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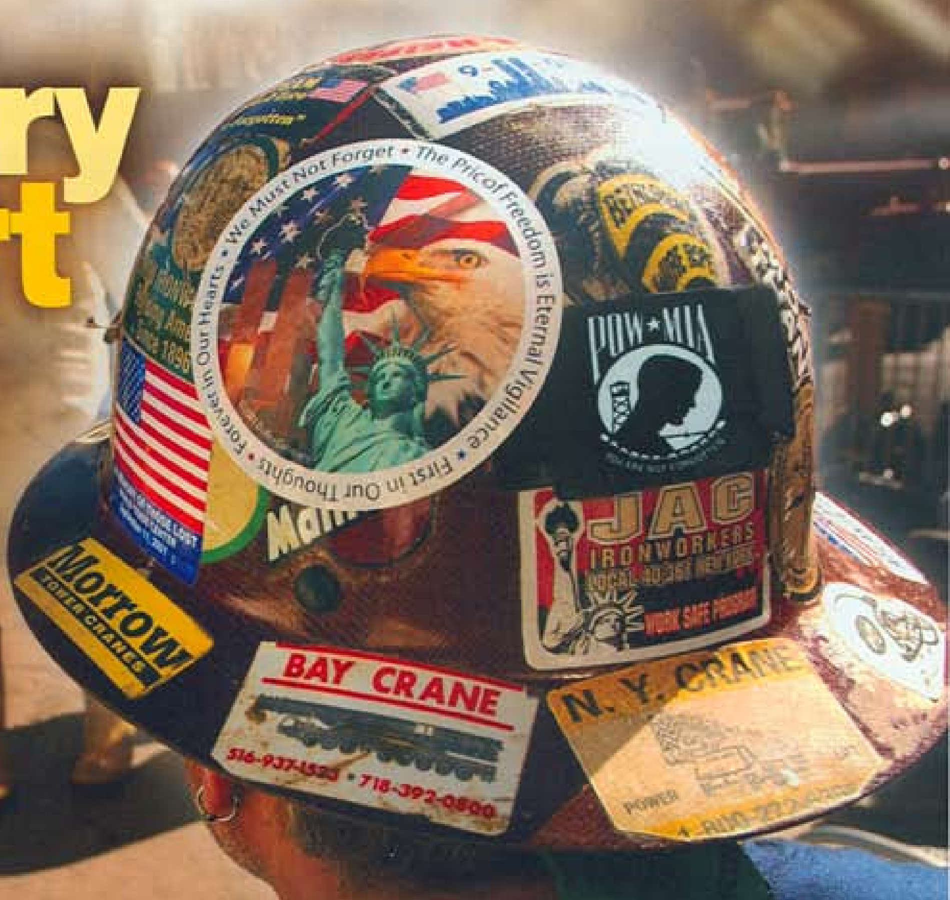

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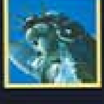

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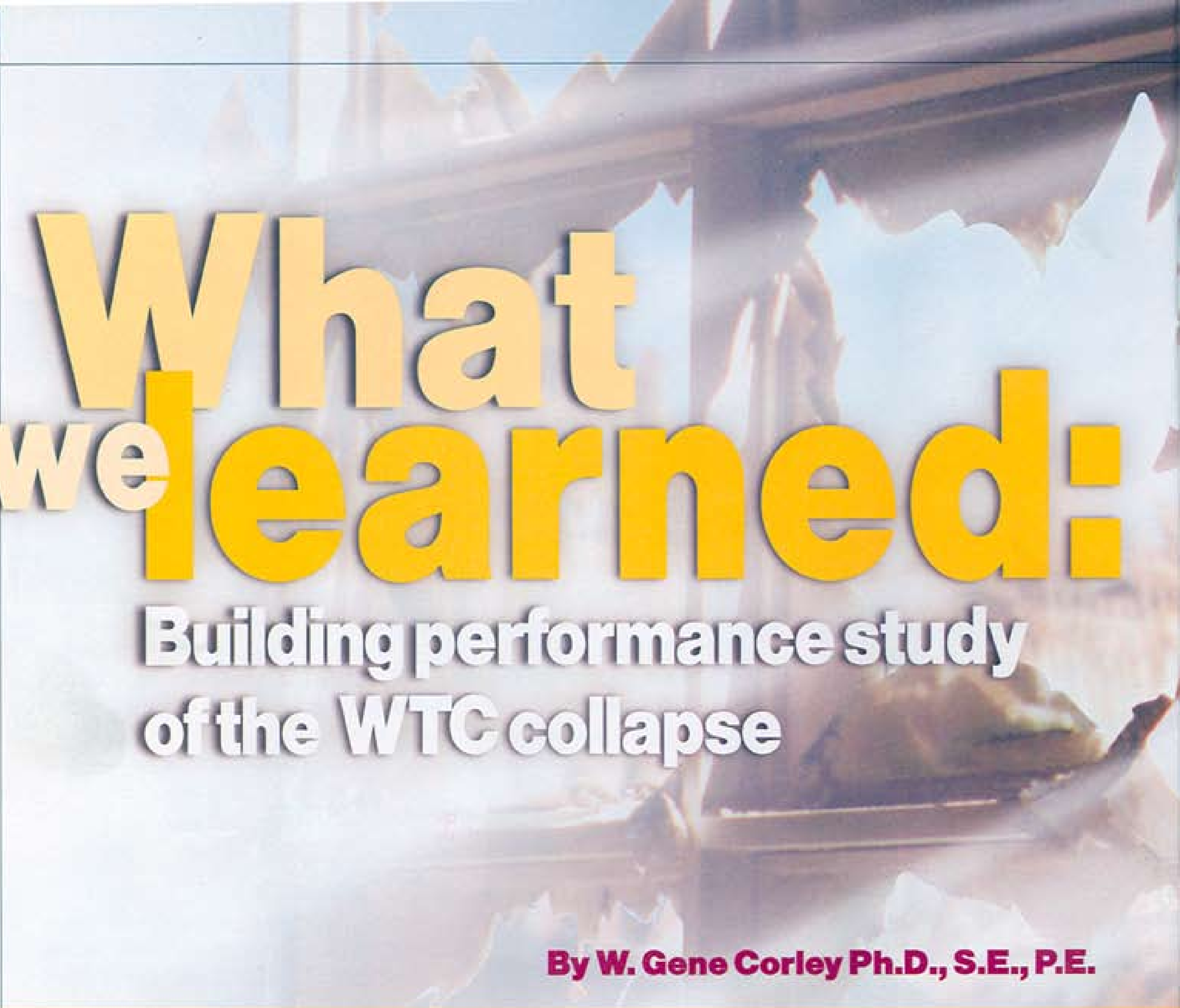

What we learned: Building performance study of the WTC collapse

By W. Gene Corley Ph.D., S.E., P.E.

Following the Sept. 11, attacks on the World Trade Center (WTC), the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), in association with New York City and several other federal/state agencies and professional organizations, deployed a team of 23 civil, structural, and fire protection engineers to study the performance of buildings at the WTC site. The team's efforts were sponsored by SEI/ASCE and FEMA.

This article, drawn from the team's preliminary report, "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations," written by William Baker, Jonathan Barnet, Ronald Hamburger, James Milke, and me, presents some of the study's more significant findings, the conclusions one can draw from them, and the issues most in need of further investigation.

WTC Towers

Structural design —The structural design of the two main towers consisted of 60, closely spaced (3 feet-4 inches o.c.) exterior columns connected to each other with deep spandrel plates. The columns and spandrel plates were prefabricated into panels that were three columns wide by three stories high. The columns and spandrel plates formed a load-bearing tube that was stiff, both laterally and vertically. Interior cores, formed by larger, more widely spaced steel columns, housed elevator shafts and stairwells. The floor slabs — lightweight concrete over steel decking — were supported by a robust and redundant system of trusses. Double trusses spanned between the exterior wall spandrel plates and interior core columns. Transverse trusses and intermediate angles also helped support floor decking.

Damage from aircraft impact — Flying at about 470 mph, American Airlines Flight 11 struck the north face of World Trade Center Tower 1 (WTC 1) between the 94^{th} and 98^{th} floors. At the central zone of impact, at least five of the prefabricated wall sections were torn loose, and some others were pushed inside the tower, which experienced partial floor collapse where exterior wall supports were knocked out.

Additional damage occurred where the jet's wings hit the wall, with 31 to 36 columns destroyed over a four-story range (see Figure 1). This damage lead to partial floor collapse over a horizontal length of about 65 feet. Some damage to steel framing at the center core also was apparent. Eyewitnesses described evidence of partial floor collapse inside the building, including areas on the 91^{st} floor that were blocked by debris from higher floors (see Figure 2).

Flying at about 590 mph, United Airlines

Flight 175 struck World Trade Center Tower 2 (WTC 2) near its southeast corner. The tower was hit about 20 stories lower than the impact zone of WTC 1, so considerably more weight was above the impact zone. Because the core of the WTC 2 was only 35 feet from the building perimeter, the plane also struck closer to the core columns. Therefore, the impact likely caused more damage to the core at WTC 2 than at WTC 1.

Fire development — Each aircraft carried about 10,000 gallons of fuel at the time of collision. Because no flame was evident immediately upon impact, it is likely that the fuel was distributed in a flammable cloud over the impact area. Ignition of the fuel caused a rapid rise in pressure, followed by the expulsion of relatively slow-building fireballs into shafts and through openings.

These fireballs did not explode or generate a shock wave, thus, they did not in themselves cause structural damage. Calculations indicate that the fireballs did, however, burn 1,000 to 3,000 gallons of jet fuel quickly. The remaining fuel appears to have burned off within the first few minutes, generating enough heat to ignite virtually all combustible materials on the impacted floors and within the planes.

Computer modeling suggests that the fire energy output for each tower peaked at 3 to 5 trillion BTU per hour (1 to 1.5 gigawatts) — similar to the power output of a commercial generating station. Temperatures reached as high as 900 to 1,100 degrees Celsius (1,700 to 2,000 degrees Fahrenheit) in some areas and 400 to 800 degrees Celsius (800 to 1,500 degrees Fahrenheit) in others. Air to support the fire was supplied mainly through openings torn in the building by aircraft impact and fireballs. An estimated area of 14,639 square feet was open on floors 92 through 98 of WTC 1.

Evacuation — Overall, the success rate of

Summary of findings

- Both towers survived the impact of the aircraft.
- Fire that weakened structural members and connections eventually brought down the towers.
- Redundancy and robustness of the structural system helped keep the towers standing.
- Transfer trusses need special consideration.
- Fire resistance of connections is important. Further study is needed to predict behavior of connections under conditions that can develop in a burnout.
- Fire-protection measures need to be related to potential fire loads.
- In buildings that may be subject to impact, placement and design of exit stairways should provide a physical separation of egress alternatives.

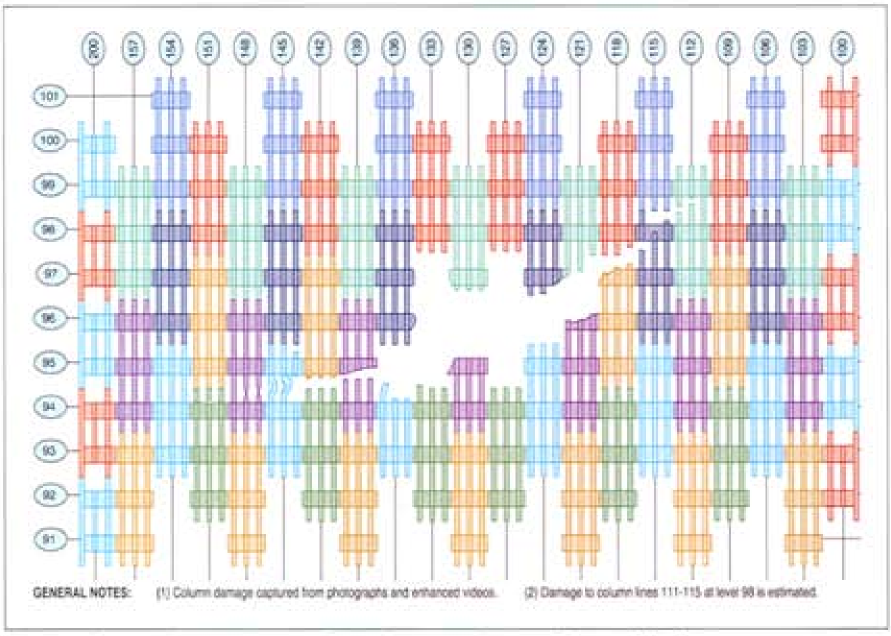

Figure 1: Impact damage to exterior columns on the north face of WTC 1.

the evacuation was as high as is thought possible under the circumstances, with 99 perent of people who were located below the point of impact in each building surviving. As soon as WTC 2 was hit, authorities ordered the evacuation of WTC 1 below the point of impact. Many people began evacuating WTC 2 immediately after WTC 1 was hit.

Steps taken after the WTC bombing in 1993, including the addition of emergency lighting and luminescent paint in stairways, and safety training of building occupants, are believed to have improved the effectiveness of the evacuation.

Structural response to fire loading — Aircraft impact degraded the strength of the structures and their ability to withstand additional loading. Although it is impossible to determine precisely the steps that led to the collapse of the towers, the following fire effects likely were contributing factors:

- Impact force, fireballs, and the field of debris probably compromised spray-applied fire protection on structural members.
- As the temperature of column steel rises, the columns' yield strength, modulus of elasticity, and critical buckling strength decrease, potentially initiating buckling even if lateral support is maintained. A similar scenario might have occurred, which most likely would have affected the collapse of the interior core columns
- Loads transferred from destroyed and damaged structural elements put remaining columns under elevated stresses.
- Debris that fell through partially collapsed floor areas imposed heavier loads on remaining floor framing.
- As the fire heated floor framing and slabs, those structural elements expanded and potentially developed major additional stresses in some elements. If the resulting stress state exceeded the capacity of some members or their connections, it could have initiated a series of failures (see Figure 3).
- As the temperature of floor slabs and support framing increased, these elements may have lost rigidity and sagged. Then, the horizontal framing elements and floor slabs could have become tensile elements; this effect could have caused end connections to fail and allowed supported floors to collapse onto the floors below.

Progression of collapse — Once collapse began, potential energy stored in the upper part of the structure was converted rapidly 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 collapse of the floors left tall, freestanding portions of the exterior wall. As the unsupported height of these freestanding exterior wall elements increased, they buckled at the bolted column splice connections and also collapsed. The process of collapse was essentially the same for both towers.

WTC Building 5

Two nine-story and one eight-story steel-framed office buildings (WTC 4, WTC 5, and WTC 6) were located on the north and east sides of the WTC Plaza (see Figure 4). When the first two towers collapsed, all three were subjected to severe impact damage as well as fires that developed from the flaming debris. Most of WTC 4 collapsed when the exterior column debris from WTC 2 hit it; the remaining section had a complete burnout. Debris from WTC 1 impacted both WTC 5 and WTC 6, causing large sections of localized collapse and subsequent fires. All three buildings resisted

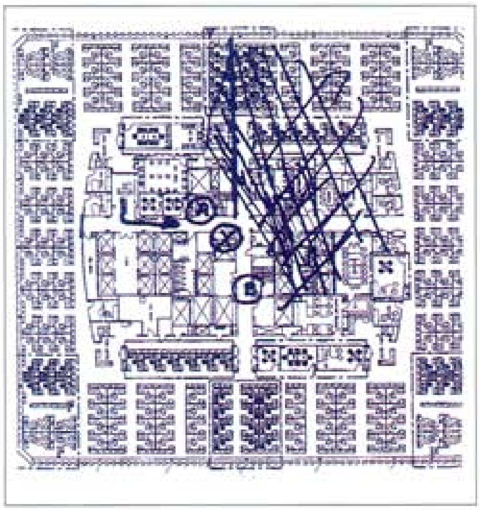

Figure 2: (Right) This sketch, made during survivor interviews, shows approximate debris location on the 91st floor of WTC 1.

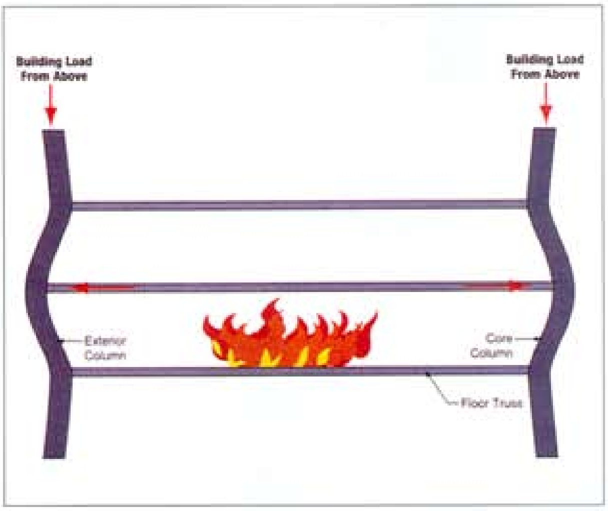

Figure 3: (Far right) Expansion of floor slabs and framing results in outward deflection of columns and potential overload.

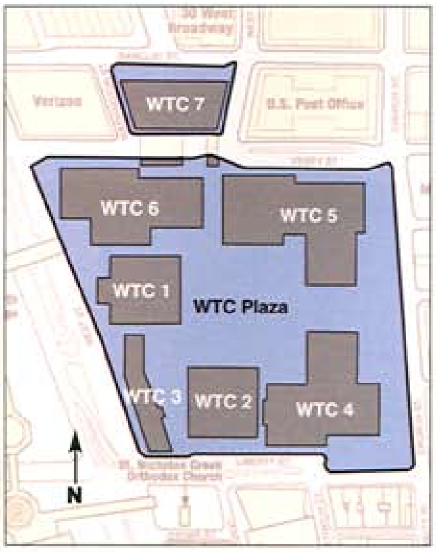

Figure 4: Site plan of the WTC complex.

progressive collapse, however, in spite of the extensive local collapses.

Additionally, all three buildings had similar design features, though somewhat different configurations. Most site observations were made in WTC 5, however, so the following discussion focuses primarily on that building, but is assumed to apply to all three.

Structural design — Each 120,000-square-foot floor was constructed of four-inch-thick, lightweight concrete fill on metal deck, supported by structural steel framing. Wide-flange structural columns were placed on a regular, 30-foot-square grid pattern. The floor plates cantilevered out 15 feet from the exterior column lines on all sides.

A pair of wide-flange beams at each column line supported this cantilever and provided lateral resistance for the structure. At interior column lines, a column-tree system was used, with a four-foot-long stub shop-welded to the column on each side, and the floor girder simply connected with shear tabs to the cantilevers.

Impact and fire damage — Damage from the impact of falling debris was severe, causing localized collapses from the roof to the third floor. Fires ignited by burning debris caused a localized collapse from the fourth to the ninth floor.

Local collapse mechanisms — Two areas in WTC 5 experienced local collapse under an intact portion of the roof. Although there was debris impact near this area, the symmetry of the collapse suggests that uncontrolled fires caused these failures. Columns in this area remained straight and freestanding — an observation that lends support to this theory (see Figure 5). Local collapse appears to have begun at the field connection where beams were connected to shop-fabricated beam stubs and column assemblies.

It seems that the structural collapse resulted from excessive shear loads on bolted connections and unanticipated tensile forces resulting from the beams' catenary sagging. High shear loads, probably attributable to collapsing floor loads above, were evident in many of the column-tree beam stub cantilevers.

Apparently, fire also weakened the steel, which contributed to large shear-induced deformations in several of the cantilever beams. The shear failures observed at connection ends in several of the beam web samples suggest the magnitude of tensile forces that developed.

Steel framing connection samples recovered from floors six, seven, and eight of WTC 5 indicate that the deformed structure subjected the bolted shear connection to a large tensile force. At 550 degrees Celsius (1,022 degrees Fahrenheit), the ultimate resistance of the three bolts is about 45 kips. The capacity increases to about 90 kips at room temperature, so the connection failure probably occurred between these bounds.

On the lower floors, the steel beams showed heat damage from direct fire exposure. There was little or no evidence of shop painting, indicating that fireproofing material was either missing before the fire or delaminated early in the fire exposure.

Additionally, it was determined that the automatic sprinkler system did not control the fires. Some sprinkler heads fused, but there was no evidence of significant water damage; there was no water in the sprinkler system. These findings are consistent with the lack of water damage in the bookstore on the lower level and the burnout of the upper floors.

WTC Building 7

World Trade Center Building 7, a 47-story office building completed in 1987, collapsed at 5:20 p.m. on Sept. 11, causing no known casualties. The performance of WTC 7 is interesting, because the collapse appears to be due primarily to fire, rather than impact damage from the collapsing towers. Before this event, the fire-induced collapse of large, fire-protected steel buildings was unknown.

Thus far, little has been discovered 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 early in the afternoon.

Figure 5: Internal collapsed areas in WTC 5.

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

Fires may have exposed structural elements (most likely transfer trusses between floors five and seven) to high temperatures over a period of time long enough to reduce their strength to the point of causing collapse. If the collapse began at these transfer trusses, it would explain why the building imploded and produced a limited debris field as the exterior walls were pulled downward. The collapse then may have spread to the west. At that point, the building would likely have had extensive interior structural failures that led to its overall collapse.

Conclusion

From the study of the WTC towers and the buildings damaged by falling debris and fire, several observed building performance issues were found to be critical in one or more of the structures. These issues fall into several broad topics that should be considered for buildings being evaluated or designed for extreme events. See the sidebar "More to learn: Significant findings from the WTC investigation" on Page 31 for more about these topics. Perhaps some of these issues should be considered for all buildings; however, additional studies are required before general recommendations, if any, can be made. ■

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