THE DISASTERS OF SEPTEMBER 11, 2001

DAVID T. BIGGS, P.E.

Principal
Ryan-Biggs Associates, P.C.
Troy, New York USA

SUMMARY

This paper presents some structural observations, findings, and recommendations regarding the masonry performance of the buildings affected by the September 11 attacks in New York City and Washington D.C.

INTRODUCTION

September 11, 2001, is a day that will be remembered always in the United States. As a result of terrorist attacks in New York and Washington D.C., two 110-story office towers and a third 47-story office building at the World Trade Center (WTC) in New York collapsed and portions of the Pentagon were destroyed. The four other WTC buildings were demolished.

The towers essentially had no masonry components. However, many of the surrounding buildings were impacted by the collapses but survived in some part, due to the masonry used in their construction. The area of the Pentagon damaged on September 11 had been partially restored prior to the attack. This paper will address the performance of the masonry in the buildings surrounding the World Trade Center plaza and the Pentagon.

In May 2002, the report "World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations" (www.fema.gov) was released by the Federal Emergency Management Agency (FEMA) and the American Society for Civil Engineers (ASCE). The Building Performance Assessment Team (BPAT) that investigated the disaster included representatives from various professional societies. The author represented both The Masonry Society (TMS) and ASCE on the BPAT. Subsequently, he authored "Masonry Aspects of the World Trade Center" which is available from TMS (www.masonrysociety.org).

In January 2003, the report "Pentagon Building Performance Report" was released by ASCE and is available at http://www.fire.nist.gov/bfrlpubs/build03/PDF/b03017.pdf. The Pentagon images in this paper were provided by James Harris who was a member of the Pentagon BPAT.

WORLD TRADE CENTER - NEW YORK

The steel-framed towers of the World Trade Center complex were constructed in the early 1970s. They were the focal point of a plaza that included five additional buildings ranging in height from 8 to 47 stories. None of the plaza buildings survived the disaster (Figure 1).

All of the surrounding buildings suffered damage from the falling debris, wreckage, and fires caused by the collapse of the towers (WTC 1 and WTC 2) and WTC 7. Figure 2 shows the debris field created by the collapses of the towers. The inner circle around each building represents the primary location of the debris from the walls with the outer circles being an approximate maximum limit. The collapse of WTC 7 impacted adjacent buildings also.

While the impact of portions of the collapsing buildings did the majority of the damage, there was also damage resulting from flying debris and the air pressure created by the collapses. Figure 3 shows the debris and dust cloud created by the collapse of WTC 1.

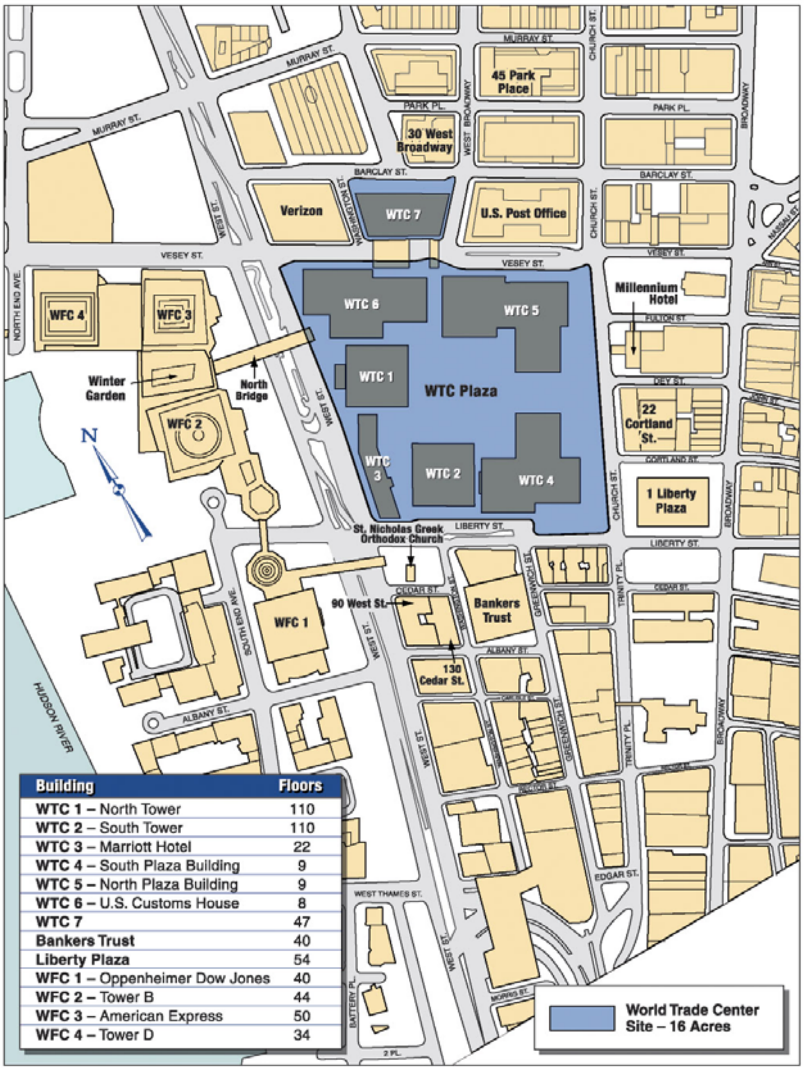

Figure 1 - Site Plan of World Trade Center Plaza and surrounding buildings

As discussed in the FEMA-ASCE report, the New York City Department of Design and Construction (DDC), Department of Buildings (DoB), consultants, and volunteer engineers determined the extent of damage to the surrounding buildings and the foundation of the plaza. Damage was described as either structural or collateral. Subsequently, the buildings were inspected and detailed reports and photographic documentation were assembled for DDC and the building owners.

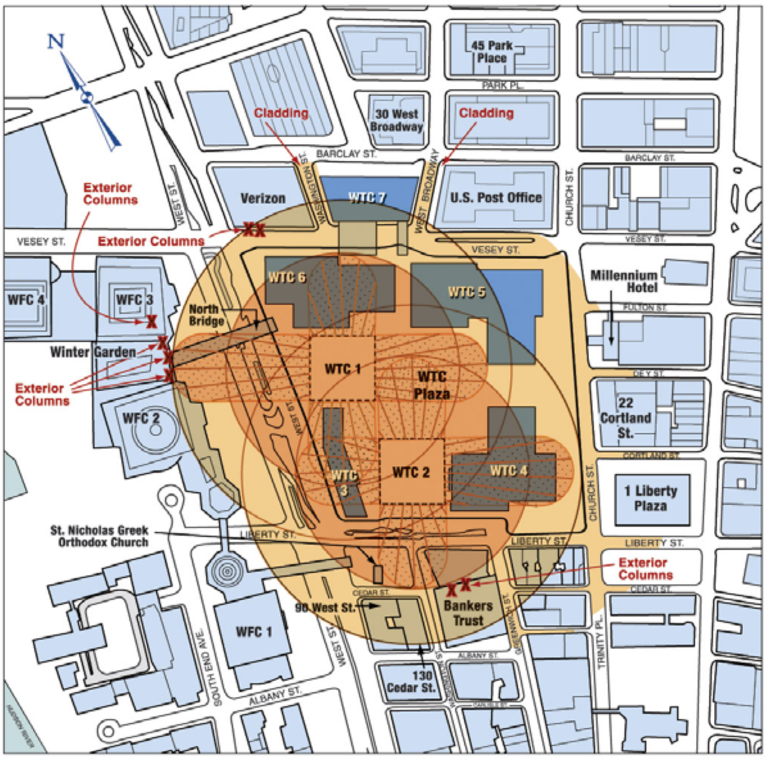

Figure 2 - Outline of debris fields from collapse of WTC 1 and WTC 2.

The following discussions are based upon data provided in the DDC evaluations or personal observations of the author. Each of these buildings was generally damaged by direct impact from the towers or WTC 7, air-borne debris from the collapses, or air pressure created by the collapses.

Lessons Learned

The masonry lessons learned from the World Trade Center disaster can be summarized as:

1. Older framed buildings with masonry components performed generally better than the newer buildings with lightweight curtain wall construction.
   a. Masonry infill absorbed impact energy to minimize damage locally.
   b. Masonry partition walls provided redundant lateral stiffness and fire protection in the older buildings.
2. Masonry infill for walls and beams served both as fireproofing and provided significant structural redundancy. The wall infill also provided an alternate load path to transfer gravity loads from damaged steel columns and prevented collapse of portions of several buildings.
3. Masonry veneers and panelized systems sustained localized damage and could be readily repaired. The performance of the masonry veneer was dependent upon the type of veneer and the anchorage system used.
4. Masonry flat arches in the floors of 90 West Street performed better under fire than the modern steel framing of WTC 3, 4, and 5, which were a total loss.

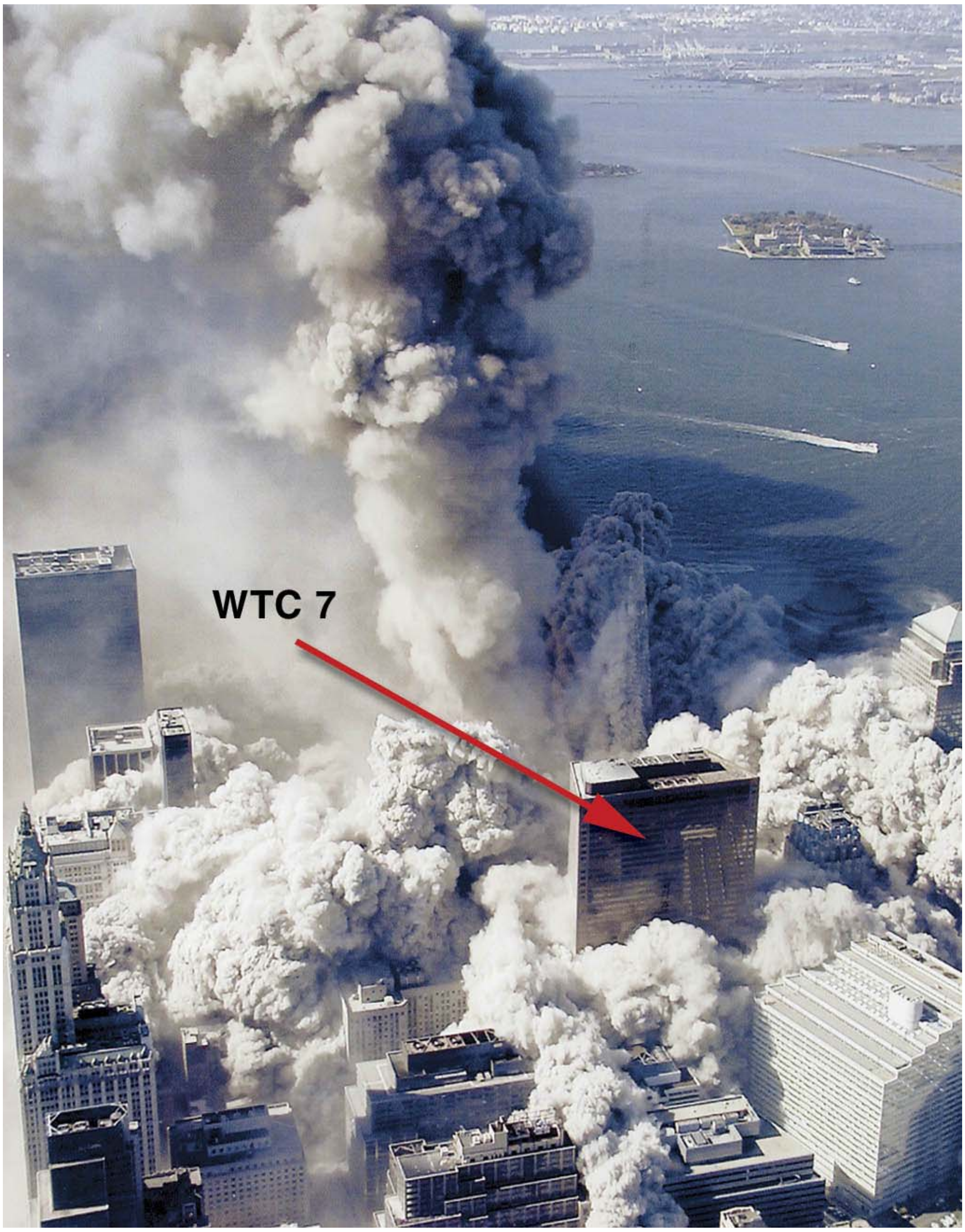

Figure 3 - Dust cloud from the collapse of WTC 1 viewed from the north. WTC 7 in foreground.

Examples

1. Frame Buildings
   Several buildings sustained localized damage resulting from impact from the collapse of the towers and WTC 7.
   a. Figure 4 shows the east wall of the Verizon building at 140 West Street (c 1924) which is just north of Tower 1. This wall was damaged by the collapsed of WTC 7. Impact from the north tower resulted in several penetrations on the south walls. The exterior walls are at least 300-mm thick brick with clay tile backup.

Figure 4 - East elevation of Verizon building damaged by WTC 7.

b. In contrast to the masonry walls of the older frame buildings, the modern curtain walls did not provide protection to the frame. Figure 5 shows the curtain wall damage to 130 Liberty Street primarily resulting from wind borne debris and impact from the south tower (No. 2). This building was ultimately demolished.

2. Masonry Infill
   a. Masonry encasement of steel framed structures proved beneficial for several buildings. Figure 6 shows one of the damaged columns that deflected out-of-plane but remained stable and did not collapse because of the structural redundancy provided by the masonry infill.
   b. Infill provided redundancy for beams and girders as well. In Figure 4, except for the outer leaf of the wall, the masonry is in plane with the perimeter framing; this provided redundancy to the framing and allowed the walls to arch over openings created by the damage.
3. Masonry Veneer and Panels
   a. In comparison to lightweight wall systems, masonry veneer was capable of absorbing significant impact energy and protecting the underlying frame. Figure 7 shows a building impacted by the south tower. The masonry veneer was damaged by replaceable; the framing was repaired.
   b. Lightweight masonry systems were not as protective as masonry veneer but still performed better than curtain wall systems. Thin granite panels with a steel subframing were stripped away on the buildings to the west of the towers. The panelization allowed the masonry to be replaced relatively easily.
4. Fire-rated floors

   Masonry floor structures within an historic building performed better than the floors of any modern building. Figure 8 shows a portion of the floor system from the 1906 building at the corner of West and Liberty. The framing includes built-up and rolled section steel columns and beams. Columns are spaced at approximately 5.5 m on center. The girders run north-south with beams spanning in the east-west direction. The slabs are constructed of terra cotta flat arches covered with cinder-concrete fill

that also encased the steel floor framing. Tie rods were used in the end two bays to resist the thrust of the flat arches. Exterior columns were encased in masonry; interior columns were covered in plaster.

Figure 5 – 130 Liberty Street, Banker's Trust

Figure 6 – Redundancy of masonry infill

Figure 7 – Panel damage showing sub-frame

In spite of a complete burnout, fire damage only reduced the structural strength of the affected floors; no structural failures because of fire were observed. Terra cotta charring and damage were reported throughout the fire areas.

Figure 8 shows the exposed framing and flat arches where a portion of WTC 2 penetrated the building and damaged the floor. The adjacent bays remained intact in spite of the subsequent fire exposure.

Figure 8 - Flat arches intact except from debris damage from WTC 2.

In contrast to these floor slabs, Figure 9 shows one floor area of WTC 5. WTC 5 was one of the modern office buildings in the plaza that was damaged by fire. Notice the significant warping of the framing due to the heat. Fireproofing is charred and flaked off. The older building with the masonry floor slabs and fireproofing performed better.

Figure 9 - Floor framing damage from fire in WTC 5

The World Trade Center Towers

As previously stated, there were no masonry elements in the towers or plaza office buildings. Apparently, the designers of the WTC towers wanted to use fire-rated materials that were lightweight and decided not to use interior masonry partitions in the stairs, elevator, and mechanical room enclosures. The materials selected were gypsum wallboard partitions and a gypsum product called Shaft Wall™. Gypsum panel products came into use in the 1960s, and the World Trade Center towers were by far the largest buildings to use them. Previously, the world's major high-rise structures, such as the Empire State Building constructed in 1931, used masonry enclosures and encasement for steel frames.

While it is presumptuous to assume that masonry enclosures would have survived the attacks, it is obvious that more durable wall systems would have afforded a better chance for survival for more occupants above the levels of impact. Future research will be devoted to evaluating and developing durable, fire-rated egress enclosures for high-rise buildings. Reinforced masonry and concrete are two effective solutions that can be used without further development.

Pentagon - Washington D.C.

Constructed between September 1941 and January 1943 as temporary office space, the Pentagon was designed for post-war use as a storage facility for files and documents. It was designed to support heavier loads than ordinary office buildings. However following World War II, it became the headquarters of the Defense Department.

Prior to September 11, 2001, the building was undergoing a renovation that was twenty percent completed. Most of the renovations were non-structural except that the exterior walls and windows were upgraded for greater resistance to extreme pressures.

The building was constructed with five stories, five sides, and five circumferential rings. The framing was cast-in-place concrete with a specified compressive strength of 17.2 MPa and reinforcement with a minimum yield strength of 275.8 MPa. Column sizes vary throughout but were generally 533mm x 533mm at the first floor to 356mm x 356mm at the fifth floor. The 140mm floor slabs span 3.05m to concrete beams.

The roof has a gable shape on the inner and outer rings and is flat at the other three rings. The gable area has a 114mm slab supported by purlins. The flat areas use a pan joist and 70mm slab system; joists were spaced 0.66m on center.

The exterior walls were typically 127mm thick limestone over 200mm unreinforced brick. In the area of the attack, the walls had been upgraded using steel framing.

The airliner entered the building at the first floor level at about a 42 degree angle. The ends of the wings were partially removed by the impact with the ground and a generator building and did not enter the building. Debris from the wings damaged the façade.

The impact area was approximately 36.6m along the exterior wall. There was relatively limited impact damage to the second floor. Fire damage occurred throughout. Approximately 20 minutes after the attack, the exterior wall partially collapsed because of the loss of first floor columns (Figure 10).

Figure 10 – Collapsed front wall at impact

Comments

1. Overall, there was a high degree of energy absorption in the structural system and the walls.
2. Direct impact of the crash destroyed approximately 50 columns on the first floor and six second-floor columns along the exterior walls. Many columns withstood the extreme lateral loads. Spirally reinforced columns performed much better than the hoop tied columns.

3. Following the crash, the structural system redistributed the weight of the building and its contents among the columns left standing, thereby limiting the collapse of floors above the point of impact. The beneficial system included short spans between structural supports; redundant and alternate load paths; and substantial continuity of steel floor reinforcement through the supports.
4. The masonry infill provided structural redundancy for the exterior walls. Figure 11 shows the arching action of masonry preventing collapse of the frame.
5. Upgraded walls performed very well.

Figure 11 – Masonry infill

Acknowledgements

FEMA and ASCE for the approval to use graphics and text taken from the BPAT reports. The BPAT reports provide credits for specific photographs in the report.