The World Trade Center collapse and its implications for International Standards

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Following the September 11, 2001, attacks on New York City's World Trade Center (WTC), a team of civil, structural, and fire protection engineers was deployed to study the performance of buildings at the site. This article, drawn from the team's preliminary report[1)], presents some of the study's findings and the implications these may have for International Standards development.

World Trade Center Towers (WTC 1 and WTC 2)

The structural design of the two main towers consisted of closely spaced 1016 mm exterior columns connected to each other with deep spandrel plates. The columns and spandrel plates were prefabricated into panels that together formed a load-bearing tube, stiff both laterally and vertically. Interior cores, formed by larger, more widely spaced steel columns, housed elevator shafts and stairwells. Floor slabs were light-weight concrete over steel decking, supported by a robust and redundant system of trusses.

Fire development

The aircraft that struck the twin towers each carried about 37 850 liters of fuel at the time of impact. As no flame was evident immediately upon impact, the fuel likely was distributed in a flammable cloud throughout the impact area. Its ignition caused a rapid rise in pressure, then the expulsion of fireballs into shafts and through openings.

KEYSTONE/AP Photo/Aurora/Robert Clark

These fireballs did not explode or generate a shock wave, and thus did not in themselves cause structural damage. Calculations show they did, however, burn 3785 to 11 360 liters of jet fuel quickly. The remaining fuel appears to have burned off within minutes, generating enough heat to ignite virtually all the combustible materials on the impacted floors and within the planes.

Computer modelling suggests that the fire energy output for each tower peaked at 3-5 trillion BTU/hr (1-1.5 gigawatts) – similar to the power output of a commercial generating station. Temperatures reached as high as 1100 °C (2000 °F) in some areas, and 800 °C (1500 °F) in others. Air to support the fire was supplied mainly through openings torn in the building by aircraft impact and fireballs.

"The fire that weakened structural members and connections eventually brought down the towers."

Structural response to fire loading

Aircraft impact degraded the strength of the structure and its ability to withstand additional loading. Although the specific steps are uncertain, the following fire effects likely contributed:

- Impact force, fireballs, and debris compromised spray-applied fire protection on structural members.
- Loads transferred from damaged structural elements put columns under elevated stresses.
- Debris that fell through partially collapsed floor areas increased loads on floor framing.
- Fire-heated floor framing and slabs expanded, developing additional stresses. Resulting stress that exceeded the capacity of some members or connections could have initiated a series of failures.
- Increased temperatures may have caused floor slabs and support framing to lose rigidity and sag. This could have caused end connections to fail and allow supported floors to collapse onto the floors below.

1) Corley, W.G., et al., "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations," *Federal Emergency Management Agency Mitigation Directorate*, FEMA 403, Washington, D.C., May 2002.

- Increased temperature of column steel would reduce the columns' yield strength, modulus of elasticity and critical buckling strength, potentially initiating buckling. This most likely affected the failure of the interior core columns.

Progression of collapse

Once the collapse began, potential energy stored in the upper part of the structure during construction was rapidly converted into kinetic energy. Collapsing floors above accelerated and impacted on the floors below, causing an immediate, progressive series of floor failures, each punching in turn onto the floor below. The process of collapse was essentially the same for both towers 1 and 2.

WTC 7, a 47-story office building that was part of the WTC complex, collapsed at 17:20 on September 11, 2001, causing no known casualties. The performance of WTC 7 is significant, because the collapse appears to be due primarily to fire, rather than any impact damage from the collapsing towers. Before this event, the fire-induced collapse of large, fire-protected steel buildings was virtually unknown.

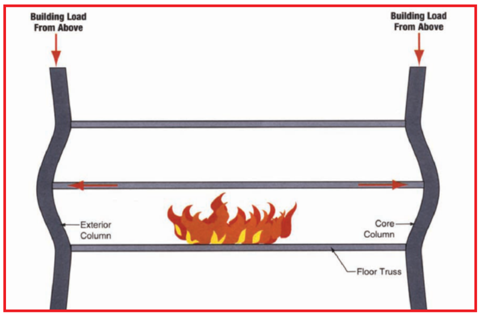
Little is known about the ignition and development of the fires, but they are presumed to have started from burning debris. Smoke appeared at several locations in the building soon after WTC 1 collapsed.

Probable collapse sequence

The collapse began on the east side of WTC 7 on the interior, as the east penthouse disappeared into the building. Next, the west penthouse disappeared, and a fault or "kink" developed on the east half of WTC 7. The collapse then began at the lower floor levels, and the building completely collapsed to the ground. Collapse appears to have begun inside at the lower levels and progressed up, as the fault extended from the lower levels to the top.

The findings: more from fire than from impact effects

- The towers survived the impact of the aircraft.
- The fire that weakened structural members and connections eventually brought down the towers.
- The redundancy and robustness of the structural system helped keep the towers standing.
- Transfer trusses like those in WTC 7 need special consideration.
- The fire resistance of connections is important and needs further study to predict their behaviour under overload conditions.
- Relate fire-protection measures to potential fire loads.
- Consider potential impact in the placement and design of exit stairways.



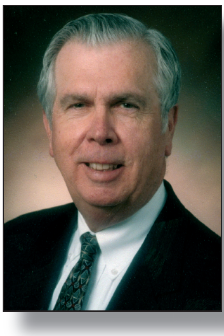
Expansion of floor slabs and framing results in outward deflection of columns and potential overload.

WTC and International Standards

The knowledge that the collapse of WTC buildings resulted more from fire than from impact effects on structural members points up the importance of examining and improving fire safety standards. Standards that apply to construction materials, to structural components, and to design features such as exit stairways need to be reevaluated. They also should be international in scope. The World Trade Center was advanced for its time, in that most of its structural steel was manufactured in Japan, then fabricated into structural members in the USA. All work was done to very high standards.

Today, almost 40 years later, global distribution of construction materials is common. Building owners and occupants throughout the world need assurance that materials conform to high standards of quality and safety, regardless of where they are produced.

About the author



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