Oklahoma Murrah Federal Building Collapse

Sue Nopachinda

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On April 19, 1995, Oklahoma City was the target of a terrorist act when a bomb exploded in front of the Alfred P. Murrah Federal Building. A rental truck containing 4,000 pounds of TNT was detonated on the north side of the building, causing the collapse of nine stories, 168 fatalities, and 426 injuries. An extensive investigation by a Building Performance Assessment Team (BPAT) was ensued to determine the cause of collapse and necessary changes in both building codes and design standards to prevent damage from future terrorist attacks. An in-depth analysis of the blast and its effect on the structure revealed that the building codes used to design the Murrah Building were inadequate to resist blast or earthquake loading. Since the incident, building codes have been improved to account for security threats on both government buildings and tall buildings, including changes in design standards, research on blast resistant framing systems, and countermeasures against threats for current buildings. While the Oklahoma Murrah Building bombing was one of the biggest terrorist attacks in the US at the time, the lessons learned spearheaded the countermeasures against similar threats that current building codes have today.

Built in Oklahoma City, Oklahoma in 1977, the Oklahoma Murrah Building consisted of a 9 story reinforced concrete building, an ancillary in the east and west wing, and a parking structure across the office building. The Murrah Building was used to house numerous government agencies including the United States Secret Service, the Drug Enforcement Administration, and the US Army recruitment offices with traffic of about 600 federal employees. Following design code at the time, the building was designed as a regular office building consisting of an Ordinary Moment framing system supported by columns along its perimeter – 220 feet in the east-west direction and 100 feet in the north-south direction. The south side of the structure consisted of the core area with shear walls and local columns. To support the intermediate columns, a transfer girder was installed in the third floor which allowed 40 foot column spacing for the first two levels on the north side. Additionally, the transfer girder allowed the structure's exterior curtain wall to be set further within the building, creating "tiers" between the first two floors and the rest of the building as shown in Figure 1. While the Murrah Building was designed as an ordinary office building, its structural systems could not withstand blast forces from potential terrorist attacks or threats.

Figure 1: Murrah Building in 1977 before the bombing. (Source: thirdworldparanormal.weebly.com)

On April 19, 1995 at 9:02 AM, a bomb inside a 24 foot Ryder rental truck was detonated in front of the north side of the Murrah Building. The explosion caused all nine stories of the north face to collapse, effectively destroying a third of the building (Figure 2). During the time of the bombing, about 600 federal workers and 250 visitors were on site. The collapse caused 168 fatalities, including 9 children, and 426 injuries. About 90% of fatalities were due to falling debris while a majority of injuries stemmed from lacerations from airborne projectiles such as glass and debris. Additionally, the blast damaged numerous buildings in a 48 square block area including roof damage on a water resources building, masonry damage to a journal record building, and glazing destruction of a YMCA facility. Financial damage was estimated to be at least $510 million. $200 million was attributed to the damage on the Murrah building, $28 million to rebuild the building (not including demolition costs), and at least $50 million worth of damages to nearby buildings. Considered to be one of the biggest terrorist attacks in its time, the federal government was involved to determine the cause of the collapse and establish standards to prevent similar attacks in the future.

Figure 2: Collapse of the north side of the Murrah building. (Source: www.ssa.gov)

To carry out the forensic investigation and determine the cause of the Murrah Building collapse, the Federal Emergency Management Agency (FEMA) dispatched a Building Performance Assessment Team (BPAT) composed of engineers from the American Society of Civil Engineers (ASCE) and the Federal Government. The primary goals of the team were to (1) investigate the amount of damage caused by the blast, (2) determine the failure mechanism of the structure, and (3) provide feedback on current design methods or building codes to prevent or mitigate future attacks on existing or new buildings. The investigation included interviews with those responsible for the building design, materials testing to verify if the design abided by code and did not contribute to the collapse, blast analysis to determine the amount of blast force on the structure, and failure mechanism analysis to determine the root cause of the collapse.

BPAT first investigated the damage caused by the blast. From Figure 3, damage from the blast mainly effected the north, west, and east faces of the building. Major wall damage was sustained on the east face including fractured granite panels failing in flexture and glazing failure. Collapse of the north face (column line G) were due to the blast force from the bomb except for a small piece of the transfer girder on the third floor. The south face did not sustain as much damage since it consisted of the core structure and concrete masonry partition walls. Interior damage included failure of floor slabs, roof slabs, and masonry walls between column lines G12 and G28. Referring to Figure 4, floor panels between column lines 22 and 26 and lines E and F were lost once column F24 was destroyed. In total, about 62% of all floor panels above the second floor were destroyed from the blast.

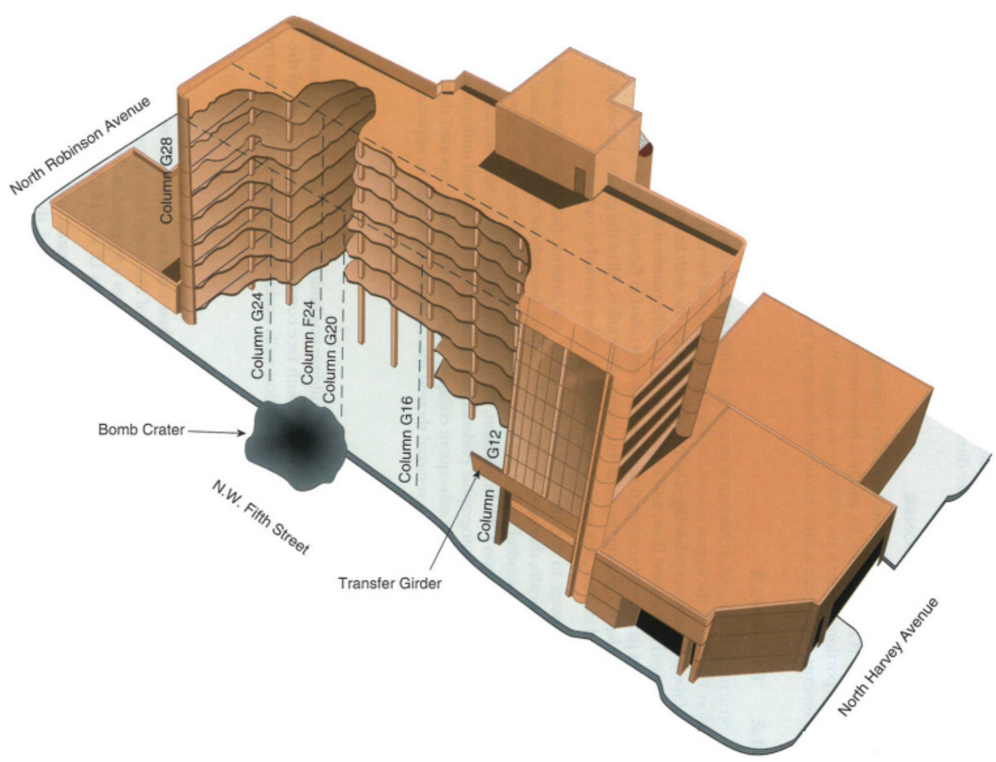

Figure 3: Failure due to blast (Source: www.fema.gov)

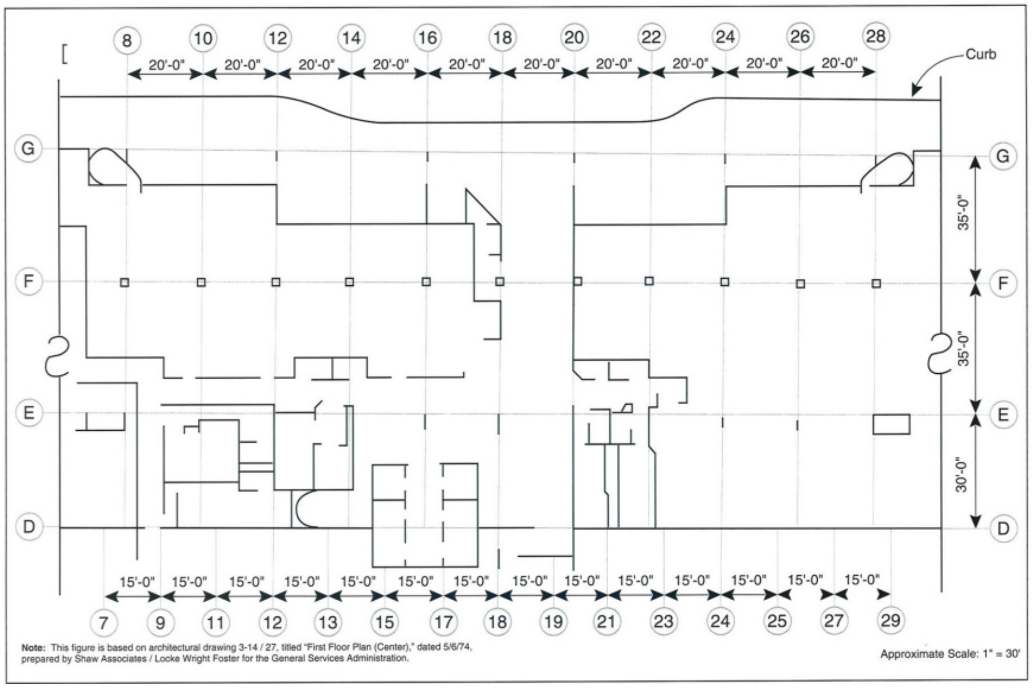

Figure 4: Plan view of first floor north face (Source: www.fema.gov)

To determine if the building's design contributed to the collapse, BPAT interviewed several members of the design team and outside consultants, examined structural drawings and systems, and conducted materials testing on concrete samples from the site. Based on the interviews with the structural engineer of record and several structural engineering consultants, the design of the Murrah Building did not require blast resistance, earthquake, or other extreme loading effects as they was not required by building codes during the design phase. The structure was designed as a typical office building with consideration to wind loads only. Structural drawings of the building revealed that the Murrah Building was designed with conventional reinforced beams, columns, girders, and one way slab system in accordance to the ACI building codes. Material testing of concrete samples from the site showed that the concrete designed met or exceeded the standards required by the design specifications and was within the 4,000 psi range. Additionally, reinforcement bars also surpassed the minimum yield stress required by the specifications. From this, while the Murrah Building was not designed to withstand blast forces, its design followed standard building codes and abided by the required specifications.

BPAT then proceeded to conduct analysis on blast loading and building's response. To determine the amount of explosives detonated, the team measured the depth and diameter of the crater that was left behind by the blast. With a diameter of 28 feet and depth of 2.8 feet, the estimated amount of detonated explosives was 4,000 pounds of TNT. From this, the blast response for Columns G20, 24, and 16 were analyzed. Based on the scaled distances for each column, only column G20 was completely obliterated by brisance effects. This is supported by the fact that no remnants of Column G20 were found at the site. Columns G24 and G16, however, experienced brittle failure. Since the direction of the blast impacted about 1400 psi of pressure on the column's weak axis, the shear at the supports exceeded the column's capacity of only 54 psi. As a result, these two columns failed at the top as the axial prestress and shear capacity was much greater on the first floor than at the third floor. Figure 5 shows the overall damage of Columns G20, 24, and 16 which are consistent with the analysis results.

Figure 5: Damage along Column Line G (Source: www.fema.gov)

Similar analysis to investigate failure of the floor slabs revealed that the slabs from the first to fifth floor failed when the bomb detonated. Typical floor slab details revealed that reinforcement placed near the bottom, effectively reducing resistance against upward loading. About 163 psi of pressure was induced to the bottom of the floor slabs, causing the slabs to deflect 9.3 inches and exceeding their ultimate capacity. Figure 6 shows a schematic of the overall damage at the north face.

To pinpoint the exact causes for the collapse, BPAT analyzed two possible

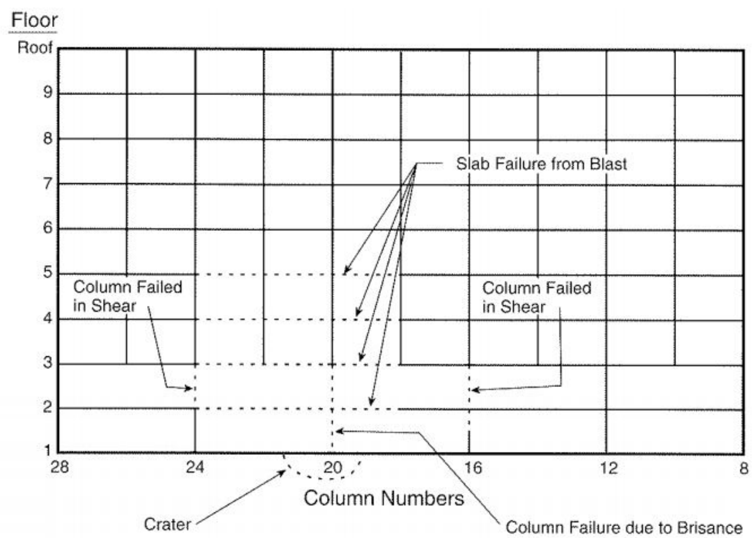

Figure 6: Damage on the north face (Source: www.fema.gov)

failure mechanisms. Mechanism 1 (Figure 7(a)) considers the typical collapse system in the as-built condition. It is assumed that the moment capacity at Column Line 22 is finite since bottom-flange reinforcement is continuous. The moment capacities of the girders on floors four through nine and the roof are zero since bottom-flange reinforcement stops at the support. Mechanism 2 (Figure 7(b)) considers Column G20 removed which is akin to the blast response. The positive moment capacity at the support is assumed to be zero at Column Line 20 since bottom-flange reinforcement terminates. Analysis was conducted on these two mechanisms to determine the unit strengths for Column Line G. Mechanism 1 had a unit strength of 490 to 530 psi while Mechanism 2 has a unit strength of 60 to 70. Knowing that the building unit weight is about 150 to 200 psf from prior analysis, it is evident that Mechanism 1 was able to sustain this load while Mechanism 2 could not. Therefore, Column Line G cannot sustain its own tributary weight if any interior column is removed. Considering Columns G20, 24, and 16 were destroyed, there is no plausible way that the transfer girder on the third floor could sustain itself.

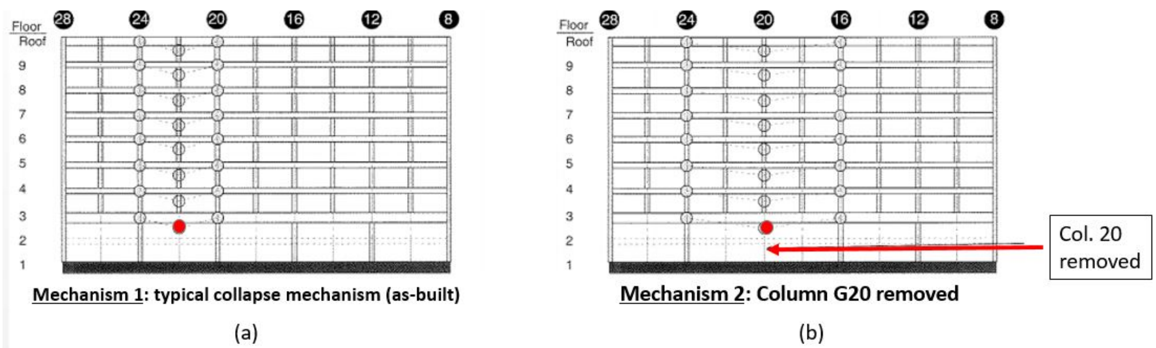

Figure 7: Two collapse mechanisms considered (Source: www.fema.gov)

Following the incident, building codes and design standards against blast attacks underwent stricter requirements and revisions for future and existing buildings. Several federal government agencies including the General Services Admission (GSA) and the Department of Defense provided detailed requirements for both security and prevention during the design phase of new buildings. Different framing systems such as Special Moment Frames (SMF) and Dual Systems were required for federal or tall buildings as these systems are able to dissipate blast energy throughout a structure much better than Ordinary Moment Frames. Additionally, structural elements such as glazing were required to be blast-resistant to mitigate the number of injuries. Security measures including bollards or doors also required consideration. For existing buildings, possible considerations include retrofitting walls, windows, and columns to resist blast, supplementing the framing system with additional redundancies, and column jacking. From these recommendations, an analysis was done to determine the amount of damage that would have been caused if the Murrah Building was designed as a SMF and to validate these countermeasures.

From an analysis on the building's response to blast as a SMF, it was revealed that the damage would have been greatly reduced by 80%. While Column G20 would have still been obliterated, the damage would have been localized around this area. Columns G24 and 16 would have been damaged but not undergo brittle failure. Since these columns and the transfer girder would theoretically contain much more reinforcement and an increase in ductility, the progressive collapse would not have occurred. To implement the Special Moment Framing system would have cost about $14,500 - only 1% to 2% of the total building cost. While design for blast using SMF or Dual Systems would have greatly mitigated much of the damage, standards for these systems were made first available in 1985, 10 years after the bombing occurred.

Based on the facts gathered and analysis conducted, the Murrah Building collapsed from failure of three columns on the first and second floor, leading to a progressive collapse of floors three to nine. Once columns G20, 24, and 16 failed, the transfer girder supporting nine columns from floors three to nine failed. Since the building was designed by 1977 building code which did not require federal buildings to consider blast loads, the standard of care was still upheld by the design team. In fact, no defects were detected in any of the drawing specifications reviewed or construction of the building. Therefore, no lawsuits were made against the design teams but instead against the perpetrators who planned the attack.

The bombing and collapse of the Oklahoma Murrah Federal Building highlighted the inadequacy of 1970's building codes and design standards against blast attacks. While this tragedy resulted the deaths of 168 people and $510 million in damages, this provided the need for government agencies create an effort to prevent future attacks against federal or tall buildings. As a result, detailed guidelines and stricter standards were enforced during the design and construction in what building codes imbue today. While it was unfortunate that these standards were implemented only after an attack of this magnitude occurred, the lessons learned from this event has given light on the potential threats that buildings may face and the tools to prevent future attacks to occur.

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