The World Trade Center Disaster: Analysis and Recommendations

by

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ABSTRACT

The terrorist attacks of September 11, 2001 brought about the destruction of two symbols of American economic strength, the twin towers of the World Trade Center in New York City. These towers remained standing for some time after the initial aircraft impact, allowing many occupants to escape, but eventually collapsed to the ground. Much research has been done to determine the precise mechanisms of collapse, but there is not yet a consensus. This thesis explores and summarizes the leading theories to date, with particular emphasis on the ongoing research by the National Institute of Standards and Technology (NIST). Several ideas for improving building performance and for preventing progressive collapse are also presented.

Thesis supervisor: Eduardo Kausel
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Acknowledgements

Thank you Mom and Dad for believing I could make it at MIT.

To the Boston Botanical Center project team: Thanks for helping me believe in team projects again.

To all the MEng'ers of 2005: You guys made this year survivable. I think I learned as much from you as I did from our esteemed professors. It's been a great ride ever since Bigmama tossed me into the Kennebec River. Best wishes for wherever you go from here.

To all those affected by the events of September 11th: Engineering can't solve all of the world's problems, but as engineers we take seriously our responsibility to create a safe built environment that earns the confidence of its occupants. I hope that the research which has been summarized in this thesis will lead to safer buildings in the future, and that never again will so many people suffer from a tragedy of such a nature and magnitude.

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1.0 Introduction

Everyone is familiar with the terrible events of September 11, 2001. Two commercial aircraft were used as missiles and flown into the twin towers at the World Trade Center in New York City. Another plane crashed into the Pentagon in Washington, D.C., and a fourth was brought down in rural Pennsylvania before striking its target. These acts of terrorism targeted symbols of America's political, military, and economic strength. The two towers at the World Trade Center Site remained standing for some time after the collision, but eventually collapsed into a pile of rubble.

This paper takes an in-depth look at the World Trade Center towers (Figure 1). It begins with a brief history of their construction and use. A summary of the events of September 11th follows. Then detailed consideration is made of the damage the towers sustained from the aircraft impact, the resulting fires, and the ensuing collapse. Many engineering professionals have undertaken to provide an explanation of the collapse mechanism, but opinions vary widely. The Federal Emergency Management Agency produced a review of the event and a summary of much of the data collected following the event (FEMA 2002). This report formed the basis for much of the following research by others. The National Institute of Standards and Technology (NIST) picked up the task where FEMA left it, and is currently undertaking the most comprehensive study of the disaster (NIST 2004). Many other engineers and researchers have published the results of their own analyses. In this thesis comparisons will be made among the various hypotheses, with intent to identify the most probable cause of global collapse. Additionally, a summary will be made of various proposed methods to prevent global collapse in similar future events.

2.0 Tower Construction and History

The architectural and engineering design of the "twin" 110 story towers was begun in the 1960's. Construction started in 1965, and was completed by 1972. The structural engineer of record was Leslie E. Robertson & Associates. The architect was Minoru Yamasaki. The tower structure was a "frame-tube" concept, with 207 foot square sides. Several engineering innovations were used in their construction, including the use of two-way truss framed floors, prefabricated column and spandrel panels, and spray-applied fireproofing. The tube-frame concept was itself an innovation. Overall, 14 different grades of steel were used in the buildings

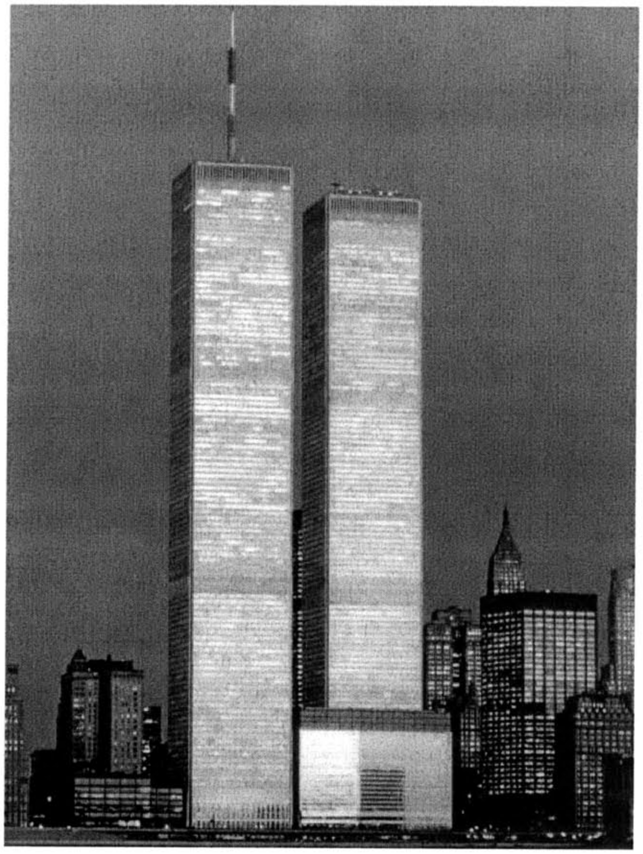

Figure 1. The World Trade Center towers (www.lera.com).

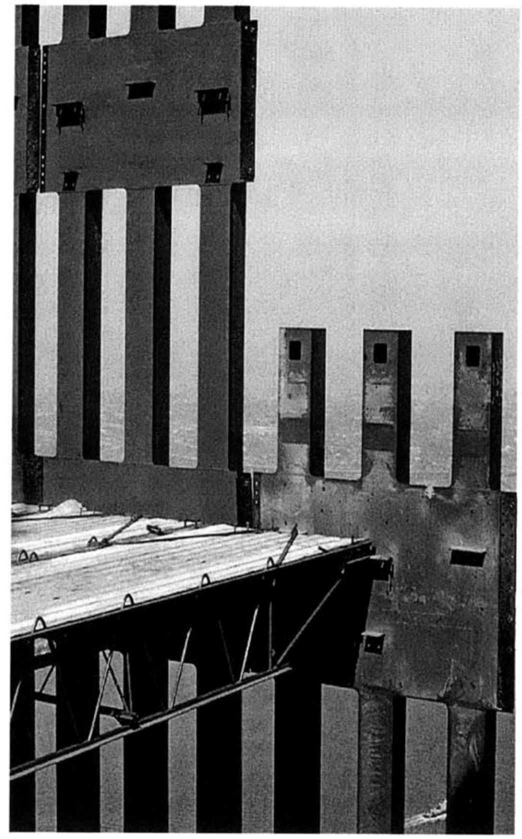

Figure 2. Floor trusses and perimeter columns during construction (NIST 2005b).

among their various column sections, floor trusses and floor deck. The steel yield stresses ranged from 36 to 100 ksi.

The perimeter tube structure had 59 columns per side. These columns were prefabricated into panels 3 columns wide and three stories high for easy and fast erection (see Figure 2). The perimeter columns were built up from steel plates welded together approximately 14" square, and were spaced closely together at 40" on center. The plate steel varied from ¼" thick near the top of the towers to 2" thick at the base. The columns were joined by 52" deep spandrel plates at each floor level. Bolted splice plates occurred between the floor levels at every third story. Aluminum sheathing wrapped the exterior of the columns to create the desired architectural finish.

Each tower had a central core which was 87' x 137'. At the lower floors, the core columns were built-up box columns 12" x 52", made of plates up to 7" thick. On upper floors the columns were changed to wide flange shapes at staggered intervals. The structure of the core was designed to carry about 60% of the total gravity loads imposed on the structure, but was not designed as part of the lateral load resisting system.

The floor slab (outside of the core) was 4" of lightweight concrete on corrugated steel decking. The steel trusses were used to create two-way spans in the four corners of the tower, and one-way spans elsewhere (see Figure 3). The longest spans were nearly 60'. To facilitate erection, the floor was pre-assembled in modules that were 20' wide. The trusses were set in pairs at 6'-8" on center (locating them at alternating exterior columns). A seat angle connected the ends of the trusses to the spandrels along the exterior column lines (see Figure 4). Each angle supported the ends of two trusses. The bottom angles of each truss top chord were attached to the seat angle by means of one 5/8" diameter bolt. The seat angle was welded to two stand-off plates, which were welded to the spandrel beam. A gusset plate connected the top of the truss top chord to the spandrel. The bottom chords of each pair of trusses were connected to the spandrel with a visco-elastic damper, a feature which helped limit sway in the towers. The dampers had a slip capacity of 5 kips. At the core end of each truss, a seat was formed from one horizontal plate and two vertical stiffeners, which were attached to channels running continuously along the core columns (see Figure 5).

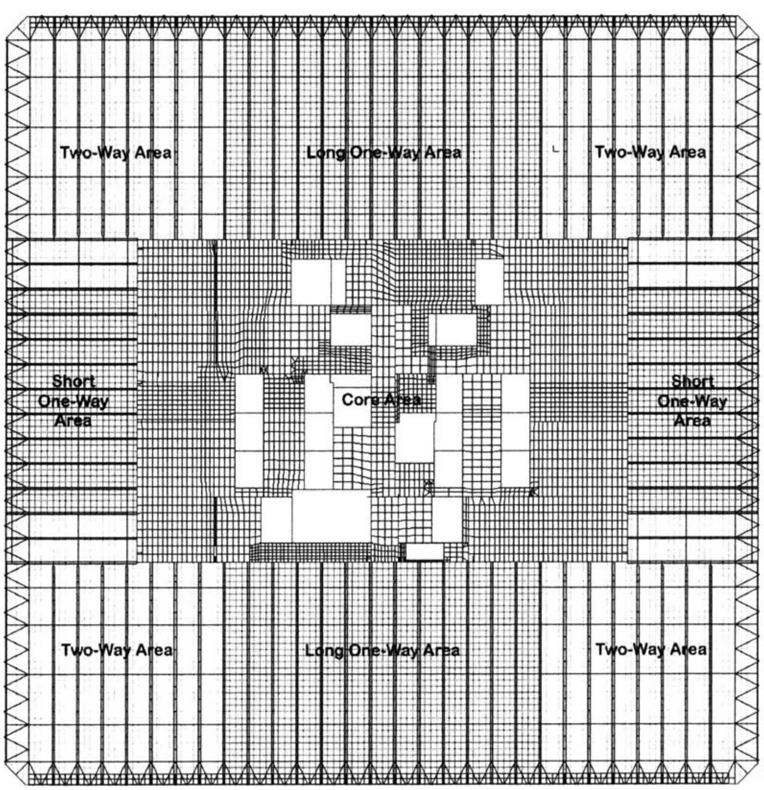

Figure 3. Typical floor framing system (NIST 2004, Appendix B).

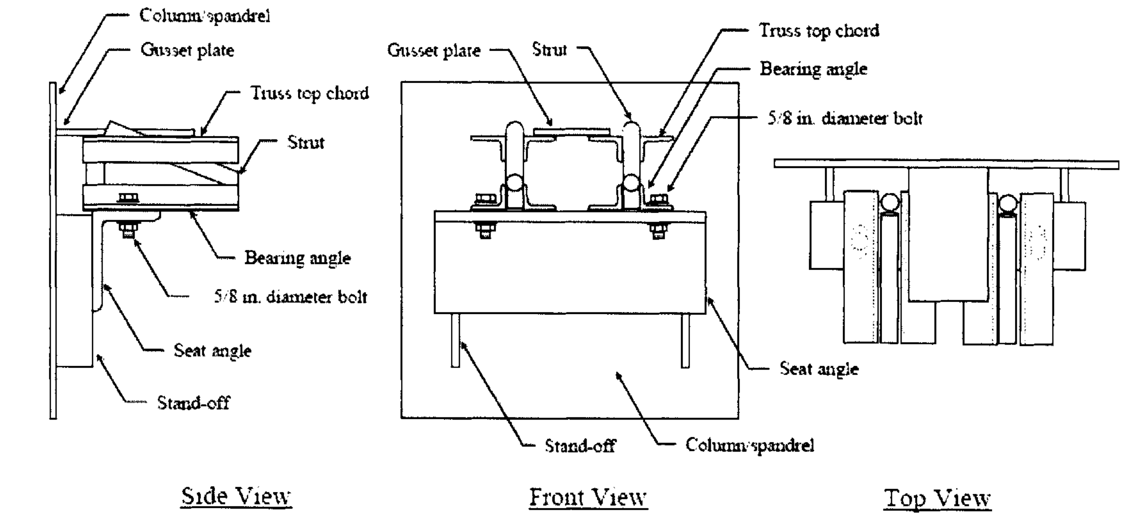

Figure 4. Exterior truss seat (NIST 2004, Appendix K).

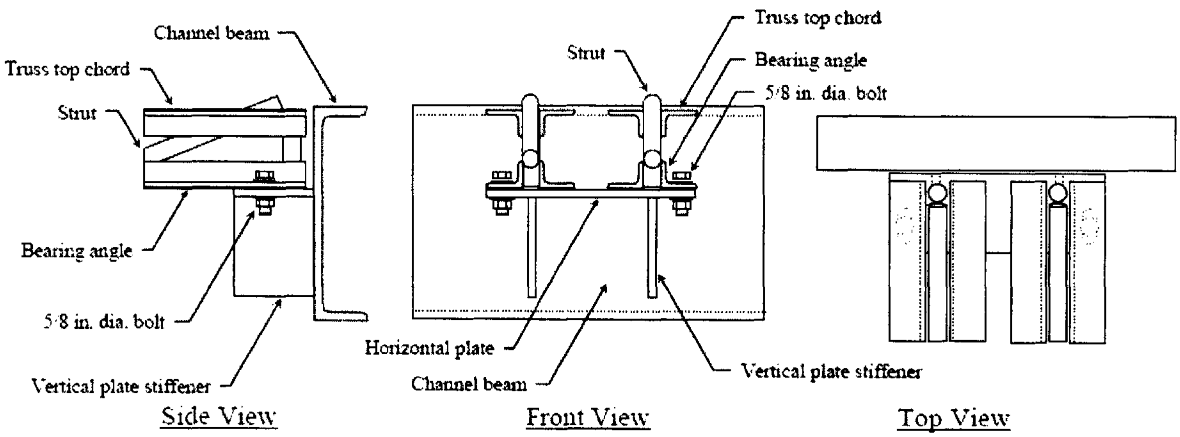

Figure 5. Interior truss seat (NIST 2004, Appendix K).

In the core area, the floor slab was 5.75" normal-weight concrete on metal deck. The supporting structure was wide flange steel beams which acted compositely with the slab, and were rigidly connected to the columns.

The initial design of the towers called for spray applied fire proofing (SFRM, or sprayed fire resistant material) on all structural members. Although the towers were not required to meet the New York City building code (the towers were under the jurisdiction of the Port Authority of New York and New Jersey, PANYNJ), the designers intended to meet or exceed all pertinent code requirements. The code required all columns to have a three hour fire rating, and for all floor members to have a two hour rating. The as-built thickness for the fireproofing on the floor trusses was 0.5". During the years leading up to the attack on September 11, the Port Authority was in the process of upgrading the fireproofing in the towers to meet current, more restrictive standards. All of the floors in the damaged zone of WTC 1 had been upgraded to the new fireproofing thickness of 1.5". In the affected floors of WTC 2, only floor 78 had received the upgraded fireproofing.

The top four stories of each tower (floors 107-110) formed a "hat-truss", which helped restrict lateral sway. On WTC 1 the truss also supported an antenna. The truss was formed of large diagonal braces (see Figure 6) (NIST 2004).

The towers were a powerful symbol of American financial strength. Together they had twelve million square feet of office space occupied by hundreds of firms. They were large enough to have their own zip code. A restaurant at the top of one tower offered a commanding view of the city. At 415 m, they were the tallest buildings in the world at the time of their completion and dominated New York's skyline (Kausel et al 2002). Because of their symbolic value, the towers were chosen by the terrorists for attack.

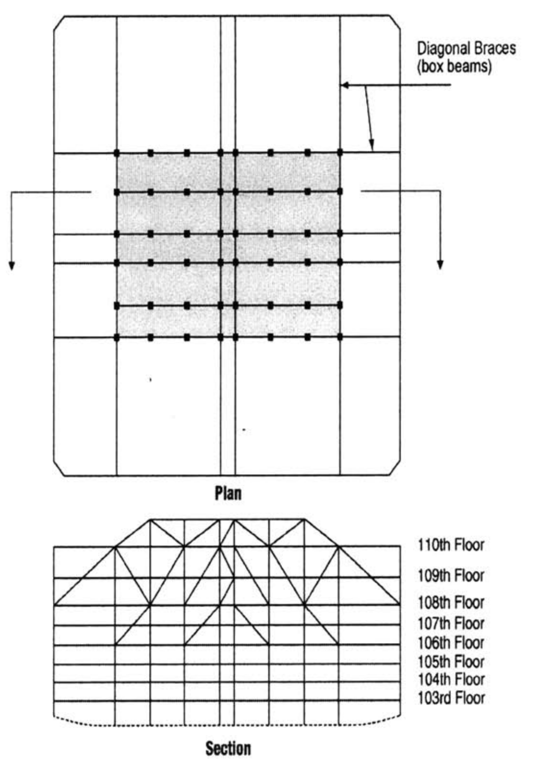

Figure 6. Plan and section of hat truss (NIST 2004, Appendix E).

3.0 Tower Destruction

At 8:46 am on September 11, 2001, the first airplane, a Boeing 767-200 ER was flown into the 96th floor of the North tower, WTC 1. Amazingly, the event was captured on video by some bystanders. The plane hit nearly in the center of the north face of the tower at a roll of 25°. A short while later, at 9:02 am, the second airplane, also a Boeing 767, impacted the south face of the south tower (WTC 2), at the 80th floor level. This impact was more eccentric to the building center. The plane's lateral approach angle was 13° off of a directly perpendicular impact, and its roll angle was about 38° (see Figures 7 and 8). Large fireballs were seen to exit each tower at the moment of impact (NIST 2005a). Pertinent data is summarized in Table 1.

Many occupants of WTC 2 began evacuating after WTC 1 was hit. It is estimated that 17,400 people were in the towers on the day of the attack. Most of them were evacuated to safety. 2830 people died on that day, including some of the emergency responders aiding in the

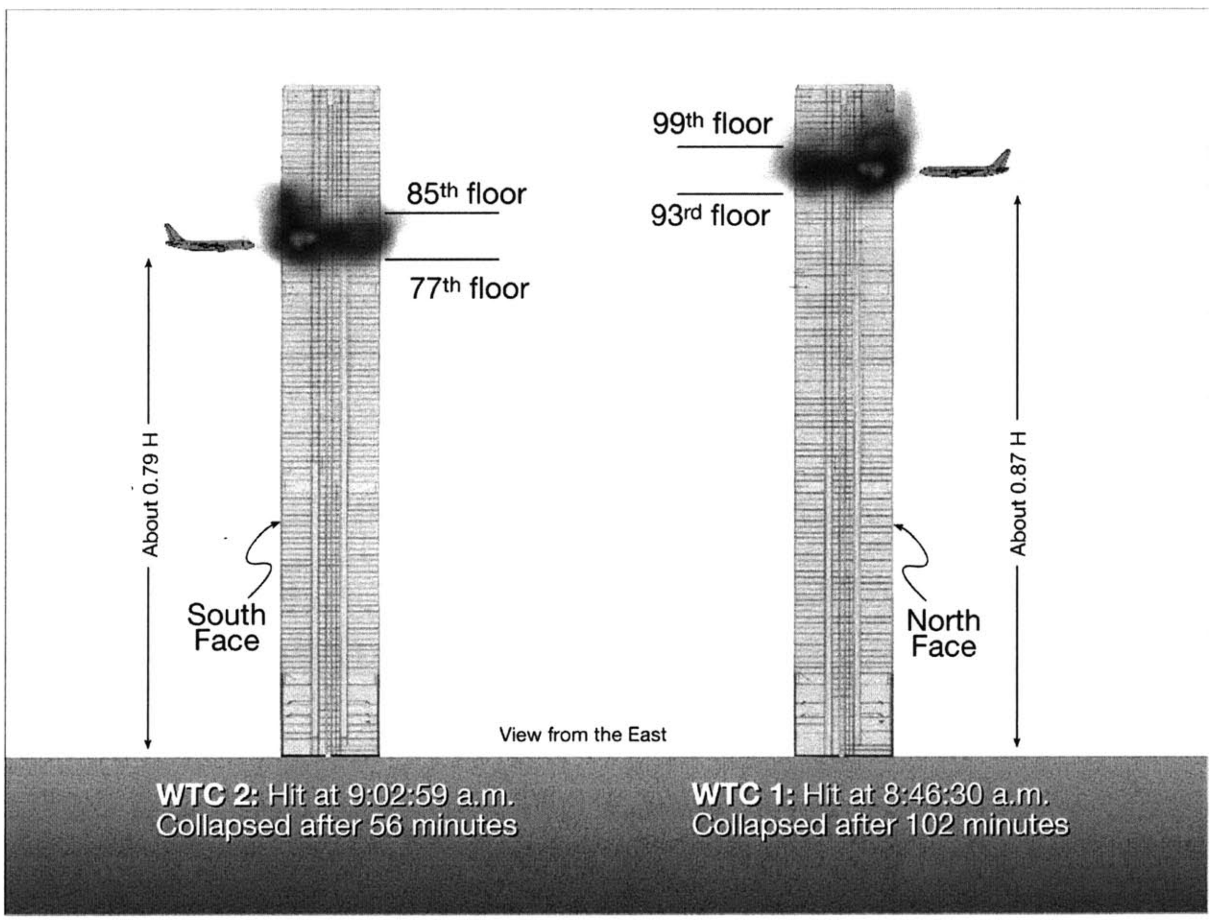

Figure 7. Elevation of impact locations (NIST 2005a).

evacuation. WTC 2 collapsed suddenly at 9:58 am, 56 minutes after the impact. WTC 1 fell at 10:28 am, having stood for 1 hour 42 minutes after impact. Both towers collapsed in about 10-12 seconds, at nearly the speed of a free fall. The pile of debris was about eleven stories tall (NIST 2004).

Tower	Time of Impact	Time of Collapse	Duration	Speed of aircraft	Damaged floors
WTC 1	8:46 am	10:28 am	102 minutes	433 mph	93-99
WTC 2	9:03 am	9:59 am	56 minutes	542 mph	77-85

Table 1. Important data of each tower (adapted from NIST 2004).

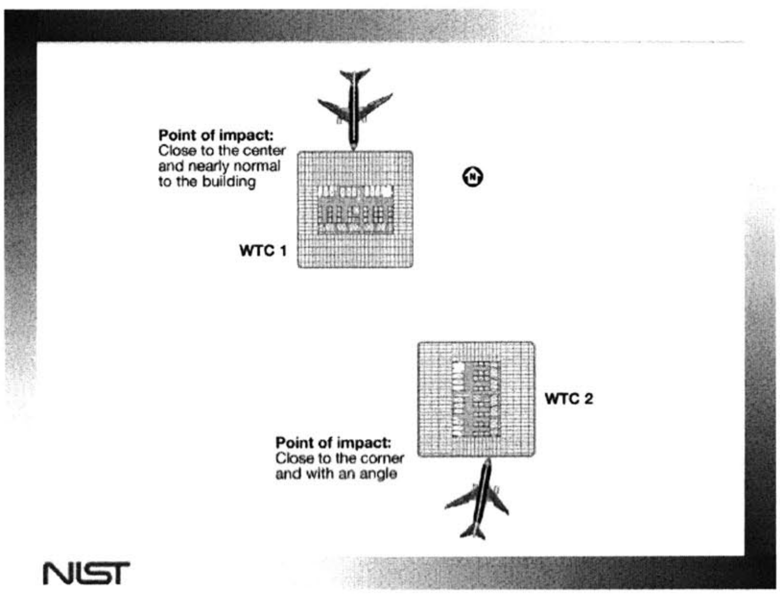

Figure 8. Impact location and orientation for each tower (NIST 2005b).

4.0 Analysis: Why the towers fell

It is possible to hypothesize many reasons why the towers stood for some time and then fell. Early reports in the press suggested that the fires had burned so hotly that the steel structure had actually melted (this is later shown to be unrealistic). More reasonable estimates of fire damage propose that steel columns or trusses were weakened (but not melted), and then buckled under loadings that were much less than what they could sustain at normal temperatures. Failure might also have occurred by compression yielding. Another theory is that the connections of the floor trusses to the columns failed, and that the floors dropped one on top of the other, causing large dynamic forces which led to progressive collapse. Still another failure mechanism considers that the loads of floors above the impact area were resolved upwards into the hat truss, causing column splices to fail in tension, a directional force for which the splices were not designed. Each mechanism must be examined to see if it will lead to the type of collapse actually observed in the towers. They must be shown to result in abrupt and progressive failure.

4.1 The initial report by FEMA and ASCE

The report by the Federal Emergency Management Agency and the American Society of Civil Engineers (FEMA 2002) did not offer definitive explanations of the tower collapse. The report did recognize the significance of the fires as the second major factor other than the airplane impact which brought the towers down. The fuel from the jets burned off quickly, some in the large fireballs seen outside the towers, and some inside the buildings. FEMA estimated that the fuel was consumed within 60 seconds of impact. Although the heat from the fuel fires was not sufficient to cause collapse, the fuel fires served the further purpose to ignite and spread fire to the building contents over a vast area inside the towers.

FEMA's review did not find the structural design of the towers to be substandard to code requirements in any way. In fact it exceeded the code in some instances. A particular benefit of the towers' design was the redundancy and robustness of the perimeter tube frame. The towers had three lines of defense against fire damage. The first element of protection was the sprinkler system; the second was active firefighting by the fire department; and the third was the passive resistance supplied by the fibrous barrier applied directly to the structural elements. The sprinkler system was compromised immediately by the impact. FEMA suggested that there were a few potential weaknesses in the structural system that warranted further study. These included the innovative floor truss system and the spray-applied fire-proofing, with particular interest paid to the ability of fire-proofing to adhere to the steel surface under blast loading.

4.2 Research focusing on initiation of collapse in the floors

4.2.1 Research at MIT

One of the earliest publications of analysis of the World Trade Center collapse came from researchers at the Massachusetts Institute of Technology (Kausel et al 2002). An online collection of essays, the work included a history of the towers, computations of the speed and inclination at which the planes struck the towers, a hypothesis of the mechanism which led to collapse, and suggestions for improvements to life safety provisions in buildings in the future.

Professors Buyukozturk and Ulm addressed the material and structural failure of the towers, and described the failure as a three step process: (1) the impact of the airplane, (2) failure of an elevated floor system, and (3) a dynamic crash. They were in agreement with FEMA's deduction that the airplane impact was not the primary cause of global collapse. Instead the authors suggest that there was a lack of redundancy in the structure, at both material and macro levels, which meant that global collapse occurred sooner than anticipated.

The initial impact and fireball probably removed some of the fireproofing from structural steel members. At fire temperatures in the range of 600-800° C, any exposed steel could have suffered severe thermal damage. Steel will melt around 1700° C, but will lose as much as half of its stiffness and strength in the range of temperatures postulated for the WTC towers. Thermal damage to some part of the floor truss system is suspected to be the initiating event leading to collapse. Had a uniform heating of the floor trusses occurred (which would have been the case if all of the fireproofing was intact), the trusses would have deformed plastically and suffered large deformations. However, this mode of failure is ductile, and would not lead to sudden collapse. Therefore it's not likely the trusses were uniformly heated. Rather, a non-uniform heating is likely. A finite element analysis is provided in which one end of the truss is assumed to rapidly heat to the full fire temperature (see Figure 9). This would occur if fireproofing was missing from that end of the truss, or if the truss connection was not protected from fire. The result is a rigid body motion of the truss, which fails at the heated end at a time of about 45 minutes. Thus the end support of the truss is seen as the weak link in the structural system. It may be that the connecting bolts softened, or that the end members of the truss were severely deformed. There is some evidence of this sort of damage in the recovered steel of the towers.

One failed truss would be insufficient to bring down an entire floor. If several adjacent trusses lost support at one end, and were hanging from the concrete slab (due to the composite nature of the deck/truss system), they would spread their load laterally to adjacent trusses. This may lead to overloading of adjacent trusses and cause a zipper effect of truss support failures across a large floor area. Thus a large portion of floor slab might fall onto the floor below. If the floor below had already been overloaded with debris from the impact, this additional floor (with its associated impact force) would probably be enough to fail the lower floor, and initiate a progression of collapse.

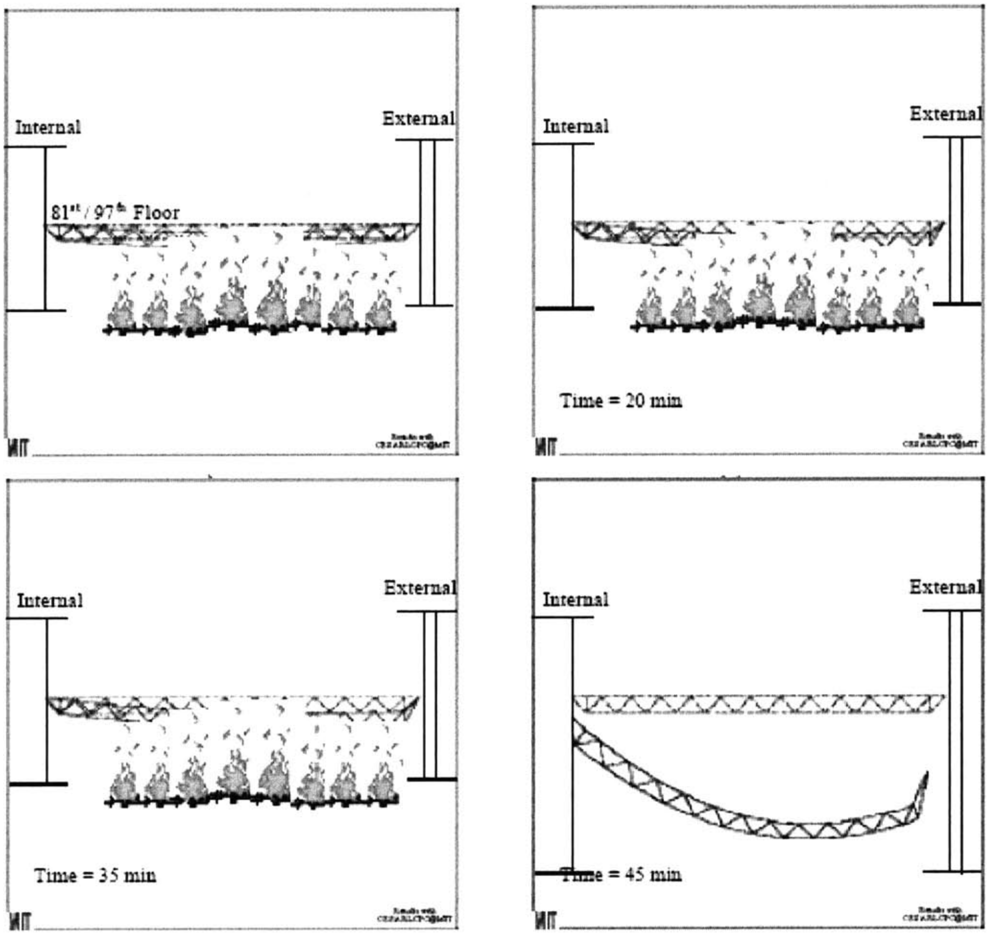

Figure 9. MIT's finite element analysis (Kausel et al 2002).

Upon the loss of lateral bracing from the floor slab, a column (whether it is a perimeter or core column) will immediately lose some of its resistance to buckling. A doubling of the unbraced length of a column will reduce its buckling resistance by a factor of four; a tripling of the unbraced length by a factor of 9, and so on. Given that a typical structural column has a buckling resistance safety factor between 5 and 10, it is apparent that only one or two floors must be lost before the column might buckle. So the initiating event is the loss of support of a floor system, with a nearly simultaneous buckling of the columns. At this point, the mass of the structure above the damaged zone is no longer supported and begins to fall. The increasing momentum of this mass overcomes any remaining resistance in the structure below, and carries it to the ground.

Wierzbicki's analysis in the MIT collection focuses on the initial damage which the towers sustained from the impact of the aircraft. Using conservation of energy methods, he estimates that between 4 and 12 core columns were ruptured in the North tower (WTC 1), and 7-20 were destroyed in the South tower (WTC 2). He states that the core columns carried 60% of the vertical loads of the towers, and were generally stronger than the perimeter columns. The initial aircraft impact was a stronger contributor to collapse for the South tower. One reason for this was the asymmetric direction and location of the impact.

In this initial research, Wierzbicki calculated that the strength of the core was reduced by 16-45% from the impact. This may have overloaded the columns by a factor of 1.2 to 2.5. In the south tower, a "mirror effect" effectively doubled the number of peripheral core columns that were rendered ineffective. This is because the core was essentially balancing on the central undamaged columns, not being able to lean away from those peripheral columns that were damaged.

Wierzbicki's later research (Wierzbicki 2003) deals with the energy required for the airplane to cut through the outside of the structure. Some may have been surprised at the ease with which this occurred, considering the robustness of the structure. But the equivalent mass of an airplane's wing has a thickness of over 100 mm, compared to the 9.5 mm thickness of the perimeter columns of the towers. Wierzbicki estimates that 6.7% of the kinetic energy was removed from the airplane by the exterior columns, and the remaining 93.3% damaged the interior potions of the towers. He also determined that had the aircraft been traveling at a slower speed of about 100 m/s, this fracture would not have occurred. Instead, the columns would have deflected the aircraft wings. The steel strength is another variable which could have produced different results. Had the steel been high strength, with a yield stress of 700 MPa, it might have deflected the airplane wings.

Thomas W. Eager and Christopher Musso (2001) wrote an early study of the collapse in the *Journal of Materials*. They give a brief description of the buildings, and the events of September 11, and the ensuing aggravated conditions imposed on the structures. They note the newness of the structural system of the towers, comparing the lightness of the steel frames to former standards in tall building design which mostly used heavy, closely spaced columns and load bearing masonry. The WTC towers were still considered to be redundant and robust. Since there was little wind on September 11, the stresses in the columns prior to the airplane impact were estimated to be about 1/3 of their capacity.

The authors note the difference between temperature and heat, emphasizing that while there was an immense amount of heat during the event (due to the large size and spatial extent of the fires), the steel was not likely exposed to an inordinately high temperature. The fires in the WTC were a diffuse flame type, which produces lower temperatures than either a pre-mixed or jet burner flame. When burning in air, a diffuse flame will usually not exceed 1000° C, and will be even less in a fuel rich environment such as was the case in the WTC towers. The authors suggest that the towers only experienced fire temperatures around 750-800° C.

At 450° C a softening begins to occur in structural steel, and about half of its strength is lost when it reaches 650°. However, since the columns were loaded much less than their design capacity on the day of the attack, even such a weakening would not have led to collapse. The fires did cause distortion of the steel by temperature differentials which caused bowing in columns or buckling of trusses. Stresses can reach yield limits in a section by a temperature differential of merely 150° C. These distortions, coupled with the thermal weakening, caused the eventual collapse.

Eager and Musso point to the angle clips which connected the floor trusses to the columns as a likely weak point in the structure. They put forth a scenario in which heavily burned floors fall, followed by outward bowing of the perimeter columns, and then the descent of the floors above. This crashing mass fractured the clip angles on the floors below, which up to this point had been undamaged.

One further note of interest addressed by the authors is a response to the common question of why the towers did not fall sideways. First of all, the buildings were 95% air. In addition to this, the center of gravity of the tower would have to move 100 feet to the side to create an overturning moment. Such motion could not be created even by the high velocity impact of the aircraft.

4.2.2 Kajima Corporation

Researchers at the Kajima Corporation in Japan recently published a rather thorough investigation into the structural responses of the towers (Omika et al 2005), beginning with a simple lumped mass model to determine the behavior during impact, continuing with a more detailed finite element model to determine the structural damage due to impact, and finally a stress analysis of the events leading to collapse. The purpose of their study was to determine why the towers stood some time after impact, and why one tower stood longer than the other. Many assumptions were made, as the authors did not have access to much of the specific design data of the towers.

The impact model consisted of 110 beam-lumped masses. The shear and bending stiffnesses were separated for wind analysis. A Rayliegh damping of 3% was used. Good deflection results were obtained from this model for the impact loading (50 cm at floor 110). This was less than the deflection from design wind loads. The calculated story shear forces from impact exceeded the design wind load shears, but were less than the ultimate story strength. This is an indication of why the towers did not immediately collapse.

The authors state that their finite element model provided good correlation between calculated damage to the exterior columns and the visual evidence of damage. For WTC 1, the model indicated that 90 perimeter columns were broken. 104 perimeter columns were broken in WTC 2. The model calculated that 26 core columns were broken in WTC 1, with an additional 6 columns judged to have failed in some other manner. In WTC 2, one core column was determined to be broken, and 8 failed in another fashion. Of course core column damage cannot be confirmed by the visual record.

To determine the stress state of the structure after impact, the researchers modeled the entire frame. The columns and beams were modeled as bilinear material. The column splices were assumed to have strength equivalent to the base members. The results indicate that the worst case axial stress in the perimeter columns of WTC 1 increased from 135 N/mm^2 prior to impact to 472 N/mm^2 after impact. In WTC 2 the stress increased to 459 N/mm^2. In both towers the final stress exceeded the yield stress of 448 N/mm^2. The core columns suffered a similar fate, where the axial stress increased from 216 N/mm^2 to 273 N/mm^2 in WTC 1, and to 268 N/mm^2 in WTC 2, exceeding the allowable of 248 N/mm^2 in both cases.

The location and influence of the outrigger truss played a key role in the results obtained in this research. Floors 107 to 110 of both towers contained diagonal members that acted as a hat truss for added stiffness of the buildings. After the impact damage, these trusses redistributed loads from damaged to undamaged areas of the structure. In the North-South direction, there were six of these trusses, and four of them in the East-West direction. Loads that had been carried by some damaged core columns were resolved up into the outrigger by tension in the columns above. This probably caused some of those higher columns to yield. This analysis assumes the columns splices were strong enough to transmit those forces. Damaged core columns that did not have a direct load path up to the outrigger were forced to try to distribute load laterally to undamaged columns through means of the core floor beams. However, this analysis indicates that those core beams yielded at an early stage, and it is therefore likely that a core floor fell down. The authors also state that a failure of an outer floor span is likely, due to fracture of the floor connection to the outer columns. The perimeter columns were able to redistribute load by means of the spandrel beams. But the failure of core floor beams resulted in fracture, and led to floor slabs collapsing simultaneously over several stories, and then progressive global collapse.

The asymmetry of the impact damage to WTC 2 is seen as the primary reason that tower fell earlier than the other. This caused an imbalance, and higher column stresses in WTC 2.

4.2.3 Research at the University of Maryland

Quintiere et al (2002) have produced research with remarkable correlation between the actual and theoretical time to collapse, based on the failure of the diagonal rods of the floor trusses. In agreement with other sources, Quintiere notes that the jet fuel only burned for a few minutes, and did not in itself cause much damage. It did, however, serve to ignite the building contents, which burned for the duration. The main focus of their study is on the 27.7 mm (1.09") diameter rods in the transverse and main floor trusses. These are the structural elements with the lowest cross-sectional mass, and therefore would heat fastest in the fire.

Quintiere's hypothesis is as follows. The first buckling occurred in the web diagonals of the transverse (secondary) trusses which were closest to the main trusses. They buckled under elongation caused by thermal expansion. This was followed by buckling of other diagonals in these same transverse trusses. This resulted in sagging of the entire transverse truss, and corresponding sagging of the floor deck. The deck may then have begun to act as a membrane hung between the main trusses. The bottom chord of the transverse truss probably kept the deck from completely collapsing for some time, but eventually gave way, causing the deck and truss to fall to the floor below.

Simultaneous deterioration occurred in the main trusses. The diagonals began to fail due to constrained elongation similar to the transverse trusses. The top chord also tried to expand against its supports, inducing a bending moment in the truss about its neutral axis. The compressive forces eventually buckled the truss out of the plane of the floor, at which point the truss began to act as a cable hung between the core and exterior columns. In this state the truss exerted tensile force on its connections to the columns, and finally sheared the bolts at these connections. The floor then fell onto the one below. Once several floors had failed in this manner and accumulated on an undamaged floor below, the combined loads would overstress that floor and the failure would progress down the building. Additional evidence of a floor failure comes from images of the collapse which show a burst of smoke and flame pushing out from the building just prior to global collapse.

This analysis uses the fireproofing values given in the FEMA report. WTC 2 had 38.1 mm (1.5") on the trusses on all of the impacted floors, while WTC 1 had 19.1 mm (3/4") on all of the impacted floors except floor 78, which had 38.1 mm (1.5"). The fireproofing was Cafco DC/F, a sprayed mineral fiber.

The failure of the truss diagonals results from the time-dependent effects of the fire, namely the reduction in the elastic modulus at higher temperatures and the increased compressive forces caused by constrained expansion. The actual fire conditions in the WTC towers were estimated from CIB tests (done in the UK in 1972). The estimated fire duration, based on available fuel and ventilation, was 80-100 minutes. Given that the WTC 1 burned for only 103 minutes before collapse, the authors speculate that the towers may have survived if they had been able to stand for just a little while longer until the fires had died out. The fire temperature used in the analysis was 900° C. According the manufacturer of the fireproofing, it had a conductivity of 0.046 W/m-K at room temperature.

The acoustic ceiling tiles were estimated to delay the heating of the steel by about 10 minutes. In areas directly affected by the impact, the ceiling tiles were probably removed. However, there was not likely to be an accumulation of combustible material in the impact region, so the fires there were not fully developed. The fully developed fires were more likely to occur away from the impact area, and therefore the ceiling tiles were probably still in place there. The same reasoning applies to the presence or removal of the fireproofing on the trusses. If the fireproofing was absent in a location with a fully developed fire, the bare steel would probably fail within 10 or 15 minutes. Since such quick failure did not occur, it is expected that the main fires occurred in areas where the fire protection was still intact.

The truss diagonals were A36 steel rods about 0.889 m (35") long. It is shown that compression loads were more critical than tension. Given standard safety factors, and an estimated actual load in the truss prior to the fire, the authors determine a critical bucking stress and the temperature at which it will occur. This temperature will be between 630° and 770° C. The time for the truss rods to reach this temperature is determined from the fire scenario. For WTC 1, the average time to failure is 95 minutes. When the 10 minute delay provided by the ceiling tiles is considered, the total time of 105 minutes nearly matches the 102 minutes for which the tower actually stood. The results for WTC 2 are also very good, with the calculated time of 51 minutes being very close to the actual time of 56 minutes.

A consulting engineer from the UK, Dr. Barbara Lane (2003), questions Quintiere's hypothesis, based on current research in fire engineering. She contends that the response of the full structure under fire can be quite different from that of a single element, and therefore it is inappropriate to base an analysis on a single element. Reference is made to the Cardington Large Building Test Frame program in the UK. Geometrically non-linear analysis is suggested as a more appropriate method, including thermal expansion effects. The author states that different mechanisms of collapse were possible which would not depend on the presence or absence of the fireproofing on the steel members. It is important to first establish the relative importance of the floor trusses to the overall stability of the towers, as well as the capacity of the columns to take tensile force if the trusses devolve to catenary action.

4.2.4 Research in the UK

Usmani et al (2003) attempt to answer the following question: "Had there been no structural damage would the structure have survived fires of a similar magnitude?". This research is carried out with a finite element model and a wide range of fire conditions. They state that they have made no unreasonable assumptions, and therefore their results aren't vulnerable to some of the criticisms of other analyses. Their conclusion is that the structure of the WTC towers was unusually susceptible to a large fire. The collapse mechanism is probably more related to the geometric effects of thermal expansion than to weakening of material properties. This line of reasoning is similar to that of Lane. The current authors also base their hypothesis on recent research conducted in the UK. This research has indicated that composite steel frames are more robust than previously thought in fire conditions (except for unusual conditions such as existed in the WTC towers). Specific reasons for the favorable performance are due to tensile and compressive membrane action in the slabs and thermally induced lateral prestress in the slabs.

Usmani comments on Quintiere's theory of collapse. They are in agreement with the large deflections in the floor trusses, but disagree that the tensile membrane action developed in the floor would have failed the connections. Usmani notes that many connections would have to fail simultaneously, or nearly so, for enough kinetic energy to be developed by the falling members to cause progressive collapse. The Cardington tests have indicated that connections remain in compression for the durations of the fire and only reverse to tension after the fires have died out.

The work presented here by Usmani uses a simple 2-D model and ignores damage to the structure. The hypothesis focuses on the weakness of the floor plate to resist compression and out-of-plane buckling, since it is long and slender. If the floors buckle, they will no longer provide the lateral restraint required by the perimeter columns. A range of likely fire temperatures is considered. The model represents a vertical slice of the tower, including twelve floors. Fires are modeled on one to three of the floors. The fire distribution chosen has the highest temperatures at the perimeter, and the coolest at the core. The indicator of collapse is taken as the "pseudo-velocity" of the connection of the floor to the columns. The results are nearly the same for all scenarios considered, that is, geometric changes in the structure cause instability leading to failure. The material strength is not a significant factor. Temperatures at failure can be as low as 500° C, depending on the number of floors involved in the fire. In these models, the main fire floor tends to expand outwardly, then buckle, pulling the perimeter column in. The authors do not address the capacity of the connections with regards to this pulling force.

The authors state that the most likely failure initiation mechanism is the buckling of the columns. The pin connections will fail once collapse has begun, "but this is 'effect' not 'cause'". The column buckling was inward, not outward. There are additional effects the authors would like to consider, such as the dynamic effect of the columns "snapping" inward when the slabs buckle. Another consideration is the lateral support provided to the perimeter columns in the direction orthogonal to the floor trusses.

4.2.5 Other Research

Bernard Monahan published some brief technical notes on the WTC collapse (Monahan 2002). He suggested that the fire environment caused temperatures exceeding 2000° F, which exceeded the fireproofing rating of 1600° F. The collapse was caused by buckling of the perimeter columns, which had lost lateral support from the floors which were damaged in the impact. The floors dropped onto the floors below, causing a self-perpetuating collapse all the way to the ground.

Monahan also comments on the slurry basement walls of the towers. These walls were three feet thick reinforced concrete, and reached 65 feet below grade to keep the Hudson River out of the foundation.

W. Gene Corley, the leader of FEMA's investigation team, summarized the findings in an article in May 2004 (Corley 2004). A few interesting notes he makes include the following. No explosion or shock wave was caused by the initial fireballs. An estimated 1360 m^2 opening was created in the perimeter wall of WTC 1. The structure was affected by such factors as damaged fireproofing, elevated stresses from redistributed loads, added loads from debris on the floors, expansion and sagging of the floor slabs, and buckling of columns due to heat effects. During the collapse, floors pancaked. This left columns unsupported over several story heights. The columns buckled at their splice plates and fell.

4.3 Research focusing on initiation of collapse at the columns

4.3.1 Research at Northwestern University

Bazant and Zhou (2002a) postulate a theory of collapse initiating with creep buckling of the columns, both in the perimeter and core. They do not substantiate this theory, but move on from it to a proof of the inevitability of progressive collapse, once the initiating event had occurred. Their collapse scenario is broken down into five steps. In Stage 1, the column steel is exposed to temperatures in excess of 800° C. They assume there is probably a loss of fireproofing as a result of the aircraft impact. The columns suffer creep buckling in Stage 2 and lose load carrying capacity. In Stage 3 more than half of the columns on a given floor have buckled, and the upper mass of the building begins to fall. The upper structure impacts the lower structure in Stage 4, creating a large dynamic force which exceeds the capacity of the lower structure. This causes failure of a multi-story segment below this critical floor. This failure occurs by failure of the floor-truss connections to the columns, which may be simultaneous with buckling of the columns in the core and perimeter tube. Stage 5 is the buckling of the columns, with the buckling length probably being several stories high. Initially, the buckling is plastic, but fracture soon follows in the plastic hinges. This impact and failure process continues all the way down the building.

The authors acknowledge the great complexities in the analysis of the collapse, and the many assumptions that must be made. One variant is displayed in the tilting of the South tower at the initiation of collapse. This is evidence of the non-uniformity of the impact forces during collapse. To strengthen the support for their theory, Bazant and Zhou have taken the assumptions that are most optimistic concerning the survival of the towers. For instance, they assume that the impact force is distributed equally among all of the columns on a given floor. They also ignored fracture as a failure mechanism in the steel members, and assumed the steel behaved elastically with limitless ductility.

Modeling the structure below the impact zone as an elastic spring, with a spring constant C $\cong$ 71 GN/m, it is found that the columns could dissipate a maximum of 12% of the gravitational potential energy of the falling upper structure. This is obviously not enough to arrest the fall. The dynamic overload factor resulting from this analysis is an astonishing 31 (i.e. the ratio of the impact force to the resisting capacity of the lower structure).

Various failure scenarios were considered. There could be local buckling of the columns. The floor trusses could shear off at their connections to the columns. The upper part of the structure could wedge into the lower part as it falls, pushing out the perimeter walls. The authors considered the most likely scenario to be a combination of these latter two, because there is photographic evidence of large sections of the perimeter frames freefalling during collapse. A minimum of one plastic hinge, and a maximum of four, are required for collapse to occur. Continuing to choose the most optimistic option (to preserve the structure), the authors analyzed the case with four plastic hinges, and determined that the structure could dissipate a maximum of 0.5 GN-m. However, the estimated kinetic energy of the falling upper structures is 4.2 GN-m, which is 8.4 times larger than the absorption capacity, indicating that in no way could the steel frame arrest the progression of collapse.

Bazant and Zhou further make some simple calculations related to the impact velocity imparted to the buildings by the aircraft. Some may have wondered why the towers did not immediately collapse, or show large motion upon impact. But when the relative masses of the tower and airplane are compared, and conservation of momentum is considered, it is obvious that only slight motion would be seen in the tower. The authors calculate that the velocity of the top of the tower was 0.19 m/s, and the maximum deflection was about 0.4 m, which is well within the elastic motion capacity of the towers.

In an addendum to their first paper (Bazant and Zhou 2002b), the authors answer some additional questions related to the collapse of the towers. First they consider what may have resulted from aircraft impact at a higher floor. Following the reasoning from their first article, one still comes up with very high overload factors, even if the impact area is very near the top of the tower. But two additional aspects may be considered which will alter this result. First is the fact that the columns of a tower are usually not reduced in size or strength in a linear progression from bottom to top. They are often held to a constant larger size near the top for architectural or fabrication reasons, meaning that their capacity is higher and that the dynamic overload may be only on the order of two (compared to 31 from the earlier results). The second reason for which an impact at an upper floor may not be as severe has to do with whether or not the structure above the impact will behave as a rigid body. In the case in which the aspect ratio (height to width) of the upper structure is much less than one, this upper structure may in fact behave more like a flexible plate, instead of a rigid body. In such a configuration, it is more likely that the structure will collapse in several separate units, with corresponding smaller impact loads. These smaller loads are less likely to cause global collapse. This leads to a suggested method for avoiding progressive collapse: a smart system that generates gradual collapse of the upper portions of the structure, with smaller resulting impact forces.

The authors further note that columns in the structure above the impact zone are likely to buckle along with buckling of the structure below during global collapse. In other words, in addition to the downward propagating front of the collapse, there is also an upward progressing front. The difference in the two fronts is that the number of floors above the upward front diminishes with the progression (i.e. the inertial mass diminishes).

Concerning other weaknesses or failure mechanisms in the tower structures, Bazant and Zhou dismiss them as being an order of magnitude less in significance than the dynamic loads. It is specifically noted that even if the floor truss to column connections were insufficient in strength, they made no difference regarding the total tower collapse.

Usmani et al (2003) offer some comments on the analysis of Bazant and Zhou, noting its importance in demonstrating the dynamic overload once collapse had begun. But Usmani further notes that Bazant's work does not really address the initiating event in a satisfactory way. Bazant's claim that thermal creep of the columns was the root cause can not be substantiated, because FEMA (2002) noted that temperatures of a magnitude sufficient to fail the columns in this manner were not likely to exist over the whole affected area at the same time. Usmani finds further evidence of a reduced fire environment in the fact that large flames were not visible around the exterior for the full duration, meaning that there was not enhanced ventilation conditions to fuel a hotter fire. The unlikelihood that the columns suffered creep buckling is also due to the fact that the service loads in the columns on the day of the event were much lower than their design capacity. Furthermore, if consistent temperatures of 800° C had existed during the event over an entire floor where some of the fireproofing had been removed, the structure would have collapsed much sooner.

4.3.2 Research performed for insurance claims

Some research was initiated by lease holders of the WTC property. Various engineering firms were employed to study the collapse of the towers. Engineers from Weidlinger Associates (Abboud et al 2003) employed extensive review of photographic evidence and finite element analysis as the basis for their understanding of the collapse. They determined the speed of the aircraft impact for WTC 1 to be 500 mph, and for WTC 2 to be 550 mph. Their nonlinear model of the towers did not include the architectural components of the buildings, so their estimate of damage due to initial impact is an upper bound. Similar to other researchers, they found that vierendeel truss action provided load redistribution in the perimeter columns. They state that the core columns redistributed loads up into the hat truss. This load eventually caused the buckling of eight of the hat truss diagonals in WTC 2, in the south and east sides. No hat truss buckling occurred in WTC 1.

This research focused on failure of the columns because the authors believed there was no evidence of extensive floor slab failure. This is based on their analysis of the smoke or fire spread patterns. In WTC 1, the core columns are seen to be the location of failure initiation. The axial capacity of the core columns is exceeded, and when the hat truss is no longer able to redistribute the core column loads (due to buckling of the truss diagonals) the core sinks down as the core columns begin to crush. Photographic evidence confirms that the core area was seen to sink before global collapse. The antenna on top of the tower began to fall ahead of the perimeter. The collapse mechanism for WTC 2 differs in that collapse initiation is determined to begin at the perimeter columns on the southeast, east, and northeast faces. The load from these columns tried to redistribute to the core columns, but the core columns also failed. At this point, the diagonals of the hat truss also failed. The perimeter columns on the east side of floors 80-82 (those nearest the impact zone) failed in a zipper like effect.

The research from Weidlinger was based in part on fire analysis performed by researchers at Hughes Associates, Inc. in Baltimore (Beyler et al 2003). The authors of this study find the evidence to show that the fires in the WTC towers were not at intense as a typical fully developed building fire. They also believe that the fire conditions in the two towers were essentially the same, and therefore the difference in time to collapse was not due to differences in the fire environment.

The evidence regarding window damage was investigated by Beyler. Windows crack in a temperature range of 70-100° C, and are assumed to be lost when temperatures reach 400-700° C. In the range of 500-600° C flashover occurs. Since many windows in the impact zones of the WTC towers were observed to remain in place for the duration of the event, it is apparent that temperatures did not reach as high as in a traditional fully developed fire. Some windows broke during the fire duration, but this occurred in a slow manner, and in distinct locations as the fire moved and spread. Those windows that did break during the initial impact event broke directly because of that impact, and not because of the fireball. Fireballs cause only low pressures, but a controlled combustion explosion can cause pressures of 830 KPa. Windows will break at pressures of 3.4-6.9 KPa.

The authors also studied the burning effects of the material contents of the towers. This included fuel and combustible and non-combustible material from the building and from the airplane. Much of the material in the impact zones was pulverized, and created a dust-like layer on the structure. Fire tests were performed with a white pine dust and plexiglass representing the dust of the debris. The results showed that the burning rate was greatly reduced by the dust, and the ignition time was increased. This explains why fires were smaller in the areas directly around the impact zone, but were greater in more remote areas.

Further evidence of conditions less than those of a fully developed fire comes from an analysis of the total heat release rate as determined by the smoke plume. The estimated rate of 80-200 kW/m^2 is less than that of a standard fire. The extent of the open wall area also indicates that the fires were over-ventilated, a condition which will reduce temperatures. At the impact face, the smoke outflow was in a single plane. This is evidence of the loss of floor slabs in this zone. However, at other parts of the building, the outflow of smoke was divided at each floor, indicating that floors there were intact. Smoke flow in a standard fire occurs in the upper two-thirds of an opening. But at the impact region of the WTC towers, the smoke outflow plane was above the midpoint of the opening, which suggests excess airflow. The conclusion is that the temperature in the towers was in the range of 400-700° C. While not as extreme as the typical building fire, these temperatures are still structurally significant.

A study by the Thornton-Tomasetti Group (Thater et al 2003) provided a summary of the damage to the towers and an analysis of the debris field, and was used in the analysis of Abboud et al. They note that WTC 1 sustained light damage when WTC 2 collapsed, but that this was not responsible for the global collapse of WTC 1.

4.4 Ongoing research by NIST

The National Institute of Standards and Technology (NIST) is undertaking the largest and most comprehensive investigation of the World Trade Center disaster. This research was begun on August 21, 2002. To date its cost has been $16 million. NIST released a progress report on its findings in June 2004 (NIST 2004). This included the current status of the eight projects encompassed by NIST's work, as well as a working hypothesis of the collapse sequence. In April 2005 a public presentation was given in New York, updating the status reports and giving a "probable sequence of collapse" (NIST 2005a). The data from this presentation were available in the format of the presentation slides, but NIST's final draft will not be published until June 2005, not in time to be reviewed in this thesis.

NIST's findings corroborate the hypothesis that the aircraft impact did not initiate the global collapse of the towers. They examined several possible effects that the fire may have had on the tower structure: weakening of the core columns and floors; weakening of the main floor spans, causing connection failure; or bowing of the perimeter columns due to differential temperatures.

NIST's extensive review of photographic and first-person interview evidence brought forth many pertinent facts about the collapse. One observation was the propagation of exterior column instability just prior to or during the collapse. This phenomenon may have been aided by hoop-like action of the perimeter spandrel beams. The tilting of the top of WTC 2 may have caused additional shear and torsion in the columns, aiding the lateral spread of instability. Some partially collapsed floors were visible in WTC2 (see Figure 10). None were observed on WTC 1.

NIST has developed several computational models for analysis of subsystems and the entire structures. The subsystems modeled include a truss-framed floor, a beam-framed floor, a single story column, and an exterior wall assembly 9 columns wide by 9 stories high. NIST performed a simplified 2-dimensional analysis under gravity and fire loads. The results showed that the floor

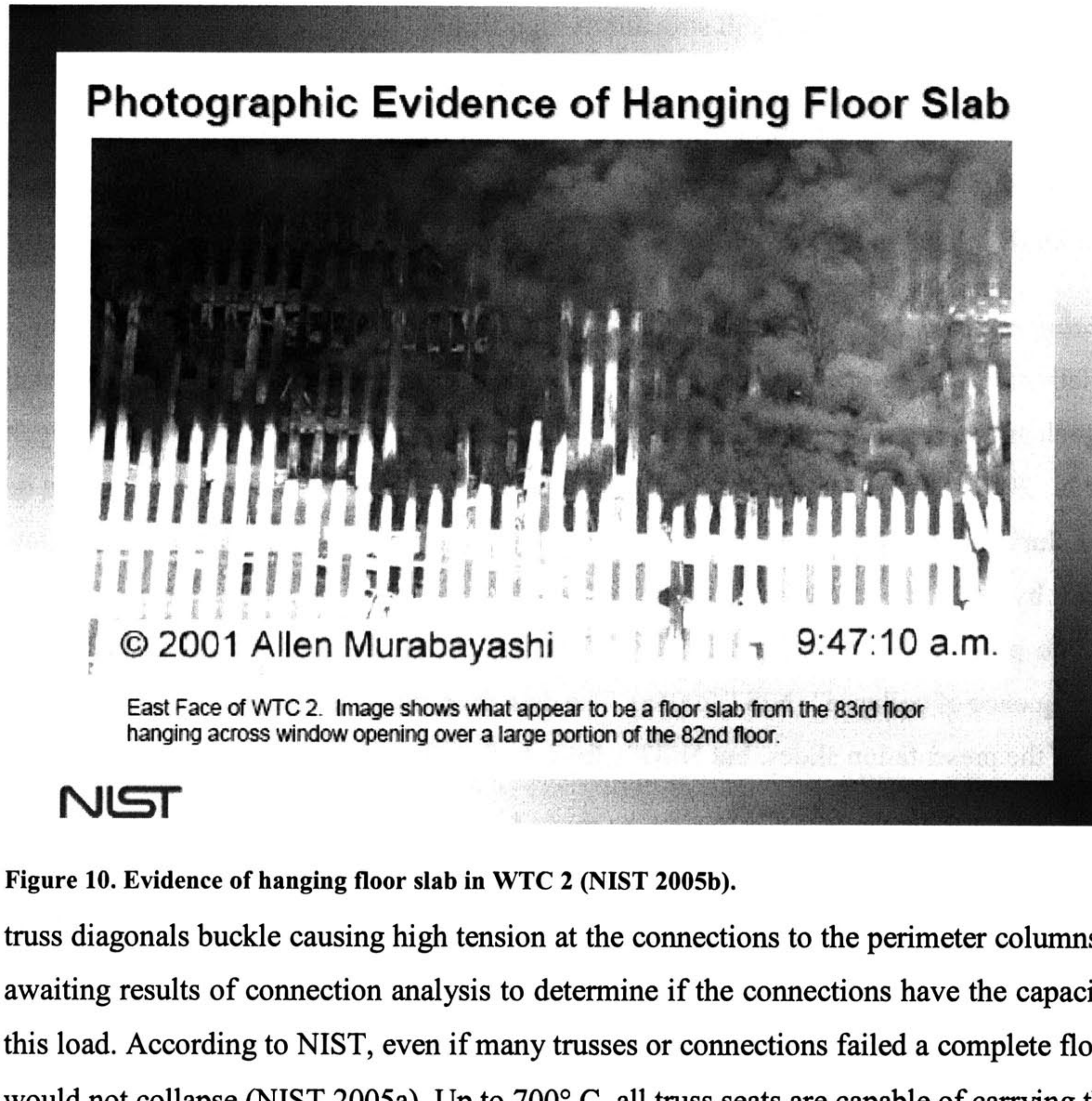

Figure 10. Evidence of hanging floor slab in WTC 2 (NIST 2005b).

truss diagonals buckle causing high tension at the connections to the perimeter columns. NIST is awaiting results of connection analysis to determine if the connections have the capacity to take this load. According to NIST, even if many trusses or connections failed a complete floor system would not collapse (NIST 2005a). Up to 700° C, all truss seats are capable of carrying the weight of two floors (not considering impact loading). If impact is considered, a truss seat will not fail from the drop of one upper floor up to a temperature of 400° C, but the interior end of the truss may walk off the seat (NIST 2005b).

It is of course impossible to know exactly how much fireproofing was dislodged from the structure. NIST made a conservative estimate by considering the fireproofing to be damaged only on members in the direct path of the airplane debris. However evidence shows that fireproofing may dislodge even on exterior columns that were not impacted directly. Strong vibrations may also damage fireproofing, as well as ceiling tiles and walls. NIST's calculations allowed for some variation in the amount of missing fire protection to account for the uncertainty.

The most current theory of collapse put forth by NIST (2005b) is as follows. The sequence differs slightly between the north and south towers, but both follow a progression through three stages: impact damage, fire damage, and collapse initiation. In the north tower (WTC 1), the damage from the initial aircraft impact included severed columns from floors 93 to 98 in the exterior tube framing, damaged floor framing, and damaged core columns through the entire width of the core from north to south. One column on the exterior south face was also severed. The perimeter structure on the north face above the impact zone sagged down after the impact. Loads redistributed immediately so that the north and south faces of the tube carried 7% less gravity load, the east and west faces carried 7% more load, and the core carried only 1% more. The ensuing fires caused further damage. During the phase of fire damage, core columns experienced a net negative strain (shortening). The thermal expansion in these columns was overcome by high thermal creep and elastic strains. The loads produced by the axial shortening were distributed up to the hat truss and transferred to the perimeter tube structure. The redistribution of loads in this stage resulted in a 10% increase of the loads carried by the north and south faces of the building, a 25% increase in the east and west faces, and a 20% reduction of load in the core. The increases in load were still not significant enough to fail the columns. This thermal degradation phase also affected the floor assembly. Sagging of floors 95-99 occurred. These floors then contracted on the north side as the fire cooled in this area. Fires reached the south side later in the event, causing similar sagging in the floors there. Seat connections were weakened by the fire, and about 20% of the connections failed on floors 97 and 98 as the floors pulled inward on the columns. The columns on the south face bowed in due to the tension in the floors as well as temperature differentials within the columns themselves (see Figure 11). The collapse initiation phase began as the perimeter columns on the south face bowed and lost stability. Load was removed from the south wall and resolved to the core through the hat truss, and also around the perimeter corners to the east and west walls of the tube by means of the spandrel beam. The structure above the impact zone tilted rigidly 8° to the south. Column instability rapidly progressed from the south face to the east and west faces. The change in potential energy produced by this motion was more that could be absorbed by the structure, and collapse ensued.

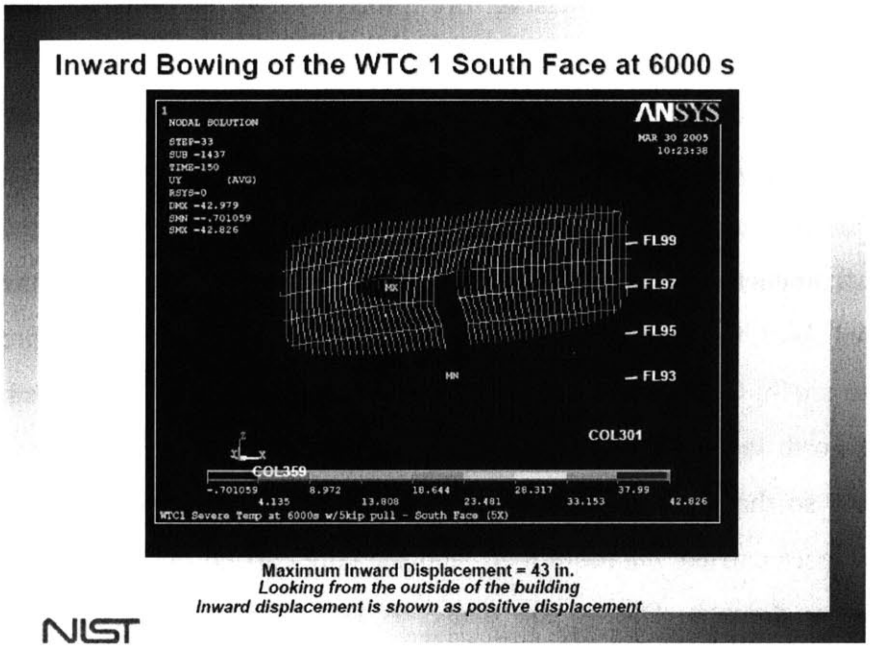

Figure 11. Inward bowing of perimeter columns on the south face of WTC 1 (NIST 2005a).

The south tower (WTC 2) followed a similar, though not identical process. In the impact phase damage was sustained by exterior columns on floors 78 to 84 on the south face. The columns and floors in the core were primarily damaged in the south-east corner. On the east side of the core at stories 80 and 81, from ¼ to ½ of the truss seats were severed. Over $^{1}/_{3}$ of the truss seats connecting the trusses to the perimeter columns were severed on the east wall of story 83. In this stage, perimeter wall loads were mostly distributed to adjacent perimeter columns, and core loads were mostly redistributed within the core. The hat truss resisted deflection of the south wall, as it sagged over the impact hole. At this point, the north face structure carried 10% less loads than before the impact, the east wall carried 24% more, the west face carried 3% more, and the south face carried 2% more. Loads in the core were about 6% less than prior to impact. Damage due to the fires was similar to that suffered by the north tower. Creep and plastic strains occurred in the core columns. This shortening caused the core to tilt towards the east and south. This tilting was exacerbated by failure of column splices at the hat truss above the south-east corner. As fire weakened the floor structure, floors 79-83 sagged and pulled in on the east wall perimeter columns. On floor 83, an additional $^{1}/_{3}$ of the truss seat connections failed at the perimeter columns. The east wall bowed in. Collapse initiation began with instability of these east wall columns. The columns unloaded by means of the hat truss and spandrel beams. The upper structure tilted rigidly 8° to the east and 4° to the south, and then tilted still further as global collapse began, rotating as much as 25° to the east (see Figure 12).

Figure 12. Tilting of WTC 2 at collapse initiation (Kausel et al 2002).

In both towers the major exterior column bowing occurred on a tower face parallel to the core's long dimension. This face was associated with the less stiff direction of the buildings. Furthermore, this face was associated with the longest floor truss span, where the trusses' top chords were subjected to higher demand-to-capacity ratios. Several factors influenced the quicker collapse of WTC 2. The damage to that tower was asymmetric, and since the airplane hit a face that was closer to the core, the core columns sustained greater damage in this tower. The airplane that hit WTC 2 was also traveling faster, and could cause more destruction.

Several aspects of the towers' design are noted to have enhanced their performance in the attack. The dense spacing of the perimeter columns and the deep spandrel beams provided a tough initial barrier. Wind loads used in the design were higher than the code minimums. The capability of the floors to resolve loads in two directions helped avoid greater collapse from the initial impact. The large dimensional size of the towers was beneficial; they completely absorbed the size of the aircraft, whereas a smaller building might nearly have been sliced in two. The hat truss provided redundancy in its ability to redistribute loads. Because of these factors, NIST concludes that "had the fireproofing not been dislodged by [the] debris field, temperature rise of [the] structural components would likely not have been sufficient to induce global collapse."

One of the unusual aspects in the design of the towers was the use of wind tunnel testing to determine design loads. NIST commissioned new wind tunnel tests to compare the design loads with the current state of the art. The WTC design loads were found to be acceptable by codes and standard practices at the time of construction, but were less than what would be required today. Greater drift was allowed than is standard practice. However, since wind loads on September 11 were not high, this issue is not of importance (NIST 2005b).

NIST makes comparison between the results of its analysis and those of Quintiere (NIST 2004a). In NIST's model, up to seven web members can buckle before the truss collapses. The buckling occurs inelastically, and it is apparent that the truss maintains a great deal of reserve capacity over its initial loading. No explanation is given of why different results were obtained. NIST also ran some model simulations with conditions similar to Usmani's. The columns did not buckle in NIST's model. The explanation offered is a possible sensitivity of the failure modes to material properties.

5.0 Recommendations for life safety improvements to buildings in the future

Various researchers have postulated ways in which to prevent progressive collapse in tall buildings. Among the first to write after the WTC disaster were David Newland and David Cebon (2002). Referring to a New York Times article by J. Glanz, they note that a structure must either be sufficiently strong in the region of impact to deal with the damage or that there must be sufficient capacity of energy absorption elsewhere in the building to stop the falling structure.

A collapse barrier must have the ability to absorb energy, and also to cushion the falling mass so that the dynamic force is reduced to within the carrying capacity of the structure. This dynamic reduction will require a certain minimum distance to stop the falling mass, and is independent of the properties of the cushioning material. Through simplified calculations the authors determine that a collapse barrier would need to be located on every floor of a building, creating a virtually continuous mechanism of absorption.

Two types of materials are put forth as good candidates for energy absorption: foams and honeycombs. Copper foams are said to be the best absorbers, but they are very expensive. Aluminum foams may be more efficient economically. Honeycombs generally have lower absorption capacity than foam, on a unit volume basis, though they may perform better on a unit cost basis. Besides cost and weight, other important factors include amount of floor space taken up by the material and the need for headroom after collapse (which is a function of the densification of the material).

The authors proceed to examine an example of how aluminum foam would have performed in the WTC towers. The density of aluminum foam is around 1 Mg/m^3, and it has a densification strain of 40%. The plateau stress (at which most of the energy absorption occurs) is 40 MPa. It can absorb 16 MJ/m^3. For a 4 m floor height, the headroom after collapse will be 2.2 m less the thickness of the floor structure. The aluminum foam will take up about 33 m^2 of the floor space, which represents about 1% of the total floor space. The weight added to the building represents about 6.5% of the total building weight.

The location of the collapse barriers is an important consideration. They must fully engage the falling mass (if bypassed, they would be ineffective), and they must be far enough away from the main columns that they are not compromised when those columns collapse or buckle. Placing the foam in a telescoping cylinder is one possible configuration (see Figure 13). The top end of the cylinder can be connected to the floor above, and the lower end connected to either the lower floor or the bottom of the structural column. An alternative would be to place the foam in a metal tube which will crush along with the foam, using the tube as a second absorption mechanism. Hydraulic dampers are yet another method of stopping collapse.

The authors estimate that the cost of this foam system in the WTC would have been about \$0.65 million per floor, or about \$72 million total. This would represent an increase of 11% in the total cost of the buildings. The decision has to be made whether this cost is justifiable in terms of the added safety.

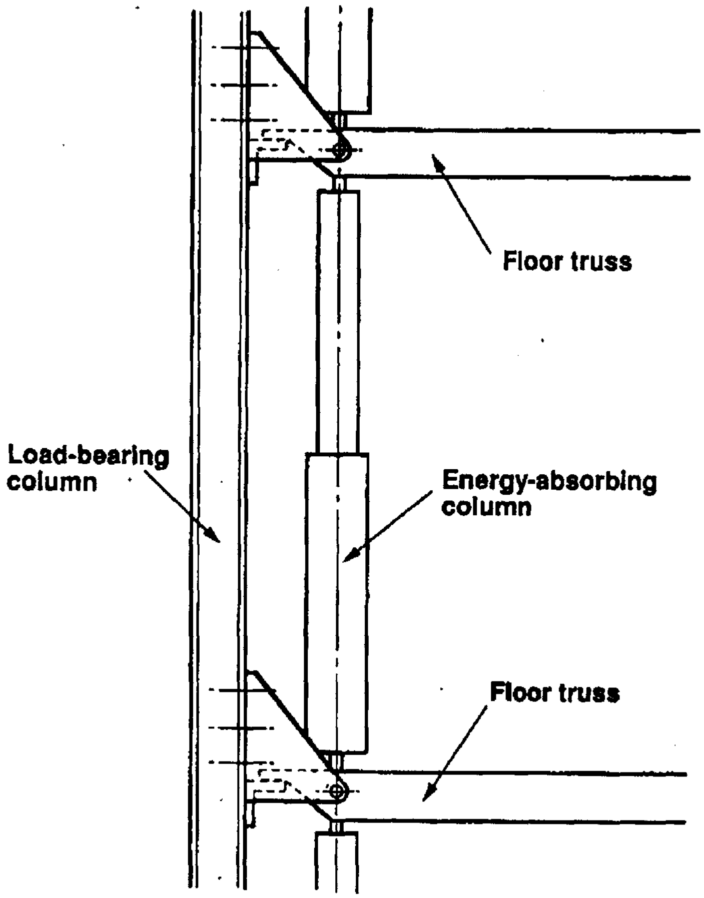

Figure 13. EA device (Newland & Cebon 2002).

Zhou and Yu (2004) introduce a parameter they call the Collapse Stability Index to indicate the capacity of a structure to resist progressive collapse. Tall buildings are not generally designed to withstand vertical impact, such as occurs in a progressive collapse. In the case of the WTC towers, this impact failed floors that had not been damaged in any other way. The Collapse Stability Index ψ represents the ratio of the dissipation capacity of floor to the energy released by the falling mass. If ψ is less than one, the structure is unstable, but if it is greater than one, the structure is inherently stable. The collapse stability of the WTC towers was estimated to be about 0.36.

The required properties of a good absorbing material are that it is porous, and can therefore bend, rotate, buckle, etc., thereby absorbing energy. There is generally a tradeoff between crushing force and compaction ratio. The authors consider here a metal honeycomb as a device to absorb energy (see Figure 14). It could be either steel or aluminum. They performed a finite element analysis of an aluminum honeycomb, 400×400 mm square by 600 mm high, with cells that were 50 mm square with 4 mm thick walls. This device compacted to 71.4%, much more than the foam in Newland and Cebon's scheme. The compressive strength was 27.5 MPa, less than the 40% MPa of Newland and Cebon. The authors state that such devices are relatively easy to fabricate, either by simple fabrication methods or by extrusion.

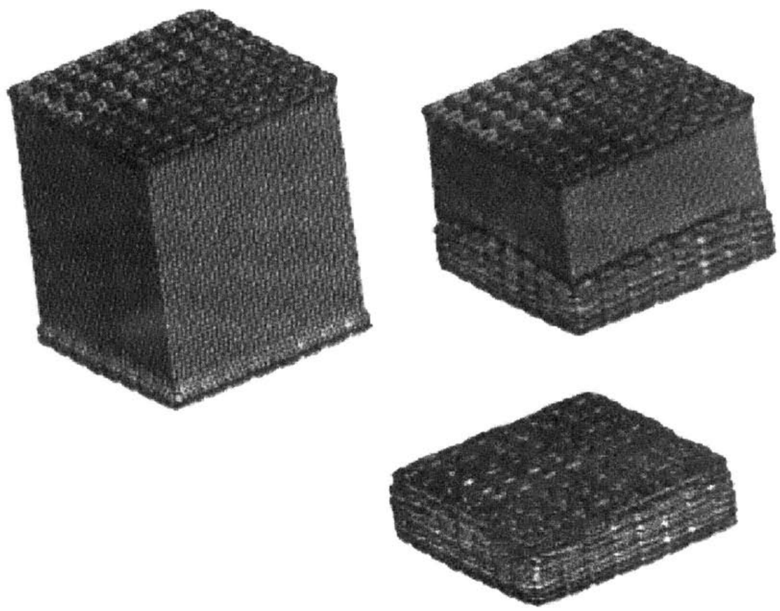

Figure 14. Crushing of aluminum honeycomb (Zhou and Yu 2004).

Using their example system in the WTC towers, the authors estimate that the absorption devices would have taken up about 4% of the available floor space, and added about 4.25% to the building mass. In the case of WTC 1, if the upper stories fell a distance of three floor at the initiation of global collapse, four floors below the impact zone would collapse before the fall was arrested. In comparison to Newland and Cebon's (2002) example with aluminum foam, the current authors predict a halt to the collapse in just 4 stories, compared to 6 stories for Newland and Cebon.

To resist buckling of the energy absorbing (EA) device, the cross section must be bulky, say 1m × 1m. Other things to be considered in the design of a progressive collapse resistance system are the primary mode in which the main structure will collapse, strain hardening or brittleness of the metal, and strain-rate dependence. The absorption system will probably vary from top to bottom of the structure. At higher floors not as much absorption is needed, but what is provided must still be spread out sufficiently to engage all of the structure and to engage it uniformly. For this purpose, lower capacity material may be used in greater volumes. By comparison, at lower floors higher capacity material may be used that has greater absorption per unit volume so that it doesn't take up as much space. It may be possible to divide the building into zones of impact resistance, instead of having EA devices on every floor.

The cost of EA systems is expected to be moderate because most of the technology already exists. The materials and fabrication methods are also standard. The authors believe that systems could also be designed that can be easily installed in existing buildings.

It is of interest to note that providing a means of resisting progressive collapse is more effective than trying to protect against the damaging event in the first place. This is because the damaging event (airplanes, bombs, acts of nature) is a large unknown. But the progressive collapse of a building is based on a few quantifiable parameters, chiefly the potential (gravitational) energy in the building.

Bazant and Zhou (2002a) make various brief comments on preventative measures that may be employed against such building failures in the future. First is use of thicker insulation for protection of the steel members. Concrete columns are not seen as performing much better than steel ones, because of explosive thermal spalling under high temperatures and other material degradation properties. High strength concrete is even more susceptible to these weaknesses than standard concrete. Other materials may be considered, such as refractory concretes, special alloys, or refractory ceramic composites, but cost will likely be a significant factor.

NIST also recommends some potential basic improvements for buildings (2004a). Fireproofing should be made to adhere better in explosive environments. Steel properties could be improved so strength and stiffness do not degrade so quickly in high temperatures. A greater mass in perimeter and floor systems would provide better thermal performance and buckling resistance.

6.0 Conclusion

No one wants to see the events of September 11, 2001 repeated. But in today's uncertain world precautions must be made to ensure the physical safety and peace of mind of citizens. This is why it is so important to understand the way the World Trade Center towers performed under the devastating attacks of that day. Yet the complexity of the towers and the unknown factors of the damage they sustained make this task very difficult. This is evident from the varying opinions of researcher reported here.

Following NIST's presentation in New York on April 5, 2005, there were many dissident opinions expressed about the findings presented (Post 2005). Critics claim there is much "speculation, innuendo and incorrect" findings in the report. Jon D. Magnusson of Magnusson Klemencic Assoc, believes it is inappropriate for NIST to make recommendations for changes to the building codes based on one event that occurred to a single, singular building. Others feel that the report overemphasizes the role of fire engineers, and will lead to unnecessary code mandated involvement of fire engineers in future projects.

These may be valid concerns. It is hoped that they will be addressed by NIST in its final report. Hopefully the thoroughness of NIST's research will also reconcile the differences between the many other failure hypotheses. As a result of all of the research so far, the state-of-the-art is advancing in the fields of fire engineering, finite element analysis, and protective design. Hopefully this will continue, and in this way we will see the horror of 9/11 be transformed to good for all of us.

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