The Importance of a Safe Construction in the Fight Against Terrorism

A historical analysis of buildings subjected to terrorist attacks and the changes in structural and safety design

ARA011 Architectural History Thesis

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Abstract: Terrorism is something the United States of America has had to deal with since 1789. Near the end of the 20th century such attacks had become more frequent and devastating with the most casualties caused by a single individual with the Oklahoma City bombing in 1995. This has led to a nationwide uncertainty if more buildings were at risk to be damaged and how could this be prevented in the future. This thesis will analyze what changes are made in designing after a terrorist attack to determine how we approach structural and safety design differently. For this analysis The World Trade Center bombing (1993), The Oklahoma City bombing (1995) and The September 11 attacks (2001) will be discussed. In all 3 cases most changes were made in order to either improve structures to isolate damage at the location of the blast or to improve the safety of people in the building at the moment of an attack or during the evacuation.

Terrorism, the act of the intentionally use of violence, is something the United States of America has had to deal with since 1782 with the Gnadenhutten massacre. Unfortunately, from 1970 the act of terrorism has become more frequent and devastating in the US. In this period public and government buildings increasingly became the target with the purpose to destroy the building resulting in lots of casualties and fear. The Oklahoma bombing in 1995 is known as the incident with the most casualties incited by one individual at that period of time, through destroying a third of the building with one single explosion (Osteraas, 2006). The blast caused the construction to become unstable and therefore had to be demolished. Although this was not the first-time terrorist tried to destroy a building, it was the first time they managed to damage the building on a structural level. This has led to a nationwide uncertainty if more buildings were at risk to be damaged and how could this be prevented in the future?

This thesis puts forward the hypothesis that the increasing destruction caused by terrorist attacks have become a key component in the design of governmental buildings, as well as well-known public buildings that have been constructed in the US to ensure the safety of the construction and their users.

the purpose of this thesis is to analyze what these changes are and why these attacks led to certain changes; to determine how we approach structural and safety design differently.

For this thesis three case-studies will be examined where a building has suffered from a terrorist attack and their replacement building where such one exists. The focus of the case-studies will be on the structural integrity and safety of the building directly after the attack. In order to achieve this, the following is examined for each case-study: what kind of damage did the attack cause? was the structure's safety at risk after the attack? what improvements were made to the existing structure if possible or how did the design of the replacement building deviate from the destroyed building?

The three selected case-studies will be discussed in the thesis in the following order: The World Trade Center bombing (1993), The Oklahoma City bombing (1995) and The September 11 attacks (2001). For the Oklahoma City bombing and The September 11 attacks their replacements buildings will also be studied to determine how the attack influenced their design to defend the building against a similar attack.

This research will start off with the analyses of the forementioned cases to determine what kind of damage the attacks caused to the buildings and how this affected the building on a structural level. This will be followed by an examination what changes were made to the structure if possible or how this affected the new design for the replacement building. After its determined what changes were made to the individual cases, a chronological comparison will be made between the different cases to determine if changes that were made to one case were implemented in the original design of the following cases.

Chapter 1. The World Trade Center Bombers (1993)

On September 20, 1962, Minoru Yamasaki was selected by the Port Authority to be the lead architect with associate architects Emery Roth & Sons to design the World Trade Center (WTC) Complex in Lower Manhattan, New York City. This complex (Figure 1), consisting of 7 individual buildings (from here on referred to as WTC 1 through WTC 7), housed over 430 companies trafficking 50.000 employees and 140.000 visitors on a daily average. Construction started in march 1965 with the clearance of the site and in December 1970 the first tenants moved into the complex. The whole complex was complete by 1987 with the opening of the WTC 7 building (Manning, 1993).

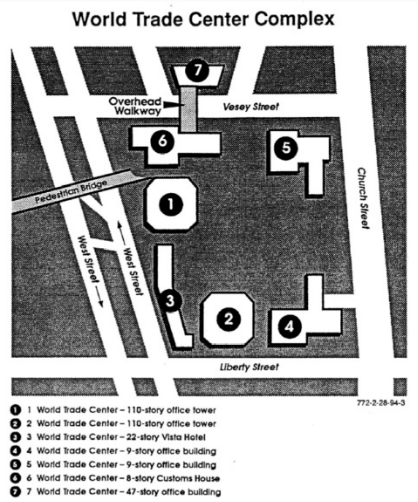
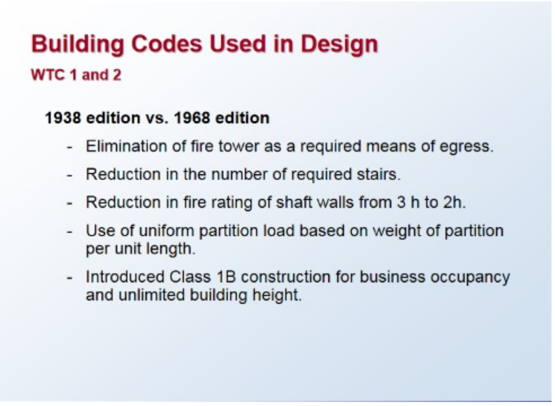


Fig.1 World Trade Center Complex Overview (Manning, 1993).



Building Codes Used in Design

WTC 1 and 2

1938 edition vs. 1968 edition

- Elimination of fire tower as a required means of egress.
- Reduction in the number of required stairs.
- Reduction in fire rating of shaft walls from 3 h to 2h.
- Use of uniform partition load based on weight of partition per unit length.
- Introduced Class 1B construction for business occupancy and unlimited building height.

Fig.2 Comparison between the New York building codes from 1938 and 1958 (NIST,2005).

Two of these buildings, named WTC 1 and WTC 2, became the symbol of the WTC and that of the international economic power of America. These building were referred to as the Twin Towers because of their near identical appearance and impressive height. The structural design of the Twin Towers did not have to comply with the New York City's laws and regulations since the Port Authority was considered an interstate agency. Nevertheless, the Port Authority did require the architects and structural engineers to follow a draft version of the new building codes and regulations that in 1968 replaced the old format from 1938 (Figure 2).

Before the construction of the buildings could begin, a 21m deep and 1m wide concrete wall was cast around the site perimeter using the slurry-trench method (9-11 research, z.d.). Once this wall was completed, 1 million cubic meters of rock was excavated creating world's largest basement nicknamed the "bathtub". However, this wall would collapse under the hydrostatic pressure from outside the basement. Therefore, it had to be reinforced with the use of 1.400 exterior anchors (Figure 3). After the completion of the bathtub its six elevations provided 200 million square meters to house its technical installations and over 2.000 cars to pe parked (9-11 research, z.d.).

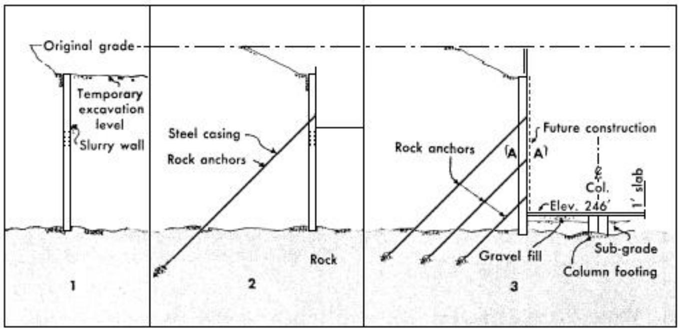


Fig.3 Construction of the Bathtub using the slurry-trench method and steel anchors (9-11 research, z.d.).

Once construction of the WTC complex reached above street level people saw the Twin Tower and the rest of the complex evolve day by day. The Twin Towers were designed with a structural core, housing the vertical transportation and buildings installations, surrounded with an open office space from its core to the façade to allow maximal flexibility in use. A detailed analysis of the design and construction of the Twin Towers will be addressed in chapter 3.

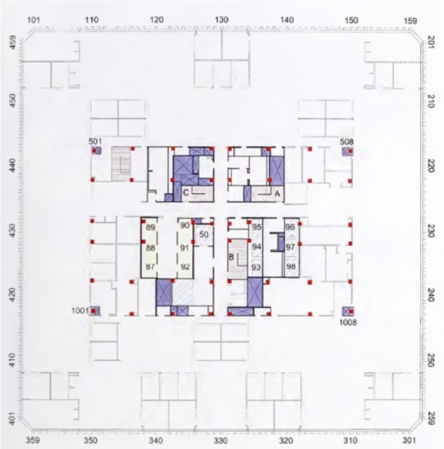


Fig.4 General floorplan Twin Towers (NIST, 2005).

1.1 The Attack on the WTC Complex

On Friday around noon, February 26, 1993, a van pulled into the subterranean public parking at the North Tower entrance. In that van a nitrourea bomb of 1.500 pounds, combined with hydrogen cylinders for additional impact damage, was parked on the B-2 level of the garage (Manning, 1993). Moments after the bomb was detonated it created a 30 meters wide hole on the B-2 level floor and additional holes on B-1 and the concourse level. 16 steel columns were damaged and had no lateral support anymore and were at risk of collapsing. Debris from the explosion falls down the openings on B-3 and B-4 level and land at the refrigeration pipes in the refrigeration room at B-5 level. The primary power lines were damaged and the emergency generators on the B-6 level kick in. however due to the impact from the debris on the pipes ruptured and were unable to provide water to the generators. With no back up batteries the generators failed to provide secondary power to the complex shutting down all emergency systems as well as the elevators and ventilation system. At the same time roughly 200 cars were damaged by either the blast or the impact with the falling debris which caused most to catch on fire. The sprinkler system in the subterrain levels was inoperable after the explosion (Figure 5).

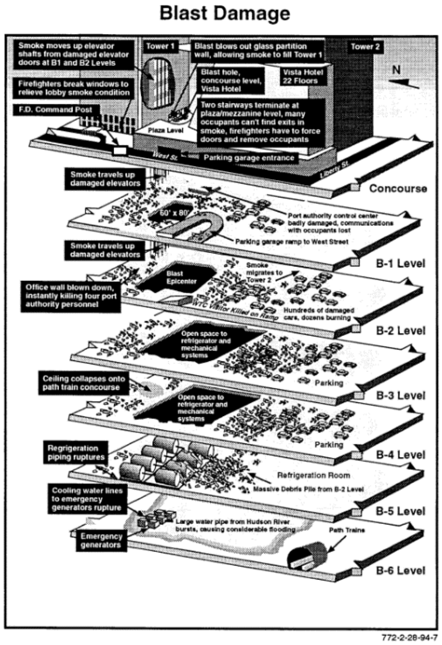


Fig.5 Overview of the situation after the bomb was detonated (Manning, 1993).

At the WTC 3 building, the Vista hotel, the blast created a hole in the meeting room and shattered parts of the glass wall between the hotel and the North Tower. Through this hole the smoke rose up and filled the hotel and the tower with smoke. Vibrations from the explosion caused ceilings to fall down and walls to partially collapse which blocked most exist ways out of the hotel (Manning, 1993).

As smoke starts to fill the lobby and elevator shafts from the North Tower people attempted to evacuate the building though the thick smoke and absence of emergency lights. As the smoke reached the 20th floor the fire department decided to break the windows at the front floor to speed up evacuation and allow fresh air into the building. In the 110th story high tower, approximately 25.000 people had to evacuate using only the stairways (Manning, 1993). As most people relied on the elevators to move though the building most occupants were not familiar with the stairway's location and use, since of the three stairways only one of them spanned the whole 110 stories and was the only one to go to the lobby's concourse level (Figure 6 & 7). The other two stopped at the mezzanine level in the lobby where a walkway formed a connection with the hotels' patio.

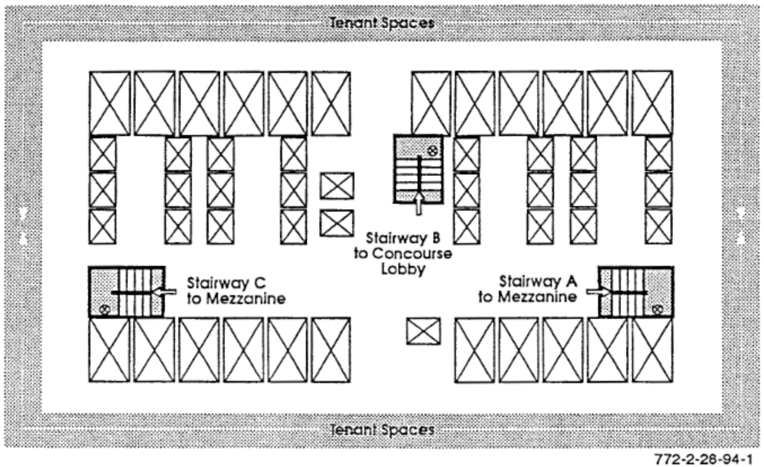


Fig.6 General floorplan with the stairway's location (Manning, 1993)

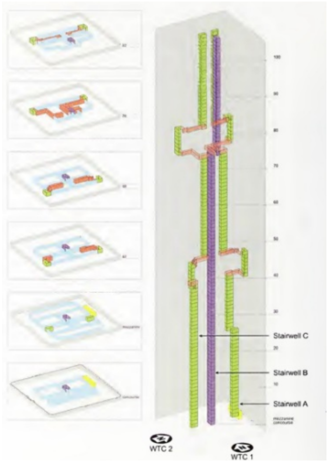


Fig.7 Stairway's layout and connection (NIST, 2005).

Meanwhile at the South Tower people saw the developments in the North Tower and started evacuating. Just like in the North Tower the elevators shafts started to fill with smoke but at a much slower pace since there was no direct fire beneath the building. The evacuation of the South Tower went relatively smooth except for those who forgot or disregarded the elevator warning and were stuck in the shafts for up to 11 hours (Manning, 1993).

1.2 The Aftermath of the WTC Complex

4 hours after the explosion, the fire department regained enough control over the fire for Chief Engineer, Eugene Fasullo, of the Port Authority to conduct an assessment of the damage caused in the subterranean levels and determine the structural integrity of the complex. At the time of the explosion, it was believed that the explosion was caused from a faulty transformer, however Fasullo quickly determined that the crater had to be the result of a bomb. From his visual inspection of the North Tower support columns Fasullo decided that they were structurally sound since no cracks or any sign of distortion was visible, this was later confirmed to be true (Manning, 1993). As for the columns supporting the Vista Hotel, the crater from the explosion resulted in a loss of lateral support for the columns meaning its load bearing capacity had greatly reduced and were at risk. The columns at the B-5 level were covered with debris from the upper floors which provided these columns lateral support and it was determined to keep the debris in place until these columns could be reinforced. Due to the ruptured pipelines the B-6 level was filled with almost 8 million liters of water that needed to be pumped out before the emergency generators could be repaired (Manning, 1993).

Based on a thorough analyses of plans, drawings, construction records and eyewitness rapports the conclusion was drawn that the WTC complex was designed and constructed accordingly to the draft version of the 1968 building code on all aspects, even exceeding it in some areas (Manning, 1993). It is believed that with the detonated bomb did not put the WTC complex at risk of (partially) collapsing and that the intension of this attack was primarily to havoc chaos and fill the buildings with smoke (Parachini, 200). However, the explosion did manage to sever the emergency systems and communication throughout the complex, leaving many people blind to the what had occurred and the severity of the situation they were in. these factors combined created a situation where people were unable to calmly and safely evacuate the building therefore prolonging the initial evacuation time and putting more lives at risk (Manning, 1993).

1.3 The response to the WTC Complex attack

The bombing of the WTC and the events that followed from it is described as a "worst-case scenario" in providing a save evacuation in case of an emergency. With the restauration of the affected systems a number of enhancements have been made, according to the building regulations and standards, turned the WTC in to the safest complex in New York City on paper (Manning, 1993). Secondary backup generators have been installed in case the primary generators fail and both groups are equipped with batteries to temporarily provide electricity should the water supply fail to work. On top of that, the complex can receive electricity through a hardwired cable connected to the New Jersey Public Service Electric & Gas Company from New Jersey runs into the complex should New York electrical services be unable to provide electricity. To ensure peoples safety while descending the Twin Towers 1.600 emergency battery powered lighting fixtures have been installed in stairwells and elevators. On each floor phosphorescent signs have been installed to guide people to the nearest stairwell and phosphorescent paint has been applied to stair threads, handrails, and the perimeters of doorways. To speed up rescue work for people stuck in elevators when electricity is unavailable each elevator has been equipped with a battery backup unit to power the elevator emergency phones and power the floor indicator so that people could contact the WTC personnel and inform them off their location in the building. The final addition to the complex was the installation of delta barriers at each entrance to the subterranean parking to prevent unauthorized vehicles from gaining access to the underground levels.

Chapter 2. The Oklahoma City bombing (1995)

In May 1974 the construction of the Alfred P. Murrah Federal Building started in Oklahoma City, Oklahoma (Figure 8). This building, named after federal judge Alfred P. Murrah was designed by architects Stephen H. Horton and Wendell Locke of Locke, Wright and Associates. During the period between May 1974 to March 1977 the Murrah building was constructed by the J.W. Bateson construction company resulting in a 9-story office building to be used for the United States federal government (Corle et al,1998).

Fig.8 Alfred P. Murrah Federal Building (Osteraas, 2006).

The structural design consisted of a moment-resisting concrete frame supported on columns with an overall dimension of roughly 61 by 21.4 meters and a height of 36 meters (Figure 9). The structural system consisted of column placement on a 3 by 11 grid forming 20 constructive areas of 6.1mx10.7m. Gridline G, F and E span across the length of the building with line G in the North Façade facing the street. The width of the building is divided from gridline 8 to 28 (only even numbers are used) with gridline 8 at the West Façade. Situated at the South side of the building are the elevators and emergency staircases. A monolithic (cast-in situation) floor construction was supported by concrete beam. These beams spanned over a distance of 10.4 meters from column to column. The facade construction consists of a curtain wall system with concrete transfer girders (TG) (Corle et al,1998).

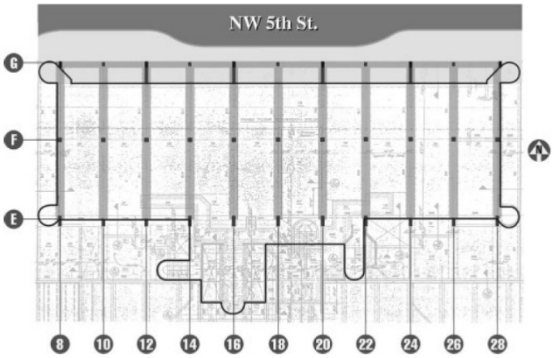
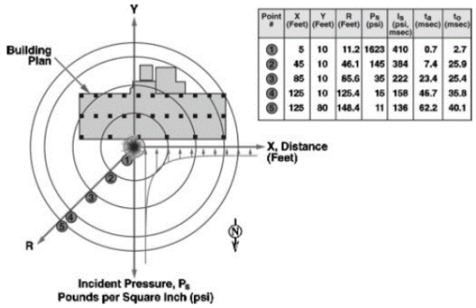


Fig.9 Structural floor plan (Corle et al,1998)

2.1 The attack on the Murrah building

On the morning of April 19, 1995, a delivery truck was parked right in front of the North façade of the building. In this truck were 13 barrels turned into homemade bombs with an approximate 1.800kg worth of TNT explosive power. The explosion itself was so powerful that it was detected over 89km away and caused an earthquake of 3.0 on the scale of Richter 30km from the site (Figure 10).

At a distance of approximately 4 meters from column G20 the bomb was initiated creating a pressure difference at its origin, creating a crater of proximately 8,5 meters (Corle et al,1998).



Point #	X (Feet)	Y (Feet)	R (Feet)	P_s (psi)	I_s (psi, msec)	t_a (msec)	t_o (msec)
①	5	10	11.2	1623	410	0.7	2.7
②	45	10	46.1	145	384	7.4	25.9
③	85	10	85.6	35	222	23.4	25.4
④	125	10	125.4	15	158	46.7	35.8
⑤	125	80	148.4	11	136	62.2	40.1

Fig.10 Epicenter of the explosion and pressure predicaments
(Osteraas, 2006)

It is believed that the pressure applied on the G20 column was enough to shatter the concrete leaving only the steel reinforcements behind. With the absent of the G20 column the façade between G18 and G22 was insufficiently supported resulting in it collapse over the full building height (Osteraas, 2006).

As the blast wave expanded it, exerted an upward force on the floor slabs which were not constructed to resist upward forces exciding its own weight. Therefore, a force stronger than that was already enough to lift the slabs (Figure 11). Since the slab were directly cast on the beams and extra reinforcement were used to stiffen the structure, the force applied to the floor slabs were transferred over to the beams which were also not constructed to resist upward forces. This resulted in upward bending in the beams causing shear cracks located at the columns. Due to these cracks the concrete separated from the reinforced steel causing weak connections and even gaps between the beams and the columns (Figure 12). Since the floor slabs are well connected to the concrete girders in the façade the catenary force pulls the top of the third-floor girder making it rotate into the building (Corle et al,1998).

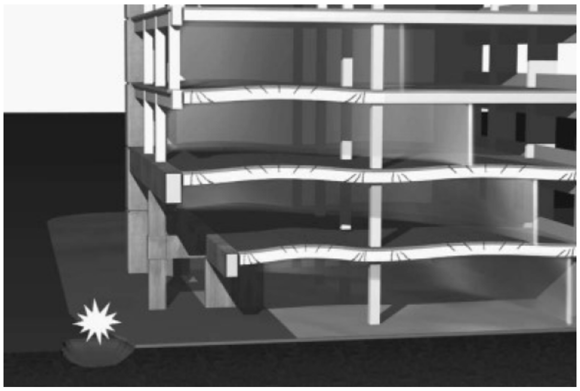


Fig.11 Deformation of the slabs due to upwards pressure
(Osteraas, 2006)

Fig.12 Damaged connection between beam and column
(Osteraas, 2006)

Once the initial blast wave had passed the upward force dropped leaving its own weight as the only force on the slabs. As the slabs are proceeding to return to their original bend it fails to transfer its force to the columns due to the damaged connection. The gravitational downwards force start to bend the slabs further downwards then its original state. At first the fourth and fifth floors collapsed onto the third floor. The added weight was too much for the floor to be supported following to its collapse and along with it causing 10 constructive areas to fail along the northern half of the structure. (Figure 13). The time that had passed between the detonation of the bomb and the collapse of the northern half of the structure is believed to have been roughly 7 seconds (Osteraas, 2006).

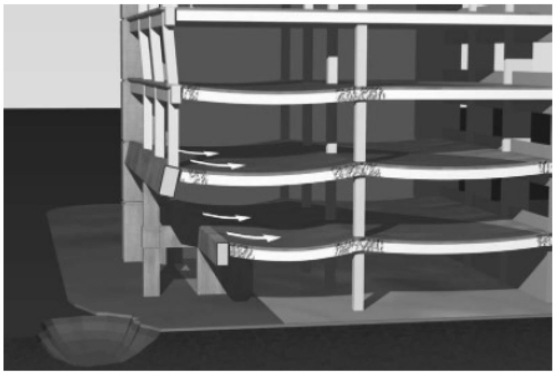


Fig.13 Sagging of floors due to connection failure (Osteraas, 2006).

Half of the constructive area's had collapsed completely over all elevations of the building (Figure 14). The 4 columns named G16, G20, G24 and F24 did not remain intact and are deemed crucial for the partly failure of the building's construction. As mentioned before, it is believed that of those 4 columns, G20, failed as a direct result of the explosion. Among the debris parts of column G16 and G24 can be found suggesting their failure is due to shearing caused by the added load that used to be supported by G20. On top of G16 and G24 parts of the TG can be seen lying on a 90 degrees inward rotation (Figure 15) (Corle et al,1998).

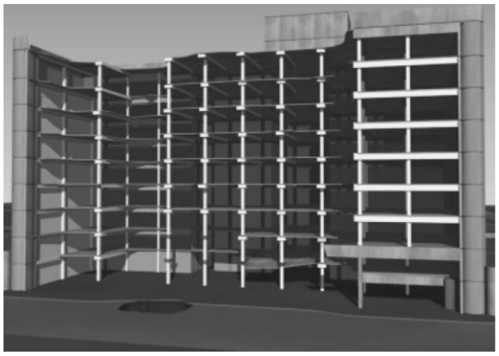


Fig.14 Overview of construction after the attack (Osteraas, 2006).

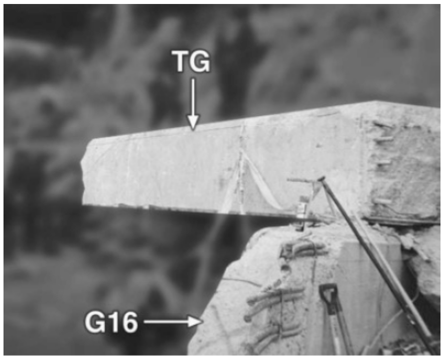


Fig.15 TG laying on top of the G16 column (Osteraas, 2006).

2.2 The Aftermath of the Murrah building

Based on a thorough analyses of plans, drawing and construction records, the conclusion was drawn that the Murrah building was designed and constructed accordingly as a reinforced-concrete-frame-structure meeting the requirements that were applicable at the time for constructions in the state of Oklahoma (Corle et al,1998). Above that the design was also in line with the building code required for all governmental buildings. However, in the design there were no requirements taken in consideration of events like earthquakes, extreme winds or blast impact. Important is to note that even though the initial blast resulted in the loss of 4 columns and partial of the damaged floors; it is believed that this is only accountable for a small portion of the damage caused. Most of the damage caused was due to the progressive collapse as an effect of the loss of these columns (Corle et al,1998).

At the time of construction moment-resisting frames were known for having a limited capacity in dealing with extreme energetic forces such as earthquakes or blast impact. However, 10 years after the Murrah building was constructed, the National Earthquake Hazards Reduction Program (NEHRP) introduced the special moment-resisting frame and a dual system with an integrated special moment-resisting frame which were significant more capable in dispersing extreme energetic forces. It is believed that if form of construction had been present for the Murrah building at the time of the blast, columns G16 and G24 would be strong enough to overcome the shearing forces applied to them after the destruction of G20. In either case G20 would probably not have survived the blast. Three scenarios have been created to determine the results if such a construction was indeed present in the Murrah building (Corle et al,1998): In the first scenario the G20 column would have survived the blast. The only structural damage would have been inflicted at the floor slabs directly damaged from the blast's shockwave, reducing the total damage caused with estimated 85 percent. In the second scenario the G20 column would not have survived the blast however the G16 and G24 column would have. In this case the G16 and G24 column would have been able to support the added load from the failed G20 column. Combined with the improved connections the chances for TG at the third floor to not collapse would be greatly improved. In this case the only damage the building would sustain would be from the blast's shockwave. Here the estimated percentage in damage reduction would be around 80 percent. In the third scenario the G20 column would not survive the blast and the G16 and G24 column would not be able to support the added load. In this case the damage would be caused from both the blast's shockwave and the collapse of the zones located between line G to F and 16 to 24. If this were to happened the reduction in damage caused would be estimated at 50 percent.

2.3 The response to the Oklahoma bombing

Based on the gathered information from both visual inspection and the analyses of the damage that happened to the Murrah building caused by the truck bomb, it is concluded that the damage caused from the collapse was not a result from the blast but from the structural design in place. This form of collapse damage, resulting in nearly half the destruction of the building, is something that can be expected form buildings constructed around the mid-1970s, with a similar structural type and detailing, when exposed to a large explosion (Corle et al,1998).

In response to this the Federal Emergency Management Agency (FEMA) has developed recommended structural design procedures for new buildings to become more resilient to blast impact. In general, these designs are significantly tougher and more flexible than buildings constructed in the 1970s. in addition the Department of Housing and Urban Design (HUD) has allocated more resources into the research on reducing the effect of progressive collapse when a building is exposed to external threats such as bombs (Corle et al,1998).

During the time of the investigation the jersey barriers (Figure 16) were placed in front of federal buildings as a temporary measurement to prevent vehicles from getting too close to these buildings, which were later on replaced by more integral designed elements to protect the buildings while also look esthetically appealing. However, this measurement has only limited effect when buildings are relatively close to the streets. To protect these building modifications to the buildings itself should be considered such as erecting walls to compartmentalize the building, adding supplemental support frames and reinforcing existing columns with steel and concrete (Corle et al,1998).

Fig.16 Jersey barrier (CorreiaPM -Wikipedia, 2008).

Chapter 3. The September 11 Attacks (2001)

On September 1962 architect Minoru Yamasaki was selected to design part of the WTC complex. In his design, 2 near identical 80-stories tall towers sit in the center of the complex and provide most of the required office space. These towers later became known as the Twin Towers. However, to fulfill the requirements of the Port Authority to accommodate 930.000m^2 throughout the WTC complex of office space, the Twin Towers would have to be 110-stories tall with a square floorplan of 63,4m wide (NIST, 2005). One of the major problems during the design of the towers was its height. At that time a building of 80-stories was considered the limit from an economical and logistics point of view, since more stories means more elevators which means less rentable space. To counter this problem, they introduced a new system with the concept of sky lobbies which acted as central hubs where people would switch from express elevators to local elevators to get to the desired floor (Figure 17). The benefits of such a system are that multiple elevators can make use of the same elevator shaft thus reducing the required amount of shaft needed and making the additional 30 floors economically feasible (NIST, 2005).

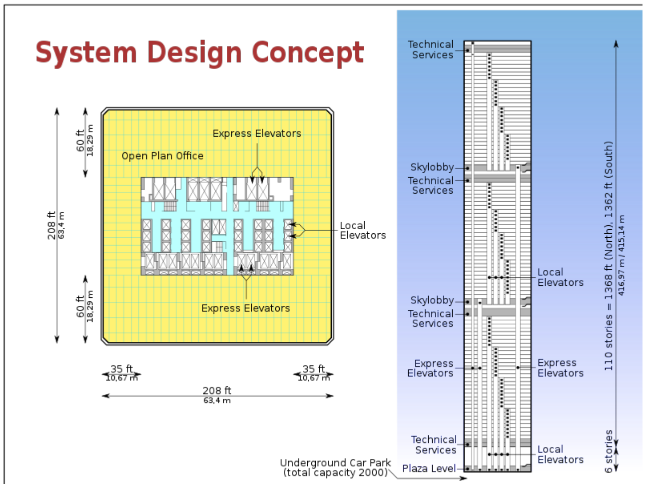


Fig.17 Elevator system design with use of sky lobbies in the Twin Towers (MacRudi- Wikipedia, 2008)

The structural design included a variety of innovating design changes that allowed the buildings to be feasible to construct. At the time most skyscrapers were built with a skeleton of columns spread out through the interior. However, for this design an exterior framed-tube system was chosen to allow an uninterrupted floorplan from its core to its façade (Figure 18). This exterior frame consisted of 236 narrow columns, 59 in each side. These columns were welded to steel plates to create a prefabricated element spanning three stories tall and were three columns wide which could be installed with ease (McAllister et al, 2013).

For the floors a truss system with cast-in situation concrete was chosen (Figure 19). This system not only supported gravitational loads but it also provided lateral stability for the exterior structure and distributed wind loads evenly among the facades. Each floor consists of 102 mm thick lightweight cast-in situation concrete on top of a metal deck, supported by lightweight steel trusses either 18,3m or 10,7m long. The web extends above the top cord and are referred to as knuckles. When the concrete floor is poured these knuckles become embedded into the slab creating a stiff connection between the slab and the truss. Each truss is spaced 2 meters apart from each other and are connected through bridging trusses every 4 meters. The top cords of the trusses were longer than the bottom cords so that the top cord could rest on top of a truss seat welded to the exterior. The bottom cords were connected to the exterior by viscoelastic dampers to reduce the sway and vibration of the towers when submitted to wind loads (McAllister et al, 2013).

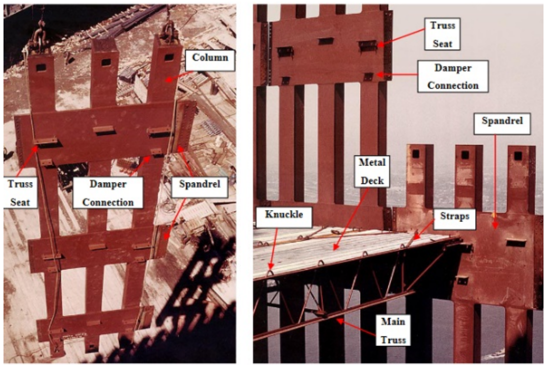


Fig.18 Exterior columns prefab panel being placed (McAllister, 2013).

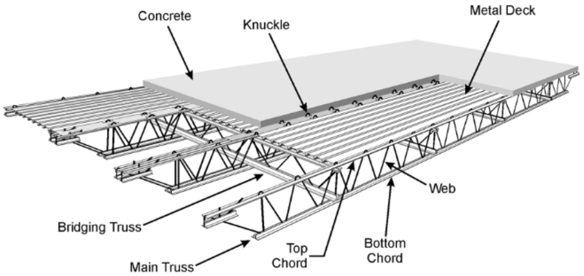


Fig.19 Floor system used in the Twin Towers (McAllister, 2013).

3.1 The attack on the Twin Towers

On the morning of Tuesday, September 11, 2001, an airplane was hijacked midair and deviated its course and headed towards the Twin Towers. A few minutes later the plane flew towards the North Tower with its nose slightly downwards and on banking to the left. The airplane hit the North façade of the tower with its nose at the 96th floor and made a cut in the building from the 93th to the 99th floor (Figure 20). The 94th was severely damaged (NIST, 2005). The midsection of the left wing, filled with fuel, and the left engine destroyed 17 exterior columns and heavily damaged 4 more. Several pieces heavily damaged the core columns of the building and ripped of the insulation around the trusses. Most of the damage was to the 95th and 96th floor where the inner left wing hit the concrete slab from floor 95, destroying the whole floor from exterior to the core and went another 6 meters into the core itself. The main body of the plane hit the 96th floor slab and filled a space covering the 95th and 96th floor top to bottom. In total 35 exterior columns and 6 core columns were destroyed and 2 exterior columns and 3 core columns were badly damaged. 43 of the 47 core columns were stripped of their insulation on 1 or more floors and roughly 5.600 m^2 of insulation was ripped off the floor trusses (Figure 21).

Even though the impact of the plane had caused severe damage to the North Tower it was still structurally standing. However, the impact did severe the pipes for the sprinkler system, causing water to pour into the stairwells, and collapsed the walls of these stairwells as well as rendering the elevators' unusable for the top 60 floors, which resulted in a blockade of all escape paths from the 92th floor and up (NIST, 2005).

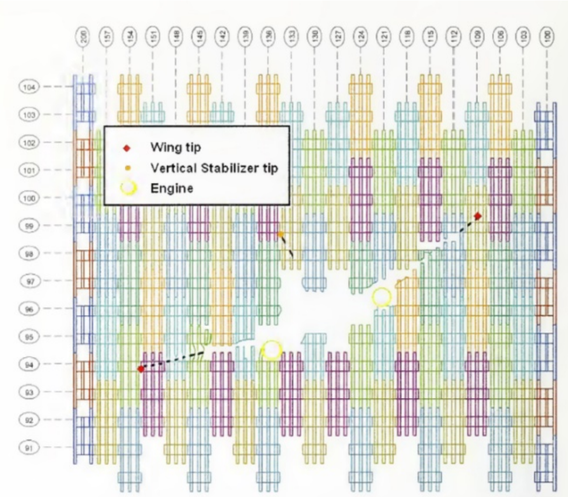


Fig.20 South façade impact zone at the North Tower (NIST, 2005).

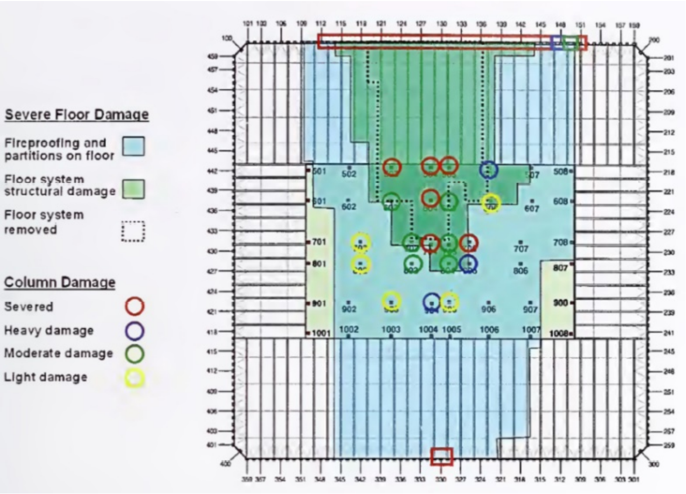
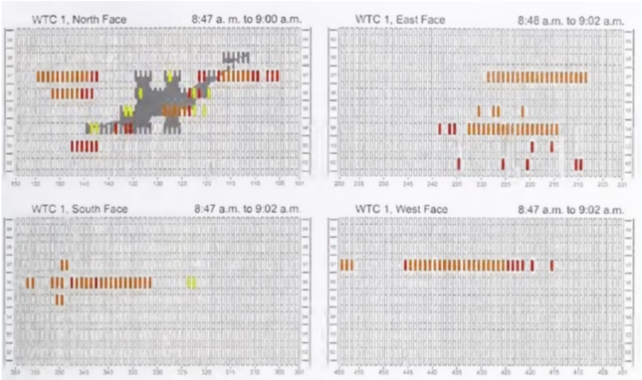


Fig.21 Cumulative impact damage from floor 93 through 98 of the North Tower (NIST, 2005).

On impact, the fuel tanks of the airplane were cut open by the exterior columns which resulted in the fuel spewing in all directions. As the jet fuel used in the plane is highly flammable, some of it ignited on contact with both the hot debris and electrical devices (NIST, 2005). Combined with the dust from damaged walls and floors the ignition resulted in fireballs and an extreme overpressure in the building which blew out windows in the east and south side of the tower. After the fireballs had disappeared over half of the fuel was still inside the building and caught on fire upon ignition (Figure 22). Due to the blown-out windows the fire was fed with fresh air and continued to intensify over time. There was no way to fight against the fires as the sprinkler system was inoperable and there was no access to the floors. Even if the sprinkler system was operable, it would have been activated immediately at triple capacity within the first 13 minutes to overcome the fires. Any later would have been too late.

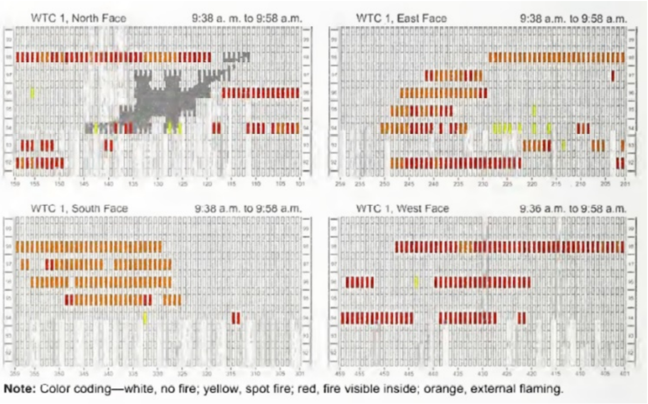


Note: Color coding—white, no fire; yellow, spot fire; red, fire visible inside; orange, external flaming.

Fig.22 Exterior view of the fire development in the North Tower between 8:47a.m. and 9:02a.m. (NIST, 2005).

15 minutes after the impact with the North Tower a second airplane flew towards the Twin Towers. This airplane, approaching from the south, flew into the South Tower and a similar scenario developed around the 80th floor of the building.

As the fires continued to burn in the North Tower the aluminum frames from the windows started to weaken and were either push outward or suck inwards to supply more fresh air to the fire and provide a path for the hot gasses and smoke (Figure 23).



WTC 1, North Face 9:38 a. m. to 9:58 a.m.

WTC 1, East Face 9:38 a.m. to 9:58 a.m.

WTC 1, South Face 9:38 a.m. to 9:58 a.m.

WTC 1, West Face 9:36 a.m. to 9:58 a.m.

Note: Color coding—white, no fire; yellow, spot fire; red, fire visible inside; orange, external flaming.

Fig.23 Exterior view of the fire development in the North Tower between 9:38a.m. and 9:58a.m. (NIST, 2005).

75 minutes after the impact with the North Tower, the South Tower collapsed without a warning. 226.000 metric tons of steel and concrete fell to the ground causing the earth to vibrate up to 160km away. In the air, the collapse caused a pressure wave to hit the North Tower, which made the fire more intense (NIST, 2005).

After the collapse of the South Tower the temperatures in the North Tower had increased ranging from 500°C to 1.000°C. As most of the insulation had been torn of on impact, the exterior columns, core columns and the floor trusses started to rise in temperature. As the temperature of the steel increased, its strength decreased resulting in a loss of loadbearing capacity and lateral load resistance. The high temperatures in the steel causes the beams to become more and more elastic and start to bend. Over time the floors in the affected areas started to sag and in doing so pulled the exterior columns inwards (NIST, 2005).

3 of the 4 structural components were heavily affected and weakened by the impact and the fires. The moment the south exterior wall failed to transfer it load to the remaining structure, the part of the building above the impact zone started to tilt and floors started to collapse. In the following 12 seconds all of the North Tower had collapsed (NIST, 2005).

3.1.2 The South Tower

As the airplane flew into the North Tower, the occupants in the South Tower quickly started evacuating the building. Within just 5 minutes over half of the occupants had left their floor and made their way to the concourse level. 16 minutes after impact approximately 3.000 people had evacuated the building (NIST, 2005).

While the evacuation of the South Tower was in progress another airplane was hijacked and changed its course towards the south façade of the South Tower. The center of the plane hit the building on the 81st floor slab in a slightly downwards pitch and was banked slightly to the left and caused destruction over 9 floors on impact (Figure 24). On the 78th floor 9 exterior columns and 19 windows were destroyed. From the exterior to the core the insulation was ripped off the floor trusses. On the 79th floor an 8-meter-deep portion of the floor slab was shattered all the way into the core structure herby destroying 15 exterior columns, 9 core columns and stripped of all insulation of the floor trusses east of the core. Most of the damage was inflicted on the 80th and 81st floor which were directly hit by the main body of the plain. Just as on the 79th floor a large chunk of floor was shattered on the 80th floor in the same position and 10 exterior columns were destroyed. In addition, a 21-meter-deep strip of floor was crushed along the east side of the core which caused the northern part of the floor to sag on the east side. 10 core columns were destroyed directly above those that were hit on the 79th floor. Most of the insulation was stripped of 2/3 of the core structure and from the trusses along the east side of the floor. On the 80th floor shattered a 12-meter section of the floor slab including a part of the southeast corner of the core structure. In total 33 exterior columns and 10 core columns were destroyed. 39 of the 47 core columns were stripped of their insulation on one or more floors and roughly 7.400 m^2 of insulation was ripped off the floor trusses (Figure 25).

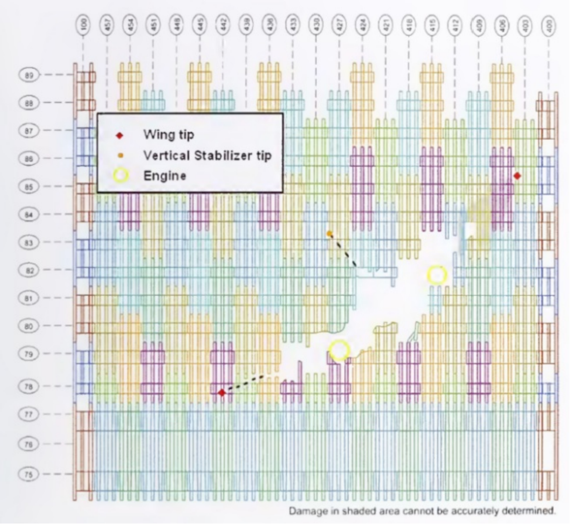


Fig.24 South façade impact zone at the South Tower (NIST, 2005).

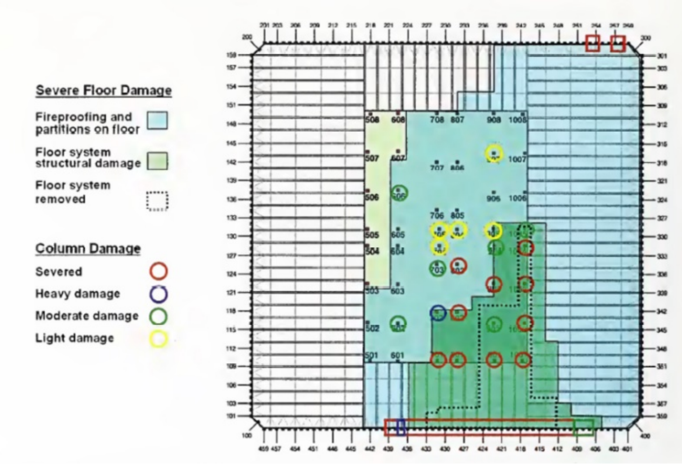


Fig.25 Cumulative impact damage from floor 78 through 83 of the South Tower (NIST, 2005).

Just like to the North Tower the impact of the airplane had caused severe damage to the South Tower yet it was still structurally standing (NIST, 2005). Once again pipes had been severed that fed water to the sprinkler system and all elevators were out of service at the impacted floors and upward. Fortunately, unlike what happened at the North Tower, here the northern stairwell was still passable on the impacted floors providing an escape route for the upper part of the tower.

As the fuel was scattered around, several fireballs could be seen bursting out of the windows which supplied the starting fires with air (Figure 26). For the following 30 minutes the small fires intensified around the debris and started to spread and grow. As the southeast corner of the core structure was severed, this load had to be absorbed by the exterior columns on the east and south façade and the east wall of the core structure. The affected floors on the east side of the building started to increase in temperature and sag. This led to the exterior columns in the east façade to be pulled inwards one by one over time and losing their loadbearing abilities with each displacement. With the exterior columns at the east façade unable to provide loadbearing capacity, the already weakened core system was unable to provide support and the top of the building started to lean to the south east after which the South Tower collapsed.

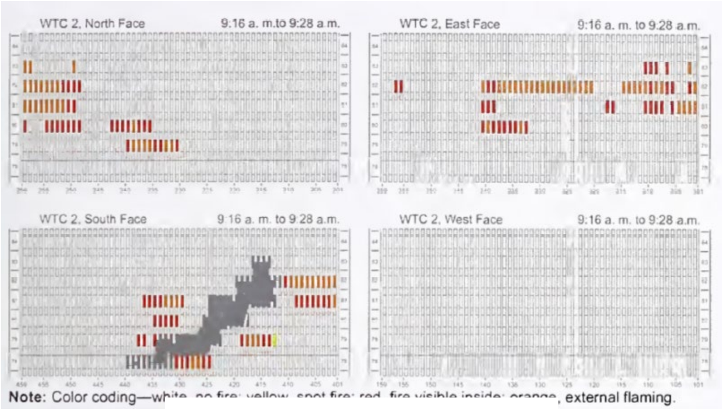


Fig.26 Exterior view of the fire development in the South Tower between 9:16a.m. and 9:28a.m. (NIST, 2005).

Around 7pm, 10 hours after the first airplane hit the North Tower, all 7 buildings of the World Trade Center Complex had been destroyed (Figure 27).

Fig.27 Aerial view after the collapse of all WTC buildings. (NIST, 2005).

3.2 The Aftermath of the Twin Towers

Based on photographs, media footage, eyewitnesses, debris analyses and rapports from the NYPD and FDNY, Leslie E. Robertson Associates (LERA) was contracted to construct a reference model (Figure

28 to 31) with use of the SAP2000 v8 software. This reference model was used to perform computer simulation in order to establish the capacity of the buildings to simulate what would happen if an airplane impacted the building and to reconstruct the mechanics of the airplane impact damage, heat from fires and to construct a timeframe of local failures resulting in the building collapse (NIST, 2005).

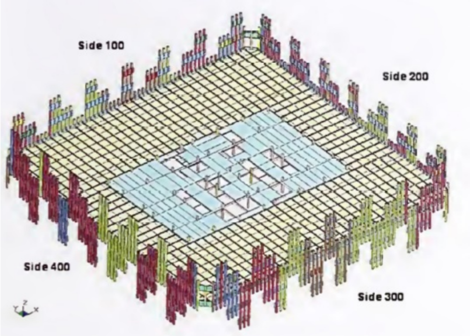


Fig.28 Structural model of the 96th floor of WTC 1. (NIST, 2005).

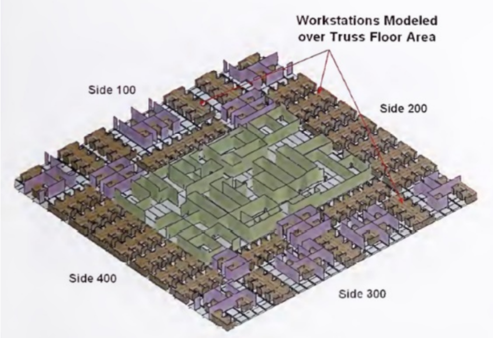


Fig.29 Model of the 96th floor of WTC 1, including interior. (NIST, 2005).

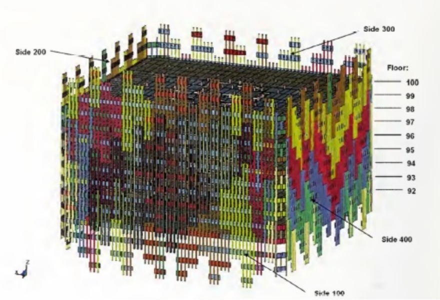


Fig.30 Multi-floor global model of WTC 1 Northside. (NIST, 2005).

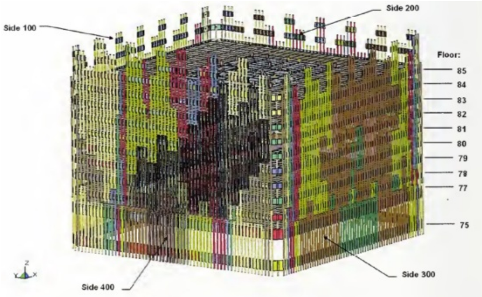


Fig.31 Multi-floor global model of WTC 2 Southside. (NIST, 2005).

Regarding the core framing structure, the analyses and simulations concluded the following: in the North Tower the core structure was most weakened from the rising temperatures at the center of the southside of the core and in the South Tower the core structure was most weakened from the rising temperatures at the southeast corner along the eastside of the core (NIST, 2005).

For the floor trusses system, the analyses and simulations concluded the following: as the floors were heated and reached a temperature between 100°C to 400°C they started to thermally expand and puss the exterior columns outwards. During this expansion no floor started to deform up- or downwards since the exterior columns were not able to create a sufficient reaction force to resist the outwards push. When temperatures above 400°C were reaches the floors started to sag as stiffness and strength reduced in the heated steel. From here on the floors stop exerting an outwards force on the exterior columns and now exerted an inwards force on the exterior columns (NIST, 2005).

As for the exterior columns structure, the analyses and simulations concluded the following: The inward bowing at the affected floors had to be from inward pull forces, which were caused by the floors as mentioned above. The extreme heat did play a role in the deformation but was not the main factor. From the inward motion of the exterior columns, it was concluded that most floors were still connected to the exterior structure (NIST, 2005).

Immediately after the impact with the North Tower the exterior columns on the north and south side of the building lost 7 percent of their loading capacity which had to be compensated by the east and west side. After the impact with the South Tower the exterior columns on the south and east side of the building lost 12 percent of their loading capacity which had to be compensated by the north and west side. The increasing temperatures resulted in an expansion of the concrete and steel in the core. As the steel heated up faster than the concrete walls surrounding it, the steel wanted to expand upwards but was pushed back through the construction causing more exerted force on the core columns. As the floor temperature increased it started to sag due to the reduction of strength and stiffness of the trusses pulling the exterior columns into the building. As fires became more intense the core columns started to weaken and shorten and began to transfer their load to the exterior. At 43 minutes past the impact with the South Tower the east exterior columns became unstable and started to bend inwards. At 100 minutes past the impact with the North Tower approximately 20 percent of the core loads had been transferred to the exterior columns. The inward pull on the exterior columns caused columns of both towers to become unstable and unable to provide structural support. This meant that more loads had to be supported by the core and remaining exterior columns which were already at their limit. As the building section above the impact zone started to tilt the instability of the remaining exterior columns increased which increased the load on the weakened core columns. In the North Tower building part above the impact zone began to move downwards the affected area of the impact transferring more load on the core columns. At different times both towers were unable to transfer loads from the core columns to the remaining exterior columns resulting in a failure of both cores leading to the collapse of the Twin Towers (NIST, 2005).

3.3 The response to the 9/11 attack

Based on the gathered information from both visual inspection and the analyses of the damage that happened to the Twin Towers caused by impact with 2 airplanes, it is concluded that the buildings would have remained standing after the impact were it not for the removal of the insulation and the fires that could not be controlled due to the failure of the sprinkler system. Following this investigation from the NIST 30 recommendations were formed to improve the buildings safety and structural integrity in case of an emergency or attack. These recommendations can be divided into the following 8 topics: 1) Increase structural integrity to prevent progressive collapse and enhance stability in tall buildings. 2) Enhance fire endurance of structure including the technical basis for determining construction classification and fire resistance ratings. 3) Introduce new structural design to resist fires including the objective of a burnout of a building without collapsing. 4) Improve active fire protection into the design. 5) Improve building evacuation through rapid and safe egress out of the building. 6) Improve emergency response with better access to each floor and form communication throughout the building. 7) Improve procedures and practices for buildings in case of an emergency. 8) Introduce education and training of fire protection to engineers, architects and building regulatory.

Chapter 4. Analyzing the replacement buildings

Following the aftermath of the Oklahoma City Bombing in 1995 planning for a new federal building started within a few months (U.S. General Services Administration, 2004). It was decided by the municipality of Oklahoma City that the site of the destroyed Murrah building would be used to create a national memorial to commemorate the tragedy (U.S. General Services Administration, 2004). 2 city blocks were allocated for the new building northwest of the memorial and architect Carol Ross of Ross Barney + Jankowski architects was to design the building under strict surveillance of Ed Feiner, GSA's chief architect (Pollalis, 2006). Construction of the building started in October 2001 and was completed in

December 2003 (Figure 32, 33). The concept of the design was to provide openness to the public while at the same time provide security to its tenants.

Fig.32 Site plan of the Oklahoma City Federal building with the adjacent park and parking (U.S. General Services Administration,

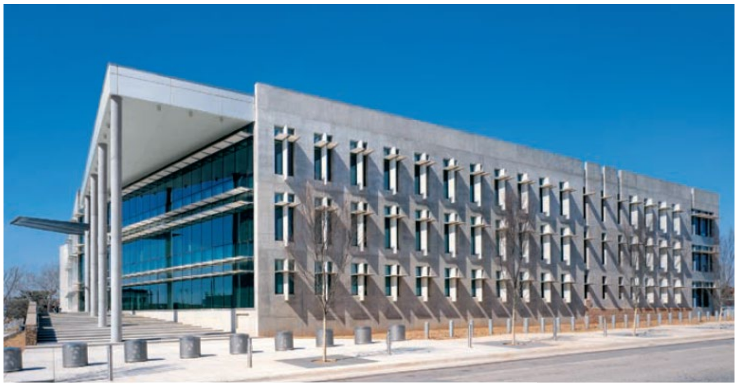


Fig.33 A view from across the street of the Oklahoma City Federal building (U.S. General Services Administration, 2004)

The U.S. General Services Administration (GSA), in charge of developing the new federal building, developed new security guidelines for federal buildings after the bombing and most of these features have been implemented in the design (U.S. General Services Administration, 2004).

As mentioned in chapter 2, the Murrah building was constructed with the use of a moment resisting frame that was cast in situation. the new design also includes a moment resisting frame cast in situation but in this case with a dual system to prevent a progressive collapse of structural elements when one such elements is damaged as has been the case during the ‘95 bombing. To prevent vehicles from coming to close to the building a new regulation was introduced with the requirement that a government building must be at least 15m from the street and that loading and unloading is not allowed closer than 6m from the building. In addition, protective barriers were erected around the building to make it even more difficult for vehicles to get close to it. A deliberate choice was made not to include the car park under the building, but to the north of the complex with restricted access in order to prevent attacks such as the ‘93 WTC bombing (U.S. General Services Administration, 2004). However, it is unknown whether the introduction of these regulations was formed as a result of the ’93 bombing or other factors.

A major cause of injury during the ’95 bombing was caused by shards of glass flying into the building as a result of the explosion. In the new design, therefore, laminated glass was chosen that breaks but does not fly into the building, combined with an aluminum window frame designed to bend in place (U.S. General Services Administration, 2004).

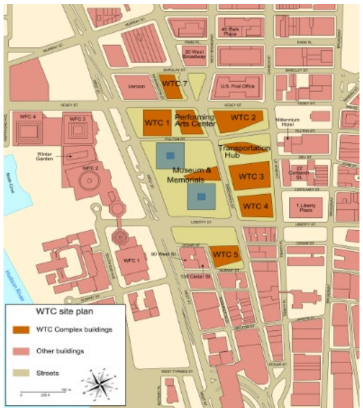
The lobby, on the south side of the building, is open to the public and allows people to access the open space at the north of the building without going to security. In order to guarantee the safety of the users, the two blast-resistant walls between the lobby and the workplaces are designed to minimize damage by sending the blast upward instead of further into the building towards the office spaces (Pollalis, 2006)(Figure 34).

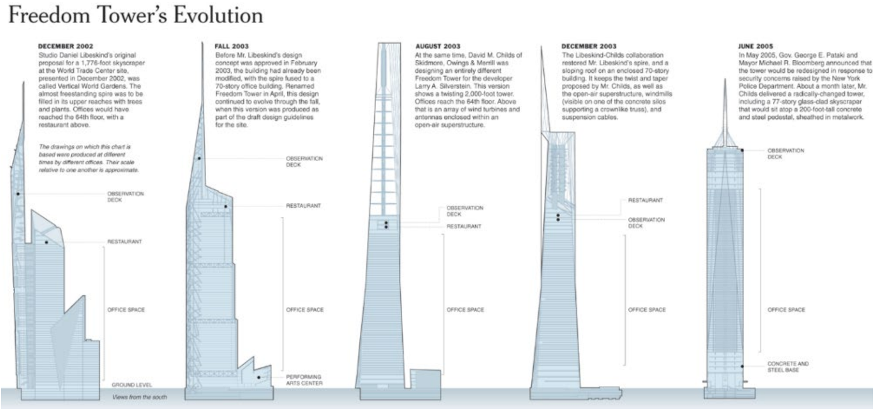
Fig.34 Section of the lobby showing a blast-resistant wall between the lobby and the office space (Pollalis, 2006).

As construction of the new building began within a month after the 9/11 incident and no mentions of changes based on this incident can be found in reports it can be concluded that the 9/11 incident did not influence the design of the Oklahoma City Federal Building. In an article from the Los Angeles Times in December 2001, Feiner stated that "Oklahoma City was our baptism of fire; 9/11 was a horrible tragedy, but we had a lot of, let's say, prep work, because we experienced a lot in the Murrah building. The new federal building under construction in Oklahoma City may be used as a template for new civic architecture after 9/11.'' (Pollalis, 2006). With this statement, Feiner reinforces the argument that the 9/11 incident did not affect the design of the new Oklahoma building.

4.3 One World Trade Center

Following the 9/11 tragedy in 2001 proposals for the site's reconstruction started almost immediately in 2002 with a design competition held by the Lower Manhattan Development Corporation. These proposals led to the design as seen in Figure 35 where the new complex would be constructed around the old site of the Twin Towers which was to become a memorial. The WTC 1 building of the new complex was envisioned to be the replacement of the Twin Towers and to become the new icon of the complex. Over a 3-year period several designs were proposed resulting in a merger of the designs from Studio Daniel Libeskind and Skidmore, Owings & Merrill (SOM) in 2005 (Figure 36) which was later refer to as the One Word Trace Center or One WTC. The final changes in design were to ensure the building was especially designed to withstand attacks such as the '93 bombing and the 9/11 attacks because the One WTC will most likely to become a target for such attacks in the future (Jester, 2016).





Freedom Tower's Evolution

DECEMBER 2002
Studio Daniel Libeskind's original proposal for a 1,776-foot skyscraper at the World Trade Center site, presented in December 2002, was called Vertical World Gardens. The almost freestanding spire was to be filled in its upper reaches with trees and plants. Offices would have reached the 64th floor, with a restaurant above.

The drawings on which this chart is based were produced at different times by different offices. Their scale relative to one another is approximate.

FALL 2003
Before Mr. Libeskind's design concept was approved in February 2003, the building had already been modified, with the spire fused to a 70-story office building. Renamed Freedom Tower in April, this design continued to evolve through the fall, when this version was produced as part of the draft design guidelines for the site.

AUGUST 2003
At the same time, David M. Childs of Skidmore, Owings & Merrill was designing an entirely different Freedom Tower for the developer Larry A. Silverstein. This version shows a twisting 2,000-foot tower. Offices reach the 64th floor. Above that is an array of wind turbines and antennas enclosed within an open-air superstructure.

DECEMBER 2003
The Libeskind-Childs collaboration restored Mr. Libeskind's spire, and a sloping roof on an enclosed 70-story building. It keeps the twist and taper proposed by Mr. Childs, as well as the open-air superstructure, windmills (visible on one of the concrete silos supporting a crownlike truss), and suspension cables.

JUNE 2005
In May 2005, Gov. George E. Pataki and Mayor Michael R. Bloomberg announced that the tower would be redesigned in response to security concerns raised by the New York Police Department. About a month later, Mr. Childs delivered a radically-changed tower, including a 77-story glass-clad skyscraper that would sit atop a 200-foot-tall concrete and steel pedestal, sheathed in metalwork.

Fig.35 New WTC floorplan with 9/11 memorial (Mamgomann88-Wikipedia, 2011).

Fig.36 Evolvement of Freedom Tower/WTC 1 building (NYCurbanism, 2019)

The design of the One WTC is quite similar to that of the Twin Towers. The footprint of the One WTC is the same size as that of the Twin Towers and the top of the building, excluding the antenna, is for symbolic reasons constructed at the same height the Twin Towers used to be. however, difference in the design can be seen starting from the 20th floor when the corners stare to taper all the way to the top of the building. Because of this no office floor is exactly the same and floors can be categorized in 3 variants (Figure 37).

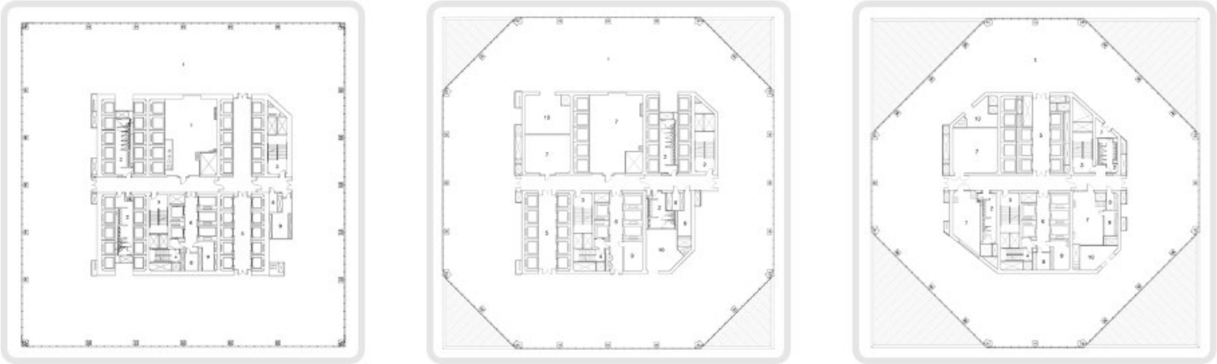


Fig.37 Different variants of floorplans in the One WTC (Architectmagazine, z.d.)

The construction makes use of a steel and concrete core and a moment resisting steel frame at the façade. Just like in the Twin Towers this creates and open space from core to façade. However, in the One WTC design larger steel columns are used to create a more open façade and stronger construction (Figure 38). As the corners of the building tapers into the building, both the core and exterior structure deviate from their square layout to a more complex form. The vertical columns needed for this construction significantly add to the stiffness of the structure. It is noticeable that the exterior of the first 20 floors consists of solid concrete walls, referred to as the podium, instead of an open steel structure to protect the base of the tower against truck bombing (Mennella & Gottesdiener, z.d.).

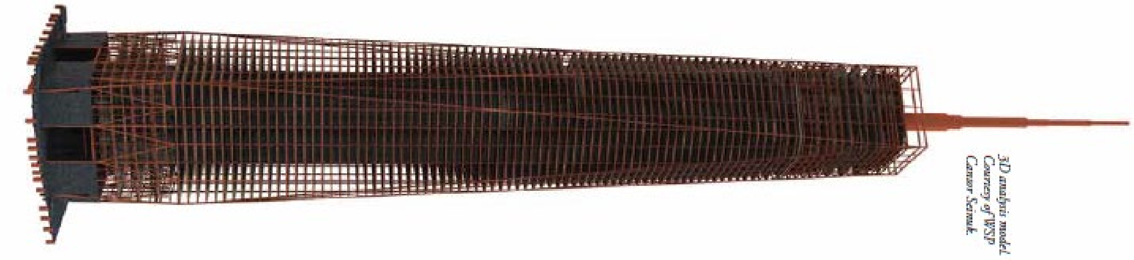


Fig.38 Structural design of the One WTC (Rahimian & Eilon, 2012).

Instead of using a truss system in for the floors, solid steel beams are used to support a metal deck with a cast-in place concrete floor. Even though these steel beams are significantly heavier than a truss the added mass greatly increases it resilience to failure caused by rising temperatures in the steel (Mennella & Gottesdiener, z.d.).

As mentioned before the core structure is a combination of steel and concrete similar to the Twin Towers. Just like the exterior columns the shape of the core changes from floor to floor and forms a stronger construction. not only the shape of the core makes the structure stronger, but also the high-pressure concrete used, which has a higher density than normal concrete due to less air pockets, contributes to its overall strength. Because of this, the core is the key element of the structure and is considered a fortress in the building providing life safety and communicative systems in case of an emergency. In the event of an emergency, emergency services personnel can use a dedicated first responder stair and elevator which spans the whole building height. To ensure a fast and safe evacuation of the building all staircases are 50% bigger in comparison to those of the Twin Tower and are 20% bigger than required by code (Figure 39). On top of that are all stairwells air pressured to prevent smoke and fire to enter herby improving visibility and safety during evacuation (Mennella & Gottesdiener, z.d.).

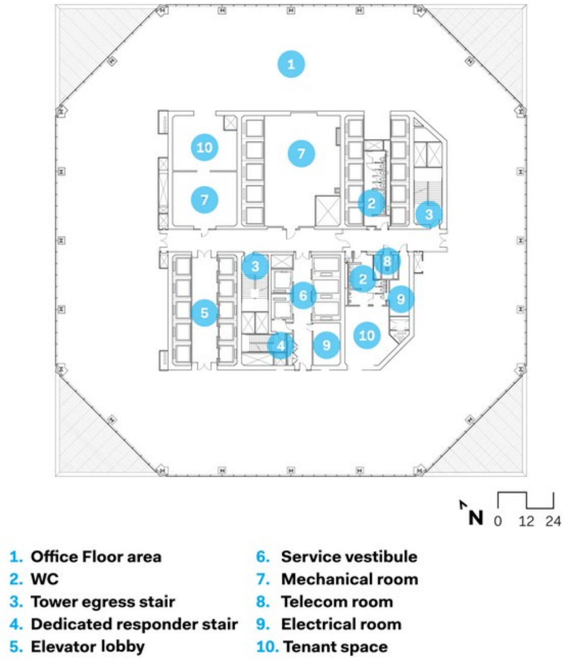


Fig.39 Detailed floorplan with core functions layout
(Architectmagazine, z.d.)

Chapter 5. Conclusion

The purpose of this thesis was to analyze what changes were made in designing after a terrorist attack to determine how we approach structural and safety design differently by analyzing 3 case studies and their replacement buildings.

From the analyses of the World Trade Center Bomber in 1993 the conclusion was drawn that the bomb, exploded on the B-2 subterranean level, caused a significant amount of damage to the complex but the complex was not at risk of collapsing. The damage done to the emergency generators and the sprinkler system caused a blackout in the complex and rising fires could not be put out. Smoke from the subterranean levels rose upward into the Twin Towers through the elevator shafts and stairwells. Without guidance, rising smoke and unfamiliarity with exit routes chaos erupted thereby endangering lives. First responders had trouble clearing all floors of the building due to poor connection and access to the floors. As a result, from this attack several changes were made to the building. Additional backup generators with batteries were installed to ensure power throughout the building. On each floor and in each elevator means of communication were introduced to speedup evacuation time. Illuminating paint and signs were installed in the staircases to provide directions and practice drills were introduced. Finally, the entrance of the subterranean parking would be restricted and each vehicle was checked before entering.

From the analyses of the Oklahoma City bombing in 1995 and the replacement building the conclusion was drawn that the destruction of the Murrah building was due to a vehicle containing explosives was able to detonate within a short distance of the building. The destruction of the G20 column led to a progressive collapse of half of the building as a result from the structural design and most casualties were caused from flying shards of glass from the windows exposed to the blast. In the replacement design vehicles are not able to get within 15m of the building's façade due to the use of integrated barriers. If an explosion happened close to the building the improved structure would ensure that with a failure of 1 component no progressive collapse would occur. In addition, laminated glass is used with window frames that deform on contact with shock waves to protect building occupants from flying debris. Finally, the offices are separated from the lobby by blast resistance walls that disperse shockwaves upward out of the building.

From the analyses of the 9/11 attacks in 2001 and the replacement building the conclusion was drawn that the impact with an airplane in each tower caused a significant amount of damage to the Structure but both towers were not at risk of collapsing if it wasn't for the fires that couldn't be controlled in time. Once again emergency systems were inoperable therefore the fires couldn't be put out. Emergency services tried reaching the affected floors but were significantly slowed down on the staircases due to the evacuation of personnel through the same staircases. Occupants above the impact zone had no escape route to the ground since the core was not strong enough to prevent the collapse of the stairwells at the impacted floors. On impact a significant amount of fireproof insulation was stripped of the steel construction which started to rise in temperature due to the fires and stated to weaken until no longer functionable leading to the collapse of both towers. In the replacement building high pressure concrete is used to construct a stronger and sturdier core in the building to protect life safety and communicative systems in case of an emergency. The moment resisting exterior columns combined with the steel floor beams are larger and more massive than in the Twin Towers to slow down load bearing capacity as it takes longer to rise in temperature. The staircases are 50 wider than before and all staircases are pressured to keep out fire and smoke. For emergency services a dedicated first responder stair and elevator are implemented into the core of the building. Finally, the first 20 floors are protected from vehicle explosion due to the concrete outer walls.

In all 3 cases most changes were made in order to either improve structures to isolate damage at the location of the blast or to improve the safety of people in the building at the moment of an attack or during the evacuation.

Sources

~ National Institute of Standards, & Technology (US). (2005). Final report on the collapse of the World Trade Center towers (Vol. 13). US Department of Commerce, Technology Administration, National Institute of Standards and Technology.

~ Gene Corley, W., F. Mlakar Sr., P., A. Sozen, M., & H. Thornton, C. (1998, 8 januari). Downloaded 939 times TECHNICAL PAPERS The Oklahoma City Bombing: Summary and Recommendations for

Multihazard Mitigation. ASCE, x. https://ascelibrary-org.tudelft.idm.oclc.org/doi/10.1061/%28ASCE%290887-3828%281998%2912%3A3%28100%29

~ NIST. (2005). Final Report of the Collapse of the World Trade Center Towers. https://nvlpubs.nist.gov/nistpubs/Legacy/NCSTAR/ncstar1.pdf

~ Manning, W. A. (Ed.). (1993). The World Trade Center Bombing: Report and Analysis. Fire Engineering.

~ V. Parachini, J. (2000). The World Trade Center Bombers (1993). nonproliferation. https://www.nonproliferation.org/wp-content/uploads/2016/05/world_trade_center_bombers.pdf

~ Osteraas, J. D. (2006). Murrah building bombing revisited: A qualitative assessment of blast damage and collapse patterns. Journal of performance of Constructed Facilities, 20(4), 330-335.

~ Sunder, S. S. (2008). NIST Response to the World Trade Center Disaster Federal Building and Fire Safety Investigation of the World Trade Center Disaster.

~ McAllister, T. P., Sadek, F., Gross, J. L., Averill, J. D., & Gann, R. G. (2013). Overview of the structural design of World Trade Center 1, 2, and 7 buildings. Fire technology, 49(3), 587-613.

~ U.S. General Services Administration. (2004). OKLAHOMA CITY FEDERAL BUILDING. https://www.gsa.gov/cdnstatic/Oklahoma_City_Federal_Building__Oklahoma_City__OK.pdf

~ Rahimian, A., & Eilon, Y. (2012). *The Rise of One World Trade Center*. structuremag.org. https://www.structuremag.org/wp-content/uploads/F-WTC-Nov121.pdf

~ Mennella, M. T. C., & Gottesdiener, T. S. (z.d.). *One World Trade Center, the tallest building in the Western Hemisphere*. WSPglobal. https://www.wsp.com/en-GL/projects/one-world-trade-center#Services

~ Pollalis, S. N. (2006, september). OKLAHOMA CITY FEDERAL BUILDING. Harvard. http://www.gsd.harvard.edu/wp-content/uploads/2016/06/pollalis-case-Oklahoma-Sept2006-public.pdf

~ Some Articles from Engineering News Record. (z.d.). 9–11 Research. Geraadpleegd op 12 maart 2021, van https://911research.wtc7.net/mirrors/guardian2/wtc/eng-news-record.htm

~ Jester, J. (2016, 2 september). *Post-9/11 WTC security: Never forget, never again*. CNBC. https://www.cnbc.com/2016/09/02/post-911-wtc-security-never-forget-never-again.html