Final Report for Period: 10/2001 - 09/2002 **Submitted on:** 11/07/2005

Principal Investigator: Astaneh-Asl, Abolhassan . **Award ID:** 0139542

Organization: U of Cal Berkeley

Title:

World Trade Center Post-Disaster Reconnaisance and Perishable Structural Engineering Data Collection

Project Participants

Senior Personnel

Name: Astaneh-Asl, Abolhassan

Worked for more than 160 Hours: Yes

Contribution to Project:

A. Astaneh was PI for this Small Grant for Exploratory Research (SGER) of NSF. One week after the tragic collapse of the World Trade Center, supported by this GSER, he travelled to New Yourk and stayed for two weeks in Hotel Tribeaa which was few blocks from Ground Zero. First he met with Mr. Leslie Robertson and vsisted Ground Zero with him. Mr. Robertson is the structural designer of the collpased World Trade Center Towers.

Post-doc

Graduate Student

Name: Zhao, Qiuhong

Worked for more than 160 Hours: Yes

Contribution to Project:

Qiuhong Zhao worked on analyzing the Finiate Element model of the WTC , north tower, impacted by the plane.

Undergraduate Student

Name: Thomas, Mark

Worked for more than 160 Hours: Yes

Contribution to Project:

The undergrad student, Mark Thomas was involved in processing drawings and data collected on the project. He also built a physical, smal-scale model of the WTC.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

MSC Software Corporation donated their powerful analysis software, Dytran/Patran to this project free of charge. The engineers from MSC software, Casey Heydari and Vijay Tunga assisted the research team in learning how to use the powerful programs.

Activities and Findings

Research and Education Activities:

The project was a Small Grant for Exploratory Research. The main goal was to condyuct reconnaissance of collapsed WTC towers and to collect perishable data. Dr. Astaneh, P.I. has traveled to New York City twice to conduct investigation of structure of WTC. Early investigation was done near Ground Zero as steel was being transported to recycling plants. Later investigations were conducted at the recycling plant where steel is being recycled. Some data on drawings and structures of WTC were obtained, and continues to be obtained from design offices of the structural firms who have designed the original structures. Photos taken during or immediately after the collapse have been purchased.

Findings To Date: During the 1st ten days of stay, most of the investigation was on the structure of Building 7 of the WTC. The 47-story structure was burning for almost 7 hours before it collapsed. During the 2nd 10 days of his stay in NYC, Dr. Astaneh has been able to establish contact with one of the recycling plants in New Jersey recycling the majority of steel from the WTC. He has conducted more systematic part of his investigation there. He has been able to investigate and document a large number of steel structural members. Some of his most striking achievements have been to identify and save at least four members (columns and beams) from the WTC Towers that appear to be important pieces perhaps from the floors that were subjected to intense heat.

On May 6th 2002, Dr. Astaneh testified before the Committee on Science of House of Representatives.

Findings: (See PDF version submitted by PI at the end of the report)

See Attached file. The achievement and conclusions are contained in the file which is a published paper in a refereed conference. The paper was given as the 'key note speech' at the conference

Training and Development:

There was one undergraduate student involved in the project who was from architecture/structural engineering program and who did work on processing the data, drawings and making a model of the WTC. There was a doctoral student involved in the project who developed Finite Element analysis model of the WTC using DYTRAN software and subjected it to impact of airplane. During the process, she learned abut how to model impact of an airplane hitting a structure and conducting dynamic analyses of the case.
For the P.I., Abolhassan Astaneh-Asl, the project provided enough information, to be used in developing a very successful Freshman Seminar-Skyscrapers and the World Tarde Center, which he teaches every year. The course is very popular with freshman stuidents and as soon as it is opened for registration it is filled. The student evaluation of teaching of this cours by Professor Astaneh has always given him more than 6.3 out of seven *(maximum) and in one semester it was 7 out of seven which meant all 20 students in the class have given him a perfect grade of 7 out of 7.

Outreach Activities:

Principal Investigators has given more than 89 interviews to reporters in the public media and provided public with his findings. He has given more than 20 public lectures on his NSF funded World Trade Center project in the US and other countries.
He has given 2 nmajor key-note speaches at international conferences.

Journal Publications

Books or Other One-time Publications

Abolhassan Astanhe-Asl, "World Trade Center collapse, field investigation and analysis", (2003). Key-note Speech Paper in the Proceedings of the Conference, Published
Collection: Proceedings (Invited Key-note Speech) , The 9th Arab Structural Engineering Conf., Nov. 29 ? Dec. 1, 2003, Abu Dhabi, UAE
Bibliography: Astaneh-Asl, A. , (2003) ?World Trade Center collapse, field investigation and analysis?, Proceedings (Invited Key-note Speech) , The 9th Arab Structural Engineering Conf., Nov. 29

Abolhassan Astaneh-Asl, "Field investigation and analysis of the collapse of the World Trade Center", (2002). Conference Proceedings Paper, Published
Collection: Proceedings (Key-note Speech)Paper
Bibliography: 1. Astaneh-Asl, A., (2002), ?Field investigation and analysis of the collapse of the World Trade Center?, Proceedings (Key-note Speech), Steel Structures-ISSS?02, Seoul, S. Korea,

Web/Internet Site

Other Specific Products

Product Type:

Audio or video products

Product Description:

Has participated in creation of two major documentaries produced by BBC of UK and NBC of the US on collapse of the World Trade center and his NSF funded work on the World Trade Center has been featured in these documentaries. The documentaries have been bradcast numerous times specially near the anniversaries of the 9/11 on national as well as cable channels.
Has produced a video of analytical results of plane impacting the WTC and has provided NSF with a copy of the video, as requested. The video is about to be posted on the NSf site (2005)

Sharing Information:

All products have been shared with public.

Contributions

Contributions within Discipline:

Principal Investigator, Abolhassan Astaneh-Asl, was invited in May of 2002 to testify before the Committee on Science of House of Representatives. The 4- hour testimony and Q/A session resulted in formulation of a bill :' National Construction Safety Team' which passed both House of Representatives and Senate in 2002.

Contributions to Other Disciplines:

The result of this investigation which was primarily on structural aspects , were used by fire engineering community as well.

Contributions to Human Resource Development:

The main contributions were to develop analytical skills of two students (one undergrad and one doctoral) as well as the abilities of teh Principal Investigator in conducting field investigation of buildings collapsed due to impact of airplane and ensuing fire.

Contributions to Resources for Research and Education:

Mny of teh results of this project, which was on reconnaissance and collection of perishable data, were used by teachers and others , downloading the information from the internet.

Contributions Beyond Science and Engineering:

The P.I.'s testimony before the Committe on Science of House of Representative had major impact in formulation of 'National Construction Safety Team' act which designated NISt as the agency to incvestgate catastrophic collapse of construction projects.

Categories for which nothing is reported:

Organizational Partners

Any Journal

Any Web/Internet Site

Field Investigation and Analyses of the Collapse of the World Trade Center

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This work is dedicated to the memory of all victims of the September 11 , 2001 and in particular to those first responders who so heroically sacrificed their lives to save others.

Abstract
The paper discusses the results of a field reconnaissance, investigation and analysis of the collapse of the World Trade Center conducted by the author since September 11, 2002 terrorist attack. The investigation included: (a) field studies of the collapsed World Trade Center, (b) collection of data on design and construction of the towers, (c) collection of material including steel for further testing and analysis, and (d) formulating a collapse scenario that fit the evidence. The studies indicated that in the opinion of the author, the main cause of the loss of so many lives was insufficiency of fireproofing and lack of egress routes. The insufficient fire-proofing eventually leading to collapse of the towers and lack of egress routes resulting in so many people trapped in the floors above the impact area and not being able to escape in time and before perishing in the collapse of towers. This project was sponsored by a grant from the National Science Foundation of the U.S. Federal Government.
Keywords: World Trade Center, Steel Structures, Fire Engineering, Tall Buildings, Structural Collapse

1. Introduction

On September 11, 2001, terrorists using two passenger jets attacked the two 110-story towers of the World Trade Center. The planes, almost intact entered the towers, exploded inside and started an intense fire. While the towers did not collapse due to initial structural damage, eventually after about an hour and 1.5 hour of intense fire, both towers completely collapsed. One week after the collapse, the author, supported by a research grant (Astaneh-Asl, 2001b) from the National Science Foundation (www.nsf.gov) traveled to New York and began an investigation of the collapsed steel structures. The main objectives of this activity were to conduct a reconnaissance of the collapse and to collect perishable data and material for future studies of this very tragic and structurally important collapse.

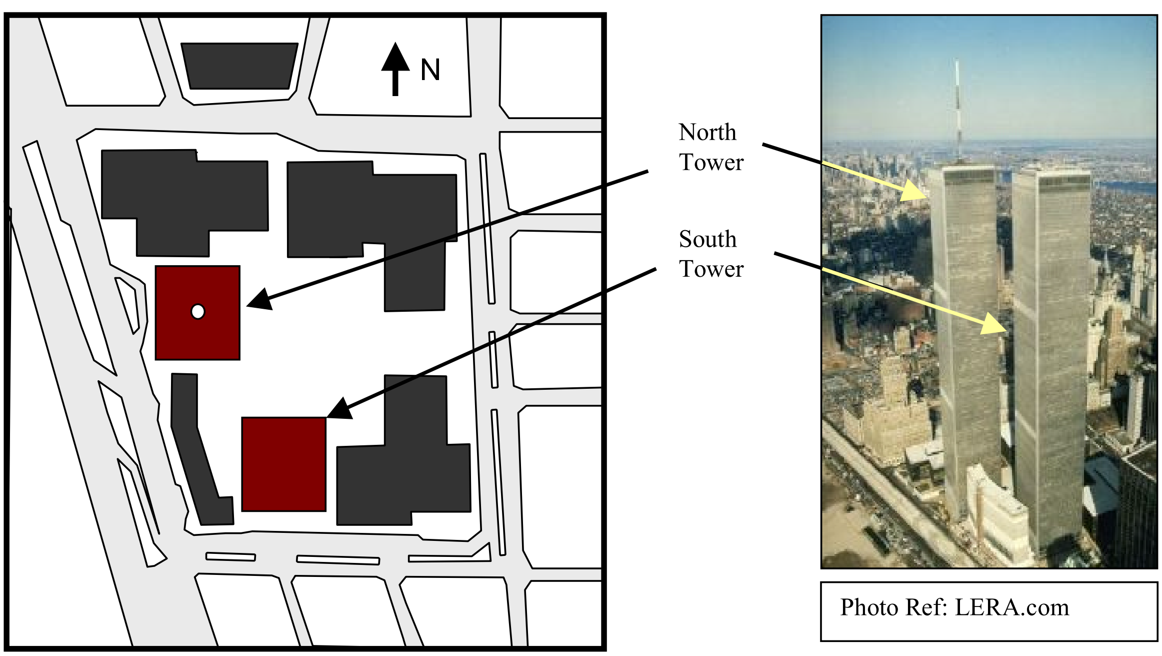


Figure 1. Plan View of the Site of the World Trade Center (Ref: Astaneh-Asl, 2002b)

2. Architectural Aspects

Figure 1 shows a site plan of the World Trade Center complex. The site included seven buildings. The 110 story towers were completed in 1972 and 1973 and at the time of their completion, with the height of 417 m and 421 m; the towers were the two tallest buildings in the world. The primary architect of the project was Minoru Yamasaki (1912-1985).

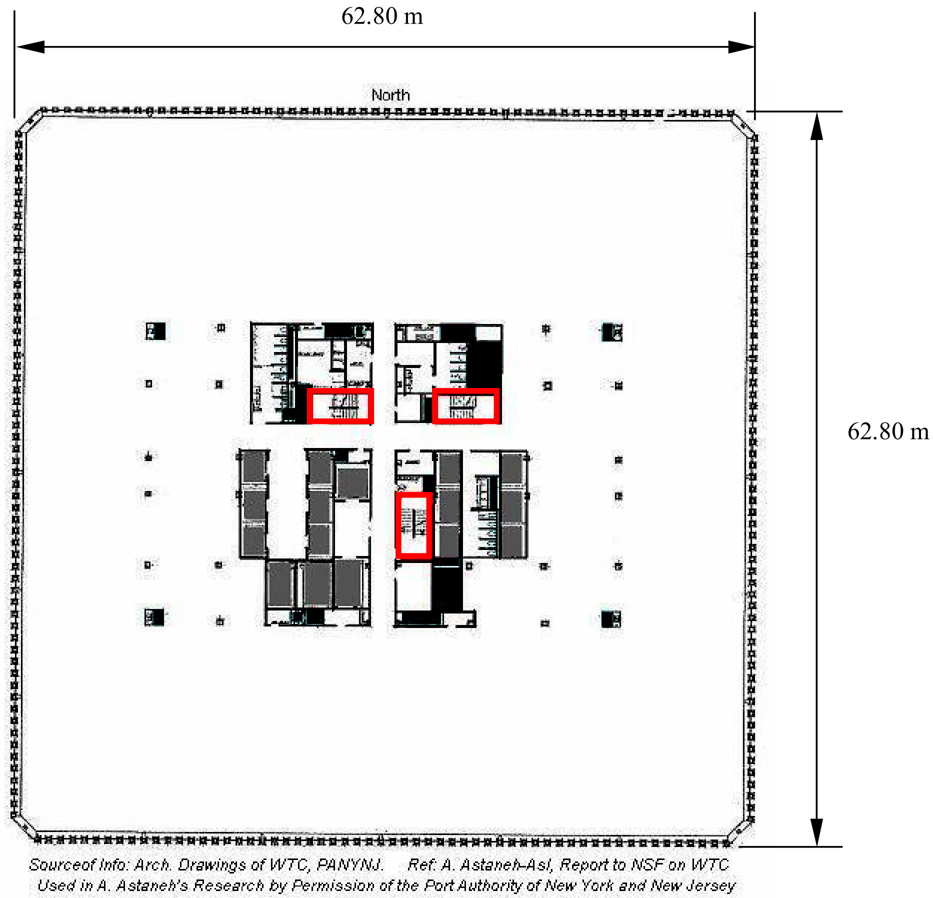
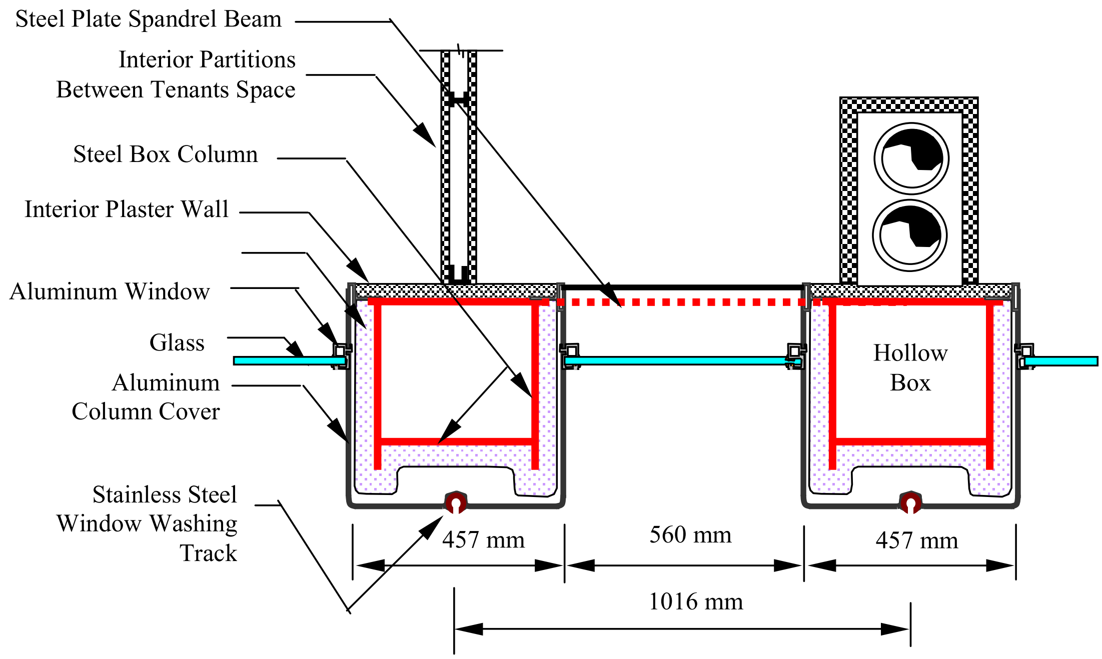


Figure 2. A Representative Architectural Plan View (96th Floor of the North Tower) (Ref: Astaneh-Asl, 2002b)

Figure 2 shows a representative architectural floor plan for the towers. The plan represents the 96th floor of the north tower. The main features of the plan are the perimeter tube, the core area and the open (column-free) office space. The perimeter tube consisted of closely spaced steel box columns and horizontal spandrel beams. The horizontal spandrel beams were steel plates only. The steel columns were spaced about 1.02 meters center to center. The deminsions of the columns were about 46 by 46 cm 14x14 inches. The opening between the two adjacent columns was about 0.56 m which was used for windows. Figure 3 shows details of exterior columns and their finishes. The steel columns of exterior tube were covered on three outside faces with sprayed on fireproofing. Aluminum façade sheets then were added to the three outside faces of the exterior columns. On the interior face, the steel columns were covered with plaster wall panels as finished surfaces of the office.

The core area of each floor was generally used for elevators, stairwells, ducts, pipelines for utilities and bathrooms. 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 4. Express elevators would take passengers to transfer levels at floor levels 44 and 78 where passengers could take the local elevators to reach their desired floors. Each tower had three stairwells at the center of the buildings as shown in Figure 2. 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 m.



Ref: A. Astaneh-Asl, 2002, Report to NSF

Figure 3. Schematic Architectural Features of the Exterior Box Columns (Ref: Astaneh-Asl, 2002b)

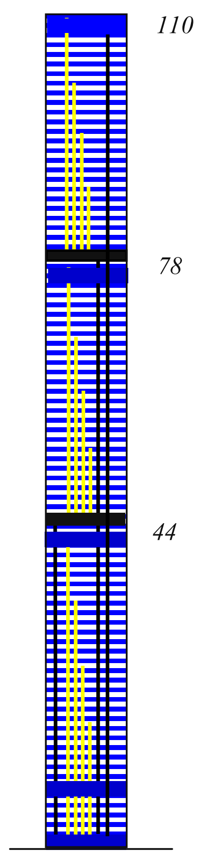


Figure 4. Elevators in the World Trade Center
(Ref: Astaneh-Asl, 2002b)

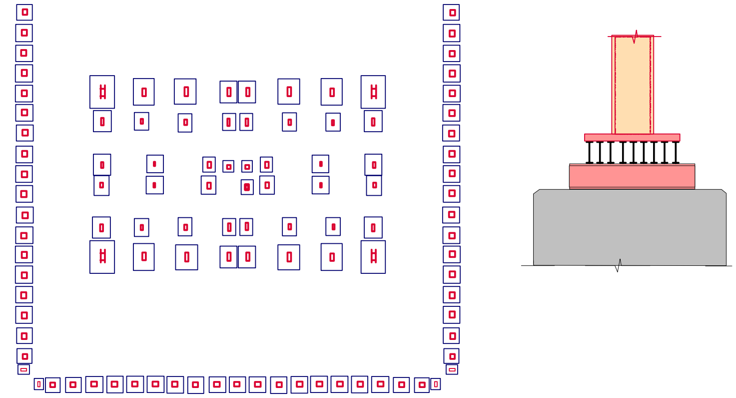


Figure 5. Schematic Plan of Foundations of the WTC Towers
(Ref: Astaneh-Asl, 2002b)

3.1. Geotechnical Aspects and Foundations: The World Trade Center was located on the west side of Manhattan Island in New York and was supported on the "Manhattan Schist" bedrock. The bedrock is located about 70 feet below the ground level. The foundations were isolated footings for exterior and interior columns as shown in Figure 5.

3.2. Structure of the Towers
Structure of the towers was unique and consisted of three major elements: (a) an exterior steel tube, (b) and interior steel core and (c) the reinforced concrete floor slabs supported on steel truss joists which in turn were simply-supported on the exterior columns and perimeter girders of the interior steel core. Figure 6 shows a typical framing plan for the upper floors of the tower.

The exterior steel tube consisted of 3-story pre-fabricated units such as those shown in Figure 7 with a length of about 11 m and a width of about 3 m. Each pre-fabricated unit consisted of three all-welded box-columns and three horizontal plates. The prefabricated units were field bolted during the erection process. Both ends of each column had end plates with 4 or 6 bolt holes. During the erection process these end plates were bolted to each other as shown in Figure 7. Both ends of spandrel beams on each prefabricated unit had one or two rows of holes. During erection process, two ends of 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. It is interesting to mention that the early, pre-construction renderings of the structure show flanges for the spandrel beams. However, in the final drawings and in the as-built structure, the spandrel beams connecting the exterior columns were only plates vertically positioned as a web of a beam with no flanges.

All exterior columns were steel boxes. They were fabricated by welding three exterior plates to each other to form a U shaped section then welding the U section to the fourth plate that was the interior face of the column. All exterior box columns had an outside dimensions of about 350 by 350 mm. Thickness of the walls of the steel box columns decreased with the decreasing number of the floors supported by them. The center-to-center distance of exterior columns was 1016 mm for the façade columns and slightly less for the last spans near the corners.

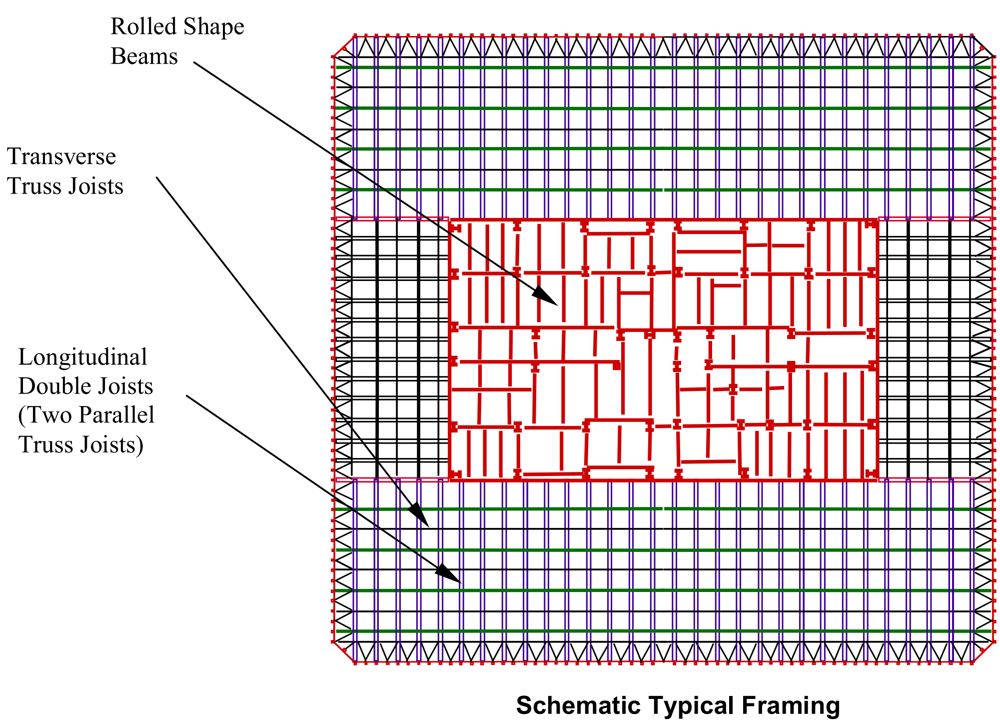


Figure 6. Typical Framing Plan and Details of Longitudinal and Transverse Trusses
(Ref: Astaneh-Asl, 2002b)

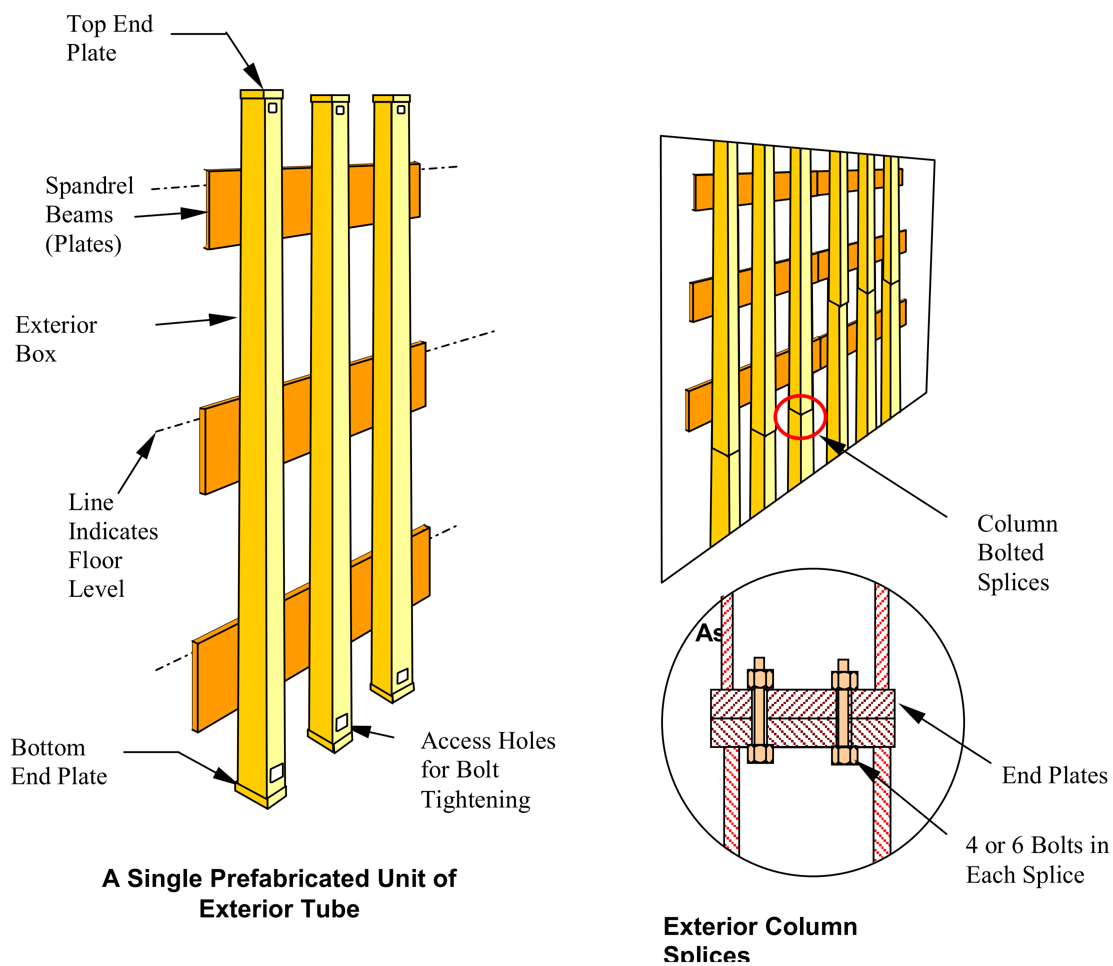


Figure 7. Prefabricated Units of Exterior Tube of the World Trade Center Towers
(Ref: Astaneh-Asl, 2002b)

The floors in the towers of World Trade Center consisted of 100 mm lightweight concrete on 40 mm corrugated steel deck making the total thickness of the floor 140 mm. The ribs in the corrugated steel deck were parallel to the longitudinal trusses. The decks were supported on transverse trusses and the transverse trusses in turn were supported on longitudinal double trusses (see Fig 6). The longitudinal double trusses had span of about 18 m and 10 m (see Fig. 6). Wire mesh and reinforcing bars were used in the slab. Figure 8 shows longitudinal and transverse trusses, their connections to columns and the crossing of transverse truss joists through the longitudinal joists. The transverse trusses were essentially supported on longitudinal double trusses. The longitudinal double trusses were in turn supported on seat angles on the exterior columns and channel beams on the perimeter of the core of the building, (see Fig. 8)

The truss joists consisted of double angle top and bottom chords and rebar diagonals. The joists were all welded. The diagonal bars had their bent above the top of the top chord acting as shear studs as shown in Figure 8. The longitudinal double joists were placed every 2032 mm and were supported on the un-stiffened seat angles welded to every other external column and on the channel beams on the perimeter of the interior core. One vertical bolt connected the end of each truss to its support angle or flange of the channel. The holes in the seat angles for these bolts were long slotted. An additional role of double joists was to brace the external columns and prevent their out of plane buckling. Every other external column was not supporting floor truss joists. To brace these columns against out of plane buckling, two plates in the shape of a V connected each Unbraced external column to the adjacent truss joists. These braces for external columns can be seen in Figure 6 around the perimeter of the floor.

The bottom chord of each longitudinal truss was connected to external column (but not internal supports) by a visco-elastic damper. About 10,000 dampers were used in each tower. The role of these dampers was to increase the building damping, resulting in reducing the wind drifts and accelerations to acceptable level. Considering the fact that floor trusses were simply supported on exterior columns and interior core beams, it can be concluded that there was not much of a frame action between the perimeter tube and the interior core. The perimeter tube was responsible to resist all lateral load and its share of gravity while the interior core structure was responsible to carry its own share of gravity load.

The structure of the core consisted of rectangular box columns, sometimes with an added middle web for heavy lower floor columns and just rolled wide flanges for very top floor (about 90th floor and above). The core structure was generally a simply supported frame system responsible primarily for carrying its tributary gravity load. The beams and girders in the core were generally wide flanges with some channels used in the perimeter of the core. The splices of the columns were in most cases, field partial penetration welds or cover plate splices. However, since the core columns were gravity columns with relatively high compression in them and remote likelihood of being subjected to tension, the column splices in the core appeared to be minimal erection splices.

As architectural plan shown in Figure 2 indicates, the floor in the core region had numerous openings to permit passage of elevators, stairwells and a variety of utility ducts. It is not clear at this time what role these floor openings might have played in the fire that ensued after the planes entered the towers and ignited an intense fire.

As far as structural walls, there appears to be none in the floors above the 10th floors of the towers. Drywalls (gypsum walls) were used throughout the towers around the elevator shafts and stairwells. The fireproofing in the structure consisted of sprayed-on fireproofing on areas of steel that were not covered by the drywalls.

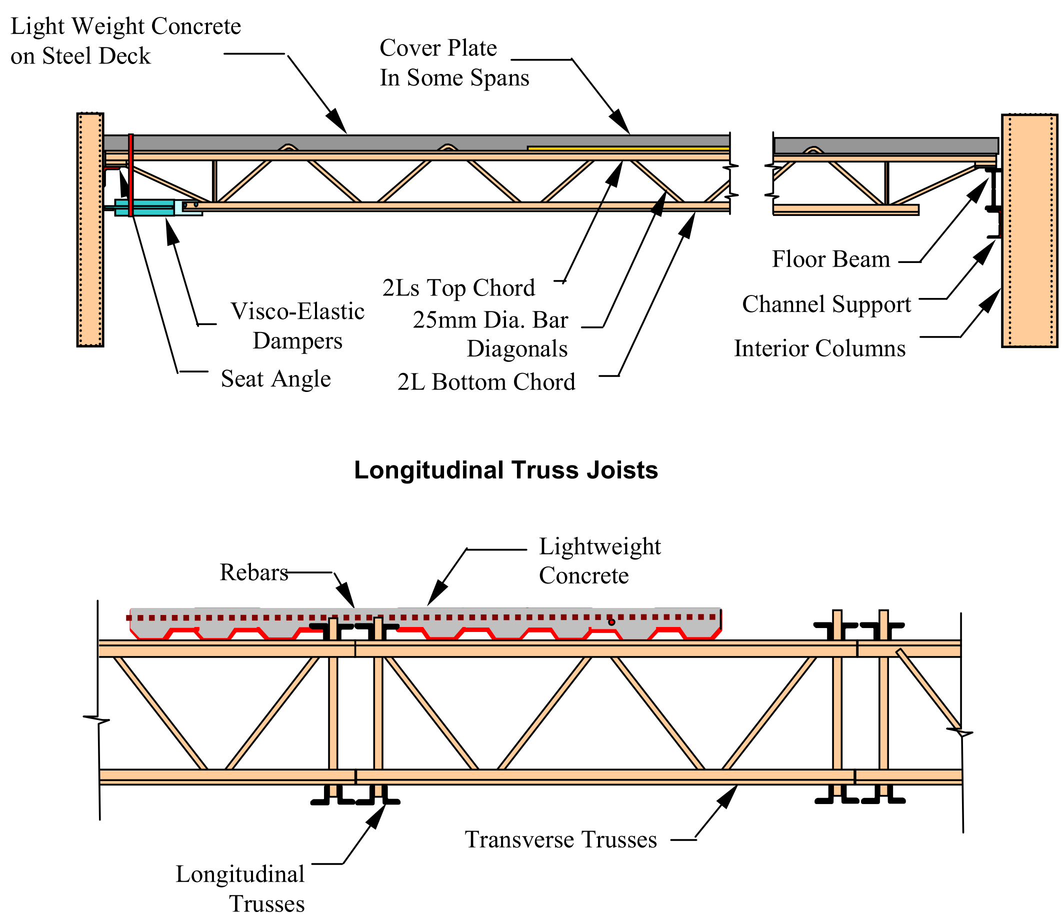


Figure 8. Longitudinal Truss Joists (top) and Transverse Truss Joists (bottom)
(Ref: Astaneh-Asl, 2002b)

3. Field Investigation of the Collapse of the World Trade Center

A few days after the collapse of World Trade Center, having submitted a proposal (Astaneh-Asl, 2001b), I received a research grant from the National Science Foundation to conduct a reconnaissance of the collapsed structures and to collect perishable data and material for further studies and testing. My research project was primarily focused on structural aspects. There were seven other research grants from the National Science Foundation on the World Trade Center, each focusing on diffewrent aspects of the tragedy such as fire engineering, environmental and social aspects. A complete listing and abstracts for these projects can be found at NSF web site: www.nsf.gov.

Figure 9. A View of Ground Zero, the Day After the Collapse of World Trade Center (Ref: Astaneh-Asl, 2002b)

After receiving the go-ahead from NSF, I travelled to New York City a week after the collapse and stayed for about three weeks and conducted a field investigation of the collapsed steel structures. Later, I made two more trips and further investigated the structural elements prior to their recycling. Figure 9 shows a view of the Ground Zero the day after the collapse taken by Bill Farrington (Author's photographer for this project). After arriving in New York, I met with Mr. Leslie Robertson, the lead structural engineer of the World Trade Center. After preliminary discussions on design, construction and what might have caused the collapse, the two of us along with Mr. David Morris, an architect friend of mine, who was participating and assisting me in the initial part of investigation, went to Ground Zero. At the time, Ground Zero was still burning and a large number of first responders, rescue workers, security personnel and others were working there 24 hours a day to locate and hopefully rescue survivals as well as collect data on this most heineous crime. As Figure 9 shows, Ground Zero was not a place to conduct research. This was primarily due to emotional and personnal feelings of great loss and the fact that thousands of bodies of innocent people were still buried under the debris. After paying my deepest respects to all victims we left the site without stepping inside the hallow grounds where the victims were still buried under the debris.

At the time, the City government was not permitting researchers to conduct research at Ground Zero. For some researchers, entering ground Zero and collection of data from Ground Zero was essential. In my case, being interested in structural steel, not being able to work at Ground Zero was not a major hinderence. For the remainder of the investigation, I conducted inspections and investigation of the collapsed structure either near Ground Zero where the steel brought out of Ground Zero was temprarily kept or later at recycling plant in New Jersey where the steel from the WTC was delivered for recycling.

The main goals of my investigations in New York City 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.

The first part of investigation involved inspection of steel being removed from ground zero. Most of this steel was from Building 7 of the World Trade Center. Building 7, a 47-story steel structure, caught fire apparently after being hit by the falling debris from the towers and was burning for more than seven hours before collapsing in the afternoon of September 11. Figure 10 shows an example of steel removed from the site of the collapsed Building 7. The inspection of steel indicated that there was very intense fire inside the building. Fortunately, since this building was evacuated after the planes have hit the towers, no lives was reported lost in this building. The exact cause of collapse of this structure has not been established. According to press reports, this building apparently had a large emergency fuel tank that may have contributed to intensity of the fire in this building.

Figure 10. A Beam Removed From the World Trade Centerthe Site Most Probably From Building 7 (Ref: Astaneh-Asl, 2002b)

Figure 11 shows typical views of various components of the World Trade Center Towers after collapse. Figures 11(a) shows a view of one of the pre-fabricated units of the exterior tube. This unit appeared to be bent in a way that it may have been buckled while under the load instead of being bent due to drop from the height. The surface of this piece also appeared to clearly indicate exposure to intense and uniform fire throughout the clear length of column. In addition, there was no visible dent or damage that would indicate the bending might have been the result of other members falling on this particular member. Considering all these issues, which could be established by close and careful examination of structural pieces, one could reasonably conclude that this particular piece may have been damaged while the structure was still standing. This distinction is very important since if further identification of the piece indicate that indeed this piece may have been in a location that could have been subjected to intense fire, then by testing this element many valuable pieces of data could be gathered. There were a number of other pieces such as these that the author was able to identify as possibly important pieces and keep for further investigation.

Figure 11(b) shows typical appearance of the seat angles supporting the floor double joists. The seat angle supports were on the every-other exterior columnsIn general most seat angles that were inspected had their outstanding legs bent downward possibly due to the impact of collapsing floors from above. In some cases, the seat angles were gone due to failure of welds connecting them to the two outstanding plates behind them.

Figure 11(c) shows a view of the end plate splice connection of exterior box columns. In almost all cases that were inspected, The failure of splice was due to bolt failure in tension combined with bending.

Figure 11(d) shows appearance of typical bolted double plate splices of the horizontal spandrel plates of the exterior tube.

Figure 11(e) shows interior columns of the towers stacked on top of each other at recycling plant. Almost all interior column pieces that were inspected were intact and did not show failure of welds. As indicated earlier, these columns were gravity columns and their splices did not need to be designed for any amount of tension or bending. However, a minimal splice was provided for these columns presumably for secondary forces and the forces during construction. Obviously, such minimal splices did not have a chance during the collapse stage to keep the columns together and had fractured. Observing the fact that the interior column splices were not needed and were so minimal, it is not clear if when the attacking Boeing 767 airplanes entered the towers any of the interior column were actually dislodged and eliminated or bent due to failure of their splices.

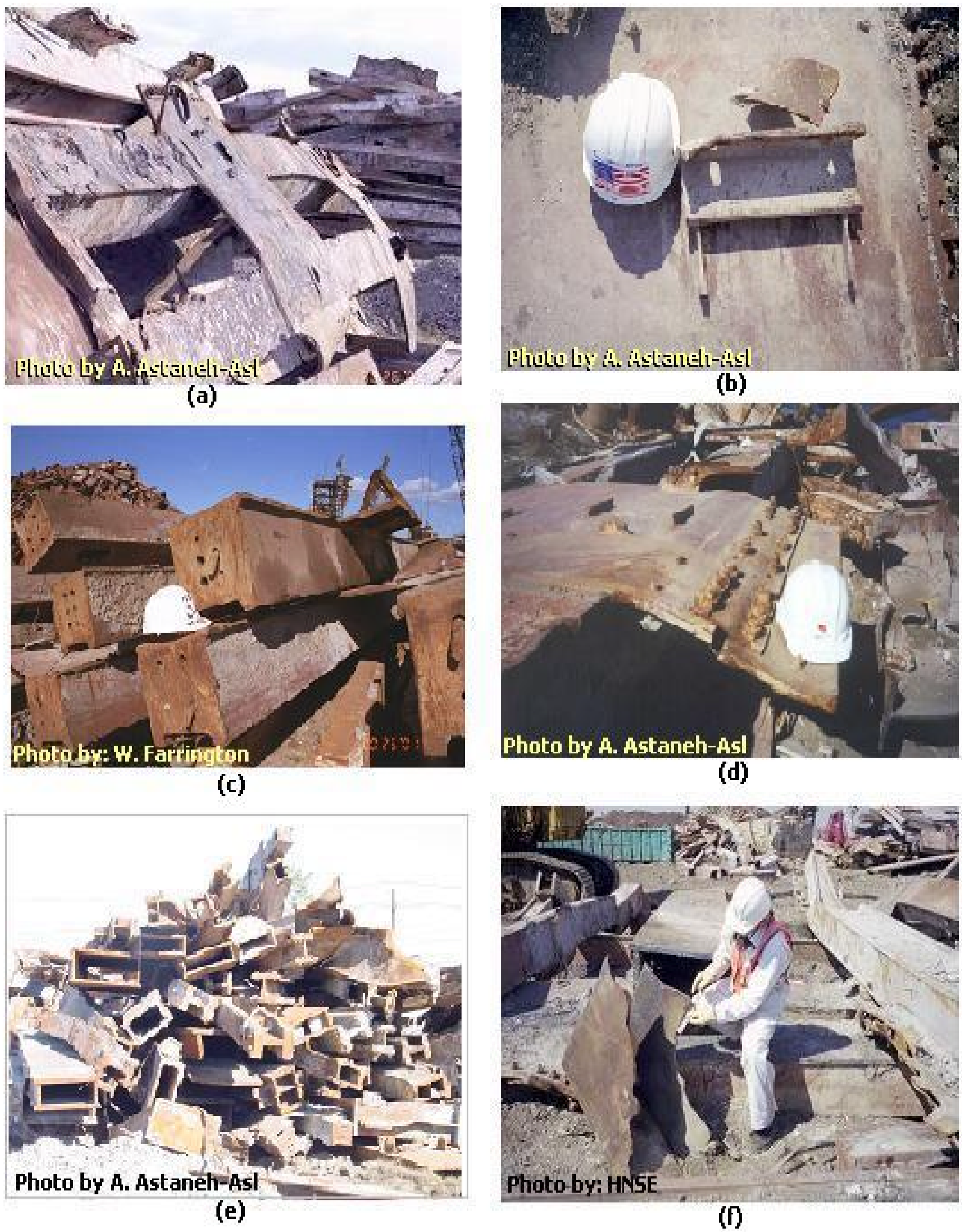


Figure 11. Components of World Trade Center After Collapse , (Ref.: A. Astaneh-Asl, 2002b)

Figure 11(f) shows the author inspecting a piece of interior column that arose quite a lot of interest. The piese showed very clear signs of a large, round and fast moving object entering from the left side of the box and cutting a quarter of a circle hole in the column. It appeared at the time of its discovery among the steel at recycling plant that this column could be from the south tower. However, not having access to structural drawings at the time, it could not positively be identified as being at a floor level that could have been hit by the engine of the airliner entering the south tower. Further investigation of this piece can positively locate it and establish whether or not it is indeed hit by the airplane engine.

5. A Proposed Scenario for the Collapse of the World Trade Center Towers

Based on the field observations of the collapsed structure, study of the design and other documents, photos and videos related to design, construction and collapse of the World Trade Center, the following scenario of collapse was formulated and presented in March 2002 (Astaneh-Asl, 2002a). The scenario of collapse is more or less the same that was presented by the author to the public and the reporters on the day of tragedy on September 11, 2001 (Astaneh-Asl, 2001a).

The author, at this writing, believes that a plausible scenario for the collapse of towers is as shown in Figure 12 and may have occurred in the following steps. The steps for both towers may have been:

1. The plane reached the tower and started impacting it.

2. The plane entered the building by cutting the relatively small but numerous box columns of the exterior tube. During this entry, it is believed that not much damage was done to the plane. However, the impact of the plane might have shaken the building, as indicated by the survivors, to cause separation of most of the sprayed-on fireproofing. Of course, due to large number of columns closely spaced on the perimeter to form the tube, the loss of columns that were severed by the planes did not cause the collapse and the towers were able to continue to stand up and carry its gravity load.

3. As the plane entered the tower, the floor system between the exterior tube and interior core in front of the plane was crushed and severely damaged. This is due to the fact that the floor system, as shown earlier, was made of floor truss joists and lightweight concrete. The author could not consider the trusses to be a match to the inertia of the entering plane and stand against the plane. However, the 10-14 cm horizontal floor slabs could have caused serious damage to the plane by cutting through it while getting crushed. It is possible that at this stage, the wings which contained the jet fuel, or part of the wings, might have severed and sprayed the jet fuel over large areas of three floors that were impacted by the plane. The fire may have started at this point.

4. The damaged plane, due to its inertia, continued to move forward and hit the core columns. These columns were generally much stronger than the outside columns and were able to better withstand the impact forces of the plane and inflict severe damage to the soft parts of the plane such as wings, tail and fuselage. Of course, those columns that were directly hit by the heavy and strong parts of the plane such as engines might have sustained serious damage and may have been severed. All these activities must have resulted in tearing apart the plane and spraying any remaining jet fuel inside the building. If the fire had not started earlier, these events at the core would have resulted in initiating the fire and spraying it throughout the floor. As indicated earlier, the core of the building had no heavy walls. All the walls in the core were drywalls (gypsum boards). The impact not only might have caused the collapse of these lightweight and relatively weak walls in the core, but also collapsed the floors and stairwells in the core. As reported in the press reports (Glanz and Lipton, 2002), all three stairwells in one tower and two of three in the second tower had collapsed cutting the egress routs for those who were trapped in the floors above the impact floors.

5. As the fire continued, the main structural elements: the exterior tube columns, the floor truss joists and the core columns and beams were subjected to fire due to burning jet fuel and the contents. As the fires burned, the strength of steel and its modulus of elasticity continued to decrease with increasing temperatures. The author believes that the first element to lose enough strength to collapse may have been the floor joists. These joists not only may have lost their fireproofing but also were heavily damaged due to entry and impact of the plane.

6. The collapse of truss joists may have resulted in doubling the buckling length of the exterior columns thus reducing their compressive capacity to one-quarter of their original capacity. In the meantime, these exterior columns were exposed to intense fire themselves and their original strength might have decreased substantially.

7. With the collapse of floor joists even over a portion of the floor, the affected columns would have buckled and collapsed almost immediately after the loss of their bracing. The buckling of these columns might have resulted in the load shifted to nearby columns and in fast moving domino effect collapse of all columns around the perimeter. Of course collapse of columns would have resulted in dropping of the upper portion of the structure on the lower portion as shown in Figure 12 and seen by millions throughout the world on September 11, 2001. The impact of the upper part dropping on the lower part caused the inevitable complete and vertical collapse of both towers under the acceleration of gravity.

6. Conclusions and Lessons Learned

Based on the studies done by the author so far following conclusions could be reached and lessons learned:

1. The structures were able to withstand the initial impact of the planes without collapse.

2. The collapse was related to loss of strength of structural elements in the floors with intense fire and collapse of the upper portion on the lower portion due to the pull of gravity.

3. There is a need for better fire protection for tall structures. The fire-proofing not only should be able to isolate the structural elements from the intense heat of fire, but the fireproofing needs to be strong enough or needs to be reinforced to stay on the element that it is protecting. Also, creating large office spaces, without partitioning walls, should looked at carefully to ensure that such large spaces will not spread the fire throughout without walls stopping it.

4. There is a need for architects to provide better egress routes for the occupants in tall buildings especially in skyscrapers. Having all stairwells concentrated at one location in the large floors, as was the case in the World Trade Center, will not help rapid evacuation of occupants if the fire is near the stairwells.

5. There is a need to study and develop new concepts and systems that can tolerate the loss of several load-carrying members without full collapse in a progressive manner.

6. The most important lesson, in the opinion of the author, is that in design of a tall building the developers, architects, structural engineers, fire engineers and first respondents (firefighters, emergency personnel,) should work together from the start of the project and consider safety of the occupants and their evacuation in case of an emergency the highest priority regardless of the cost.

7. Acknowledgments

The research project summarized here was sponsored by the National Science Foundation, Directorate of Engineering, Division of Civil and Mechanical Systems. The support and guidance provided by the Program Directors Drs. P. Nelson, P. Chang and R. Fragaszy of the National Science Foundation are acknowledged and sincerely appreciated. In particular, the author, as a scientist and engineer, would like to thank the above directors and others in NSF for their very rapid review of the proposals to study various aspects of the World Trade Center collapse, including this work, and for sending the research teams so rapidly to collect invaluable data from the field.

The author would also like to thank Mr. David Morris for his support and contributions to this work while author was in New York. Finally, this work would not have been possible without the support of faculty and staff at the University of California Berkeley in particular, Professors W. Williamson, K. Mosalam, C, Ostertag , A. Kanafani and staff members W. Mac Cracken, S. Sullivan and G. Partee.

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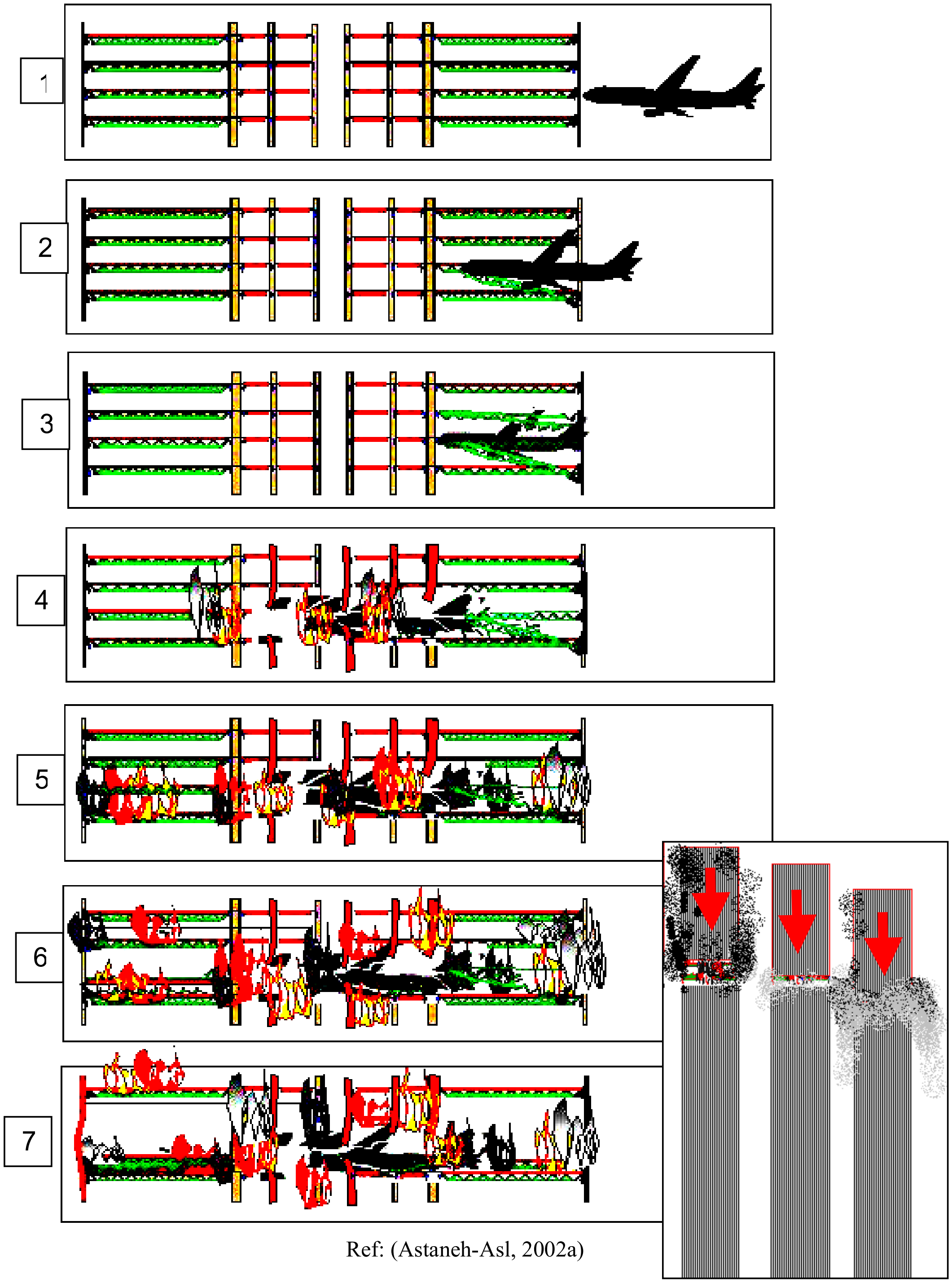

Figure 12. Sequence of Events in the Scenario of Collapse Proposed by A. Astaneh-Asl (2002a)