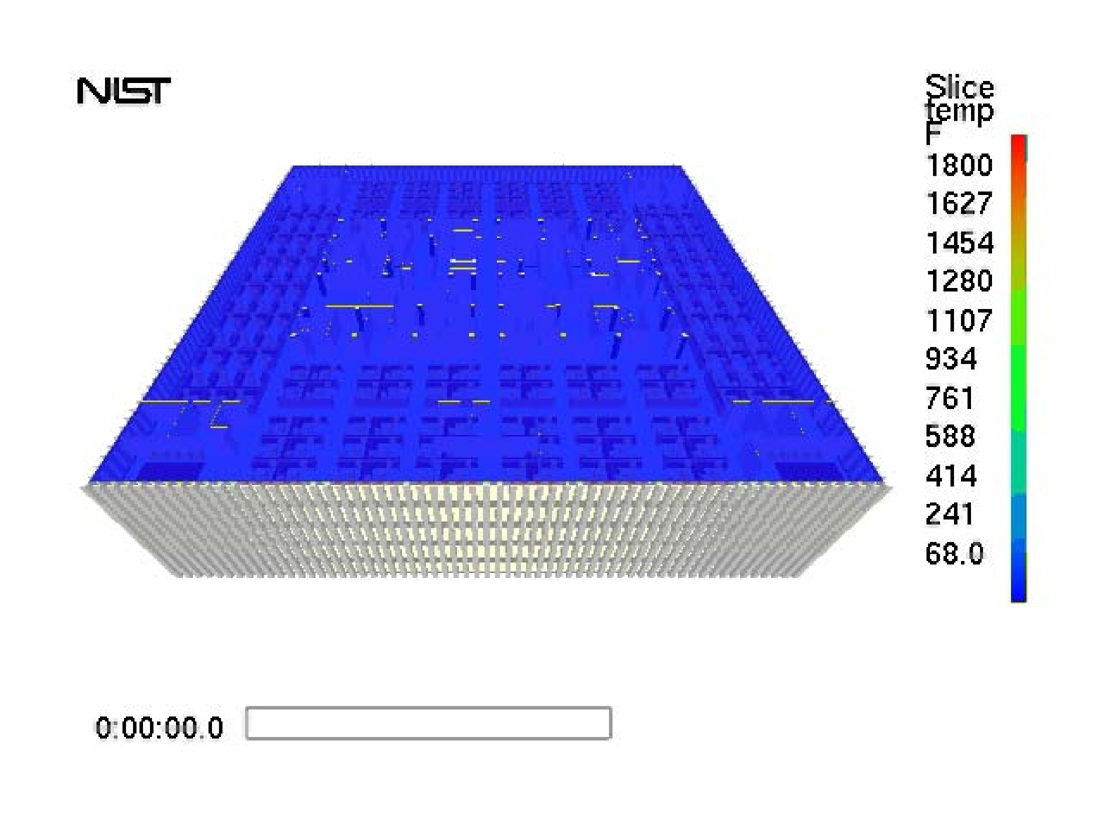
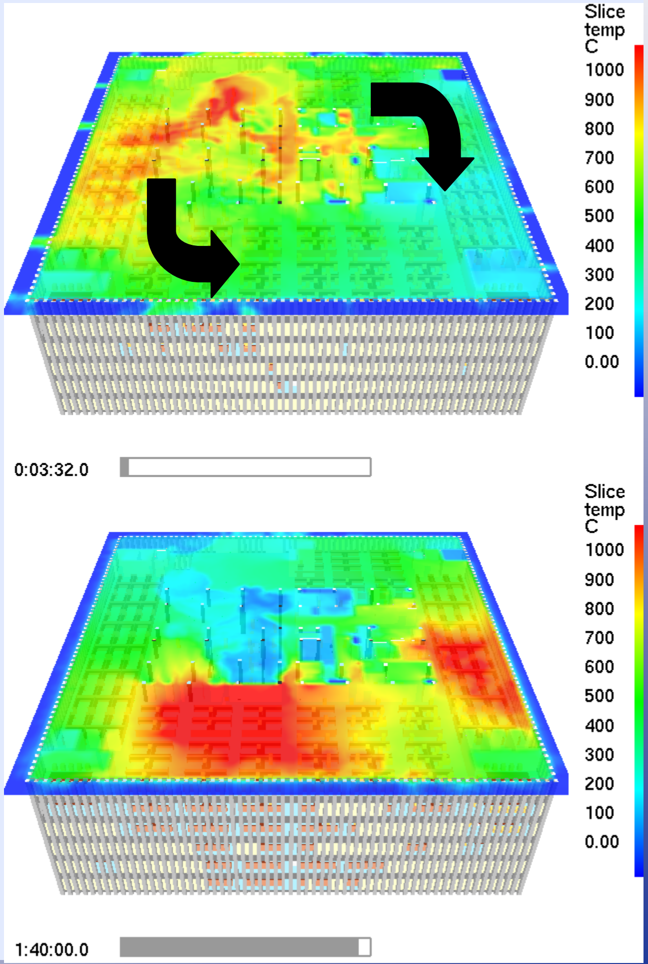
D. Predicted Fire Spread and Structure Temperatures



FDS Computational Domain

Upper Layer Temperatures
(WTC 1, Floor 97)





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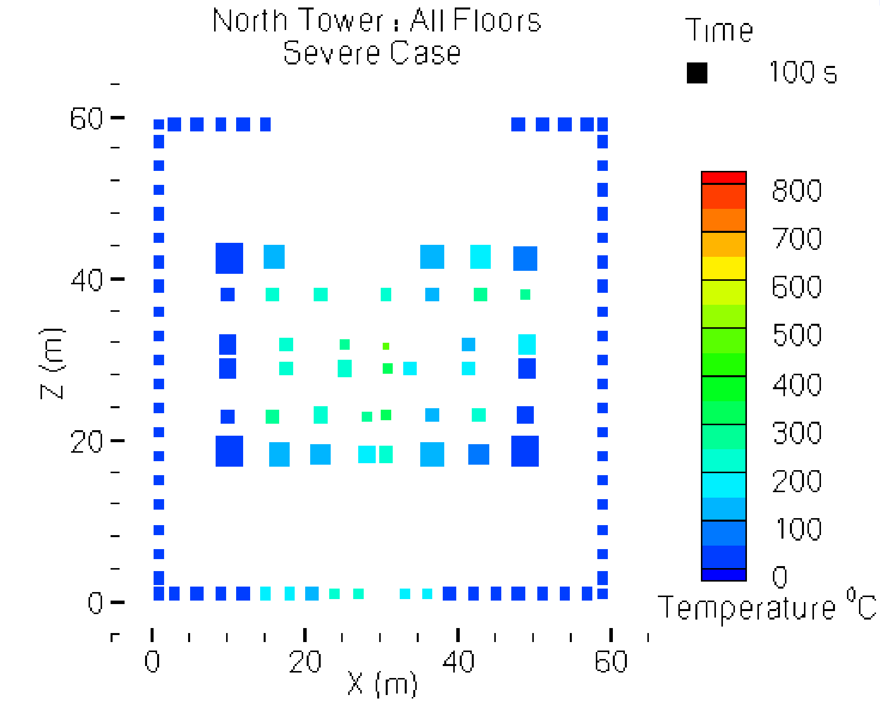
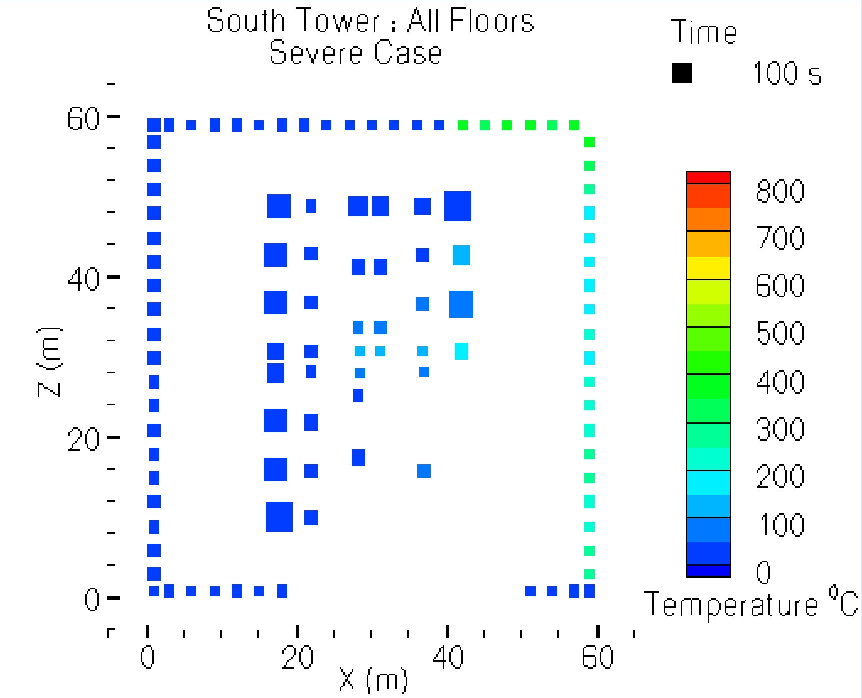
Predicted Column Temperatures

WTC 1



WTC 2



Shows maximum temperature reached by each column.

III. EGRESS ISSUES AND EVACUATION MODELING*

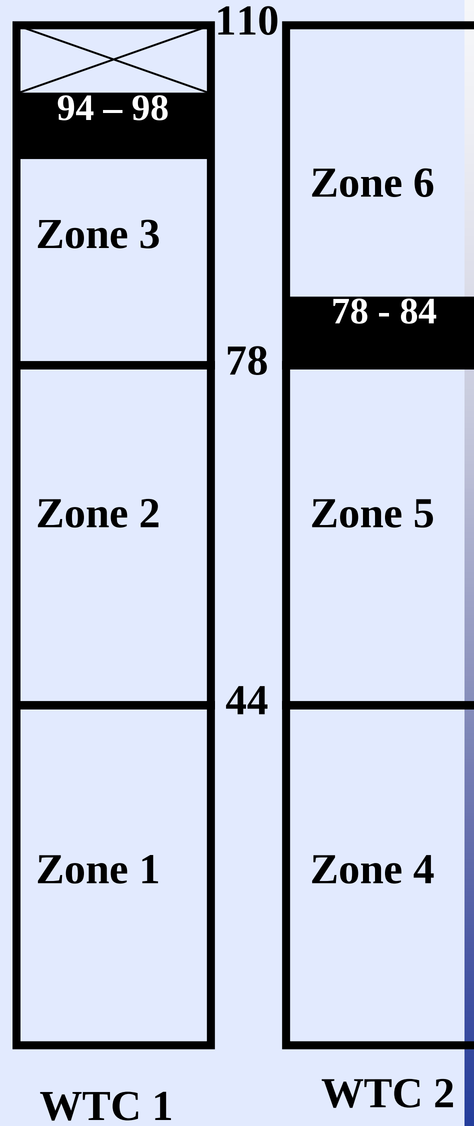
A. Methods and Data Sources
B. Evacuation Process
C. Key Findings

***Condensed from presentation by KATHLEEN TIERNEY at the AIA Annual Convention, Las Vegas, May 20, 2005**

A. Methods and Data Sources

- 745 published “first-person” accounts, reduced to 435 separate accounts of occupant experiences
- Systematically selected random sample of 803 survivors, interviewed by telephone: both towers, lower, mid-level, and higher floors
- More than 200 face-to-face interviews designed to elicit accurate recall of occupant experiences on September 11
- Six focus group discussions
- Egress modeling using alternative scenarios

Stratification Strategy



B. Evacuation Process

- Evacuations initiated by building occupants themselves.
- 91% of survivors in WTC 1 had begun evacuating before second plane hit tower 2.
- After attack on WTC 1, WTC 2 occupants began evacuating spontaneously.
- Nearly 20% of tower 2 survivors used elevators.
- 87% of WTC2 occupants started evacuating before second plane hit.
- 75% of WTC2 occupants above floor 78 had gotten to that floor or below before the plane struck.
- Evacuation already under way at 9 a.m. when announcement made that WTC2 occupants should return to their offices.
- Most of those evacuating WTC2 did not hear that announcement.
- 41% of WTC2 survivors had already left before second plane hit.
- Self-evacuation and use of elevators saved 3,000 lives in tower 2.
- Most occupants moved quickly to leave, but many delayed.

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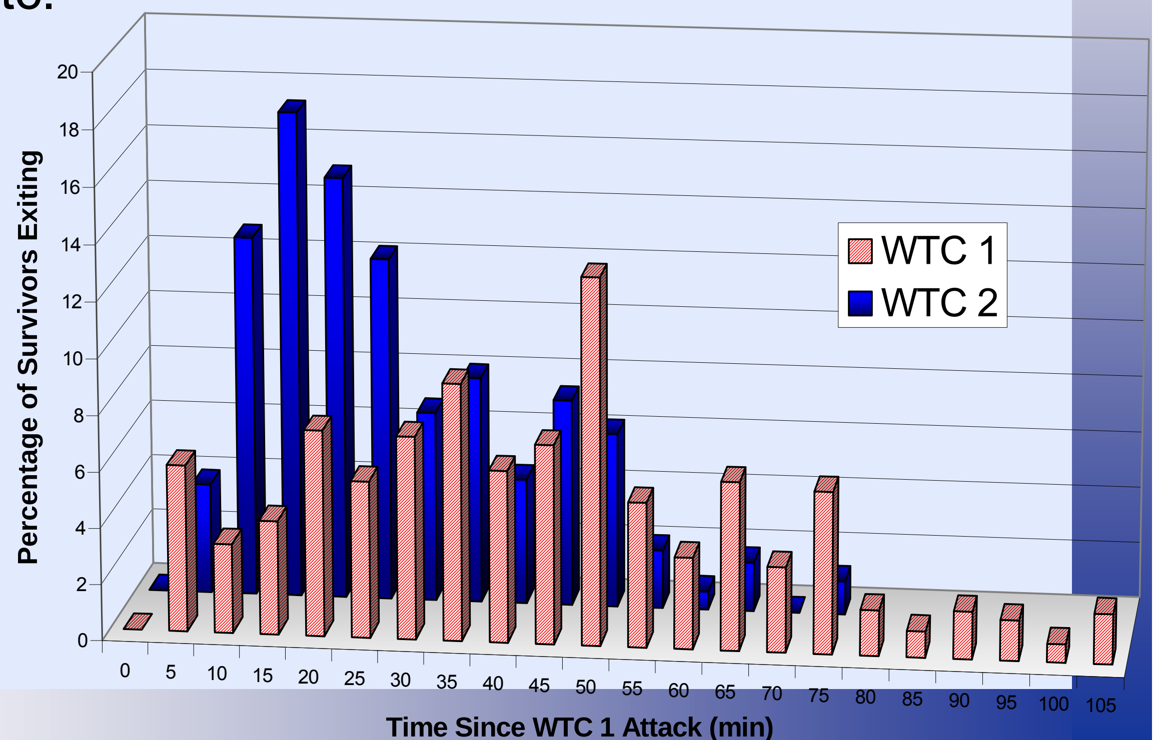
Evacuation Process (2)

- Delayed departure proved fatal for those on/ above impact floors in WTC 2.
- “Milling”: Normal response to uncertain but urgent circumstances, involving information-seeking, information exchange, observation.
- “Preparatory Behaviors”: Gathering materials, phone calls, computer back-up and shut-down, etc.
- Variations in behavior attributable to experience with/knowledge of 1993 bombing:
  --Leave Immediately
  --Wait for Instructions
  --Don’t rely on Port
  Authority



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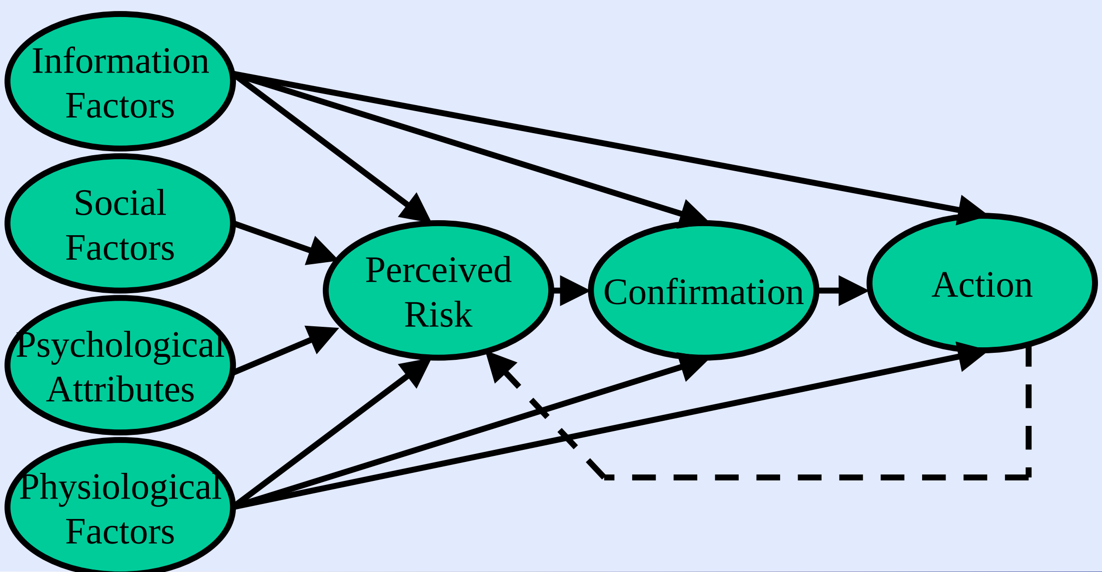
Quote from Tower 2

"I was there during the 1993 bombing. I did evacuate—with a group of people who had no clue as to where we were going. What I learned from that experience was not to trust the Port Authority's announcements. Had I not experienced that, I might have listened to the Port Authority announcement and stayed put."



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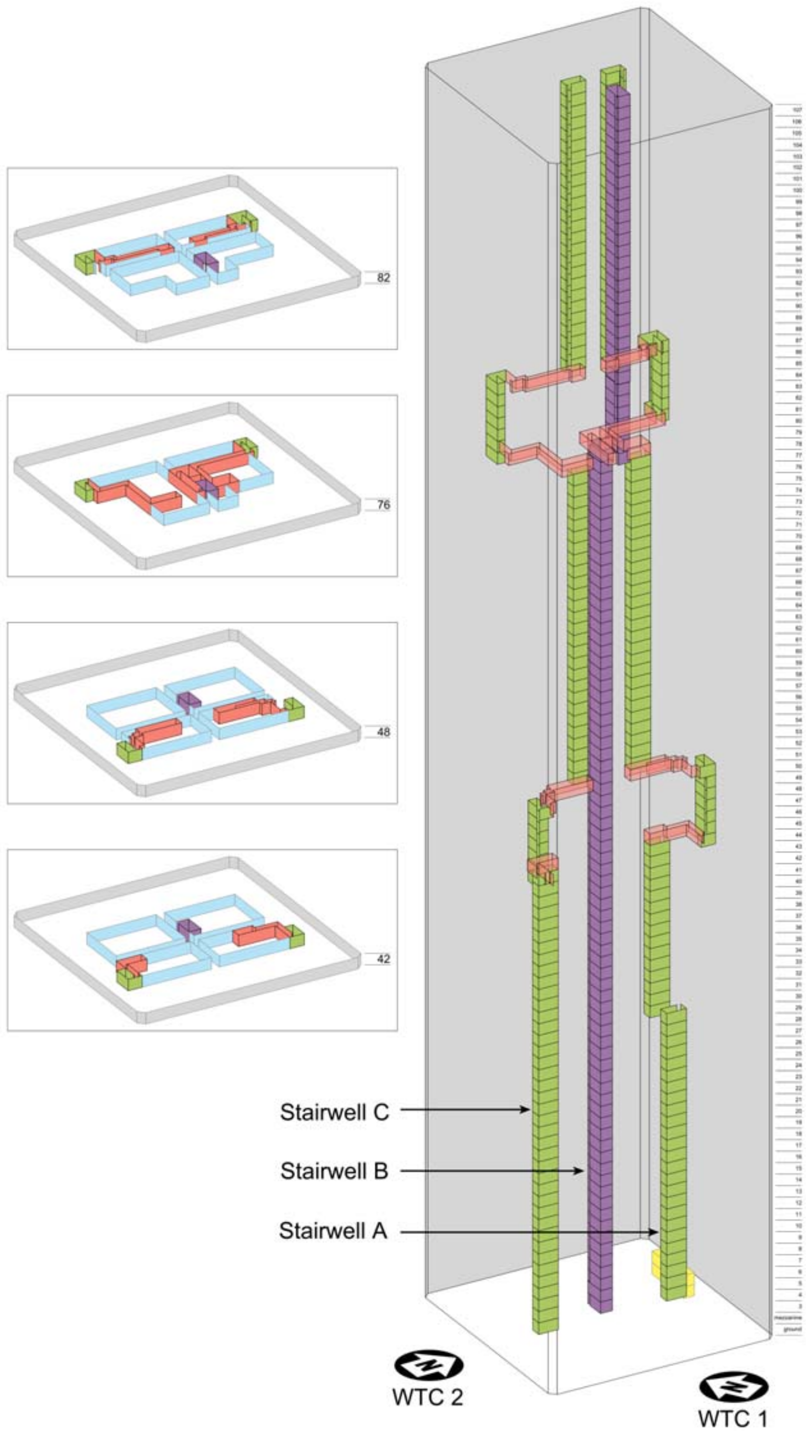
Evacuation Process (3)

- Average evacuation time for WTC1 survivors was 42 minutes.
- Average times ranged from 29 to 70 minutes, depending on floor height.
- Influential factors:
  - Encountering debris, damage, dangerous conditions
  - Evacuating from a higher floor
  - Interrupting evacuation process (helping others, leaving stairwells, reversing direction
  - Encountering transfer hallways
- Factors that did not have a statistically significant impact:
  - Perceptions regarding counterflow
  - Perceptions regarding crowding
- Simulex, buildingEXODUS, EXIT89 used to model phased and full-building evacuations under different conditions.

Evacuation Process (4)

- Under full occupant and visitor loads (25,000 in each tower) and with no delays, models indicate evacuation would have taken close to 2-1/2 hours (compared to ~ 4 hours based upon observed egress rate on Sept. 11).
- In Tower 2, 7700 people would have been trapped above the impact floors.
- 14,577 people would still have been in the towers when they collapsed.



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C. Key Egress Findings

Preparedness and Training Before Sept. 11:

- Egress Systems and Preparedness Measures Upgraded After ’93 Bombing
- 66% of Survey Respondents Had Taken Part in a Fire Drill in 12 Months Before 9-11
- Training Only at Most Basic Level—Important Guidance Lacking
- Survivors Considered Training Useful

Key Egress Findings (2)

Mobility Impaired Occupants:

- Ambulatory mobility impaired occupants typically walked down stairs with one hand on each hand rail, took one step at a time, and were accompanied by another person. This blocked others behind them from moving more rapidly.
- FDNY and PAPD personnel found 40 to 60 mobility impaired occupants on 12th floor of WTC 1 as they went down and attempted to clear each floor on their way out. These impaired individuals had been placed on this floor in an attempt to clear stairways.
- Emergency responders were assisting approximately 20 of these mobility impaired people down staircase just prior to the collapse of WTC 1. It is unknown how many fatalities occurred with this group.

Key Egress Findings (3)

- Stairwell separation ranged from 70 ft (including the impact region in WTC 1) to 200 ft (including the impact region in WTC 2).
- Building egress systems are not designed to accommodate full building evacuation.
- There is a lack of egress models and performance-based egress methodology accounting for human behavior during evacuation.
- Remarkably successful evacuation, given conditions Tower occupants faced on September 11
- Spontaneous evacuation, use of elevators saved many lives
- But what if there had been 50,000 people in the Towers, instead of 17,000?

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IV. EMERGENCY RESPONSE

A. Background

B. Operations and Situation Awareness

C. FDNY Access to Towers

D. Communications

E. Command and Control

Background

Changes after 1993 Bombing:

- FDNY worked with PANYNJ to upgrade WTC fire protection
- FDNY high-rise radio repeater was installed
- Fire Command Desks installed in WTC 1 and 2
- Elevator intercom system was upgraded
- New Operations Control Center was added to complex on B1 level of WTC 2
- Multiple power sources installed for emergency lighting
- New decentralized fire alarm system was installed at WTC
- Various fire drills were conducted at WTC and some included FDNY participation

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Background (2)

Role of Emergency Responders:

FDNY - Established operational control and Incident Command Post for WTC operations, conducted evacuation and rescue operations, and fought fires.

PAPD - Established security at WTC and conducted evacuation and rescue operations.

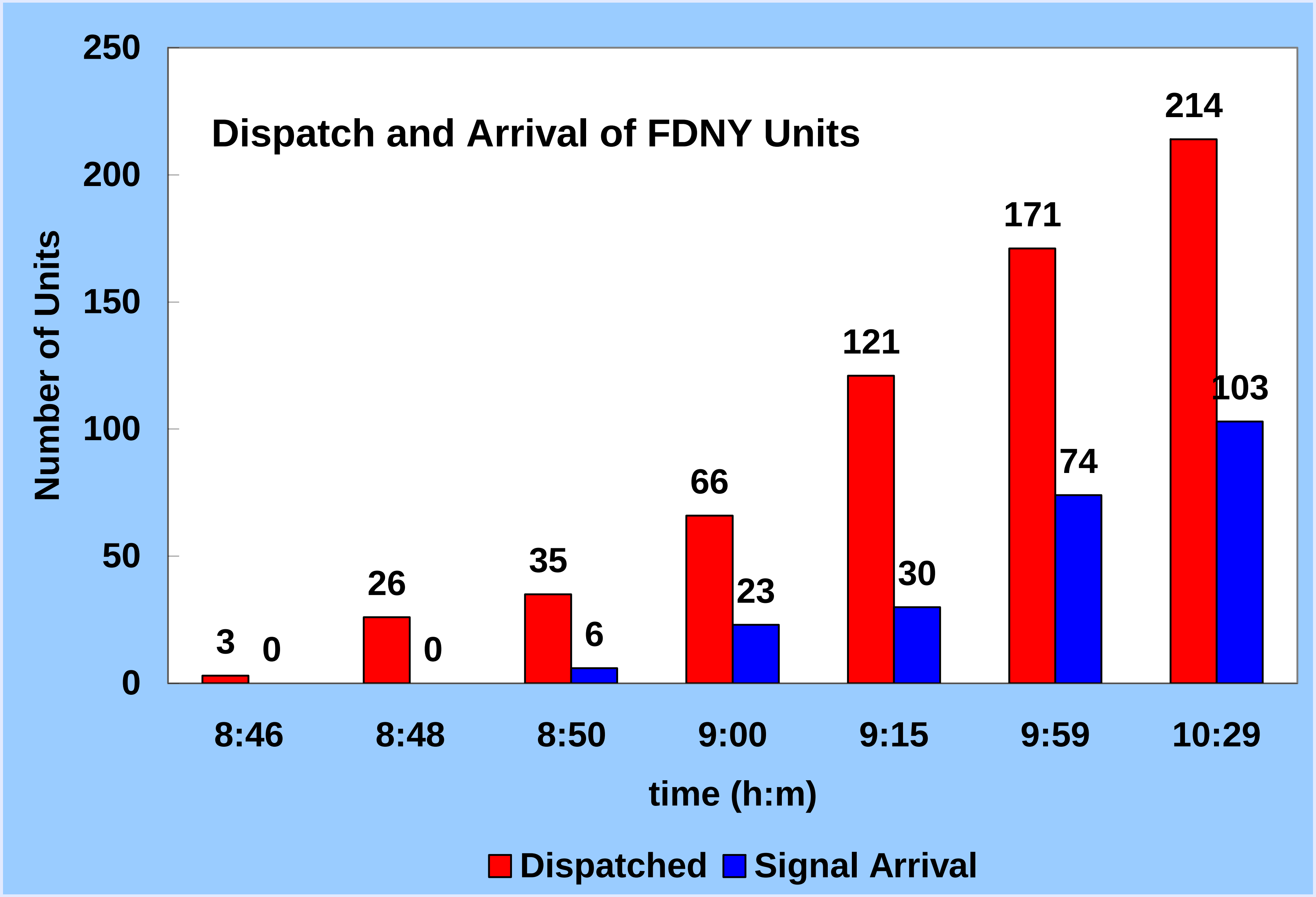
NYPD - Established traffic control, perimeter security at site, security for command posts, and conducted evacuation and rescue operations inside. Aviation units supplied observation capabilities and assessed potential for roof rescue.

OEM - Functioned as multi-agency command resource center and provided support for all agencies and departments working at disaster.

B. Operations

FDNY's Initial "Size-up" of WTC Conditions:

- A large aircraft had hit the WTC 1 building.
- Large fires were burning on multiple floors at and above impact zone.
- Elevators were not working and people were trapped inside many of the elevators.
- Sprinkler system and standpipe systems were likely compromised.
- Likely that no water supply was available to fight fires at and above impact zone.
- Likely that many occupants trapped at and above impact zone were already dead or would die before help could get to them.


Dispatch and Arrival of FDNY Units
Number of Units
250
200
150
100
50
0
3
0
26
0
35
6
66
23
121
30
171
74
214
103
8:46
8:48
8:50
9:00
9:15
9:59
10:29
time (h:m)
Dispatched
Signal Arrival

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Operations (2)

Outside Command Posts, and Inside Command Communicating with Outside Command Posts:

- Fires in buildings were too large, located too high, to accomplish fire fighting activities that could save lives of occupants above the fires.
- **Objective: evacuate and rescue all below the fires.**

Command Officers for Inside Operations:

- Fires were too large to extinguish.
- **Objective: get enough personnel and equipment upstairs to cut path through fire to rescue occupants above, and also evacuate and rescue all below fires.**

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Operations (3)

Company Level Command:

- Conventional but large high-rise fire.
- **Objective: get up to fire floors and extinguish fires.**

In some cases, firefighters were persuaded by higher ranking officers to switch from fire fighting to evacuation and rescue operations.

No first responder interviewed by NIST thought that the WTC towers would collapse.

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C. FDNY Access to the WTC Towers

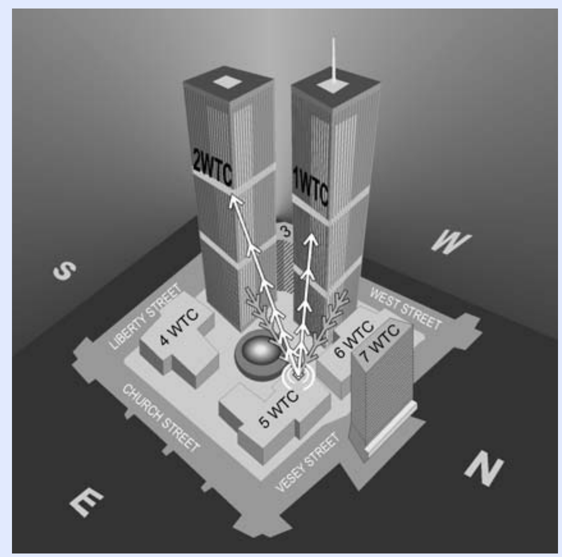
- After aircraft impact, only two elevators out of 198 were operating: from lobby to 16th floor (WTC1), and from lobby to 40th floor (WTC2).
- Stairways were filled with occupants evacuating buildings.
- Counterflow in stairs for FDNY personnel and other emergency responders caused:
  - difficulty for carrying equipment up stairs;
  - teams of emergency responders to become separated, leading to delays and disrupting team operations.
- Time to begin operations for first responding FDNY units: 7 to 15 minutes.
- Estimated climbing rate based on a 60 minute climbing period to their maximum height: 1.4 to 2 minutes/floor

D. Communications

- FDNY, NYPD & PAPD all experienced difficulties with radio communications.

- Each department was aware of shortfalls associated with their radio communications systems as they related to operations in high-rise buildings.

- Two basic issues with radio communications:
  - Normal function of the radio equipment in high-rise environments. (Radio <u>signal attenuation</u> in steel and concrete buildings).
  - The <u>volume of radio traffic</u>

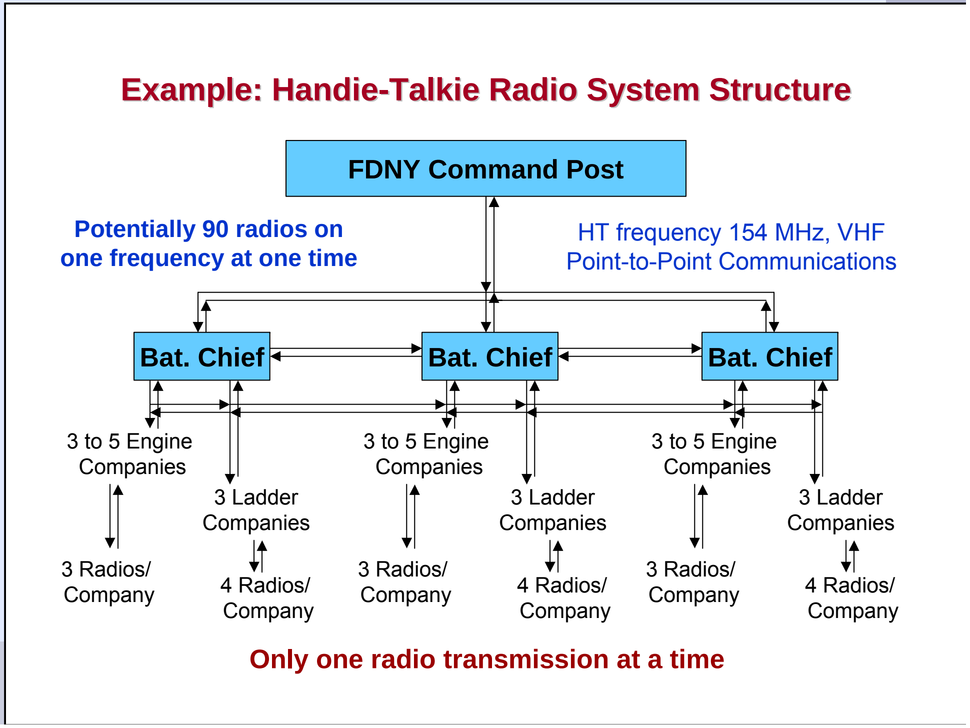


Schematic of WTC Radio Repeater System

Communications (2)

Impact of unsatisfactory radio communications:

- Emergency responders who could view building from outside and communicate over radios -- adequate situational awareness.
- Personnel who observed building damage and fires from outside experienced -- difficulty maintaining awareness after entering.
- Emergency responders working inside who could not see what was happening outside and had poor radio communications -- situational awareness was poor.
- Emergency responders working inside of buildings, who could not see what was happening outside and had good radio communications -- better situational awareness.



Communication from NYPD Aviation Unit

<u>10:06 am</u>

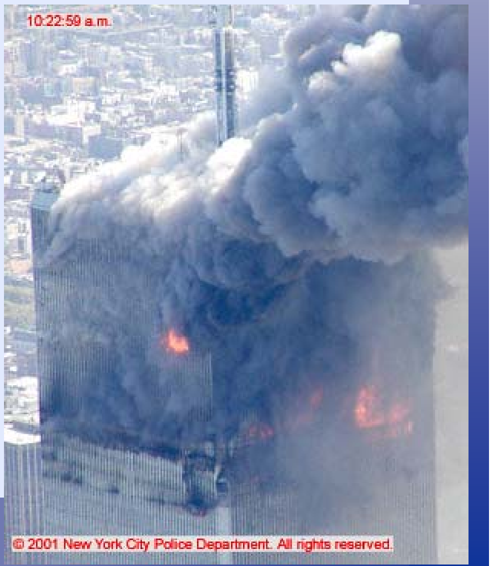
Advises everybody to evacuate area in vicinity of Battery Park City and states that, about 15 floors from top, it is totally glowing red on inside and collapse was inevitable. Advises that it is isn't going to take much longer before North tower comes down and to pull emergency vehicles back from building.

<u>10:21 am</u>

First reports that top of tower might be leaning, then confirms that it is buckling and leaning to the South. Reports that North tower is leaning to the Southwest and appears to be buckling in Southwest corner. Advises that all personnel close to building pull back three blocks in every direction.

<u>10:28 am</u>

Reports that roof is going to come down very shortly. Reports that tower is collapsing.



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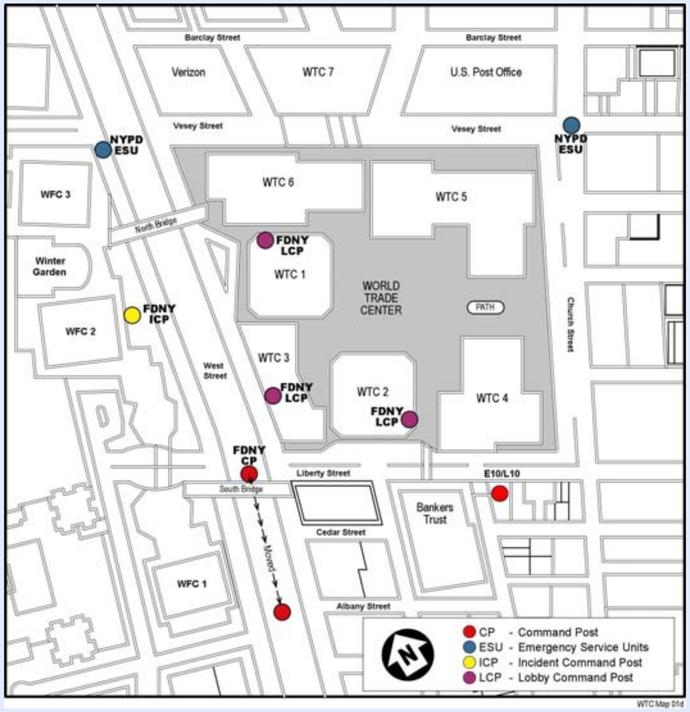
E. Command and Control

- Three FDNY suitcase-based, magnetic Command Boards were set up at the incident site.
- FDNY command and control was seriously affected by lack of good communications.
- Large numbers of fire fighters and ambulances officially dispatched (or self-dispatched) to WTC site before adequate command posts and staff could be assembled.
- Interagency operations detrimentally affected with loss of OEM command center in WTC 7.

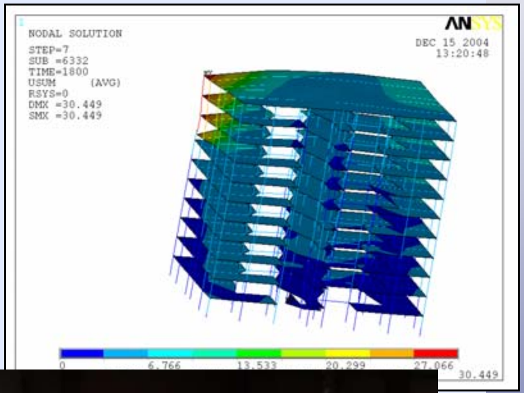
Command and Control (2)

- A significant amount of evidence (first person interviews, reports, and photographic data) suggests that:
  - Departments attempted to work together to save as many lives as possible and protect citizens on September 11.
  - Some issues related to a given department’s operational responsibility and competitive nature of departments did exist during operations; some problems experienced were due to personnel not understanding operating practices of other agencies.
  - Inter-agency competition had minimal effect on operations at WTC complex before towers collapsed.



V. RESEARCH, IMPLEMENTATION OF RECOMMENDATIONS

A. WTC R&D -- Safety of Threatened Buildings Program



- **Objective:** provide technical foundation that supports improvements to codes, standards, and practices that reduce impact of extreme threats to safety of buildings, their occupants & emergency responders.

- **Outcomes:**
  - Increased Structural Integrity
  - Enhanced Fire Resistance
  - Improved Emergency Egress & Access
  - Building & Emergency Equip. Standards & Guidelines

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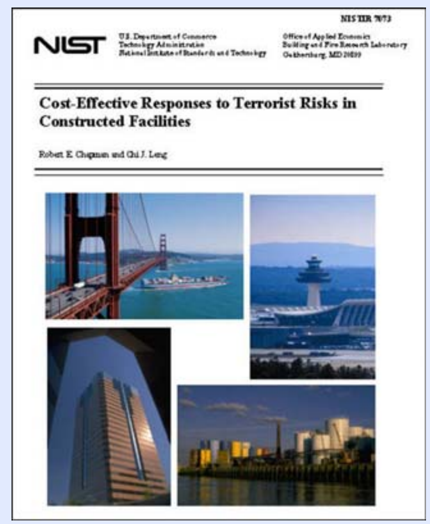
B. DTAP -- Dissemination and Technical Assistance Program

- Complement and support parallel efforts of engineering societies and codes/standards organizations to improve technology, codes, and standards
- Provide advice on best practices, guidance on vulnerability assessment, guidance on standards and codes needs
- Disseminate and implement R&D outputs



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Cost-Effective Responses to Terrorist Risks in Constructed Facilities

Robert E. Chapman and Chi J. Leng

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