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

ANALYSIS OF BUILDING AND FIRE CODES AND PRACTICES

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National Institute of Standards and Technology
U.S. Department of Commerce

NIST

WTC Investigation Objective #3

Determine procedures and practices used in the design, construction, operation, and maintenance of WTC 1, 2, and 7.

Project #1 Areas of Focus

Criteria and Procedures for:

- Design and construction
- New and innovative design features
- New and innovative technologies and materials
- Passive and active fire safety systems
- Emergency access and egress systems
- Structural modifications, inspection, and maintenance

Scope

- Document the design and construction of structural systems
- Document the design and construction of fire protection and egress systems
- Compare then current building regulatory and code requirements
- Document maintenance and modifications to structural, fire protection, and egress systems
- Document the fuel system for emergency power in WTC 7

Document Design and Construction of Structural Systems

- Provisions used to design and construct the buildings
- Tests performed to support the design
- Criteria that governed the design of the structural systems
- Methods used to proportion structural members
- Innovative systems, technologies, and acceptance procedures used by PANYNJ
- Details of variances granted by PANYNJ
- Special fabrication and inspection requirements at the fabrication yard
- Inspection protocol during construction

Status of Project

- Contractor submitted near final drafts on:
  - Design and construction of structural systems
  - Design and construction of fire protection and egress systems
  - Then current building regulatory and code requirements
  - Maintenance and modifications to structural and fire protection and egress systems
  - Fuel system for emergency power in WTC 7

WTC 1 and 2

Architects:

Minoru Yamasaki & Associates

Emery Roth & Sons (Architect of Record)

Structural Engineers:

Skilling, Helle, Christiansen & Jackson

Skilling, Helle, Christiansen & Robertson (1964)
(Engineer of Record)

Building Codes Used in Design

WTC 1 and 2

WTC 1 and 2

Initial design:

Port Authority instructed architect & engineer in May 1963 to use the1938 edition of New York City Building Code.

Final design:

Port Authority instructed architect & engineer in September 1965 to revise design in accordance with the second and third draft of new code (adopted in December 1968).

Building Codes Used in Design

WTC 1 and 2

1938 edition vs. 1968 edition

- Elimination of fire tower as a required means of egress.
- Reduction in the number of required stairs.
- Reduction in fire rating of shaft walls from 3 h to 2h.
- Use of uniform partition load based on weight of partition per unit length.
- Introduced Class 1B construction for business occupancy and unlimited building height.

Review of Drawings by New York City Department of Buildings

1975 Letter from Architect of Record to Port Authority

- NYC/DOB reviewed WTC 1 & 2 drawings in early 1968.
- Made 6 comments concerning the plans in relation to the 1938 code.
- Architect submitted responses to the comments to Port Authority in March 1968.

Code Conformance Agreement between Port Authority and NYC Building Department

1993 MOU between Port Authority and NYC Building Department

- Reaffirmation of longstanding stated policy of Port Authority to conform to New York City Building Code.
- Each project reviewed and examined for code compliance by Port Authority.
- Plans prepared and sealed by NY State licensed design professional.
- Port Authority design professional approving the plans would not have assisted in the preparation of the plans.
- Variances from code, acceptable to Port Authority, would be submitted to New York City Building Department for review and concurrence.

Code Conformance Agreement between Port Authority and NYC Building Department

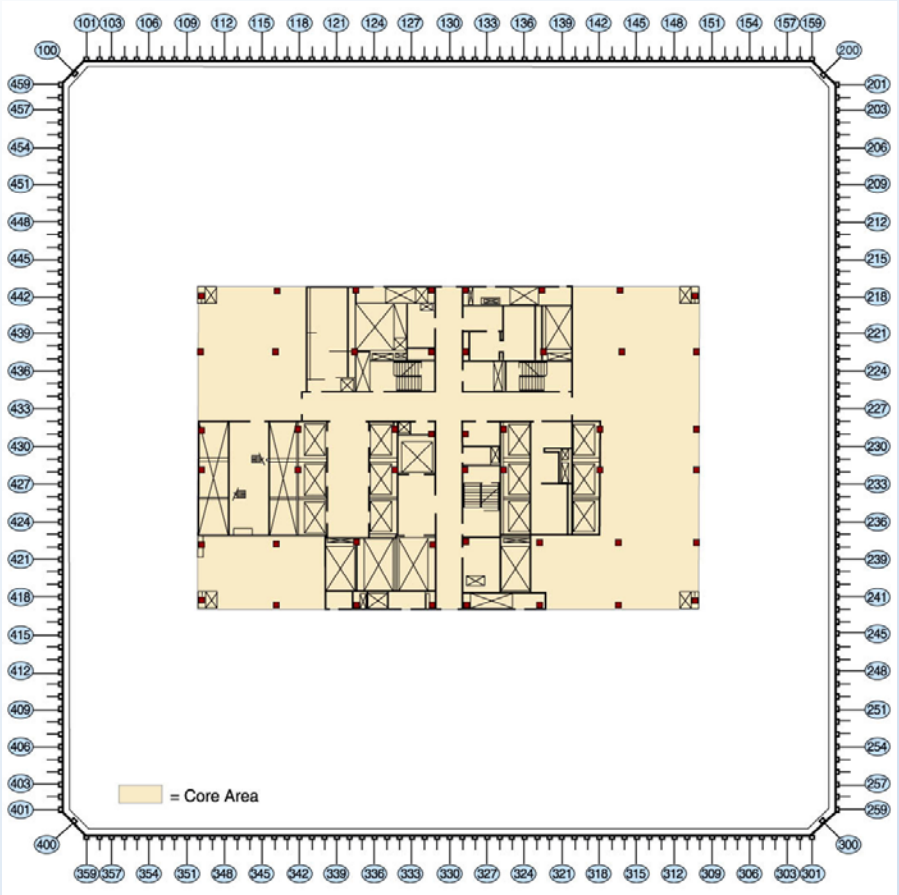
1995 Supplement to 1993 MOU

- In lieu of any review by Port Authority, tenant may engage NY State licensed design professionals to prepare and review tenant's plan and to certify that plans conform to NYC Building Code.
- Design professionals reviewing and certifying plans for WTC tenants should not be the same design professionals providing certification that the project was constructed in accordance with the plans and specifications.

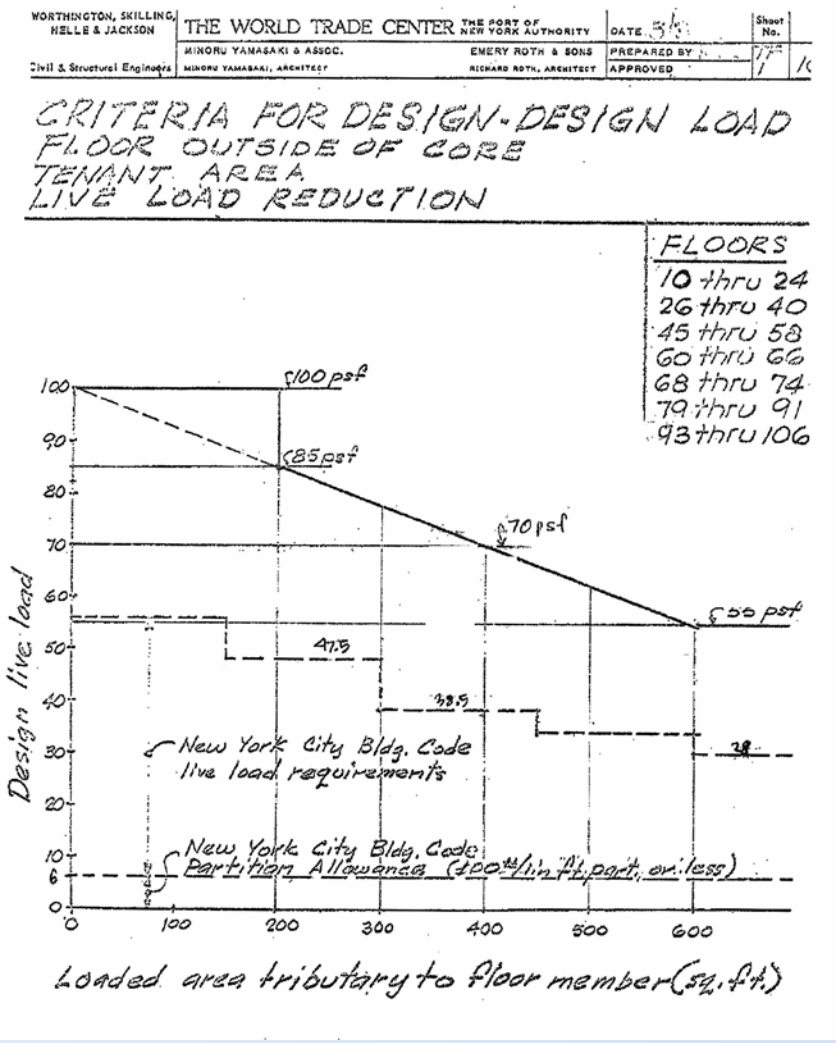
Structural Requirements

- Dead loads
- Live loads
- Live load reduction
- Lateral loads

WTC 1 and 2



WTC 1 and 2 – Live Load Reduction



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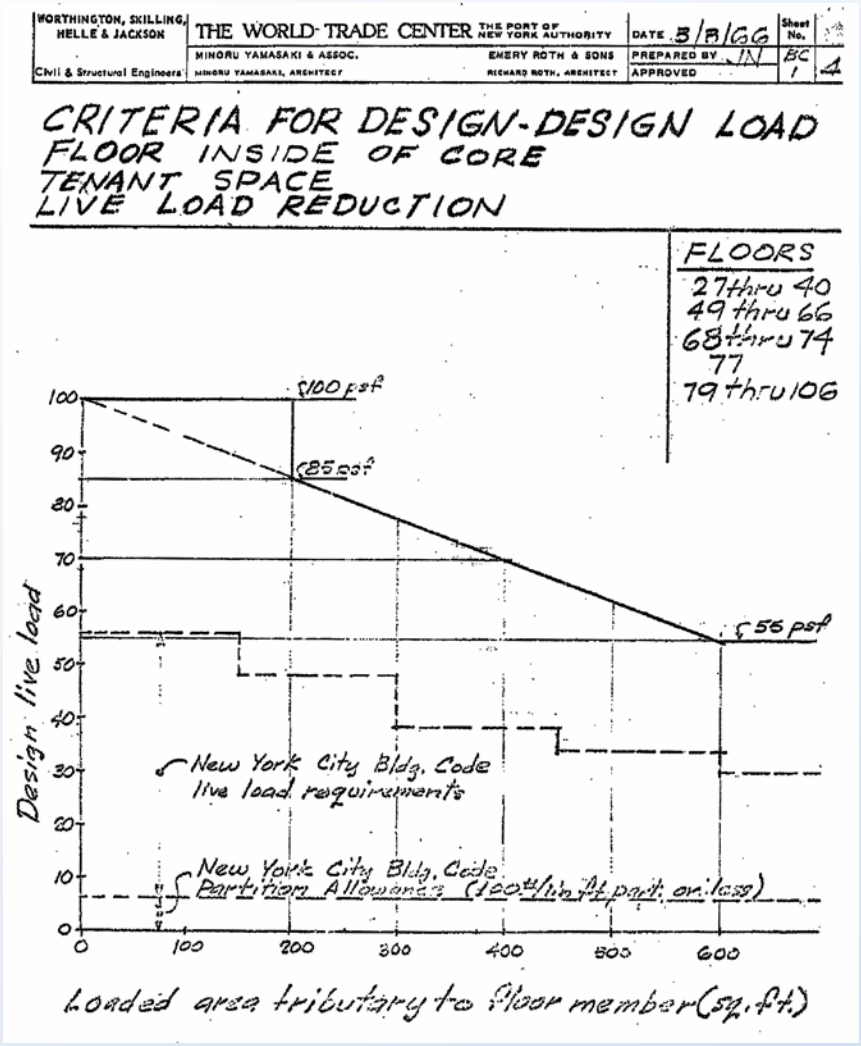
WTC 1 and 2 – Live Load Reduction



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Design Wind Pressures
1968 NYC Building Code

Height Zone (ft above curb level)	Design Wind Pressure on Vertical Surfaces (psf of projected solid surface)	
	Structural Frame	Glass Panels
0 – 50[a]	15	–
0 – 100	20	30
101 – 300	25	30
301 – 600	30	35
601 – 1000	35	40
Over 1000	40	40

Design Wind Pressures
1968 NYC Building Code

- Alternate method
  - "Suitably conducted model tests"
  - Fastest-mile wind velocity of 80 mph at 30 ft above ground
  - Simulate and include all factors involved in consideration of wind pressure
    - Pressure and suction effects
    - Shape factors
    - Gust, etc.

Design Wind Load for WTC 1 & 2

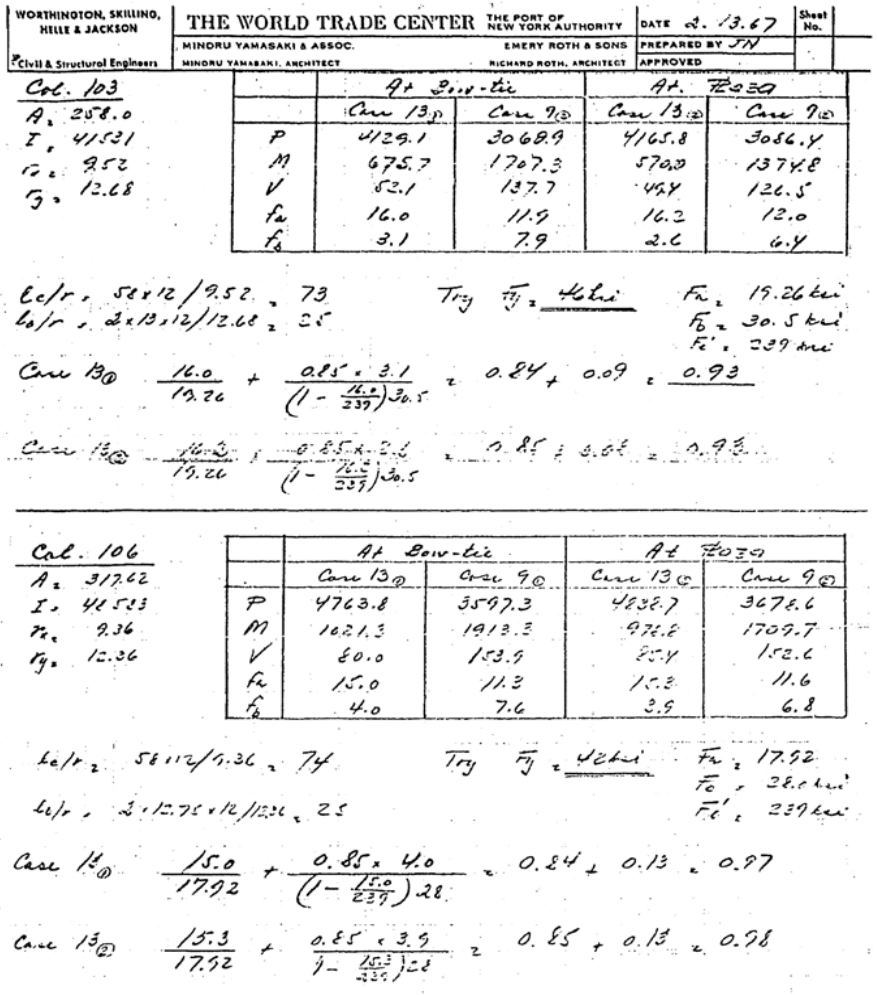
$$S = \overline{S} \pm S'$$ - Story Shear

$$M = \overline{M} \pm M'$$ - Story Moment

$$\overline{S}(z) = \tfrac{1}{2}\,\rho\; V_o^{\,2}\; D\; H\; C_S(z)$$

$$\overline{M}(z) = \frac{1}{2}\rho V_o^{\,2}\; DH^{\,2} C_M(z)$$

Sample Column Design for WTC 1



WORTHINGTON, SKILLING, HELLE & JACKSON — Civil & Structural Engineers

THE WORLD TRADE CENTER — THE PORT OF NEW YORK AUTHORITY

MINORU YAMASAKI & ASSOC. — MINORU YAMASAKI, ARCHITECT

EMERY ROTH & SONS — RICHARD ROTH, ARCHITECT

DATE 2. 13. 67 — PREPARED BY JN — APPROVED — Sheet No.

Col. 103

A_s = 258.0
I = 41531
r_x = 9.52
r_y = 12.68

	At Bow-tie		At #030	
	Case 13①	Case 9②	Case 13②	Case 9②
P	4129.1	3068.9	4165.8	3086.4
M	675.7	1707.3	570.3	1374.8
V	52.1	137.7	44.4	126.5
f_a	16.0	11.9	16.2	12.0
f_b	3.1	7.9	2.6	6.4

Le/r = 58×12/9.52 = 73 — Try F_y = 46 ksi — F_a = 19.26 ksi
Lb/r = 2×13.12×12/12.68 = 25 — F_b = 30.5 ksi
F_e' = 239 ksi

Case 13① $\frac{16.0}{19.26} + \frac{0.85 \times 3.1}{\left(1 - \frac{16.0}{239}\right)30.5} = 0.84 + 0.09 = 0.93$

Case 13② $\frac{16.2}{19.26} + \frac{0.85 \times 2.6}{\left(1 - \frac{16.2}{239}\right)30.5} = 0.85 + 0.08 = 0.93$

Col. 106

A_s = 317.62
I = 41533
r_x = 9.36
r_y = 12.36

	At Bow-tie		At #030	
	Case 13①	Case 9②	Case 13②	Case 9②
P	4763.8	3597.3	4838.7	3678.6
M	1621.3	1913.3	978.6	1709.7
V	60.0	153.9	55.4	152.6
f_a	15.0	11.3	15.2	11.6
f_b	4.0	7.6	3.5	6.8

Le/r = 58×12/11.36 = 74 — Try F_y = 42 ksi — F_a = 17.92
Lb/r = 2×12.75×12/12.36 = 25 — F_b = 28.8 ksi
F_e' = 239 ksi

Case 13① $\frac{15.0}{17.92} + \frac{0.85 \times 4.0}{\left(1 - \frac{15.0}{239}\right)28.8} = 0.84 + 0.13 = 0.97$

Case 13② $\frac{15.3}{17.92} + \frac{0.85 \times 3.5}{\left(1 - \frac{15.3}{239}\right)28.8} = 0.85 + 0.13 = 0.98$

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Design Wind Load for WTC 1 & 2

$$S = \overline{S} \pm S'$$ - Story Shear

$$M = \overline{M} \pm M'$$ - Story Moment

$$\overline{S}(z) = \tfrac{1}{2}\,\rho\; V_o^{\,2}\; D\; H\; C_S(z)$$

$$\overline{M}(z) = \frac{1}{2}\rho V_o^{\,2}\; DH^{\,2} C_M(z)$$

Design Wind Load for WTC 1 & 2

- Aerodynamic coefficients for shear (C_S) and moment (C_M) are determined from wind tunnel-based pressure coefficients.
- Wind tunnel tests conducted at Colorado State University and National Physical Laboratory, U.K.
- Actual values of C_S and C_M used to obtain shear and moment values are not available.
- NIST is working with LERA (under a contract to NIST) to determine baseline performance for original design.

WTC 7

Architect of Record:

Emery Roth & Sons

Structural Engineer of Record:

The Office of Irwin G. Cantor

Building Codes Used in Design

WTC 7

Design:

Developed by Seven World Trade Company and Silverstein Development Corp as a “Tenant Alteration Project.”

Based on 1968 New York City Building Code as amended by Local Laws.

Design Loads for WTC 7

LOADING SCHEDULE

AREA \ LOAD (PSF)	CONCRETE SLAB	FILL, FINISH, ROOFING	CEILING, DUCTWORK	PARTITIONS	FLOORING	BEAMS, ENCASEMENT, FIREPROOFING	TOTAL DEAD LOAD	LIVE LOAD	TOTAL LOAD
MAIN ROOF, BULKHEAD ROOF	50	10	8			7	75	30	105
8TH-20TH FL. 24TH, 46TH FL	50		5	12		8	75	50	125
21ST-23RD FL.	50		5	12	15	8	90	75	165
7TH FLOOR NORTH SIDE	80		5	12		93	190	50	240
7TH FLOOR SOUTH SIDE	80	38	8	12		27	165	50	215
6TH FLOOR OFFICE SPACE	56		5	12		7	80	50	130
6TH FLOOR SWITCHBOARD ROOM	62	38				55	155	100	255
5TH FLOOR OFFICE SPACE	150	38	5			17	210	50	260
5TH FLOOR MECHANICAL SPACE	150	38	5			17	210	150	360
4TH FLOOR	56	75	5			10	146	100	246
3RD FLOOR NEW CONSTRUCTION	56	75	5			10	146	100	246
3RD FLOOR OVER EXISTING SUBSTATION							240	100	340
2ND FLOOR NEW CONSTRUCTION	56	60	5			10	131	150	281
2ND FLOOR EXISTING SUBSTATION							240	150	390
1ST FLOOR LOBBY	175	90				50	315	100	415
1ST FLOOR EXISTING SUBSTATION							300	225	525

NOTE:
ALL SPECIAL EQUIPMENT LOADS SHALL BE ADDED SEPARATELY TO ABOVE LOADING

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Standards Used for Structural System Design

WTC 1 & 2

Steel – 1963 AISC Specifications
Concrete – 1963 ACI BuildingCode
Prequalifying load tests

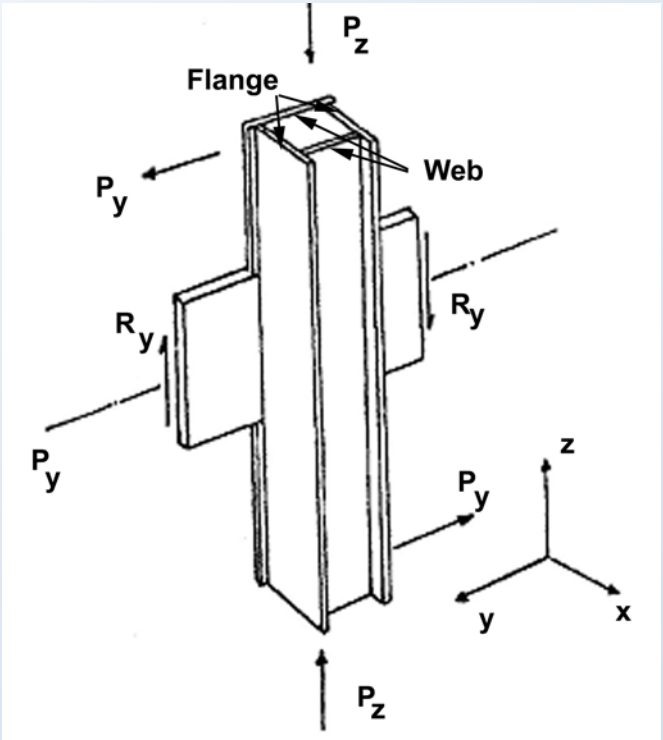
WTC 7

Steel – 1978 AISC Specifications
Concrete – 1977 ACI Building Code

Tests Performed to Support the Design

Exterior Wall Panel Tests

- University of Western Ontario
- Load-deflection characteristics
- “Most effective construction” for wall panels
- 15 different tests were run replicating the 20th, 47th, and 74th floor exterior walls



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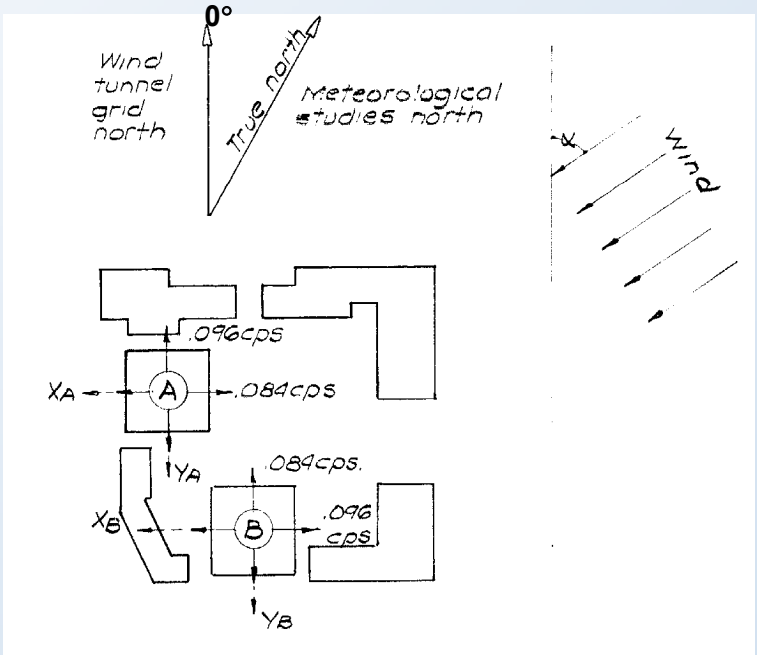
Tests Performed to Support the Design

Wind Tunnel Tests

- Meteorological Program
- Wind Tunnel Program
- Structure Damping Program
- Physiological Program



Tests Performed to Support the Design
WTC 1 and 2

Viscoelastic Damping Unit Tests

- Conducted in accordance with specifications to measure mechanical properties of damping units
- Two sets of tests
  - Massachusetts Institute of Technology
  - Minnesota Mining and Manufacturing Company (3M)

Tests Performed to Support the Design
WTC 1 and 2

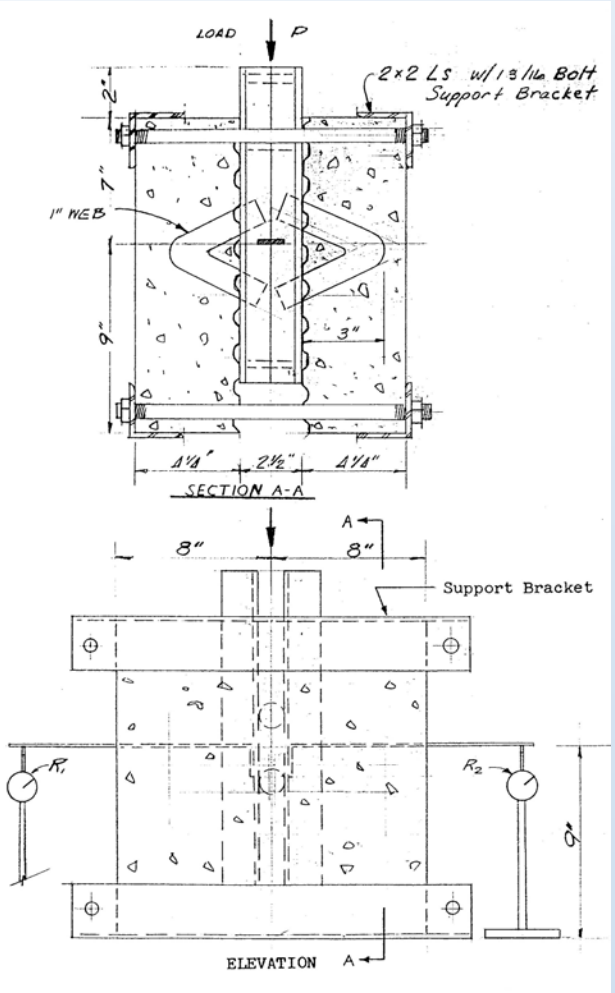
Floor Truss Tests

- Full-scale flexural tests
- Interior panel connection tests
  (Between floor truss and bridging truss)
- Bearing capacity tests
- Shear knuckle tests

Tests Performed to Support the Design

WTC 1 and 2

Shear Knuckle Tests



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Innovative Systems, Technologies and Materials
WTC 1 & 2

- Framed – tube framing system for lateral load resisting of high-rise steel building.
- Steel floor truss – concrete composite system to provide lateral stability and diaphragm action.
- Uniform exterior column geometry by employing 14 different grades of steel.
- Application of viscoelastic dampers to control building motion.
- Wind tunnel testing to establish design wind values for super tall building.
- Use of 3-story prefabricated exterior steel-column panels to expedite construction process.

Document Modifications to Structural Systems

- PANYNJ Guidelines for Inspection, Repair and Modifications to Structural Systems of WTC 1, 2, and 7

  - Tenant Construction Review Manuals
    - 1971, 1979, 1984 (revised 1990), 1997
    - Technical criteria to be used by tenants of Port Authority facilities

      Scope of work, design criteria, and plans

      Design by registered architect or professional engineer
    - Structural Requirements
    - Inspection Program

Document Modifications to Structural Systems

- Architectural and Structural Design Guidelines (1998)
  - Requirements for tenant alterations in WTC 1 and 2
  - Structural design guide

    Minimum floor loads, core hole sizes, HVAC equipment
  - Structural specifications
  - Standard details

Document Modifications to Structural Systems

- PANYNJ Programs for Inspection, Repair and Modifications to Structural Systems of WTC 1, 2, and 7

  - Facility Condition Survey (1990, 1991, 1997, 2000)
    - Condition of buildings
    - Recommendations for repairs and upgrading
  - Structural Integrity Inspection Program (1991,1992,1993,1995, 1996, 1997, 1998, 1999, 2000)
    - Detect, record and correct distresses and deterioration that could lead to structural problems

Document Modifications to Structural Systems

Structural Integrity Inspection

- Inspection/monitoring of 16 items, including
  - Space usage
  - Accessible columns
  - Bracing below elevation 294 ft
  - Hat trusses
  - Floor framing over mechanical areas
  - Floor framing over tenant areas
  - Natural frequency measurements
  - Natural frequency of floors
  - Damping units

Structural Integrity Inspection
WTC 1 and 2

- Space usage – identify possible overloading
  - Distribute granite slabs on floor106 over a larger area (1995).
- Accessible columns – check condition of columns in elevator shafts.
  - Missing fireproofing on columns (1996, 1998).
- Bracing below elevation 294 ft.
  - No priority recommendation (1991, 1995).
- Hat trusses – check overall condition.
  - No priority recommendation (1992, 1995).
- Floor framing over mechanical areas – check concrete and steel (1992, 1996, 1999).
  - Repair fireproofing.

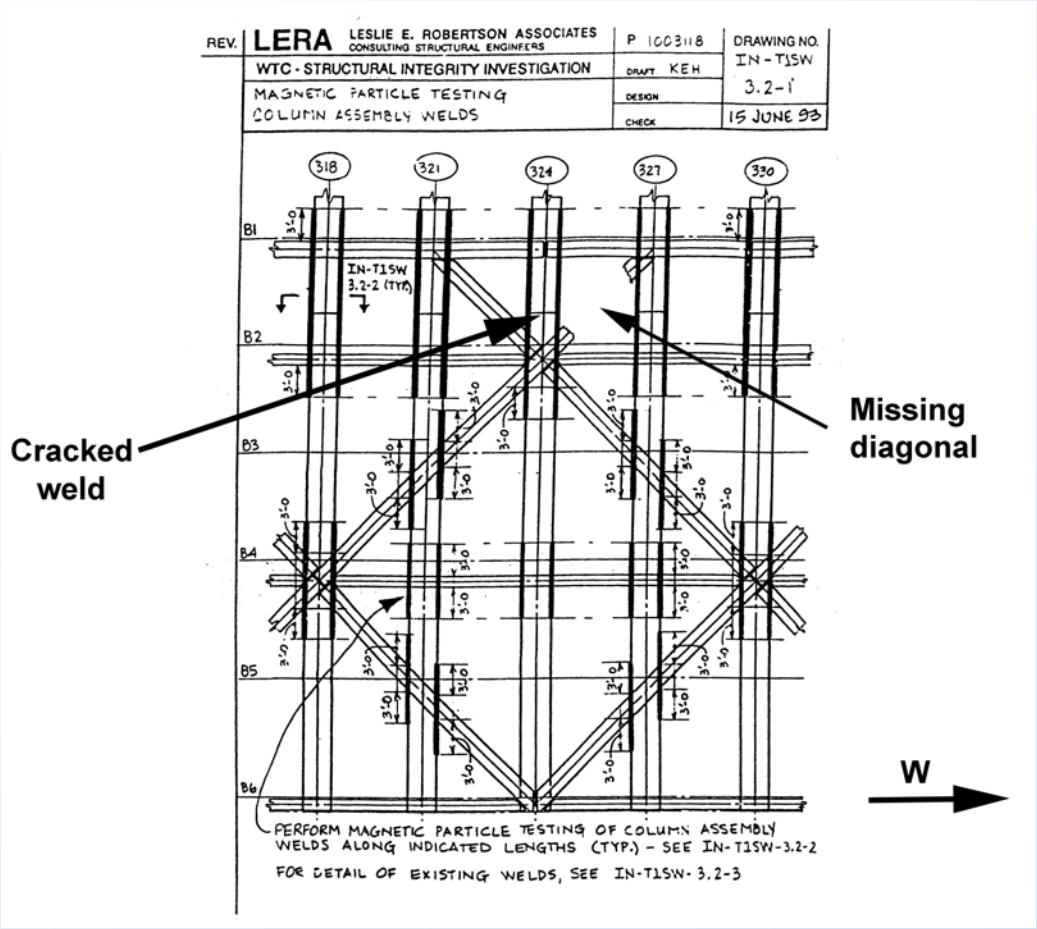
Structural Integrity Inspection

- Floor framing over tenant spaces – check overall condition of floor framing system (1992, 1995, 1997, 1999).
  - Missing fireproofing on columns (1996, 1998).
- Natural frequency measurements – WTC 1 only (1993, 1995, 2000).
  - Measure and computed values are similar (1993, 1995).
  - No analysis made since 1998.
- Natural frequency of floors – WTC 1 & 2 (1996).
  - No appreciable difference between analysis and measured values.
- Viscoelastic damping units – WTC 1 & 2.
  - Damping units were in good condition.
- Post 1993 explosion – pre and post repair inspections.
  - Six inspections were made by LERA, U.S. Army COE, WJE, Proto Mfg, and Lucius Pitkin.

Document Modifications to Structural System

- Modification and Repairs to Structural Framing Systems of WTC 1 and 2
  - Repairs Related to Explosion of February 16, 1993
    - Bowed Column 324 above Level B2
    - Missing and bowed diagonals between Column 324 (Level B2) and Column 327 (Level B1)
    - Cracked column splice at Column 324
    - Bent spandrels and damaged floor beam connections

Document Modifications to Structural System



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Document Modifications to Structural System

Modification and Repairs to the Structural Framing System of WTC 7

- Floor slabs removed on the east side of building to accommodate trading floors for Salomon Brothers Inc.
- Columns were reinforced with plates.
- Penthouse addition on east side of building.
- Replacement of previously removed floor framing.

Interim Findings
WTC 1 and 2

- Changes made to building design and classification due to change in code provisions:
  - Eliminated fire tower as a required means of egress.
  - Reduction in the number of required stairwells from 6 to 3.
  - Reduced size of doors to stairs from 44 in. to 36 in.
  - Reduced fire rating of shaft walls from 3 h to 2h.
  - Changed partition loads from 20 psf to one based on weight of partition per unit length.
  - WTC 1 and 2 classified as Class 1B construction for business occupancy and unlimited building height.

Interim Findings

WTC 1 and 2

- New York City Department of Buildings reviewed the design drawings in 1968.
- Code conformance agreement (MOU) established between Port Authority and New York City Department of Buildings in 1993, amended 1995.
- Port Authority developed structural inspection program to examine systematically the integrity of structural systems.

Interim Findings

WTC 1 and 2

Design loads:

Dead load: Greater than or equal to design loads specified in NYC Building Code.

Live load: Greater than or equal to design loads specified in NYC Building Code.

Live Load Reduction:

Equal to or more stringent than NYC Building Code requirements.

Wind load: Information on design values is not available. (Wind tunnel tests were conducted at Colorado State University and National Physical Laboratory, U.K.)

Interim Findings

WTC 7

Design loads:

Dead load: Greater than or equal to design loads specified in NYC Building Code.

Live load: Design values base on anticipated live loads.

Live Load Reduction:

No information available.

Wind load: Information on design values is not available. (Wind tunnel tests were conducted at University of Western Ontario.)

Fire Resistance Ratings (1968 NYC Building Code)
WTC 1 and 2

- Construction Class 1B (3 hour protected)
  - 3 hours on columns
  - 2 hours on floors
  - 2 hours on exit access corridors
    - 1 hr permitted but 2 hr used to permit 100 foot dead ends
  - 2 hours for shaft enclosures
  - 1 hour for tenant separation (demising) walls

Means of Egress

WTC 1 and 2

- Occupant load (per floor) 390
  - 39000 sq ft net @ 100 sq ft per person for group E
- Units of exit width required, 6
  - 390 @ 60 persons per 22 in. unit on stairs
- Min clear width of stairs 44 in.
- Door widths 36 in. (min) to 48 in. (max)

Elevators (99 in each tower)

WTC 1 and 2

- By Code not utilized for fire service access nor for occupant egress during an emergency.
  - Elevators were used for occupant egress in WTC 2 after 1 was hit and before 2 was hit.
- Three elevator "zones" with sky lobbies (concourse, 44th and 78th floors).
  - 8 express concourse to 44.
  - 10 express concourse to 78.
  - 24 locals per zone in groups of 6.
  - 7 freight elevators (1 serving all floors).
  - All retrofit with Firefighters Emergency Service (per ASME A17.1).

Fire Suppression
WTC 1 and 2

- Standpipes
  - Located within 145 feet of any point
  - Outlets located within stairways
  - Tanks on mechanical floors and cross connection of standpipes
  - Standpipe communication system
- Sprinklers only required below grade

Fire Alarm System

WTC 1 and 2

- Installed in corridors above minimum code requirements
- Smoke detectors
  - 4 per floor at air return grilles to prevent recirculation of smoke.
  - No manual initiating devices.

Miscellaneous Requirements

WTC 1 and 2

- Emergency power not required.
- Stair pressurization not required.
- Smoke purge system not required.
- Some requirements for exit signs and lighting in means of egress.

Fire Resistance Ratings
WTC 7

- Construction Class
  - 1C (2 hour sprinklered) per Fire Safety Plan filed for the building in 1990 (permitted under LL16 1984)
  - 1B (3 hour protected) per PA supported by correspondence and drawings

	Type 1B	Type 1C
Columns	3	2
Floors	2	1-1/2
Shaft enclosures	2	2
Tenant separation (demising) walls	1	1

Means of Egress
WTC 7

- Two 58 in. stairs provided 6 units of exit width or 360 persons per floor.
  - Area of 44,000 sq ft net @ 100 for group E would yield 440 per floor.
- Total building daytime population estimated as 2000 (3 partially handicapped, no wheelchairs) with 200 visitors (1990 Fire Safety Plan).

Elevators
WTC 7

- By Code not utilized for fire service access nor for occupant egress during an emergency.
- 38 elevators total (all equipped with FES):
  - 28 passenger and 2 freight serving all floors.
  - 2 passenger serving floors 28-45.
  - 2 passenger serving floors 44-47.
  - 3 passenger serving floors 45-46.
  - 1 passenger serving floors 2-3 (auditorium).

Fire Suppression
WTC 7

- Complete sprinkler system (LL16-1984).
- Standpipes
  - Located within 145 feet of any point.
  - Outlets located within stairways.
  - Tanks on intermediate floors.
  - Standpipe communication system.

Fire Alarm System
WTC 7

- Class E alarm and voice communication system
- Fire command station in lobby
- Floor warden stations
- Smoke Detectors
  - Elevator lobbies
  - Sprinkler waterflow
  - HVAC protection
- Manual initiating devices
  - Report to fire department

Miscellaneous Requirements
WTC 7

- Emergency Power
  - Alarm & Communication system
  - Fire pumps
  - 3 elevators
  - Emergency lighting
  - Smoke control and stair pressurization
- Controlled inspection of Spray Applied Fireproofing and firestopping

Modifications

WTC 1 and 2

- LL5-1973 and LL16-1984 had major impacts on WTC 1 and 2 but were incorporated into initial WTC 7 design
  - Compartmentation
    - 7500 sq ft with 1-hr
    - 10,000 sq ft with 2-hr
    - 15,000 sq ft with 2-hr and smoke detectors
    - Not required if sprinklered
  - Class E alarm and voice communication system
  - Fire command station in garage (later moved to lobbies)
  - Emergency power for exit signs and egress lighting
  - Sprinkler system
  - Smoke control/purge
  - Controlled inspection of Spray Applied Fireproofing and firestopping
  - Carpet in exit access corridors
  - Stair re-entry every four floors

Modifications
WTC 7

- Review of 120 tenant alteration reports revealed that the only modification to fire and life safety systems was the relocation of sprinkler heads and detectors to accommodate partition locations.

MOU's Between PA and FDNY Covering All PA Facilities in NYC

- PA policy to implement FDNY recommendations after inspections of PA facilities and for prior review of fire safety systems introduced or added to PA facilities adopted April 15, 1993 and formally executed December 30, 1993.
  - Inspections generally coordinated with PA but can be unannounced.
  - Report of findings and recommendations from Bureau of Fire Prevention to PA will be implemented and formally responded.
  - Plans for new systems or modifications to existing systems will be submitted for review and approval.
  - Intent to comply with local codes and regulations.
  - PA reserves the right to petition for variances in unusual circumstances.

- Formally amended February 2, 1995 to provide for plans review and certification by licensed engineer or architect not involved in preparation of the plans and retained by PA in lieu of FDNY review and approval.
  - Follows the MOU between PA and DOB dated November 3, 1993 and amended in June 1995 with regard to building regulations.

Interim Findings

- While not subject to the building and fire regulations of New York City, the PA generally followed these at the design stage and as they evolved over the life of the buildings through the adoption of local laws:
  - LL5-1973
  - LL16-1984
- The fire and life safety systems in WTC 1, 2, and 7 were generally consistent with the requirements of national codes, standards, and accepted practices.
- PA developed tenant manuals and alteration procedures, and conducted regular condition surveys.
- PA addressed some problems over an extended period of time:
  - Adequacy of and upgrades to fireproofing.
  - Tenant separation walls.
  - Sprinkler retrofits.
  - Inspection by independent third parties.