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INTEGRATED DESIGN OF SAFE SKYSCRAPERS: PROBLEMS, CHALLENGES AND PROSPECTS

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Abstract

The September 11, 2001 attack on the World Trade Center (WTC) resulting in the collapse of the two major icons of New York City has been a world-shaking event. This paper reflects on this disaster and then explores the multi-faceted issues involving the performance of future tall buildings that may be vulnerable to assaults. It examines the viability of future tall buildings from a multi-disciplinary perspective, i.e., considering the technological, architectural, and socio-economic implications. The paper focuses on external aircraft attacks on high-profile buildings rather than other possible assaults, such as: biological, chemical and nuclear, and discusses the future of tall buildings. It concludes that safer buildings are on the horizon based on lessons learned from the WTC disaster and that skyscrapers will continue to be built in the future.

Keywords: Tall buildings, Integration, Terrorist-resistant design, Accidental loading, Fire protection, Structural safety

1. Introduction

The attack on the World Trade Center (WTC) in New York City in 1993, the 1995 bombing of the Murrah Federal Building in Oklahoma City, the 1998 bombing of the American Embassy in Nairobi, etc. led the U.S. Government's initiation of terrorist-resistant design of U.S. missions across the world. This has, however, gained great momentum after the September 11, 2001 attack on the WTC, that not only has drawn considerable attention of the U.S. Government, but also of the construction industry. It signaled a new era in planning, designing and building of skyscrapers with improved techniques of structural design, vertical transportation, HVAC, fireproofing, skin, materials, etc.

In this paper the collapse of the WTC will be briefly examined and the three questions will be addressed and answered: 1) Is the state-of-the-art knowledge of tall buildings adequate for terrorist attacks? 2) How should future skyscrapers be built differently? and 3) Will skyscrapers be viable in the future? Alternate but not unrelated questions to be answered by the building community are: What do the skyscrapers represent? What is our urban civilization's obsession in building all the skyscrapers at business center of large cities? Should the skyscraper phenomenon be accepted as a natural growth to cater to the demands of our civilization and hence be protected and nurtured or has it reached the end of its history?

2. The Collapse of the WTC Towers

Built in 1973, the WTC consisted of two majestic towers. The North tower measured 1370 ft. (415m) and the South tower 1376 ft (417m) in height. They had 110 stories each.

The towers were designed by architect Minoru Yamasaki and engineered by Leslie Robertson. The structural system was made of a steel framed tube with closely spaced perimeter columns with steel floor trusses extending between the exterior frame and the central core. The few core columns carried floor loads only. On September 11, 2001, the towers initially survived the impact of Boeing 767 airliners because of their robustness and a high degree of redundancy, even though they were designed for the impact of a Boeing 707 aircraft. However, the inferno caused by 10,000 gallons of jet fuel in each aircraft ultimately brought the towers down. There have been many failure theories since then (Bazant and Zhou, 2001; Clifton, 2001; *Civil Engineering*, 2002). Although the south tower was hit later, it was the first one to collapse. The second plane hit it at a lower level asymmetrically, knocking out part of the core and the exterior columns, tilting it, thereby probably hastening its collapse.

According to some the floors that were hit collapsed on the floors below resulting in progressive failure. Once the floor trusses expanded under heat, sagged and pulled out of the connections, the already weakened columns lost lateral support and gravity took control. Others feel, the sudden failure was initiated when the core failed with the trusses and the building telescoped. While some emphasized the failure of floor trusses as the triggering mechanism of collapse, others suggested that the columns failed first and the floor truss system acting as a membrane rather than a one-way system collapsed later (*ENR*, 2002). It has been argued that if the floor trusses had collapsed first, there would have been a "mass of smoke as opposed to a differentiated smoke, floor by floor." At each tower, the hat trusses at the building's top initially helped redistribute the loads away from the damaged areas and transferred them to the core. It may be postulated that the core columns already weakened by impact failed first because of the overstressing caused by the transferred loads and loss of strength due to temperature rise resulting in an inward, "implosion" type failure (as if by an explosion or blast used in demolition) rather than toppling of the towers. It is also possible that there was more than one dominant mechanism of failure occurring in different parts of the buildings. The failure of the central core triggering the collapse of the north tower is confirmed by a review of the videotapes of the event. We may never know the exact chain of events leading to the failure, but this much we do know: the buildings were robust for the impact but fragile for the fire. We also know that no matter how constructed, no tall building could withstand this kind of assault with flying bombs creating the effect of 2.4 million sticks of dynamite or an atomic bomb. Further, we know that despite the major catastrophe that took place, about 25,000 people were able to escape while 2,830 were killed. Helicopter rescue efforts from rooftop were not possible because of the intense flames. Many firefighters were killed due to lack of radio communication.

It is also suspected that with impact and enormous heat the spray-on fireproofing normally used to protect steel in today's tall buildings, while cost effective, could flake off easily. WTC thus became vulnerable once the fireproofing was lost and the sprinklers, as many suspect, stopped functioning. Older buildings protected steel with masonry or concrete that increased their endurance against fire. The FEMA-ASCE Report greatly emphasized the issue of fire protection with respect to structural framing, connections, fire protection ratings and egress systems (FEMA-ASCE, 2002). Another study, however, exonerated the steel's fireproofing based on computer models (*ENR*, 2002). For WTC, the stairwells were too narrow for evacuation, although this was not a hindrance for people to escape.

3. State-of-the-Art Knowledge in Terror-Proof Design

Terrorist assault on buildings in general and tall buildings in particular is a relatively new phenomenon. Research in this area is now being carried out to help engineers and architects understand the complexities of this subject and to provide further insights as to how the structures respond to highly dynamic and impact-type loads. Thus far, a number of studies on concrete structures have been done by the U.S. Department of Defense and other investigators (Ali, 2002). Steel buildings are currently provided with spray-on fireproofing and sprinkler system. The fireproofing is generally good for normal fires but is questionable for high impact loads and enormous fires. Research is needed in this area and the effectiveness of sprinkler system that was knocked down in the WTC. The issue of fire protection and fire endurance is of utmost importance. Recent trend toward minimalist glass box design is not satisfactory for both impact and fire. The International Style and the Modernist movement, Post-Modernism and currently popular pluralistic design styles too often use light façade. The attempt to optimize the structures for cost-effectiveness and elegance has also led to lighter structure. For buildings with political sensitivity "more is better" rather than the Miesian architectural paradigm "less is more" may be the way to go. From this point of view, the Empire State Building (Fig. 1) with heavy masonry walls and enclosures will probably perform better than the WTC because of the slower propagation of fire and a delayed collapse of the structure. It is noted, however, that there is no major fault in the design and construction of the WTC towers for the perceived accidental loads for which they were designed. None of the supertall buildings built prior to September 11 could have survived such a massive attack, although the nature and extent of their performance would definitely vary.

People above the impact zones of the WTC towers were trapped. The same thing would probably happen for any other skyscraper. There is a great need for not only better egress, wider stairs, multiple stairs at strategic locations, but also emergency rescue procedures, albeit increasing the cost.

From a structural point of view, most tall buildings are adequate to safely carry specified loads. The problem lies more with the integration of fire and structural elements. As the Building Performance Study Team observed, "The existing prescriptive fire resistance rating method (ASTM E119) does not provide sufficient information to determine how long a building component in a structural system can be expected to perform in an actual fire. A method of assessing performance of structural members and connections as part of a structural system in building fires is needed for designers and emergency personnel" (FEMA-ASCE, 2002). It will be interesting to study some major existing skyscrapers such as the Empire State Building, the Sears Tower (Fig. 2), the Petronas Towers (Fig. 3), etc. to see how the structural systems and building materials would perform under similar possible assaults as on the WTC. This will also help architects and engineers to find ways and means to upgrade existing structures against accidental loads and deliberate attacks. Needless to say that new vertical scale of the urban centers has caused new problems, that are further aggravated by recent social and political turmoil.

4. Systems Integration and Multi-Disciplinary Design Approach

The issue of interdisciplinary approaches to tall building design was addressed by Ali (1995) and by Ali and Armstrong (1995). Integration of different systems in building design is currently being emphasized by both the engineering and architectural communities. The collapse of the WTC has underscored this issue. Therefore, all tall buildings should be designed as "total systems" considering all aspects of architecture, structure, fire protection, mechanical and electrical systems. The FEMA-ASCE study has also recommended the interaction of structural, fire protection, mechanical, architectural, blast, seismic and wind engineering communities to "develop guidance for vulnerability assessment, retrofit, and the design of concrete and steel structures to mitigate or reduce the probability of progressive collapse under single- and multiple-hazard scenarios", (FEMA-ASCE, 2002).

Fig.1 The Empire State Building

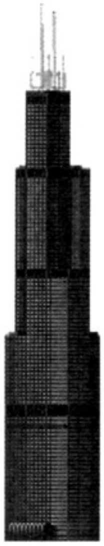

Fig.2 The Sears Tower

Fire hazards and life safety are of enormous concern in tall buildings. The towering heights of skyscrapers and their vulnerability to deliberate assaults give a new dimension to this concern. Although fires in one- and two-story buildings injure and kill more people every year than fires in tall buildings, there is a psychological factor attached to the latter. A fire in a tall building endangers the life and safety of a large number of people at one time and the height of the buildings coupled with the possible disfunction of elevators during a fire induce panic and feelings of insecurity in the minds of the occupants. The aspect of preventive fire safety design has been discussed extensively in the literature (FEMA-ASCE, 2002; Buchanan 2002; Ali and Armstrong, 1995; Khan, 1974), to name a few. While structural design and construction technology has made great strides in the second half of the twentieth century, innovations in vertical transportation systems, architectural details, and mechanical and electrical systems are not far behind. Technical innovations in mechanical, electrical, plumbing, and computer engineering have yielded a series of electrical alarm systems as well as ventilation and builtin fire fighting systems. New concepts in building planning by architects have also made integrated tall building development and operation a feasible objective. The major obstacles are generally administrative and political as well as financial, not necessarily technical. The collapse of the WTC has brought up some of the problems of failure in airport security as well as commurication and coordination difficulties. For symbolic and politically sensitive buildings, additional care and precaution must be taken for explosions and fire propagation.

5. Protective Design of Skyscrapers Against Assaults

There can never be a perfectly terror-proof building unless we spend an enormous amount of resources to make a fortress out of a building. Our conception and values of openness will not allow us to work in bomb shelters. The probability that any particular building out of thousands in a nation might suffer an assault is so low that it would not make economic sense to make all or most of them terror-proof. As cost and safety are not compatible goals, only buildings of symbolic nature or political sensitivity need to be designed for added safety against blast and impact as well as prolonged fire endurance. Existing signature buildings can be retrofitted as part of an overhaul by adding new structural elements and creating better escape systems. The structure must be made *robust*, i.e., it must withstand hazards in an acceptable way, and *redundant*, i.e., it must have the ability to transfer loads to other elements through redistribution. Numerous suggestions and propositions by experts have appeared in the media and the web. They are too many to enumerate here. Only some of the main ideas are presented here.

The structural system and materials are important for preventing an attack. The stronger and more massive the exterior frame and façade are, the better the building for external assaults. This favors a tubular building with very closely spaced exterior columns such as WTC's that proved to be effective against impact. Consideration should be given to use concrete and masonry in the structure to increase the mass, the thermal inertia and for improving fire protection. Concrete structures have a reputation for good behavior in fire and resistance against blast and impact. Many concrete buildings with rare exceptions have performed very well in the past (Buchanan, 2001). Concrete is non-combustible and undergoes an endothermic reaction when heated, which helps in reducing the temperature rise in concrete structures subjected to fire. Also, concrete tends to remain in place during a fire, with the concrete in the cover protecting the reinforcing steel with the cooler inner mass carrying the load for a longer time. Lightweight concrete has excellent fire resistance due to its lower thermal conductivity than normal weight concrete. Many lightweight aggregates are manufactured at high temperatures, so they remain stable when exposed to fire. Lightweight concrete is also an ideal material to reduce the building's weight. An example of an entirely lightweight high-rise building is the 52-story One Shell Plaza of 1971 in Houston (Ali, 2001). Also, high-strength concrete is desirable for columns in tall buildings to reduce their size at lower levels. Notwithstanding its many virtues, concrete has its own problems. Both lightweight and high-strength concrete may have spalling problems at very high temperatures. Some lightweight concretes may not perform well under severe conditions and could spall. Also, high-strength concrete loses strength at high temperatures and may experience explosive spalling. A high performance concrete that has fire retardant admixture and an increased cover thickness in the structural elements will be appropriate for such buildings. The addition of polypropylene fibers to the concrete mix (0.15 to 0.3%) of high-strength concrete will minimize spalling (Buchanan, 2001). Further, beam-column joints will undergo large shear deformations at high temperatures, which must be countered. These issues warrant more research.

Another advantage of concrete structures is the continuity in the system because of rigid and integral connection of the floor slabs and girders. In the 1950s, Frank Lloyd Wright proposed the ultimate skyscraper--the well known "mile high tower." In as early as 1986, Joseph Colaco carried out an investigation on a hypothetical mile-high concrete building. He was assisted by a group of experts from several disciplines. He concluded that such a building was indeed technically feasible. Although steel, for such a building, would provide strength and ductility, Colaco favored concrete because of its stiffness, damping and fireproofing characteristics. A composite construction employing steel and concrete is also a good possibility for a robust and fire-resistant structural system. The structure of the Petronas Towers in Kuala Lumpur primarily utilized concrete for the frame of beams and columns, anchored to core walls and steel-framed cantilevers to reach beyond the perimeter columns. Bank of China building in Hong Kong (Fig. 4) and Jin Mao building in Shanghai (Fig. 5) also mainly employed a mixed steel-concrete construction with concrete as the principal structural material for the latter.

Noting that most of the 2,830 people, who perished in the WTC disaster, were trapped above the floors of impact, we may conclude that the vertical egress system, if it remains in place without major damages throughout the entire height of the building, can save most lives. If the vertical core can remain intact and smoke-free and the building can stay stable for a prolonged period, most lives can be saved. A strong concrete core wall is thus highly desirable. It will act as an inner tube together with an exterior framed tube (steel, concrete or composite), giving rise to a tube-in-tube, and can act as a second line of defense. Where economy permits, more than one core should be considered. If a core is adequately designed for impact and strengthened by steel plates to prevent shatter and to act as a second line of defense after the closely spaced perimeter columns are pierced by flying objects, the structure will perform as desired. The core should not be the only element to resist impact. Once the exterior frame is penetrated, the kinetic energy will be largely dissipated and the secondary impact forces on the core will be significantly reduced. Even if the core is partly damaged, the integrity provided by it as a whole is advantageous for redistributing the load after a local failure. Also, with the employment of concrete outrigger walls or steel vierendeel trusses at roof and at other high elevations, the loads from the floors above the damaged perimeter columns could be transferred to the stiff core giving stability to these floors. Seismic detailing should be used for the steel reinforcement to provide ductility and increased shock-absorption capacity to the elements of the concrete structural system. With latest structural analysis softwares, innovative structural systems of various geometry and forms

Fig.3 The Petronas Towers

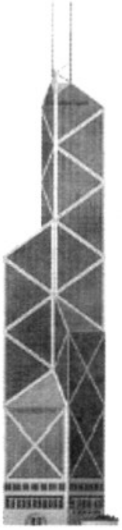

Fig.4 The Bank of China

can be now investigated by structural engineers more efficiently. Potential structural systems can be analyzed for impact and shock loading as well for heat transfer during a major fire event. Connections need special attention.

There has to be optimum use of glass that is blast and fire-resistant. Non-combustible and less flammable materials should be used for partitions, cladding, ceiling, etc. The conflagration of the consumables needs further study and better estimation. Better fire suppression systems are needed. Escape routes should be pressurized and kept smoke-free. Stairs should be wide with intermediate handrails. Layer of the façade by an exoskeleton structure that will remain stable when the inner structure is on fire could prove useful and may even provide additional escape routes. Helicopter rescues, although occasionally successful, should be discouraged in supertall buildings simply because they are dangerous under stressful circumstances. Nonetheless, the ready availability of helicopters with experienced pilots may be necessary only in cases where people can go to the roof only. Better emergency rescue and extraction techniques should be researched for high-rise fire.

Compartmentalization, both horizontally with fire walls and vertically with occasional stronger, more fire-resistant macro-floors are some other notions that will prevent rapid propagation of fires but will of course add to the cost. Jackets of graphite fibers wrapped around columns and refractory fibers that feature prominently in reinforced plastics and heat insulating materials may be put to use. Other types of fibers and materials that have desirable properties for many high temperature applications should be consciously sought during the design process. A theory for the spread of fuel oil is highly desirable.

Building "smart" or "intelligent" structures attached with sensors to monitor stresses and strains under loads or fire should be seriously considered. Similarly, smart materials that are capable of reacting to the environment and changing their structural characteristics immediately should be thoroughly researched. Smart devices and actuators that allow structures to adapt to their environments by altering the shape, stiffness, position, natural frequencies and other mechanical and physical properties in response to changes in temperatures, electromagnetic fields or other stimuli should be considered.

6. The Future of Skyscrapers

Historically, there has been a widespread apathy toward high-rises by skyscraper theorists and activists. Questions are often raised about how high buildings can go or should go. What about sensible and societal constraints? Some sociologists vehemently argue that tall buildings create a rat-cage mentality among people living and working in them. Some architects have even questioned the need for skyscrapers. Some have compared them in the context of a city with the tombstones in a cemetery resembling the skyscrapers. Others have argued that skyscrapers have become a force for cultural homogeneity, especially a global culture based on Western hegemony, and are blurring the identities of individual cities and observing a sense of place with a few exceptions, e.g., the Petronas Towers, the Bank of China, the Hong Kong Shanghai Bank, etc. Others object to the idea of skyscraper as a focus of capitalist and elitist values. Salingaros (1998) outlined some basic principles of urban form by reporting that the processes that generate the urban web involve nodes, connections, and the principles of hierarchy. A city needs to have alternative connections in order to stay healthy and should avoid the excessive concentration of nodes. When segregated-use zoning and monofunctional mega-towers are created, it kills the city by creating a mathematical singularity, where one or more quantities become extremely large or approach infinity. Skyscrapers, once they take off from land, develop their own context in the open space above and are robbed of the natural context of the city at the ground level. They work against society because they prevent the units of social importance--the family, the neighborhood, etc.--from functioning naturally. Ironically, these critics, while strong in their criticism of skyscrapers, do not produce or propose any viable pragmatic alternatives about how future urban civilization should grow 50 years or a century from now. However, there is no denying the fact that skyscrapers are under attack once again and they face a crisis of identity at the beginning of the twenty-first century. Questions then arise: What is the meaning of skyscrapers and why do we need skyscrapers in present and future cities?

The well-known Chicago Tribune competition of 1924 demonstrated to some extent the meaning of skyscrapers through the proposals of architects like Paul Gerhard, Adolf Loos, Raymond Hood, Eliel Saarinen, etc. In the proposals by Loos and by Gerhard, the buildings were two towering columns reminiscent of Egyptian temples, in which the columns held up a painted sky ceiling. The skyscrapers are in effect columns supporting the sky. The development of the three parts of the column--base, shaft and crest--accounts for the transformation in the skyscraper. Like all architecture, there is a fundamental contradiction in skyscrapers, i.e., form versus function or art versus technique. Although the tall building is a pragmatic solution to the problems of rapid urban growth, it is acceptable if it has the capability to represent past values through the architectural styles and present values of the time through progress (Agrest, 1977). Whereas structural innovations keep pace with technological and economic demands, stylistic ideology remains deeply rooted in previous eras. The skyscraper is important not only in terms of technological progress and as a manifestation of the ideology of free enterprise, competition and consumption, i.e., as a building type relevant to the global ideology but also to architectural ideology by way of producing a meaning in architecture and usefulness to society. The monumentality of the skyscraper does not reside in the building itself, but rather in the process by which symbolic interrelationships exist between buildings and between buildings and the urban fabric. Skyscrapers stretch the architects' imagination away from the earth toward the sky. The two WTC towers themselves took the form of a door or gateway to the city clearly visible from Staten Island and New Jersey, i.e., the principal access points to the great city. The two parallel towers together reaching the sky at infinity were great spacemarkers for the metropolis.

Indeed, skyscrapers have a symbolic performance in a city. It declares the glory of urban civilization, a sense of pride, romanticism and inspiration, a conscious search for style and visual interest to beautify a city. Human nature is resilient. We design "earthquake-resistant" buildings and do it better after every tremor when more lessons are learned. We survive hurricanes and floods and build habitations to minimize damage. Ada Louise Huxtable said it best, "The human capacity to forget or to minimize catastrophe, to learn to live with it, ameliorates pain and suffering and anesthetizes memory" (Huxtable, 2002). However, while discussing the WTC, Henry Petroski (2002) observed, "The collapse of those New York City megatowers . . . signaled the beginning of a new era in the planning, design, construction and use of the skyscrapers everywhere. For the foreseeable future, there are not likely to be new supertall buildings proposed, and only those currently under construction will be added to the skylines of the great cities of the world." Similar concerns were recently raised by others (Kunstler and Salingaros, 2001). The author, however, believes the buildings' collapse does not signal the end of skyscraper construction. The terrorists also attacked the Pentagon--not a high-rise. They attacked symbols, not just two towers.

Since the late nineteenth century, tall buildings evolved both in height and style in Chicago, New York and other American cities and later in other parts of the world, notably the Pacific Rim cities of Asia. Some remarkable skyscrapers are now under construction: Taipei Financial Center in Taipei; and Union Square (Fig. 6) and 2 International Financial Center in Hong Kong. Tall buildings grew as a necessity to solve the problem of population density and not out of whimsical impulse. Egos will always want to go higher. The global population explosion also practically guarantees the future construction of tall buildings. Everywhere in the world people are moving from rural areas to cities for better opportunities, and land is becoming more scarce in big cities leaving developers and builders nowhere to go but up. In the final analysis, the real estate economy, civic infrastructure and other social and environmental factors--not the terrorist attack--will dictate whether super-tall buildings are built. Economy, convenience and necessity demand tall buildings. People didn't stop building large ships or traveling by sea because the Titanic hit a glacier and sank. Nor do they stop flying simply because airplanes crash or are hijacked. They are willing to take risks if the probability of a mishap is low.

This is not to say that people will readily accept tall buildings. Skyscrapers and skylines raise a host of psychological issues. Related to the physical dimensions of the images of collapsing towers after the planes hit the WTC and the empty space of ground zero repeatedly shown on the television, the fear and phobia will stay for some time. But human beings are capable of overcoming grief and taking up new challenges. Although there will be a short pause for a few years, super-tall buildings will be built again. Imagining big cities without skyscrapers in the modern world is antithetical to the human spirit, pride and identity. Magnifying a city only horizontally results in intractable urban infrastructure and land-use problems: urban sprawl, over-reliance on automobiles, reduced human interaction, excessive energy consumption and waste of time, resulting in loss of productivity. Skyscrapers nicely resolve all these problems; they also enliven street and plaza life by creating open spaces around them.

Fig. 5 The Jin Mao Tower

Fig. 6 The Union Square

Conclusions

The vulnerability of existing and new high-profile skyscrapers to terrorist attacks, although quite unforeseen, is likely to be present until humanity is healed of its political, ethnic and religious tensions and divisiveness. While little can be done to prevent collapse or damage against major assaults, we can plan, design and build better. We can attempt to improve the egress strategies and prolong the failure of buildings during fire events. Changes in current design approaches are likely to occur and be incorporated into new building codes and standards. The roles of fire engineers, structural engineers, architects and other professionals need to be more clearly defined. Emergency lights should not go off during a catastrophic event. All these and other issues will be addressed for future supertall buildings. As with the twentieth century, which was a skyscraper century, the tall building will remain a dominant building typology and symbol of cities world wide. Integrated design of skyscrapers treating them as total systems will assume more significance in which architects, engineers and other professionals will need to act together. Such an integrated system will consider various combinations of floor planning principles, fast evacuation, early warning, fireproofing, extinguishing systems and structural systems. More research is needed in this area. For implementing the total vision for sky-high working and living in a safe and functional skyscraper of great heights or of other symbolic value, a symbiosis of talents of architects and engineers is necessary. We have once again learned this lesson from the tragedy of the WTC disaster.

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