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STRUCTURAL INVESTIGATION OF THE NEW YORK WORLD TRADE CENTER COLLAPSE

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Abstract

This paper presents some findings of the FEMA- and SEA/AISC-sponsored investigation into the structural performance of New York's World Trade Center following the attacks of September 11, 2001. The structures' collapse was caused not by aircraft impact alone, but by the combination of impact and the resulting fire that weakened structural members and connections. The preliminary report calls for further study in a number of areas.

Keywords: Structural performance, World Trade Center, Fire damage, Collapse, Aircraft impact

1. Introduction

Following the September 11, 2001, attacks on New York City's 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 agencies and professional organizations, deployed a team of civil, structural, and fire protection engineers to study the performance of buildings at the WTC site. This paper, drawn from the team's preliminary report(1), presents some of the study's more significant findings, the conclusions one can draw from them, and the areas most in need of further investigation.

2. World Trade Center Investigation

FEMA and ASCE began discussing site studies and teams on September 23, as engineers and emergency management agencies all over the nation rallied to provide support. A number of the team members were at the site immediately after the attacks to assist as needed.

As soon as the rescue operations were halted and the FEMA Urban Search and Rescue teams left the site, the BPS Team mobilized to the WTC site and conducted field observations during the week of October 7, 2001. While in New York, the team inspected and photographed the site and individual building conditions, visited the salvage yards receiving steel from the collapsed buildings, attended presentations by design professionals associated with WTC buildings, and reviewed available building drawings.

Upon completion of the site visit, the team members continued to collect extensive information and data, including photographs, video footage, and emergency response radio communications; continued surveillance of steel delivered to the recycling yards with the support of SEAoNY volunteers; and conducted additional interviews with direct witnesses of the events as well as participants in the original building design, construction, and maintenance. This information led to the development of a timeline of building loading events and allowed an initial engineering assessment of building performance. The study focus was to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events.

The Team conducted field observations at the WTC site and steel salvage yards, removed and tested samples of the collapsed structures, viewed hundreds of hours of video and thousands of still photographs, conducted interviews with witnesses and persons involved in the design, construction, and maintenance of each of the affected buildings, reviewed construction documents, and conducted preliminary analyses of the damage to the WTC towers.

2.1 World Trade Center Towers (WTC1 and WTC2)

Structural design of the two main towers consisted of closely spaced (3 ft 4 in. o.c.) exterior columns connected to each other with deep spandrel plates. The columns and spandrel plates were prefabricated into panels, each three columns wide by three stories high. The columns and spandrel plates 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 lightweight concrete over steel decking, supported by a robust and redundant system of trusses. Double trusses spanned between the exterior wall spandrel plates and interior core columns (Fig. 1). Transverse trusses and intermediate angles also helped support floor decking.

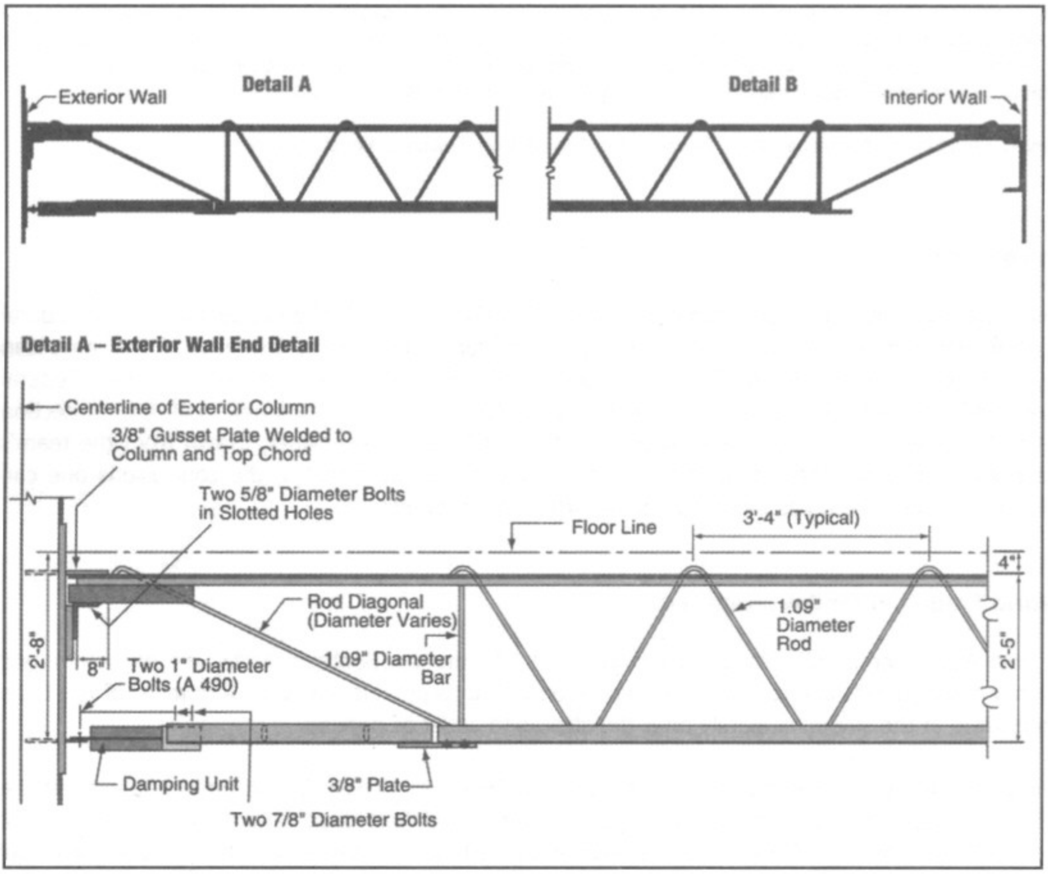

Fig. 1. Floor truss member with exterior wall end detail

2.1.1. Damage from Aircraft Impact

Flying at about 470 mph, the first aircraft struck the north face of WTC1 between the 94th and 98th 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 experienced partial floor collapse where exterior wall supports were knocked out.

There was additional damage where the jet's wings hit the wall, with 31 to 36 columns destroyed over a four-story range (Figs. 2 and 3), leading to partial floor collapse over a horizontal length of about 65 ft. Some damage to steel framing at the center core also was apparent. Eyewitnesses described evidence of partial floor collapse closer to the building interior, including areas on the 91st floor that were blocked by debris from higher floors.

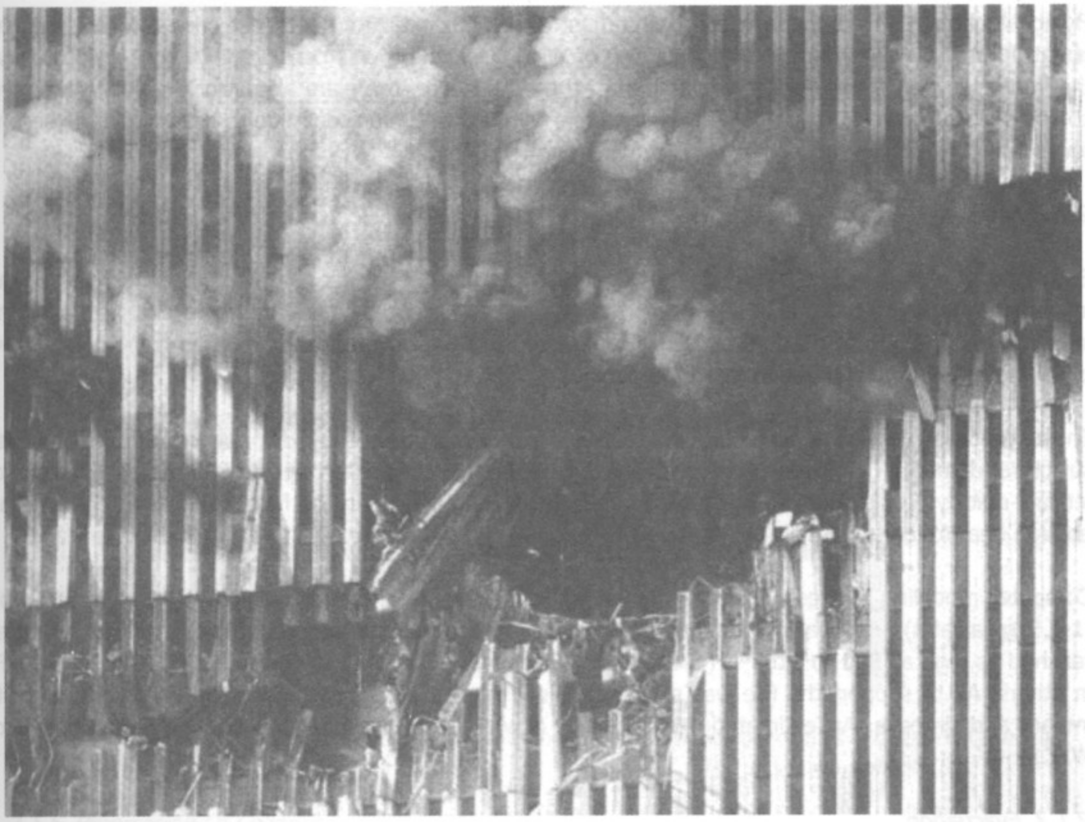

Fig. 2. Impact damage to the north face of WTC1

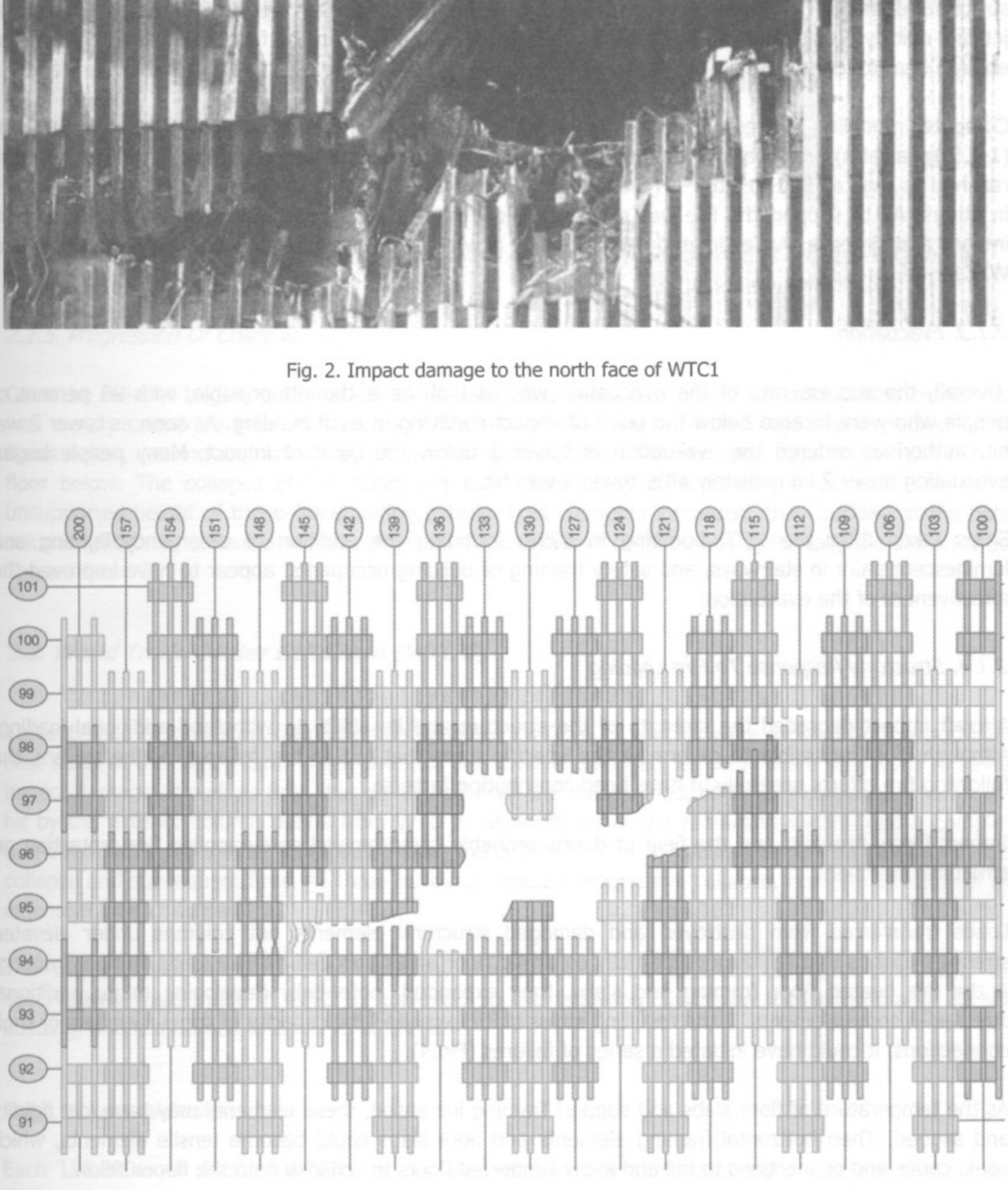

Fig. 3. Impact damage to exterior columns on the north face of WTC1

Flying at about 590 mph, the second aircraft struck WTC2 near its southeast corner. WTC2 was hit about 20 stories lower than the impact zone of WTC 1, so there was considerably more weight above the impact zone. Because of the orientation of the WTC2 core, the plane also struck closer to the core columns (only about 35 ft), so it likely caused more impact and more damage to the core in the second tower.

2.1.2. Fire Development

Each aircraft carried about 10,000 gallons of fuel at the time of impact. Because no flame was evident immediately upon impact, it is likely that the fuel was distributed in a flammable cloud all over the impact area. Ignition of the fuel caused a rapid rise in pressure, then 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 3-5 trillion BTU/hr (1-1.5 gigawatts) – similar to the power output of a commercial generating station. Temperatures reached as high as 900 to 1100ºC (1700 to 2000ºF) in some areas, and 400 to 800ºC (800 to 1500ºF) in others. Air to support the fire was supplied mainly through openings torn in the building by aircraft impact and fireballs. An estimated 14,639 sq.ft. of wall area was open on floors 92 through 98 of WTC1.

2.1.3. Evacuation

Overall, the success rate of the evacuation was as high as is thought possible, with 99 percent of people who were located below the point of impact surviving in each building. As soon as tower 2 was hit, authorities ordered the evacuation of tower 1 below the point of impact. Many people began evacuating tower 2 immediately after tower 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, appear to have improved the effectiveness of the evacuation.

2.1.4. Structural Response To Fire Loading

Aircraft impact degraded the strength of the structure and its ability to withstand additional loading. Although it is impossible to determine the specific steps that led to the collapse of the towers, the following fire effects are likely to have been contributing factors:

Impact force, fireballs, and the field of debris probably compromised spray-applied fire protection on structural members.

Loads transferred from destroyed and damaged structural elements put columns under elevated stresses. Debris that fell through partially collapsed floor areas imposed heavier loads on floor framing. A the fire heated floor framing and slabs, they expanded, potentially developing 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 (Fig.4).

As the temperature of floor slabs and support framing increased, these elements may have lost rigidity and sagged. Then horizontal framing elements and floor slabs could become tensile elements, which could cause end connections to fail and allow supported floors to collapse onto the floors below.

As the temperature of column steel rises, the columns' yield strength, modulus of elasticity and critical buckling strength would decrease, potentially initiating buckling, even if lateral support is maintained. This most likely affected the failure of the interior core columns.

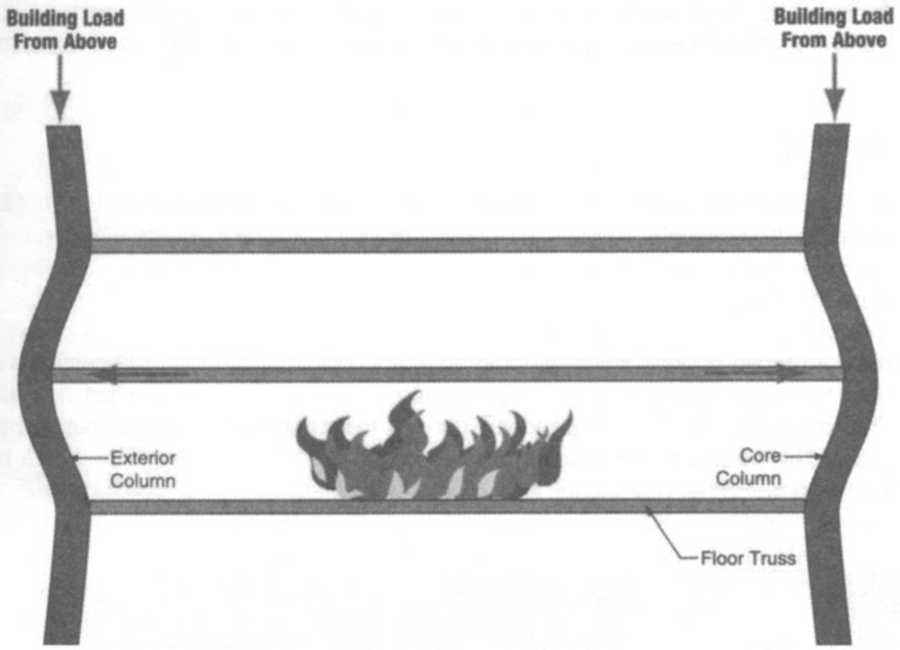

Fig. 4. Expansion of floor slabs and framing results in outward deflection of columns and potential overload

2.1.5. 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 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 1 and 2.

2.2. World Trade Center Building 5 (WTC 5)

Three 8- and 9-story steel-framed office buildings (WTC 4, 5, and 6) were located on the north and east sides of the WTC Plaza. When the first two towers collapsed, all three were subjected to severe impact damage as well as fires that developed from the debris. Most of WTC 4 collapsed when it was hit by the exterior column debris from WTC 2; upper floors of 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 progressive collapse, however, in spite of the extensive local collapses.

The 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, and is assumed to apply to all three.

2.2.1. Structural Design

Each 120,000-sq-ft floor of WTC5 was constructed of 4-inch-thick lightweight concrete fill on metal deck, supported by structural steel framing. Wide-flange structural columns were placed on a regular 30-ft-square grid pattern. The floor plates cantilevered out 15 ft 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 4-ft-long stub shop-welded to the column on each side, and the floor girder simply connected with shear tabs to the cantilevers.

2.2.2. Impact And Fire Damage

Damage from the impact of falling debris was severe, causing localized collapses from the roof to the 3rd floor. Fires ignited by burning debris caused a localized collapse from the 9th to the 4th floor.

2.2.3. 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. The columns in this area remained straight and freestanding, which lends support to this theory (see Fig. 5). This local collapse appears to have begun at the field connection where beams were connected to shop-fabricated beam stubs and column assemblies.

Fig. 5. Internal collapsed areas in WTC5

The structural collapse of portions of WTC5 seems to have resulted from excessive shear loads on bolted connections and unanticipated tensile forces due to the beams' catenary sagging. High shear loads, probably due to collapsing floor loads from above, were evident in many of the column-tree beam stub cantilevers.

Fire also apparently weakened the steel, contributing 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 6, 7 and 8 of WTC 5 indicate that the deformed structure subjected the bolted shear connection to a large tensile force. At 550ºC (1,022ºF), 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 impact. There was little or no evidence of shop painting, which indicates that fireproofing material was either missing before the fire or delaminated early in the fire exposure.

The automatic sprinkler system did not control the fires. Some sprinkler heads fused, but there was no evidence of significant water damage, due to a lack of water. This is consistent with the lack of water damage in the bookstore on the lower level and the burnout of the upper floors.

2.3 WTC 7

WTC 7, a 47-story office building completed in 1987, collapsed at 4:20 p.m. on September 11, 2001, causing no known casualties. The performance of WTC 7 is important, because the collapse appears to be due primarily to fire, rather than from severe impact damage from the collapsing towers. Before this event, the fire-induced collapse of large, fire-protected steel buildings had never occurred.

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 early in the afternoon.

2.3.1. Probable Collapse Sequence

The collapse began on the east side of the building 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. The collapse appears to have begun 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 5 and 7) to high temperatures 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, producing 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.

Conclusions

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

References

1. As shown in "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations," Federal Emergency Management Agency Mitigation Directorate, FEMA 403, Washington, DC. (Corley, et al, 2002)