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Collapse of WTC — Its impact on skyscraper construction

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A skyscraper is a symbol of a city's urban development and global outlook, besides being a practical solution to the continuous demographic explosion and skyrocketing land prices. The author discusses the effect of the collapse of the World Trade Centre (WTC), New York, in the aftermath of the September 11 attack, on skyscraper construction and future trends while describing the design aspects, collapse and damage suffered by the WTC.

Skyscrapers are a product of the industrial revolution, which began in England in the eighteenth century. They provided a solution to the problems of overcrowding of urban spaces – since they save space on the ground. The first skyscraper was built in 1884 in the city of Chicago, Illinois. It was only ten-storeys high. Construction of skyscrapers was aided by the high-speed elevator invented by Otis in 1857. In 1913, the Woolworth Building in New York dared to reach fifty-five storeys, soaring up 241 m. Eighteen years later, the Empire State Building, reached 102 storeys with a height of 381 m.

The skyscraper has become the preferred symbol of belonging to the modern, global world. According to the list compiled by the Council on Tall Buildings and Urban Habitat (CTBUH) at Lehigh University, only four of the world's tallest buildings are in the United States. After the collapse of WTC

in New York the figure has been reduced to two – the Sears Towers in Chicago (built in the year 1974 with a height of 443 m) and

the Empire State Building. The world's tallest building is in Malaysia – the Petronas Twin Towers in Kuala Lumpur, designed by the American architect Cesar Pelli; (of course, the CN Tower in Canada, built in 1976 is the tallest in the world having a height of 550 m).

Debates about the significance, efficacy and even the morality of skyscrapers have been raging since the building type was



Fig 1 View of the entrance of World Trade Centre (Note the close spacing of columns)

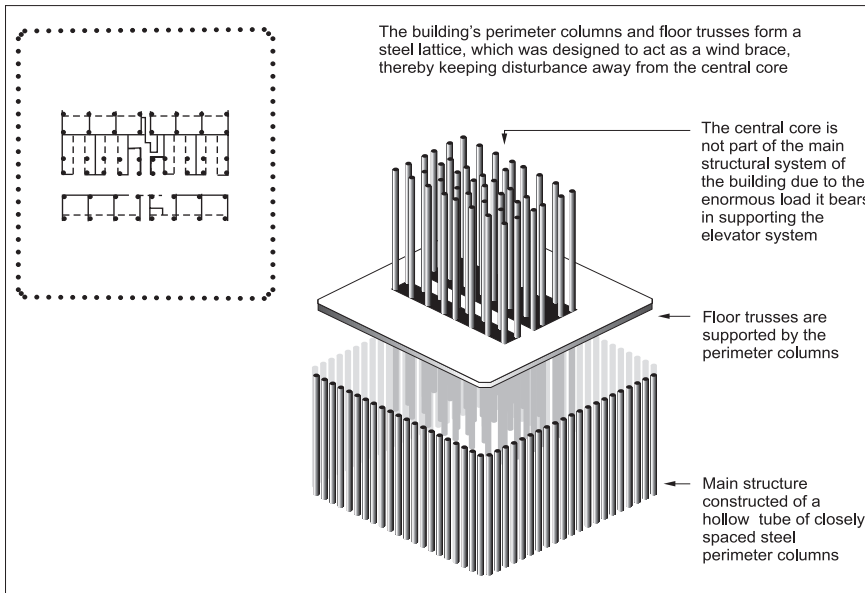


Fig 2 Floor plan and structural arrangement of WTC

fixed to the reinforced steel core. For the elevators, to serve 110 storeys with a traditional configuration would have required half the area of the lower storeys be used for shaft ways. Otis Elevators developed an express and local system, whereby passengers would change at “sky lobbies” on the 44th and 78th floors, halving the number of shaft ways.

The 63.4-m wide façade was, in effect, a prefabricated steel lattice, with the columns spaced at 990 mm centres, acting as wind bracing to resist all overturning forces. The central core was designed to take only the gravity loads of the building. This resulted in an economic structure, with wind bracing at the most efficient place – the outside surface of the building. This type of arrangement did not transfer the force through the floor members to the core, as in most curtain-wall structures. The office spaces between the outer wall and the inner core thus did not have any internal columns. Each floor had 4020 m² of office space.

The floor construction was of prefabricated trussed steel with a depth of 838 mm, which spanned the 18.3 m between the outer columns and the internal lift core, Fig 2, and acted as a diaphragm to stiffen the outside wall against lateral buckling resulting from wind load pressures. These

invented in Chicago more than a hundred years ago. There were fear of heights (ironically, the architect of the WTC, Minoru Yamasaki, was slightly acrophobic — one reason why the windows were so narrow) and fear of fire (that many people legitimately experience in high structures). But the recent terrorist attacks on WTC, have renewed the debate that these types of structures make ideal targets for terrorists – stable, highly visible and big.

transitioned in an arch-like formation increasing the spacing to 3.05 m for the lower storeys, Fig 1.

The twin towers were the first super tall buildings designed without masonry. Worried that the intense air pressure created by the building’s high-speed elevators might buckle conventional shafts, engineers designed a solution using a dry wall system

Twin towers of WTC

The twin towers of WTC with heights of 417 m and 415 m were owned by the Port Authority of New York and New Jersey. With Minoru Yamasaki, of Emery Roth and Sons Consulting as architect and John Skilling and Leslie Robertson, of Worthington, Skilling, Helle and Jackson as engineers, construction started on August 5, 1966. It was inaugurated on April 4, 1973.

The architect and the engineers worked closely and employed an innovative structural model: a “rigid hollow tube” of closely spaced steel columns with floor trusses extending across to the central core. The 355 mm steel box columns, finished with silver-coloured aluminium alloy were spaced at 990 mm on centres, making the towers appear windowless from a distance. At the third floor level, the columns



Fig 3 WTC under attack

trusses supported the 100-mm thick concrete slab on metal deck of each floor. The construction required 200,000 t of steel, 325,000 m³ of concrete and 5575 m² of glass window area and 239 elevators.

The collapse

On September 11, 2001, two hijacked Boeing 767 air planes, one with 92 people on board and the other with 65, crashed into the WTC twin towers, disappearing within and triggering fire and explosions, Fig 3. The north tower, called One WTC, was hit at 8.45 a.m. at about the 90th floor, and the south tower, Two WTC, at 9.03 a.m. at about the 60th floor. This resulted in the complete collapse of the south tower at 10 a.m. and the north tower at 10.29 a.m.

Prof Frank Moscatelli, a physics professor from Swarthmore College in Pennsylvania, calculated that the gravitational potential energy unloaded when the buildings in WTC came down was about 6.8×10^{11} J. (Compared to this, the energy of a severe earthquake would be 10^{17} J and the annual energy output of a reasonably large power station would be 10^{16} J). As a matter of fact, the collapse created an earthquake of magnitude 2.4 on the Richter scale. However, unlike a normal earthquake, they were richer in low frequency energy and poorer in high frequency energy, the main reason for this being the gravitational potential energy due to the falling of building material. According to Prof Mackin, of the University of Illinois at Urbana-Champaign, an aircraft has the equivalent power of a small-scale commercial power plant. The kinetic energy of a 767 jet at impact is of the order of 40 mega joules as shown below:

$$KE = \frac{1}{2} mv^2$$

where,

$$m = \text{mass} = 204 \times 10^3 \text{ kg}$$

$$v = \text{velocity} = 19.7 \text{ m/s}$$

$$KE = \text{kinetic energy} = 39.6 \times 10^6 \text{ J}$$

Though this energy is considerable, it is clear that the towers withstood this impact. Though damaged, Two WTC managed to remain standing for approximately one hour, and One WTC for 90 minutes.

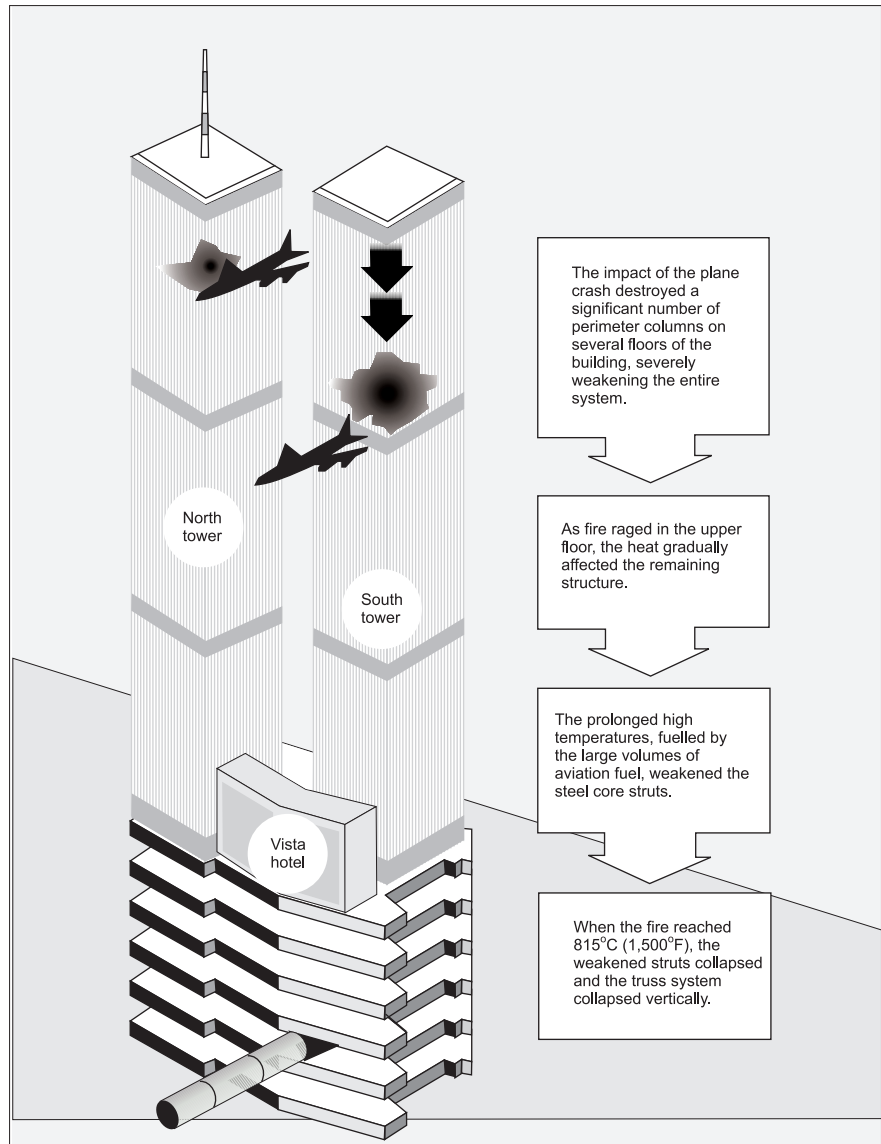


Fig 4 The failure scenario

As such, it was not the impact, but the energy in the fuel that affected the structural integrity of the building. The energy content of fuel is approximately 35×10^6 joules per litre. (Jet fuel may have even greater energy content). Assuming that the jet had 75,700 litres of fuel, (fuel capacity of 767 jet is 90,764 litres) and it detonated at once, the resulting energy would be 792×10^9 joules. This would amount to the equivalent of 2,376,000 sticks of dynamite! (3 sticks of dynamite will have 1 mega joule of energy).

If we assume that the jet liner with a weight of 205 t was travelling at cruising

speed (850 kmph) and dissipated all of its energy in one second, then

$$\text{Torque on the building} = F \times \text{moment arm} = 857,000 \text{ kNm}$$

where,

$$F = MV = \text{momentum per second} = 4018 \text{ kN}$$

Thus the impact force will be 4018 kN and assuming that the planes hit the 70th floor, the torque at the base of the building is 857,000 kNm. The building withstood even this high impact.

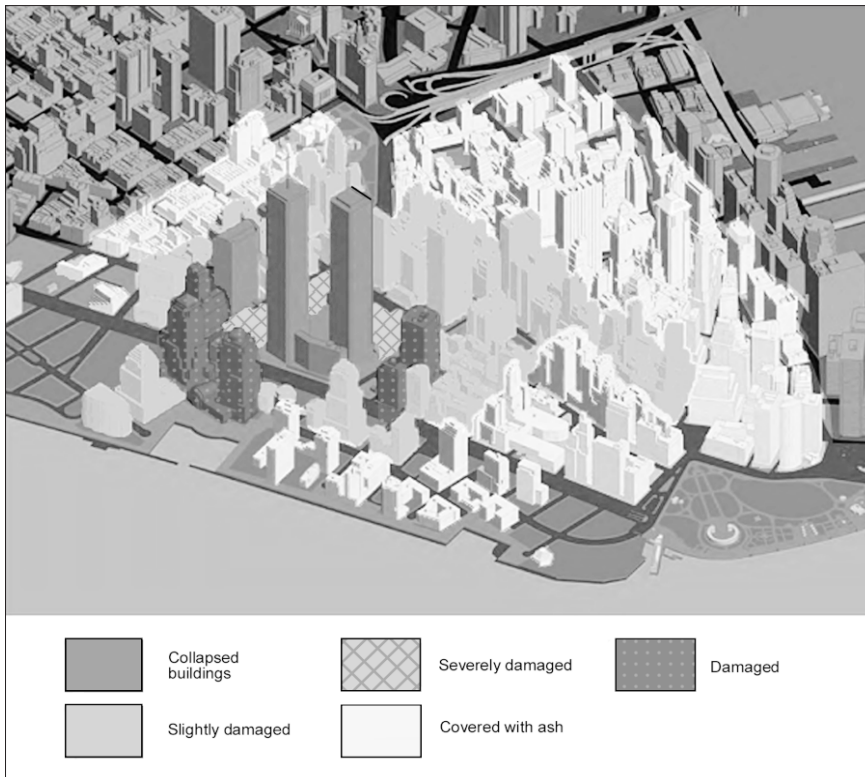


Fig 5 Three dimensional view of the damage (courtesy: CNN)

Hence, it is seen that the flame temperature of fuel (1727°C) melted the steel columns (melting temperature of steel is approximately 1570°C). Even if the temperature was half the flame temperature, the steel would creep rapidly, losing its strength, resulting in buckling. When one floor collapsed, the weight of the floors above created an instantaneous ‘pancake effect’, each floor collapsing on the floor below. The outer skin peeled back like an onion once detached from the floor slabs, Fig 4. It was as if the top of the building was acting like a huge pile driver, crushing down the floors below. Actually the impact force is related to the failure strain in steel, the weight above the failed floor, the drop height and the intact building height. Prof Mackin calculated and found that this impact force is roughly 30 times the weight of the tower above (at the 70th floor level). This implies that the building should have been designed with a factor of safety of 30 in order to withstand the forces. Based on a simplified analysis, Bezzant and Zhou arrived at a similar over load ratio due to the impact of the upper floors of WTC⁸.

Modern structures are designed to resist fire for a specific length of time. Safety

features such as fire retarding materials and sprinkler system help to contain fire, help extinguish flames, or prevent steel from being exposed to excessively high temperature. The WTC twin towers were the first ones to use non-asbestos fireproofing. The fibres of the spray on fire proofing product were reportedly ceramic. Originally the north tower contained asbestos in its cementitious fire proofing as did the first 30 storeys of the south tower. But it was removed after the 1993 bombing. This gives the occupants time to escape and allow fire fighters to extinguish blazes, before the building is catastrophically damaged. Naturally, in this case, the jet fuel generated fire conditions significantly more severe than those anticipated in a typical office fire. These conditions may have overcome the buildings’ fire defense system considerably faster than expected.

Damage

In addition to the collapse of the twin towers, the 47-storey high, Seven WTC collapsed in the evening of September 11. The falling debris also caused the destruction of buildings 4,5 and 6 at the WTC. This office complex was the largest in the United States.

At least 22 buildings, including a church were destroyed or seriously damaged in the catastrophe. At least 3646 people died and more than 6000 people were injured. About 1.25 million m² of commercial office space was destroyed in the attacks and an additional 1.4 million m² of property in nearby buildings were damaged. Fig 5 shows a three-dimensional view of the damages to the various buildings in New York. Larry A. Silverstein, who acquired a \$3 billion, 99-year lease to operate the WTC in July, is seeking \$7.2 billion from insurers for the destruction of the WTC, twice the amount insurers say he can claim. (The two hijacked airlines that struck the 110-storey twin towers were separate “occurrences” for insurance purposes).

The WTC disaster will cost New York City’s economy as much as \$90-\$105 billion over the next two years, according to a report. This includes a property loss of about \$34 billion (which is nearly twice the damage from Hurricane Andrew, previously the worst disaster in American history), cleanup and rescue of \$14 billion (the pulverised ash of concrete covered an area of 16 acres), other continuing costs in fiscal 2002 and 2003 at a minimum of \$31 billion and a rough estimate of \$11 billion to account for lifetime wages of the 3646 workers killed in the attack. It may take a year or more to remove the mountain of debris. Business interruption costs have radiated far beyond lower Manhattan. Airlines and airfreight were down for two days. Reagan National Airport was closed for 23 days at a cost of \$330 million to the airport and Northern Virginia businesses and \$27 billion to state and local tax revenues. The \$126 billion commercial insurance industry is facing a \$30 to \$50 billion payout. In the aftermath of destruction, the hotel and tourism industry and the US postal service have suffered huge losses in their businesses.

Impact on skyscraper construction

The debate about the significance of skyscrapers has started again, due to this collapse. The people who are against skyscrapers predict that the age of skyscrapers has come to an end. They argue that this ‘experimental’ building topology has failed and predict that no new mega towers will be built in the near future. It is of interest to note that the tenants of Empire State Building are planning to shift their offices to

smaller buildings. (In contrast to WTC, the Pentagon after the air-plane attack, continued to burn for two days – but the fire fighters were able to tackle the blaze right away, even with improper equipment. Also, the Pentagon may be restored even before any decision is made about what to do with the land on which the WTC once stood). A recent poll conducted by USA Today/CNN/Gallup shows that 35 percent of Americans fear to enter a skyscraper.

Many felt that the impact of the failure of WTC may be short-lived. There are a number of tall buildings under construction throughout the world and none of them is reported to be postponed or halted. Moreover with limited land, skyrocketing land prices and continuous demographic explosion in big cities worldwide, there is no other possibility than to build high-rise structures. Even the WTC's operator, Larry Silverstein has reported that his consortium is planning to construct four 50-storey buildings in place of the collapsed WTC towers, with a memorial to those who died in the WTC towers. It has to be borne in mind that over reliance on the horizontal growth of cities will create new problems of urban sprawl and density. It may result in loss of valuable agricultural land. It will also result in extra expenditure on infrastructure facilities and added energy consumption. Of course, due to the internet and world wide web, we now have the means for efficient and instantaneous communications throughout the world, and diminished need for compact contiguous space. Hence, it may not be necessary to build super tall skyscrapers having more than 50 storeys.

Future trends

It is seen that traditional steel structures cannot sustain such terrorist attacks. It is necessary to invent better insulating materials for steel sections, which will prevent the decay of steel in case of excessive temperatures. Even buildings constructed with concrete cannot withstand such temperature, since the concrete will undergo explosive thermal cracking, thermal fracture and disintegration due to dehydration. Building structures, which would look like fortresses or nuclear reactors, with very thick members, is also not feasible for the public.

Non-traditional structural materials such as ceramics might someday provide

the framework for new fire-resistant skyscrapers. However, ceramics are much more brittle than steel, more susceptible to snapping under impact. Of course, high performance fibre-reinforced concrete structures may provide more stability and fire resistance than steel. However, they may work out to be a costlier proposition.

Furthermore, the engineering of tall buildings involve, much more than structural materials. They present enormous problems in vertical transportation when fire breaks out and elevators stop working. For example, during the 1993 WTC bombing, people had to find their way down through dark and smoke-filled stairwells, underlining the importance of evacuation plans. It is of interest to note that the Petronas Towers have a sky-bridge between them – which provides an alternate exit from the highest floors. Similarly the fire systems should be updated. More emphasis should be given to life safety.

It may be prudent to strengthen the existing tall buildings for possible attacks. The columns may be wrapped with carbon fibre reinforced sheets, as done in earthquake retrofits in California, USA and Kobe, Japan. Windows may be made relatively shatterproof. (In the Pentagon, blast-resistant windows on either side of the impact area remained intact above the second floor. In these windows, the glass is nearly 50 mm thick and each window costs \$10,000!) Interior wall coverings made from blast-resistant cloth similar to kevlar may be stretched between beams (as done in the Pentagon) to prevent debris from becoming shrapnel in the event of an external explosion. Such expensive measures may not be necessary in all tall buildings, but only in those, which are considered icons of national pride.

Conclusion

Though the WTC twin tower failures show the vulnerability of such super tall structures for terrorist attacks, they may not put a full stop to the construction of tall skyscrapers. Although there may be a delay in the resumption of such projects for a few years, tall buildings will continue to be built because of human ego and practical real estate demands. In this context, there is an urgent need to develop innovative architectural, structural and emergency technolo-

gies to prevent the failure of structures due to such attacks, delay the propagation of fire and to rescue people. More emphasis has to be given to life safety in such constructions and alternative routes for safe fire escapes should be provided in such tall buildings. More research has to be conducted on blast-resistant building design and construction, and in the development of fire-resistant building materials. Use of high performance fibre reinforced concretes and similar composites, though with increased costs, may result in better performance than conventional steel or reinforced concrete structures.

References

1. PETROSKI, H. Onward but perhaps not upward, *The Washington Post*, September 16, 2001.
2. FORGEY, B. Reach for the sky – Despite their vulnerability, towers fill a tall order, *The Washington Post*, September 22, 2001.
3. POST, N.M. and WINSTON, S. Massive assault doomed towers, *Engineering News Record*, September 12, 2001 (www.enr.com)
4. DORTON, E. Divided we stand: A Biography of New York's World Trade Centre, *Basic Books*, pp. 260, 2001.
5. <http://www.Civil.usyd.edu.au/wtc.htm>
6. <http://www.greatbuildings.com>
7. <http://www.skyscraper.org>
8. BEZANT, Z.P. and ZHOU, Y. Why did World Trade Centre Collapse – Simple Analysis, *Communication sent to RILEM*, September 2001.
9. SUBRAMANIAN, N. and VENUGOPAL, M.S. Fire safety of multi-storey buildings, *National Symposium on Building Services*, New Delhi, March 1984.
10. SUBRAMANIAN, N. Computer analysis and design of tall structures, *Civil Engineering and Construction Review*, April 1995, Vol.8, No.4, pp. 42-46.



Dr N Subramanian is the chief executive of Computer Design Consultants, Chennai. The highlights of his professional career of 20 years include: designing multi-storey concrete buildings, steel towers, industrial buildings and space frames. Dr Subramanian has contributed more than 150 technical papers in seminars and journals and published 17 books. Active in many professional bodies, he is the past vice president of The Indian Concrete Institute and The Association of Consulting Civil Engineers (ACCE). He is the recipient of ACCE-Nagadi Award (for his book on space structures) and Tamil Nadu Scientist Award.

