eJSE International

Electronic Journal of Structural Engineering

9/11: Five Years on - Changes in Tall Building Design?

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ABSTRACT:

This article discusses the changes in tall building design practice after the World Trade Centre (WTC) buildings collapse. Although many suggestions were made post-9/11, regarding the improvement of the performance of buildings, no major changes have yet been implemented. These suggestions and the lessons learnt from the collapse are discussed in the paper.

1 INSTRUCTION

This article discusses the changes in tall building design practice after the World Trade Centre (WTC) buildings collapse. Although many suggestions were made post-9/11, regarding the improvement of the performance of buildings, no major changes have yet been implemented. These suggestions and the lessons learnt from the collapse are discussed in the paper.

The 2001 September 11 tragedy in New York caused the death of more than 2800 people and the destruction of what were the fifth and sixth highest buildings in the world at the time. That buildings that took six years to build were brought to complete collapse over such a short period of time highlighted the need to pay special attention to high-rise constructions: their location, design, use of material, and other safety measures.

Despite the threat of terrorism, many new high-rise buildings are being designed and built around the world. Various social and economic factors, such as increases in land values in urban areas and higher density populations, have led to this increase in the number of tall buildings. Tall commercial buildings are built in response to the demands of businesses that want to be close to city centers, putting intense pressure on available land space. But it is not only tall commercial buildings that are currently being built; many tall residential apartment buildings are either planned or have been built in major cities. For example, one of the world's tallest apartment buildings (300 m)—Eureka Tower—was recently completed in Melbourne, Australia. The rapid growth of the urban population, and the consequent pressure on limited space, has considerably influenced the growth of city residential development.

Although the probability of the occurrence of a terrorist attack on civilian structures is quite small, the consequences of structural failure are great, both in terms of the loss of property and loss of lives. For high-risk facilities, such as public and commercial tall buildings, it is important that the potential for attack is taken into account in their design, in order to minimise the losses. Following the 9/11 WTC collapse it was recommended that the guidelines on abnormal load cases and the provisions on progressive collapse prevention should be included in Building Regulations and Design Standards. Yet, apart from changes to local standards in New York and in some other cities in the USA, most other countries, including Australia, have not incorporated these elements into their building standards.

The technological hazards to tall buildings may range from accidental sources, such as a gas explosion or the impact of a light airplane, to terrorist attacks, such as a car bomb, the impact of a missile or a commercial jet. For these assaults the source can originate either externally or internally to the structure. The ultimate goal of structural protection is to minimize injuries and loss of life, and facilitate the evacuation and rescue of survivors. The casualties that will occur in the immediate vicinity of the explosion or impact may be unavoidable, but by preventing progressive collapse, remaining occupants may be spared injury or death. Achieving these objectives requires a thorough review of the design of a building and then identification of the weaknesses that may put occupants at risk. Attention must be paid to the behaviour of the structural elements to improve their redundancy, toughness, and ductility.

Since September 11 many experts have discussed the growing need for an assessment procedure for tall building structures under extreme loads. It is widely agreed that it is impossible to design high-rise buildings to resist the impact of a commercial jet, as in the case of the WTC. However, experts recommended that building design should take into account the accidental impact of a light aircraft and the effect of fire caused by burning fuel.

Assessing structures for progressive collapse is also a crucial part of blast and impact resistant design. Progressive collapse is characterised by the loss of the load-carrying capacity of a relatively small portion of the structure due to an abnormal load, which can trigger a cascade of failures affecting a major portion of the structure. Several buildings have collapsed in this fashion, such as the Murrah building in Oklahoma (1995) and the recent collapse of the World Trade Centre. It was estimated that 80% of the deaths in the Oklahoma bombing were caused by the progressive collapse of the building rather than the blast itself. As a result, how to prevent progressive collapse is of continuing concern within the structural engineering community. The ultimate aim is to localise the damage to the impact or blast site and prevent progressive collapse of the building; or at least delay collapse long enough to allow evacuation of the building.

Some design recommendations on progressive collapse analysis have been included in the British Standards since 1968, following the collapse of the Ronan Point apartment (a 22-storey building) from a gas explosion. In recognition of this issue, a number of European countries, the US, and Canada have incorporated some progressive collapse provisions into their building codes. However, it should be noted that these provisions are not adequate, as they are based on a building collapse due to a minor gas explosion. There are no provisions or recommendations in the current Australian standards with regard to progressive collapse.

Since 9/11, a comprehensive investigation, led by A/Professor Mendis, has been carried out at the University of Melbourne, focusing on the progressive collapse of concrete tall buildings in Australia when subjected to abnormal loading, such as blast and aircraft impact. A typical tall building, modified from an existing building, was investigated using some advanced computational methods. The structural stability and integrity of the building was assessed by considering the effects of the failure of some perimeter columns, spandrel beams and floor slabs due to blast overpressure or aircraft impact. The criterion of the analysis is to determine if the failure of any primary structural member will cause progressive collapse propagating beyond one level above or below the affected member vertically, or to the next primary structural member vertically. This work has been presented at a number of conferences and other forums in Australia and overseas.

The tall buildings around the world are only designed to withstand the low intensity lateral forces from high winds or minor earth tremors. A bomb blast or collision is of a short duration and high intensity load, which such buildings are not designed to withstand. Australia’s tall buildings, as with many others around the world, are designed around a central core that contains things such as the lifts and emergency stairs. This core is designed to take most, if not all, of the loading that comes from forces such as strong winds or earthquakes. The external frame is designed to take vertical loading only in the form of weight from the structure above, and from people and materials on each level. Therefore these buildings can be subject to progressive collapse.

2 SPECIAL LESSONS LEARNT FROM THE WTC BUILDING PERFORMANCE STUDY

Following the September 11 attacks on the World Trade Centre (WTC), the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), in association with New York City and several other US Federal and State agencies and professional organizations, deployed a team of 23 civil, structural, and fire protection engineers, led by Dr Gene Corley, to study the performance of buildings at the WTC site. The report "World Trade Centre Building Performance Study: Data Collection, Preliminary Observations, and Recommendations" was released in September 2002. The report presented some of the study's more significant findings, some conclusions, and the issues most in need of further investigation.

Following the preliminary report, the National Institute of Standards and Technology (NIST) conducted a 3-year building and fire safety investigation to study the factors contributing to the probable cause (or causes) of the post-impact collapse of the WTC Towers (WTC 1 and 2) and WTC 7. This investigation expanded its research into areas of high-priority, such as the prevention of progressive collapse, fire resistant design, the retrofitting of structures, and fire resistant coatings for structural steel. The final report was released in October 2005, however the conclusions were very similar to the earlier findings of the preliminary investigation.

2.1 *Main findings of the Report*

The structural design of the two main towers consisted of 60 closely spaced (1m) exterior columns connected to each other with deep spandrel plates. Flying at about 750 km/h, American Airlines Flight 11 struck the north face of World Trade Centre Tower 1 (WTC 1) between the 94th and 98th floors. At the central zone of impact at least five of the prefabricated wall sections were destroyed, and some others were pushed inside the tower, which experienced partial floor collapse where the exterior wall supports were knocked out. Eyewitnesses also described evidence of this partial floor collapse inside the building.

Flying at about 950 km/h, United Airlines Flight 175 struck World Trade Centre Tower 2 (WTC 2) near its southeast comer. The tower was hit about 20 storeys lower than the impact zone of WTC 1, so considerably more weight was above the impact zone. Because the core of WTC 2 was only 35 feet from the building perimeter, the plane also struck closer to the core columns. Therefore, the impact likely caused more damage to the core of WTC 2 than in the case of WTC 1.

Each aircraft carried about 10,000 gallons of fuel at the time of collision. Because no flame was evident immediately upon impact, it is likely that the fuel was distributed in a flammable cloud over the impact area. Ignition of the fuel caused a rapid rise in pressure, followed by the expulsion of relatively slow-building fireballs into shafts and through openings. These fireballs did not explode or generate a shock wave, thus they did not in themselves cause structural damage. Calculations indicate that the fireballs did, however, burn 1000 to 3000 gallons of jet fuel quickly. The remaining fuel appears to have burned off within the first few minutes, generating enough heat to ignite virtually all combustible materials on the impacted floors and within the planes. Computer modelling suggests that the fire energy output for each tower peaked at 3 to 5 trillion BTU per hour (1 to 1.5 gigawatts),similar to the power output of a commercial generating station. Temperatures reached as high as 900 to 1100 degrees Celsius in some areas and 400 to 800 degrees Celsius in others.

Overall, the success rate of the evacuation was as high as is thought possible under the circumstances, with 99% of people who were located below the point of impact in each building surviving.

2.2 *Summery of the main findings*

- Both towers survived the impact of the aircraft
- Fire that weakened structural members and connections eventually brought down the towers.
- Redundancy and robustness of the structural system helped keep the towers standing.
- Transfer trusses need special consideration.
- Fire resistance of connections is important. Further study is needed to predict behavior of connections under conditions that can develop in a burnout.
- Fire-protection measures need to be related to potential fire loads.
- In buildings that may be subject to impact, the placement and design of exit stairways should provide a physical separation of egress alternatives.

Lessons for building design

- Consider redundancy in building design.
- Consider robustness (over-strength) in building design.
- Consider fire resistance in relation to the importance of structural members. (For example, consider a higher fire protection requirement for structurally critical members.)

Lessons for fireproofing

- Fireproofing must adhere under impact.
- Fireproofing must adhere under deformations.
- Fireproofing must remain effective after the attack.

Lessons for fire protection

- Sprinklers should have a reliable and redundant water supply.
- Sprinklers that do not have a water supply are ineffective and cannot contribute to the fire protection system.

Lessons for egress

- Consider redundancy in egress locations.
- Consider robustness in egress design. (For example, the stair tower should be over-strengthened to provide safe passage.)
- Consider separation of stair towers. (For example, physically increase the distance between them.)
- Consider impact resistance of stair tower enclosure.

Several senior engineering experts have criticised the recommendations published in the final report prepared by the National Institute of Standards and Technology (NIST) based on its $16 million study of the World Trade Center disaster. According to these experts, the importance of establishing design hazards and performance objectives was totally absent from the NIST's recommendations, although these should be the first step in a rational design. The main shortcoming of the report was the failure to recommend the design hazards that have to be considered when designing a tall building; i.e. if a building is designed for an explosion effect then a quantification of the charge weight is required. There were also no comments on whether an impact from an airplane should be considered when designing new buildings. Once the design hazards are established, then the performance objectives for the building can be established. The acceptable level of damage has to be established to quantify the design actions; for example, an acceptable level could be no damage and no injuries, or some damage and minor injuries. In a large event, the building may need to be demolished in the end, but the safety of the occupants is maintained.

3 CHANGES SINCE 9/11

It was evident in the aftermath of 9/11 that the occupants of buildings are generally very poorly informed or even misinformed about the performance of buildings and their surroundings after impact or explosion. While there was a rush to write new code provisions, as was mentioned earlier, there was no agreement on what hazards had to be covered; for example, should buildings be designed to resist aircraft impact or blast loading? Another question raised was whether only "high risk" buildings should be covered. And what is a "high risk" building? Again, due to the additional costs involved, a lot of developers have opted not to consider these additional hazards.

The areas that attracted the special attention of engineers, architects and developers in designing tall buildings can be categorised into the following areas:

3.1 *Structural Integrity*

The main issues are:

- Possibility of progressive collapse;
- The need for the buildings to be strengthened;
- Whether certain types of construction are more susceptible to collapse than others.
- The design hazards;
- If the triggering event is an explosion from a car or truck bomb, then there is a need to provide adequate "stand-off distance" to mitigate the damage.

The issues relating to progressive collapse were covered earlier. The WTC collapse has not brought about any major changes in the design of buildings for structural integrity, however some significant changes can be incorporated with only an extra cost of about 5% of the total cost of the building. Some simple detailing rules, which would improve building performance, have not been considered, such as the continuous top and bottom reinforcement of floor slabs. Currently, Design Standards only require top reinforcement. Under loads the top reinforcing steel of floor slabs will rip out, resulting in collapse of the floor. If a piece of bottom reinforcement is run through the slab into the column, when the floor slab fractures, the bottom reinforcement acts like a net, catching the floor and holding it in place.

Researchers at the University of Melbourne and other universities are also looking at ways of designing buildings so that their vertical load is distributed throughout a range of support areas. This way, if one or more support columns and beams are destroyed, progressive collapse is prevented, as the load from above is distributed laterally and onto other columns and beams. These suggestions have not yet been adopted in practice.

3.2 *Emergency Management, Resilience and Building egress*

It is very important for buildings to recover within a short time after an event. Although this was considered to be of great importance following 9/11, no special strategy has been adopted in planning tall buildings. There were also suggestions that fire fighters should be given basic training in the structural performance of buildings, and that structural drawings of major buildings should be provided, to allow fire fighters to make more informed decisions when entering a building damaged by an explosion or any other hazard. Building designers were encouraged to prepare detailed emergency response plans before a building was built. But many of these suggestions have not been followed in the last five years, although there is more awareness about these issues.

As mentioned earlier, many people who were below the impact locations survived in WTC 1 and WTC 2. It must be noted that occupants in these buildings had frequent emergency evacuation drills after the 1993 bombing of the WTC. Occupants in other tall buildings may not be prepared in emergency evacuation procedures to this extent. Many questions were asked about building egresses; such as, should more exit stairs be required? Should exit stairs be wider to accommodate two-way traffic? Should the stairs be located inside the building core or at the perimeter of the building? Should the stairs be located in hardened enclosures? Should lighting be improved? Should there be a staged evacuation or a mass evacuation?

Some buildings are provided with refuge floors and pressurized staircases to avoid smoke getting into stairs and lift wells. This is one of the major changes since 9/11. Refuge floors are areas with special fire protection and hardened walls. In an event, occupants can gather in these intermediate floors rather than needing to evacuate to the ground level, avoiding the congestion of stairs.

3.3 *Fire Protection*

The most significant amount of investigation and research is being conducted in the area of fire protection. The fire proofing of structural steel members has been called into question in the aftermath of 9/11. A large amount of fireproofing was dislodged from the steel members as a result of the initial impact and the explosion of the aircraft. Questions have been raised as to whether the fire-proofing should be thickened, and whether there is a requirement to develop new products.

The fire designs carried out now are based on standard fires. Fires originating from jet fuel, such as in the WTC, are hydrocarbon fires, which are different to standard fires. In hydrocarbon fires the temperature increases rapidly (in a few seconds) compared to a standard fire, in which the maximum temperature is reached after some time. Concrete, which is the main construction material for tall buildings, is susceptible to shattering (spalling) under rapid and high intensity heat; for example, following the ignition of hydrocarbon fuel. Even steel members may behave differently under a hydrocarbon fire. The collaborative research project at the University of Melbourne will, in the near future, test the fire resistance and structural behaviour of HSC under impact and hydrocarbon fire. Concrete has not been tested under these conditions before, so nobody knows if, in its current form, it is a suitable construction material to use to strengthen buildings against extreme loads. As tall buildings continue to be built to meet the need for space in cities, it is essential for planners and builders to pay attention to disasters that have already occurred, to visualise the possibility of these events in the future, and conduct research and development work that mobilises the support of practising engineers and scientific personnel, including collaborating with specialists in universities and other research organisations. This will mean that designers will begin to do things differently, and this will enhance the safety of the occupants of tall buildings that are susceptible to extreme loads.

REFRENCES

Klemencic, R., Task Group on Tall buildings: CIB TG50, *Proceedings of the CIB-CTBUH Conference on Tall Buildings: Strategies for Performance in the Aftermath of the World Trade Centre* (Eds. Shafii. F., Bukowski., R. and Klemencic, R.), Kuala Lumpur, Malaysia, 20^{th}-23^{rd} October, (2003).