NIST Response to the World Trade Center Disaster

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

NIBS/MMC
WTC Recommendations Committee

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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 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 procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings
- **Identify specific areas in current national building and fire model codes, standards, and practices that warrant revision**

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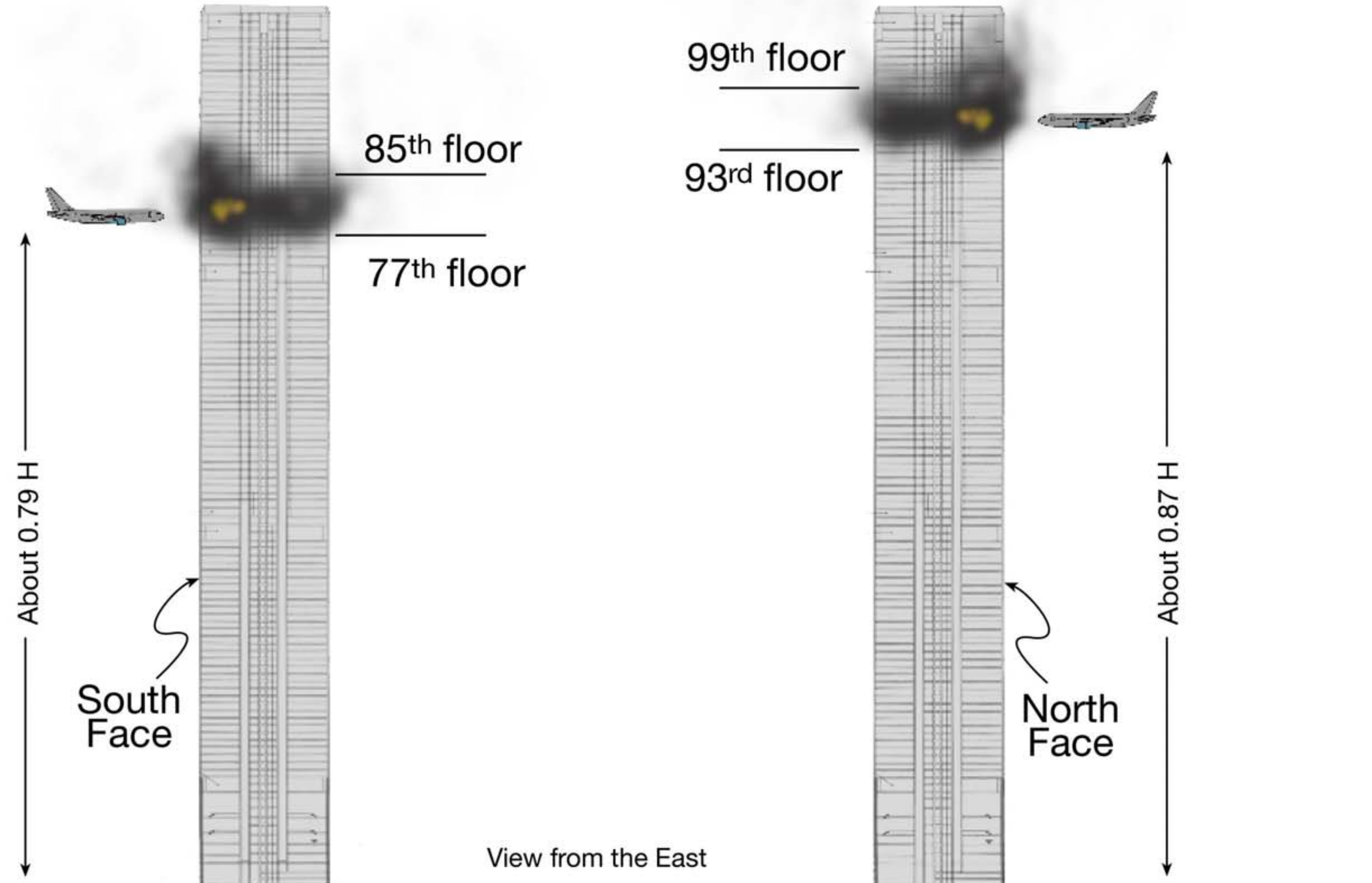

WTC 2: Hit at 9:02:59 a.m.
Collapsed after 56 minutes

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

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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 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.

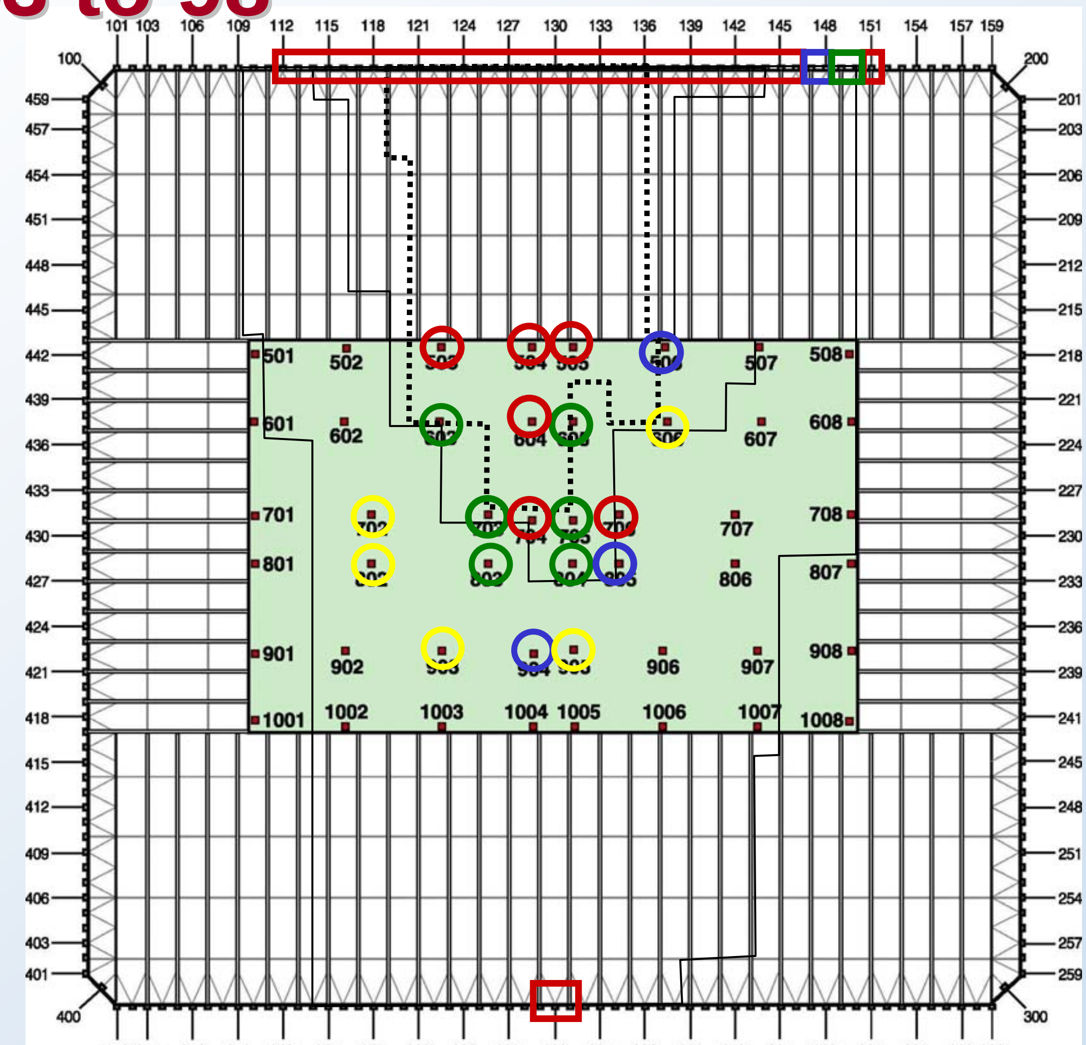
WTC 1 Damage: Composite Summary for Floors 93 to 98

Severe Floor Damage

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

Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



WTC 2 Damage: Composite Summary for Floors 78 to 83

Floor Damage

Fireproofing and partitions

Floor system structural damage

Floor system removed

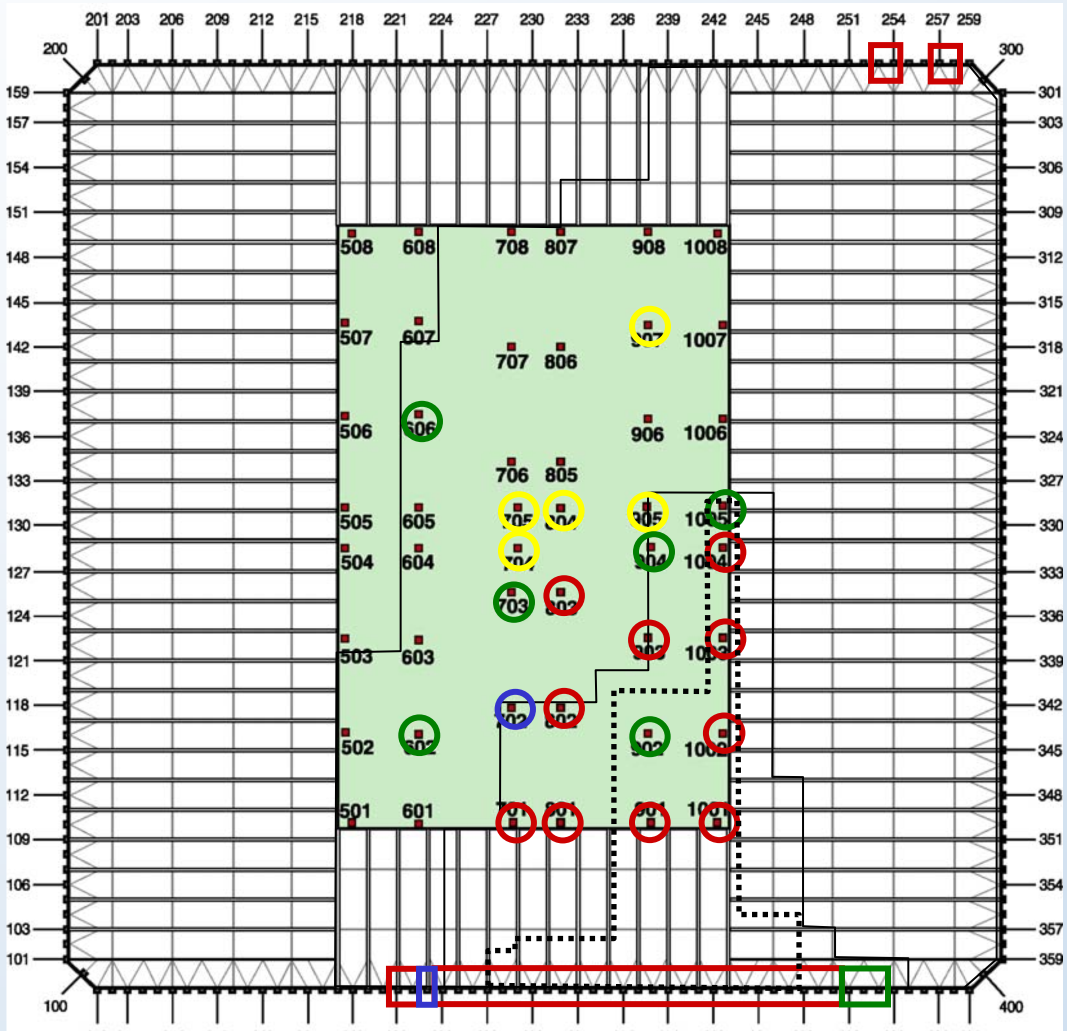
Column Damage

Severed

Heavy Damage

Moderate Damage

Light Damage

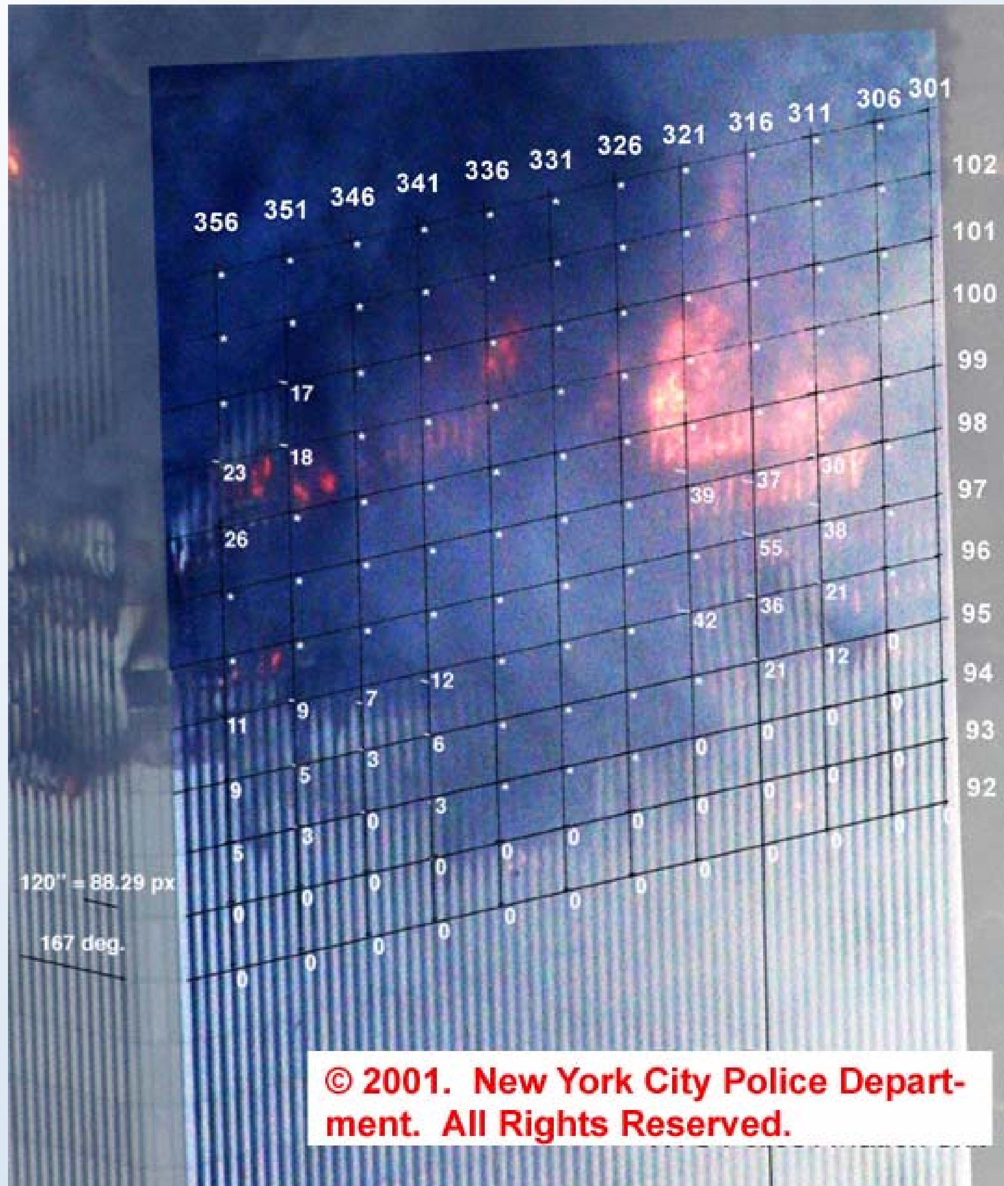


South Face of WTC1

- Time: 10:22 AM

- Measurements of inward bowing (inches)

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



- Floor locations approximate
- Blue tinted region digitally enhanced

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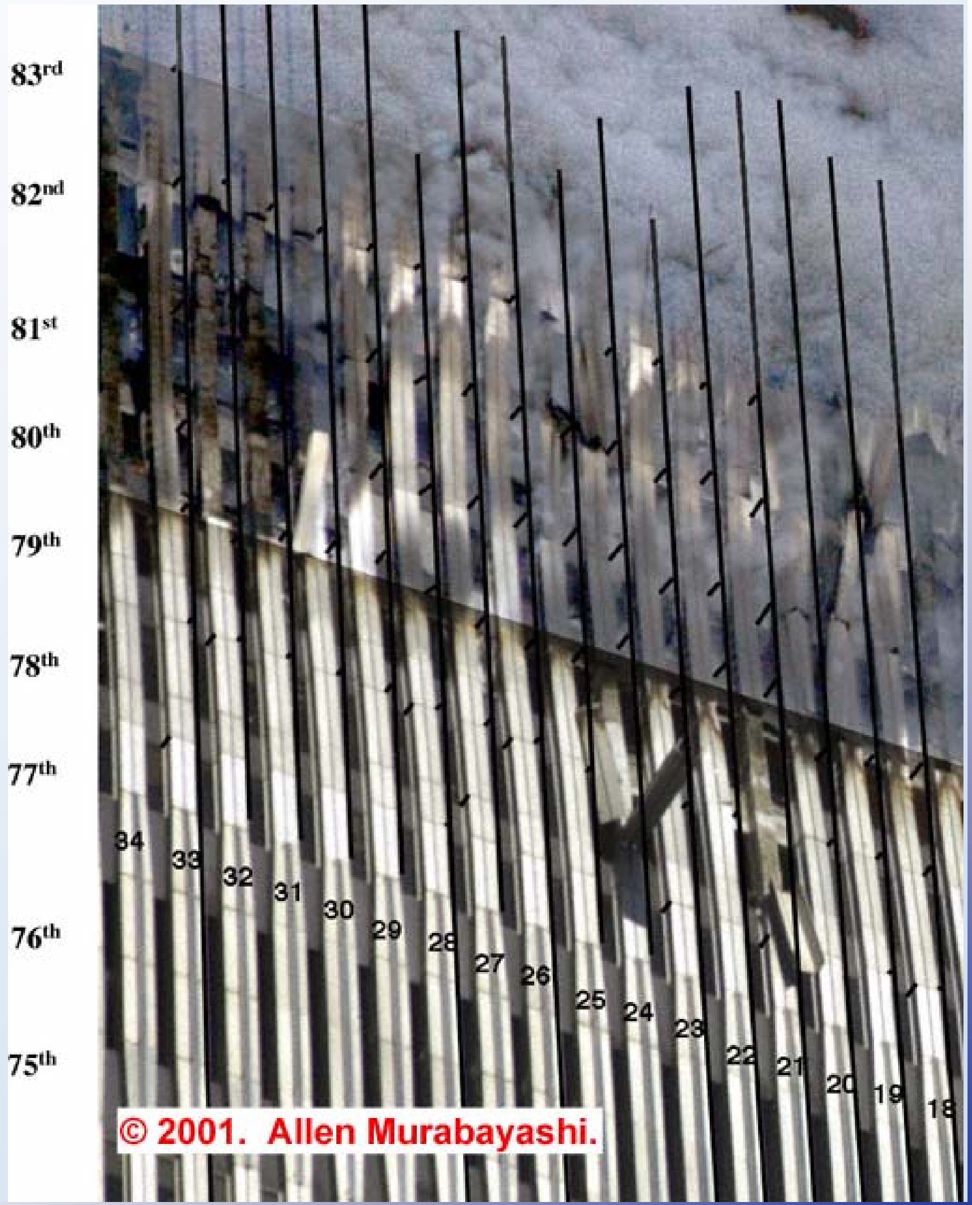
WTC2: East Face

Time: 9:21:29 AM

~18 minutes post impact

Maximum inward bowing of columns approximately 10 inches



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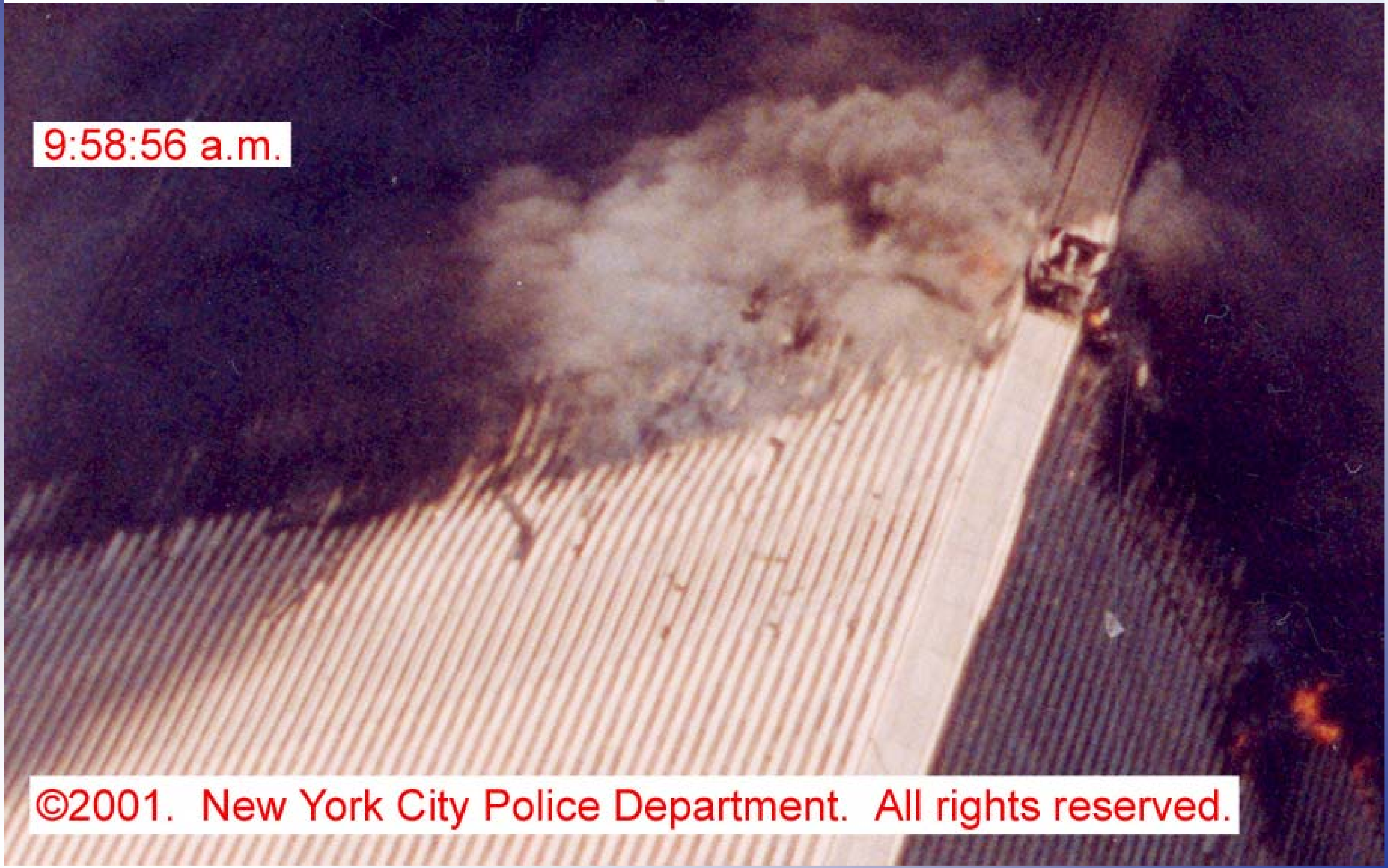
Inward Bowing of Perimeter Columns About 2 Minutes Prior to Collapse: WTC 2 East Face



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Tilting of Building Sections

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

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

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 for Class 1-B construction:
  - ❑ 1/2 in. specified when WTC towers were built to maintain Class 1-A (not 1-B) fire rating requirement of NYC Building Code
  - ❑ 1-1/2 in. specified for upgrades some years prior to 2001

- **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 could not be determined without testing.

Results From NIST Sponsored Tests at UL

Test	Description	Times to Reach End-Point Criteria (min): Temperature on Unexposed Surface – Average (Ambient +250ºF)	Temperature on Unexposed Surface – Maximum (Ambient +325ºF)	Steel Temperatures – Average (1100ºF)	Steel Temperatures – Maximum (1300ºF)	Failure to Support Load	Test Terminated (min)	Standard Fire Test Rating: ASTM E 119-61 – Rating (hr)	ASTM E 119-00 – Restrained Rating (hr)	ASTM E 119-00 – Unrestrained 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.

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

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.

Evacuation and Emergency Response

Based on 1,056 interviews of surviving WTC occupants and 116 interviews of emergency responders.

- It is estimated that **17,400 occupants** (± 1,200) **were present in the WTC towers on the morning of September 11, 2001.**
- The **initial population of each tower was similar**: 8,900 (± 750) in WTC 1 and 8,500 (± 900) in WTC 2.
  - **About 6 percent of the surviving occupants (about 1,000 people) reported a pre-existing limitation to their mobility.**
- Approximately **87 percent of the WTC tower occupants were able to evacuate successfully, including more than 99 percent of those below the floors of impact**.

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Evacuation Rates in the WTC Towers

- **Roughly 3000 survivors self-evacuated WTC 2** using the **functioning elevators and stairwells** during the **16 minutes prior to aircraft impact.**

- The **egress capacity was adequate** to accommodate survivors who were seeking and able to reach the exits and stairways.

- **A full capacity evacuation with 20,000 people in each WTC tower**—two to three times the occupancy on September 11, 2001—**would have required about 3 hours.**
  - Under this scenario, it is estimated that **roughly 14,000 people may have lost their lives** and the **egress capacity would have been inadequate** for the time available.
  - The egress capacity required by current building codes is based on evacuating a single floor.

Occupant Preparedness

- Occupants were often **unprepared for the physical challenge** of full building evacuation.
  - The average surviving occupant **moved slower down stairs and through stairwell exits** than previously reported for non-emergency evacuations.
  - In WTC 1, **the average surviving occupant spent 48 seconds per floor descending the stairwell.**
- After the collapse of WTC 2, emergency responders found **mobility impaired occupants** of WTC 1 still in the staircases going down.
  - Ambulatory mobility impaired occupants **blocked others behind them from moving more rapidly down the stairs.**
  - **FDNY and PAPD personnel found 40 to 60 mobility impaired occupants on the 12th floor of WTC 1.** They had been placed on this floor in an attempt to clear the stairways.

Emergency Response in High-Rise Buildings

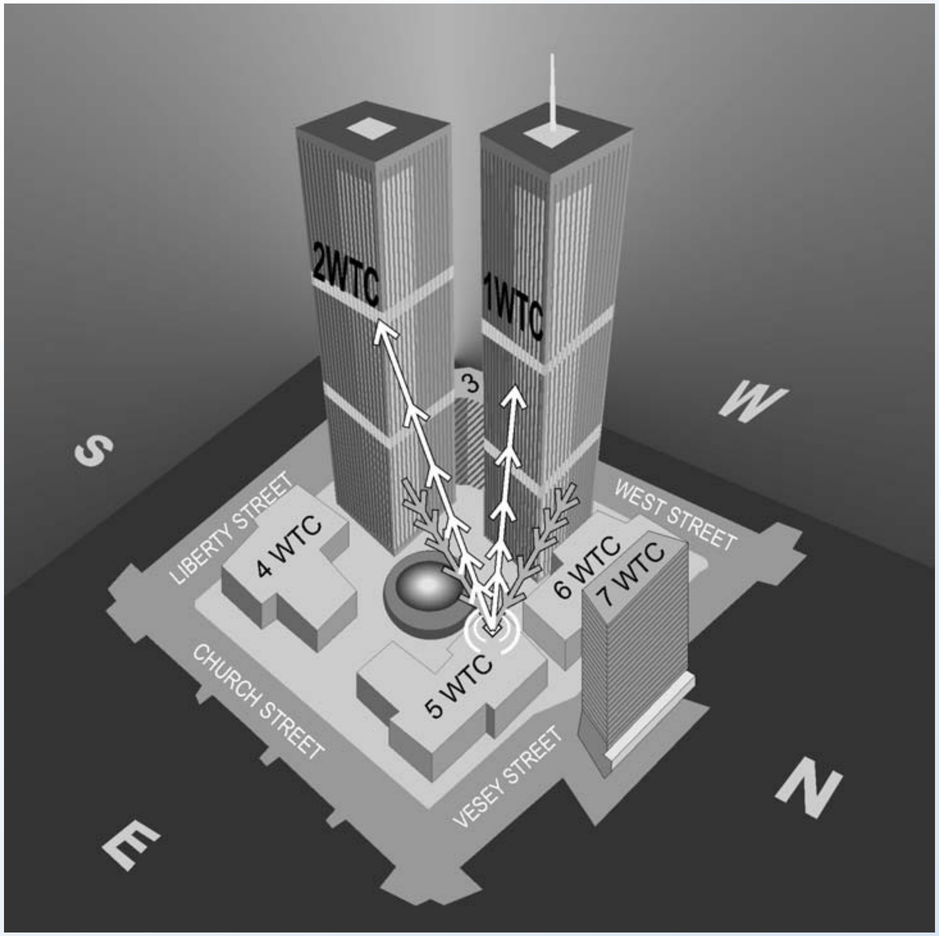
Example: Response to a 60 story high-rise building, occupants trapped above fires on the 58th floor and no operating elevators.

Firefighters:
With equipment ~ 125 minutes
Without equipment ~ 90 minutes

Estimated firefighter climbing rate
(60 minute climbing period to max height)
2 min/floor with equipment
1.4 min/floor without equipment

Firefighters begin to climb 7-15 minutes
Fire department arrival 4-10 minutes

Radio Communications in High-Rise Buildings



Schematic of WTC Radio Repeater System

- ***Intra-operability*** within an emergency responder organization:
  - Buildings pose a challenging radio-frequency environment.
  - Capacity, protocols, and training for large-scale operations.
- ***Interoperability*** among different emergency responder organizations.

Context for Recommendations

- The tragic consequences of the September 11, 2001, attacks were directly attributable to the fact that terrorists flew large jet-fuel laden commercial airliners into the WTC towers.

- **Buildings for use by the general population are not designed to withstand aircraft attacks;** building codes do not require consideration of aircraft impact.

- In our cities, there has been **no experience with evacuation and emergency response in a building disaster of this magnitude,** nor has there been any in which the total collapse of a high-rise building occurred so rapidly and with little warning.

- Documents suggest that **the WTC towers generally were designed and maintained consistent with the requirements of the 1968 New York City Building Code.**

Context for Recommendations (2)

- 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.

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

    Structural Design

    - Improved Active Fire Protection
    - Improved Building Evacuation
    - Improved Emergency Response

    Life Safety Systems

    - Improved Procedures and Practices
    - Education and Training Programs

    Practices & Development

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

Enhanced Fire Resistance of Structures

Evaluate -- and where needed improve -- the technical basis for determining ***construction classification and fire rating requirements (especially for tall buildings)***…and make related code changes now as much as possible by explicitly considering:

- ***timely access*** by emergency responders and ***full evacuation*** of occupants, or time required for ***burnout without partial collapse;***
- extent to which *redundancy* in active fire protection (sprinkler and standpipe, fire alarm, and smoke management) systems *should be credited* for occupant life safety;
- need for ***redundancy in fire protection systems*** critical to structural integrity;
- ability of the structure and local floor systems to withstand ***maximum credible fire scenario without collapse*** -- recognizing that sprinklers could be compromised, not operational, or non-existent; (continued)

Enhanced Fire Resistance of Structures (2)

- ***compartmentation*** requirements to protect the structure, including:
  - fire rated doors and automatic enclosures, and
  - limiting air supply (e.g., thermally resistant window assemblies)

  to retard fire spread in buildings with large, open floor plans,

- effect of spaces containing ***unusually large fuel concentrations*** for the expected occupancy of the building; and

- extent to which fire control systems -- including suppression by automatic or manual means -- should be credited as part of the prevention of fire spread. Rec. #4

Enhanced Fire Resistance of Structures (3)

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

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

Improved Active Fire Protection

Enhance performance and possibly the ***redundancy of active fire protection systems*** to accommodate ***higher risks associated with tall buildings.*** Rec. #12

Develop ***advanced fire alarm and communication systems*** that provide ***continuous, reliable, and accurate information on life safety conditions*** to manage the evacuation process; all communication and control paths in buildings need to be designed and installed to have the same resistance to failure and increased survivability above that specified in present standards. Rec. #13

Adapt advanced fire/emergency control panels to accept and interpret more – and more reliable -- information from the active fire protection systems to provide ***tactical decision aids.*** Rec. #14

Develop and require systems for ***improved transmission to emergency responders, and off-site or black-box storage, of information*** from building monitoring systems. Rec. #15

Improved Building Evacuation

Develop and carry out ***public education and training campaigns*** to improve building ***occupants' preparedness for evacuation*** in case of building emergencies. Rec. #16

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

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Improved Building Evacuation (2)

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

Improved Building Evacuation (3)

Building owners, managers, and emergency responders should develop a joint plan and ***ensure accurate emergency information is communicated*** in a timely manner ***to enhance awareness of occupants and emergency responders*** through:

- better coordination of information among different emergency responder groups,
- efficient sharing of that information among building occupants and emergency responders,
- more robust design of emergency public address systems,
- improved emergency responder communication systems, and
- use of the Emergency Broadcast System (the Integrated Public Alert and Warning System) and Community Emergency Alert Networks. Rec. #19

Improved Building Evacuation (4)

Evaluate the full range of current and ***next generation evacuation technologies*** for future use, including:

- protected/hardened elevators,
- exterior escape devices, and
- stairwell descent devices,

which may allow all occupants an ***equal opportunity for evacuation*** and facilitate emergency response access. Rec. #20

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Improved Emergency Response Technologies and Procedures

Install ***fire-protected and structurally hardened elevators in tall buildings*** to provide timely emergency access to responders and allow evacuation of mobility impaired building occupants.

- Such elevators should be for exclusive use by emergency responders during emergencies.
- In tall buildings, consideration also should be given to installing such elevators for use by all occupants. Rec. #21

Install, inspect, and test ***emergency communications systems, radio communications, and associated operating protocols*** to ensure that the systems and protocols:

- are effective for ***large-scale emergencies*** in buildings with ***challenging radio frequency propagation environments,*** and
- can be used to ***identify, locate, and track emergency responders*** within indoor building environments and in the field. Rec. #22

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Improved Emergency Response Technologies and Procedures (2)

Establish and implement detailed procedures and methods for gathering, processing, and delivering critical information through ***integration of relevant voice, video, graphical, and written data*** to enhance situational awareness of all emergency responders. Establish an ***information intelligence sector*** to coordinate each incident. Rec. #23

Establish and implement codes and protocols for ensuring ***effective and uninterrupted operation of the command and control system*** for large-scale building emergencies. Rec. #24

Improved Procedures and Practices

Nongovernmental and quasi-governmental entities that own or lease buildings -- and are not subject to building and fire safety code requirements of any governmental jurisdiction -- should be encouraged to provide a ***level of safety that equals or exceeds*** the level of safety that would be provided by ***strict compliance with the code requirements of an appropriate governmental jurisdiction.***

- As-designed and as-built safety should be ***certified by a qualified third party*****,** independent of the building owner(s).
- The process ***should not use self-approval*** for code enforcement in areas including:
  - interpretation of code provisions,
  - design approval,
  - product acceptance,
  - certification of the final construction, and
  - post-occupancy inspections over the life of the buildings. #25

Improved Procedures and Practices (2)

State and local jurisdictions adopt and ***aggressively enforce building codes to ensure that egress and sprinkler requirements are met*** by existing buildings. Further, occupancy requirements should be modified where needed (such as when there are assembly use spaces within an office building) to meet the model building codes. Rec. #26

Building codes should require building owners to ***retain documents*** related to building design, construction, maintenance and modifications ***over the entire life of the building.*** Means should be developed for ***offsite storage and maintenance of the documents.*** Relevant information should be ***easily accessible by responders*** during emergencies. Rec. #27

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Improved Procedures and Practices (3)

The role of the “Design Professional in Responsible Charge” be clarified to ensure that ***all appropriate design professionals*** (including the fire protection and structural engineers) ***are part of the team*** designing ***buildings that employ innovative or unusual structural and fire safety systems.*** Rec. #28

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Education and Training

Continuing education curricula should be developed and programs be implemented for:

- training fire protection engineers and architects in ***structural engineering principles and design,*** and
- training structural engineers, architects, fire protection engineers, and code enforcement officials in ***modern fire protection principles and technologies,*** including ***fire-resistance design of structures.***
- training building regulatory and fire service personnel to upgrade their understanding and skills to conduct the ***review, inspection, and approval tasks*** for which they are responsible. Rec. #29

Academic, professional ***short-course,*** and web-based ***training materials*** in the use of ***computational fire dynamics and thermostructural analysis tools*** be developed. Rec. #30

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Achieving "Real" Safety Improvements

- NIST believes that the **recommendations are realistic, appropriate, and achievable** within a reasonable period of time**.**
  - Aim of design is to anticipate rare design events in a rational manner
  - Unanticipated events have surprised the design community (e.g., Northridge earthquake)
  - Historical statistics do not adequately capture rare design events (tails of distributions)

- **Only a few of the recommendations call for new requirements in standards and codes.** Most of the recommendations deal with:
  - Improving an existing standard or code requirement
  - Establishing a standard for an existing practice without one
  - Establishing the technical basis for an existing requirement
  - Making a current requirement risk-consistent
  - Adopting or enforcing a current requirement
  - Establishing a performance-based alternative to a current prescriptive requirement

- **Implementation of the recommendations would make buildings, occupants, and emergency responders safer in future emergencies.**

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Call for Action

- NIST is assigning ***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*.

- NIST has:
  - identified ***specific*** codes, standards, and practices affected by each of the 30 recommendations in its final report, and
  - reached out to the responsible organizations to pave the way for a ***timely, expedited consideration*** of the recommendations.

- NIST held a **conference** September 13-15, 2005 attended by **over 200 people, including *all major standards and codes developers.***

- NIST has awarded a contract to the National Institute of Building Sciences—a Congressionally authorized non-profit, non-governmental organization—to **turn appropriate recommendations into code language suitable for submission** of code change proposals **to the two national model code developers.** NIBS is drawing upon building code experts to carry out this task.

- NIST will implement a web-based system so that the public can track progress on implementing the recommendations.

Next Steps

- NIST plans to release final versions of the 43 reports on the WTC towers, totaling some 10,000 pages, on October 26, 2005.
- The summary WTC towers report is about 250 pages and contains the principal findings and recommendations from the investigation.
- Next spring, NIST plans to release an additional five reports on the investigation of WTC 7 as drafts for pubic comment.

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