

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

**Technical Conference on the Federal
Building and Fire Safety Investigation of
the
World Trade Center Disaster**

Building and Fire Codes and Practices

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National Institute of Standards and Technology
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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
 - **And how these influenced the design and construction**
- Document maintenance and modifications to structural, fire protection, and egress systems
 - **And how these were influenced by changes to codes, standards, and practices during the life of the building**
- Document the fuel system for emergency power in WTC 7

WTC 1 and 2

Architects:

Minoru Yamasaki & Associates

Emery Roth & Sons ([ARCHITECT-OF-RECORD](#) or Code Architect)

Structural Engineers:

Skilling, Helle, Christiansen & Robertson ([Structural Engineer of Record](#))

Documents Reviewed and Indexed

- Complete set of design, construction and maintenance documents kept in WTC 1 destroyed during collapse
- Construction documents were not retained by the General Contractor (Tishman Construction Co.) after 7 years
- More than 8,000 documents from:
 - Port Authority
 - LERA
 - Silverstein Properties
 - New York City (Fire Department, Police Department, Law Department, Department of Buildings, Department of Design and Construction, and Office of Emergency Management)
 - Group of companies that insured the towers
 - Laclede Steel
 - Isolatek
 - FEMA
- Indexed database available for future access to document archive

Support Contractors

- Rolf Jensen & Associates, Inc.
- S. K. Ghosh Associates, Inc
- Rosenwasser/Grossman Consulting Engineers P.C.

New York City Building Code

- Building Code not based on any model code, but developed by volunteer committees
 - Adopted and modified by Local Laws passed by City Council
 - Interpreted by Building Commissioner through Rules
- Interpretations and explanation in *Policy and Procedures Notices* and *Rules* issued by the Building Commissioner
- No Fire Code, but *Rules of the City of New York* issued by the Fire Commissioner
- Reference Standards based on national consensus standards but adapted and adopted for local conditions and practices

Origin of 1968 NYC Building Code

- 1962 - Brooklyn Polytechnic Institute was contracted to develop a draft code drawing from BOCA, current practice, and utilizing volunteer committees
- December 6, 1968 - Local Law 76 (1968) repealed 1938 Code and adopted 1968 Code
- Between 1969 and 2002 there were 79 Local Laws that modified the 1968 Code

Rationale for the Selection of the 1968 NYC Building Code for the WTC Towers

- June 22, 1965 letter from John M. Kyle, Chief Engineer to Malcolm Levy, Chief, Planning Division, WTC:
- “This will confirm my advice that, **in view of the more liberal provisions of the proposed new New York City Building Code, I feel we should take advantage of its provisions.**
- This decision is based on the following:
 1. **The new code has received thorough review by interested technical groups and representatives of the City and has been modified to meet all major objections.**
 2. It is scheduled to be officially submitted to the City in September and should be approved well before we construct our buildings.
 3. **The Commissioner has stated that he favors the approach taken by the Port Authority in using advanced techniques in the design of the World Trade Center.** He also stated that the Port Authority is not subject to the provisions of the Building Code.”

Rationale for the Selection of the 1968 NYC Building Code for the WTC Towers

- September 29, 1965 letter from Malcolm P. Levy, Chief, Planning Division, WTC to Minoru Yamasaki, Architect:
- “... Generally the tower core should be redesigned to eliminate the fire tower and **to take advantage of the more lenient provisions regarding exit stairs...**”
- May 19, 1966 memorandum from Guy F. Tozzoli, Director, World Trade Department to John M. Kyle, Chief Engineer:
- “The decision to follow the new Code was, as you pointed out, in your memorandum to Mr. Levy of June 22, 1965, based on the fact that: (1) **The new Code had been thoroughly review by interested technical groups and was modified to meet all major objections;** (2) it would probably be adopted before we constructed our buildings; and (3) **the Commissioner favored the approach of using advanced techniques in the design of the World Trade Center** and that the Port Authority, according to him, was not subject to the provisions of the Building Code.”

Rationale for the Selection of the 1968 NYC Building Code for the WTC Towers

- Memorandum dated January 15, 1967, from Lester S. Feld (Chief, Structural Engineer, World Trade Department, PANYNJ) to Robert J. Linn (Deputy Director for Physical Facilities, WTD, PANYNJ): Subject: The World Trade Center – Towers and Plaza Buildings Fire Rating per NYC Building Code Revision Effective 12-6-68.
- Paragraph 2. B. states:
- **“For office buildings there is no economic advantage in using Class 1A Construction, and ER&S used Class 1B Construction for the WTC Towers and Plaza Buildings which are Occupancy Group “E” (Business) with a fire index of 2 hours. As such, columns must have a three hour rating and floor construction with a 2 hour rating.”**

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 stairways from 6 to 3 (by increasing the stair capacity from 30 to 60 per 22 inch unit of exit width) 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).

Review of Drawings by New York City Department of Buildings

1975 Letter from Code Architect 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 (all dealt with egress issues)
- Architect submitted responses to the comments to Port Authority in March 1968.

January 1968 letter from Solomon of Emory Roth to Levy of PANYNJ

1. Occupant load per floor is <365, stair capacity is 390
2. Max travel distance is 140 ft, 200 ft permitted in unsprinklered Class E
3. No fire tower required
4. Cellar stairs are enclosed 2 h and lead to street or Concourse (deemed an underground street by PANYNJ)
5. Cellar stairs used for tenant storage are <10% of area, considered as office for egress requirements
6. Sprinklered garage meets 150 ft travel distance requirement

Port Authority Policies and Procedures

Design and Construction

- PONYA (PANYNJ after 1972) created in 1921 to operate transportation facilities (ports, bridges, airports)
- As an “interstate compact” organization under the U.S. Constitution they are not subject to laws of any lower jurisdictions, including building regulations
- 1965 - Instructed architects and engineers to follow 2nd and 3rd drafts of 1968 Code for WTC 1 & 2, documenting differences from 1938 Code as variances justified as acceptable engineering practice or proposed for the 1968 code.

Port Authority Policies and Procedures

Maintenance and Modifications

- While not required, Local Laws were followed even where not retroactive
 - LL5/73 and LL16/84
- Tenant manuals and review systems were developed and implemented to manage modifications
 - PANYNJ office
 - Outside consultants (LERA)
 - Due Diligence reviews
- Upgrades after 1993 bombing

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 had been constructed in accordance with the plans and specifications.

While the PANYNJ entered into agreements with the NYC Department of Buildings in the 1990s with regard to conformance of PANYNJ buildings constructed in New York City to the NYC Building Code, **the PANYNJ did not yield jurisdictional authority for regulatory and enforcement oversight to the NYC Department of Buildings.**

Fire and Life Safety Systems

Building Codes Reviewed (Fire Protection and Egress Systems)

- NYC Building Code - 1968 edition
- NY State Building Code - 1964 edition
- Chicago Building Code - 1967 edition
- BOCA Basic Building Code - 1965 edition
(National Model Building Code)
- NYC Building Code - 2001 edition
- NFPA 101 - 1966 edition

National Fire Safety Standards Adopted by 1968 NYC Building Codes

- Sprinkler systems
 - RS 17-2:NFPA 13 (1966)
- Fire alarm systems
 - RS 17-5:NFPA 72 (1967)
- Smoke management
 - RS 13-1:NFPA 90A (1967)
- Egress systems
 - Covered in the Building Code

Review of Code Provisions

- Construction Classes – Unsprinklered
 - Class 1A and 1B: NYC 68, NYS 64, BOCA 65 (Unlimited height)
 - Class 1A and 1B: NYC 01 (Height limited to 75 ft. unless sprinklered)
 - Class 1A only: Chicago 67 (Unlimited height)
- Fire Resistance Rating (all codes, except NYC 01)
 - Class 1A
 - Columns: 4 hours (supporting more than one floor)
 - Beams : 3 hours (floor construction)
 - Class 1B
 - Columns: 3 hours (supporting more than one floor)
 - Beams : 2 hours (floor construction)

NYC Building Code Provisions (Fire Resistance in hours)

| | 1938 | 1968* | 2001** |
|---------|------|-------|--------|
| Columns | 4 | 3 | 2 |
| Floors | 3 | 2 | 1-1/2 |

* Building code governing original design and occupancy

** Sprinklers required for buildings of unlimited height

Review of Code Provisions

- Codes establish minimum requirements and do not provide rationale for selecting a higher Construction Class (1A vs. 1B)
 - BCNYC permits 100 ft dead ends with 2 h corridor enclosures and 50 ft with 1 h.
- Selection of Construction Class is at discretion of Owner/Architect

Review of Code Provisions

- NYC Local Law 5 (1973) for New and Existing Buildings (Full compliance by 1988)
 - Applicable to new office buildings and retroactively to existing office buildings over 100 ft in height
 - Compartmentation required for unsprinklered floor areas greater than 7500 ft²
 - Complete sprinkler protection could be provided in lieu of compartmentation
 - Automatic stair door unlocking or unlocked every 4 floors
 - Approved evacuation plan and drills

Review of Code Provisions

- NYC Local Law 5 (1973) for New and Existing Buildings (Full compliance by 1988)
 - Fire safety director and fire wardens
 - Fire command station in lobby
 - Voice communication system
 - Elevator recall
 - Zone smoke control and stair pressurization
 - Stair pressurization not required if fully sprinklered

Review of Code Provisions

- NYC Local Law 16 (1984)
 - Required sprinklers for buildings taller than 75 ft for new business, new and existing hotels
 - Emergency lighting in exits and corridors
 - Remoteness of exits (30 ft or 1/3 travel distance)
 - Full compliance by 1987

Code Provisions and Contemporary Practice for Fire Protection and Egress Systems

- Sprinklers mainly in industrial and storage spaces
 - Rare even in high-rise buildings (except underground)
- Fire alarm systems
 - Manual initiation for occupant notification
 - Control of fans and dampers to prevent smoke circulation
 - Coded audible to indicate location of fire
- Smoke management not yet developed
 - Required by insurance to mitigate property loss
 - “smoke proof towers” and top vented stairs
- Egress system design based on 22 in. units of exit width
 - Occupant loads and capacities consistent
 - Scissor stairs common in NYC, remoteness addressed in LL16

Due Diligence Review by RJA and JB&B

November 22, 1996

- Category A (no plans to correct)
 - Stairs A and C discharge at mezzanine (PA position is that Plaza is a “public way”)
 - Exit stair venting (PA position is that the shaft height precludes compliance)
- Category B (remedied or in progress)
 - Upgrading of fireproofing
 - Tenant separation and corridor walls being extended to slab above
 - Individual fire command stations and additional manual pulls and speakers
- Category C (remediation plans in process)
 - Doors to mechanical spaces in stairways
 - Standpipes exceed 145 foot limit on some floors
 - Egress issues at Mall and B-1
- Category D (Miscellaneous)
 - Smoke control at PATH mezzanine
 - Code compliance oversight
 - Lack of Certificate of Occupancy

Fire Resistance Ratings

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

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 ft². Floor areas could be increased up to 15,000 ft² 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.**

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 ½
 - 390 @ 60 persons per 22 in unit on stairs
- Min clear width of stairs 44 in (2x44, 1x56)
- Door widths 36in (min) to 48 in (max)

Egress from Windows on the World

- Assembly occupancy located on the 106th and 107th floors of WTC 1
 - Windows on the World Restaurant (original to the building)
 - Greatest Bar on Earth
 - Multiple function rooms and support spaces
 - Occupancy of 1130 per floor
- Closed following the 1993 bombing, re-opened in 1996
- Dec. 1994 meeting between PANYNJ and DOB regarding exiting
 - 2-h separation into areas of refuge containing one stair and elevator (27-367 NYCBC)
 - 2 such spaces doubles exit capacity, 3 or more triples to 1170 (27-372 NYCBC)
 - Agreed in Jan. 1995 memo
- Approach extended to Top of the World in WTC 2

Egress from Top of the World

- Observation Deck located on the 107th floor of WTC 2 (original to the building)
- Tenant/operator notified to follow agreed approach, hired local designer
- Divided floor into three areas of refuge (1751 total)
 - Area 1 – 935
 - Area 2 – 343
 - Area 3 – 473
 - Did not include occupant load of roof deck which exited through floor
- PANYNJ informed tenant to limit occupancy to 1130
 - Reported by PANYNJ that turnstiles were not effective
 - Monitored by staff

Required Fourth Stairway

- Building codes (including NYCBC) require 2 stairs,
 - 3 where occupant load >500, and
 - 4 where occupant load >1000
- NYCBC 27-367 states additional load not counted if space is <20% of the principle use.
 - PANYNJ interpretation (2005)

“Based on PA's meeting on exits from the Windows on the World with the DOB on December 6, 1994, it's PA's understanding that "20% of the floor area" in section 27-367 is intended to be the total floor area in the building occupied by the principal use.”

DOB interpretation (2005)

“The idea behind the 20% allowance is the fact that the PA [NIST note – PA refers to Public Assembly] space is used by the same tenant employees who are very familiar with the building and regularly participate in the fire drills. If we are talking about a roof top restaurant or an observation deck that is opened for the general public and tourists, the concept of exit reduction shall not be allowed.”

NIST concludes that four stairways were required. Never mentioned in context of discussions on egress from Assembly spaces or in due diligence reviews.

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 (original)

- 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 prior to LL16/84

Fire Alarm System (original)

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

Miscellaneous Requirements (original)

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

Modifications

- LL5-1973 and LL16-1984 resulted in major changes to WTC 1 and 2 but were incorporated into initial WTC 7 design because of timing
 - 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

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 were generally consistent with the requirements of national codes, standards, and accepted practices
- PA developed detailed 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
- **Recommendation 25.** 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 are nevertheless concerned about the safety of the building occupants and the responding emergency personnel. NIST recommends that such entities 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. To gain broad public confidence in the safety of such buildings, NIST further recommends that it is important that as-designed and as-built safety 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.
- **Recommendation 26.** NIST recommends that state and local jurisdictions should adopt and aggressively enforce available provisions in building codes to ensure that egress and sprinkler requirements are met by existing buildings⁴⁴. Further, occupancy requirements should be modified where needed (such as when there are assembly use spaces within an office building) to meet the requirements in model building codes.
- **Recommendation 28.** NIST recommend that the role of the “Design Professional in Responsible Charge”⁴⁶ should be clarified to ensure that: (1) all appropriate design professionals (including, e.g., the fire protection engineer) are part of the design team providing the standard of care when designing buildings employing innovative or unusual fire safety systems, and (2) all appropriate design professionals (including, e.g., the structural engineer and the fire protection engineer) are part of the design team providing the standard of care when designing the structure to resist fires, in buildings that employ innovative or unusual structural and fire safety systems.

Structural Design, Modifications and Inspections

Objectives

- Comparison of structural provisions in selected codes
 - 1968 NYC Code
 - 1964 NYS Code
 - 1965 BOCA Basic Building Code
 - 1967 Chicago Code
 - 2001 NYC Code

Objectives

- Document the design, construction, modification, and maintenance of the structural systems
 - Provisions used to design and construct the buildings
 - Design criteria
 - Methods used to proportion structural members
 - Tests performed to support the design
 - Innovative features of structural systems
 - Deviations granted by PANYNJ
 - Inspection protocols during construction
 - Maintenance of and modifications to structural systems

Reports

- NCSTAR 1-1 “Design, Construction and Maintenance of Structural and Life Safety Systems”
 - NCSTAR 1-1A “Design and Construction of Structural Systems”
 - NCSTAR 1-1B “Comparison of Building Code Structural Requirements”
 - NCSTAR 1-1C “Maintenance and Modifications to Structural Systems”
 - NCSTAR 1-1F “Comparison of 1968 and Current (2003) New York city Building Code Provisions”

Building Codes Used in Design

Initial design:

- May 1963- Port Authority instructed architect & engineer to use the 1938 edition of New York City Building Code

Final design:

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

Port Authority adopted the provisions of the proposed 1968 New York City Building Code more than 3 years before it went into effect.

Changes to 1938 Code Related to Structural Design

- Uniform partition load based on weight of partition per unit length; 1938 required 20 psf minimum load
- Permitted wind tunnel tests using models to establish design values for wind load

Comparison of Code Structural Requirements

- Dead loads
- Live loads
- Live load reduction
- Lateral loads (wind and earthquake)
- Progressive collapse resistance
- Design standards

Dead Loads

- Permanent loads
 - Structural members, permanent partitions, finishes...
 - Codes have similar values for partition loads and loads due to finishes
- Building codes provide unit weights (densities) of materials for calculating design dead loads
 - Codes have similar densities for building materials, e.g., steel = 490 pcf, concrete = 150 pcf

Live Loads

- Loads produced by use and occupancy
- Codes specify basic live load values for design
- Code values are based on experience and load surveys
- Expressed as equivalent uniform loads
 - Codes have similar values,
e.g., Office = 50 psf, Lobby = 100 psf
- Concentrated loads treated separately
 - Placed so as to produce maximum stresses

Live Load Reduction

Codes allow reduction of basic live load in proportioning supporting members because it is unlikely that:

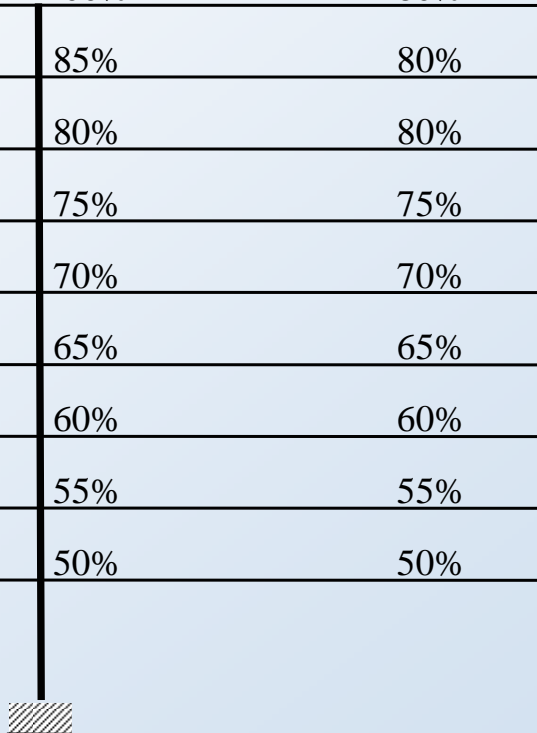
- All floors are fully loaded simultaneously
 - Affects design loads for columns and walls
- Entire floor area is loaded to design value
 - Affects design load for girders and beams

Live Load Reduction Methods

- **Percentage method** (columns and walls)
Live load reduction increases with increasing number of floors (up to a limit)
- **Tributary area method**
Live load is reduced as the accumulated tributary area increases; maximum permitted reduction depends on ratio of LL to DL

Reduced Live Load for Columns and Walls (Percentage Method)

| | NYC Building Code (Alternative Method) Chicago Code | NY State Building Code |
|-----------------------------------------------|-----------------------------------------------------------|---------------------------|
| Roof | 100% | 80% |
| 1 st floor below | 85% | 80% |
| 2 nd floor below | 80% | 80% |
| 3 rd floor below | 75% | 75% |
| 4 th floor below | 70% | 70% |
| 5 th floor below | 65% | 65% |
| 6 th floor below | 60% | 60% |
| 7 th floor below | 55% | 55% |
| 8 th and subsequent floor below | 50% | 50% |

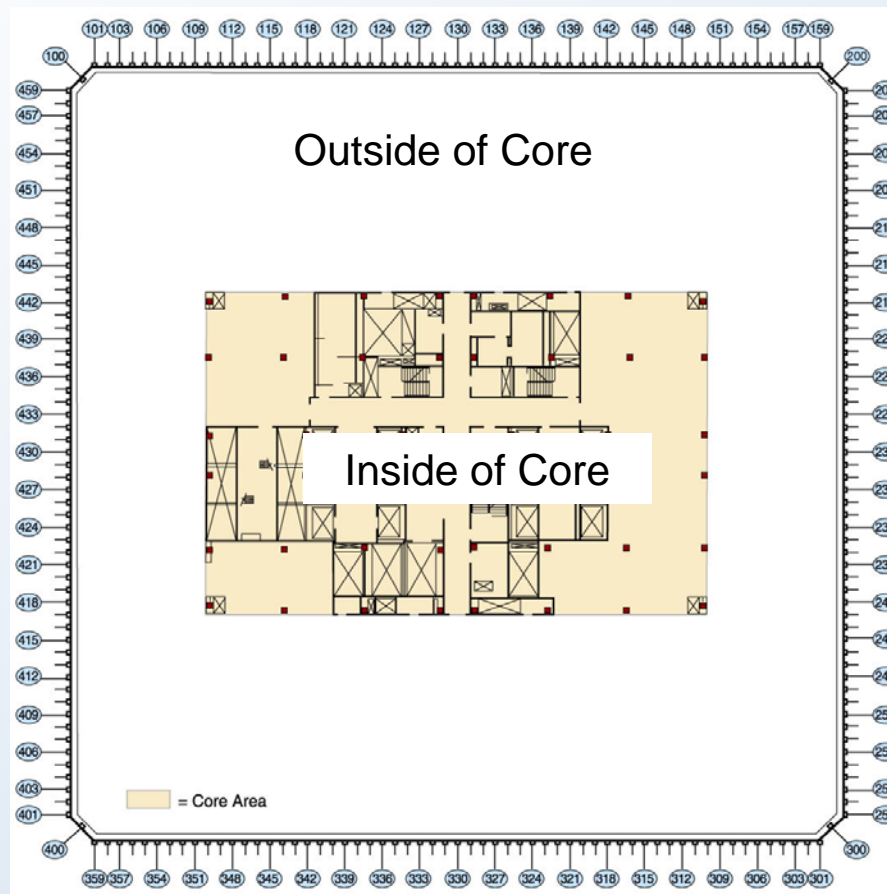


Reduced Live Load for Beams, Girders and Columns (Tributary Area Method)

| Contributory Area (sq ft) | NYC Building Code* | Chicago Code | NY State / BOCA** Codes |
|------------------------------|--------------------|---------------------------------------|----------------------------|
| 100 or less | 100 | 100 | 100 |
| 100 - 150 | 100 | 95 | 100 |
| 150 - 200 | 80 - 85 | Also depends on the DL/LL ratio | 84 - 88 |
| 200 - 300 | 80 - 85 | | 76 - 84 |
| 300 - 450 | 60 - 75 | | 64 - 76 |
| 450 - 600 | 50 - 70 | | 52 - 64 |
| 600 - and more | 40 - 65 | | 40 - 52 |

* For columns, limited to 80% ** Limited to 40% or value based on DL/LL

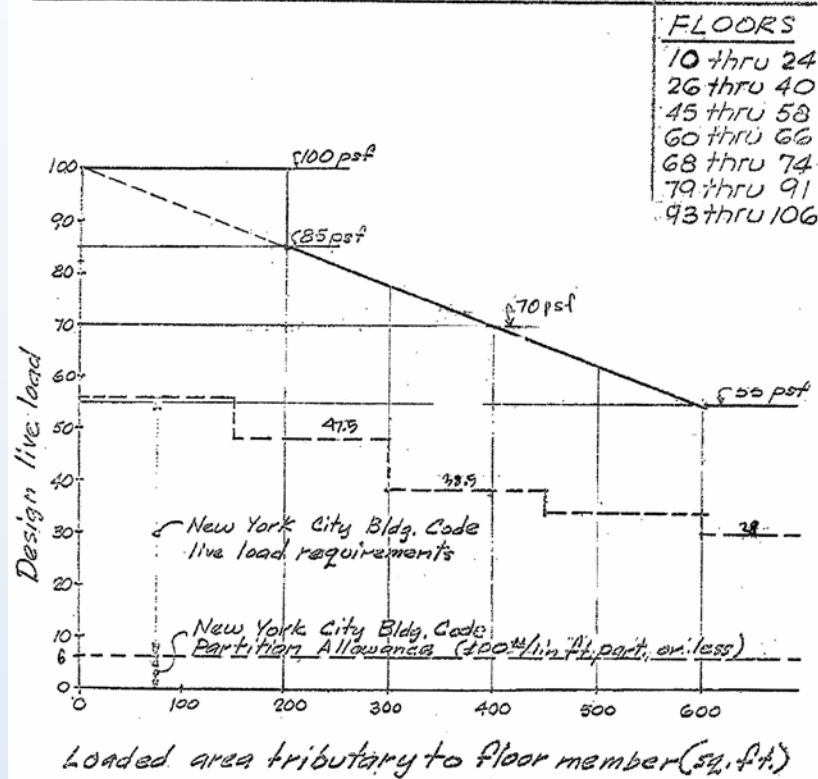
Live Load Reduction Used



Live Load Reduction

WORTHINGTON, SKILLING, HELLE & JACKSON
 THE WORLD TRADE CENTER THE PORT OF NEW YORK AUTHORITY
 MINORU YAMASAKI & ASSOC. EMERY ROTH & SONS
 CIVIL & Structural Engineers MINORU YAMASAKI, ARCHITECT RICHARD ROTH, ARCHITECT
 DATE 5/5/77
 PREPARED BY 77
 APPROVED 1/1/77

CRITERIA FOR DESIGN-DESIGN LOAD FLOOR OUTSIDE OF CORE TENANT AREA LIVE LOAD REDUCTION

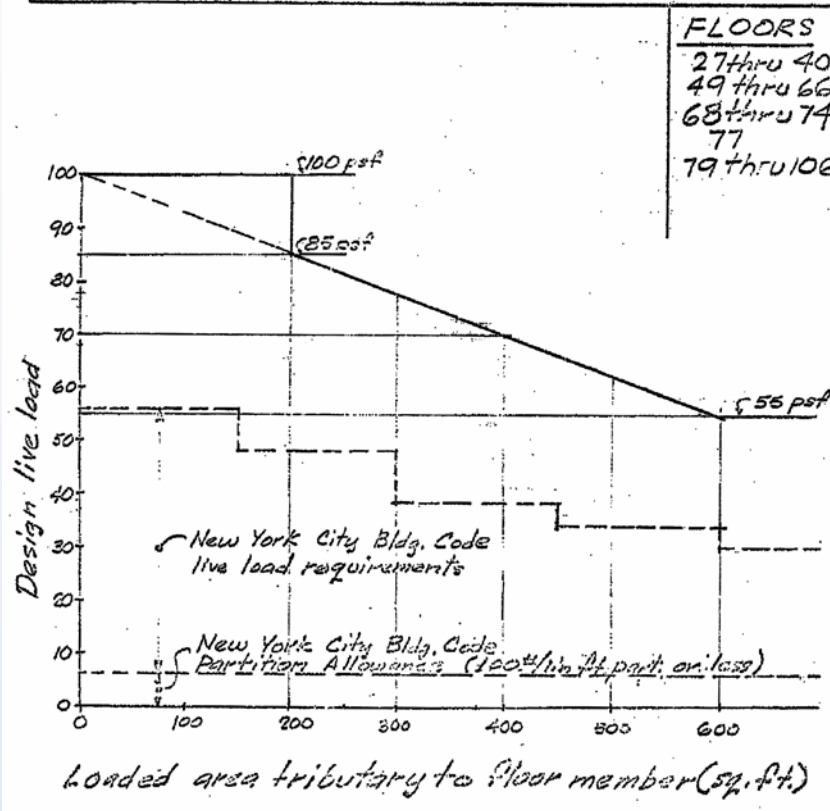


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Live Load Reduction

| | | | |
|-------------------------------------------|-------------------------------------------------------------------------|----------------|--------------|
| WORTHINGTON, SKILLING, HELLE & JACKSON | THE WORLD TRADE CENTER THE PORT OF NEW YORK AUTHORITY | DATE 3/8/66 | Sheet No. |
| Civil & Structural Engineers | MINORU YAMASAKI & ASSOC. ENRY ROTH & SONS RICHARD ROTH, ARCHITECT | PREPARED BY JN | BC 1 |
| | | APPROVED | 4 |

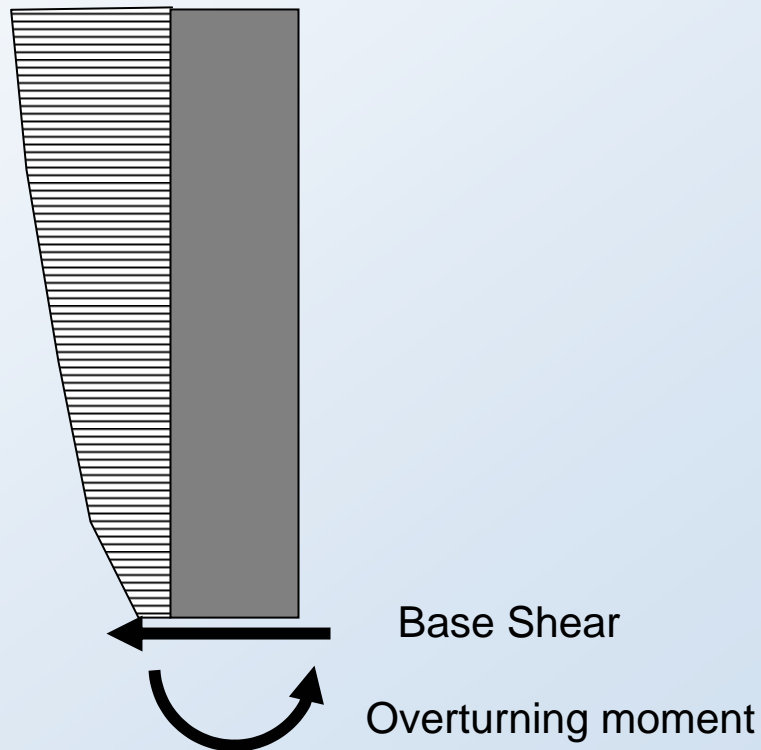
CRITERIA FOR DESIGN-DESIGN LOAD FLOOR INSIDE OF CORE TENANT SPACE LIVE LOAD REDUCTION



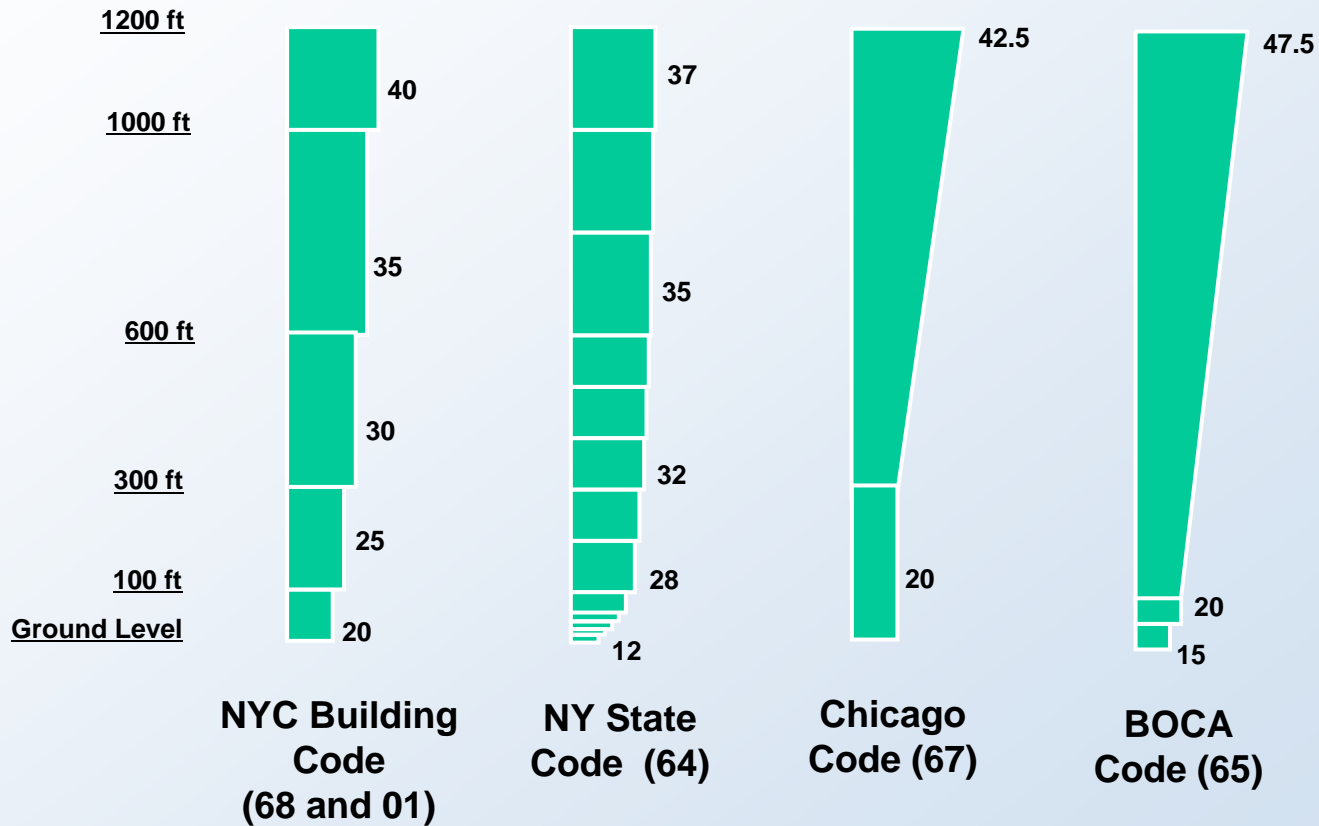
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Wind Load

- Effect of wind is considered as a lateral pressure acting on the faces of the building



Wind Pressure Distributions of Different Building Codes



Design Wind Pressure: 1968 NYC Building Code

Alternative method

- “Suitably conducted model tests”
- Fastest-mile wind speed of 80 mph at 30 ft above ground
- Include all factors involved in consideration of wind pressure
 - Pressure and suction effects
 - Shape factors
 - Gust ...

Earthquake Load

- NYC Building Code (1968) - **No provisions**
- NY State Building Code (1964) - **No provisions**
- Chicago Building Code (1967) - **No provisions**
- BOCA Basic Building Code (1965)
Based 1961 UBC (Base shear $V = ZKCW$)
- NYC Building Code (2001)
Based on 1988 UBC (Base shear $V = ZIKCSW$)

Provision for Progressive Collapse Resistance

- NYC Building Code (1968)
 - No provision
- NYC Building Code-Rules of the City of New York, 1973
 - Alternate path method
 - Specific local resistance method
 - August 7, 1973 clarification: applicable to structures with connections that rely on friction

Design Loads for WTC 1 and 2

- Dead load:
 - Greater than or equal to design loads specified by 1968 NYC Building Code
- Live load:
 - Greater than or equal to design loads specified by 1968 NYC Building Code
- Live Load Reduction:
 - Equal to or more stringent than 1968 NYC Building Code requirements
- Wind load:
 - Wind tunnel test results were significantly greater than prescriptive pressures in 1968 NYC Building Code

Wind Load Design Values

| | 1968 NYC Building Code | Wind Tunnel Tests |
|---------------------------------------------------|-----------------------------------|------------------------------|
| Base Shear (kips) | 9,250 | 13,100 |
| Overturning Moment (10 ³ ft kip) | 7,621 | 12,600 |

National Structural Design Standards

- NYCBC (68)
1963 AISC Specifications, 1963 ACI 318 Code
- NY State BC (64)
Appropriate national standards
- Chicago BC (67)
1963 AISC Specifications, 1963 ACI 318 Code
- BOCA Basic Building Code (65)
1963 AISC Specifications, 1963 ACI 318 Code
- NYC Building Code (01)
1989 AISC Specifications, 1989 ACI 318 Code

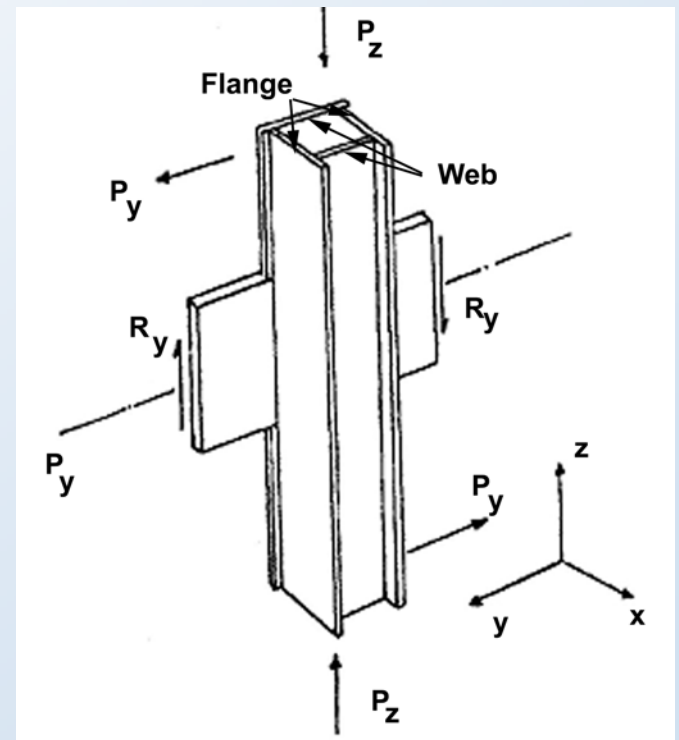
Tests Performed to Support Design

- Exterior wall panel tests
- Wind effect tests
- Tests of viscoelastic dampers
- Tests of floor trusses
- Stud shear connector tests

Tests Performed to Support Design

Exterior Wall Panel Model Tests

- University of Western Ontario
- Linear-elastic tests using plastic models
- Load-deflection characteristics
- Examine “most effective construction” for wall panels
- 15 different tests; replicating the 20th, 47th, and 4th floor exterior walls



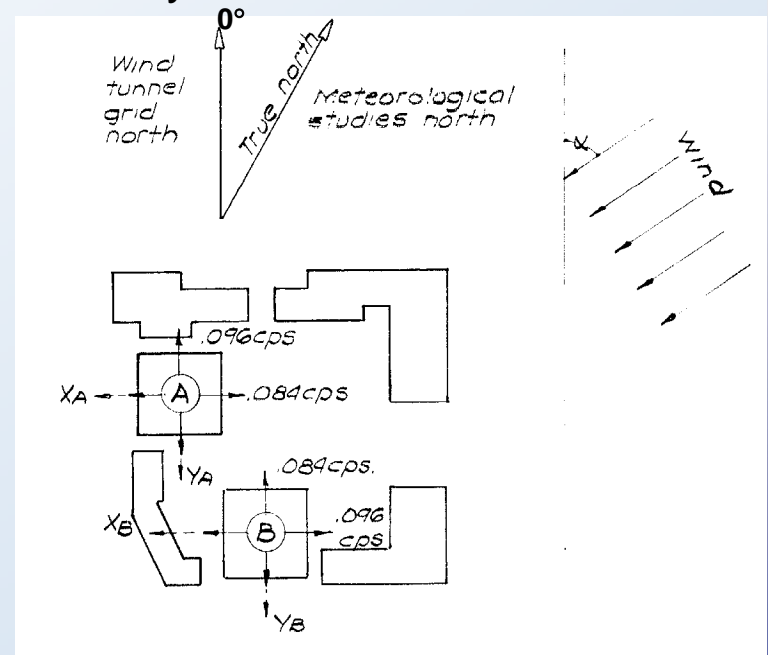
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Tests Performed to Support Design

Wind Effects Tests

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

Grid System for Wind Tunnel Test



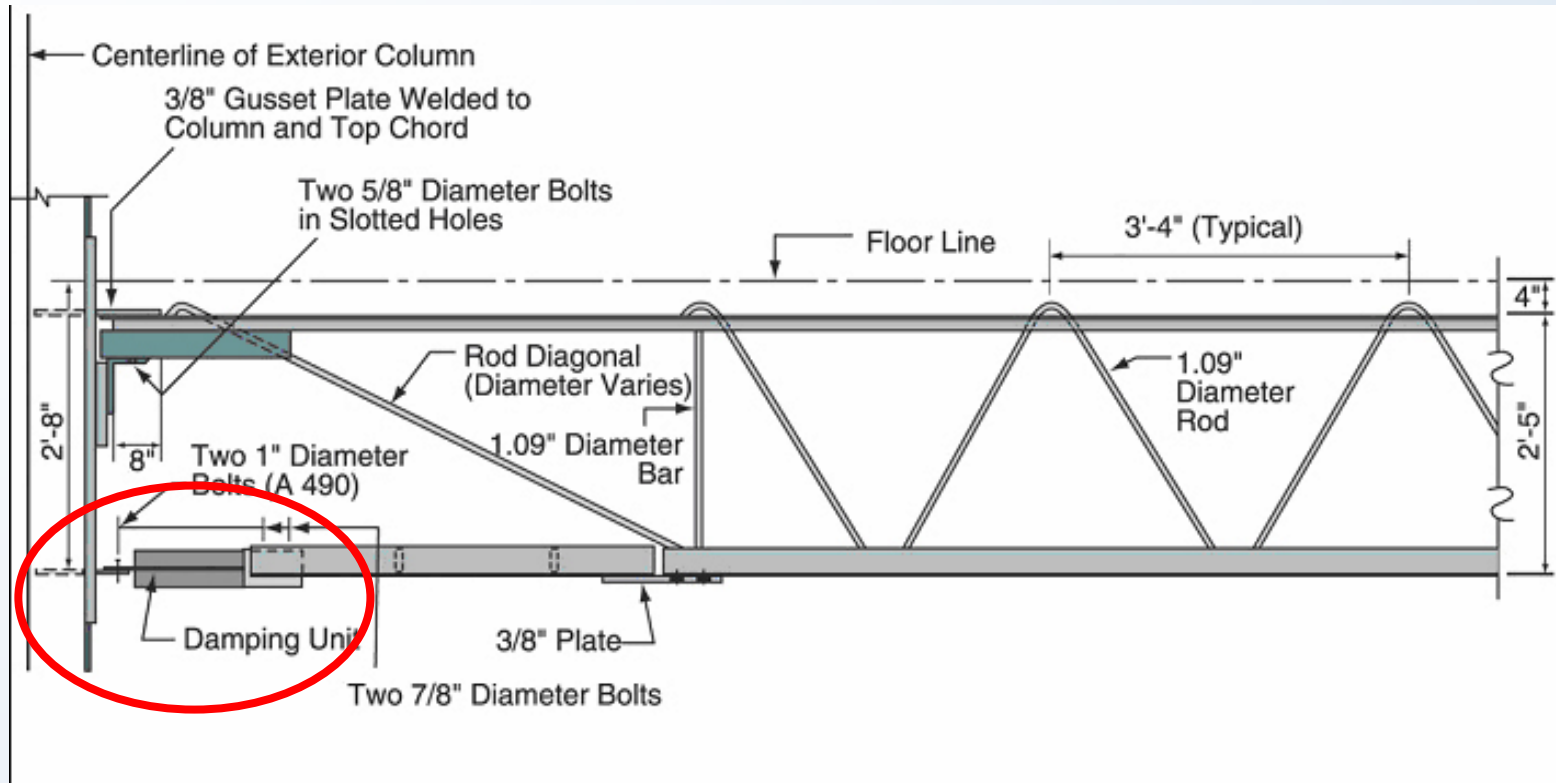
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Tests Performed to Support Design

Viscoelastic Damping Unit Tests

- Conducted to confirm effectiveness of the damping units in controlling building motion due to wind
- Two sets of tests
 - 1967: Minnesota Mining and Manufacturing Company (3M)
 - 1968-1969: Massachusetts Institute of Technology

Damping Units



Source: FEMA WTC Report

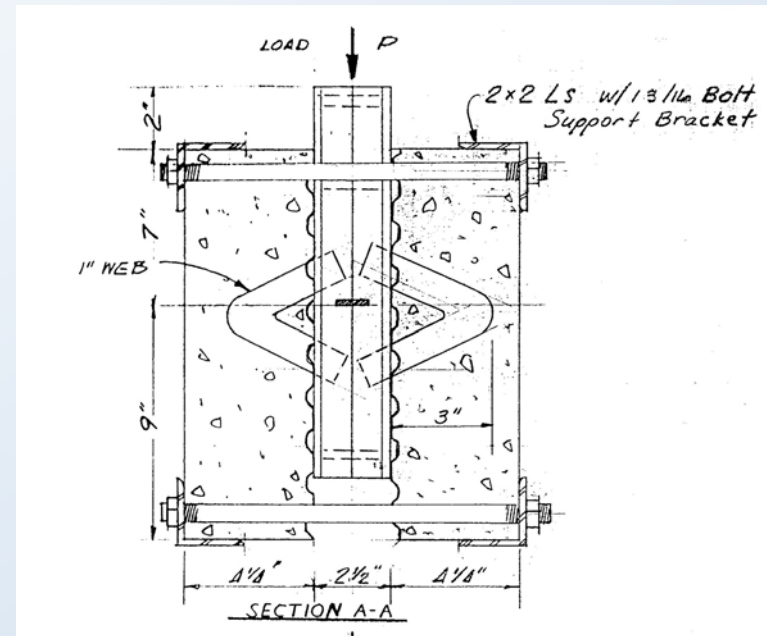
Tests Performed to Support Design

Floor Truss Tests

- Full-scale flexural tests
- Interior panel connection tests
(between floor truss and bridging truss)
- Bearing capacity (at ends of truss) tests
- Shear knuckle tests

Tests Performed to Support Design

Shear Knuckle Tests



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Guidelines for Inspection, Repair and Modifications of Structural Systems

- Tenant Construction Review Manuals
- Architectural and Structural Design Guidelines
- Structural Integrity Inspection Program
- Facility Condition Surveys

Modifications to Structural Systems

Tenant Construction Review Manuals

- 1971, 1979, 1984 (revised 1990), 1997
- Technical criteria to be used by tenants of all Port Authority facilities
 - Applications: scope of work, design criteria, and plans
 - Structural requirements: design by registered architect or professional engineer in accordance with applicable codes
 - Inspection program

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 loads
- Structural specifications
- Standard details

Structural Integrity Inspection Program

- Structural integrity inspections conducted in 1991, 1992, 1993, 1995, 1996, 1997, 1998, 1999, and 2000
- Detect, record and correct distresses and deterioration that could lead to structural problems

Structural Integrity Inspections

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

Structural Integrity Inspection

- Space usage – identify possible overloading
 - Distribute granite slabs on floor 106 over a larger area (1995)
- Accessible columns – check condition of columns in elevator shafts
 - Missing thermal insulation on columns (1996, 1998)
- Bracing below grade
 - No priority recommendations (1991, 1995)
- Hat trusses – check overall condition
 - No priority recommendations (1992, 1995)
- Floor framing over mechanical areas – check concrete and steel (1992, 1996, 1999)
 - Repair thermal insulation

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

Structural Integrity Inspection

- 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

Facility Condition Survey

- Conducted by Engineering Quality Assurance Division (EQAD) of PANYNJ
- Based on sampling plan and NDT test methods
- Surveys in 1990, 1991, 1997, 2000
 - Exterior wall system
 - Core columns
 - Hat truss
 - Floor system
 - Damping system

Findings

- Building codes and standards lack explicit structural integrity provisions to mitigate progressive collapse
- *Recommendation 1*
 - *Progressive collapse should be prevented in buildings through the development and adoption of consensus standards and code provisions*
 - *Standard methodology should be developed to predict complex failure in structural systems*

Findings

- Building codes allow determination of wind pressures from wind tunnel tests for use in design
- *Recommendation 2*
 - *Performance standards should be developed for conducting wind tunnel testing and estimating wind loads and their effects on buildings for use in design*

Findings

- Building Codes lack minimum structural integrity provisions for the means of egress in the building core that are critical to life safety
- *Recommendation 18 (2)*
 - *Egress systems should be designed to maintain their functional integrity*

Findings

- State and local jurisdictions do not require retention of documents related to design, construction , maintenance, and modifications of buildings
- *Recommendation 27*
 - *Building codes should incorporate a provision that requires building owners to retain documents over the life of the building*