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An Investigation on World Trade Center Collapse Mechanism

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ABSTRACT: On September 11th, 2001, New York World Trade Center towers collapsed after being hit by two commercial aircrafts. The incident was a complete tragedy and more than 280 people lost their lives that day, including 400 emergency responders. This report will present the details of the towers and the collapse mechanism of the towers from time of plane crash to total collapse. Some information is given about the 3D models of the towers and discussions are made about the subject.

ÖZET: 11 Eylül 2001 günü, New York Dünya Ticaret Merkezi kuleleri 2 yolcu uçağının çarpması sonucu çökmüşlerdir. 280 çalışan ve 400 itfaiye memuru olay anı yaşamlarını kaybetmişlerdir. Bu bildiride kule bilgileri ve çökme mekanizmaları detaylı olarak verilmektedir. Kulelerin 3 boyutlu analiz modelleri ile ilgili bilgiler verilmiş ve konu hakkında çeşitli yorumlar yapılmıştır.

Keywords : World Trade Center; WTC, 11th September, Progressive Colapse, Steel under heat

World Trade Center

New York World Trade Center Towers were the world's highest buildings for a short period, 1973 to 1974 until the completition of the construction of Sears Tower in Chicago.

The World Trade Center Towers, named shortly as WTC1 and WTC2 were the primary components of the whole World Trade Center Complex that consisted of 7 buildings. The World Trade Center Complex was located at the lower Manhatan, bounded by West Street and Church street. The site was totally 16 acres. (Fig. 1)

The World Trace Center Complex was constructed during early 1970s and the construction was completed in 1973. The architectural design of the towers were by Minoru Yamasaki, a famous architect.

Each of the towers were 110 stories in height and approximately the North Tower was in 1368 feet (417m) and the South Tower was in 1362 feet (416m) in height. Also the North Tower supported a 108m television and radio transmission antenna. WTC towers were similar but not completely identical. The orientation of the cores in each tower were different. The core of WTC1 was east to west and the core of WTC2 was north to south.

Each tower were mainly designed for commercial purpose. The 110 story height towers provided 730000 m² rentable floor space, approximately equivalent of fifty city blocks.

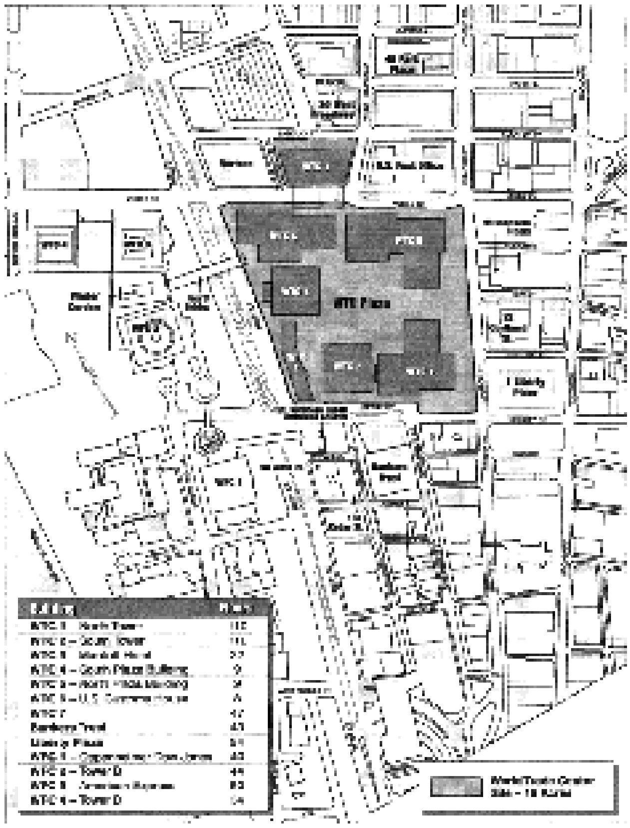

Figure 1. World Trade Center Complex

The towers were in 63.4m by 63.4m in cross sectional dimensions(Fig. 2). The brillant design of the towers provided large floor spacings on each floor without the problem of lack of daylight.

Fire Protection System

The buildings were equipped with interdependent fire protection features, including suppression systems, detection systems, notification devices, smoke management systems, and passive systems such as compartmentation and structural protection. The main default of the complete system was that the failure of even one system would result in the complete failure of the whole system of the buildings.

WTC Towers in Concept of Tubular Form Structures

World Trade Center Towers were a tube in tube type structure which consists of an inner and an outer tube. The floor height of each tower were 3.66m. The inner tube was the core of the structure and it was a composite type. The 24m by 42 m core was connected to the outer tube (63.5m x 63.5m) by means of a Vierendeel Type truss system. It was the long span truss systems that provided large floor spacings for the towers (Fig. 4). The outer tube of the tower consisted of 59 columns on each side totally 236 columns. The clear spacing between each outer tube column was 60 cm, able to form a narrow window in between. The outer tube columns were the combination of two U sections with a web and flange thickness of around 2 cm.

The construction of outer tube panels were carried on site by combination of 3 floor height and two column width panels (Fig. 3). On each floor levels, the outer tube columns were surrounded by 120cm deep steel girder providing a lateral support for the tube. As can be seen in the figures, the 120cm deep girder system and the outer tube columns were bolt connected. Approximately 11 m columns were connected to the other level columns by 4 bolt connections. The end of the columns were plate closed and a small hole is left on side for the easiness of the work of steel workers.

The reinforced concrete core consisted of 44 columns and various lateral bracings. The outer tube was mainly designed for lateral rigidity and approximately 40% of the vertical load was assumed to be carried by the outer tube. The remaining 60% was distributed among the huge core.

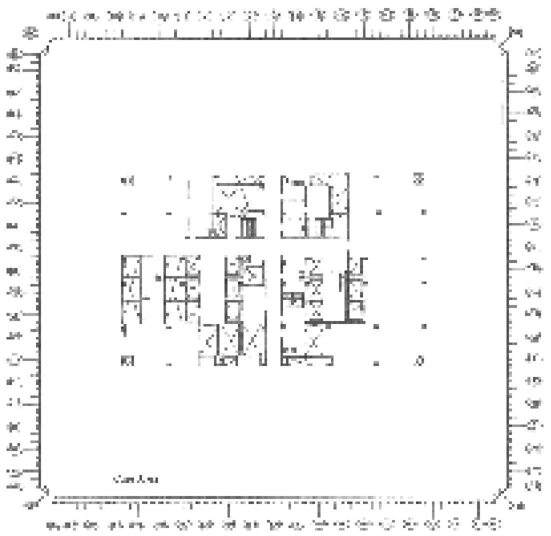

Figure 2. Typical Floor Plan

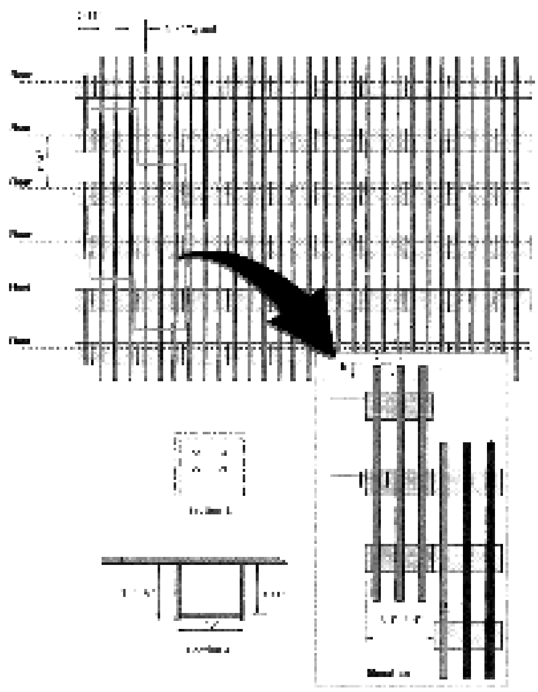

Figure 3. Outer Tube Column Panels

Vierendeel Truss System

The Vierendeel type trusses that connected each of outer tube columns to the core consisted of 5 U sections on top and 3 U sections on bottom each. The trusses were fastened to light steel beams that ran along the interior columns. Along the truss system, two steel bars were zigzagged down the truss, creating a 3D structural form (Fig. 4).

The large surface area to volume ratio of the trusses was a dominant factor in heating up in the case of a fire.

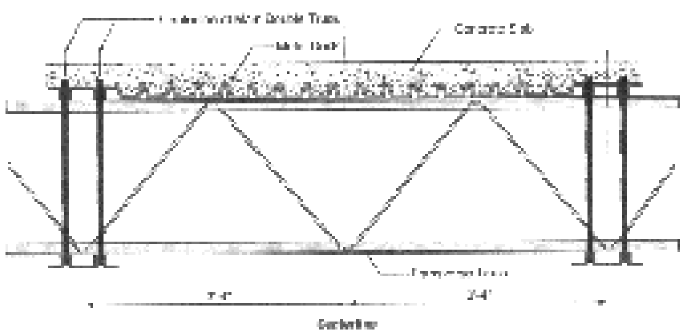

Figure 4. Sectional View of Vierendeel Type Truss System

Loading

The towers were mainly designed for commercial purpose. The floor construction consisted of 10cm lightweight concrete on 4cm non composite steel decks. In the core area, the slab thickness was 13cm. Floors were designed for a uniform live load of 500kg/m² over any area, including the allowable live load reductions.

The Collapse Mechanism

On the day of 11th of September, two hijacked commercial aircrafts hit the WTC towers. The first plane, American Airlines Flight 11, crashed on the north face of North Tower (WTC1) at 8:46 a.m. The second plane, United Airlines Flight 175, crashed into the south face of South Tower at 9:03 a.m.

There were 92 people on board flight 11 and 65 people on board flight 175. Both aircrafts were fully loaded with high octane hydrocarbon jet fuel, approximately about 10000 gallons per plane.

The collapse mechanism can be divided into 2 basic steps.

-The loss of strength and

-The progressive collapse

When the impact of planes to the towers are concerned, the impact period and the type of impact were not identical. Since the crash of the American Airlines Flight #11 aircraft was such a symmetric crash (approximately middle of the north face of the tower) it is easier to model and investigate such a damaged structure.

In the short period of impact, the aircraft cut the outer tube of the North Tower like a knife, damaging 3 floor level exterior columns with a width of 40m. The exact floors of impact were the floor levels 95 to 98. Not only the exterior columns but contributing vierendeel truss system were completely damaged. Many assumptions done about the time of impact upto now shows us that there were local collapses inside the tower at the floors below floor level 94. Also the interviews with the survivors working on floor 91 explains that the zone of impact were 3 floor levels and the core of floor #91 were covered with floor debris from above levels. So their only escape were the easternmost exit stairways.

As discussed before, the load distribution between the outer tube and core were 40% and 60% each. After the time of impact, load distributions changed and the outer tube started carrying more load than designed.

The total collapse of the tower started with an initial collapse of the 3 floor levels discussed above. The total 15 floor levels falling onto 90^{th} floor level created a huge impact force for the floors above.

The Vierendeel trusses were vulnerable to fire because of their high ratio of surface area to volume. The extreme heat caused the steel soften and reduce its ability to support floors. Also with the deformation of the truss system, having lost its lateral support, the outer tube columns were not able to withstand more and the collapse began.

As the temperature of column steel increases, the yield strength and modulus of elasticity degrade and the critical buckling strength of the columns will decrease, potentially initiating buckling, even if lateral support is maintained. This effect is most likely to have been significant in the failure of the interior core columns.

The situation is same at the floor spacing between core and outer tube. Loss of strength in truss system and the thermal expansion resulted in the complete loss of lateral support of the outer columns and the collapse of floor trusses. As the laterally unsupported height of the freestanding exterior tube wall elements increased, they buckled at the bolted column splice connections.

As seen clearly on video shots, the initial collapse of the towers were on the floor levels 94 to 98. With the huge impact force because of the nearly free fall of the 15 floors above, the progressive failure continued resulting with total collapse.

When refered to Zdenek P. Bazant's paper on collapse mechanism analysis of WTC Towers dated 22/09/01, its specified that the failure cause was the dynamic consequence of the prolonged heating of the steel columns to very hight temperature. The heat inside the building, around the floor of impact apparently exceeded 800°C. The heating is probably accelerated by a loss of the protective thermal insulation of steel during the initial blast. At such temperatures, structural steel suffers a decrease of yield strength and exhibits significant viscoplastic deformation. Bazant's idea on progressive collapse was the existence of the vertical impact of the mass of the upper part of tower onto the lower part, applying enormous vertical dynamic load on the underlying structure, far exceeding its load capacity, even if it is not heated. The collapse continued with the buckling of core columns and the overall buckling of the framed tube. The part of building lying beneath is impacted again by an even larger mass falling with greater velocity, and the series of impacts and failures then proceeds all the way down (Fig. 5).

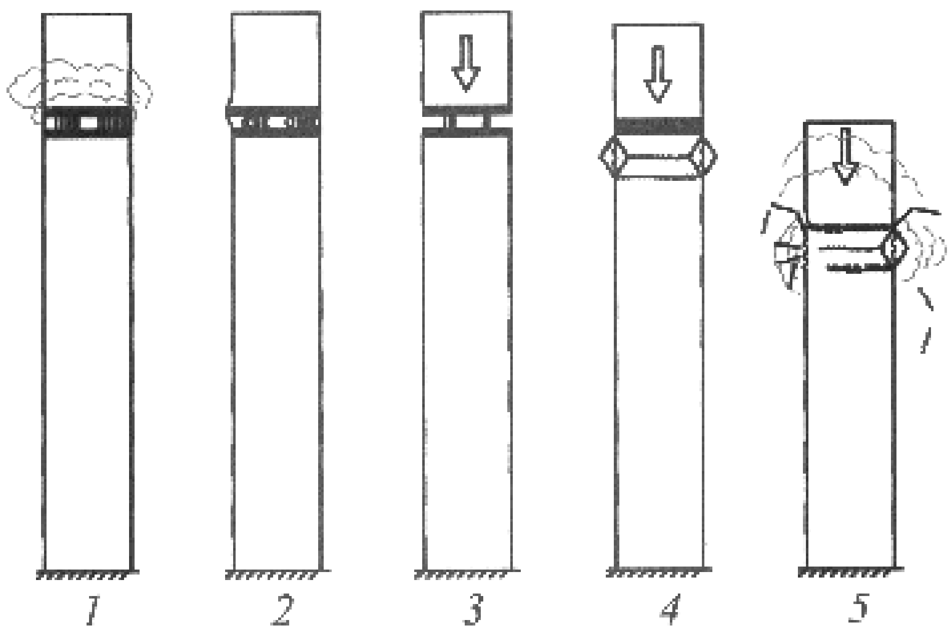

Figure 5. Basic Sketch of Bazant's Collapse Mechanism

3D Modeling

3D modeling of the towers are carried on SAP2000. 110 story height model of one tower consists of approximately 2.000.000 frame elements thus a need of a great hardware for analysis. Though a complete model of the towers is not necessary to understand the failure scenario but the main aim is to achieve the exact frame forces of the elements at the time of collapse. After various reductions in the model, like using no slab and concentrating the floor loads to the girders uniformly the model was still unable to be analysed. The approximate media length of each towers stiffness matrix were 1.7GB. One idea was just analysing the floors of first collapse. Thus the floors between 90th and 110th floors were modelled. The model was reduced to 20 story height structure, all the joints at base fully restrained. The effects of the initial impact, that is the visible damage on exterior columns and the truss system on the floor of impact were carried to the model (Fig. 6 and Fig. 7).

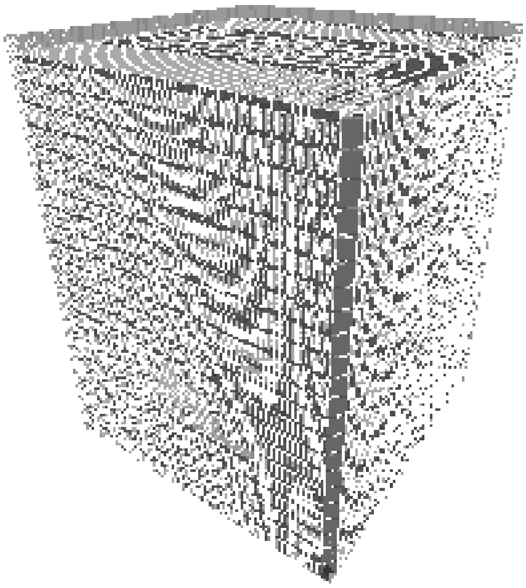

Figure 6. Reduced 3D model of The North Tower

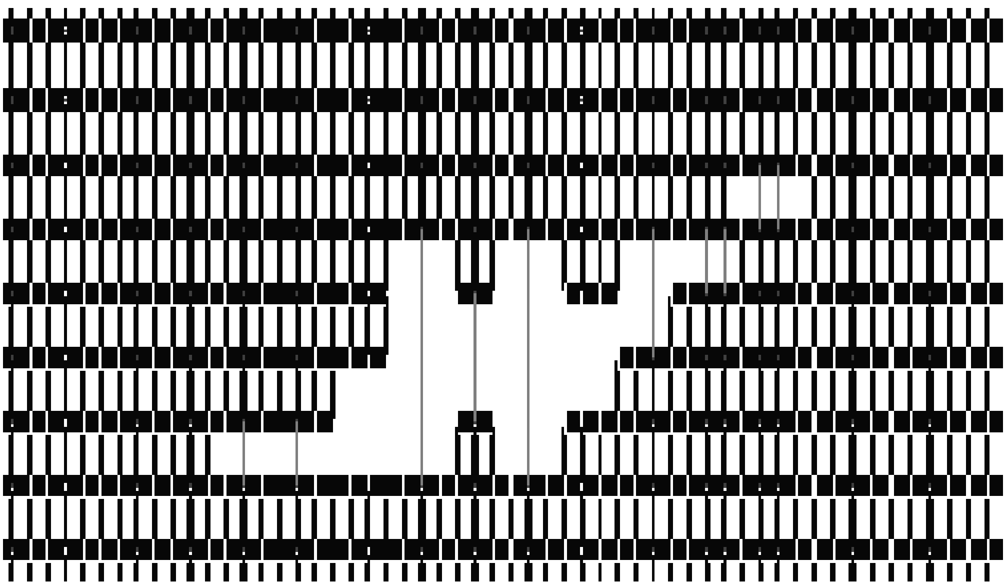

Figure 7. Exterior tube damage on 3D Model

Conclusion

The towers stood long enough for survival after impact. If WTC towers were reinforced concrete they could stand now but it would never be possible to reach that high. Steel structure couldn’t stand such an enormous fire temperature 800°C. In tall building design such a height of 417 m, it is better to use bundle tube structures that can be stand such local impact and fire resistance. In tube in tube structure, there is no load distribution to other than tube supports itself as inner and outer tube. However, in bundle tube tall building structures, load distribution and redistribution will be taken by many other tubes. Bundle tube structures can be preferred in forthcoming tall building design considering unexpected local collapse or damages.

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