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WORLD TRADE CENTER COLLAPSE, FIELD INVESTIGATIONS AND ANALYSES

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This study is dedicated to the memories of all victims of September 11, 2001 terrorist attacks and particularly to the firefighters and other first responders who so heroically sacrificed their lives to save others.

ABSTRACT: The main structure of the World Trade Center consisted of an external tube, internal gravity columns and steel truss Joists connecting the interior columns to exterior columns. A field investigation of the World Trade Center structural remains and an ongoing nonlinear dynamic analysis indicate that the many innovations that were used in design and construction of the WTC may have affected the structural performance in a positive way. However, the performance under fire was not as good resulting in eventual collapse.

INTRODUCTION

On September 11, 2001, terrorists flew two passenger planes into the upper floors of the two 110 story towers of the World Trade Center in New York City. The planes broke the exterior columns, entered the building, caused damage to interior structure of the towers and exploded inside the buildings. Although the towers did not collapse during the first impact, as a result of ensuing fire which had started by the jet fuel in the planes, both towers collapsed and more than 2800 innocent occupants lost their lives. A week after the collapse of the towers, the author arrived at New York and started collection of perishable data and a field investigation of the collapse.

The World Trade Center consisted of seven buildings; two of them were the 110-story towers. This paper focuses on the two towers and presents a summary of the main architectural and structural features and the post collapse field investigation conducted by the author. In addition, a summary of an ongoing non-linear analysis of the impact of the planes on the towers and partial results are provided. Finally, lessons that are learned from this tragedy and could be applied to other skyscrapers to save lives in the future will be presented. Many innovative concepts were used in architectural as well as structural design of the WTC towers. The emphasis herein is on those aspects and new concepts that were used in the design of the towers and may have had significant effect on the performance of the structure during the impact and ensuing fire as well as on the survivability of the occupants.

ARCHITECTURAL AND STRUCTURAL ASPECTS OF WTC

The towers of the World Trade Center were completed in 1972 and 1973 and were 417 m and 421 meters high. Figure 1 shows plan view of the floors of the World Trade Center. The main features of the towers were the perimeter tube, the core area and the open (column-free) office space created between the perimeter tube and the core service area. The perimeter tube consisted of closely spaced steel box columns and horizontal plates at floor levels acting as spandrel beams. The center to center distance of columns in the perimeter tube was about one meter. Figure 2 shows details of the perimeter column, the window attachments and the fire-proofing. The box columns generally had 46 by 46 centimeter outside dimensions and varying thicknesses. The window opening between the two adjacent box columns of perimeter frame was about 56 centimeter. The fireproofing consisted of sprayed-on material. Aluminum façade sheets were added to the three outside faces of the exterior columns, Figure 2. According to architectural drawings and as shown in Figure 2, on the interior face, the steel columns were covered with plaster wall panels as finished surfaces of the offices.

The core area of each floor was generally used for elevators, stairwells, ducts, pipelines for utilities and restrooms. In design of this building, in order to accommodate large number of elevators needed to reach the upper floors, the elevators were stacked in three theirs, each tier serving approximately one third of the height of the building as shown in Figure 1. There were three stairwells, all near the center of the building. The walls around the stairwells were gypsum boards. The floors were generally made of lightweight concrete slab cast on steel corrugated deck. The concrete floors were supported on the truss joists, which were about 80 cm deep. The floor-to-floor height of each story was 3.65 meters.

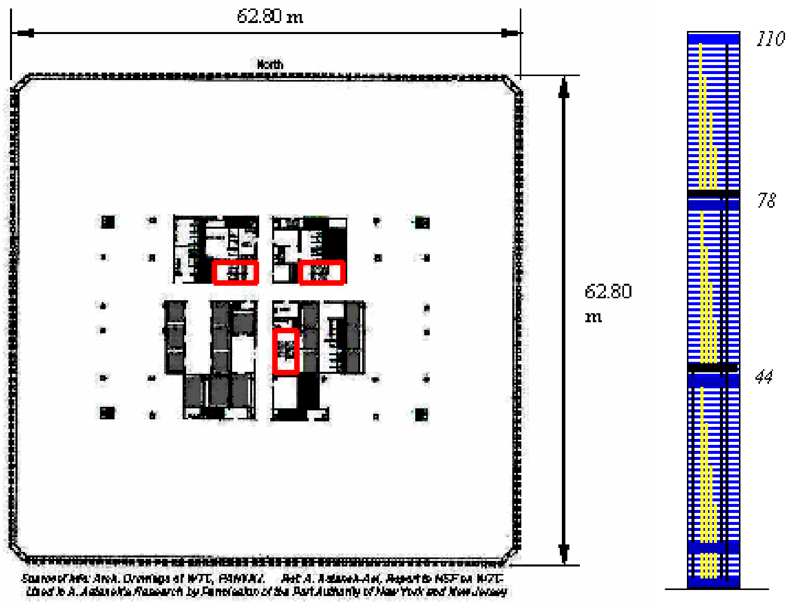

Figure 1. A sample of typical floor plans of the World Trade Center and view of elevators

The structure of the towers was a new system made of three main elements: (a) an exterior steel tube with closely spaced column to carry gravity and lateral load, (b) interior steel core columns and beams to carry gravity only and; (c) the light weight concrete on steel deck floors supported on simply supported steel truss joists. Figure 3 shows a typical framing plan for the upper floors. Figure 4 shows cross section of a typical upper floor. The World Trade Center was constructed using 3-story pre-fabricated welded units. Figure 5 shows the units used for exterior tube. The 3-story units were bolted to each other at the site using end plate connection shown in

Figure 5. The end plates had 4 or 6 bolts. Both ends of the spandrel plates beams on each prefabricated unit had one or two rows of holes. During erection process, two ends of the spandrel plate in adjacent pre-fabricated units were connected by adding doubler plates on both sides and bolting the resulting splice. The horizontal spandrel plates were about 80 cm deep and had varied thicknesses depending on location. The horizontal plates acted as spandrel beams and were almost at the same level as the floor truss joists as shown in Figure 4.

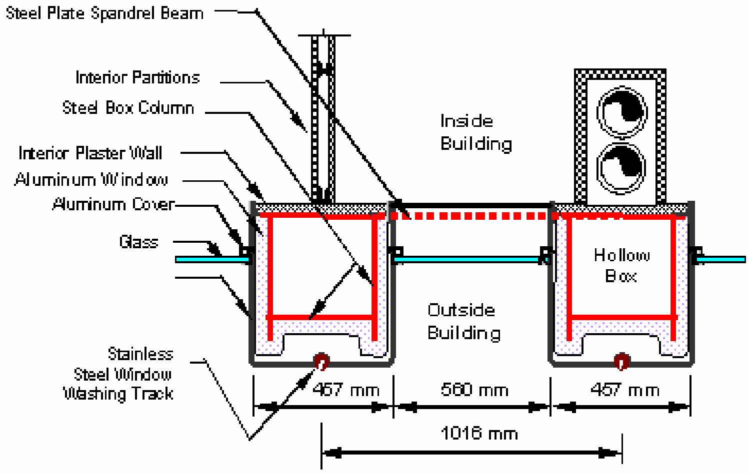

Figure 2. Details of exterior box columns, fireproofing and windows

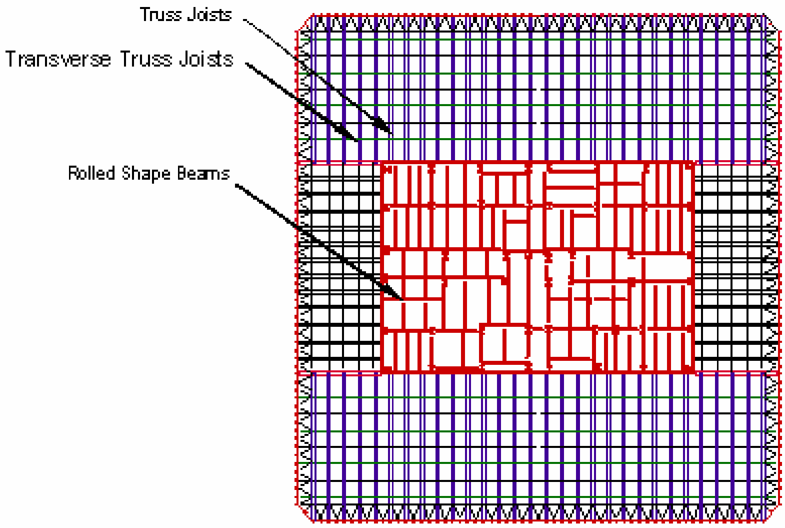

Figure 3. Typical floor framing plan of the World Trade Center for floors above 10th floor

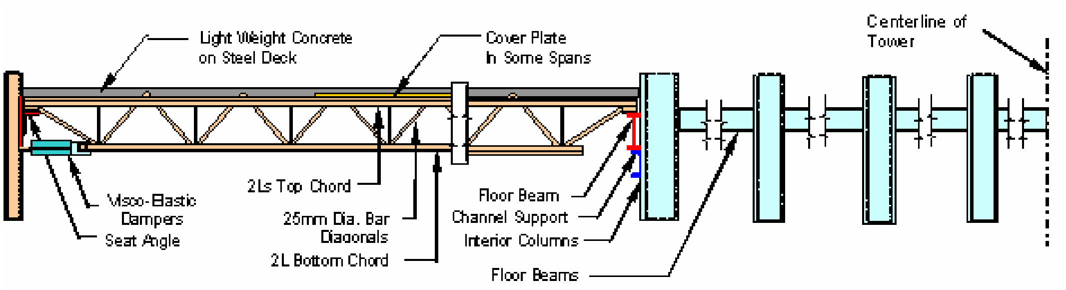

Figure 4. Cross section of structural system used in World Trade Center Towers

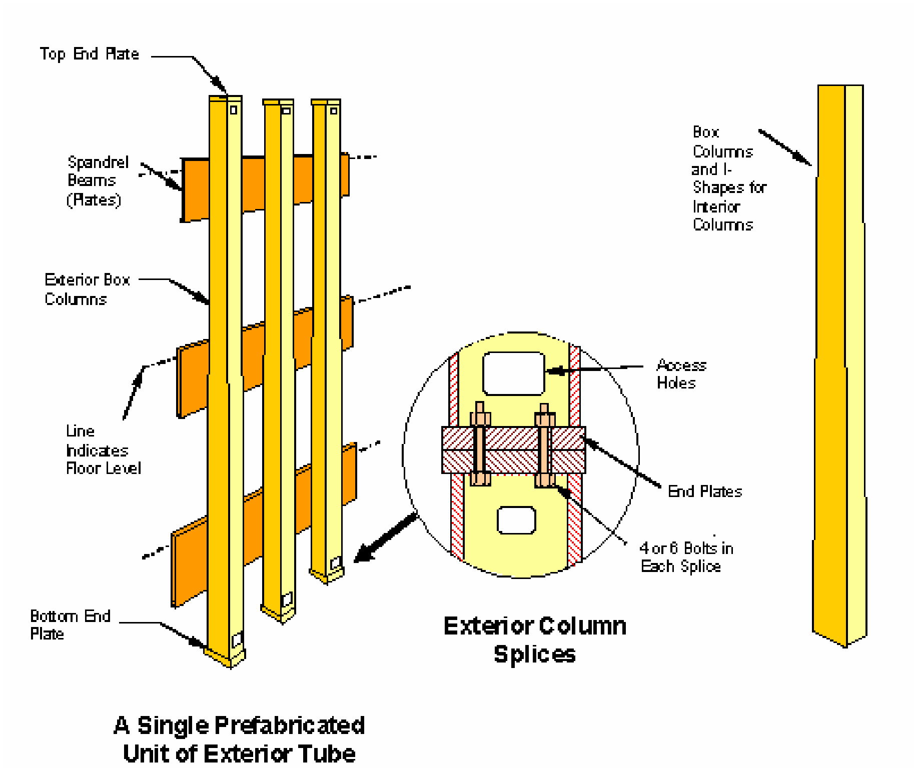

Figure 5. Exterior tube 3-story units, column splices and an interior core column

FIELD INVESTIGATION OF THE COLLAPSE[1]

One week aftert the collapse of the World Trade Center, the author, armed with a research grant from the National Science Foundation, arrived in New york and started collection of perishable data and investigating the remains of structural steel from the World Trade Center buildings. The main goals of the author's field investigations were:

a. To visit the site and map the collapsed structure and the debris.
b. Inspect quality of construction
c. Collect samples of material for further studies
d. Collect drawings and information on design, construction and maintanence

e. Establish failure modes and formulate a hypothesis for causes of collapse.

Figures 6 shows views of various components of the World Trade Center Towers after collapse. By inspecting the remains of the steel structure visually, it appeared that the construction and fabrication of the steel structure was of high quality and no apparent flaws could be observed. Several components of the steel structure appeared to be from the impact areas although at the time of inspection it was not possible to identify the location of these pieces. Such pieces were preserved and later were turned over to the National Institute of Standards and Technology for testing and identification.

Figure 6. Views of the damaged components of the World Trade center towers[1]

A HYPOTHESIS FOR WHY THE TOWERS COLLAPSED[1]

Studying the remains of the collapsed WTC towers and the architectural and structural drawigs of the towers, it is the author's opinion that the following sequence of events might have resulted in the final demise of the towers:

1. When the planes hit the towers with very high speed, the impact of the plane broke many exterior columns and their bolted splices with relative ease without much damage inflicted to the plane itself. This was due to the fact that the box columns of the exterior tube were relatively thin at the higher floors where the planes hit. The shock of impact must have shaken the sprayed-on fireproofing off the structure at least in the floors near the impact area.

2. When the planes entered the towers their fuselodge and wings had not been significantly damaged and the planes had the bulk of their jet fuel delivered inside the building. After entering the towers, the planes hit the floor slabs in 3-4 floors and most likely demolished relatively light joists and the floor slab. It is likely that the floor slabs must have inflicted serious damage to the plane or its wings cutting through them. At this time most likely the jet fuel was spread inside the buildings and the fire must have started.
3. After entering the towers and demolishing the floors,the damaged planes continued to move inside the buildings until they hit the relatively heavy structures of the core. It appears that at this point the damaged planes must have been brocken apart and in case of the South tower, the plane exploded. After planes exploded inside, the heavy parts like engines still continued flying inside the towers and in fact one engine was found several block away from the towers. At this time all the fuel was spread within the open space of several floors. Notice that as Figure 1 shows, the towers had very large open spaces without strong firewalls to compartmentalize the large open space. As a result, the fire spread very rapidly throughout the entre floors that were impacted.
4. When the planes hit the core of the building, they must have demolished the stairways on their path. As indicated earlier, the stairways in the tower had only relatively light and weak gypsum board walls. It is established that only one of the three stairwells in the south tower survived the impact of the planes and was partially open for the occupants' escape. In the North tower, all three stairways apparently were demolished and closed preventing the occupants from escaping before the towers collapsed.
5. After the planes hit the core and broke apart, the jet fuel spread throughout the open floors which conatined furniture and particularly very flamable paper material. The fire that most likely had started earlier, continued with more intensity as more and more contents reached flash point. Since probably there was not much of fireproofing left on the steel elements, the fire started warming up the relatively thin and exposed floor joists as well as the exterior columns. The properties of steel and concrete under high temperature is well known. As shown in Figure 7, when the temperature reaches about 500 to600 degree Celsius, the yield strength as well as modulus of elasticity of steel drops rapidly. As the fires went on, it is likely that the floor joists collapsed frst resulting in elimination of bracing that they were providing to the columns. Since the unbraced length of the columns now had increased significantly, the columns buckled and initiated the final collapse.
6. As a result of buckling of exterior columns, and perhaps some of the interior columns, the top portion of the towers, above the impact floors dropped on the lower portion and under the pull of the acceleration of gravity ponded the lower floors down to complete vertical collapse.

ANALYSIS OF THE PLANE IMAPCT ON WTC TOWERS

In order to study structural performance of the WTC towers when hit by a passenger plane similar to Boing 767, a non-linear model of a 10-story segment of the north tower was built and is being subjected to simulated attack by a nonlinear model of a plane. Figure 8 shows snap shots of the simulated plane flying into the simulated model of the upper floors of the north tower. The studies so far have indicated that indeed the exterior columns were not able to resist the inertia force of the plane and either the columns or their bolted splice connections fail upon impact by the plane.

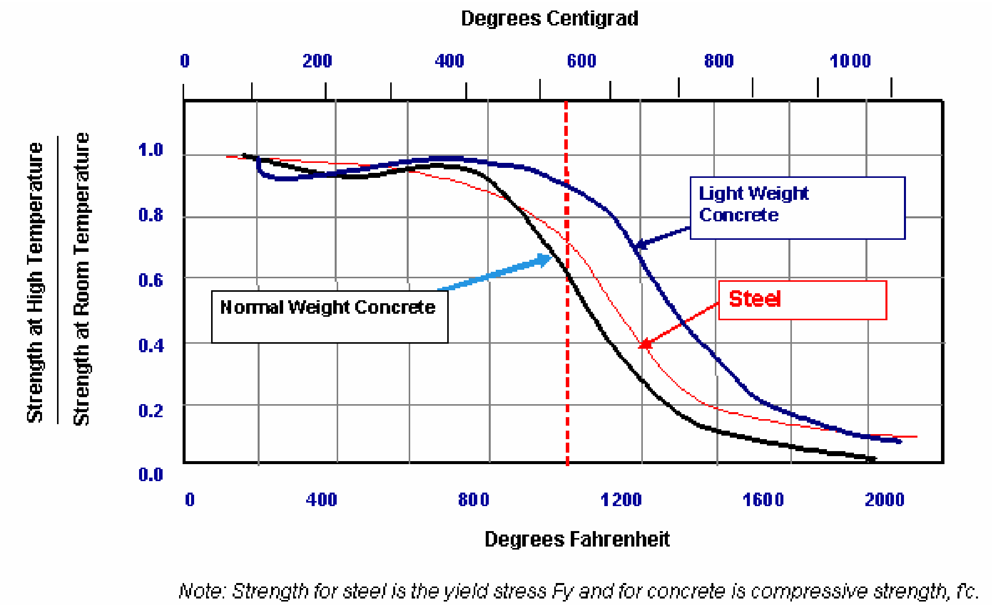

Figure 7. Approximate variation of properties of steel and concrete under high temperatures[4]

The main objective of the ongoing analytical studies is to learn as much as possible from this tragedy and try to find answers to at least some of the many unanswered yet very important questions.

Some of the questions to be answered are:

1. What would have happened if the exterior tube system of the World Trade Center was not the closely spaced yet relatively light steel columns and instead it was more traditional perimeter moemnt frame with relatively heavy steel or composite columns spaced 5-7 meters apart as is done in most high rises? Could these stronger exterior columns inflict enough damage to the plane that the plane will drop its wings and the jet fuel within them outside the buildings? Or, due to impact of the plane a few of these strong columns will collapse and result in immeidiate progressive collapse of the towers?
2. What would have happened if the floor beams instead of being the truss joists connected to the exterior and interior columns by simple seat supports, were traditional rolled wide flange girders or traditional trusses connected to the columns by moment connections?
3. What would have happened if the walls around the elevator shafts and specially the stairwells instead of being gypsum boards were masonry, reinforced concrete or composite shear walls? Could the stronger walls resist the impact of the plane and protect the stairways so that the occupants above the impact area could escape to safety?

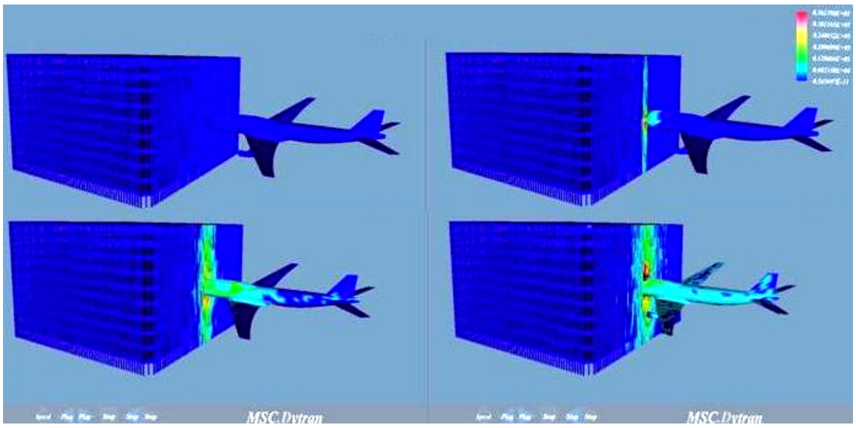

Figure 8. Snapshots of analysis results to simulate impact of the plane on WTC towers

TENTATIVE CONCLUSIONS

Based on the field investigation and study of drawings and other design related documents, it is the opinion of the author that the highly redundant exterior tube of the World Trade Center with many closely spaced columns was able to tolerate the loss of many columns and support the gravity while almost all occupants who could use a stairway escaped to safety. The collapse of the towers was most likely due to the intense fire initiated by the jet fuel of the planes and continued due to burning of the building contents. It is also the opinion of the author that had there been better fireproofing installed to delay the steel structure, specially the light weight truss joists and exterior columns from reaching high temperature until the content of the buildings burned out, probably the collapse could be avoided and the victims above the impact area rescued. Finally, in the opinion of the author, if the walls around the stairwells were stronger and the stairwells were not all located at one place, many of the victims who were trapped in the floors above the impact area probably could find a useable staircase and escape to safety.

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REFERENCES

1. A. Astaneh-Asl, "World Trade Center Post-Disaster Reconnaissance and Perishable Structural Engineering Data Collection", *Report Number: UCB/CE-Steel-05/2002,* Final Report to National Science Foundation, Department of Civil and Environmental Engineering, University of California, Berkeley, CA, December 2003.