Michigan State University College of Engineering

High-rise Buildings in Post 9-11 Period

Venkatesh Kodur
Michigan State University

Outline

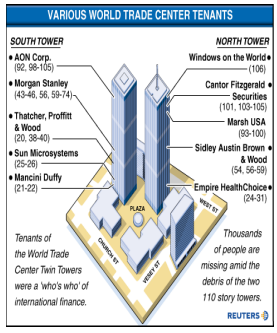
- The 9/11 Incident
  - Background
  - Sequence of Events
  - Damage Assessment
  - Twin Towers
    - Features
    - Science Behind Collapse
  - Other Buildings
  - Recommendations
- High-rise Buildings in US in Post 9-11 Period
  - Innovations for Improved Performance
  - Case Studies - Improved Performance
  - Changes in Building Codes
  - R& D Activities in Structural Fire Safety Area

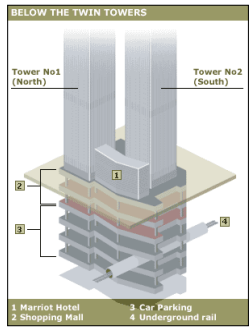
Facts – WTC

WTC complex	7 buildings
Owner	Port Authority of NY & NJ
Twin Towers (N&S)	WTC 1 & WTC 2
Height	110 stories, 1368 & 1362 ft
Total area	12 million sq ft
Capacity	50,000 Employees
Elevators	239
Escalators	71
Rest rooms	1200
Architect, Engineer & Contractor	Minoru Yamasaki Assoc. Skilling, Hellie, Robertson & Christianson Tishman Construction Co.
	Reputed Firms
Opened	April 4th, 1973

Excerpt from TIME magazine

Twin Towers – High & Mighty





Excerpt from Reuters

Manhattan Prior to Attack

Lower Manhattan

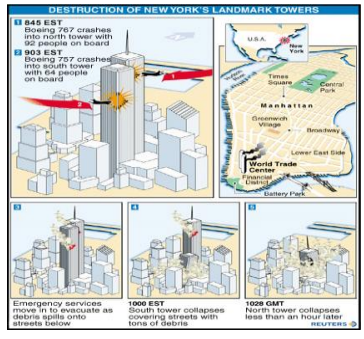
WTC – Looking Up

The Incident

September 11, 2001

AA 11, BOS – LAX
Hit N Tower at 8:46 am

UA 175, BOS - LAX
Hit S Tower at 9:03 am



Excerpt from Reuters

South Tower – Fire Ball

South Tower Collapsing

People Fleeing

People on Highways

WTC 3

WTC 7

NYC – Post 9/11

NYC Skyline – Before & After 9/11

Aug. 14, 2000

Before Attack….

Sept. 12, 2001

…and After Attack

WTC Disaster

September 11, 2001

- Terrorist attack
  - Buildings and infrastructure – disaster
    - Colossal damage and destruction
  - Building performance / investigation
    - Engineering profession
  - Building Performance Assessment Team (BPAT)
    - 23 member expert team
    - Lead by FEMA/ASCE + 15 organization
    - Structural Engg, fire, blast tall building failure investigations, metallurgy

BPAT – Objectives

- Obtain, record and preserve perishable data
- Damage Assessment
- Understand what happened
- Determine if there are obvious lessons to be learned
- Recommend any needed Code changes
- Recommend more

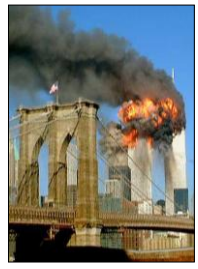
Ground Zero Situation

WTC site visit

- 8-10 Blocks cordoned off, high security
- Fires burning and smoldering
- Dust: breathing apparatus and glasses required
- No power PC buildings
- Safety issues
- Health issues
  - Asbestos fire protectio

Damage Assessment

- 2830 lives lost
  - Fire, Police, rescue personnel (403)
  - 880 injured
- Collapse / damage to buildings
  - 1/3 of NYC financial district
- Damage to infrastructure
- Total losses – billions of dollars



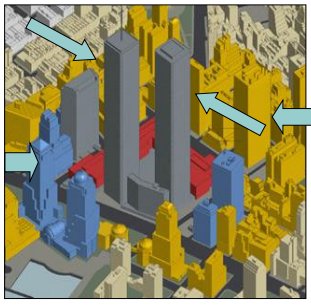
Damage – Buildings

- Collapsed – 4
- Partially collapsed – 4
- Major structural damage – 9
- Minor structural damage – 18
- Needed cleaning – Number of buildings
- Buildings inspected – 406
- Loss of office space – 30 million sq. ft.
- Affected area – 1 to 2 miles radius

New York Financial District

Excerpt from FEMA report

Sequence of Events



1. Aircraft strikes WTC 1 at 92-96th floor (8:46 am)
2. Aircraft strikes WTC 2 at 78-84th floor (9:03 am)
3. WTC 2 collapses (56 m), & the debris hit
   - ✓ Bankers Trust
   - ✓ American Express
   - ✓ Vista Hotel
4. WTC 1 collapses (1h 42 m), debris hit
   Vista hotel, WTC 4, 5, 6, 7
5. WTC 3, 4, 5, 6 collapse (4-6 hrs)
6. WTC 7 collapse (7 hrs)
7. Damage to other buildings

Collapsed Buildings

- 4 Buildings
  - WTC 1 - 110 stories
  - WTC 2 - 110 stories
  - WTC 3 - 22 stories
  - WTC 7 - 47 stories
- Steel framed office buildings
- Impact – Major factor
- Blast – Minor factor
- Structural – Major factor
- Fire – Major factor
- Progressive collapse
- Huge amount of Debris - cleared in 1 year

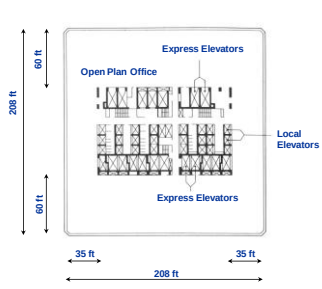
WTC 1 & WTC 2 – Features

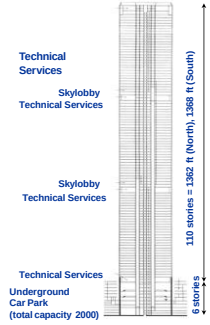
- 110 stories
- Floor plate of 207' x 207'
- 40,000 sq. ft./floor
- Constructed 1971
- Steel framed buildings
  - Concrete deck slab
- Not Twins - Siblings of same family!

Building	WTC 1	WTC 2
Height	1360+ Ant.	1368
Antenna	Y	N
Core	E-W	N-S
Wind effects	Diff.	Diff.

- Innovations

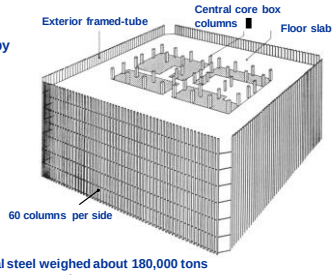
WTC Overall System Design





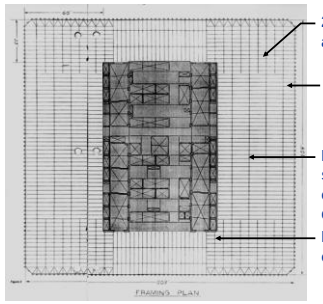
Structural System

- Gravity loads due to dead and live loads are carried by an exterior framed-tube system and a central core.
- Lateral loads due to winds (and earthquakes) are resisted by the exterior framed-tube only.
- Typical total load = 286,000 tons per floor



Structural steel weighed about 180,000 tons per tower.

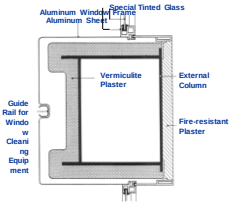
Structural Framing



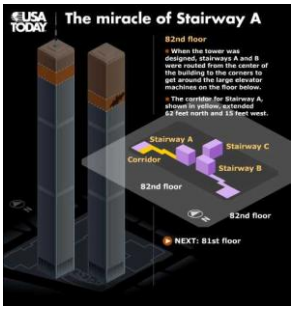
- 2-way framing at corners
- Closely spaced (3' 3") perimeter columns (tube & spandrel system)
- Long span trusses support lightweight concrete fill on metal deck
- Rectangular box columns at core

Fire Protection Features

- Code requirement:
  2/3 hour FRR
  - Asbestos abatement in 80's
  - Vermiculite plaster sprayed on outside of steel
  - Cafco type D, made of ceramic fibers, as fire-resistant plaster on the inside.
- Sprinklered Systems
- Water for extinguishing fires is available in 18,500 liter tanks, installed on 4 technical services floors.
- Occupancy
  - 25,000 occupants/tower, plus 25,000 visitors
  - Over 400 companies in Towers
- Emergency Staircases - 3 Stairwells – A, B, C
  - A and C were 112 cm (44") wide
  - Stairwell B was 142 cm (56")
- All stairs in the Elevator (central) core
- Number of steps between landings varied (probably from 6, 9, 11 and 13 steps)

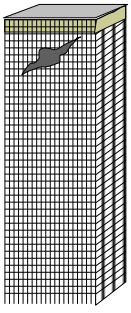


Emergency Stairways in Towers



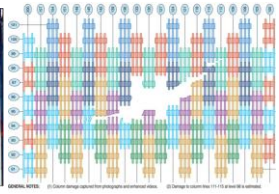
Effects of Aircraft Impact

- Impact shattered and fractured 2/3 of columns on one face
- Partial collapse of floors occurred at
- Impacted columns
- Debris penetrated building core
  - Damaged core columns
  - Damaged stair shafts & elevators
- Impact caused failure of fireproofing in affected area
- Initiated fire



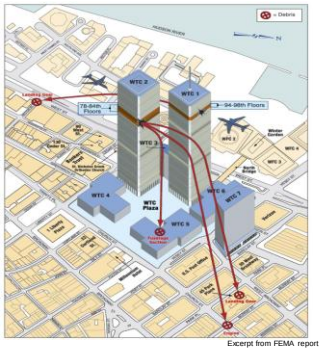
State of Structural System

Impact damage to N face of WTC 1



Impact damage to ext. columns on N face of WTC 1

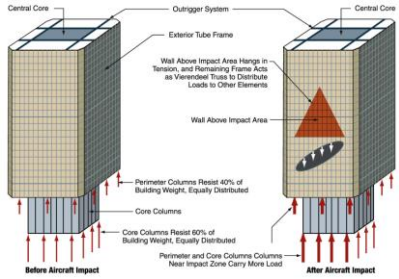
Significance of Impact



Excerpt from FEMA report

- Debris penetrated building core
- Damage to core columns

Structural Analysis



Excerpt from FEMA report

Effect of Fire

- 45,000 liters in each plane
  - 25% Fire balls
  - 25% Shafts
  - 50% Consumed in few minutes
- Fire size – 3-5 GW
  - Energy – nuclear plant
- Fire temperatures – 1100° C
  - Rate of rise of temp
- Ignited several floors

Evacuation of Occupants

- Occupancy of WTC 1, 2
  - Sept. 11: 15,000-20,000 people
  - Capacity: 40,000 to 50,000 people
- Damaged stair shafts and elevators
- Virtually all fatalities were located on impact floors or floors above
  - Only 16 (4) occupants from impact floors or above survived
  - 99% of occupants below impact floors survived

Role of Fire Issues

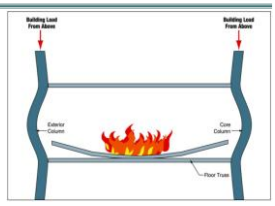
- State of the structural system
- Fire growth
  - Jet fuel
- Fire proofing
- Active fire protection
- Fire fighting
- Performance of structural

South Tower Collapsing

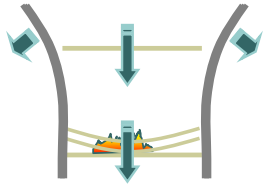
Collapse of WTC 1 & WTC 2

Performance of Structural Elements

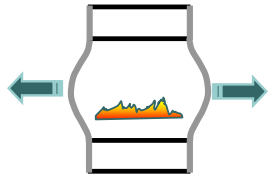
- Impact caused failure of fireproofing on structural elements
  - Damage much more in trusses
  - Floor trusses relatively flimsy
    - difficult to fire protect
  - Connections played crucial role
- Effect of Fire on Steel
  - Steel when heated
    - Expands
    - Looses flexural rigidity
    - Looses strength
  - Increased demand



Collapse Mechanisms



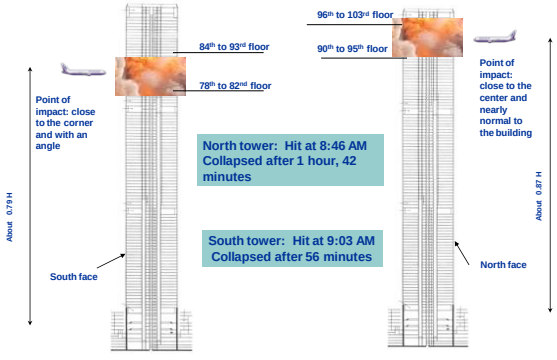
Floor System Failure



Instability of Columns
(Longitudinal Unsupported Lengths)

Excerpt from FEMA report

Collapse Contradictions



North tower: Hit at 8:46 AM
Collapsed after 1 hour, 42 minutes

South tower: Hit at 9:03 AM
Collapsed after 56 minutes

Successful Evacuation

Reasons for Low Fatalities

- Low occupancy
- Overall good conditions on floors and stairwells
- Limited delay to start evacuation
- Occupants remained calm
- Past experience from 1993 evacuation
  - Improvements after 1993 Bombing
  - PLM paint on stairs and handrails
  - Fire Safety Teams in WTC complex
  - Fire Drill every 6 months (since 1993)
- Rescuers &co-workers helped disabled & injured
- Robustness of Towers

5000 to 7000 people in each tower (USA Today) - (1/4 at work)

- Election day in New York
- First day of school
- People start work at 9:00-9:30 AM

Fatalities - Total Numbers (USA Today – Dec. 19 01)

Tower 1 (1,431)
1,259 fatalities above 92nd floor
72 died on 91st floor and lower
Tower 2 (599)
597 fatalities above 78th floor
2 died below 78th floor (4 died)
479 workers (403 rescuers: 343 fire, 37 police)
157 in 2 airplanes
147 guards, delivery people, day workers
10 bystanders outside
• 880 injured

Collapsed Buildings – WTC 3

- WTC 3 – Vista WTC Hotel
  - 22-storey steel-framed bldg
  - 6-storey below sub-grade
  - 64 x 330 ft. in plan
- 1993 WTC bombing slab collapse
- Arrested progressive collapse survived debris from WTC 2
- Evacuation - WTC 2 to lobby
- Local collapse – 22 to 7 stories did not spread

Collapsed Buildings – WTC 7

- 47-storey steel framed bldg
  - Floors 1- 6
  - Con Edison sub-station
  - Emergency generator
  - 91,000 litres of diesel fuel storage
- Fires initiated after WTC 2 collapsed
  - Floors 7- 47: offices
  - Burned uncontrolled for 8 hours
  - No suppression (pressure in water mains significantly reduced after collapse of WTC 1, WTC 2)
  - Collapsed at 5.20 pm(~ 7 h after WTC 1)
  - Failure of critical elements –

Partially Collapsed Buildings

4 Buildings — WTC 5

- WTC 4 – 9 storey
- WTC 5 – 9 storey
- WTC 6 – 8 storey
- Winter Garden – glass & steel barrel vault
  - One of the largest covered public spaces in NYC

Steel framed office buildings — WTC 6

Fire – major factor

Structural – major factor

Impact (debris) – factor

Tensile membrane action – Cardington tests

To be demolished

Major Damaged Buildings

9 buildings

- 90 West – 24 stories
- AMEX – 50 stories
- VERIZON – 30 stories
- Merrill Lynch – 44 stories
- Bankers Trust – 40 stories

Bankers Trust
View from 16th floor

Steel framed office buildings

Structural – major factor

Impact (debris) – major factor

Fire – not a major factor

Under repair / renovation

Arrested progressive collapse
22nd to 8th floor

Moderate Damaged Buildings

18 buildings

- 1 Liberty street – steel – 54 stories
- Fed PO building – steel – 30 to 40 stories
- Millennium (Hilton) – concrete – 30 to 40 stories
- 124 Liberty Street – Fire station

Office / hotel buildings

Fire – not a factor

Structural damage – minor

Broken glass, debris

Under repair / renovation

Damage – Infrastructure

Subway system

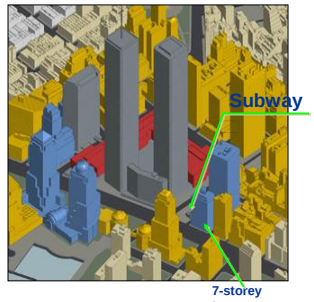
- Closed in the area
- Access to stations damaged
- Foot bridge (North) – (WG to WTC 7)
- St. Nicholas Greek Orthodox Church

Slurry wall

- Waterproof barrier used to hold water and earth
- Gas / water / power / telephone grid
- Roads, pavement

Affected area – 2-3 km radius

New York Financial District



Rescue & Recovery – Ground Zero

Rescue and Recovery

Debris removal

- Land-fill, scrap yards
- Trucks

– Barge (Hudson river)

1.5 to 2 million tons of debris

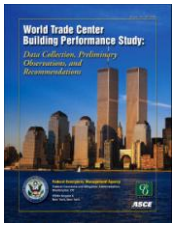
- 150 000 to 200 000 tons removed (Oct.10)
  - Steel recycled as it arrived

Access was restricted

BPAT Report - Recommendations

- Aircraft impact – extreme events
- Fire-proofing materials – adhesion, cohesion
- Egress systems – staircases
  - location, number, impact resistant
- Robustness of structural framing
- Minimize progressive collapse
- Connections – fire performance
- Sprinklers – effectiveness, water supply
- Design for fire
  - integrate design process
  - interaction of professions
- Emergency preparedness

Report - 300 pages, 8 Chapters, 9 Appendices
www.fema.org



- Follow-up Studies - NIST
  - WTC 1, 2, 7
  - Data & samples

WTC Disaster – High Rise Buildings in Post 9-11 Era

Sept. 11 Incidents

- Performance demands
  - Built infrastructure
- Tall buildings
  - Critical for commerce, trade
    - Concern of occupants
    - Drop in real estate value
- Innovations
  - Enhance safety
  - Minimize damage / collapse
    - Cost-effectiveness
    - Current Building Practice

Fire – Severe Hazard & Threat

- Fires cause thousands of deaths & billions of $$ of damage yearly
- 2011 Data – Fire Losses in USA
  - 1,389,500 fire incidents (4.4% increase over 2010)
  - 3005 fire deaths (one every 208 min), 17,500 injuries (one every 30 min)
  - $11.7 billion property losses
  - Total cost > $50 billion
  - Residential fires are the most significant
  - A fire occurs in a structure at the rate of one every 65 seconds
  - 84% of fire deaths, 27% of fires, 60% of the total $ loss
- Fire represents most severe condition, and can occur as:
  - Primary event – natural origin (e.g., lightning, accidental)
  - Secondary event - Post EQ, blast, explosion, impact
- Fire risk be mitigated through conscientious design & maintenance
  - It is impossible to prevent ALL major fires
- Fire safety depends on numerous factors
  - Fire prevention, suppression & extinction
  - Successful evacuation of occupants
  - Structural fire safety – Fire resistance
- Provisions in fire safety measures is critical for:
  - Safe evacuation of occupants & fire personnel
  - Minimize property damage
  - Control spread of fire
  - Public Safety, Homeland Security & Economic Activity

Improvements in Building Features – Safety and Security

Structural features:
1. Strengthening of elevators core.
2. Resilience/Progressive collapse (removal of columns).
3. Strengthening of connections (adding thick plates).
4. Composite construction.

Materials:
1. Use of concrete/masonry in place of gypsum boards (LWC)
2. Additional detailing for fire insulation.

Fire protection features:
1. Back up water supply for fire fighting & Sprinklers.
2. Enhanced stair width (44" to 52").
3. Improve design of stairs – PLM Paint.
4. Stairs – more exit points to street
5. Regular evacuation drills.
6. Thicker fire proofing (& periodic inspection).

Security features:
1. Enhanced communication system (Signal amplifiers/radio).
2. Air intake for ventilation off ground level/inaccessible.
3. Chemical/Biological filters for air intake
4. Entry restrictions.
5. Sandwich glass for windows – prevent fragmentation.
6. Specific Command center.
7. Thickened concrete core at lower floors.

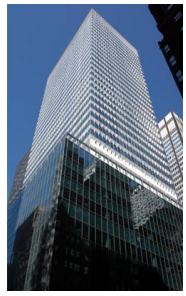
Emergency and Rescue Procedures:
1. Owner, Municipal, State and Federal levels

CIBC Building – General Information

Building:	CIBC Building
Location:	300 Madison Avenue, NYC
Stories:	38
Construction started:	2001
Estimated completion:	2003
Cost:	$300 million
Floor area:	1,200,000 sq ft (111,484 m²)
Height:	
Roof:	575 ft (175 m)
Elevators/Escalators	26/7
Occupancy	Office/hotel/condos

CIBC Building – New Features (Safety & Security)

New Safety and Security Features:
1. Box section for columns (instead of H sections)
2. Improved connections (thicker plates to stiffen flanges)
3. An additional hour of fireproofing for all members (+1 hour > required by NYC building code).
   - Additional costs of $4 mill. in lower-column fireproofing and structural connection improvements.
4. Security film (laminating glass) on windows of floors 2 through 8 (sandwich window glasses).
5. Additional sprinkler riser (system).
6. Triple-wide staircases at trading floors.
7. 60,000-gallon make-up water tank that would go into operation in the event of a loss of city water
8. Domestic water tanks holding 24 hours of additional storage for the trading floors.
9. Emergency back up power for all life support and critical functions equipment to provide a max. power of 10,250 KW
10. Camera surveillance encircling the perimeters and in all elevators
11. Computerized access to building/parking entries.



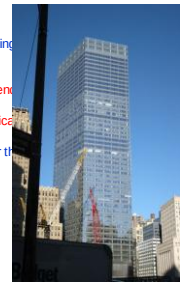
7 WTC – General Information

- Building: WTC-7
- Location: Lower Manhattan in NYC
- Stories: 52
- Site: 250 Greenwich Street, NY.
- Construction started: 2002
- Completion: 2006
- Cost: $700 million
- Floor area: 1,700,000 sq ft (160,000 m²)
- Height:
  - Roof: 743 ft (226 m)
  - Top floor: 679 ft (207 m)
- Elevators/Escalators 29
- Main contractor: Tishman Construction
- Architect: David Childs (Skidmore, Owings & M.)
- Developer: Silverstein Properties
- Structural engineer: WSP Cantor Seinuk
- The building was promoted as the safest skyscraper in the U.S.
- The building was the first commercial office building in NY to receive the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) certification (gold rating)

7 WTC – New Features (Safety and Security)

New Safety and Security Features:

1. Tower built with redundancy in the steel frame.
2. Two-feet-thick concrete core (f'c is 10,000 psi), floor slabs ranging 8-14 inches thick and walls are 12-27 inches thick.
3. Super fireproofing material for steel members.
4. 20% wider and better-lit stairs, more ground-level exits, emergen generators, and a redundant emergency command center.
5. Elevators, utilities infrastructure, and exit stairs encased in vertica (concrete) core.
6. Twice (dual standpipes) the required water-storage capacity for t sprinkler system
7. Pressurized ventilation to filter out air contaminants.



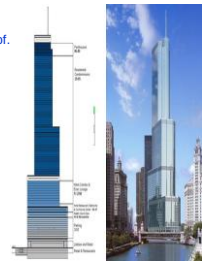
Trump Tower – General Information

- Building: Trump Tower
- Location: Chicago, IL.
- Stories: 92
- Site: 401 N. Wabash Ave. Chicago, IL.
- Construction started: 2005
- Completion: 2009
- Cost: $847 million
- Floor area: 2,600,000 sq ft (240,000 m²)
- Height:
  - Roof: 1,389 ft (423 m)
- Main contractor: Bovis Lend Lease
- Architect: Adrian Smith, Skidmore & OM.
- Developer: Trump Organization
- Structural engineer: William F. Baker
- Became the second-tallest building in the Western Hemisphere

Trump Tower – New Features (Safety and Security)

New Safety and Security Features:

1. Height reduced from 136 to 92 floors.
2. Steel framing changed to concrete framing.
3. Extensive use of concrete makes the building more fireproof.
4. Wider staircases.
5. Use of HSC for structural members.
6. Use of SCC for explored matt foundation.
7. Use of Refugee floors (Blocks smoke/fire).



One WTC – General Information

- Building: One WTC (Freedom Tower)
- Location: Lower Manhattan in NYC
- Stories: 105
- Site: NW corner of WTC site, (old WTC 6)
- Construction started: April 27, 2006
- Estimated completion: late 2013 or early 2014
- Cost: $3.1 billion ($1,150 per square foot)
- Floor area: 2,600,000 sq ft (241,548 m²)
- Height:
  - Antenna spire: 1,776 ft (541.32 m)
  - Roof: 1,368 ft (417 m)
  - Top floor: 1,314 ft (401 m)
- Elevators/Escalators 70/9
- Main contractor: Tishman Construction
- Architect: David Childs (Skidmore, Owings & M.)
- Developer: Port Authority of NY and NJ
- Structural engineer: WSP Cantor Seinuk
- Owner: Port Authority of NY and NJ

One WTC – New Features (Structural)

New Structural Features:

- Steel-Concrete composite framing
- Structure is designed around a strong, redundant steel moment outer core frame consisting of beams & columns through a combination of welding and bolting.
- The moment frame lends substantial rigidity and redundancy to the overall building structure while providing column-free interior spans for maximum flexibility.
- Core is of cast-in-place, RC construction.
- Use of HSC for columns in the inner core (83-97 MPa)
- Provision of blast resistance.
- Extra-strong 1m concrete casing protecting central section
- Reinforced, window-less base.
- These features minimize progressive collapse.

One WTC – New Features (Safety and Security)

New Safety and Security Features:

1. Air intake to Towers through special "suction machines" that are high-up (where the air is clean) and equipped with Biological &chemical filters throughout its ventilation system.

2. Central upright section equipped with key safety features, including water-proof lifts, and 1 out of 3 staircases, reserved for firefighters.

3. Extra-strong (1 m) concrete casing protecting the central section of sprinklers.

4. Sandwich glass panels to protect from blast/explosions .

One WTC – New Features (Safety and Security)

New Safety and Security Features:

Special technology will keep any smoke out.
- Central section will also contain lifts, made water-proof to prevent damage from water sprinklers, & 2 escape staircases.
- Stairs have 4 street-level exits allowing a quicker escape
- Special fire proofing systems
- Extra-wide, pressurized stairwells (20% wider than code requirements)

Security:
- All vehicles will be screened before entering the site via the underground roadway, including for radioactive materials.
- Visitors to the 9-11 memorial will undergo airport-style screening
- 400 closed-circuit surveillance cameras to placed in and around the site, with live camera feeds being monitored around the clock by the NYPD
- A computer system will use video-analytic computer software designed to detect potential threats such as unattended bags and retrieve images based on descriptions of terror or other criminal suspects
- NYC and Port Authority police will patrol the site

Post 9/11 Changes in Building Codes/Standards

IBC (2012) New Safety and Security Features

1. Use of impact resistant materials in the construction of staircases and elevator shaft.
2. Inclusion of more stairwells or wider stairwells in buildings.
3. Marking the egress path, doors and stairs with photo-luminescent paints.
4. Work with the Department of City Planning to exclude floor area of "fire towers" from Floor Area Ratio (FAR) calculations to encourage their use.
5. Controlled inspections to ensure that fireproofing is fully intact.
6. Require all high-rise commercial buildings over 100 feet without automatic sprinklers to install sprinklers.
7. Install fire-protected (up to 45 min) and structurally hardened elevators and fire service access elevators for fire fighters.
8. Develop/use of new fire resistive coating and protection materials.
9. Passive fire protection measures should demonstrate post-event effectiveness

Changes in Building Codes/Standards - Post 9/11 era

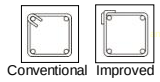
ASCE-7 (2005) Minimum Design Loads for Buildings and Other Structures:
- Loading for fire design $w_{fire} = 1.2w_{DL} + 0.5w_{LL}$

ACI 216.1 (2007) Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies:
- Provisions for mitigating spalling in HSC
- Tie configuration for HSC columns
- Use of PP fibers

SFPE Fire Standards (2003):
- Design fire for structural fire design
- Thermal analysis of structural members
- Structural analysis analysis of structures

AISC-LRFD Manual (2011/2016):
- HT material properties of steel (EC3)
- Some calculation methods for fire resistance

NYC Building code:
- Wider stairs & better designed (PLM paint)
- Additional fire proofing (+1 hr)
- Regular evacuation drills



Conventional Improved

Research in Structural Fire Safety Area in US

- Prior to 9-11, no major research programs in US universities in structural fire safety.
- Number of faculty initiated fire research in structural fire safety.
- MSU, UTA, Princeton Univ., Purdue Univ.
- NIST – WTC Investigation
- NIST – NRFL facility

- Numerous fire safety related workshops/meetings.

- Fire Safety in Infrastructure

MSU structural fire test furnace

Fire safety in infrastructure

Recent Bridge/Tunnel fires:

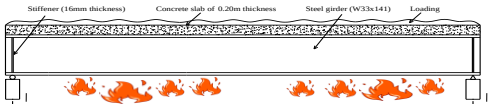
- **I-580 freeway at MacArthur Maze interchange, Oakland, CA (April 29, 2007):**
  - Fuel tanker transporting 32,500 litters of fuel overturned under the bridge.
  - Intense heat (temp. around **1100˚C**).
  - Strength & stiffness of steel girders deteriorated leading to large deflections.
  - Significant fire induced forces in girders & connections led to partial collapse in **22 min.**
  - Losses estimated at **$9 million.**
- **I-95 Howard Avenue Overpass, Bridgeport, CT (March 23, 2003):**
  - Collision between a car & a fuel tanker transporting 50,000 liters of heating oil.
  - Fire lasted for **two hours** & the temp. reached about **1100˚C.**
  - Fire caused significant buckling of steel girders & **partial collapse** of steel girders.
  - Fire damage costed **$11.2 million**
- **I-75 Expressway near Hazel Park, MI (July 15, 2009):**
  - Fuel tanker carrying highly flammable fuel crashed into a truck.
  - Steel girders weakened & collapsed in **20 min.**
  - The collapse of the overpass caused significant losses & traffic delays
- **CA Tunnel – (October 12, 2007)**
  - 550 ft long tunnel
  - Burned for 7 hrs – 1400˚C
  - Severe damage – Spalling of concrete

MacArthur Maze interchange

I-75 Expressway

MSU-Princeton Project on Fire mitigation in Steel bridges

- An approach for classification of bridges for fire risk
  - 4 risk grades; low, medium, high & critical.
- An approach for modeling response of bridges exposed to fire
- An approach for evaluating residual strength of fire damaged bridge (girders)
- Guidelines for mitigating fire risk to steel girders

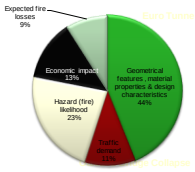


Approach to Evaluate Importance Factor

- Fire risk associated with bridges is grouped into four grades namely low, medium, high & critical.
- About 5% of bridges fall under "critical" risk category.
- Vulnerability of bridges in "critical" or "high" fire risk category, can be minimized by providing fire protection to structural members.

Table 1 Risk grades & associated importance factors for fire design of bridges

Risk grade	Overall class coefficient (λ)	Importance factor (IF)
Critical	≥0.95	1.5
High	0.51-0.94	1.2
Medium	0.20-0.50	1.0
Low	<0.20	0.8



Contribution of different classes (factors) to the overall importance factor

The National Fire Research Laboratory (NFRL)

- No facilities for experiments on real-scale structural systems under realistic fire & mechanical loading in controlled laboratory conditions.
- NFRL is a unique facility & will enable experiments on the performance of structural elements, subassemblies, and systems exposed to fires up to 20 MW and will contribute to the technical basis for performance-based design methodologies for structures exposed to fire.
- Will allow structures, ranging in size from small components to large systems up to 2 stories in height 9 m (30 ft) and 2 bays × 3 bays in plan, to be tested under fully-developed building fires up to 20 MW using natural gas, liquid hydrocarbons, wood cribs, or actual building contents.
- The test area will consist of a 486 m² (5400 sq ft) strong floor with multiple anchor points and a 9 m (30 ft) high strong wall

The National Fire Research Laboratory

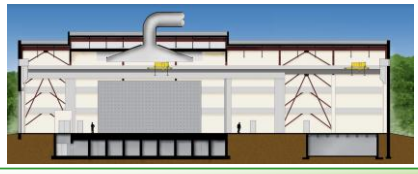
Specifications / Capabilities:

- Strong Floor
  - 18.3 m x 27.4 m (60 ft x 90 ft) post- tensioned floor with full basement
  - 9 cell RC box girder with 406 mm (16 in) thick shear walls at 3.0 m (10 ft) o.c.
  - Basement ceiling height: 2.7 m (9 ft)
  - Floor thickness: 1.07 m (3 ft-6 in) with 152 mm (6 in) sacrificial top surface
  - 1218 anchor points on 0.61 m x 0.61 m (2 ft x 2 ft) grid (sleeves or anchors)
  - Load per anchor point: 445 kN (100 kips) up or down
  - Shear capacity per anchor point: 222 kN (50 kips) (at top of slab)
  - Moment capacity per anchor point: 136 kN-m (100 ft kips) (at c.g. of strong floor)

The National Fire Research Laboratory

Specifications / Capabilities:

- Strong Wall
  - 9.1 m high x 18.3 m wide (30 ft high x 60 ft wide)
  - 1.2 m (4 ft) deep post-tensioned concrete wall
  - 420 anchor points on 0.61 x 0.61 m (2 ft x 2 ft) grid
  - Horizontal Load 146 kN/m (10 kips per lineal ft) at 9.14 m (30 ft)
- Environmental control system (ECS) Hood and Pollution Control System
  - 13.7 m x 15.2 m (45 ft x 50 ft) steel hood
  - Height above floor: 12.5 m (41 ft)(excluding skirts)
  - ECS maximum sustained capacity: 20 MW
  - ECS maximum flow rate: 5100 m³/min (180,000 cfm)



The National Fire Research Laboratory

Specifications / Capabilities:

- Cranes
  - Two 178 kN (20 ton-force) bridge cranes (sharing single set of rails)
  - Height of rails above floor: 11.2 m (36 ft-8 in)
  - Clearance, bottom of bridge-to-floor: 9.8 m (32 ft)

- Configurable Hydraulic Loading System
  - Hydraulic Power Unit 340 lpm (90 gpm)
  - Actuators (double acting) 762 mm (30 in)stroke w/ servo valve, load cell, and swivels
    - Eight 240 kN (55 kip) Tension, & 365 kN (80 kip) Compression
    - Two 445 kN (100 kip) Tension, & 650 kN (145 kip) Compression
    - Two 956 kN (215 kip) Tension, & 1470 kN (330 kip) Compression
- Four hydraulic service manifolds
- Controller

Thank You

Questions ???