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Fire Plays a Devastating Role
World Trade Center building performance study
By Venkatesh Kodur, Ph.D., P.Eng.

The 9/11 terrorist incidents caused colossal destruction and significant damage to a number of buildings in the World Trade Center (WTC) vicinity of New York City (NYC), N.Y. It was the worst building disaster in history resulting in the largest loss of life from building collapse in North America. Following the disaster, the Federal Emergency Management Agency (FEMA), the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), NYC and several other federal agencies and organizations established a team of experts to investigate the collapse and damage to the buildings. The building performance study (BPS) was led by FEMA, SEI and ASCE.

The BPS team consisted of experts in tall buildings, steel structures, connections, fire engineering, blast effects and structural investigations.[1]

The BPS team visited Ground Zero, surveyed the site, landfill and steel recycling centres, reviewed videotape records, eyewitness accounts, conducted interviews with building design teams and performed analyses using computer models. Based on this information, the BPS team compiled a report that was presented to the Science Committee of the U.S. Congress in May 2002.[2] A brief overview of the factors leading to the collapse of the Twin Towers, the extent of damage and some of the key recommendations from the BPS, are presented here.

WTC and the Twin Towers

The Twin Towers, comprising WTC 1 (north tower) and WTC 2 (south tower), were the primary components of the seven-building World Trade Center complex in Manhattan. These towers, built in the late 1960s, were 110 stories above grade and seven stories below grade, making them the world's tallest buildings until the completion of the Sears Tower in Chicago, Ill. in 1973. The floor space at each storey level was about 3,716 sq. m (40,000 sq. ft.) and the Twin Towers provided more than 929,030 sq. m (10 million sq. ft.) of office space in total. The full occupancy of the towers was approximately 50,000 people and the tenants included many prominent multi-national financial service companies.

WTC 1 and WTC 2 were similar buildings, but not identical. Each building had a square floor plate about 63-m (207-ft.) long on each side, chamfered 2 m (7 ft.) at each corner. In the centre of each building, a rectangular service core, measuring 26.5 x 41.8 m (87 x 137 ft.), housed three exit stairways, nearly 100 elevators and 16 escalators. The roof height of WTC 1 was 417 m (1,368 ft.) while the roof height of WTC 2 measured 414.5 m (1,360 ft.).

The WTC buildings were built as a unique structural system known as a 'tube tower': stiff exterior walls and columns with a gravity load-bearing frame at the central core connected by deep spandrel beams to minimize horizontal deflection. The vertical fenestration was the main architectural feature and incorporated a series of closely spaced tubular steel columns spaced 1 m (3.33 ft.) apart. The floor construction typically consisted of 102-mm (4-in.) lightweight concrete fill (127 mm [5 in.] in core area) on a 38-mm (1.5-in.) 22-gauge corrugated metal deck.

Both WTC 1 and WTC 2 buildings were designed to withstand the accidental impact of a Boeing 707 jet aircraft, which was the state-of-the-art aircraft at the time of construction. However, the original design did not account for the fuel carried by such aircraft.[3]

The fire protection features in each of the towers included smoke control, fire detection and notification systems, sprinklers and structural fire protection. Each tower had three emergency fire exit stairways located in the central core. The passive fire protection to structural members followed the requirements of the 1970 NYC building code.[2,4] A combination of different fire protection materials was used to obtain these fire resistance ratings.

Initially, the spray-applied coatings contained asbestos fibre materials up to the 39th floor of WTC 1. However, due to concerns with asbestos-related health hazards, the coating was later abated and the balance of WTC 1 and all of WTC 2 floors were completed using mineral fibre-based products.[4] Providing the required two-hour fire resistance rating for the stairs and elevator shafts were steel-stud walls comprising two layers of 16-mm (0.63-in.) type-X gypsum board (wallboard with heat-resistant and non-combustible materials added to its core) on the exterior face, and one layer of 16-mm (0.625-in.) type X gypsum wallboard on the interior face.

The incident

On September 11, 2001, American Airlines Flight 11, en route from Boston, Mass. to Los Angeles, Calif. was hijacked and crashed into WTC's north tower at 8:46 a.m. Shortly thereafter, a second hijacked plane, United Airlines Flight 175, crashed into the south tower. The first aircraft, a Boeing 767-200ER, struck the center of the north face between the 92nd and 96th floors, while the second aircraft, also a Boeing 767-200ER, struck the corner of the south and east faces of WTC 2 between the 78th and 84th floors.

The massive impacts from each of the aircraft resulted in severe structural damage on several floors in each tower. The planes penetrated the central core causing considerable damage to columns. Up to half of Tower One's columns along the north building face appear to have been destroyed over portions of a six-storey range. Partial collapse of floors at the impacted levels occurred in both towers.

The structures remained standing, at least initially, despite this heavy but localized damage. Immediately after the impact, jet fuel ignited on several floors. The intense fires further weakened the damaged structure, resulting in the partial collapse of the floors with the worst fire conditions. This vertical impact load caused the collapse of underlying multi-floor segments of the tower, with the failure of the floor-carrying trusses' connections accompanied by buckling of core columns or overall buckling of the framed tube, probably spanning the height of many floors. The load started a progressive collapse resulting in the complete collapse of the towers.

The Twin Towers withstood the impact, despite significant damage, due to a highly redundant structural system and low utilization ratio (ratio of applied stress to ultimate stress) in the exterior columns. Based on the preliminary analysis,[2] in the absence of a severe loading event, the Twin Towers could have remained standing in a damaged state until subjected to significant additional load. However, the severe fires brought down

WTC 2 and WTC 1 at 59 and 89 minutes, respectively. The early collapse of WTC 2, as compared to WTC 1, could be attributed to some of the following factors:
● Larger structural damage due to the fact that the impact of the jet was on the corner of the south and east faces.
● Higher speed of the aircraft (about 949 km/h [590 mph]) at the time of impact.
● Some differences in structural fire protection at the level of the impacted floors.[2]

Damage assessment

As the towers collapsed, massive debris clouds consisting of crushed and broken building components fell onto and blew into surrounding structures, causing extensive collateral damage. Two prominent buildings in the WTC complex, WTC 3, a 22-storey steel-framed building housing a Marriott Hotel, and WTC 7, a 47-storey steel-framed office building fully collapsed on that day. While the WTC 3 collapse was predominantly due to falling debris, WTC 7 collapsed entirely due to fire after burning for seven hours. This was the first ever steel-framed building to have experienced a fire-induced collapse. In addition, St. Nicholas Greek Orthodox Church just south of WTC 2 was completely destroyed by falling debris.

The remaining three buildings in the complex, WTC 4, 5 and 6, suffered partial collapse and were deemed beyond repair. Fire played a major role in the collapse or damage of these buildings with fire-induced connection failures being the main factor in the partial collapse of WTC 5. The Winter Garden building experienced severe damage after massive quantities of debris fell on it.

Another nine major buildings in the area experienced partial local collapse or major structural failure as a result of this incident. The most affected buildings included 90 West Street, the Bankers Trust building, World Financial Center 3, the Verizon building, 30 West Broadway and 130 Cedar Street. Many of the affected buildings suffered structural damage, but arrested collapse to localized areas. The performance of these buildings demonstrates the inherent ability of redundant steel-framed structures to withstand extensive damage from earthquakes, blasts and other extreme events without progressive collapse.

About 18 major buildings experienced minor damage (broken glass, ceiling damage, etc.), and the city had to inspect about 400 buildings for safety issues. Approximately 2.8 million-sq. m (30 million-sq. ft.) of commercial office space was removed from service either temporarily or permanently. An estimated 1.1 million-sq. m (12 million-sq. ft.) of this space was from buildings housed in the WTC complex.

A total of 2,830 people lost their lives that day, and 880 were injured. Most of the deaths were occupants in the Twin Towers at or above the level of impact.

Key issues

The BPS team, as part of the WTC investigation, has identified a number of issues arising from the disaster. These issues were compiled based on the observed building performance of the Twin Towers and other damaged buildings in the vicinity of the site, and are applicable for buildings under extreme events. Many of these concerns require further research before making any general recommendations.

Aircraft impact
The team deliberated on the question of whether building codes should be changed in some way to make future buildings more resistant to incidents such as aircraft impact. The FEMA report concludes there is insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes.
On September 11, the Twin Towers and surrounding buildings were subjected to extreme events. Further, the level of impact, as well as the ensuing fires, depends on the size of the aircraft. Therefore, it may not be technically feasible to develop design provisions enabling all structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design practically impossible.

Redundancy and robustness
The Twin Towers withstood the impact, despite significant damage, due to a highly redundant structural system, enabling the towers to redistribute loads to the remaining structural elements and overcome immediate collapse. The BPS team recommends structural framing systems have redundancy and robustness, so that alternative paths or additional capacity are available for transmitting loads when building damage occurs. Also, connections play a major role under extreme conditions in transferring loads from one element to another. The performance of connections under impact loads and during fire loads needs to be analytically understood and quantified for improved capabilities.

Fireproofing
In steel-framed buildings, some kind of fireproof material—such as gypsum board or a spray-on material—is usually wrapped around structural members.[5] Normally, this fireproofing would have protected the steel frame from the heat for a longer period of time. A large impact, such as the one on the towers, can knock off the fireproofing. In the FEMA report, the BPA team recommends testing fireproofing for durability (adhesion and cohesion when exposed to abrasion, shock, vibration, rapid temperature rise and high temperature exposures). This is to ensure fireproofing adheres to steel members under impact and fire conditions to provide the intended protection. (At present, there is a lack of guidelines and standards for evaluating the performance of fireproofing.)

Active fire protection
The sprinklers were ineffective in WTC 1 and WTC 2, as well as in surrounding buildings, due to massive fires and possibly damaged water supply. The team recommends a reliable and redundant water supply for sprinklers.

Egress systems
Most of the casualties occurred in the Twin Towers at the stories at or above the level of impact. One of the main reasons was possible damage to the egress systems. The towers each had three staircases, although building codes required only two. However, the stairs were located in the central core of the structures, which is where most of the damage

occurred. When these staircases were damaged, people above the impact floors could not escape. The BPS team recommends evaluating current egress systems in existing buildings for redundancy and robustness to provide safe exit when building damage occurs. For example, staircases could be strengthened (to withstand an impact), widened and placed in various locations throughout a building.

Fire-structure interaction

The present approach of fire resistance evaluation is prescriptive, not realistic, and has some drawbacks.[6] A better approach is to predict a structural system's performance under realistic fire conditions, but it requires the development of tools for designing structural systems in fire scenarios.[7] Also, connection performance under fire scenarios needs to be analytically understood and quantified as critical components in structural frames.

Interaction of professions

Various professions—structural, fire protection, mechanical, architectural, blast, explosion, earthquake and wind engineering communities—need to work together to develop guidelines for vulnerability assessment, retrofit and the design of concrete and steel structures to reduce the probability of progressive collapse under single- and multiple-hazard scenarios.

[AUTHOR BIOGRAPHY]

Venkatesh Kodur, Ph.D., P.Eng., is a scientist and senior research officer at the National Research Council (NRC) of Canada in Ottawa, Ont. He is a world expert in fire resistance and the effect of fire on building materials. His expertise includes evaluating the fire resistance of structural members and non-linear design and analysis of structures. He is an adjunct professor at Queen's University, chairman of the ASCE Committee on Structural Fire Protection, member of the American Concrete Institute (ACI) Fire Resistance Standards and Canadian Standards Association (CSA) Committee on Fibre-Reinforced Polymer (FRP) Structural Components for Buildings. Kodur can be reached at (613) 993-9729.

Acknowledgement

The primary technical source for the preparation of this paper is FEMA Report 403 *World Trade Center Building Performance Study*. The author acknowledges the contributions of fellow BPS members.

Notes

1. The author was the only member from outside of the United States invited to join the team.

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6. Wang, Y.C. and Kodur, V.R., "Research Toward the use of Unprotected Steel Structures," *ASCE Journal of Structural Engineering*, 126(12), 1442-1450, 2000.
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[SIDEBAR A]

Damage to the WTC and surrounding buildings

Significant damage occurred in the seven buildings of the WTC complex and to a number of high-rise buildings around the WTC (within a radius of about one kilometre):

- Four buildings (Towers 1 and 2, Buildings 3 and 7 of the WTC) completely collapsed
- Four buildings around the towers partially collapsed (beyond repair)
- Nine buildings incurred major structural damage
- 18 other buildings experienced minor damage
- 400 high-rise buildings required full structural assessment

[SIDEBAR B]

The building performance study team represents a coalition of leading engineering organizations brought together and led by ASCE and FEMA, including the American Institute of Steel Construction Inc. (AISC), American Concrete Institute (ACI), Council on Tall Buildings and Urban Habitat (CTBUH), International Code Council (ICC), NFPA, Society of Fire Protection Engineers (SFPE), Structural Engineers Association of New York (SEAoNY), The Masonry Society (TMS), National Council of Structural Engineers Associations (NCSEA), Structural Engineering Institute (SEI) of ASCE and New York Department of Design and Construction (DDC).