REVIEW ON THE WORLD TRADE CENTER TERRORIST ATTACK FIRES

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ABSTRACT

The disastrous terrorist attack on New York World Trade Center (WTC) on 11 September 2001 (9.11) has raised concerns on the fire safety provisions of high-rise buildings. In this paper, fire safety provisions with some description related to the structural design, construction and materials of the WTC appeared in the literature will be briefly reviewed. The extraordinary building height can be given by the high strength steel structure. As pointed out, thermal effect on the structural steel members should be watched eventhough it can stand for over an hour before collapsing.

1. INTRODUCTION

The World Trade Center (WTC) in New York was among the 4th or 5th tallest building in the world with its 110-story twin towers completed in 1973. The 1362-ft and 1368-ft high towers were the landmark of the city with the host of this project, Port Authority of New York and New Jersey spending US$ 700 million on it. In return, the symbolic skyscrapers have appealed hundreds of tenants including international trading companies, leading investment, law and accounting firms in which about 55,000 office workers were employed.

On 11 September 2001, two hijacked civilian aircrafts were piloted to hit intentionally towards the twin towers. As reported [1], devastating impact was made on the upper part of the towers at about the 80th and 95th floor. Each of the jetliners was carrying about 10,000 gallons of jet fuel. The towers were able to stand after the severe crash causing damages to many floors. As stated by the structural engineers concerned, the original design is capable of withstanding impact of a civil jetliner commonly used at the time the towers were constructed. The structural design was proved to be workable in this incident. However, after burning such a huge fire for one hour, the two towers collapsed together with several other buildings of the complex.

This incident has raised public concern on the fire safety provisions in high-rise buildings. As the primary structural elements in the towers were of 2-hour or 4-hour fire resistance periods (FRP), the two buildings collapsed after 1 hour and 1¾ hours respectively [2]. Professionals and authorities are reviewing whether designing fire safety provisions just for accidental fire is sufficient. Therefore, fires not only caused by accidents in high-rise buildings should be studied.

In this paper, a case study on WTC would be carried out. The structural design, materials used and fire safety provisions would be reviewed based on the information available in the published works.

2. STRUCTURAL DESIGN AND CONSTRUCTION

At the time of constructing the WTC, the prevailing and widely used design for skyscrapers was to make the central core as the primary load-bearing structure. But an innovative structural design was applied in the WTC twin towers project [3]. A central core composed of a cluster of steel columns was used to support the elevators and stairs. It was not enduring the weight of the whole structure but only the load of gravity of a portion of the building. Steel columns, spacing 40” apart at the center, distributed on the perimeter were the main load-bearing structure to support the whole building. A giant rigid tube was created by closely spaced columns, 59 on each side, standing on the perimeter; which is so-called “tubular structure”. It was envisaged as a more efficient way to withstand the horizontal wind loads. The closely spaced columns on the perimeter were transitioned in an arch-like configuration to a 10-ft spacing for the first three lower stories.

Steel trusses, 29” in depth, running between the internal and perimeter steel column groups were holding up the 4” lightweight concrete floor slab plates as well as stabilizing the outer structure. Metal deck in the core area was filled with concrete of thickness 5”.

The structural design [1] would be capable of withstanding the forces from natural hazards, such as hurricanes, floods and earthquakes. Note that

wind loading was regarded as the most important factor to consider. The building was not designed for disasters such as terrorist attack. However, it appeared that the building was able to withstand the impact of an aircraft as it can stand wind loading for wind speeds up to 200 miles per hour (mph).

A column-free office floor space was created by the rigid steel column sets connected by horizontal floor composite system of 33" in depth and spanning 60 feet underneath the concrete floor slab. The rentable office space per floor was up to 40,000 ft^2. The central core containing lift shafts and three exit stairways was of the size 87 feet by 137 feet (about 12,300 ft^2).

For the traditional elevator system, it might require more than half of the floor space for the immense size of the elevators to serve 110 stories. In order to maximize the rentable office area and give better lift traffic such as increasing the traveling speed, an express and local lift system was developed with "sky lobbies" on the 44th and 78th floors. There, passengers would change elevators for vertical transportation. Elevated system commonly used nowadays in skyscrapers would free up about 75 % of the total floor area.

3. MATERIALS

The major framework of the WTC twin towers was constructed of steel. That included the exterior tube-like structure, the internal core and the steel trusses supporting the floors. The floor construction was made of concrete. Glass curtain wall was installed in between the densely spaced exterior columns. The limited width of the glass windows could relieve occupants' discomfort at the extremely high stories. As reported [4], the twin towers were constructed with more than 200,000 tons of steel, 425,000 cubic yards of concrete and 600,000 ft^2 glass in 43,000 windows. Each floor, constructed of reinforced concrete pad, metal deck as well as the underneath steel trusses, was weighing about 4.8 million pounds.

On the steel columns, silver-colored aluminum alloy was finished. Moreover, fire protection was provided with a spray-applied product containing asbestos on the structural steel members up to the 39th floor. Asbestos-free mineral fiber materials were sprayed on those in the other floors and in the South tower of WTC.

4. FIRE SAFETY DESIGN

Passive building designs for fire protection, including compartmentation, means of escape (MoE), means of access (MoA) [5] and FRP [2], are required in this type of modern architecture as specified in the National Building Code [6] in USA. However, those regulations appear to be set for accidental fires starting from ignition, such as burning paper or furniture. The fire resulted from accident is small in comparing with the fire resulted from terrorist attack in the September 11 (9.11) tragedy. The fire compartments, fire-rated corridors, fire doors and escape routes might not be functioning after the planes had crashed into the buildings.

Structural stability is the most significant issue under such a vast ruin. The time to evacuate the 110-story towers under full occupant loading is about 2 hours [7]. Therefore, structures were designed to have an FRP of 2 to 2.5 hours in order to provide enough time for evacuation. Steel can stand impact as demonstrated in the 1993 bombing of the same building. In that violent explosion, the building was ripped through in the 16-acre subbasement, which is the lowest part of the skyscrapers. Only a 60-by-60-foot hole was resulted in terms of structural damage, but not the entire collapse of the building. However, the thermal inertia of steel is small and it would start losing its strength at about 550 °C. For a 5 MW fire, the temperature of steel members would rise up to that critical temperature after burning for about half an hour. Therefore, a fireproof coating must be provided on its exposed surface. The structural steel members of the twin towers were sprayed with a thick layer of insulation providing 3-hour FRP and that would be able to resist heating at about 800 to 870 °C. After the 1993 bombing, the thickness of the fireproofing on the steel members was increased from ¾" to 1½" to enhance the structural stability if there is another such attack [8]. However, only 31 floors, including the whole impact zone in the North tower and part of the impact zone in the South tower, have been upgraded with the thicker layer of fireproofing material.

Fire detection system and fire alarm had been installed inside the tower and automatic sprinkler system was required to control the fire in high-rise buildings before the fire brigade's arrival. But the towers did not have any automatic fire sprinkler system [1] installed until 1990. Smoke management system and emergency lighting were also in place.

As mentioned before, an emergency egress plan was worked out to manage the occupants evacuation. The evaluated time to descend the

110-story building was approximately 2 hours. But studies showed that in the 1993 offensive explosion, only 40 % of the office workers came out of the tower within an hour; 52 % took one to three hours and the remainder took more than 3 hours. Moreover, the standard practice for a high-rise building is to evacuate the immediate vicinity, including the floors below and above the fire floor as well as the fire floor, and leave other people at desk. This "phased evacuation" made the floor underneath the fire origin clear and the staircases enough room for fire fighters to get in.

In the WTC twin towers, the three independent exit stairways were located in the central core but not at the opposite ends of the floor area [1]. They were transferred to other stairways on some of the floors between the buildings. That means the stairways were not running through the structure all the way up. It was built for economic reasons. Identical effectiveness may be achieved in both the core- and corner-cases in a traditional fire, but it was another issue for a huge fire like this.

Safety management was also taken into consideration as there was bombing in 1993. For example, fire wardens were trained and fire drills were held regularly throughout the year. Evacuation training program was set up after the 1993 bombing incident.

5. TERRORIST ATTACK ON SEPTEMBER 11

It has been the biggest catastrophe in terms of death tolls, injuries and property loss in USA since World War II. In the morning of 11 September 2001, when 55,000 office workers went back to the two symbolic towers for their duties, two Boeing 767s, which had been scheduled for transcontinental flight, were piloted to hit into the North and South towers respectively at a time interval of about 15 minutes. The towers were intentionally hit at the weakest point, at about the 95th and 80th floor, by the fully loaded and fueled jetliners. The 180-ton hijacked plane was found carrying about 38,000 liters of jet fuel [1].

The towers remained standing up immediately after the great impact of the civilian jets. As claimed by the building designers, the skyscrapers were built to withstand the impact of Boeing 707 for which the design flight speed was around 180 mph [1] and the significant wind forces. However, the second tower being hit collapsed entirely after about an hour and was followed by the collapse of the first tower that stood up for about 1¾ hours. The second one fell down first because it was hit at the corner, rather than the center, where the load-bearing steel columns were located. The impact zone was much lower than that at the North tower. Some of the structural steel joists were protected by a thicker layer of fireproofing materials since 1993 [8], but some were not. It was found that one of the jetliners had punched at the floors with full fireproofing enhancement in the North tower whilst the other one hit at the floors without thickened fireproofing layers in the South tower. Moreover, the second airliner was piloted much faster, with an impact speed estimated at about 590 mph, while that of the first one was estimated at 470 mph. As a result, the second tower being hit became more vulnerable than the first one.

The cause of the total collapse of this strong tubular structure was revealed to be the vast amount of burning jet fuel which followed the impact of aircrafts. Indeed, the planes were probably pounded into the central core structure and the fuel then penetrated through the vertical elevator shafts to a couple of floors. With sufficient air supplied through the enormous openings dug by the plane crashes, flammable cloud of jet fuel distributed across the damaged floor area was ignited and that resulted in fireballs which accounted for the considerably high heat flux. The enormous fireball and huge fire spread rapidly. It was estimated that the fire temperature had risen up to about 1000 °C, which exceeded the insulation capacity of the fireproof coating on the steel members. Those materials were most probably being knocked down by the crash. The exposure of steel and the burning jet fuel led to rapid heating up of the steel members. As discussed before, steel would lose its strength at about 550 °C. When the horizontal steel trusses, which were used to stabilize the outer main structure, softened or even melted, the concrete floors lost their support and just fell on the top of the ones below them.

When one or some floors lost their supporting strength, the structure above became a giant mass falling onto the rest of the tower below. It was estimated that the floors dropped one by one and the accumulated upper floors were weighing 100,000 tons. Simultaneously, the outer closely spaced columns lost connection with the steel girders and the stiff tubular structure just kept the concrete floors sagged straight down without swaying to the side.

Several buildings nearby the WTC towers had also entirely or partially fallen down some time after the twin towers' collapse. It might be due to the tremendous explosions and the smashup of the twin towers. The radiative heat flux from the intensive fire occurred in the twin towers was considered so high that, along with the giant impact by the twin towers' rubbles, seriously damaged those shorter

high-rise buildings in the vicinity. It was fortunate that they were all evacuated before collapsing.

After the fire was detected, announcement had been made through the emergency broadcast system to the workers inside the towers. They were told to remain in place until further notification, just like the usual practice in a high-rise building when there is an outbreak of fire. Phased evacuation is an effective way for most of the traditional fires, however, the wrong instruction became one of the fatal causes for the tremendous death tolls in this casualty.

It was also opined that the automatic sprinkler system could not have desirable performance. Since the unimaginable impact by the hijacked planes had already destroyed the piping network and water supply, not enough water could be used to suppress the intensive fire. Moreover, the fire was mainly ignited by the aviation fuel, which is classified as Class B fire [9], and could only be snuffed out by foam sprinklers.

6. STEEL STRUCTURE IN COMPARISON WITH REINFORCED CONCRETE STRUCTURE

The structural stability of the steel columns of the WTC towers has been proved by the one-hour standing after the crashes. However, its characteristic high thermal conductivity, by which the conductive heat transfer is largely influenced, makes it lose its strength easily under excessive heating. The thermal conductivity of steel is 30 to 50 times that of concrete [10]. The critical temperature of steel is found to be about 550 °C. Due to the high heat release rate from liquid fuel and also the unusual thermal radiation emitted from the hydrocarbon fireball, air temperature in the attacked zones were believed to have reached a value far higher than the tolerate temperature of steel members promptly after the fire occurred. Their strength would be lost first followed by softening and melting.

Concrete is envisaged as having much higher fire resistance. It is assumed that a reinforced concrete structure would be able to resist the fire for a longer period in the same case. So that the occupants evacuation could be enhanced by the massive reinforced concrete stairwells. However, on the other hand, concrete is not capable of tolerating such a powerful smash. The massive concrete structure would probably fall down sideway and get more neighboring buildings involved. When the concrete layer falls down, the reinforced steel tubes inside left exposed would be heated up rapidly and result in a severe fire as well.

For instance, in the 1995 Oklahoma city bomb attack [11], the concrete building was not able to withstand the impact and it collapsed soon afterwards, leaving no time for occupants evacuation.

It was shown that reinforced concrete buildings are preferable in a big fire, nevertheless, strength to resist impact of hundreds of tons is inherent in steel structure. In addition, such an extreme verticality could not be reached by a reinforced concrete structure.

7. CONCLUSIONS

The 9.11 tragedy has aroused public concern on the safety problems of skyscrapers, in particular the ultra highrise buildings. There are numerous ultra highrise buildings throughout the world, gaining the reputation and attracting potential tenants and visitors.

Existing fire regulations, providing protection in terms of fire resisting construction, means of escape, means of access and fire services installation, might not be adequate under this kind of events. The codes were basically established for accidental fires, much smaller than that in the 9.11 incident. Professionals are now paying lots of effort on studying the necessity to revise the current codes. Further study should be carried out to decide in which aspects and how the existing building codes should be reviewed to give sufficient protection against terrorist attack. This is very difficult in comparing with the other accidental fires, arson fires or mass fires due to natural disasters. Apart from the requirements on “safety”, “security” should be included. Upgrading the security systems can prevent trespassers from entering the properties or cockpit as in this incident.

The force leading to the total collapse of WTC was reported to be due to the conflagration rather than the big smash. The estimated heat release rate of liquid pool fire and the radiant heat flux of hydrocarbon fire were found to be extremely high that would give rise to the rapid temperature rise of steel members to exceed the critical temperature of its strength [12]. As a result, the domino-like collapse led to the immeasurable ruin in the WTC tragedy.

The WTC twin towers were considered too vulnerable to such kind of terrorist attack, though they were built with certain protective measures. However, buildings with more than sufficient protection would have cost implication. In addition, withstanding against this kind of destruction would

give an unattractive appearance like a nuclear facility. Protection against terrorist attack fires appears to be practical only for some symbolic buildings. The frequency of occurrence might not be high enough to make hundred times of original investment. To ensure safety for a highrise building, the implementation of fire safety management [13,14] and property security become more applicable.

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