Title:	**Evolution of Building Code Requirements in a Post 9/11 World**
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Subject:	Fire & Safety
Keywords:	Building Code Code Compliance Fire Safety Life Safety
Publication Date:	2011
Original Publication:	CTBUH Journal, 2011 Issue III
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Evolution of Building Code Requirements in a Post 9/11 World

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David Drengenberg
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David joined CTLGroup in 2002 with the completion of his M.S. in Structural Engineering from the University of Illinois at Urbana-Champaign. His principal experience with CTLGroup has included: structural investigation and assessment, structural analysis and design calculations for evaluation of existing structures, solutions for construction problems, construction-related repair and rehabilitation of existing structures, on-site observation and construction services, administration, development of repairs and observation of execution of remedial structural demolition and repairs.

Gene Corley
Gene Corley leads structural evaluation projects related to industrial, transportation and parking facilities, bridges and buildings. His wide range of experience includes: evaluation of earthquake, fire and blast damaged buildings and bridges, investigation of distress in prestressed concrete structures, repair of parking garages damaged by corrosion, evaluation and repair of high-rise buildings, stadiums, silos and bridges, design and construction or repair of prestressed conventionally reinforced, precast and cast-in-place concrete, foundations and structural steel facilities.

Gene is one of the world's foremost experts in analyzing buildings damaged by bombs, earthquakes, fire and tornadoes. He led the federal investigation into the September 11, 2001, collapse of the World Trade Center's twin towers. He also conducted the investigation of the 1995 collapse of part of the Murrah Federal Building caused by the Oklahoma City bombing, and served as expert advisor during the investigation and trial resulting from the 1993 fatal fire at the Branch Davidian complex in Waco, Texas.

> "Recommendations from the original Structural Engineering Institute, ASCE and FEMA sponsored report recommended several building code changes. Additional work by NIST and NIBS has resulted in more than 17 code changes."

It is not practical to design tall buildings to resist terrorist attacks. However, the terrorist attacks of September 11, 2001 highlighted several concerns unique to tall buildings subject to extreme events. Observations resulting from the World Trade Center's post-attack performance investigation included: failure of active and passive fire protection systems, importance of structural redundancy, and performance of egress systems. These observations led to recommendations for code modifications. Many recommendations have been incorporated by the International Code Council into the International Building Code's 2012 edition.

Attack and Collapse

A coordinated terrorist attack launched on September 11, 2001 led to damage and destruction of structures in New York City and Arlington Virginia, including the World Trade Center's twin towers (WTC 1 and WTC 2). This unprecedented attack subjected both towers to extreme load conditions far beyond those considered during design.

Impact by Aircraft

Each of the twin towers was struck by commercial Boeing 767-200 aircraft, each with estimated gross weights in excess of 124,300 kilograms (274,000 pounds), including 37,900 liters (10,000 gallons) of jet fuel, and at speeds between 750 and 950 km/h (470 and 590 mph). These impacts severely damaged structural systems, ignited widespread fires, and ultimately led to collapse of both structures. Aircraft impact severely damaged exterior steel columns and the interior core. Additionally, damage to active fire suppression systems such as sprinklers, and passive systems such as fireproofing was severe.

Early Observations and Recommendations

Structural Performance

Despite the terrible loss of life and property, WTC 1 and WTC 2's ability in particular to survive initial impact loads and the resulting structural damage is notable. Undoubtedly, many hundreds of lives were saved because of the redundancy and robustness built into the structures.

Although WTC 1 and WTC 2 ultimately collapsed, they withstood initial structural damage for 102 and 56 minutes, respectively. Redundant and robust exterior steel frame and hat truss construction provided for load redistribution around areas of impact damage, bridging large, damaged areas. In the case of WTC 2, photographic evidence shows more than 30% of south face columns were destroyed over five stories (FEMA, 2002). Calculations show that, if not for the damage caused by fire, these structures could have remained globally stable (see Figure 1 and 2).

Based on these initial observations, structural recommendations included the following:

1. Structural designers should consider a robust and redundant design philosophy. Individually, structural elements should be designed to retain sufficient capacity after yielding, and be globally configured to provide multiple load paths after individual element failures.

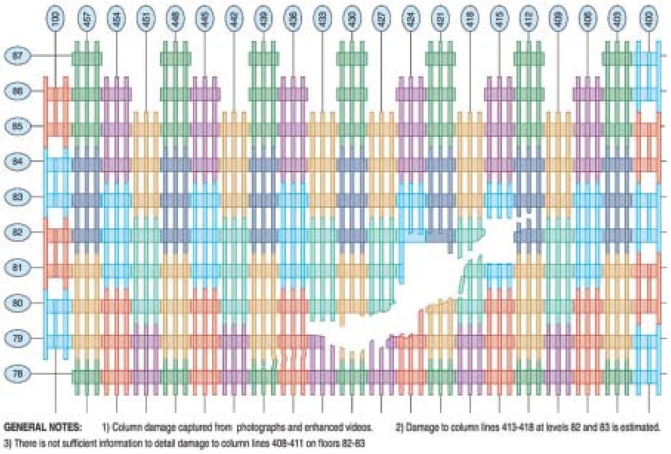

Figure 1. Damage to South Face of WTC 2 © NIST

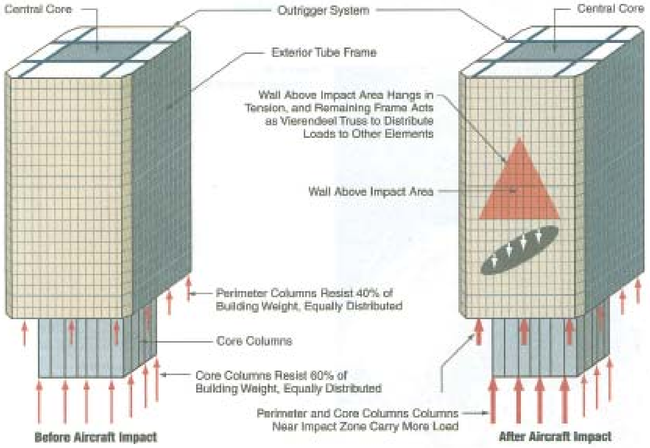

Figure 2. Post-Impact Load Redistribution © NIST

2. Designers should consider fire resistance related to member importance. Elements such as transfer girders, truss elements, and bracing should have increased protection against fire damage commensurate with the consequences of failure.
3. Definitions of credible hazards should be re-evaluated. The world trade center towers "were the first structures outside of the military and nuclear industries whose design considered the impact of a jet airliner, the Boeing 707" (FEMA, 2002. However, these loads fell far short of the extraordinary loads applied by a far larger, faster moving aircraft on September 11. Current geopolitical landscapes and accompanying motivations have raised the standard of credible hazards.

Fire Protection and Fire Suppression

Passive fire protection was provided for many structural elements. Spandrels, columns, and trusses received spray-on application of low-density fireproofing material with a specified fire rating of two or three hours. This material has limited capability to remain adhered to substrate material under deflection, and is not designed to resist abrasion or impact. Active fire suppression would have been provided by standpipes and sprinkler systems that had been retrofitted into the towers.

Sprinkler systems remain operational so long as piping is intact, and adequate water supply is provided. Both active and passive systems were vulnerable to impact damage. Water lines were likely severed, and spray-on fireproofing was stripped away from protected elements by the initial impact. Without adequate and uninterrupted water supply, sprinkler systems were rendered ineffectual, and dislodged fireproofing compromised designed fire ratings. Based on these initial observations, fire protection recommendations included the following:

1. Active fire suppression should be accomplished through the use of redundant systems.
2. To be effective, passive fireproofing must remain adhered after impact or deformation.
3. Passive fireproofing must demonstrate post-event effectiveness.

NIST Recommendations

Following congressional hearings on May 1, 2002, the National Institute of Standards and Technology (NIST), was authorized to produce a comprehensive study to develop recommendations for code changes. This work was completed and many recommendations for changes in the International Building Code have been adopted. Early observations and recommendations centered around three major areas of concern unique to tall buildings: ability to remain globally stable after major damage, durability of fire systems, and adequate access. Subsequent to the publication of their final report, the NIST awarded a contract to the National Institute of Building Sciences (NIBS) to convene a panel of building code experts, and begin implementation of the following NIST recommendations:

1. Prevent progressive collapse by development and nationwide adoption of standards and code provisions, and develop a standard methodology – supported by analytical design tools and practical design.
2. Develop national standards for (1) conducting wind tunnel testing of prototype structures and (2) estimating wind loads and their effects on tall buildings for use in design.
3. Develop criteria to enhance tall building performance by limiting sway under lateral load design conditions (e.g., winds and earthquakes).
4. Evaluate the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings), and explicitly consider factors including:
    - timely access by emergency responders
    - the extent to which redundancy in active fire systems should be credited for occupant life safety ➮

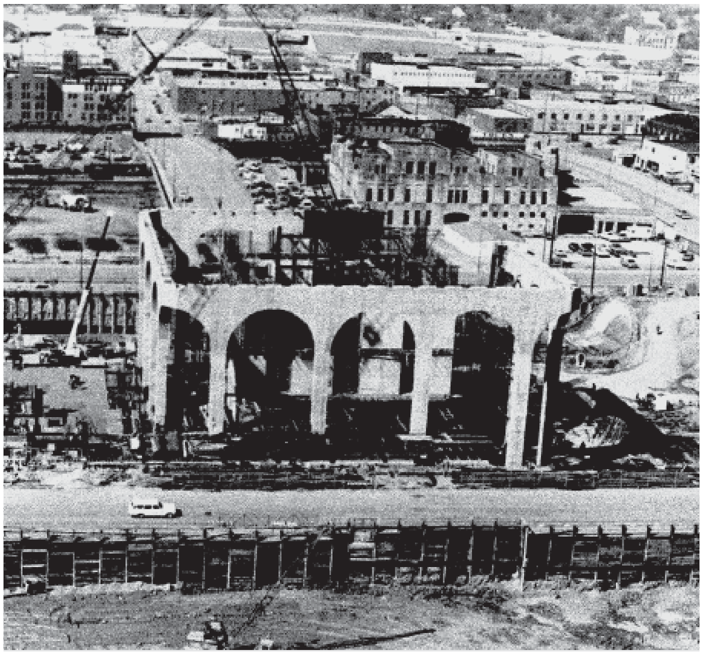

Figure 3. Former WTC Construction Progression © CTBUH Ramsey Collection

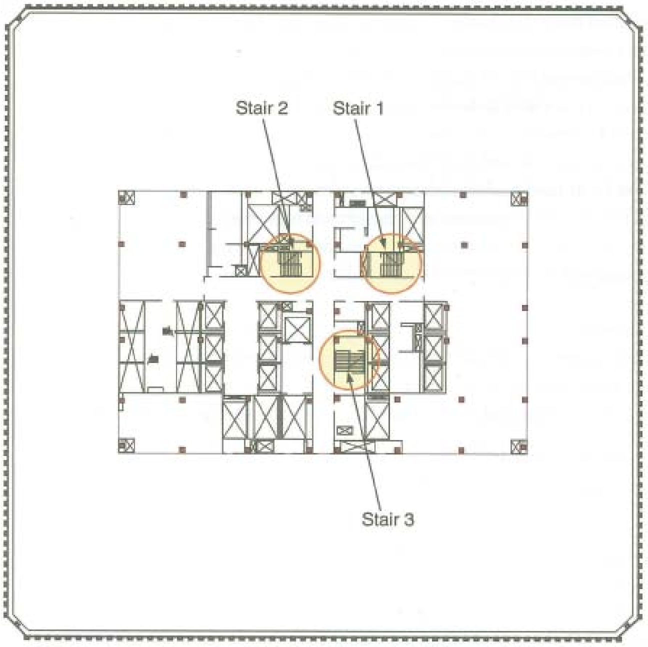

Figure 4. WTC Core Elevator and Stair Layout

- the need for redundancy in fire protection systems that are critical to structural integrity
- the ability of the structure and local floor systems to withstand a maximum credible fire scenario without collapse
- the effect of spaces containing unusually large fuel concentrations
- the extent to which fire control systems should be credited as part of the prevention of fire spread.

5. Establish a capability for studying and testing components, assemblies, and systems under realistic fire and load conditions, and improve the technical basis for the century-old standard for fire resistance testing.
6. Require a performance objective where uncontrolled building fires result in burnout without partial or global collapse.
7. Adopt and use the "structural frame" approach to fire resistance ratings.
8. Develop criteria, test methods, and standards (1) for the in-service performance of sprayed fire-resistive materials and (2) ensure that these materials, as installed, conform to conditions in tests used to establish their fire resistance rating.
9. Develop performance-based standards and code provisions, to enable the design and retrofit of structures to resist real building fire conditions, and methods necessary to evaluate the fire performance of the structure as a whole system.
10. Develop and evaluate new fire-resistive coating materials and technologies with significantly enhanced performance and durability.
11. Evaluate the performance and suitability of advanced structural steel, reinforced and pre-stressed concrete, and other high-performance material systems for use in building fires.
12. Enhance the performance and possibly the redundancy of active fire protection systems to accommodate greater risks associated with increasing building height, including higher threat profile.
13. Develop fire alarm and communications systems to provide continuous, reliable, and accurate information on the status of life safety conditions.
14. Adapt control panels at fire/emergency command stations to accept and interpret a larger quantity of more reliable information from the active fire protection systems
15. Develop (1) real-time off-site secure transmission of valuable information from fire alarm and other monitored building systems for use by emergency responders and (2) preserve information either off-site or in a black box for purposes of subsequent investigations and analysis.
16. Improve building occupants' preparedness for evacuation in case of building emergencies.
17. Design tall buildings to accommodate timely full building evacuation of occupants when required. Stairwell capacity and stair discharge door width should be adequate to accommodate counterflow due to emergency access by responders.
18. Maximize remoteness of egress components (i.e., stairs, elevators, exits) without negatively impacting the average travel distance. Maintain the functional integrity and survivability of egress components in a manner that becomes intuitive to building occupants.

19. Take steps to ensure that accurate emergency information is communicated in a timely manner through better coordination of information among different emergency responder groups.
20. Evaluate current and next generation evacuation technologies, including protected/hardened elevators, exterior escape devices, and stairwell descent devices.
21. Install fire-protected and structurally hardened elevators to improve emergency response activities in tall buildings.
22. Install emergency communications systems effective in buildings with challenging radio frequency propagation environments and able to track emergency responders.
23. Establish procedures for gathering critical information to enhance the situational awareness of emergency responders.
24. Establish and implement codes and protocols which ensure effective and uninterrupted operation of the command and control system for large-scale building emergencies.
25. Certify as-designed and as-built safety systems by a qualified third party, independent of the building owner(s).
26. Enforce available provisions in building codes to ensure that egress and sprinkler requirements are met by existing buildings.
27. Require building owners to retain documents, including supporting calculations and test data, related to building design, construction, maintenance and modifications over the entire life of the building.
28. Clarify the role of the "Design Professional in Responsible Charge" to ensure all appropriate design professionals (e.g., the fire protection engineer) are part of the design team in buildings that employ innovative or unusual structural and fire safety systems.
29. Develop continuing education curricula for training fire protection engineers and architects in structural engineering principles and design, and in modern fire protection principles and technologies.
30. Develop academic and professional short-course training materials in the use of computational fire dynamics and thermo-structural analysis tools.

ICC Code Modifications

The International Code Council (ICC) approved the following code proposals for inclusion in the 2012 Edition of the International Building Code. Committees met to approve these changes between October and November of 2009, and again in May 2010. Code modifications incorporate recommendations from NIST and industry leaders. These changes impact design, construction, egress and fire safety operations.

1. Fire Service Access Elevator: require two fire service elevators servicing every floor above the lowest level of fire department access.
2. Evacuation Plans: require evacuation plans for all occupancies, consistent across all jurisdictions.
3. Fire Command Center: require command centers to include information cards containing critical response information.
4. Elevator Recall: require key operated recall switches for fire service elevators and initiate automatic elevator recall upon fire alarm activation.
5. Water Protection: requirement that all elevator hoistways be kept free of water generated by automatic fire suppression systems.
6. Elevator Lobby Doorways: require doorways serving fire elevator access lobbies have ¾ hour fire ratings.
7. Standpipe Access: require standpipe access to floors without penetrating through elevator access lobbies.
8. Signage: require standardized marking of designated fire service elevators.
9. Passenger Elevator Recall: require key operated recall switches for each elevator.
10. Passenger Elevators: require occupant evacuation elevator activation upon fire alarm activation.
11. Radio Coverage: modify code to ensure full emergency responder radio coverage.
12. Clarified definition of secondary structural members to include roof assemblies not directly connected to building columns.
13. Egress Width: clarification of multiple requirements related to egress width.
14. Automatic Sprinklers: clarification of requirements related to sprinkler installations in elevator spaces.
15. Lobby Enclosure: clarifies requirements related to elevator discharge area protection.
16. Control Wiring: clarifies that only in-car emergency controls require protection.
17. Egress: clarifies egress stair and corridor width requirements, and requires means of emergency voice communication.

Summary

The September 11, 2001 terrorist attacks on the World Trade Center demonstrated how the twin towers reacted to unanticipated extreme loads. Despite the impact of airplanes into each tower at high speed, the towers did not immediately collapse. The time prior to collapse provided most of those below the crash floors time to escape. Even though fire finally caused collapse, the redundancy of the structural systems prevented many additional casualties.

Recommendations from the original Structural Engineering Institute, ASCE and FEMA sponsored report recommended several building code changes. Additional work by NIST and NIBS has resulted in more than 17 code changes.

These code changes will produce buildings that have significantly improved resistance to extreme loads. Although some of the changes will increase costs of tall buildings, the overall increase is expected to be relatively small. ■