The Towers Lost and Beyond

A collection of essays on the WTC by researchers at the
Massachusetts Institute of Technology

Edited by

Eduardo Kausel

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Preface

This book contains eight articles that deal with the September 11, 2001 World Trade Center (WTC) disaster and its consequences, written by researchers at the Massachusetts Institute of Technology. For the most part, these articles were prepared between September 2001 and February 2002, and were revised in part in the spring of 2002. Indeed, some of these essays were largely written in their present form in the days following the disaster, which saw the first light in September of 2001 as opinion pieces in one of MIT's internet sites, and as internal research reports.

At about the time that the rough draft for this book was finished, an important study on the WTC came to light, namely the FEMA-NIST-ASCE report, which contained a wealth of new factual data. While this report could have provided additional material for the preparation of a revised version of this book, it was felt that the essays herein were not superseded by the FEMA report, but continued instead to be relevant and worthy of publication in their own right. Indeed, the FEMA report substantiated most of the writers' earlier views as to how the towers were wounded, how the fire affected the structures, and how they ultimately collapsed.

The book begins with a brief history of the Twin Towers, then continues with several technical analyses of the collision, the fire and the collapse of the towers, and concludes with two forward looking articles, one on possible future emergency escape systems from high rise buildings, and another on the consequences of terrorism on industrial supply chains —in brief, the timely and adequate supply of raw materials and parts to factories and business.

Fernandez commences by reviewing some historical facts about the design and construction of the towers. Thereafter, Kausel reminisces about the crash of the towers and expounds his early theories as to the reasons for their collapse. He then proceeds with an analysis of the speed of the aircraft immediately prior to collision in an article that led to a cover page story in the *New York Times* last February, which was carried around the world by the major news media.

Wierzbicki follows with a detailed analysis of the collision of the aircraft, and the heavy damage that they caused to the structures. From his exacting mechanical analysis, he concludes that the North Tower must have lost between 4 and 12 core columns —out of 44— while the South Tower lost between 7 and 20 such columns, and that both were brought to the verge of collapse by the collisions. Ghoniem examines carefully the fire conditions inside the towers, and determines that the temperature within the buildings must have been close to 1000°C, hot enough to significantly lower the stiffness and strength of the steel columns and girders. He also demonstrates that the chemical power of the aircraft fuel together with the combustible materials in the building, when released as heat over the course of one hour, was a staggering one gigawatt, which is comparable to the power of a large electrical power plant. This provides substantiation to the notion that the fires played a critical role in the collapse of the towers. Buyukozturk and Ulm proceed with a materials and structures analysis of the towers, their interaction with the fires, the effects of these on the structural materials, and the mechanics of collapse. They also discuss how the vulnerability of future high rise buildings could be ameliorated by the widespread application of the concept of “redundancies”.

Fernandez elaborates on a series of new escape systems for high rise buildings under fire (or damaged by explosions) whose aim is to bypass impassable floors or blocked stairways. These would allow people trapped in higher elevations to escape safely to the street. He considers various types of devices, including those that can be deployed inside or on the exterior walls of the building. Finally, Sheffi discusses the effects that terrorist acts can have on the timely supply of raw materials and parts to industry, and on the need for a new strategy that blends on-time supplies with adequate strategic reserves, or as he succinctly puts it, “just in time and just in case”.

Eduardo Kausel
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A brief history of the World Trade Center Towers

John E. Fernandez
Assistant Professor of Architecture, Building Technology Program
Massachusetts Institute of Technology

Abstract

The history of the World Trade Center can now be fully written. The buildings no longer exist, the site has been cleared and plans are beginning to emerge for the next manifestation of buildings and open space for the area bounded by Vesey, Liberty, Church and West Streets. The complete redevelopment of this area was brought about through the influence and interest of the Rockefeller brothers in the 1960s, and its utter destruction accomplished through the insanity of fanatical devotion to a radical and wealthy Saudi. The scorched site now seems to possess a great deal more past than any clearly imaginable future, despite the many proposals for redevelopment already being offered. While the morning of September 11, 2001 still echoes in our memories, these wounded acres of Manhattan Island are now no more and no less than what will be envisioned by the people of New York City. This chapter offers a brief history of the place, the process of development, design and construction and an introduction to several key figures in the making of the World Trade Center - as we once knew it.

Conception

Lower Manhattan has served as the original anchor for the settlement of New York City and continues to be the perpetual symbolic frontier for expectant immigrants and global financial power alike. Lower Manhattan has become the steadfast prow of a business machine that has taken the form of one of the most inspiring and frenetic cities ever built. The glass and metal wall of the financial fortress that lines the island in Upper New York Bay and extends from the Brooklyn Bridge on the East River down and west through Battery Park and up beyond the towers of the World Financial Center and extending to Chambers Street is one of the most imposing and awe-inspiring walls of office towers anywhere in the world. This piece of Manhattan, jutting out into New York Harbor, has also been the location for massive civic renewal through publicly funded real estate investment and commercial office development of extremely high densities. With the birth of the idea in 1946 for a large office development on the lower Hudson, a World Trade Center, New York City was once again launching forth a remaking of itself. In that year, the New York State Legislature articulated a vision of a vast trade, commercial, hotel and convention facility that would complement the growing international center of finance that Wall Street had become. The project was initiated in the early 1960s through the influence of David Rockefeller in part to reclaim a part of the city that had fallen on hard times. The vision was meant to use the trade facility and urban renewal as tools to clear and revitalize what had become a "commercial slum". The construction of the towers yielded not only a new frontier for business but also the landfill for a new shore on the banks of the Hudson. Since the early 1980s, the World Trade Center Towers, 110 stories each, were the most prominent mark of the proven success of this vision for the revived future of trade and finance on the island. Until recently, this renewal had seemed a permanent part of New York City, as unmovable and steady as the towers themselves - a clear and indelible binary landmark on the confident skyline of American capitalism. No one expected these buildings to last a mere 30 years.

The World Trade Center project, as it was eventually realized, was the idea of David and Nelson Rockefeller. Consideration of such a center was active since after World War II, but the planning for the development of the lower Manhattan site only began in 1960 when the Downtown-Lower Manhattan Development Association proposed a renewal of the area. Long known for its many electronics stores, the displacement and improvement of "radio row" now became a pet project of the Rockefeller brothers. At the time Nelson was serving as governor of New York State and his brother David was Chairman of Chase Manhattan Bank. When the towers were completed they were nicknamed "David" and "Nelson". David had also founded the development group and was intent on bringing about a renewal of Lower Manhattan that was of a scale never before seen in New York City, nor anywhere else. The process was long and often bitter and included the demolition of 164 buildings on sixteen blocks and the closing of five streets. The area had been known as a seedy and variously industrial part of the waterfront in Lower Manhattan. Numerous warehouses, retail and repair stores, distribution houses and other small-scale enterprises formed the fabric for a down and out, dark and dangerous part of town. However, the area had its supporters and the negative aspects of urban renewal were beginning to be articulated. With the publishing of "The Life and Death of Great American Cities" Jane Jacobs questioned the real effects of the new planning strategy of urban renewal and stated, "Our present urban renewal laws are an attempt to break this particular linkage in the vicious circles by forthrightly wiping away slums and their populations, and replacing them with projects intended to produce higher tax yields, or to lure back easier populations with less expensive public requirements. The method fails. At best, it merely shifts slums from here to there, adding its own tincture of extra hardship and disruption. At worst, it destroys neighborhoods where constructive and improving communities exist and where the situation calls for encouragement rather than destruction." [1].

As a result of these and many other written words and mobilization of local community groups, the project began its life with substantial controversy that evolved into a persistent notion that the buildings themselves were out of place and not appropriate to the island of Manhattan and the rest of the city. The architectural and urban design critics were generally not happy with the sheer scale of the buildings, the new impersonal urban relationships created and the conservative aesthetics of the building design itself. Much of the criticism lay at the feet of the designer of the towers, the architect Minoru Yamasaki. Ada Louise Huxtable, wrote that Yamasaki, "has developed a curiously unsettled style, which involves decorative traceries of exotic extraction applied over structure or worked into it. His choice of delicate detail on massive construction as a means of reconciling modern structural scale to the human scale of the viewer is often more disturbing than reassuring… Here we have the world's daintiest architecture for the world's biggest buildings." [2]. Other critics also lamented the size; a scale that seemed alien to the character of New York City streets. This question of scale and the application of historicist ornamentation was to be an enduring criticism of many of the larger buildings designed by Yamasaki.

Design

After a search that engaged dozens architects and many months, Yamasaki's firm, of Troy Michigan, was chosen as the design architect and Emery Roth & Sons as associate architects for the assemblage of buildings that were to comprise 5 of the buildings within the World Trade Center complex, including both towers. These five buildings were completed at different points between 1970 and 1977. In addition, Skidmore Owings and Merrill designed the Marriot Hotel at 3 World Trade Center and 7 World trade Center was designed by Emery Roth & Sons as lead designer and built in 1987.

Table 1: World Trade Center Buildings

Building	Completed	Height (floors)	Floor plate sizes (sq. feet)	Elevators
1 World Trade North Tower	1970	110	45,000-50,000	97 passenger 6 freight
2 World Trade South Tower	1972	110	45,000-50,000	97 passenger 6 freight
3 World Trade	1980	22	21,000	8 passenger 3 freight
4 World Trade	1977	9	84,500	12 passenger 4 freight
5 World Trade	1972	9	108,400	9 passenger
6 World Trade	1975	8	80,400	8 passenger 4 freight
7 World Trade	1987	47	40,000	30 passenger 2 freight

The complex of buildings, and the two towers especially, were the most important commissions for the architect. At the time, Yamasaki was part of a loose grouping of architects that attended to the needs of the new ideas of urban renewal and mixed-use megadevelopment. His use of primary forms and simple ornamentation allowed for the functional needs of the new and often very large forms of low-income housing projects and the new and ever larger office buildings being commissioned by American and multi-national corporations. He was well enough known in 1963 to be chosen for the cover of Time magazine. At the same moment, he was much criticized for his almost servile attendance to the needs of large corporations. And yet, Yamasaki brought a certain sensitivity of material and form that had been missing from previous proposals for the World Trade Center site. His words were often self-deprecating, humorous and displayed an interest in pursuing a personal vision for a new architecture; even amid the gigantic scale of the forms he was designing. While Ya masaki espoused a conservative architecture of uncompromising modernism, his aesthetic was neither overly harsh nor dogmatic. He favored materials of a softer, gentler feel; woods, smooth and painted concrete, stainless steels and anodized aluminum plate. His buildings often bore the hints of a renewed interest in ornament and figurative form as part of a new modernism.

At the time of his selection as lead architect of the project, Yamasaki's career was progressing very well. His firm had completed important buildings across the United States including; the Saint Louis Airport Terminal, completed 1956, the Michigan Consolidated Gas Company Headquarters, completed in 1963, the Dhahran Air Terminal in Saudi Arabia, completed in 1961, the Woodrow Wilson School of Public and International Affairs at Princeton University, completed in 1965 and the IBM Office Building in Seattle Washington, completed in 1964 among others [3]. After the opening of the World trade Center, Yamasaki's place in modern architecture was assured and his firm went on to design several more important buildings, many of them towers for corporate clients. And yet, historical perspective has yielded an overall impression of Yamasaki's work as deeply problematic. Many of the most important commissions were greeted with official adulation and followed with sustained yet generally polite criticism. Clearly, here was a man whose life was dedicated to his craft and yet the buildings themselves displayed very little creative fervor while refusing to imply a greater vision for modern architecture. The work was restrained to the point of equivocation not so much in its essential forms, which were boldly modern and abstract, but in the relationships formed with the surrounding context and the building's inhabitants themselves. The buildings, which were rarely modulated by the setting in which they were placed, held themselves apart from streets, adjacent buildings and other physical links to the city. While Yamasaki himself states his keen interest in nature and the environmental context of his work, the buildings themselves seem oddly aloof [3]. This reserve permeated the Trade Center towers. The critics were quick to point to this weakness in his craft while the corporate world, from IBM to Alcoa, were quick to embrace it. The restraint and formality of Yamasaki's ornamental modernism was just what corporate and governmental clients were looking for; a bold *and* polite modernist vision.

Minoru Yamasaki was born in Seattle in 1912 to Japanese immigrant parents from the island of Honshu. While his father worked several jobs to advance the fortunes of the family, Minoru grew up and became aware of the strong racial bias of the time against the Japanese in the Pacific Northwest. Yamasaki writes of these experiences in his book "A Life in Architecture" [3]. He was motivated to become an architect after his uncle, Koken Ito graduated from the University of California in architecture and then headed to Chicago. Yamasaki enrolled at the University of Seattle during the depression and completed his studies funded by spending the summers in fish canneries of Alaska. After graduating, he made his way to New York City, where he found work scarce and had to settle for odd jobs and temporary work in a series of architectural firms. One of his first steady jobs was in the firm of Shreve, Lamb and Harmon, architects of the Empire State Building. Between 1936 and 1943, Yamasaki worked primarily in the production of construction documents for the firm. In the few months before the war, he worked on several design projects for the Department of Defense. After the attack on Pearl Harbor, Yamasaki was investigated by the FBI, the Navy and the Army but was kept gainfully employed by Shreve and, as a result, out of the "relocation camps". His brother and parents also joined him in New York when many of their friends were being directed to leave for the camps.

In 1949, Yamasaki joined with partners George Hellmuth and Joseph Leinweber to establish a firm with offices in Saint Louis and Detroit. Years later, the firm was divided between the two cities and in 1959 Yamasaki struck out on his own forming Yamasaki & Associates in Detroit. Yamasaki died in 1986 at the age of 73.

The firm of Minoru Yamasaki & Associates continues to produce designs for buildings around the world. The firm is located in Rochester Hills, Michigan, a suburb of Detroit. Seven partners now administer the work of the firm.

Leslie Robertson, the other key figure in the design of the towers, was a young member of the the firm of Skilling, Helle, Jackson of Seattle Washington at the time of the design of the towers. Robertson was the most influential engineer on the project and assumed the position of lead structural designer of the towers. Robertson had as much influence on the form of the building as anyone apart from Yamasaki himself. In fact, it is not too strong to assert that the forms of the towers were primarily a combination of the real estate development targets established and possible structural engineering solutions. While the simple forms of the buildings provided many positive attributes for modern commercial offices, such as column-free space, the architectural restraint of the volumes was absolutely necessary for the realization of an efficient structural tube. Robertson understood his role as an innovator; for nothing short of real innovation would allow such a structure to stand and fulfill the space requirements of the client. He was involved in pioneering research regarding the dampening of lateral movement of the towers due to wind pressures. He was also primarily responsible for the lightness of the floor slabs and the rigidity of the tower from using these floors as structural diaphragms.

Construction, completion and occupation

The building of the towers was an endeavor at the scale of municipal infrastructure. Five streets were closed and clearance of the site provided 16 acres for the new project. Two subway lines on the site were kept running as the foundations and basements were built around them. Construction began in 1965 and it was formalized with a groundbreaking ceremony on August 5, 1966 and finally completed with the occupation of Tower One in 1970 and Tower Two in 1972. In total, the entire complex contributed to Lower Manhattan more than 10 million square feet of office space, several hundred hotel suites, the most successful retail center in the city, an extremely busy transportation hub and dozens of service and support businesses in seven buildings.

The construction of the towers was an unique engineering challenge from the very beginning [4][5][6]. With the excavation of the foundations, the construction team had to find solutions to problems never before encountered at such a scale. With the use of slurry walls, the first time this type of foundation wall was used in the US, the construction had to proceed through highly creative solutions of materials handling, erection sequencing, joint detailing, structural engineering and architectural design.

The foundations for the towers reached down to bedrock an average of 70 feet below grade. With the excavation of 1.2 million cubic yards of earth, 23.5 acres of new land for Manhattan were created on the shores of the Hudson River. Eventually the office towers and wintergarden of the World Financial Center, designed by Cesar Pelli, and several apartment buildings were built on this new land.

The material expenditures on the towers were enormous; 192,000 tons of steel, 425,000 cubic yards of concrete, 43,600 windows with 572,000 square feet of glass, 1,143,000 square feet of aluminum sheet, 198 miles of ductwork and 12,000 miles of electrical cable. The towers also provided an extraordinary employment opportunity for the construction workers of the region. More than 3,500 people were emp loyed continuously on site during construction. A total of 10,000 people were involved in its construction. Tragically, 60 people were killed during construction.

The history of the tower form can be conceived of as the history of the relation between several building systems and their ability to address the issues of circulation, fire and structural efficiency and integrity. In the early days of tall buildings, the dominant building system relationship came between the exterior envelope and the structure. Later as towers reached higher into the sky, the mode of vertical circulation through elevators and the various systems used to monitor and suppress fires and the egress systems came to play extremely important roles as well.

The World Trade Center Towers used a type of perimeter tube structure along with an interior steel frame to resist the lateral shear and moment imposed on it by the accumulated wind pressure. Both the frame and the perimeter tube also contributed to transferring the internal loads of the building down to the foundations.

The inner steel frame housed the elevator cab shafts, mechanical shafts and other support spaces necessary on each floor. The outer tube served as the framework for the exterior wall and was made by bolting together hundreds of premanufactured 3-story tall rigid steel frames. These rigid frames carried both the internal dead and live loads from the floor plates as well as in-plane stresses. The designers were careful to alternate the height of adjacent rigid frames so that they avoided creating a continuous joint around the circumference of the tube. The elevator shafts were recruited during construction to serve double duty by being incorporated into the hydraulic lift system that secured and lifted the construction cranes.

The structure of the floors was a prefabricated unit of open web steel joists with an in-situ structural concrete slab. The floors tied together the exterior perimeter columns and the interior steel frame to resist twisting, or torsion, of the tower. The World Trade Center was one of the first structures to undergo a series of wind tunnel tests as an integral step of the structural design process.

Another innovation of the towers was the use of viscoelastic dampers to counteract oscillation of the building. This was accomplished at the bracing on the lower chord of the open web steel joists. Two layers of a high density polymer were sandwiched between steel plates that connected the joists with the perimeter box columns. These sandwiches absorbed the energy from the lateral force imposed upon the structure by the wind and released it, in the form of small amounts of heat, enabling the structure to delay the effect of the lateral load and "dampen" its resulting movement [7].

At completion the towers of the World Trade Center were the world's tallest until the Sears Tower in Chicago gained that title in 1974.

The Towers in the life of the city

During their lifetimes the towers were host to the birth of 17 babies and 19 murders. Fifty thousand people called the towers their place of work and on many days tens of thousands visited.

In 1993, the towers were attacked by terrorists who entered an underground garage and detonated a bomb that did substantial damage to several floors of the garage but left the towers intact. The bomb was extremely powerful containing 1200 pounds of urea nitrate. Six people were killed. On September 11, 2001 terrorists attacked the towers using two airliners to crash into and cause the collapse of both buildings. Each building was struck at a different height and angle. Preliminary analysis seems to indicate that the two suffered damage in different areas of the exterior wall and core and, as a result, their individual progressive collapse mechanisms were also distinct. In the end, each tower was felled by the initiation of a critical progressive collapse that toppled each building in a near free-fall condition.

Some buildings in a city become daily landmarks, confirmations of place and physical constants by which to personally gauge the subtle changes of the city. The World Trade Center Towers were just such buildings. One example is the way in which residents of the city use buildings to assess the daily weather. Is the top of the Empire State building obscured by clouds this evening? People who live in large cities are keenly aware of their environment; the particular spectrum of autumn light as it reflects off of aluminum panel and metal coated glass, the subtle changes in temperature as one passes the open doors of an office building's lobby, the clarity of the day as measured by the extent of one's view down an avenue. In this sense, the physical presence of the largest buildings in cities can lend a humanizing, reassuring anchor for one's place in a familiar environment. This intimacy with one's environment is exactly the opposite of what one might expect of living in a city. Yet, these personal measures are quickly acquired and easily processed from the physical context in which people live, whether it be the country or the city. They form one's daily mental construct of the context for living. Certain measures are at the scale of the street, the shop front, the corner deli. Others are at the scale of infrastructure, the large machine that is the city. And some are on the scale of infrastructure, the bridges, the subway trains, the tallest buildings. The World Trade Center was at the scale of infrastructure.

From far uptown on the west side, the Towers' presence was a reminder of the extent of the island; a limiting parameter of the landmass within which was contained all of the neighborhoods of Tribeca, Chelsea, Times Square, Midtown. Their sheer scale and metal armor served in the way that distant mountain ranges delineate the extent of a valley.

Their presence was also a reminder of the role of the island. The commerce, the intensity of capital in flux, the streaming trade giving legitimacy to the haughty authority that the name, World Trade Center, so embodied when it was first built. In fact, the first few years after construction were difficult ones and the wisdom of its conception were, at the time, roundly questioned. The complex experienced persistent economic difficulty, especially at its opening and during the fiscal crisis and eventual bankruptcy of the city in the 1970s. The buildings, as a viable enterprise, struggled and only turned a corner when the Port Authority itself decided to partially justify its development by occupying parts of the towers. The initial severity of the simple form gave way to a no-nonsense presence. These were buildings that housed commerce, facilitated business and went about daily events within a restrained cage of steel. What was remarkable about the towers was their sheer scale. Arriving at the center from subway tunnels below the street, the stance of the two towers spoke of forces that were global in reach. It was as if the scale of the towers was of another world, a world beyond the expanse of the island itself. This is the scale that was marked for destruction, this global reach; symb ols of a dominant power.

As Nathan Silver has written, buildings in cities "become constituent to the psyche" [8]. As much as the towers were criticized for their lack of connection to the old New York and their imperial stance, the fact that they were there at all meant that they had become a part of the city; that part of the city that New Yorkers, visitors and people around the world carried around as part of their psyches. With their absence, the loss is as much psychological as it is physical or economic. For this reason, their demise is all the more poignant. These towers, in the pride of scale that was uniquely their own, announced their confidence every morning with the rise of the sun. They displayed their metallic torsos with as much pride as a youthful athlete. They were unfazed by the decades of less than complimentary commentary. They were serving the business community well and, presumably, were here to stay.

During the attack, the ingenious engineering of the young Les Robertson kept them standing for a short, but critical period of time. Their simple forms were critically wounded and as we now know, the structural redundancy inherent in the tubular forms allowed hundreds to escape with their lives. The work of Minoru Yamasaki and Leslie Robertson allowed dozens to escape down the fire stairs and out through the lobbies and pedestrian bridges to safety. But the strikes had been too large, the aim of the terrorists too precise and soon afterwards the inconceivable collapse of each tower rendered an entire world transfixed in sadness. And yet as buildings, their inability to fend off the strikes despite their size and bulk, made us deeply sad. These buildings, once seemingly indestructible, proved critically and tragically vulnerable. In the end, their confident occupation of the sky to heights never before achieved placed them in the deadly territory of hijacked airplanes. It had never occurred to anyone that this space could become deadly beyond comprehension through the simple replacement of a dedicated pilot with a determined terrorist. It never occurred to anyone. And as a result of this understandable lack of imagination for the horrific, these towers paid the price that no other modern skyscraper ever has, complete collapse.

Futures

Recently, ideas for a redevelopment of the site have been one of the passionate discussions surrounding the events of last September. In New York's past, optimistic and ultimately transformative periods of rebuilding have followed catastrophes, such as after the fires of 1835 [9]. And after the initial study presented to Congress by FEMA and ASCE, it is clear there is substantial work to be done, both in analyzing the events of the attack and in assessing current vulnerabilities [10].

Therefore, as anyone knows that has lived or continues to live in Manhattan, the loss is felt at every scale of experience, intellectually and physically, economically and socially. There is no aspect of the life of New York City that has not been touched by the destruction and now the powerful absence of these buildings. The negation of these buildings figures prominently in our minds and hearts. Only a renewal of effort, a rebuilding, and most importantly the passage of time will be enough to continue the history of the towers.

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Inferno at the World Trade Center, NY

Eduardo Kausel
Professor of Civil & Environmental Engineering, MIT

9-11: The fateful date

As in the morning hours of September 11, 2001 I was anxiously watching on TV the dramatic events taking place in New York City, and saw the two World Trade Center towers engulfed in immense flames brought about by terrorists who deliberately crashed two passenger jets into them, my training in Structural Engineering instantly elicited in me visions of doom, and a feeling that the towers were in imminent danger of collapse. Still, knowing that half a decade earlier the towers had resisted massive damage in a terrorist attack, and being unaware of similar cases of skyscraper collapse, I hoped against reason that they might survive yet again. To my horror, I then witnessed the unthinkable unfolding in front of my eyes. In retrospect, I should have been 100% sure that they would fail, but the idea was so disgusting that I allowed my wishful thinking to prevail instead. Soon after the tragedy occurred, cooler thoughts and the engineer in me returned, and I began to ponder about the mechanics that led to the catastrophe.

Why did they collapse?

From an engineering point of view, there were three causes to the massive structural damage that led to ultimate failure. These are the impact of the aircraft, the subsequent fireball, and most importantly, the raging fire caused by the vast amounts of jet fuel carried by the planes. Burning fuel must have also cascaded down floor openings to the levels below.

It has been reported that the towers were designed for the impact of a Boeing 707 aircraft then flying the skies. Considering that one of the towers survived for at nearly an hour, and the other almost two hours before collapsing, this demonstrated crash resistance provides compelling validation to this claim. It has also been opined by some that the towers did ultimately fail because the 767 is a far bigger jet carrying much more fuel than the design 707 aircraft. This view is largely incorrect. The takeoff weight of a fully loaded Boeing 707-320 is 151 tons (336,000 lbs.), and it carries a fuel load of 87,000 liters (23,000 gallons) of jet fuel. By contrast, the maximum takeoff weight of a Boeing 767-200 is some 178 tons (395,000 lbs.), and carries a fuel load of 91,000 liters (24,000 gallons). Assuming that jet fuel weighs like kerosene, this represents some 74 tons (164,000 lbs.) of fuel, or about half the weight of a fully loaded aircraft. Thus, while the 767 is indeed a somewhat larger aircraft, it is not significantly so, while its amount of fuel load is nearly the same as in the 707. In addition, both ill-fated planes were only lightly loaded with passengers, and their fuel tanks at the moment of impact have been estimated to be no more than 50% full. Hence, these planes did not carry their full takeoff load, but weighed instead no more than some 136 tons each. Thus, the buildings may indeed have been designed for the impact load caused by a commercial airliner the size of a Boeing 767, lost in fog in its approach to Kennedy Airport at landing speeds and with a modest fuel load remaining in its tanks. However, the designers never imagined a terrorist act during which high speed planes carrying large amounts of fuel would be deliberately crashed onto the towers, causing massive initial damage and triggering uncontrollable infernos.

From information publicly available, it is known that the weight of each building was carried by an inner core of columns surrounding elevator shafts and stairways, and by a dense lattice of external columns spaced 99cm (39 inches) on center forming an outer tube intended principally to prevent the building from overturning when subjected to strong lateral forces, such as those elicited by hurricane winds. The floors where supported by a grid of truss beams that carried the weight of the floors to the columns, while the floors in turn provided lateral support that prevented buckling of the columns.

The North Tower was hit at 8:46 above the 96th floor by a Boeing 767-200 flying at 691 km/hr (429 mph), and remained erect until 10:28, that is, nearly two hours after initial impact. By contrast, the South Tower was hit at 9:03 above the 80th floor by another 767-200 flying at 810 km/hr (503 mph) and collapsed less than an hour later at 9:59. The damage to the latter was more severe, perhaps because the second plane traversed the building at an angle and blew off external columns on two adjacent faces. This asymmetry, combined with the greater weight of the 31 stories above the crash elevation led to some tilting of the upper portion down the damaged corner, causing large overturning forces in the remaining members of the floor.

The initial impact of the aircraft caused massive structural damage to the external columns, to the floors in the proximity of the impact, and to the inner core. The ensuing fireball must have exacerbated significantly this damage, possibly collapsing locally several floors, and setting the buildings ablaze in a virtually uncontrollable, fierce fire. Still, both buildings survived this initial assault, and did not give way for a remarkably long period of time after the crash. This extraordinary capability allowed many lives to be saved, and is a major credit to the designers. Ultimately, however, the intense fire heated the structural steel elements well beyond the thermal limit of some 400°C (750°F), which caused the steel to lose both its stiffness and resistance, and as supporting members gave way, the final failure of the building was initiated.

Various mechanisms may have been at play in this failure. Witnesses who escaped the buildings in time reported seeing large cracks develop on the (non-structural) walls of the staircases. This suggests a steady redistribution of vertical forces and propagation of structural failure down the building. However, the immediate failure mechanism was almost certainly initiated locally at the elevation of the crash. Truss beams heated by the fire were probably more vulnerable than columns, and may have been the first to go. As parts of the floors then collapsed and rained down onto the floors below, the weight of the accumulating debris steadily increased beyond the support capacity of those floors, and they collapsed in turn. At the same time, local collapse of the floors caused the heat-weakened columns to loose their lateral support, which under the intense weight of the floors above the level of the fire caused them to buckle, break and roll out like matchsticks. At that point, the upper floors began to fall wholesale onto the structure below, and as they gained momentum, their crushing descent became unstoppable. Indeed, with two fairly simple dynamic models I developed in the hours following the collapse, I determined that the fall of the upper building portion down the height of a single floor must have caused dynamic forces exceeding the design loads by at least an order of magnitude (i.e. more than 10 times the weight of the upper floors). Thus, there was no way in the world that the columns below could have taken this large overload, and as these gave way, an avalanche down the building ensued causing the 110 story towers to collapse in about 12 seconds in what was practically a free fall. As reported by witnesses, the crushing of one floor onto one another caused a ratchet-like noise, whose frequency can be estimated to have been around 9 Hz (=110/12).

Earthquake in New York

The enormous mass of the twin towers, by virtue of its height above the ground, contained a substantial amount of gravitational energy, which could be likened to the energy of the water rising behind the dam of a hydroelectric power plant. Straightforward calculations indicate that for each tower, this energy was on the order of 10^{19} erg, or about 1% of the energy released by a 1 kiloton nuclear weapon. By comparison, the Hiroshima bomb was about 20 kilotons strong. While the towers were crashing to the ground, this energy converted into kinetic (or motion) energy, part of which was consumed as heat of collision, deformation and destruction of the structural materials. Back of the envelope calculations indicate, however, that a good fraction of the kinetic energy must have been conserved and transferred to the ground underneath, some of it dissipating as heat near the foundation, and the rest being converted into seismic waves that radiated into the surroundings. These waves shook the nearby buildings and generated small earthquakes in New York City that were recorded 34 km away at the Lamont-Doherty Earth Observatory, and were estimated to have possessed a magnitude of about 2.3 on the Richter scale. Back-calculations from this seismic intensity to total seismic energy at the source point demonstrate in turn that the energy carried by the seismic waves was only a very small fraction (less than 0.1%) of the kinetic energy released by the crash of the towers. Where did the remainder of the kinetic energy go? Probably, a good fraction may have gone straight down into the earth as body waves that did not radiate laterally near the surface to cause measurable vibrations. Thus, the characteristics of the seismic motions caused by a falling building may not be entirely analogous to the vibrations caused by seismic fault fractures familiar to seismologists.

Why did they not fall like a tree?

Some observers have wondered why the buildings telescoped down, instead of overturning and rolling to their side like a tree. However, buildings such as the WTC towers are not like trees. For one thing, they are not solid, rigid structures, but for the most part are open space (offices, staircases, elevator shafts, etc.). Indeed, a typical building is 90% air, and only 10% solid material. Thus, it is not surprising that a 110 story structure should have collapsed into 11 stories of rubble (actually less, because the rubble spreads out laterally, and parts are compressed into the foundation). In addition, the towers did not fail from the bottom up, but from the top down instead. For a portion of the tower to roll to either side, it must first acquire angular momentum, which can only occur if the structure can pivot long enough about a stable plane (e.g. the stump in a tree). However, the forces concentrated near the pivoting area would have been so large that the columns and beams in the vicinity of that area would simply have crushed and offered no serious support permitting rolling. Also, both building sections above the crash site were not tall enough to significantly activate an inverted pendulum effect. Thus, the upper part could do nothing but simply fall down onto the lower part, thereby crushing it from the top down. While videos of the collapse of the South Tower shows the upper part inclining just as it began to collapse, it did not fully roll to the side, but instead fell down onto the lower floors in a tilted position. There is also indirect evidence that the vertical resistance to telescoping or pancaking of either tower was minimal: the duration of the collapses of some 12 seconds was nearly the same as that of an object in free fall, while any serious resistance would have slowed down the collapse. Indeed, it takes an object falling freely from a height of 411 m (1350 ft) —the height of the towers— some 9 seconds to reach the ground. In essence then, the towers did not collapse like trees because the structures, despite their strength, were too fragile to sustain such motions.

Corollary to the WTC collapse

An important lesson to be learned from the WTC collapse is that buildings are like chains in the sense that these are only as strong as their weakest link. Hence, if the structural integrity of any floor in a building should be seriously endangered for some reason, such as a blast or a massive fire —perhaps excepting the very top floor or those immediately below it— , that building is in danger of collapsing and pancaking to the ground. However, inasmuch as catastrophic damage to all load bearing members is very rare and the vast majority of modern high rise buildings are well-engineered and designed to resist office fires —but not massive multi-story fires triggered by jet fuel and lost the sprinklers— these buildings are and will continue to be very safe indeed.

Can we design buildings to resist collapse? The answer to this question depends on what is meant by *design*. Sure, if we make *low* rise buildings as solid as the containment structures in nuclear power plants, it might be possible to design not only for impact and blast forces, but also for the massive fires caused by the jet fuel. But nobody would wish to live or work in such fortresses. In addition, they would be unbearably ugly. As for tall sky scrapers, it is virtually impossible to design a wall solid enough to resist penetration by a high speed plane while simultaneously providing open spaces for windows and carrying efficiently the weight of the crash barriers to the ground.

Then again, from a practical viewpoint, the chance that any *individual* building out of hundreds of thousands in the United States might suffer an attack is so small that it would not make economic sense to attempt making them jet-crash proof —and this chance should not be confused with the probability that *some* building in the US may be hit this way. As for retrofitting existing buildings, my view is that making them jet-crash proof would make no sense whatsoever. However, it would make eminent sense to retrofit at least some buildings, perhaps as part of an overall escape system overhaul, to ensure that load bearing elements have sufficient thermal protection and the buildings can survive a fierce fire for several hours. By providing adequate redundancies in the form of both alternative egress routes and sufficient escape time, we can prevent deadly consequences to people even when we should not able to avoid ultimate structural collapse. These improvements may be needed if for no other reason than to allay the concerns of people whose fear of a similar tragedy will persist for years to come. I, for one, would not wish to live or work in a mouse trap with insufficient escape paths.

Speed of Aircraft

Eduardo Kausel
Professor of Civil & Environmental Engineering
Massachusetts Institute of Technology

Abstract

The velocity with which terrorists crashed the ill-fated planes onto the buildings on September 11, 2001 is an important parameter in any post-mortem analyses on the collapse of the buildings. As is well known, the kinetic energy carried by the planes changes with the square of the velocity, while their momentum grows in proportion to this velocity. Thus, an accurate determination of the speed is an essential datum in the estimation of the dynamic effects elicited by the collision and the initial damage to the structures.

Using various publicly available video recordings as described in this article, I have been able to obtain reasonably accurate estimates of the speed of flight of the planes that collided onto the Twin Towers. A summary of the results is as follows:

Target	Flight	Aircraft	Impact Time	**Velocity**	
				km/hr	**mph**
North Tower	AA-11	Boeing 767-200	8:46:20 AM	691	429
South Tower	UA-175	Boeing 767-200	9:02:48 AM	810	503
Pentagon	AA-77	Boeing 757-200	9:38 AM	555	345

The velocities listed in this table for the two WTC planes are in excellent agreement with flight data based on radar provided by the NTSC[1]. The radar speeds are basically 10% larger, a difference that could easily be explained by the higher altitude at which the aircraft may have remained visible to radar and the probable speedup caused by the descent. Indeed, during their final approach, the airplanes —whose transponders had been disabled— were flying as low as some 300m (1000 ft) above the ground (i.e. the height of impact), an altitude that is barely above the rooftops of the skyscrapers in lower Manhattan, so radar is likely to have been blind to them. By contrast, the estimates given herein are based on the last mile of flight prior to collision.

[1] E. Lipton and James Glanz, "First Tower to Fall Was Hit at Higher Speed, Study Finds", *The New York Times*, February 23, 2002,

On the other hand, the velocity given for the plane that plunged into the Pentagon comes from information contained in the recovered flight data recorder[2]. The flight numbers and aircraft type listed are from a report by the *Washington Post* in the days following the attack. Finally, the impact times of the planes that crashed onto the WTC are from seismic records obtained at the Palisades N.Y. seismic station, Lamont-Doherty Earth Observatory, Columbia University[3]. Since the station is 34 km away from the WTC, in the table above I have subtracted 6 seconds from the reported times to account for the estimated travel time of the seismic waves from the WTC to Palisades.

The above data indicates that the terrorists flew towards the WTC close to the ground at nearly the full cruising speed of the planes, which is about 900 km/h (560 mph) at a normal altitude of 10km (33,000 ft). It is surprising that the inexperienced pilots that the terrorists were could still steer the planes at those speeds and hit their target head on. Also, consideering that the air at low altitudes is much denser than that at the normal cruising height, the pilots greatly exceeded VNE ("never exceed velocity") and thereby risked disintegration of the aircraft by air friction.

Pitfalls in determining the speed from videos

The velocity of the two Boeing 767-200 planes that were crashed onto the Twin Towers is not precisely known, especially the speed of the North Tower plane. The speed calculations are made more complicated by the following facts:

- The original format in which the videos were recorded is not only unknown to me, but they were also converted back and forth (once or twice) between the American NTSC format and the British PAL system. These two video standards differ in various aspects, which include the number of frames displayed each second and the screen resolution. In the NTSC system, there are 30 frames per second, while in the PAL system the number is 25. This affects the time estimation obtained by counting frames in slow motion. The hardware available uses various competing ways of converting from one to the other format, the more sophisticated and expensive of which is based on image interpolations in both space and time. Most conversions, however, are done by simply moving (or deleting) scanning lines and frames in one system to the closest position in space and time in the other, or by taking averages. These introduce artifacts and confounding ghosts in the video, particularly with moving objects and/or panning cameras. An excellent description of troubles with video conversions can be found at a web site in the U.K.[4].
- Some of the videos include running time counters or indices. In principle, these can also be used to determine elapsed times by subtraction of the indices. Care is required, however, because it is unknown if these counters were added in transcription, or were already contained in the initial recordings. Also, the fractions of second run from 0:24 or 0:29, depending on whether the index format was added in PAL or NTSC.
- Many of the videos have clearly been slowed down by a factor of perhaps two or three, in order to show in more impressive detail the incoming planes immediately before collision. Thus, I had to pay careful attention to detect slow motions and discard these videos (for example, speed of flames and smoke, etc.). I could not compensate for the slow motion

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[2] "September Eleventh: The days After, The Days Ahead", *Civil Engineering*, ASCE, Vol. 71, No. 11 (November), page 48, 3rd paragraph, 1st line

[3] Won-Young et al, *EOS, Transactions, American Geophysical Union*, Vol. 82, No. 47, Nov. 20, 2001

[4] http://www.ee.surrey.ac.uk/Contrib/WorldTV/

effect, because the slowdown factors were not readily available to me or determinable from the videos alone.

- The filming position was generally not known to me, a situation that introduced an unknown degree of geometric perspective or parallax effect. However, in most cases these recording positions appeared to have been sufficiently distant from the target that the parallax effect could safely be disregarded.
- In many videos, the camera either panned or zoomed into the target (or both), a situation that greatly complicates the determination of flight distances.

The details of these estimations are detailed in the sections that follow.

Velocity of North Tower plane

A dramatic video taken by French filmmaker Jules Naudet[5] from a distance of about one kilometer to the World Trade Center shows the crash of the first Boeing 767-200 against the North Tower, and appears to be the sole graphic documentation available of this grisly event. The initial footage of this video depicts fireman Chief Joe Pfeifer at the intersection of Lispenard and Church Streets checking out a gas leak below the northeast corner of that intersection. The initial scenes are shot along Lispenard, in an East to West direction. As a jet plane is heard, Chief Pfeifer turns up his head to the sky in reaction to the engine noise just as the plane races by overhead, but the plane can't yet be seen in the video. The camera then pannes immediately into a north to south direction as well as upwards, past and up the ATT building on Church Street between Lispenard and Walker Streets, and shows the plane in its last fractions of a second racing towards the tower and hitting it with devastating effect, at which time the camera zooms into the ensuing fireball.

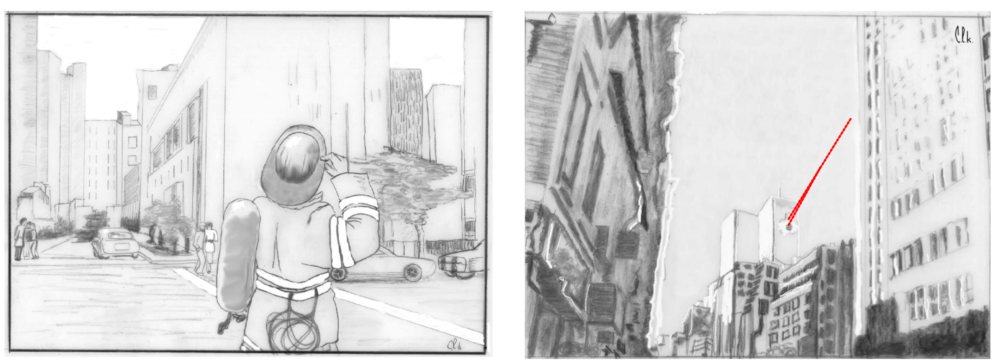


Fig. 1: Two scenes from J. Naudet's video. Drawings by Cecilia Lewis Kausel

In this video, the plane can be seen only in its last second or so before impact. In the sketch above on the right, the arrow that follows the dotted line, which in turn shows the estimated flight path, indicates this. Despite the scant evidence contained in the seven or so seconds in this sequence, this video still provides enough useful information that permits estimating the speed of flight with reasonable accuracy. This is done as follows.

[5] Alan Feuer, "Ground Zero: The Images", *The New York Times*, January 12, 2002, Late Edition, Section A, Page 1

The noise of the jet engines —a whining sound whose pitch decreases steadily because of the Doppler effect— can be heard briefly during the time it rises above the rather high background noise in the video. The sound becomes discernible as Chief Pfeifer faces the camera and a pedestrian crossing the street just disappears behind his left elbow, an instant that we can designate as time t=0. At this moment, he starts turning his body counterclockwise and looking up. The sound then vanishes below the street noise some three seconds later just as he touches his helmet and begins to lower his head.

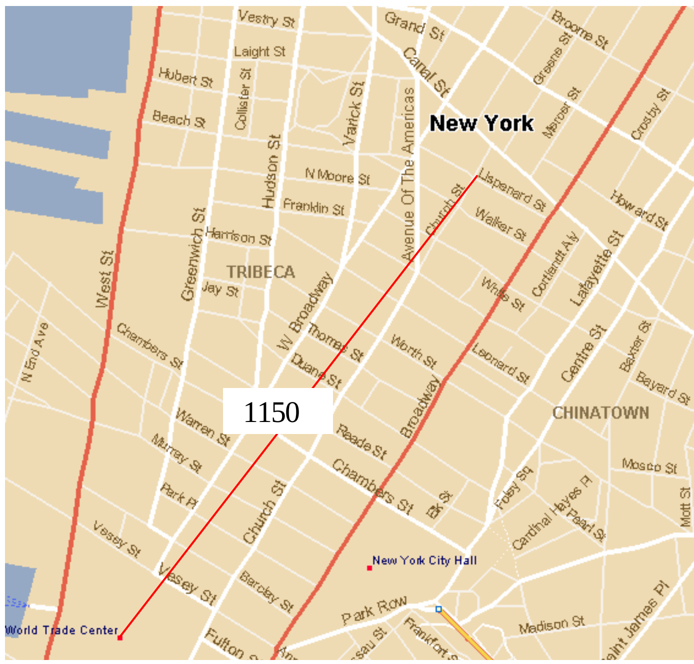


Fig. 2: Map of Lower Manhattan showing location of filming position

Now, the engine noise should be audible both before and after the passage of the plane, and in all likelihood for an equal duration before and after that fact. Thus, it is reasonable to assume that the plane flies by overhead at the center of the noise interval, that is, at time t=1.5 seconds. However, this sound must have been delayed by its travel time from the plane to the ground. Because of the direction in which the fireman looked up to the sky as well as the orientation of the towers, the likely trajectory must have been close to the arrow from the camera to the WTC on the map shown in Fig. 2, and not much further west. It is also known that the plane flew at an altitude of between 300 and 400 meters, because that is the height at which it collided with the North Tower, so that must have been the approximate distance to the ground. Considering that sound travels in air at some 340 m/s, it follows that the engine noise must have been delayed by about one second, so the plane actually flew by overhead somewhat earlier, namely at time t=1.5-1.0=0.5 s. The plane then plunged into the North Tower 194 frames after time zero, which corresponds to t=194/30 = 6.5 s. Thus, the estimated flight time from Lispenard to the WTC is T=6.5-0.50 = 6.0 s, give or take half a second or so.

On the other hand, using the *MS Streets-98* program, I determined the distance d from the video camera to the North Tower to be d=1150 m, to an accuracy of perhaps 40 m, and confirmed this distance by timing with a stopwatch the delay of the explosion boom, which is 3.4 seconds or 1156m. Hence, the estimated flight velocity is

$$v = (1150 \pm 40)/(6 \pm 0.5) = 192 \times (1 \pm 40/1150 \pm 0.5/6) = 192 \times (1 \pm 0.12) \text{ m/s}$$

that is, the speed of the North Tower plane is on the order of v=192 m/s = 691 km/hr = 429 mph, with a likely accuracy of 12%.

Velocity of South Tower plane

The speed of the plane that crashed onto the South Tower can be determined with greater confidence than that of the North Tower. This is because there are several videos taken from different angles available which show the last few seconds prior to the collision. In the pages that follow, I estimate this velocity using the following data:

- Video showing collision from a northerly view
- CNN Video showing collision from an easterly view
- Video showing collision from an easterly view
- Angle of flight inferred from the previous three videos
- Speed of plane inferred from Brooklyn Bridge video (best evidence!)

Velocity and trajectory of aircraft inferred from northerly view video

Consider the sketch of the video image together with its matching plan view shown in Fig. 3a (left side), and assume tentatively that the camera is infinitely far away so that all lines of sight are parallel to each other, i.e. neglect parallax. The angle of view can then be determined from the apparent widths a, b of the North Tower in the still images obtained from the video by relating these to the building's known width L=64m:

$$a = L\cos j \, , \qquad b = L\sin j \qquad \tan j = b/a$$

Also, let b be the angle between the plane's flight direction and the normal to the south face of the South Tower. The distance d traveled by the plane when its nose just emerges from the right edge of the image (i.e. screen, which is indicated by the vertical line) and t seconds later touches the right edge of the (visible) North Tower is

$$d = \frac{c}{\sin(j + b)} = \frac{c}{a}\,\frac{\cos j}{\sin(j + b)}\,L$$

from which the plane's speed $v = d/t$ can be determined. Now, the measured distances on the image are a=76 mm, b=45 mm, and c=205 mm, which would give for the viewing angle

$$j = \arctan\frac{b}{a} = \arctan\frac{45}{76} = 30.63^\circ$$

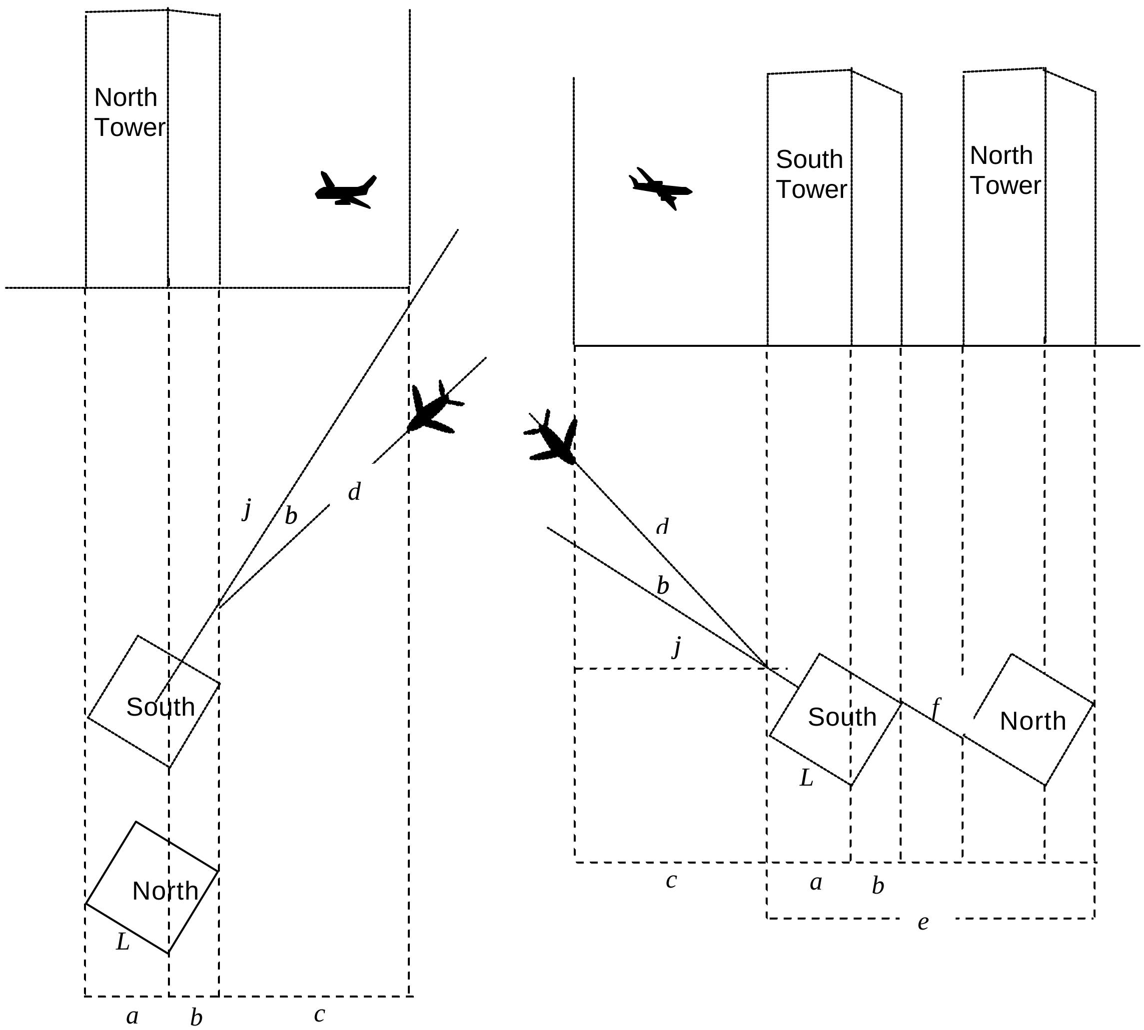


Fig. 3: Diagrams for northerly view (left) and easterly view (right) videos. (Unknown broadcaster).

Considering that the orientation of the WTC is some 27 degrees east of north, the above angle is thus only some four degrees west of north, so the camera's filming direction was nearly directly from north to south. The angle *b* can be found by combining the previous information with data from other images taken from an East-West direction. As will be seen, this angle is on the order of 15 degrees. The above values imply

$$d = \frac{205}{76}\,\frac{\cos 30.63}{\sin(30.63+15)}64 = 208\,\text{m}$$

On the other hand, the time elapsed between the appearance of the plane on the right edge of the screen until its nose crosses the line of sight to the right of the North Tower is t = 1 sec. This time interval follows both from the time counter in the video (2:57:23 to 2:58:22), and by counting the number of frames in the video, which was shot at 30 frames per second.

While the plane traverses this path, the camera gradually zooms in and pans slightly to the left, but this motion has no effect on the measured time. Thus, the plane's flight speed is on the order of 208 m/s. The actual value may perhaps be somewhat larger on account of the fact that we have neglected the parallax.

While the camera position in the still image used here is unknown, the line of sight of 4 degrees west of north would place it somewhere on Chambers Street or the Hudson River waterfront North of there. If so, the camera distance may range anywhere from 600 m to perhaps 1 km.

Velocity and trajectory of aircraft inferred from easterly view video

Consider next the still image and matching diagram shown in Fig. 3b on the right. Neglecting the parallax as in the previous section, the angle of view is

$$j = \arctan b / a$$

with a=60 mm and b=20 mm on the image. Hence, j =18 degrees. Since the towers are aligned at 27 degrees east of north, i.e. the perpendicular is 27 degrees south of east, this implies that the eastern view is at 9 degrees south of east (=27-18).

Again, let b be the angle between the plane's flight direction and the perpendicular to the south face of the South Tower. The distance d traveled by the plane when its nose just emerges from the left edge of the image (or screen) and t seconds later seems to touch the left edge of the South Tower is then

$$d = \frac{c}{\cos(j + b)} = \frac{c}{a} \frac{\cos j}{\cos(j + b)} L$$

Taking b=15 degrees and c=200 mm on the image, we obtain

$$d = \frac{200}{60} \frac{\cos(18.43)}{\cos(18.43+15)} 64 = 242 \text{ m}$$

While the plane covers the distance d=242 m from the edge of the screen to the edge of the South Tower, the time counter on the video changes from 15:07:07 to 15:08:07, which gives t=1 sec. Hence, the implied apparent flying speed is 242 m/s.

The camera position in the video image referred to previously above is unknown. The line of sight of 9 degrees south of east would place the camera somewhere in the vicinity of the Manhattan approach to the Brooklyn Bridge.

Velocity and trajectory of aircraft inferred from an easterly view CNN video

Consider now the still image and diagram in Fig. 4. The viewing angle is once more obtained as j = arctan b/a, with a=80 mm and b=30 mm on the screen image. Also, the actual length of the 767-200 seen in the image is 48.4m, while the building's width is L=64m. Thus, neglecting parallax, the viewing angle is j =21 degrees. Since the perpendicular to the towers' line of alignment is 27 degrees south of east, this implies an easterly view of the twin towers of 27+21=48 degrees south of east, which would place the camera roughly in the vicinity of Wall Street. Also, if (as will be shown) the aircraft travels at b=15 degrees from the alignment direction, then the aircraft in this video travels at 21-15=6 degrees from the image's plane (angle below horizontal in figure below).

The distances and lines shown on the sketch of the still image were measured on a flat screen while freezing the video. The left edge corresponds to the aircraft nose's position at 30 frames (i.e. 1 sec) before crossing the leftmost edge of the South Tower. The time counter at these two positions is 16:01:15 and 16:02:14. Hence, the apparent speed is

$$v = (140+175)\times 64\times \cos(21°) / 80\times \cos(9°) = 238 \text{ m/s}$$

which is consistent with the previously found values.

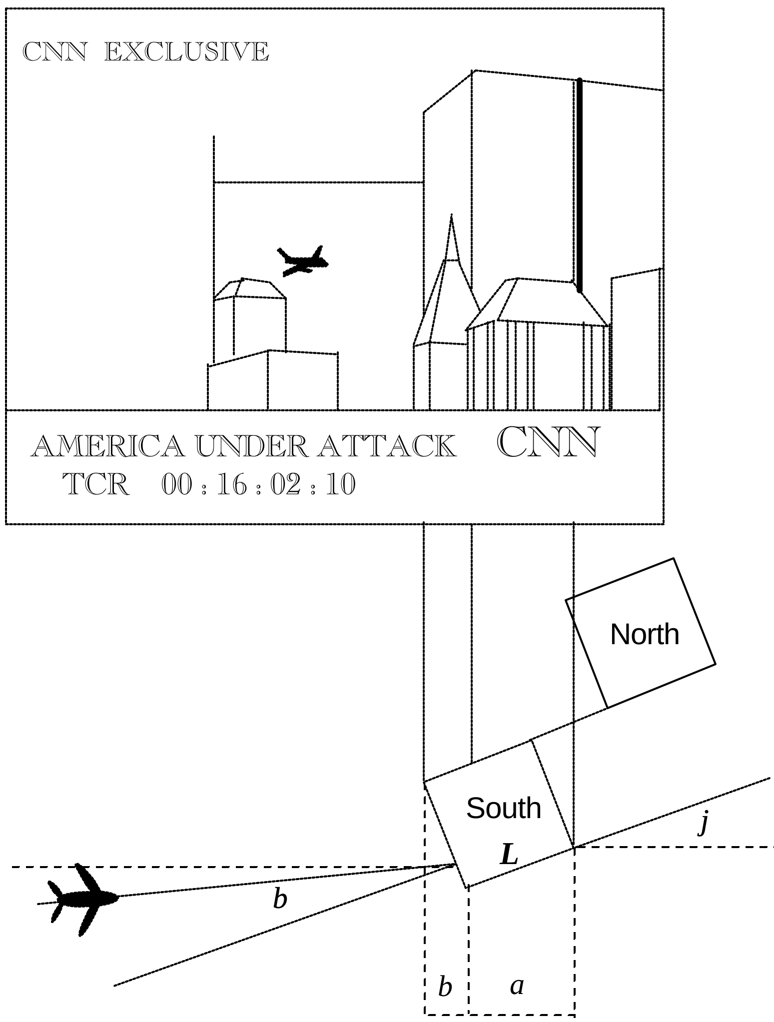


Fig. 4: Still image and diagram for easterly view CNN

Angle (azimuth) of flight

From the previous sections, the NS line of sight was 4 degrees west of north and the EW line of sight was 9 degrees south of east. These directions are indicated by the dashed arrows in the WTC neighborhood map shown in Fig. 5. Drawing parallels to the NS and EW lines of sight at the locations that match the right and left edges of the still images, respectively, which were both crossed by the aircraft at about 1 second prior to collision, we can estimate from their intersection the true location of the plane relative to the towers at this point in time. Drawing from this point the flight path to the South Tower, we obtain an angle of flight of about 15 degrees with respect to the alignment line of the two towers, which is 27 degrees east of north. Thus, this justifies the angle *b*=15 degrees we applied in the previous sections to estimate the flight velocity.

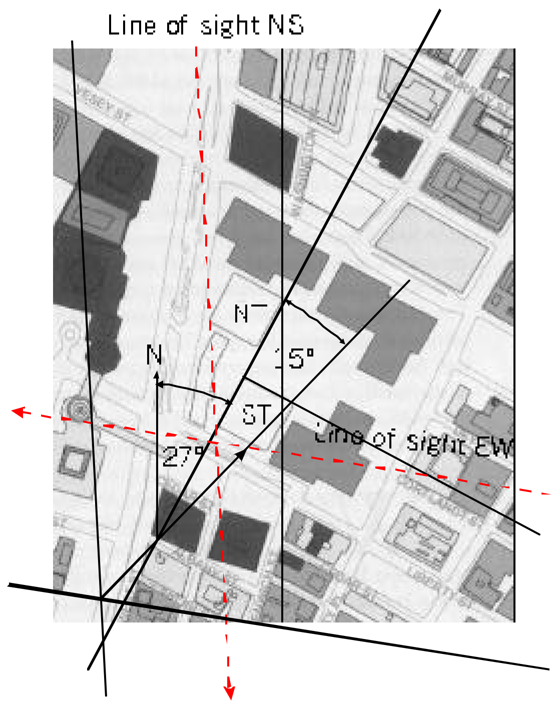


Fig. 5: Map of WTC neighborhood showing lines of sight. for northerly and easterly views

Speed of plane, as inferred from Brooklyn Bridge video

A very informative video showing the approach of the second plane to the South Tower was filmed from a position slightly to the North of the easternmost pier of the Brooklyn Bridge, almost immediately underneath the bridge. This places the filming position at about 1830 m from the World Trade Center, as determined by means of the *MS Streets-98* program. Fortuitously, the line of sight from this position to the World Trade Center is virtually perpendicular to the alignment line connecting the twin towers in the NE-SW direction (black and cyan lines shown in map below). This video, which was taken at a rate of 25 frames per second without zooming or panning, provides probably the best evidence available for determining the trajectory and speed of the plane.

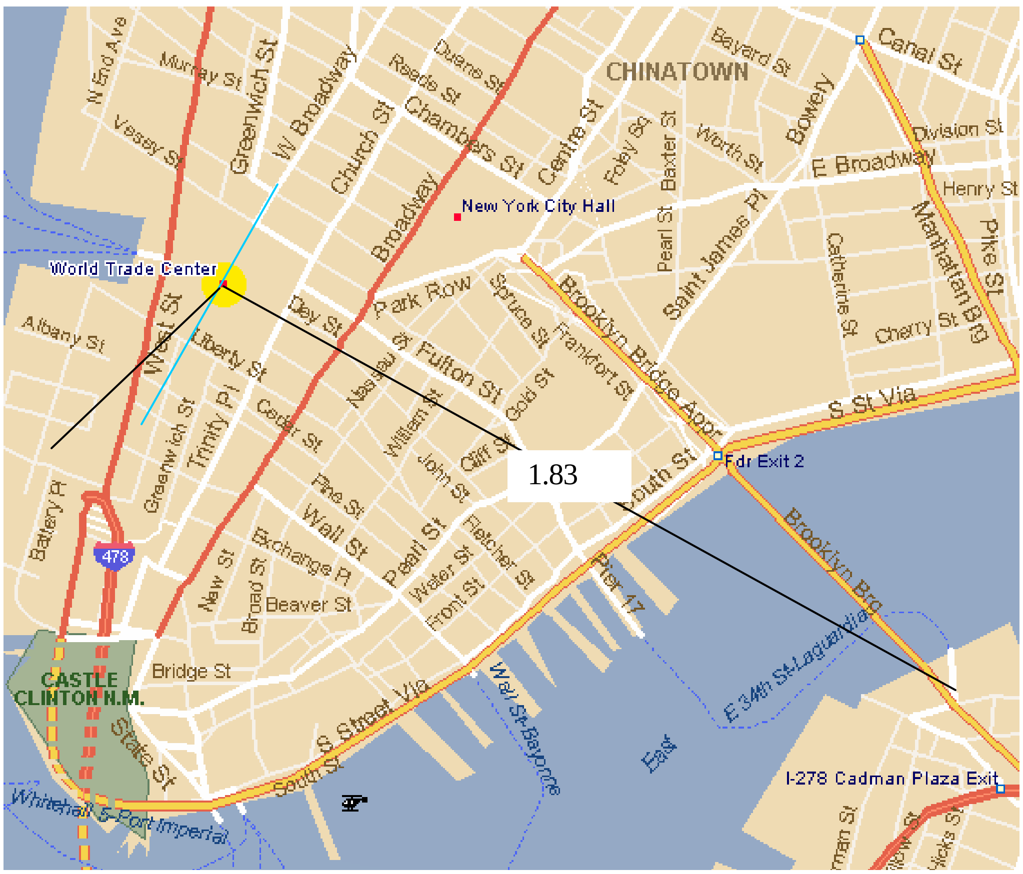


Fig. 6: Map of WTC neighborhood showing lines of sight for Brooklyn Bridge video

a) Apparent position of plane

A sequence of seven still images depicting the last four seconds of the plane's seemingly level flight toward the South Tower was used to track its position. Fig. 7 on the next page shows a sketch of the first of these images. The stills provide only the apparent position and distance of the plane to its collision point, because the plane is not traveling fully aligned with the twin towers, but at an angle of about 15 degrees further west of this direction (arrow in map).

Hence, the plane's apparent position must be corrected for parallax, which in this case can be carried out inasmuch as the filming position is known. The distance *d* between the apparent position of the plane and the South Tower can be obtained by measuring on the image the apparent position of the plane, comparing it against the known dimensions of the towers, and scaling this distance accordingly. The distance between the south face of the South Tower and the north face of the North Tower is 164m (my estimation), a reference distance that should be measured on the image at the height of flight, to compensate for the slight upwards perspective of the camera (arrows shown in the sketch below). The width itself need not be corrected for horizontal angle, because the view from the Brooklyn Bridge is virtually head on, and the difference in distance (depth) between the viewing point and the two towers (64m) is negligible compared to the camera distance (1830m). The results are as follows

Image distance [mm]	Time counter [sec]	Apparent position *d* [m]	Time to impact *t* [s]	Apparent velocity *v*=*d*/*t* [m/s]
64	15:36:18.80	750	4.12	182
57	15:36:19.40	668	3.52	189
50	15:36:19.96	586	2.96	197
41	15:36:20.60	480	2.32	206
21	15:36:21.80	246	1.12	219
12	15:36:22.25	141	0.67	210
0	15:36:22.92	0	0.00	-

Note: In the table above, we have converted the 0:24 frame index of the videos into decimal fractions of sec.

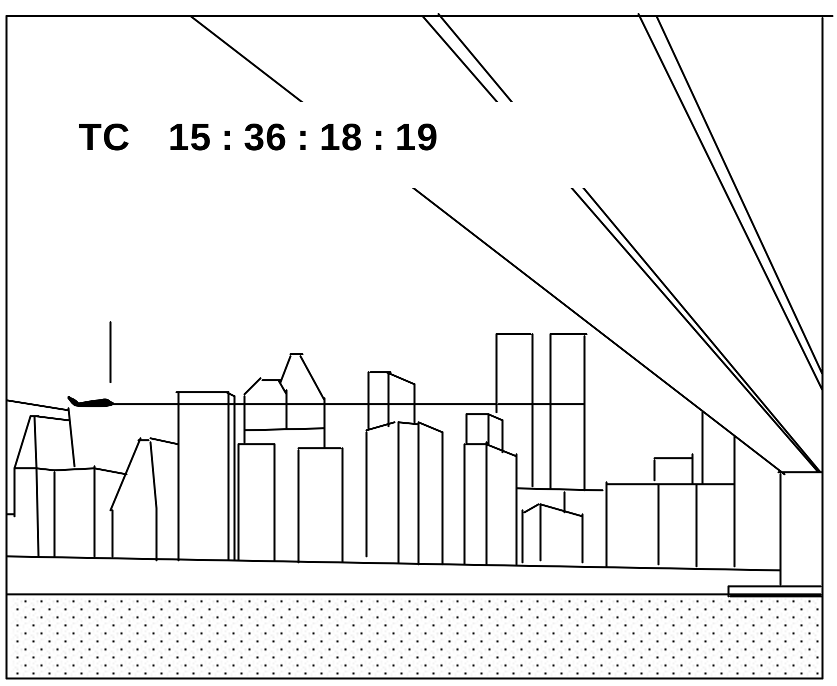


Fig. 7 a-g: Final approach, as seen from Brooklyn Bridge *b) Actual position of plane*

After measuring in the image the position *d* of the plane with respect to the South Tower, and considering the angle of flight *b* with respect to the apparent flight direction —which in the image is perpendicular to the Brooklyn Bridge line of sight— we can determine the actual position of the plane in terms of *b*, and thus the actual speed of flight. From the other videos of the WTC taken from a northern and eastern filming position, we know that the angle *b* is about 15 degrees. Thus, we can use this fact to determine the speed of flight.

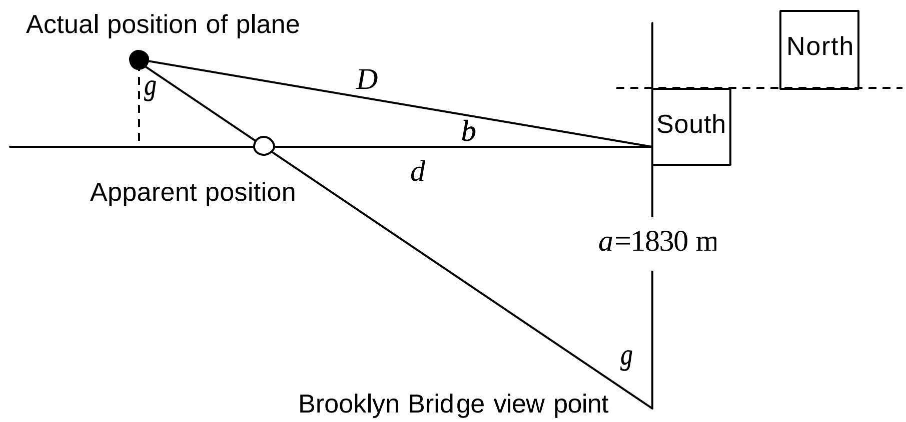


Fig. 8: Plan view of approach to South Tower, as seen from Brooklyn Bridge

From the triangles in the figure above, we can establish the following identity:

$$y = D\sin b = \left(D\cos b - d\right)/\tan g$$

Solving for D, we obtain

$$D = \frac{\cos g}{\cos(b + g)} d = md$$

with

$$\tan g = d/a$$

and

$$m = \frac{\cos g}{\cos(b + g)}$$

with m being the magnification factor for both distance and velocity.

The local coordinates of the plane relative to the impact point are then

$$x = D \cos b$$

and

$$y = D \sin b$$

Combining these formulas with the data in the previous table, we obtain the following results:

d	*g*	*b*=15°		*b*=20°	
[m]	degrees	*m*	*v*	*m*	*v*
			[m/s]		[m/s]
750	22.29	1.163	**212**	1.251	228
668	20.05	1.147	**217**	1.231	233
586	17.76	1.132	**223**	1.205	237
480	14.70	1.114	**229**	1.177	242
246	7.66	1.074	**235**	1.119	245
141	4.41	1.057	**222**	1.095	230

The above table includes a computation for an angle of 20 degrees to estimate the effect on the speed of an uncertainty in the value of the approach angle. In the light of the above results, and considering also the velocities estimated from the previous NS and EW directions, we conclude that a best estimate for the speed of approach is 225 m/s (i.e. 810 km/hr, or 503 mph). This speed is in excellent agreement with information from air traffic controllers, who reported that "Flight 175 had screamed south over the Hudson Valley at about 500 miles per hour, more than double the legal speed"[6].

[6] M. L. Wald and K. Sack, "A Nation Challenged: The Tapes", *The New York Times*, October 16, 2001, Section A, Page 1

Aircraft Impact Damage

Tomasz Wierzbicki
Professor of Applied Mechanics, MIT

Liang Xue
Ph.D. Candidate of Ocean Engineering, MIT

Meg Hendry-Brogan
Undergraduate student of Ocean Engineering, MIT

Abstract

The "post-September 11th" structural engineer, while feeling the remorse and confusion that every other American has dealt with, is also privileged with the immense education an analysis of the WTC collapse can provide. A newly found understanding for impact dynamics and failure of very large systems, as well as a comprehensive grasp of the brevity accompanying safety considerations in construction projects, will be present in industrial practice from now on. The research into the World Trade Center Towers collapse following the initial fact-gathering phase is now beginning the more ambitious tasks of reconstructing various stages of the damage and destruction of the Twin Towers. Currently, or at least as current as this paper, the FEMA/ASCE team has just released their report, [1], and an independent investigation is being conducted by the National Science Foundation study group. Preparations are also underway to launch a new program aimed at a producing a detailed simulation of the aircraft impact damage, fire damage, and the total collapse of the buildings. This work is led and coordinated by the National Institute of Standards and Technology.

This article was completed prior to the public release of the FEMA/ASCE report, therefore only the generally accessible information from the media and literature were used in the analysis. The facts documenting the first phase of the main objective of the present research is to predict the amount of internal structural damage that occurred within the Towers upon the aircraft impact and that was hardly visible from the outside. Attention is focused on three main structural components of the Towers, i.e., a lattice of exterior columns, complex floor truss assemblies, and the core load-bearing structure. A thorough understanding of failure mechanisms and the extent of damage done when a high speed aircraft impacts a large-scale structural system is a prerequisite for undertaking the next stage of the analysis, which is the weakening effect of fire and finally the self-distracting implosion of both Towers. The airplane itself, built as an assemblage of ring and stringer-stiffened panels, was also subjected

to gradual break-up and disintegration. The problem of interactive failure and fragmentation of two deformable and fracturing bodies, i.e., the aluminum airframe and steel structure, has not been addressed in the literature. Therefore, the question remains whether an estimate can be made on the internal damage of the building before the necessary computational tools are developed and small and full-scale tests are conducted? The answer to this question is yes, only if proper use is made of a few basic laws of mechanics. The method that is chosen here involves a logical progression from first principles to a recreation of the complex series of failure models, which set the stage for each Tower's final collapse. There are three basic principles of mechanics that are invoked in the present analysis

- conservation of energy
- conservation of linear momentum
- principle of virtual work

Each of the above laws of mechanics applies to a different scale. The energy conservation applies to the global scale of the entire aircraft and the affected parts of the building. It is expressed through the following equation

$$E_{kinetic} = E_{plane} + E_{external\_column} + E_{floor} + E_{core} \tag{1}$$

This equation says that the initial kinetic energy of the aircraft $E_{kinetic}$ (which is known) is converted into the energy dissipated by plastic deformation and fracture of four constituents of the collision problem, i.e., the airframe itself E_{plane}, the external column $E_{external\_column}$, the floors E_{floor}, and the core structure E_{core}. Some energy is also lost by friction and is converted into the elastic vibration of the entire building. These two contributions are small and will be neglected in the present simplified analysis.

Taking the estimated airplane mass at the point of impact to be $M = 127$ tons and the impact velocity of $V_o = 240\text{m/s}$, the energy of the striking aircraft was $E_{kinetic} = 3658\text{MJ}$. In the main body of this article, estimates are made on each component of the dissipated energy on the right hand side of Eq.(1). For each structural element, plastic energy is dissipated thought two mechanisms. The first mechanism is plastic deformation through the tensile tearing or shear plugging mode. This portion of the energy can be clearly distinguished by looking at the color-coded strain fields in computer simulation and therefore we call it "*visible*" energy. The other component of the energy loss is associated with the momentum transfer, which is difficult to see on the output of computer simulation. Accordingly, we call that contribution as the "*invisible*" energy. Depending on the impact velocity, relative magnitude of both energies could be different, but they should both be considered in a rigorous analysis of an inelastic impact.

The external columns were impacted at a very high speed and the process is controlled mainly by local inertia. As the fuselage and wings cut through the steel facade of the Towers, the affected portions of the column sheared off. It was found that the momentum transfer between the airframe and the first barrier of external columns was responsible for most of the energy dissipated in this phase. The energy to shear off the column constituted only a small fraction of that energy. A more exact calculation performed in Ref. [2] give a slightly larger value $E_{external\_column} = 26\text{MJ}$.

The floors and floor trusses were the next barrier to overcome. The floor trusses consisted of hundreds of beam-like tubular members. At this stage of the analysis it was impossible to develop a detailed computational model of this complex assembly. Therefore the entire volume of steel used by the floors was lumped into a uniform steel plate of the equivalent thickness. It was estimated that loss of kinetic energy to plow the airframe through the model structure was $E_{floor} = 1221\text{MJ}$ for North Tower and $E_{floor} = 1040\text{MJ}$ for the South

Tower. As for the airplane itself, the process of disintegration of the fuselage and wings started immediately during the entry into the wall of the exterior columns and it continued as the floors were cut and ripped apart.

Research available on high speed aircraft impacts into rigid and/or deformable bodies is limited in scope and pertains largely to reinforced concrete walls that protect nuclear power stations. The process of interaction of the airframe with a tube-like or cage-type steel structure is different. In the present calculation simpler models to crush and slice the fuselage and damage the wings into the central spar, open beam sections, ribs, and skins are used.

It was hoped that pieces of the aircraft were retrieved from "Ground Zero" to find the average size of the fragments. This will help to determine the actual energy expended through the breakup of the fuselage. The FEMA/ASCE failed to provide this information. Another source of inaccuracy in the determination of energy dissipated in failing the aircraft is the uncertainty presented by the impact orientation. The diameter of the plane is, in fact, larger than the length between floors, but different interactions will take place based on the orientation of the aircraft floors and wings with respect to the major axis of the external columns of each Tower. The calculation used to determine E_{plane} in this analysis takes these two uncertainties into consideration and attempts to make up for this error contribution by carefully superposing the energy dissipated through each step of the plane fragmentation and fracture. The calculations are completed taking both deformable and rigid body mechanics into account. Obvious rigid components, like the engines, weren't considered deformable in any part of the calculation. In the end, the lower bound on the energy expanded to distressing the aircraft was found to be $E_{plane} = 962\text{MJ}$.

The energy to be dissipated by the core structure is the difference between the total energy introduced into the Towers $E_{kinetic}$ and the energies lost on damaging the exterior columns, floors, and the aircraft itself. From Eq.(1) this energy was found to be $E_{core} = 1630\text{MJ}$ for the South Tower and $E_{core} = 141\text{MJ}$ for the North Tower. There are a lot of uncertainties as to what happened to the core structure under such high energy input. One could envisage partial damage (bending) of many columns or complete damage (severance) of fewer columns. By the time the pile of debris from the airplane and floors the load on core column would probably be much more distributed favoring severe bending rather than of core columns cutting. It is estimated that 7 to 20 core columns were destroyed or severely bent in the South Tower while only 4 to 12 core columns were ruptured in the North Tower. These initial estimates can be easily adjusted once more precise information on the geometry, material, and impact condition become available.

At the end of this article several important factors pertinent to the global collapse of buildings are discussed. However, a more precise sequence of events which trigger the ultimate implosion of buildings is left to a future continuation of this research.

The first draft of this article was actually completed in February and printed as Report #74 of the Impact and Crashworthiness Lab. Subsequently, four new reports on analytical and numerical analyses of the aircraft impact problem have been completed [10-14]. The results of these reports, whenever necessary, have been incorporated into the updated version of Report #74 which constitutes the present article.

1. Introduction

On January 28, 1986 the space shuttle Challenger exploded in mid air and plunged into the ocean at a terminal speed of 80 m/s (180 mph), shattering the crew compartment and killing everyone in it. NASA and the Presidential Commission carried out an investigation that revealed the root cause of the accident. However, the report failed to provide a reconstruction of the three stages of the accident (i.e. mid air explosion, free fall and water impact). One of the present authors (TW) carried out a separate investigation of the space shuttle disaster and presented a detailed analysis of each of the above stages of the accident in the open literature [3-5].

On September 11, 2001 another disaster of far greater proportion struck the nation. Officials immediately began clearing the site of the accident, and collecting data. As of today, six months after the accident, no step-by-step reconstruction of all the factors leading to the collapse of the WTC Towers has been released. However, there has been an ongoing debate in the academic community over many of the key elements integral to a firm structural failure theory [6]. The present analysis uses the limited, publicly available data from the crash site, to reinforce certain first principles of mechanics in order to abstract upon the events of September 11th. The recently release FEMA/ASCE report add very little into the understanding of the aircraft impact damage and focus mainly on the global collapse of the Twin Towers and the adjacent buildings. Should new information, coming from such sources as a Nation Science Foundation study group, provide additional relevant data, our analysis should be quickly modified with little additional effort because of the character of our close-form solution. Therefore, we believe that the underlying methodology employed below transcends a mere reconstruction of the crash, but more importantly provides a much-needed understanding of the structural failure processes that characterize high velocity aircraft or missile impacts with large civilian or military installations.

2. Objects and approach

The functional objective of this article is to make educated predictions of the internal structural damage that occurred within the towers and that was hardly, if at all, visible to the observer. These “invisible” parts of the buildings, i.e. the complex floor truss assemblies and the core load-bearing structure, shown in Figure 1, comprise an integral part of any analysis into the ultimate collapse of the towers. They are the elements of the collapse reconstruction that are lightly understood and highly speculated upon. This analysis attempts to achieve a higher understanding of this area of the collapse via complex, first-order modeling of the major components of the impact: the building and the plane.

From the television video clips of the accident, a terrifying truth comes to life. The airplanes collided with the buildings at a cruising speed, cut through the outer shell and disappeared inside the towers. No appreciable pieces of the airplanes were seen to fully penetrate the Towers and emerge on the other side. (In fact, according to the FEMA/ASCE report, part of the engine and landing gear as well as a small portion of fuselage penetrated the outside structure and fell a few blocks away.)

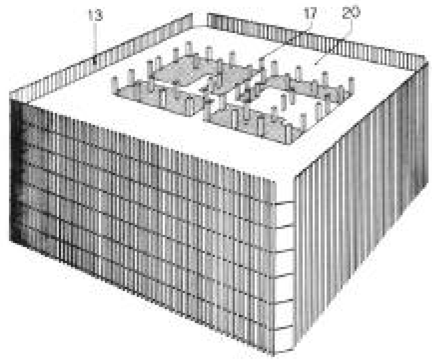


Figure 1. Double hollow tubes structures of the World Trade Center showing exterior columns (13), floors (20) and core columns (17)

In the language of mechanics the above observation can be expressed via the statement of energy balance given by Eq.(1) where all the components entering Eq.(1) are listed below.

$E_{kinetic}$ is the kinetic energy of the airplane;

E_{plane} is the energy dissipated by the crushing and breakup of the aircraft;

$E_{external\_column}$ is the energy required to cut through the exterior columns;

E_{floor} is the energy dissipated by the floors;

E_{core} is the energy absorbed by the core column destruction.

In subsequent sections we will estimate all five different terms entering Eq.(1).

This is not an easy task because the relative contribution of various terms will depend on the activated failure modes and contact forces developed between different components of the airplane and the Towers. Both the airplane and the WTC Towers are built as closed or open, thin-walled, three-dimensional structures, which deform plastically, crush and crumble, fracture and break up into small pieces. Thus, whatever evidence remained has been burned in the 10-story high pile of debris.

What tools did the present team have at its disposal for accomplishing the stated objectives? To answer this question, one must place the local aircraft impact damage in the context of existing knowledge. A distinguishing feature of the attack on the Twin Towers was the high impact velocity that the airplanes had relative to the ground vehicle collisions extensively studied in the literature. A review of recent methods and results in the area of crashworthiness engineering can be found, for example, in references [7-9]. This class of problems is dominated by membrane and bending deformation of thin, shell-like structures accompanied by large displacement, rotation, and strain of material elements, as well as internal contact. Global inertia of structural members is important, but the effect of local inertia is negligible. Fracture is seldom a problem in crashworthiness engineering.

On the other end of the spectrum are projectile impacts into solid objects and/or thin sheets causing penetration and perforation. Here, fracture and local inertia play a major role, but projectiles are treated as rigid bodies when impacting thin-walled targets. Projectile impact velocities may exceed, by an order of magnitude, those that were encountered in the WTC Towers impact. For a review of the mechanics and physics of projectile impact, the reader is referred to excellent articles by Corbett et al [10] and Goldsmith [11].

Finally, there is vast literature, scattered over journal articles and conference proceedings dealing with the effect of explosion on structures, including fragmentation [12]. Some of the methods and results that are most relevant to the problem at hand are, unfortunately, classified.

Perhaps the most powerful tools available for solving structural impact problems are commercial Finite Element codes such as ABAQUS, LS-DYNA, ADINA, PAM-CRASH, etc. These codes can also handle fracture initiation and, to a limited extent, fracture propagation when the impacting bodies are discretized by tiny solid or shell elements. In a parallel study which is being conducted in the Impact and Crashworthiness Lab [13] fracture propagation was successfully simulated at the component level (see Figure 25). However, to be computationally efficient, large-scale structures must be discretized not by solid elements but by shell elements, which are larger in size but much fewer in numbers. When fracture and fragmentation is involved, the above codes can produce correct results for tension dominated fracture but may give large errors for shear dominated fracture [12].

For the purpose of the present analysis, an analytical approach will be used in which the simple solutions of several crushing and tearing problems involving thin walled structures will be combined into a coherent failure theory. Several reports have already been completed with involvement of the present authors addressing various stages of the fracture and fragmentation of exterior columns and wing structure, [2,14,15]. Therefore, we believe that our analyses are solidly rooted in the first principle of mechanics and therefore it will give a first order approximation of this enormously complex impact phenomenon.

2.1 Aircraft orientation and speed

Before a structural analysis can be made, initial conditions for the impact problem must be determined. This includes: aircraft speed, aircraft trajectory, point of impact, roll angle and orientation with respect to the floors. Most of the above data can be calculated from video clips available from CBS, see Figure 2, CNN, and the Washington Post. The two airplanes crushed into the Twin Towers were Boeing 767-200ER. The main geometric dimensions of a Boeing 767-200ER are

Length: $l_f = 48.51\text{m}$

Wing span: $l_w = 47.57\text{m}$

Fuselage diameter: $D = 5.03\text{m}$

Max. take-off mass: $M = 179{,}330\text{kg}$

Given that the maximum take-off mass of the airplane is 179,330 kg, that the airplane was not full of passengers (only 65 of 216 maximum capacity), and that the airplane was in the air for 50 minutes before it crashed into the WTC, the mass of the airplane is estimated to be $M = 127$ tons.

The independent assessment of the initial closing speed of the impacting aircrafts into the South Towers has been performed by present authors. A table below summarizes various estimation published in open literature.

Figure 2. The aircraft approaching the South Tower

Table 1. Impact speed of American Airline Flight 11 and United Airline Flight 175

	North Tower	South Tower
FEMA/ASCE Report [1]	210 m/s	264 m/s
Kausel [16]	192 m/s	240 m/s
Wald and Sack [17]	-	222 m/s
Present authors [14]	-	220-240 m/s

For the present calculation, it is assumed that impact velocities were 240 m/s and 200 m/s for the South and North Tower respectively. Hence, the initial kinetic energy of the airplane hitting the South Tower is

$$E_{South} = \frac{1}{2} M V_0^{\,2} = 3658\text{MJ} \qquad (2)$$

The average estimated impact velocity of the United Airlines plane hitting the North Tower was $V_0 = 200m/\sec$. The corresponding kinetic energy was much lower

$$E_{North} = 2540\text{MJ} \qquad (3)$$

The above calculations do take into account the kinetic energy of the fuel, however fail to provide for the energy introduced via the explosions or fires that the fuel sustained. In the present paper, we will be using the kinetic energy given by Eqs.(2) and (3).

The relative position of the aircraft with respect to the North and South Towers is shown (to scale) in Figure 3 and Figure 4 respectively.

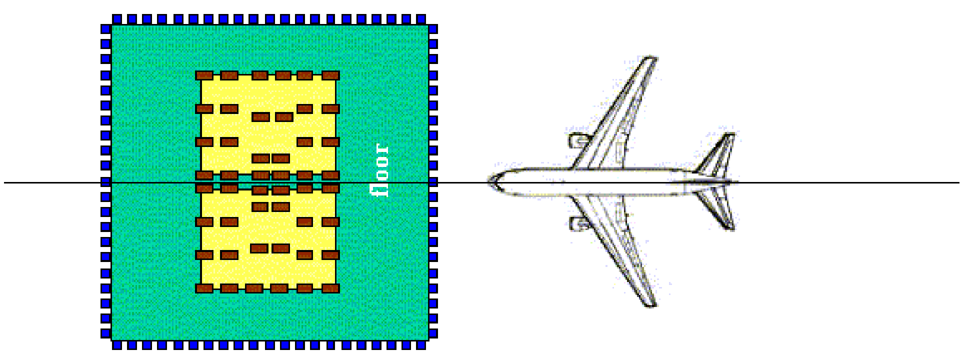


Figure 3. Orientation of North Tower head-on impact

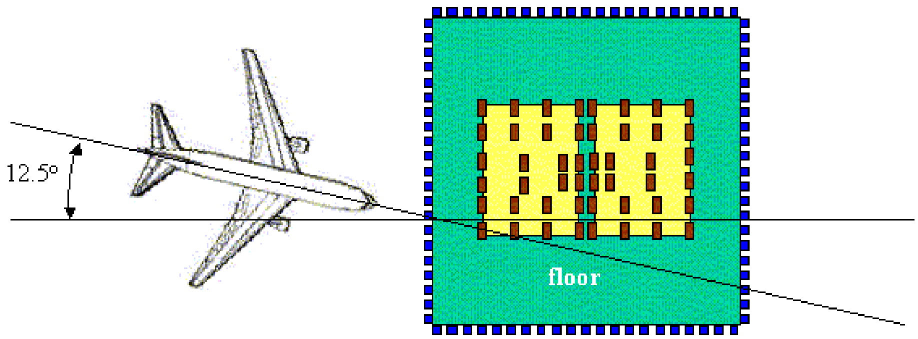


Figure 4. Orientation of South Tower oblique impact

Before colliding with the North and South Tower, the planes banked to the left and hit the Tower with a roll angle of approximately 26° and 35°. This roll angle will have significant influence on the number of destroyed floors.

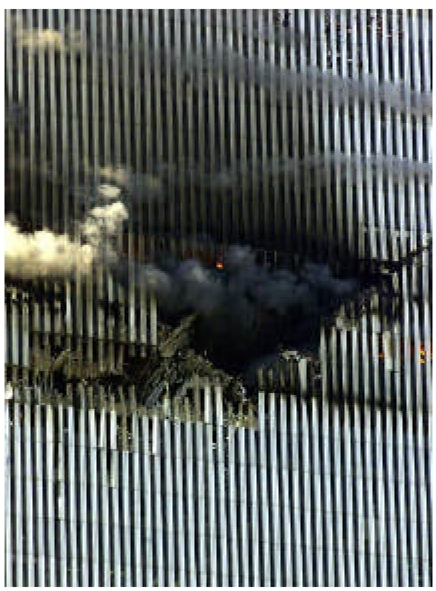


Figure 5. Damage to the exterior columns of the North Tower immediately after the impact.

The exact position of the longitudinal axis of symmetry of the plane with respect to a floor is unknown. However, we do know that the diameter of the fuselage (5.03m) was greater than the height between floors ($l = 3.7\text{m}$). Therefore, the fuselage will contact at least one floor, and more probably, two.

At the same time, the 3m diameter engines and the wings could easily fit between office floors. This will be most probably the case with the North Tower impact, which occurred with less roll angle.

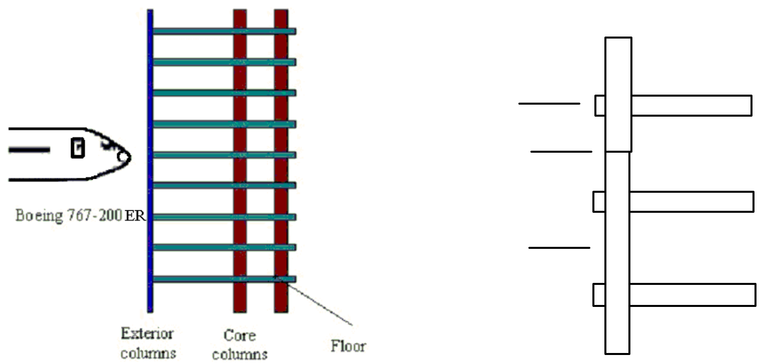


Figure 6. Relative orientation of the aircraft and the floors

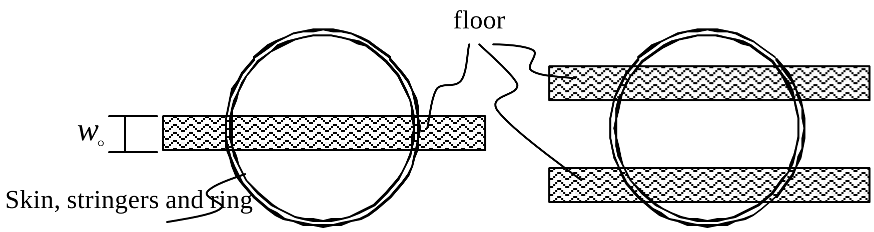


Figure 7. The 5-meter diameter of the fuselage can get engaged with one or two floors depending on the relative orientation

3. Aircraft failure

3.1 Modeling philosophy

In this engineering analysis, one must attempt to uncouple the problem of rigid vs. deformable body mechanics with respect to the airplane impact. The impact process is obviously a definite interaction between a very large stationary building and a small but fast moving airplane, both of which undergo considerable deformation. In order to make this problem mathematically tractable, some simplifying assumptions must be made. These assumptions essentially uncouple the impact interactions and then superpose them analytically. First, the building is treated as a rigid barrier and the airplane is considered deformable. Then the aircraft is treated as a rigid flying object, but the impacted structure is deformable.

The interaction between the impacting and impacted components is considered by monitoring the contact force and comparing the magnitudes of the forces required to instantaneously deform one or the other. The body that requires less force to collapse is treated as deformable, while the other is treated as rigid. This method was successfully used in the analysis of a collision between two ships [18]. The aircraft impact problem occurs at a much higher speed.

The first true "crash tests" of aircraft were conducted by Jerry Lederer at McCook Field, Ohio in 1924 [19]. Most pertinent to our research is the study initiated by Riera in 1968 for the Federal Aviation Administration [20] concerned with safety evaluation of the Three-Mile Island Nuclear Power Plant. Full-scale crash tests were conducted including the F-4D Phantom fighter [21] and DC-8 carrier [22]. Several research groups continued this line of research until recently [23-24].

One of the distinctive features of all the aircraft impact analyses performed for the nuclear industry is that all of the impacted structures (mostly dome shaped buildings) have been reinforced with 2m-thick concrete. Upon impact, there will be very little local damage to the dome in the form of crushing or scabbing and surface cracking of the concrete. Upon impact into high-rise buildings, the situation is different. The framework of beams, columns, and trusses could deform plastically and fracture. Because the contact area is small, these members, which are relatively narrow compared to the fuselage diameter, can cut and slice into main elements of the airframe before being broken themselves. Thus there is a complex iterative failure sequence between the two "opponents", building and airplane, that are of comparable strength.

3.2 Fuselage damage by steel framework

What happens to the airframe traveling with 240 m/s, encounters an absolutely rigid, but relatively narrow, obstacle such as steel columns or floors of the building? This analysis will require information on mass distribution and the structural details of a Boeing 767. Taking the data from the FEMA report, the mass of the airplane at the instant of impact is estimated to be equal 127 tons (including passenger aboard and 10,000 gallons of fuel). In the present level of approximation, the whole aircraft will be treated as being composed of three different types of structures: deformable fuselage, rigid engines and strong but crushable wings.The mass of the fuselage of a Boeing 767-300ER, which is 6.43m longer than Boeing 767-200ER, is 46.4ton. The average mass of the fuselage per unit length is thus $m = 786\text{kg/m}$. Assume this mass per unit length is the same for Boeing 767-200ER.

The fuselage consists of a system of rings and stringers attached to sheet metal. The floor separating the passenger and cargo area runs slightly below the diameter of the round fuselage. At this level of the first order engineering analysis, it is not possible to account for the individual contribution of rings, stringers, and the skin.

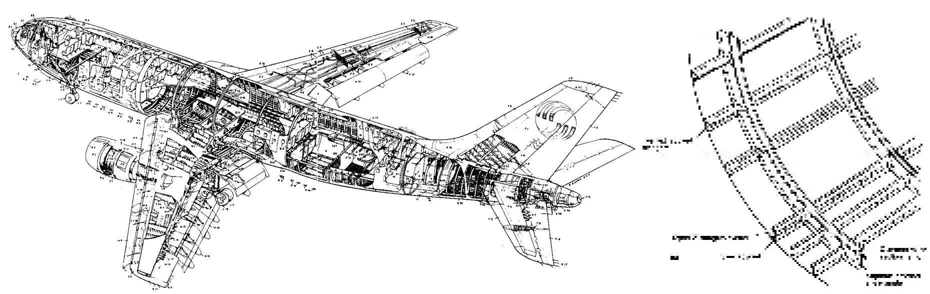


Figure 8. Internal structure of Airbus 320 (Reprinted from Ref. [25])

Instead these members are smeared into an equivalent thickness, which retains the same mass as the actual fuselage

$$p\, D t_{eq} r_{Al} = m \quad (4)$$

From the above equation, it is found that for $D = 5.03\text{m}$, the equivalent thickness is $t_{eq} = 18.4\text{mm}$.

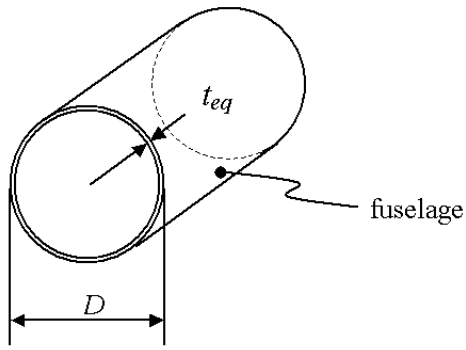


Figure 9. Simplified model of the fuselage

The building must now be characterized more exactly. The outer columns form a “fence” which can be treated as a continuous wall (see next section for the structural details). The fuselage can be assumed to crush and fold upon contact. The floor, on the other hand, is a single, relatively narrow structure of width $w_o = 0.9\text{m}$.

The quasi-static crushing of a uniform circular tube representing the fuselage has been studied by dozens of researchers including one of the present authors. Following Wierzbicki et al, the expression for the mean crushing force is, [26]

$$P_m = 7.9 s_{Al} t_{eq}^{1.5} D^{0.5} \quad (5)$$

Taking the actual data and assuming the flow stress for aluminum alloy is $s_{Al} = 350\text{MPa}$, one gets $P_m = 15.5\text{MN}$.

Multiplying the crushing force by the total length of the fuselage, the energy absorbed by crushing of the fuselage is $E_{fuselage} = P_{fuselage} \cdot l_f = 753\text{MJ}$. It will be shown later that the actual energy is smaller.

Now the fuselage is getting engaged with one or two floors of the height $w_{\circ} = 0.9m$ each. The floor is relatively narrow compared to the diameter of the fuselage and may in fact slice through the fuselage and cut it into two or three pieces. Wierzbicki [27] derived an approximate solution for plastic resistance of a blunt object cutting into thin sheet, such as tubular wall of the fuselage model. He identified the so-called “concertina” tearing mode, which consists of two diverging cracks enclosing a strip which progressively folds back and forth. A photograph of the damaged pattern induced by a rigid punch of width w_o is shown in Figure 10.

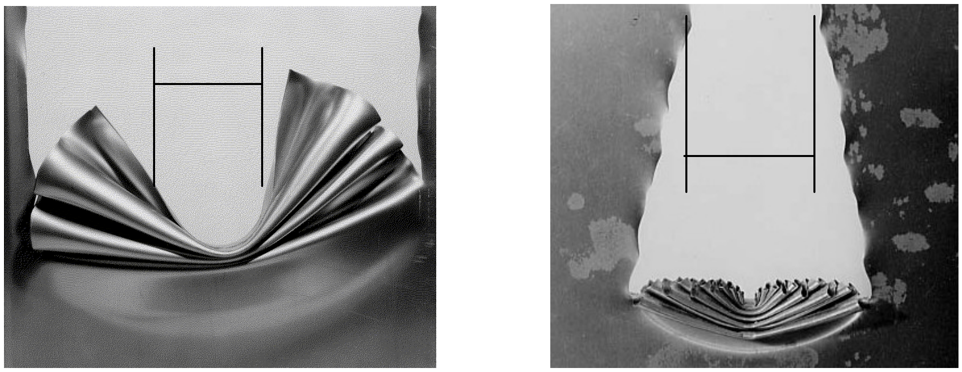


Figure 10. Concertina tearing of a sheet by a blunt object with parallel cracks (left) and diverging cracks (right)

The mean cutting force can be calculated from the equation

$$P_{cut} = 3\sigma_{Al} t_{eq}^{5/3} w_0^{1/3} \quad (6)$$

The total resistance of the fuselage to the cutting mode will depend on the relative orientation of the floor with respect to the fuselage cross-section. Some possible cases are depicted in Figure 7 for the North and South Towers.

In the case of contact with one floor, the cutting force is $P_{cut} = 2.6\text{MN}$. Should fuselage hit two floors at a time, the cutting force becomes $2P_{cut} = 5.2\text{MN}$.

The above forces are forces resulting from the so-called "*visible*" dissipated energy. As pointed out by Riera [20], another important contribution to the contact force comes from the momentum transfer and is given by

$$P_{momentum} = m_f V^2, \quad (7)$$

where m_f is mass per unit length of the cut area of the fuselage and V is the instantaneous velocity of the impacting object. It is estimated that $m_f = 89.4\text{kg/m}$ for cutting through one floor and $m_f = 178.8\text{kg/m}$ if the fuselage is engaged in two floors cutting. In the case of South Tower, Eq.(7) gives $P_{momentum} = 5.2\text{MN}$ for the scenarios of one floor and $P_{momentum} = 10.4\text{MN}$ for the scenarios of two floors cutting at a time. The total cutting force becomes then $P_{total} = 7.8\text{MN}$ and $P_{total} = 15.6\text{MN}$ for the cases of one or two floors respectively.

This force should be compared with the force needed by a "rigid" fuselage to cut through a deformable floor. The lower value of the two will be taken in the global energy balance calculation. This will be done in the next section. Should the cutting force of the fuselage by one or two floors will be smaller than the cutting force of the floors by the fuselage, then one can calculate the energy absorbed in the cutting mode as a product of the cutting force times the length of the fuselage. (The reaction force produced by Riera term, Eq.(7) does not contribute to the energy dissipation because the corresponding displacement is zero.) In our case the energy consumed in cutting the fuselage is equal to

$E_{fuselage/cut} = P_{cut} \cdot l_f = 127\text{MJ}$ or twice as much if the fuselage cuts through two floors. In the final energy calculation, we are using a mean value between those two estimates, which is $E_{fuselage/cut} = 190\text{MJ}$.

It should be noted as the fuselage would interact with the floor structure, it is likely that material debris had piled up at the head of the airplane, widened the contact area. Therefore it is possible that somewhere during that phase the rear portion of the aircraft will be subjected to progressive crush rather than cutting. However, switching from one failure mode to the other is highly speculative. The maximum possible value of the crushing energy is $E_{fuselage/crush} = P_m \times l_f = 753\text{MJ}$. In fact, the fuselage that has been weakened by two or three cuts will not develop its full resisting force which otherwise will be offer by an intact cylindrical tube. In the energy calculation, we will take only half of that energy which is $E_{crush/fuselage} = 376\text{MJ}$, but this assumption is highly speculative and clearly demonstrates the difficulty in the present damage analysis.

3.3 Engines and wing damage

The engines are the only components of the aircraft that can be considered approximately as rigid bodies. Their devastating power is unmatched until they encounter an object of similar weight and strength. In the experimental study in which an engine of a transport aircraft hit a thick concrete wall, the engine itself was crashed and fractured, so it was not rigid, [28]. However, in contact with less substantial members the engine could cut and plow through the various structural members of the WTC Towers until all their kinetic energy is absorbed.

Wings of modern transport aircrafts are quite complicated structures consist of open section beams, ribs and a skin reinforced by stringers. Together they form a very stiff and strong box-type section. Determination of the strength of the wing relative to the strength of the floor structure will require a detailed finite element analysis, which we believe has not been performed to date. In order to retain the needed degree of simplicity, two models were developed. In one model the wing material is lumped into single box-type beam. In the second model, the solidity ratio are determined for both the wing and the floor and then are compared.

The main structural part of the wing is the spar – a continuous beam that extends from one tip of the wing to the other. For modeling purposes, we assumed that the mass of the wings (excluding engine) was approximately $M_{wing} = 21300\text{kg}$. This mass does not include the mass of the fuel in the wing tanks. Assuming that this mass is now uniformly distributed over the whole wing span and the wing is modeled as a thin-walled square section cross-section ($c \times 4c$) with the thickness (t_{eqw}), the equivalent thickness of the wing beam can be found from the equation

$$\left(10ct_{eqw}\right) l_w \, r_{Al} = M_{wing} \tag{8}$$

Taking an average height of the spar to be $c = 480\text{mm}$ and the span of the aircraft $l_w = 47.57\text{m}$, the equivalent thickness becomes $t_{eqw} = 34.5\text{mm}$. The wings are swept at approximately 35^o so that upon impact, external columns are contacted sequentially, one by one. However, the problem of a hollow beam striking another hollow column at a right angle and a speed of 240 m/s has not been analyzed in the literature. Therefore it is not possible, at this point in time, to give any detailed account on this interaction, between the wings and outer column, with a higher degree of accuracy than our approximate engineering analysis. The equivalent thickness of the hollow wing beam is approximately four times larger than the thickness of the exterior columns, $t_{ext} = 9.5\text{mm}$. It is therefore reasonable to treat wings as rigid bodies upon impact with exterior columns. By the same token, the equivalent thickness of wings is smaller (about half) than the equivalent thickness of the floor structure (to be calculated in the next section). Consequently it would appear that the floors will cut through the wings without being severely damaged themselves. In actuality the wings are constructed as a 3-dimensional lattice of open section beams, ribs and sheet metal skin that maybe of comparable strength to the floor trusses. However, interaction between two 3-dimensional space frames impacting each other is too difficult to carry out analytically at the present level of approximation.

In the alternative model, we are calculating the solidity ratio of both the wing and the floor defined by $\bar{r} = \dfrac{\text{Mass}}{\text{Structural Volume}}$. Note that the structure volume is meant as a volume enclosed by the outer periphery and not the material volume. Thus, for the wing $\bar{r}_{wing} = \dfrac{21.3}{0.48*(4*0.48)*47.57} = 0.49\text{ton/m}^3$ and $\bar{r}_{floor} = \dfrac{1466}{2891*0.9} = 0.56\text{ton/m}^3$. The magnitude of both solidity ratio are similar but it would appear that structure with higher solidity ratio should cut through the one with the lower solidity ratio without being damaged. According to the above model, damage of wings and floors should occur almost simultaneously. No relative level of crush resistant can be calculated, but the energy approach will still be valid.

It can be conjectured that those portion of the wing that fit in-between the floors will penetrate all the way to the core columns and will be broken by the core columns, which are much stronger. From the comparison of the airplane with the floor plan of the South Tower, shown in [15], it appears that the wing encounters the first row of six core columns. The wing beam will most probably fail by the shear mode to be described in Section 5 or simply by crushing. Assuming a crushing mode to be more realistic, the energy absorbed during that process is equal to $E_{wing} = 4p M_{ow} l_{wc} = 20\text{MJ}$, where M_{ow} is the full plastic bending moment of the wall of the wing box and $l_{wc} = 15\text{m}$ is the estimated length of the wing that fit in-between the floors and subsequent impact the core structure. Current research is underway to determine the accuracy of this approximation.

The other part of the wing that will in touch with the floor structure would probably be fragmented into smaller pieces. It is not clear what is happening next with this already disintegrated wing structure. There are approximately 25 columns on the way of this debris. The process of cutting would have slow down the wing velocity, which have already being diminished by the earlier contact with the exterior columns and floors. The created debris will impinge into the core columns causing them to bend and stretch but not necessarily fracture. While the corresponding analysis is presented in the next section, it is impossible to make any statements about the degree to which wing structures will be subjected to further fragmentation.

In our best estimate, the plastic and fracture energy absorbed by disintegrating the airplane can be summarized as follows

Energy to crush the fuselage	$E_{fuselage/crush} = 376\text{MJ}$
Energy to of cutting the fuselage	$E_{fuselage/cut} = 190\text{MJ}$
Energy of breakup of wing(s)	$E_{wing} = 20\text{MJ}$
Total energy absorbed by airplane	$E_{airplane} = 586\text{MJ}$

4. Building failure

4.1 Design, prefabrication and construction

This section will give an overview only of those structural aspects of WTC Towers that are relevant to the subsequent failure analysis. In order for the two buildings to withstand the tremendous wind loads faced by a structure of such unprecedented height, the double "tube building" model was employed. The name "tube model" comes from the building being shaped like a stiff "hollow tube" of closely spaced columns on the exterior, and floor trusses which extend across to a central core on the interior. This shape allows the building not only to withstand wind loads, but 'reportedly' also a collision with a large commercial airplane flying at lower speed. The validity of the latter claim is questioned in this article. The vertical steel and concrete core that forms the center of the "tube" supports approximately 60% of the total gravity load of the building, while the outside shell bears the remaining 40%. The towers were built very modularly and consisted of many prefabricated pieces, such as exterior panels, floor trusses etc. On the other hand, the core structures were constructed more traditionally in the "cage" type design.

4.2 Exterior columns

The 64m (208 ft) wide façade is, in effect, a prefabricated steel lattice. The exterior columns are narrowly spaced and finished with a silver-colored aluminum cladding. The main building block of the outer structure was a prefabricated element, which was comprised of 3 floors, was 11 m high and 3.07m wide, Figure 11.

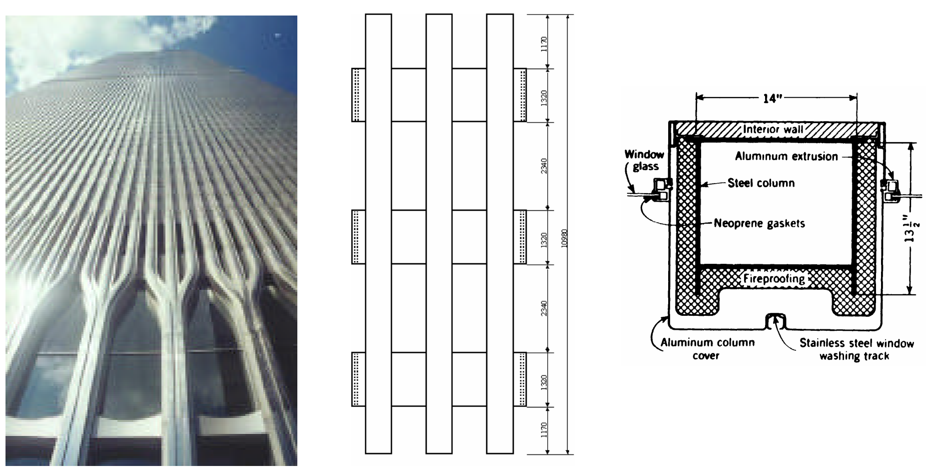


Figure 11. Prefabricated panel consisting of three columns of three-floor-high

The prefabricated panel consisted of three columns connected by 3 transverse plates, called spandrels. The steel columns are of square cross-section ($b \times b \times t = 356\text{mm} \times 356\text{mm} \times 9.5\text{mm}$). and they were spaced 570 mm apart from each other. The segments were staggered and bolted to their neighboring elements in every direction, Figure 12.

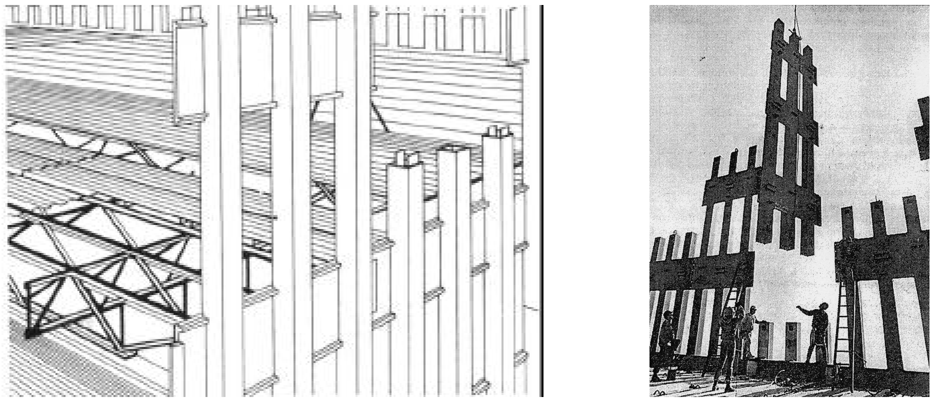


Figure 12. Assembly of the external wall units (alternately staggered in one-story heights) and floor units.

Each column was a box structure, almost square, with a assumed wall thickness of $t_{ext} = 9.5\text{mm}$. In actuality, the exterior columns were variable in thickness of 12.5mm at the bottom of the buildings to 7mm at the top. The true columns thickness of that portion that was hit is not known to the authors. In the present analysis, the columns were assumed to be made of the medium grade A36, constructional steel characterized by:

Yield Stress:	$\sigma_y = 250\text{MPa}$
Ultimate Strength:	$\sigma_u = 475\text{MPa}$
Elongation (Fracture Strain):	$\varepsilon_f = 0.23$

The so-called energy equivalent flow stress, calculated from the above values, and using the power-law approximation of the stress strain curve, is $\sigma_{A36} = 396\text{MPa}$.

4.3 Floor Structure

In addition to carrying the normal vertical loads, the floor system had to act as a diaphragm to stiffen the outside wall against lateral buckling forces from wind load pressures, and had to be very strong. Thus, in order to maintain some level of cost and weight efficiency, they were quite complex. The floor construction was of prefabricated trussed steel, 800 mm (33 in) in depth that spanned the full distance to the core. There was a primary truss system, which supported a corrugated steel plate on which was poured a 100 mm thick, lightweight concrete slab. The author did not have access to the technical drawings for each Tower. However, dimensions of many key structural members can be retrieved from generally available information, such as the total weight of the floors. The total weight of each floor is M_{floor}=2200 tons and the office floor area was A_{office}=2891 m^2. Subtracting from the total floor weight the weight of the concrete slab of 734 tons, the weight of structural steel in each floor is calculated to be 1466 tons. The above calculated data will be used to form estimates of the energy absorbed by the floor structure.

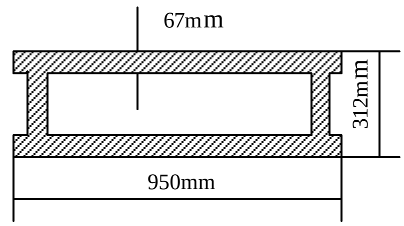


Figure 13. Relative size of core column compared to the exterior column. We have estimated the geometry of the core column from this photograph.

4.4 Core columns

Inside each tower there were 44 large, concrete reinforced, steel columns, which enclosed elevators, stairways, and utility space. Again, the author's inquiries to ascertain exact values for the core column dimensions failed. However, one is able to estimate these values by comparing the size of core columns to the size of exterior columns as captured in photographs of the site, such as the one shown below. With an accuracy compromised by the poor resolution of the photographs available, we determined that each column had a thickness of 67mm, and dimensions of $950mm \times 312mm$ in rectangular cross section. It is not certain if all core columns shared identical cross section, but our calculations could easily be revisited when more precise data on their exact geometry becomes available. It is hoped that we will be able to eventually retrieve exact dimensions of core column in the course of our continuing research.

4.5 Connections

Each prefabricated panel was bolted through spandrels to its horizontal neighbor with 2 rows of 18 bolts each. This is, again, an estimated value, but as you will see later on in this discussion, a bolted connection is so weak that the diameter of these bolts within plus and minus 5mm is really insignificant. It is easy to calculate the cross sectional shear strength of the bolts, and is approximately half of the shear strength of the parent material, and possibly less because of stress concentrations. The photographic coverage of "Ground Zero" has proven that individual, prefabricated panels were almost all separated at these bolted seems, and it can further be said that it was actually the bolts which fractured rather than the material in the spaces in-between them. Concerning the connection between the staggered, prefabricated elements in the vertical direction, there were only four bolts adhering the interfaces of two columns. The bolt cross sectional areas in these joints comprised approximately 2.3% of the column cross-section. Clearly there is a gross incompatibility between the strength of the connections (in shear and in tension) with the strength of the columns themselves. Elementary, beam-bending theory calculations show that these bolts would have failed with only 1 mm transverse deflection of the columns (loaded as a beam). For all practical purposes they may be assumed to have negligible strength in bending, shear and tension. The strength of connection between the exterior wall and floor trusses is discussed in Section 6.

5. Damage estimate

5.1 Failure of exterior columns

The overall picture of the damage to the exterior shell is shown clearly in Figure 5. An interesting overlay of the outline of the plane on the North Towers impacted face is shown in Figure 14. One can clearly distinguish the fuselage together with the vertical and horizontal fins of the tail section, as well as two smaller holes driven by the engines. In the FEMA/ASCE report, it was estimated that the length of the damage area was approximately 31m, which is shorter than the wing span which is 47.57m. Therefore, it can be concluded that the extreme portion of the wings didn't cut through the columns but is actually deflected themselves. The damage extended over five floors, which is easily to see by counting rows of detached aluminum cladding, each one story high. From Figure 15(a) and 15(b) one can see that 33 and 23 rows of columns were cut by the impacting aircraft to the North and South Towers respectively.

Let us look at the exterior columns individually. The plane could have struck the building with its nose localized at the point of a floor junction; this would have been the strongest resisting point. It could have struck where two of the steel lattices had been joined together via steel bolts; this being the weakest of the defenses. Or, it could have struck simply in the middle of the beam sections between floor junctions.

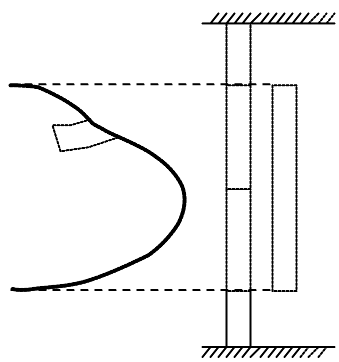


Figure 14. The shearing failure of exterior columns by the aircraft fuselage (and wings). Details given in Figure 25.

Additionally, the impacted members were continuously supported by their own lateral inertia which is proportional to the mass per unit length and the acceleration $m\ddot{w}$. The latter effect was, in fact, the decisive type of for this range of craft velocities. Most, if not all, damaged columns seen in Figure 19 exhibited a clear 'cut' produced by shear failure.

The instantaneous plastic shear force developed in the cross-section is $\frac{s_0}{\sqrt{3}}4bt$. Upon complete separation, the plastic energy dissipation is obtained by multiplying the shear force by the thickness of the sheared –off element. Thus, the upper bound on the shear energy per one cut is

$$E_{cut} = \frac{s_{A36}}{\sqrt{3}}\left[\left(2bt_{ext}\right)t_{ext} + \left(2bt_{ext}\right)b\right] = \frac{2s_{A36}}{\sqrt{3}}bt_{ext}\left(t_{ext}+b\right) \approx \frac{2s_{A36}}{\sqrt{3}}b^2 t_{ext} \qquad (9)$$

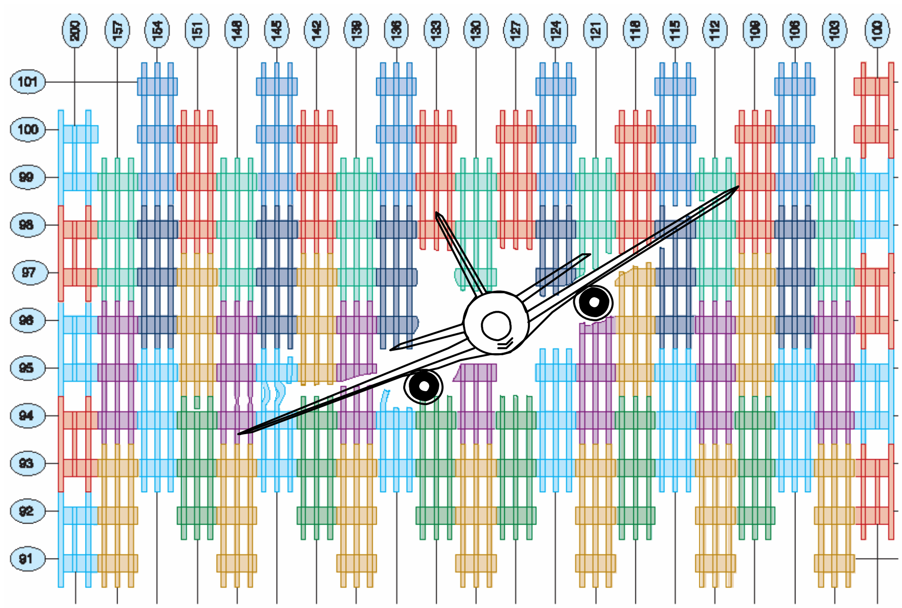


Figure 15(a). The outline of the airplane superposed on the hole driven in the exterior wall of the North Tower

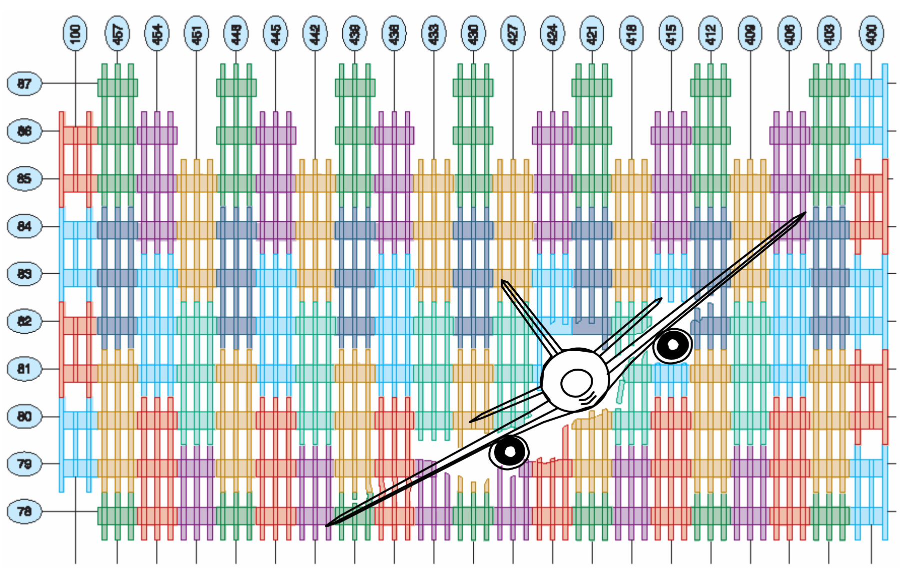


Figure 15(b). The outline of the airplane superposed on the hole driven in the exterior wall of the South Tower

The alternative failure mode is plastic bending of the cantilever beam but it is very unlike that this failure mode would occur under high velocity impact because it will require the beam inertia to be activated. Recent results of the numerical study have conclusively proven that exterior columns fail by the shear type of failure, [2], see also Figure 25.

Multiplying the energy per column (Eq. 9) by the number of damaged columns the total energy dissipated by the external columns of the South Tower is

$$E_{external\_column} = \left(\frac{2s_{ext}}{\sqrt{3}} b^2 t_{ext} \right) 2 \cdot 23 = 20\text{MJ} \qquad (10)$$

This is only a small fraction of the available kinetic energy of the aircraft.

It is recognized that there is a momentum transfer during the cutting process and additional energy is lost during that process. Teng and Wierzbicki [2] estimated that this additional energy loss is approximately $\Delta E = E_{kinetic,wing} \frac{M_{column}}{M_{coumn} + M_{wing}}$ where M_{column} and M_{wing} denote the respective masses of the columns and the wings that are in contact. According to the calculation performed by Teng and Wierzbicki [2] the mass ratio is 0.0783, which means 7.83% of the initial kinetic energy of the wings (96MJ or 2.6% of the total initial kinetic energy) is lost in cutting the exterior columns. What can be concluded with full confidence is that the plastic work used for fracturing the top and bottom of flanges as well as two webs is significantly smaller than the kinetic energy lost during the process of momentum transfer.

5.2 Failure of floors

Now that the plane has made it through the exterior membrane of the tower, the floors present the next opportunity to dissipate its remaining kinetic energy. How many floors did the plane collide with? How much energy does it take to move the airplane through the entire 10.7m all the way to the core? How can we model them? Our analysis uses several engineering approximations to effectively analyze three different models of the floor destruction.

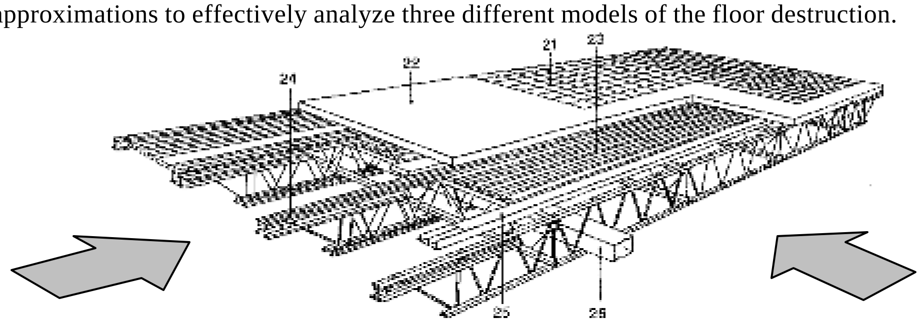


Figure 16. Aircraft impact direction with respect to the layout of floor structure

The complexity of the floor structure, as confirmed by the figure above makes the analysis very difficult. The floor structure can essentially be regarded as a longitudinally stiffened plate. Paik and Wierzbicki [29] and Braco and Wierzbicki [30] showed that a good engineering approximation for calculating resistance of such plates to crushing and cutting forces is obtained by the so called "smearing technique". In this technique the evenly spaced steel trusses are condensed into an equivalent thickness of uniform plate. Dividing the total volume of the steel imbedded in each floor by the floor area, the equivalent thickness becomes

$$t_{eq} = \frac{M_{steel}}{r_{A36} A_{floor}} = 65\text{mm} . \qquad (11)$$

Various cutting and tearing failure modes of plates were identified and studied in the Impact and Crashworthiness Laboratory at MIT in conjunction with the project on grounding damaged of oil takers and ships. Photographs of two typical failure modes are shown in Figure 17.

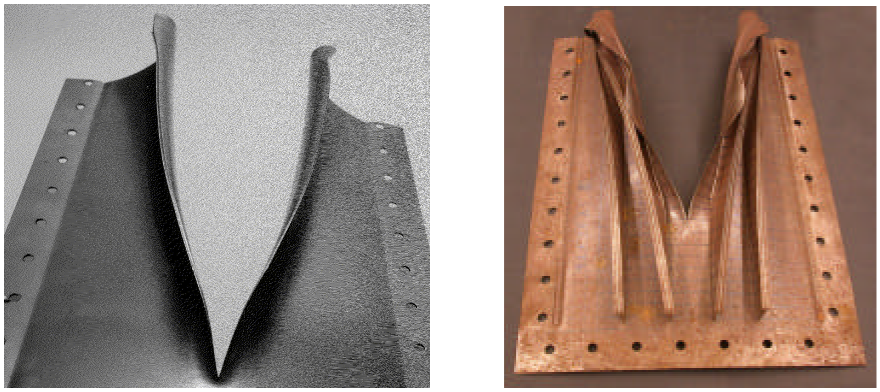


Figure 17. Unstiffened and stiffened cut by a shape wedge

The pure cutting mode shown above involves one running crack followed by curling and stretching of flaps. Note that the stiffeners, if any, are deforming and curling together with the plate. The picture of damage of longitudinally stiffened plate, shown on the right could correspond more closely to the failure of the WTC tower floors in which floor trusses could be considered as stiffeners. Because this mode can only be activated by a sharp wedge, unlike a blunt fuselage, it will not be pursued any further.

It is believed that the more applicable failure of floors could be the so called "concertina folding" mode, see Figure 10. The concertina mode can in fact be initiated by any blunt object such as the aircraft fuselage or wing. The failure mode consists of two parallel or diverging cracks with the plate folding back and forth between the cracks. The material is essentially piling up in front but this is not affecting the structural resistance. The solution to this rather complex problem involving combined plastic flow and fracture was given by Wierzbicki, [27]. Using realistic assumptions, he derived a very simple expression for the resisting force

$$F_{floor\,/\,fuselage} = 3s_{A36} t_{eq}^{5/3} D^{1/3} \tag{12}$$

where D is the width of the cut, the equivalent thickness of the floor is $t_{eq} = 65\text{mm}$ and the flow stress of A36 steel is $s_{A36} = 396MPa$. It can be shown that the force for the fuselage for the 5.03m diameter to cut through the floor is much higher than the force of the floor to slice through the fuselage. That leaves only the wings and engines as airplane member that are sufficiently strong to cut through the floor.

The diameter of the engines is approximately $D_{eng} = 3m$ while the height of the wing modeled as a single beam is $c = 480mm$. The corresponding resisting forces are

$$F_{floor\,/engine} = 3s_{A36} t_{eq}^{5/3} D_{eng}^{1/3} = 18\text{MN} \tag{13}$$

$$F_{floor\,/\,wing} = 3s_{A36} t_{eq}^{5/3} c^{1/3} = 10\text{MN}\,. \tag{14}$$

The floor span of the South Tower impacted side is 10.7m, however for a diagonal impact, see Figure 4, the length of the damaged floors will be much larger. It is observed that the left wing traveled some 10m, while the fuselage and right wing traveled an average of 50m. Therefore, taking an average between those two, the length of the damaged floor is taken to be equal $l_{floor} = 30m$ (an estimated average length of 18.3m for the North Tower), the total energy dissipated on destroying the floors are

$$E_{floor} = \left(2F_{floor/engine} + F_{floor/wing}\right) \cdot l_{floor} = 491\text{MJ} . \quad (15)$$

In the above equation the contribution of only one engine was taken into account, because the other one (or at least part of it) felt a few blocks from "Ground Zero" meaning that the engine did not engaged with the floors. For the North Tower, it also assumed that only one engine is engaged in impacting with floor. The above estimate includes only the energy in the plastic deformation and fracture but does not take into account the energy loss on the momentum transfer. The problem of simultaneous energy dissipation and momentum conservation was recently solved by Teng and Wierzbicki, [15]. According to their calculations , the additional loss of kinetic energy is proportional to the ratio of the impacted mass to the sum of impacted and impacting mass. Thus, the results of the present calculation would very much depend on the magnitude of the floor mass that was accelerated by the impacting airplane. It is a very difficult task because there is no clear indication how many floors were engaged in the contact with airplane and which part of the airplane was able to fit in-between the floors. Our best estimate is that some 15% of the initial kinetic energy was lost on pushing the floors. This additional energy loss is then $\Delta E_{floor} = 0.15 * E_{kinetic} = 549\text{MJ}$. This point will be revisited should more precise information becomes available for full-scale simulation. In summary, our best estimate on the energy loss for the damaging of the floors themselves is 1040MJ for the South Tower.

Once again, a word of caution should be added here regarding the accuracy of our mass estimate. At the present level of modeling, it was difficult to assign a unique mass of wing as well as to tell what part of the mass of the affected floors have been in contact with fuselage and wings and will accelerated during the impact event. Only a detailed finite element modeling and calculation will give definite answer to this question. Such a project is under development with possible sponsorship of NIST.

5.3 Failure of core columns

The core columns are much stronger than the exterior ones. The response of a plastic beam, loaded dynamically, occurs usually in three phases dominated respectively by shear, bending, and membrane action, Jones [31], Hoo Fatt [32]. It is assumed that by the time the core structure is reached the impacting debris of the aircraft will have been slowed by exterior columns and floors and would also have been broken down even further so that the loading induced on the core columns was distributed rather than concentrated. Under those conditions, the most probably failure mode would not be shear, as was the case with the exterior columns, but rather bending and, or membrane types of failure.

We do not have complete information on the manner in which the core columns were joined. Therefore, in order to complete this analysis, two different models could be employed. The first model, will apply to the weakly joined case, such as a single-pass weld on the thick-walled (67mm) beam. Such a joint would be easily broken and, similarly, as in the case of the exterior columns, the core columns can be treated as two cantilevered beams at fixed distances to the floors. However, the global bending mode of the core column will entail global inertia of the beam which, we think, should be excluded because of the short duration of the impact phenomenon. Therefore the bending deformation mode will not be pursued any further. In the second model it will be assumed that the connections have the same strength as a cross section of the parent material. In this case, the membrane deformation mode is appropriate.

The plastic energy required to stretch the core column in the membrane mode all the way to fracture is:

$$E_m = A l_m \sigma_{A36} \varepsilon_f \qquad (16)$$

where, $A = ab - (a-2t)(b-2t)$, is the cross sectional area, and l_m is the length of the column. Taking l_m equal to the length of one, two or three floors, the membrane energy is listed in Table 2.

Because the core columns are so strong and dissipated so much energy, assumption about the effective cross-section area and the length of the damaged column will have a decisive effect on the number of damaged columns. It is here that information from the crash site about the mode in which core column failed would be extremely helpful. In the absence of the above data, we must consider six different cases in that table below.

Table 2. Six different cases damage of a single core column

Dissipated energy (MJ)	1 floor		2 floors		3 floors	
	South	North	South	North	South	North
Membrane only (strong weld)	51	51	102	102	153	153

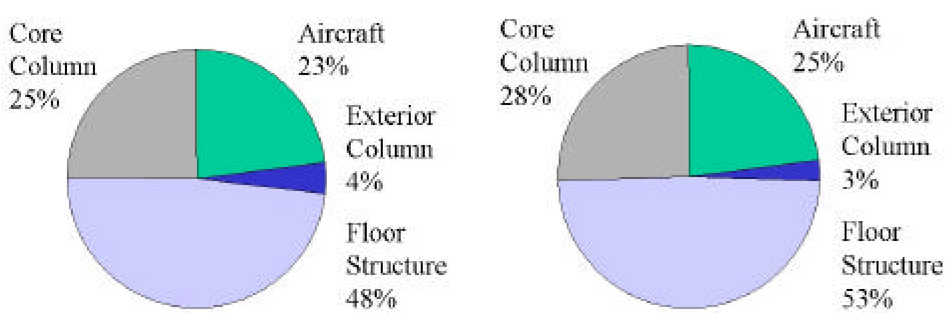
It should be noted that not all impacted core columns will be deformed and fractured. That could be the case that only a few columns while other core columns could be subjected to certain degree of bending and stretching without fracture. A devastating effect of this type of deformation on the overall survivability will be explained in the next section.

5.4 Energy balance

We are now at a sufficient point to return to the global energy balance (see Eq. 1) which can now be solved for E_{core}.

$$E_{core} = E_{kinetic} - \left(E_{plane} + E_{external\_column} + E_{floor}\right) \qquad (18)$$

The energy required to damage the exterior columns, the floors, and the aircraft itself has already been estimated. Also, we know the total energy introduced to the Tower. So, the only unknown is the total energy absorbed by the core. We can now graphically illustrate the break-down of energy dissipation in this impact.



(a) (b)

Figure 18. The contribution of various members to the energy dissipated during the initial impact. North Tower (a), South Tower (b).

According to our best estimate, the core columns absorbed $E_{core} = 1025\text{MJ}$, which is 52% of the total kinetic energy introduced by the aircraft. The total number of destroyed core columns is a ratio of the total energy available - core energy E_{core} to the amount of energy required to fail a single core column.

Depending which case considered in Table 2 will be valid, **the number of destroyed core columns in South Tower will vary between minimum of 7 and maximum of 20**. It should be noted that the prediction for the North Tower would be different for two reasons. First, the impact velocity is smaller and hence the kinetic energy induced by the airplane is less. Second, the airplane impacted the tower on different side correlating with the core structure orientation, so that the energy dissipated by these longer floors was larger. Taking the each of the factors above into consideration, **the predicted number of damaged core columns in the North Tower will vary between 4 and 12.** There will be an enormous difference between the ways in which the global collapse was initiated in both towers. Effect of the local damage on the global collapse of each tower is discussed next.

6. Comments on structural collapse

Until this point, the focus of this article has been the instantaneous damage incurred by the aircraft impact, which was localized within few floors of each tower. Yet, at the same time, the initial impact set the stage for the complex series of structural weakening and failures that finally led to a complete collapse of both towers. The manner in which these two stages of failure are related is the subject of extensive debate.

The following section in not intended to perform a full analysis of the global collapse but rather bring up few important issues relevant to the accident reconstruction. Two distinguishable schools of thought have emerged from such debate. These are

- Fire Dominated Theory
- Impact Dominated Theory

The first of these theories requires that prolonged, ultra high-temperature fire degraded the steel to such a point as to induce progressive failure from such a weakened state. By contrast, the second theory, which has been strongly supported by the analysis brought forth in this article, requires that the initial aircraft impact brought the building to the verge of instability. So close to this point, in fact, that only a small shift in loading or a minute decrease in structural strength would have resulted in the catastrophic collapse. In a brief discussion below, each of these theories is described in more detail.

6.1 Fire dominated collapse theory

While the majority of the paper only dealt with the instantaneous damage introduced by the aircraft impact, the effects produced by the secondary damage incurred by the fire deserve careful consideration. One cannot deny that the situation became much more serious on a structural level when energy was introduced in the form of burning jet fuel. The general idea is that the heat gradually affected the behavior of the remaining material after the impact, thus decreasing its elastic modulus, yield stress and increasing the deflections. This subject has been extensively covered via mass media, and one of the most important aspects of this argument is the observation that whatever fire protection the steel was prepared with, was shaken lose by the impact and thus unable to perform as designed. A jet-fueled fire is not what normal office fires are like and thus the safety systems may have been overcome considerably faster than expected. Our analysis does not deny these heat-induced contributions to the collapse, rather we fully agree that the fire effects played a large role in the deferred damage.

Yet, we do believe that the primary damage suffered by the South Tower via the initial impact alone was severe enough to bring it down with very little outside help. This is the point of view that has been given almost no attention or thought. At the same time, several arguments are introduced later in this article that support the theory that the North Tower collapse was facilitated by fire.

6.2 Initial damage dominated collapse

With respect to the impact dominated theory, the following issues, when assimilated into a cohesive failure theory, form this argument:

- Effect of Stress Concentration
- Initial Extent of Damage: as measured by the number of destroyed floors and columns
- The location of the damaged zone with respect to the axis of symmetry of the structural cross-sections
- The redundancy of the structural systems
- The safety factors which particular zones of the towers were designed for

We now proceed with a sequential discussion of the factors listed above.

Effect of stress concentration. The exterior column on each of the four sides of the building carry a uniform load in the vertical direction. This load increases from top down due to gravity. Consider a "control" section of several floors of the height l_o. The outer "facade" of a tower can be modeled as a plate strip under uniform compression. The so-called far field stress due to the weight of the portion of the building above is denoted by s .

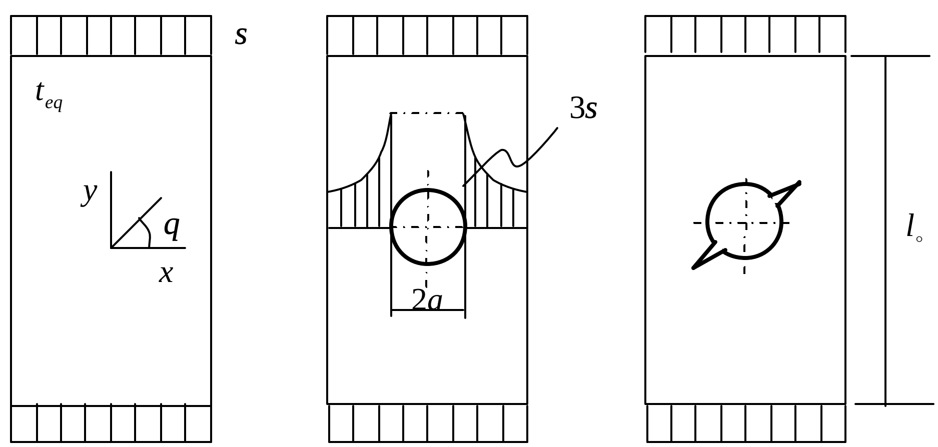


Figure 19. Stress concentration around a circular hole in a plate. Note that there is a stress singularity at the tip of any crack emanating from the hole.

Now imagine that a hole of radius a is driven into the center of the plate. The in-plane compressive stresses will be redistributed and will be concentrated near the hole. The exact elastic solution of this problem was worked out by Timoshenko [33]. The vertical component of the stress s_{yy} varies along x-axis according to

$$s_{yy} = s\left(1 + \frac{1}{2}\frac{a^2}{x^2} + \frac{3}{2}\frac{a^4}{x^2}\right) \qquad (19)$$

Denoting the maximum stress at the edge of the hole *x=0* by $\left(s_{yy}\right)_{\max}$, the stress concentration factor becomes $g = \left(s_{yy}\right)_{\max} / s = 3$. This suggests that the exterior columns adjacent to the hole could yield (or buckle) if the safety factor is less than three. We have extended the above result to the more general case of linearly variable compressive load due to gravity. The stress concentration now depends on the $\frac{l}{l_o}$ ratio (refer to Figure 20.)

$$g = \frac{3 + 1.65\frac{l}{2l_o}}{1 + \frac{l}{2l_o}} \qquad (20)$$

Taking a realistic value $\frac{l}{l_o} = 0.1$, the stress concentration factor reduces from 3 to 2.93. Thus, the variable gravity load will only reduce the stress concentration factor as compared to uniform load.

The hole driven in the outer facade by the airplane is not circular as smooth. In the next level of approximation it can be modeled by a circle with two symmetric cracks representing narrow cuts made by tips of the wings. Elastic fracture mechanics tell us that the stress concentration factor is infinitely larger at the crack tip but decays rapidly to a constant far-field value.

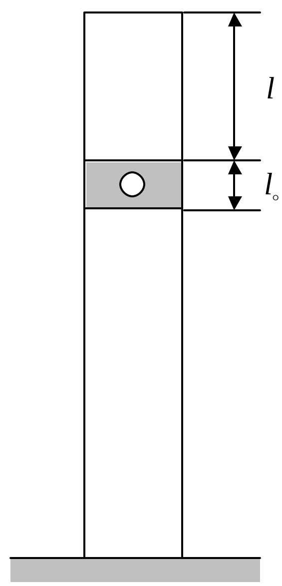


Figure 20. Stresses due to the dead weight will be concentrated around the hole

So why did the columns adjacent to the sharp edges of the hole not collapse instantaneously? This is because the assumption of the plane stress solutions are not satisfied by the grillage. The formulation of plane stress (thin plate) elastic problem requires that shear stresses be transmitted from section to section. This assumption is not met by the grillage-type external structure of the WTC Towers. The shear stiffness and strength of transverse plate strips welded to much heavier columns and bolted to adjacent, prefabricated sections is much smaller than the stiffness in the vertical direction. Therefore, local weakening in the form of a hole may not produce local stress concentration but rather more global redistribution of forces. We will therefore explore another limiting case in which shear resistance is removed altogether and the outer facade is assumed to be composed of a system of individual columns.

A limited modeling of the residual strength of the damaged façade was performed for the FEMA study (Chapter 2 in Ref.[1]). It was found that the safety factor of the exterior columns was an order of 5. However, this safety factor was reduced to unity for column at the edge of the aircraft produced hole. Therefore, the present closed-form solution is in fully agreement with the linear numerical analysis.

Initial extent of damage: The derivations of internal damage were taken purely from energy considerations, and thus, yielded only scalar representations of such damage expressed by the quantities of damaged floors and columns. For example, the number of damaged core columns, which bear approximately 60% of the entire gravity load of the building, was determined, in the previous section, to be 7 to 20 for the South tower. As the total number of core columns that existed was 44, these quantities represent more than 16% to 45% of the total core strength, respectively. Thus, is it correct to say that the remaining columns and load bearing members were immediately overloaded by a factor of 1.2 to 2.5? Well, this depends on the vectorial character of the impact and the zone which was effected. This brings us to the next issue.

Location of damaged zone: From the trajectory of the aircraft impacting the South Tower described in Figure 4. it is clear that the impacts of aircraft were not symmetric with respect to the centroids of the tower's cross-section. Both the outside columns and the inner columns were destroyed in asymmetric manners, and thus the locations of the centroid of the cross-section was shifted considerably. (See Figure 22 center) Therefore, an overturning moment, due to the gravity load, was immediately created, leading to non-uniform distribution of the load over the core and peripheral columns.

This situation is explained by a very simple, one-dimensional model of a mechanical system consisting of 3 columns, refer to Figure 21. In the intact state, the three columns are bearing equal loads of W/3 each. Two cases will be considered; one in which one of the member was entirely cut and the other one in which the same member is severely bent. If we remove F_2, that is weaken the structure symmetrically, then the load above it, W, uniformly redistributes itself and from force equilibrium, F_1 and F_3 are bearing equal loads of W/2 each, at the same time, moment equilibrium is satisfied identically. However, if we weaken the structure in an asymmetric manner, that is, remove F_1, then the force and moment equilibrium yield the following equations.

$$W + F_2 + F_3 = 0 \qquad (21)$$

$$F_2 H = WH \qquad (22)$$

where $2H$ is the width of the model.

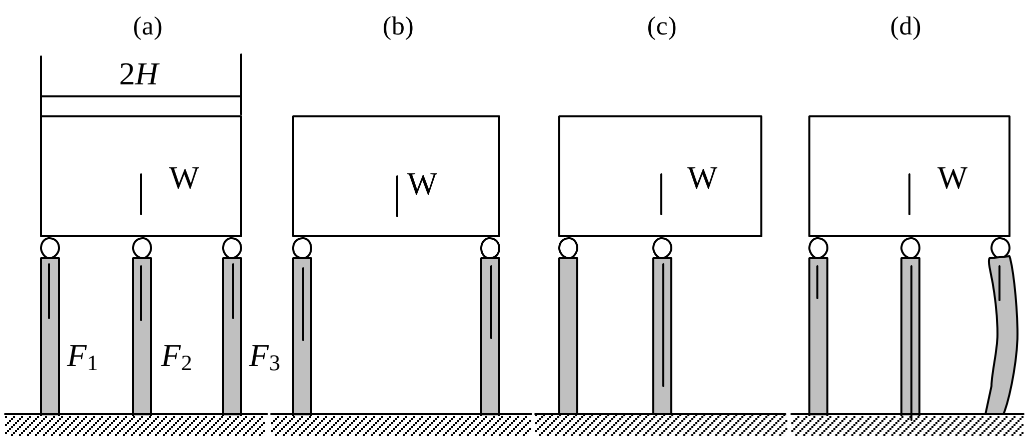


Figure 21. Simplified model of damaged eccentrically loaded system of column. Intact condition (a), center column removed (b), edge column removed (c) and edge column bent (d).

The solution of the above system is F_2 = W and F_3 = 0. This asymmetric loading situation yields an inactive load bearing section opposite of the missing columns while the central columns bear the entire load. The implication of this simple observation is that before damage the loading on each column was W/3. The symmetric damage causes the load to redistribute itself as W/2 (1.5 times its original load). Where as, the asymmetric damage causes the central column to bear the entire load, W (three times its original load). Now, we were trying to solve the second case in which the peripheral column is severely dented and bent rather than being cut. In this case, the column developed fully plastic tensile force $N = s_y A$, where A is the cross-section area of the core column. A new term will then appear in the force and moment equation above and the solution of this system is $F_1 = N$ (in tension), $F_2 = -W - 2N$ and $F_3 = N$. It can be concluded that denting of peripheral core columns will cause additional increase in the overload of the centrally located core columns.

This example is relatively concrete and holds regardless of initial assumptions. It can be generalized to fit most ideally to the realistic, 3-dimensional conditions of the impact zone. The above analysis brings us to one of the most important and interesting points of this entire article, that even though only 1/3 of the interior columns in each tower may have been destroyed, in fact, 2/3 of them were rendered inactive for bearing the dead-load above.

This example is easily generalized to encompass the actual conditions that existed in the WTC accident. A conceptual picture showing the area of active and inactive columns is shown in Figure 22. Following this generalization it is possible to graphically illustrate the location of the damaged, inactive and remaining, load-bearing columns (the shaded portions of the Figure 22) at the impact zone. In fact a photographic coverage of the onset of the global collapse (Figure 23) proves the upper part of the building tilted diagonally and felt on the low part.

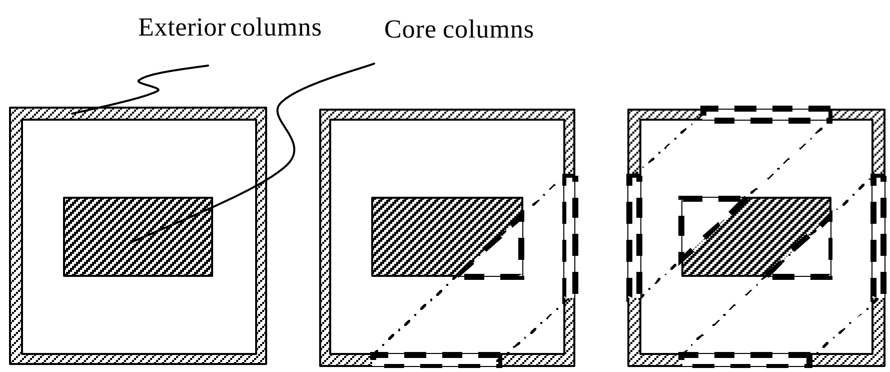


Figure 22. Conceptual sketch of the cross-section of the tower showing vertical members (left). Asymmetric damage (South Tower) removes a portion of exterior and core columns (center). Columns at mirror reflection becomes immediately inactive (right).

Figure 23. Few first seconds into the global destruction of the South Tower

Redundancy: Finally, it would be interesting to determine to what extent structural redundancy would diminish the effects of the centralized overstressing condition, which develops from asymmetric damage. The redundancy is the ability of a structure to redistribute loads around the damaged area so that one missing component will not cause global collapse of the entire system. Several lessons learned from accidents with bridges and offshore structures[1] have led to robust design of man-made structures within a large degree of redundancy.

In the case of the WTC Towers, the exact redundancy analysis would necessitate construction of a complex three-dimensional model of inner and outer tubes with continuing columns and bracing floor. Such an analysis should be performed by individuals or teams in possession of detailed structural models.

A "unique" feature of the design of the Towers was that floors were hinge-supported to the exterior columns and core structures, [1]. At the same time, shear and tensile strength of this joint was inadequate, probably an order of magnitude smaller than the local strength of members being joined.

A dramatic proof of the above statement is offered by the photograph showing large sections of the exterior wall in a free fall. No residual elements of floor truss structure could be seen attached to these sections.

What would happen if the pin-support were replaced by a built-in (welded) joint (moment connection)? An elementary beam analysis tells us that the stiffness and elastic deflection of floor beams, loaded by their own weight, be reduced by a factor of two or more. Thus, adding structural redundancy by changing the method of floor truss support will reduce or delay sagging of floor caused by fire.

[1] The Alexander Killian rig underwent a progressive collapse originated from just one failed member, causing 77 deaths.

Figure 24. Prefabricated columns of the exterior wall falling to the ground completely detached from the floor structure.

What would happen if the tensile and shear strength of joints were increased by a factor of two, four, or ten? Then, the floors will keep effectively bracing inner and outer tubes, increasing the buckling strength of exterior and interior columns. Can our analysis tell what happened first: sagging of floors, which led to the detachment of floors from columns causing them to buckle, or buckling of columns causing floors to detach and fall onto one another. We think that either can be true. The impact and, thus, the damage to the North Tower were symmetric. Also, the number of destroyed core columns was fewer. It would then appear that because there was no tilting of the building, the catastrophic collapse was initiated by each floor falling into the next. This scenario would require a more prolonged effect of fire to weaken the floor trusses, which was indeed the case. The North Tower survived the initial impact for 50 minutes longer than the South Tower and then imploded.

6. Conclusions

The analysis presented in this article has quantified the amount of damage to the main structural members of the World Trade Center Towers. These numbers have been generated with the warning that they are based on assumptions and models, which had to be made because of the vast lack of exact facts, dimensions, and general calculation methods for this class of problem. There was a lack of data in two main areas. One is the plastic deformation, structural damage, crack initiation and fracture propagation in the problem of a high velocity collision of two thin-walled structures with comparable mass and strength. Research recently completed in the Impact and Crashworthiness Lab at MIT has already clarified some important issues [2, 13-15]. A sample of interesting numerical analysis of a rigid wing cutting through plastic deforming and fracturing of exterior column. The above analytical and numerical solutions are currently available as technical reports of the Impact and Crashworthiness Lab. Publication in professional journals will follow soon. The second difficulty, which arose with respect to a lack of data, was overcome by the generality of our analysis, in which closed-form solution were derived for an entire class of structures, without the necessity of substituting exact geometric and material properties. A great deal of effort was put into retrieving the most accurate set of data available to the general public. As soon as more precise information on cross-sectional shapes and dimensions, joining metals (strengths of weldments) etc. become available, we will be able to quickly reevaluate our calculations and introduce corrections to our results.

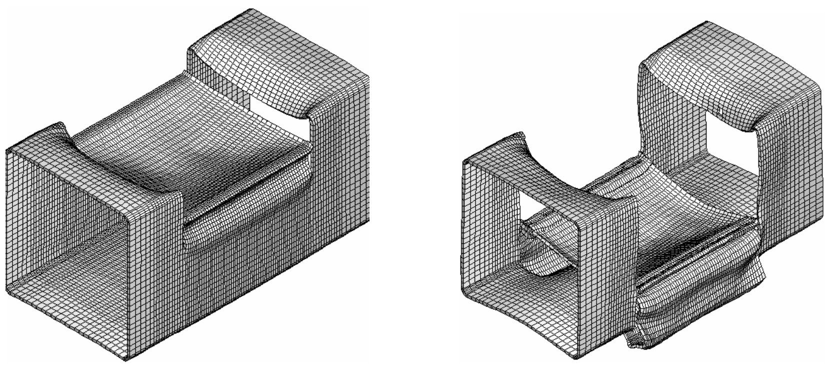


Figure 25. The problem of rigid mass (representing airplane wing) cutting through the exterior column has been solved numerically by Zheng and Wierzbicki [13].

While the extent of damage to the exterior is clearly visible, and the number of damaged floors is also easily estimated from an external perspective, the damage to the 'invisible' interior columns has, until know, remained a mystery. Given the amount of information that was available to us from the information unclassified sources, we conclude with the estimate that 7 to 20 core columns of the South Tower were destroyed upon impact.

Another interesting finding from this article stems from the consideration of safety factor and redundancy. The issue of symmetric versus asymmetric loading is an important one because unsymmetrical damage, i.e. the WTC towers, could be far more devastating in the global collapse scheme because the number of inactive columns is actually double the amount that were actually destroyed, while the amount of remaining, load carrying columns is reduced accordingly. Depending on the safety factor for which the towers were constructed, we have proven that the airplane impacts were able to bring the structures to the verge of collapse.

The prediction of the aircraft impact damage is summarized in table 3 showing the magnitude of energy dissipated by four major components involved in the collision, that is the airplane, exterior columns, floors, and core columns. Separate numbers are given for the North and South towers. The number of percentage of energy dissipated relative to the total available kinetic energy is given as well.

There were a number of factors that were not included in our analysis. For example the energy released through the explosion of jet fuel was not considered. Additionally, the effects of material and structural degradation as a result of the fires themselves were also not studied because these areas have been so extensively covered by others. Next, there has been no information on the average fragmented fuselage size, so there is no way to exactly determine the amount of fracture energy which was dissipated in the breakup of the aircraft itself. We did however, include the energy required to crush the fuselage, modeled as thin-walled cylinder and the energy to shatter wings. Finally, damage of exterior columns that were pre-stressed by the gravity load would have occurred in an explosive manner, sending around large amplitude unloading waves that could additionally weaken the structure [34]. These and many other aspects of the accident reconstruction will be brought up in future analyses of the problem.

Table 3. Distribution of energy lost in the local damage of the TWC Towers
The energy is in the unit of MJ.

Energy (MJ)	**North**		**South**	
Airplane	586	23%	586	25%
Exterior	103	4%	122	3%
Floors	1221	48%	1925	53%
Core columns	630	25%	1025	28%
Total	2540	100%	3658	100%

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The Fires

Ahmed F. Ghoniem
Professor of Mechanical Engineering
Massachusetts Institute of Technology

Abstract

Qualitative and semi-quantitative analyses presented in this article suggest that the massive fires caused by the crash of the planes into the World Trade Center Towers and the spillage of large amounts of jet fuel inside the buildings played a major role in their quick collapse on September 11, 2001. It is argued that the WTC fires, while unprecedented in form, magnitude and extent, resembled massive compartments fires in which the primary fuel —the jet fuel— spilled over a large area, ignited almost immediately, supported the formation of huge fireballs that extended outside the crash zones, and triggered very large-scale secondary fires that engulfed all available combustibles contained within the floors surrounding the impact area. These *post-flashover* fires, which sent thick smoke plumes a long distance downwind over lower Manhattan's previously cloudless skies, continued to burn long after the catastrophic collapse of the buildings. The analysis presented in this article relies on models of compartment fires to estimate the burn rate and the resulting fire and structure temperatures, incorporating rational assessment of the crash damage on the exterior and the interior of the Towers that were created by the plane impact. Using these models, scenarios for the fires during their different stages are developed, and approximate rates of overall heat release and the prevailing temperature history within the buildings are obtained. It is shown that the fire power, measured in terms of total heat release rate, was of the order of gigawatts, the fire temperatures may have exceeded 1000° C, and the structural steel elements attained dangerously high temperatures for an extended period of time. While these estimates are approximate and preliminary, they remain relatively unchanged when varying some of the assumptions and numbers used to define the burning conditions over ranges supported by available data, and confirm the assertion that the fired played a major detrimental role in the quick collapse of the Towers on that tragic day.

1. Introduction and preliminaries

On September 11, 2001, two Boeing 767-200 planes were deliberately crashed by terrorist onto the World Trade Center towers. The planes pierced through the exterior walls, immediately disintegrated, spilling huge quantities of jet fuel, and igniting massive fires that engulfed various floors and set the combustible office materials ablaze. These unprecedented fires, and the associated dense smoke plumes that results almost immediately after the crash, were visible many miles away from the disaster site, and are well documented in video footages. The role these fires played in the quick collapse of the two Towers has been the subject of much debate and some preliminary studies[1]. Much of the confusion in the early assessments regarding the importance of the fires in the WTC collapse stemmed from the enormous complexity of this event, the lack of studies of fires of similar scale, and the scarcity of data from the accident itself. Most importantly, the difficulty in applying existing standards to classify the fires, and the absence of partial, let alone full-scale models that can be used to quantify its impact on the structures, had opened the door for arbitrary interpretation and speculation. This is likely to continue until careful scientific studies are conducted.

Indeed, when attempting to elucidate the causal relationship between the fires and the collapse of the buildings, it is very important to first develop as complete a fire scenario as possible. Such a scenario should describe the different stages of the event, quantify the corresponding fire phenomena in each of these stages, and utilize both to estimate the burn rate and local temperatures and their dependence on the conditions that prevailed during the fires. These conditions include the amount of flammable materials available —both the jet fuel as well as other combustibles, such as furniture— the ventilation, the volume and surface area of the compartment where the fire raged, the outside wind conditions, etc. The conditions are strongly dependent on crash analysis and structure failure studies, and on careful examination of the video images that have been collected during the accident. Since the fire must have contributed to the structure failure, there is also tight coupling between fire progression and the building collapse, and a detailed model studying the interaction between the two should be incorporated. In the interim, one must rely on approximate estimates of the conditions to assess the fire impact.

Many fire models are available, including pool fires, fire plumes, compartment fire models, etc. [2,3], which could be used to describe some elements and stages of the fires in question. For instance, fire plume transport models could be used to back out the heat release rates near and around the crash site, given the smoke plume trajectory that have been recoded in video images [4,5]. Moreover, other fire dynamic models could be used to confirm these data by carefully observing the fire dynamics in the immediate proximity to the fuel zone [6,7]. Such studies could be very useful and insightful, and should be conducted. However, given the overall conditions of the WTC fires, the interest in assessing its impact on the structure of the Towers and their role in the tragic and quick collapse of the buildings, *compartment fire models* are chosen here. In compartment fires, fuel is spilled inside an enclosure, which initiates a fire that may or may not remain contained inside the compartment. These models have been used before, and will be applied here to obtain approximate estimates of the fire intensity, the burning rate, the fire temperature, and the temperature history of the structural elements in the WTC fires. To apply these models, the following preliminary data on the size of the WTC buildings, the crash location and the planes shall be used.

The dimensions of the South Tower were 63.5×63.5 meters on the sides, and 411.5 m in height. The North Tower was virtually identical to the South Tower, except that it was slightly taller. Both towers had 110 stories, and hence their inter-story height was about 3.75 m. The exterior of each tower was made of a dense lattice of prefabricated steel columns, while the $24\text{m} \times 42\text{m}$ interior core consisted of 48 steel columns fireproofed in concrete.

[1] Some careful studies are also being conducted, however their results were not available at the time of writing this paper [1].

The external dimensions of a Boeing 767-200 plane are 15.8 × 47.5 × 48.5 meters in height, width and length, respectively, the first two of which are measured at the tail and the wingspan. These data provide approximate numbers for estimating the size of the initial hole in the exterior steel shell of the building that was created by the crash, and the initial volume of the cavity within the tower, which resulted from the crash and very early local collapses inside each tower, where the fire started.

The takeoff weight of a fully loaded Boeing 767-200 plane is approximately 178,000 kg, and is able to carry a maximum fuel volume of some 90 m^3. The approximate density of jet fuel is 800 kg/m^3. Thus, the total maximum fuel weight is about 72,000 kg — almost half of the plane weight at take-off — and the plane's takeoff weight without fuel is 106,000 kg. It is known, however, that the two planes were only partly loaded with passengers. In addition, government sources indicate that the typical fuel loads for these types of aircraft when flying coast to coast is some 45 m^3 (12,000 gallons). When this information is considered, along with the estimations on the amount of fuel burned between the planes' departure from Boston to their arrival in New York (about 8 m^3), one concludes that the fuel tanks at the moment of impact may have been no more than 42% full (37 m^3), and that the planes must have weighed some 136,000 kg each. A substantial portion of the fuel got burned in the initial fireball on the exterior, which suggests that the fuel volume that was ignited in the interior of the towers may have been on the order of 25 m^3, or about 20,000 kg. It should be remembered, however, that the initial fireball contributed to the heating of the building and the ignition of some of its flammable material.

The enthalpy of reaction of the fuel, that is the heat generated as the fuel is burned under stoichiometric conditions in air, is almost 45 MJ/kg of fuel. Thus, for a plane fueled to capacity (72,000 kg), the total heat load — the heat generated if all the fuel is burned — is a staggering 3,240 GJ (giga-Joules). Burning this fuel continuously over a period of almost an hour, this energy generates a power of almost one gigawatt, equivalent to the power of a large conventional or nuclear power plant. A small fraction of this power is indeed capable of causing enormous damage if unleashed close to a building.

The rest of this article defines a compartment fire in its different stages, proposes the use of models of compartment fires to estimate qualitatively and at times quantitatively the conditions of the WTC infernos, and discusses the impact of a fire on the enclosing structure and the mechanisms by which the damage is incurred. The numbers required for that purpose are estimated using publicly available data on the planes, the buildings and the dependence of compartment fires on the fuel and the enclosure. Some detailed review of the dependence of burn rate of compartment fires on the conditions is included, and more detail regarding how to estimate the fire and the structure temperatures are then presented. The article relies heavily on material in Refs [2,3], and references therein.

2. Effects of a fire on a structure, and its contribution to failure

It is well known that fires affect the structural integrity of buildings in several ways, including:

i. Direct engulfment and rapid consumption of flammable building materials of relatively low ignition temperatures, including furniture, etc. If some of these materials are used as load bearing elements, a rapid collapse ensues.

ii. Intense heating of structural elements with high ignition or break down temperatures, through heat flux generated by both the flaming materials and the hot combustion products. In the case of structural steel members, this progressive heating leads to significant losses of stiffness and strength, and ultimately to failure. In concrete elements, such as floors, the intense heat induces surface spalling caused by the uneven heat expansion, vaporization of the interstitial water, dehydration and degradation of the cement paste, and chemical changes affecting the strength of the concrete.

It is reasonable to assume that both factors played important roles in the WTC collapse. The exterior steel lattice was exposed to direct contact with the initial and massive fireball that must have consumed a substantial fraction of the available jet fuel, as was clearly observed in the video footage. This initial fireball must have resulted form the burning of some of the fuel spilled following the impact, close to the collision area at the exterior walls. During the burning of the fireball, a large heat flux generated by the hot, jet-fuel-combustion products was directed toward the exterior and interior load bearing steel elements.

Direct contact between the fire and the structures produces the worst damage, because it leads to a fast rate of temperature rise and rapid softening of the steel. This is a likely scenario for the fate of the exterior lattice of the WTC, which was exposed to the initial fireball and to the subsequent interior fires (evidence of some melting of steel has been reported from careful analysis of the video footage). Direct contact also damages the insulation material used to protect the metal-based structural elements, making them more vulnerable to the intense heat. In this case, the temperature in the structural elements continues to rise even without direct flame contact, albeit at a somewhat slower rate. This is the case, because under the high temperatures prevailing in fires, both the heat fluxes due to radiation and convection cause the temperatures of the structural elements to rise continuously. Loss of insulation leads to rapid breakdown of the heat transfer resistance in the structural material and thus causes these insulation-deprived elements to experience a dangerous rise in temperature. Slender elements with high surface to volume ratios, like trusses, are more vulnerable to this effect than more massive elements, such as wide flange (or box) beams and columns.

Persistent flames can also damage structural elements normally utilized to contain the fire within one compartment, such as doors, windows, floors and ceilings. When this occurs, the fire invades neighboring compartments and expands its overall size. Thus, the collapse of the containing elements allows the fire to extend its reach far beyond its original location, and causes radiative heat fluxes to travel further within the structure. Moreover, in terms of the damage caused by a fire, not only is the maximum fire temperature important, but also the length of time that the temperature remains at or close to this value, because the prolonged heating increases the exposure of the structure. As will be seen later, the combination of a high fuel load (fuel mass per unit area) and good ventilation through holes in the exterior walls or broken windows (either natural or caused by fire damage) allow fires to burn for tens of minutes at temperatures close to, or even above 1000°C. In the case of the WTC fires, the initial massive crash created large ventilation openings on the sides of the towers that fed the fuel inside the building with sufficient air to burn fast and steadily for tens of minutes. Meanwhile, the collapse of several floors caused by the aircraft impact together with the domino effect of falling rubble accumulating on the lower floors, allowed an initial compartment to be formed that supported the early stages of the fires. As more floors became weakened and failed, the size and reach of the compartment extended, and as both got heated by the surrounding fireball, the fuel density within that compartment increased.

The total heat flux generated by a fire depends strongly on its temperature, and to some extent, on the gas motion it induces. Strong rising plumes carrying hot combustion products and some unburned fuels can be seen in all large fires. These plumes induce strong drafts towards the fire source that further enhance its ventilation. To determine the gas temperature, one must know the heat release rate, which is the rate of burning times the heat release per unit mass. Hydrocarbon fuels, such as jet fuels, and other combustibles such as building materials and furniture, have different burning rates and heat release rates, and hence produce different intensity fires. In a strong fire, it is very likely that all available material is readily turned into fuel, that is heat producing element, upon combustion, as the temperature exceeds their ignition temperature, no matter how high it is.

It is useful to distinguish between a primary fuel, which starts the fire, and a secondary fuel, which participates in the fire at a latter stage. In the WTC case, the jet fuel acted as the primary fuel, while the furniture and building material was the secondary fuel. Some of the plane material also contributed to the available combustibles. The crash must also have "snowplowed" some of this material within a relative small volume, which increased the fuel load within that volume.

3. Compartment fires: a detailed account

A *compartment fire* is defined as the fire resulting from the ignition of a fuel contained within an enclosure, normally as a result of a liquid fuel spill or solid fuel spread on the floor of the compartment, which is ventilated through wall openings [2,3]. The growth of these fires occurs in two phases, namely *pre-flashover* during which only the original fuel is burning and the fire is localized close to the primary fuel source, and *post-flashover*, during which all combustible items within the enclosure are engulfed in flames, and the fire is thought to be fully developed. Failure to escape during the first phase often leads to death as the temperature increases substantially near the ground during the post-flashover phase. Flames spilling outside lateral openings are often observed during the latter phase as some of the combustible volatiles can not find enough air inside the compartment to burn completely, and get carried out by the hot buoyant products into the cooler environment outside. With enough primary fuel in the enclosure, transition between the two phases occurs faster than the time it takes for the fully developed fire to decay. One can argue that the initial fireball seen following the plane crash into the WTC resulted form the jet fuel sloshing outside through the crash hole and broken windows, and supported latter by evaporation of fuel spilled inside.

Severe building and structural damage occurs during the latter period of a fire when the flames literally engulf the entire structure. At this stage, the heat release rate, the gas temperature and the heat flux to the structural components reach their maximum. Direct contact with the flames may cause failure of the structural barriers designed to limit the spread of the fire and hence expand the enflamed area. Direct contact also damages the insulation of the structural elements, such as steel, and hence exposes these elements to higher temperatures. At the beginning of a fire, higher temperatures occur close to the ceilings due to the strong buoyancy of the combustion products—this is why fire detectors are installed at the ceilings—and there is a chance for the occupants to escape. However, as flashover is approached, these high temperatures penetrate downwards and reach the floors as a result of the strong radiation fluxes from the ceiling and the accumulation of the hot combustion products. Factors affecting the time to transition and the burn rate during post-flashover will be discussed later.

To model the WTC fire as a compartment fire, it is necessary to estimate the area and height of the compartment within which most of the early burning took place, the area and height of the lateral openings that exposed the compartment to the outside, the fuel load within the compartment and how far it spread upon impact, the floor area of the compartment, and its total wall area. Moreover, the time history of all these quantities, following the initial impact and the onset of the series of events leading to the collapse, need to be estimated and introduced into the analysis. Clearly, it is very difficult to come up with accurate estimates for these quantities, not only because they are hard to quantify, but also because in all likelihood they evolved with time in ways that would require careful consideration of the coupling between the fire and structural analysis[2]. However, as will be shown in later sections, to arrive at a qualitative picture, one needs only rough estimates. Moreover, most of the models available for analysis are empirical and apply only approximately to the case in hand since they were derived for smaller scale compartment fires. Such initial estimates can then be used as the starting point to more comprehensive analyses in the future.

Based on the wing span as well as the height and width of the fuselage of a Boeing 767-200 plane, we estimate that as the plane hit the tower, it must have created an hole of approximate dimensions of 50m $\times$ 20m, given that the planes hit while banking at an angle with respect to the horizontal plane. Furthermore, the size of the initial compartment inside the tower, created by the severe collision, is estimated to have been 20m high, and covering almost two thirds of the available floor area of the tower, from the outer lattice to the inner core. This is based on the assumption that several floors were damaged by the collision, and the observation that debris were seen flying out of the side opposite to where the plane pierced through the tower. Thus, the initial area of damage is estimated to be about 2000 m^2, or about half of the floor space of the building between the external lattice and the concrete core, and fuel spillage must have occurred over a fraction of this area. We will use these numbers to estimate the temperature inside the tower during the fully developed stage of the fire, based on available models for the dependence of the burn rate in compartment fire on the fuel area, the opening areas, the surface area of the compartment, and other factors described next.

4. Fire stages in compartments

4.1. Initiation

Compartment fires begin at the ignition source, which is located near the primary fuel source, and consume the nearby fuel, initially at a relatively low rate. That defines the pre-flashover stage. Transition from pre- to post- flashover or fully-developed fire occurs as the heat generated by the primary fuel raises the temperature of the rest of the available combustibles to their ignition temperatures, causing them to ignite and participate in the burning. As heat is radiated and convected to the elements walls, structural elements and furniture, depending on their properties, may either ignite directly or pyrolyze first, in which case they give out volatile combustible materials able to burn at a fast rate. Confinement may cause the transition to fully developed conditions, or speed it up substantially because heat is not allowed to escape, and instead both the heat and the combustible material are trapped within the compartment.

When the primary or original fuel is available in large quantities, such as in the WTC case, the first flames inside the compartment are long enough to touch the ceilings and directly heat other combustibles, thus accelerating the transition to flashover. Indeed, much higher burn rates, up to almost an order of magnitude higher in case of hydrocarbon fuels, have been observed in the presence of ceilings. Flames touching the ceiling lead to structural failure, which in turn expands the burn area by increasing the fire intensity. During the pre-flashover stage, fires are mostly ventilation-limited since there is normally plenty of fuel but air is in short supply through the ventilation opening. This, however, mostly reverses as the fire transitions to post-flashover.

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[2] A time-dependent computational crash analysis, followed by a computational fluid dynamics analysis of the fires, which is carefully interfaced with a structural analysis code that accounts for the change in the material properties as it gets heated and/or inflamed, could offer insight and possibly a predictive tool to analyze this and similar problems. This, however is an extremely demanding computational effort.

The observation of a massive fireball outside the WTC Towers soon after the crash may be used to determine that the fires never really existed in a pre-flashover state, as the high momentum jet fuel spilling and sloshing around, following the impact, ignited both inside and outside the building, and continued to burn as long as more fuel evaporated, escaped and supported the fire ball. The contribution of this fireball to the heating of the steel elements on the outside lattice structure can not be ignored, as evidence of some steel melting was suggested by the photographs.

4.2. Transition and post-flashover

Studies suggest that the time needed for transition from localized fires, to post-flashover, fully engulfed fires is shorter for:

i. Enclosures that are well insulated where heat is trapped within small volumes.
ii. In the presence of large fuel loads, defined as total mass of fuel per unit area.
iii. When fuel is spread out uniformly over large areas, increasing the access of air.

These studies also suggest that the growth of the burn rate during this phase is proportional to $(t - t_0)^2$, where t is the current time and t_0 is an incubation period or pre-ignition delay, which must be considered in the absence of an ignition source. The conditions or criteria for transition suggested are either one of the following:

i. Heat flux of 20 KW/m^2 reaching the floor, or
ii. 500-600 °C ceiling temperature.

Given the burning intensity of jet fuel, the high fuel load resulting from the spill of the aircraft fuel in the WTC Towers, and the likelihood that this fuel did spread out widely as a result of the strong impact following the crash, the pre-flashover stage must have lasted a very short period, perhaps no more than few minutes. In the very early moments following the crash, no external flames were visible, instead very large thick smoke plumes followed by the ignition of the fireball. This could have happened because the opening created by the plane crash into the tower exterior was large, the amount of jet fuel and its density were such that the fires were indeed under-ventilated. It should also be mentioned that the massive impact must have acted as a distributed ignition source that set the jet fuel on fire almost immediately, let alone the heat generated as some of the kinetic energy of the plane was dissipated as heat (part of the plane's momentum was transferred to the building as vibrational energy). The hot engines themselves could have acted as powerful ignition sources, placed as they were very close to the jet fuel tanks. It can conservatively be estimated that in the early stages, the burning jet fuel generated at fire power of the order of megawatts, which must have made the transition to fully developed fire very fast indeed. These estimates are based on using 1% of the original fuel, deposited within the initial compartment whose dimensions were estimated as above, and burning at 20% efficiency (that is only 20 % of the available heat in the fuel is released during combustion) due to the lack of sufficient air [2].

5. Severity of fully-developed fires

5.1 Burning Rate

Conditions following the plane crash into the WTC Towers must have lead to fast transition to a post-flashover fire in the interior of the building, supported by or accompanied with a sustained fireball on the exterior of the building that contributed to the fast rise in the temperature of the material inside. It is important to attempt to estimate the burn rate inside the building and the concomitant temperatures, including that of the fire and the building material. For this purpose, we review some models for compartment fires, and use them in the quantitative analysis.

Experimental evidence suggests that the rate of burning in ventilation-controlled fires, both during the pre- and post-flashover, is proportional to the ventilation parameter $A_w\sqrt{H}$, where A_w is the *window* or opening area that exposes the fuel to a continuous supply of external air, and H is the height of this window above the floor where the original fuel pool existed. Flashover, during which full engulfment is observed, occurs only when this parameter exceeds a critical value. Following flashover, all combustibles participate in the burning and heat release process, and a much faster growth of the fire and a heat release rate are observed. This is due to two factors:

i. More material burns within the original compartment, including both the primary fuel and other combustibles available in the same area, e.g., furniture, supplies, structural material, etc.
ii. The failure of fire-confining elements, such as walls, doors and floors/ceilings, and the spread of the fire from the original compartment to neighboring space creating additional exposure to the outside and thus a bigger supply of air.

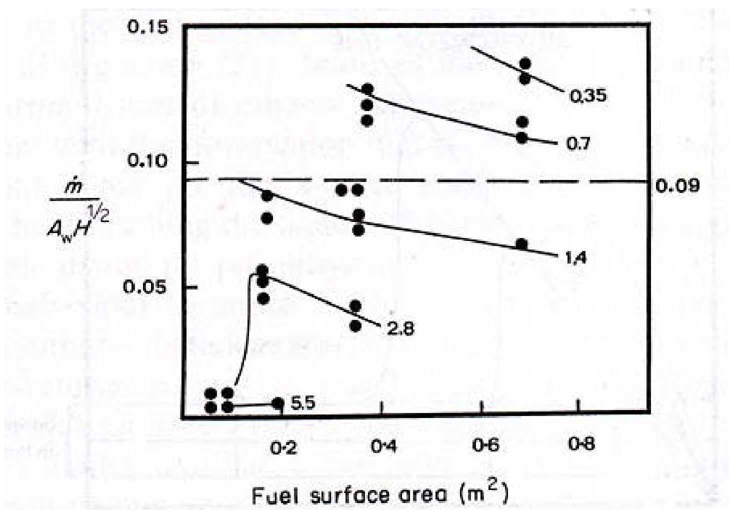

Fig. 1: Dependence of burn rate of ethanol pool fire in a small compartment on the opening parameter $A_W\sqrt{H}\,/\,A_f$ (values shown on individual curves) and the fuel surface area. Reproduced with permission from [2]

Figure 1 shows some experimental correlations for the dependence of the burn rate on the fuel surface area and the opening parameters (the ventilation parameter normalized by the fuel surface area) [2,8]. These data show how increasing the opening parameter, in the case of a large opening, positioned high with respect to the fuel pool, can impact the burning rate. The data are shown only for illustration, and will next be extrapolated to estimate the burn rate in the WTC fires (note that the burning rate itself is normalized by the opening parameter).

In the WTC fires, the direct damage done by the plane must have created an interior compartment of several floors in height where the fire started. The size of this compartment depends on the momentum of the aircraft, the vertical and horizontal angles of impact, the elevation where the plane hit, the resistance of the columns and floors to the collision, and the progressive failure of structural elements caused by the fire. It is estimated that the initial height of the compartment could have been about five stories high, based on the size of the plane and its momentum. Damage to the ceilings and floors caused by the early fires must have expanded that volume quickly, both above and below the collision area. Jet fuel must also have flowed downward through building openings, which then contributed to the propagation of the fire to lower elevations. The expansion of the burning area must have continued downward as collapsing floors applied heavier loads onto the floors underneath. Thus, it is estimated that the height of the post-crash compartment could have been 20m.

The opening in the exterior wall, through which the plane sliced into the building, can conservatively be estimated to have been 20m high and 50m wide. The external steel lattice was probably strong enough at the moment of impact that it minimized the size of this external hole. It is more difficult to estimate the extent of the interior compartment, but it may well have been comparable to the floor area facing the crash opening, which is approximately 2000 m^2. The jet fuel must have spilled over a major part of this floor area, perhaps 25-50% of it. The opening parameter defined in Fig. 1, namely $A_w\sqrt{H}/A_f$, is thus in the range of 2 – 5, where A_f is the fuel surface area. From these numbers, the total surface area of the compartment would have been approximately 10,000m^2. This is only valid immediately after the crash, as subsequent collapse must have resulted in a continuing growth of the compartment area. In the light of this very large fuel surface area, it is clear that the WTC fire parameters far exceed the ranges of prior experimental data. Thus, extrapolation of available burn rates vs. compartment size are necessary.

Performing the requisite extrapolations (in consistent units) on the curves depicted in Fig. 1, we obtain $\dot{m}/A_w\sqrt{H}$. Note that the burning rate is estimated by extrapolation of the available correlations for a different fuel, namely ethanol. The lower estimate for the fuel-mass burning rate in the WTC is thus about 50 kg/s, which leads to a heat power release rate of almost 1 - 2 gigawatts. This number is close to that estimated crudely at the beginning of this article, one the basis of the total amount of available fuel, its heat of combustion, and the overall burn time. These model based predictions are less dependent on the amount of fuel, and do not use the observed burn time.

Attempts to sharpen these fuel burn rate estimates on the basis of other experimental data are shown next, using data that were obtained from alternate experiments and physical modeling assumptions. These data cover a wider range of physical parameters than what was shown before, and hence may be somewhat more reliable. Nevertheless, they still show strong dependence of the burning rate on the opening or ventilation parameters, the fuel surface area, and the total surface area of the compartment. The model shows that the burning rate depends strongly on:

i. The fuel load, defined as the mass of combustibles, especially the primary fuel, per unit area of the total floor. In the case of the WTC fire, the mass of combustibles must also include the combustible plane materials and the building materials in the immediate vicinity of the plane crash.

ii. The fuel type, with hydrocarbons burning more intensely due to their higher volatility (see Fig. 2, and Refs [2,9]). Jet fuels are hydrocarbons capable of intense burning with high heating values.

iii. The fuel surface area, and how far it is spread horizontally following the initiation of the fires. The spillage of the fuel inside the Towers following the crash must have created an opportunity for a widespread distribution of the jet fuel.

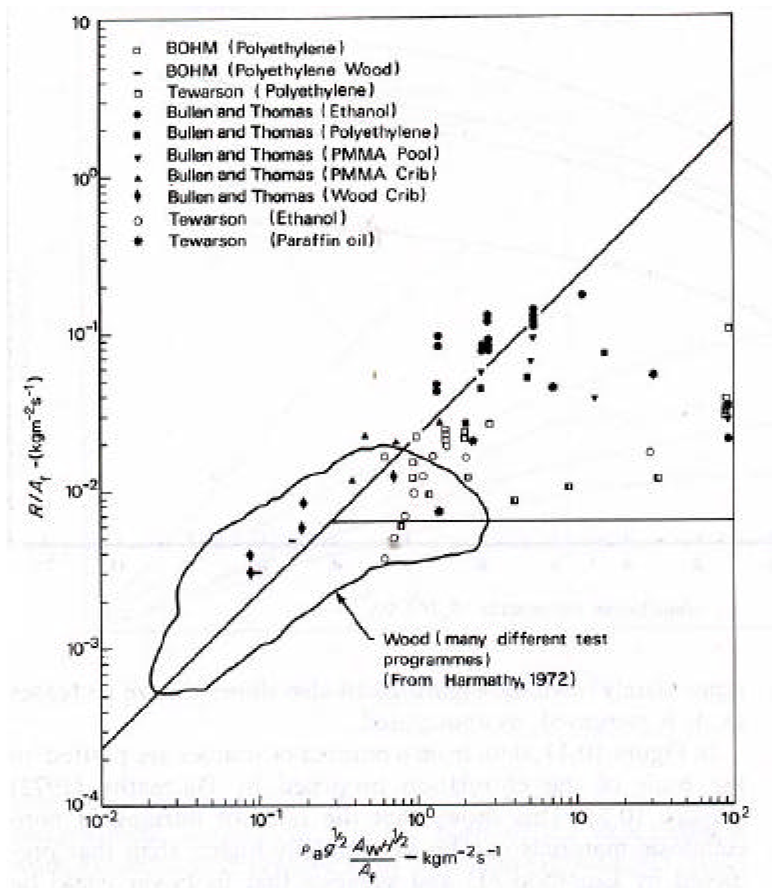

Fig. 2: Compartment fire burn rate for different fuels. While a wide scatter is exhibited, reasonable correlations are observed above the horizontal line close to the classical scaling). Reproduced with permission from [2].

Data obtained from experimental measurements and analytical models have been assembled in the fire science and engineering literature. A sample of accepted data collected from many sources is shown in Fig. 2 [2]. The impact of fuel type, characterized by the heat of combustion and heat of evaporation, on the burning rate has also been delineated in various studies, showing less than an order of magnitude variation in the burn rate as the evaporation rate of the liquid fuel varies by a factor of almost five. Perhaps not as important, but nevertheless strongly present in these empirical correlations, is the dependence on the shape of the compartment and its overall internal dimensions. The strong dependence of the burn rate on the ventilation factor ceases as $A_w\sqrt{H}$ reaches a critical value, at which point sufficient air is available to burn the available fuel and the fire becomes fuel-controlled. In the WTC, this was probably the case during most of the burning time, because: (i) more destruction to the external steel shell resulted from the post-crash damage and the early fires thus by increasing the fuel available, and (ii) larger values for the opening parameter were achieved.

Because of the complexity of the problem posed by the WTC fires together with the scarcity of data available at the moment of this writing, it is difficult to estimate with much accuracy the parameters needed for the empirical models of compartment fires referred to previously. Moreover, these numbers change with time between the moment of the crash of the aircraft into the building and the beginning of their collapse. However, one may roughly assume that the compartment created by the initial impact is several times the volume of a 767-200 plane, and that the compartment's horizontal footprint spreads over a substantial fraction of the building cross section. The plane pierced through the building at an angle, and hence it is conceivable that the initial cavity created within the tower may have been about five plane heights, while the opening created on the external lattice in all likelihood was comparable to the plane height. Using these estimates, the more elaborate definition of the opening parameters in Fig. 2 has a value in the range of 6 - 15. The numbers obtained from this figure indicate that the burning rate may have been in the range 10-100 kg/s (please note the logarithmic scale). By contrast, in our earlier analysis we obtained nearly 50 kg/s, which falls almost half way between the two new limits on the burning rate. Given the different sources for the two empirical correlations, the agreement between the different estimates is reassuring.

5.2. Fire temperature history: how hot did it get?

The temperature history of a compartment fire, including its spatial variation as well as duration, plays a very important role in determining the structural damage caused by fire. Ultimately, when assessing the impact of a fire, we are interested in how hot the structural elements, including walls, windows, beams, etc., get as a result of the burning of the surroundings, even when the elements themselves are not combustible. A sense of these values can be obtained from Fig. 3, where a compilation of the steady-state temperature of the environment due to a fire inside the compartment, is shown as a function of the previously defined opening factor [2,10]. While the data in this figure were compiled for the burning of wood, they are applicable to other fuels with similar burning characteristics, such as hydrocarbons.

The fire temperature, measured in close proximity to the flames depends on factors similar to those controlling the burn rate, namely:

i. The ventilation or opening parameter, which controls the supply of air to the fuel inside the compartment and the local stoichiometry of the fire.
ii. The primary fuel area, which defines the extent of the fires, at least in its early stages, and total exposed area in the compartment, as defined by the walls, which determines the maximum volumes of the flame before walls are damaged.
iii. The fuel type, as characterized by the heat of evaporation/volatilization, the heat of reaction or the amount of heat released as a unit fuel mass is burned, both of which determine the intensity of the fire and contribute substantially to the burn rate.
iv. The fuel load, or the distribution of combustible material per unit area, including the primary and secondary fuels.

Figure 3 shows measurements of the steady-state fire temperature for some representative fires, collected from many sources [2]. As in most controlled fire studies, wood was used as a fuel and its mass and spread was varied to change the fuel load. The ventilation factor was also varied as it was found to have an important effect on the gas temperature. These data are shown only as representative data for compartment fires, estimate for the WTC fires will be made separately.

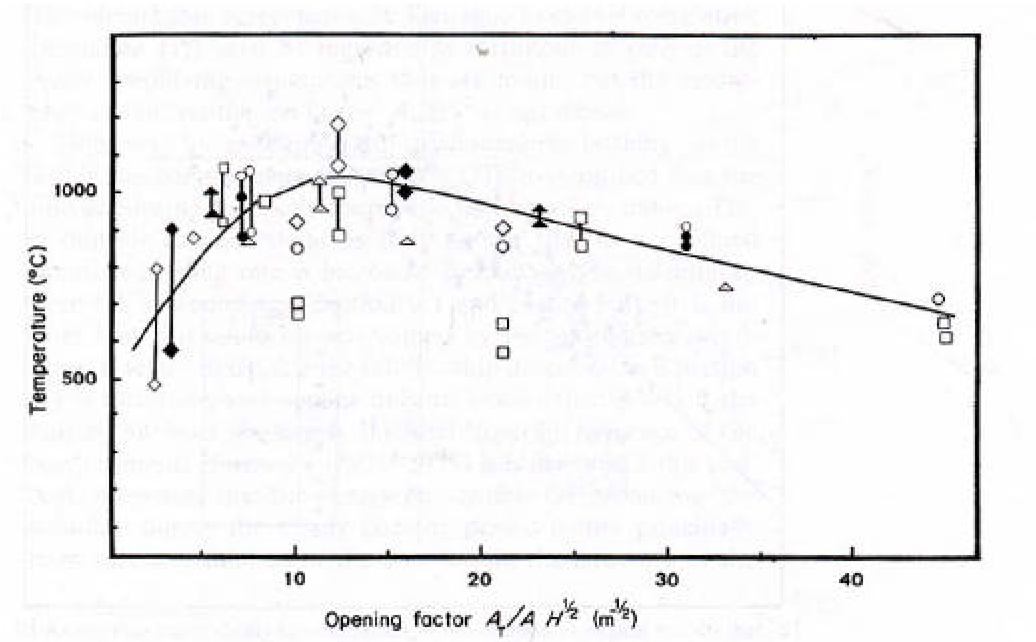

Fig. 3: Average gas temperature in a compartment fire (burning wood) and its variation with ventilation. Note that A_T is the total wall area and A is the window opening. Reproduced with permission form [2].

While the minimum observed temperature is 500° C for a poorly ventilated fire with little air supply, temperatures exceeding 1000° C are found at the transition between ventilation-controlled and fuel-controlled burning. The demarcation between the two regimes, as seen in Fig. 3, is defined by the normalized ventilation parameter $A_w\sqrt{H}\ /A_T$, with A_T being the total wall area without the openings, and the other parameters as defined previously. At this transition condition, the fuel-air stoichiometry is nearly ideal and the fire burns fast. Maximum temperatures are observed for values of the ventilation parameter in the neighborhood of 10, expressed in the units of Fig. 3. It is interesting to observe that the fire temperature falls slowly as more air becomes available, and that the range of maximum temperatures of 800-1100° C prevails for a very wide variation of the opening or ventilation parameters.

Most compartment fires exhibit external flaming following a brief period of post-flashover burning, if sufficient fuel is available. During external flaming, bright intense flames are seen to burn steadily from the windows, extending the reach of the fire to the outside walls of the compartment. External flaming is a sign of high fuel loads in the compartment, and fire plumes carrying high temperature products to the exterior of a building is an ominous sign. Temperatures observed during events of external flaming show strong dependence on both the fire area A_F and the ventilation parameter. In the WTC fires, the intense fireballs observed at the early stages, as well as later, may be thought of as a form of external flaming that exposed the outside walls of the Towers to direct flaming. The early fireball in the WTC fires most likely resulted from the early violent sloshing of the jet fuel following the strong impact and the residual momentum in the spilled fuel. The early disintegration of the fuel tank, not far from the area of collision, would have distributed the jet fuel throughout the crash zone, and left plenty of it near the area where the planes pierced into the Towers. Immediately afterward, a fireball would ensued, consuming this fuel. Later, as the interior fires expanded to include all combustible material, flames again extended through the exterior openings.

In light of the early estimates made for the WTC parameters, $A_w \sim 1000\ m^2$, $H \sim 20m$ and $A_T \sim 10{,}000\text{-}50{,}000\ m^2$, we obtain a total-area-based ventilation parameter $A_w\sqrt{H}\,/A_T$ in the range of 0.4 - 2.0, implying that temperatures in the vicinity of 1000° C are not unlikely to have been reached during the massive fires in the WTC Towers.

Fires do not burn steadily since the available fuel is progressively and rapidly consumed once flashover starts, including both the primary and the secondary fuels. In addition, the dimensions of the openings providing ventilation air continuously increase as fire damage exacerbates the building structure and challenges its integrity. At the same time, the original compartment grows in size as protective walls, ceilings and floors fail to withstand the assault of the fire, in a multi room and multi story building. Eventually, as more of the building material becomes flammable, the fire becomes fuel controlled, and the fuel load starts to decrease, leading to a concomitant decrease in temperature. This is shown in Fig. 4 for a sample fire [2,11], which also illustrates the expected and close correlation between the burn rate of the fuel and the prevailing fire temperature.

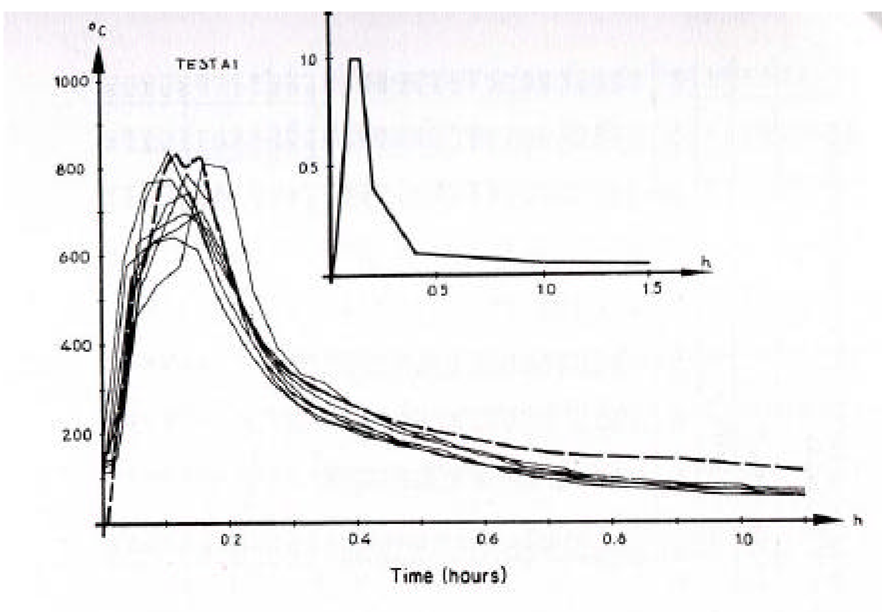

Fig. 4: Measured and modeled temperature history for a compartment fire burning wood, 96 MJ/m2 load and opening factor or 0.068 m1/2. The insert shows the burning rate for the same fire. Reproduced with permission from [2].

The history of the fire temperature demonstrates strong time-dependent trends and depends on: the opening factor, the fuel load, the thermal properties of the compartment walls, and the fuel type. The temperature estimates obtained via correlations derived from experiments and modeling studies of compartment fires, are based on spatial averages for the temperature in the compartment, in the neighborhood of the flaming zone. In general, the temperature is not uniform but may vary strongly between the location where the flames burn and the location where the combustion products mix with cool ventilation air. This average values of the fire temperature has been used to estimate the convective and radiative heat fluxes to the structure as well as the conductive heat loss through the walls. etc. In a post-flashover fire, with external flaming visible from nearly every available opening —as in the case for the WTC during the stage an external fireball was seen— flames totally engulf the outside of the building and a steep, substantial rise in the external temperature takes place. Figure 4 shows the sharp temporal variation of temperature in a typical compartment fire, measured within the compartment [2,11].

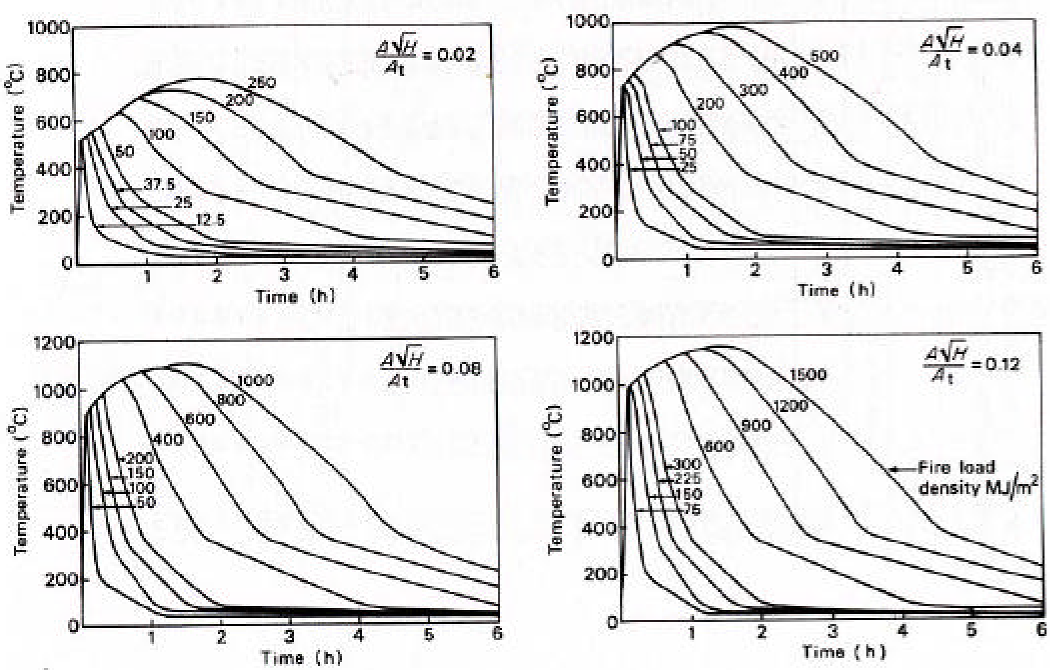

Fig. 5: Impact of fuel loading in MJ/m2 and opening factor on gas temperature history in compartment fire. Reproduced with permission from [2]

Depending on several parameters, e.g., the fuel load and the fuel type, fuel spread within the compartment, the opening parameters and ventilation factors, the gas temperature inside the compartment may rise quickly to values in the range of 600°-1100° C, then fall slowly as the primary and secondary fuels are consumed within the fire. The fuel load exerts the strongest influence on the maximum temperature reached and the duration of burning at, or close to that temperature. The higher the fuel load, the higher the maximum temperature, which exceeds 1000° C for well ventilated fires (i.e. $A_w\sqrt{H}\ /A_T \sim 0.1$) and with fuel loads, measured as total heat per unit area, exceeding 1000 MJ/m^2, or 20-50 kg/m^2. For these conditions, the fire temperature remains above 1000° C for more than one hour. Table 10.2 in Ref [2] and the set of comprehensive curves in Fig. 5 can be used to estimate the temperature history for a given opening factor and fuel load [2,11]. It should be emphasized that the total load is measured during post-flashover when every available combustible inside the room is inflamed and is actively participating in the fire. Please note that the rise time of the temperature is weakly dependent on the conditions! In well-ventilated fires, the temperature reaches its maximum value within 15-30 minutes of the start of the fires. Moreover, high-powered fires sustain the highest temperatures for a longer period of time, after which the temperature drops more slowly than in the case of weaker fires, creating more dangerous conditions for the buildings, inhabitants and fire fighters.

The preliminary estimates of fuel load for the WTC fire given earlier imply heat loads of the order of giga-Joules/m^2. Furthermore, the estimates of total area-based ventilation parameter is in the range 0.4-2.0, again confirming that the highest possible interior fire temperatures could have been reached, possibly exceeding 1000° C, as seen in Fig. 5. Such temperature could cause glowing, softening and melting.

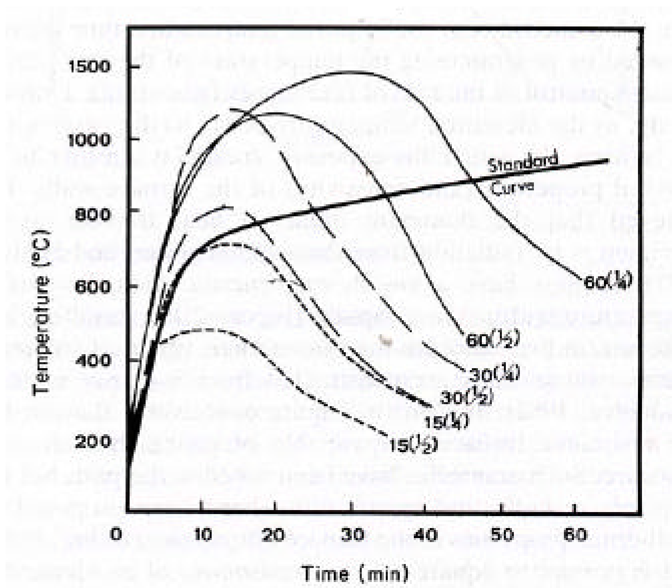

Fig. 6: Temperature history for compartment fires (burning hydrocarbons) for different fuel load, given in Kg/m^2, and ventilation expressed as % of one particular value of wall opening. Reproduced with permission from [2]

Figure 6 shows temperature histories for burning hydrocarbon fuels —which are similar to jet fuels— for different fuel loads, given in terms of fuel mass per unit area, and ventilation openings, expressed as a fraction of a standard opening [2,12]. Higher fuel load dramatically increases the fire temperature, and less ventilation slows down the temperature rise but achieves higher values. Given the estimates for the amount of fuel in the plane, and the surface area of the initial damage zone, a fuel density of 30-60 kg/m^2 is not unlikely for the initial stages of the WTC fires. The figure also includes the standard temperature curve used to estimate the impact of a hypothetical fire on a structure. Note the significance of the fuel load in determining the duration of a severe fire, or the length of time during which the temperature remains dangerously high. This duration may even be a more important consideration than the exact value of the fire temperature in determining the fire damage to the structure. Moreover, both factors grow hand in hand; hotter fires seem to last longer, although the rise time is almost the same whatever the intensity of the fire is. In all cases shown, reducing the opening by 50% increases the temperature and duration. It is likely that a large opening introduces more air and results in a fuel-lean burn (that is, less fuel than required for stochiometric burn). Reducing the air supply also reduces the burn rate and increases the fire duration.

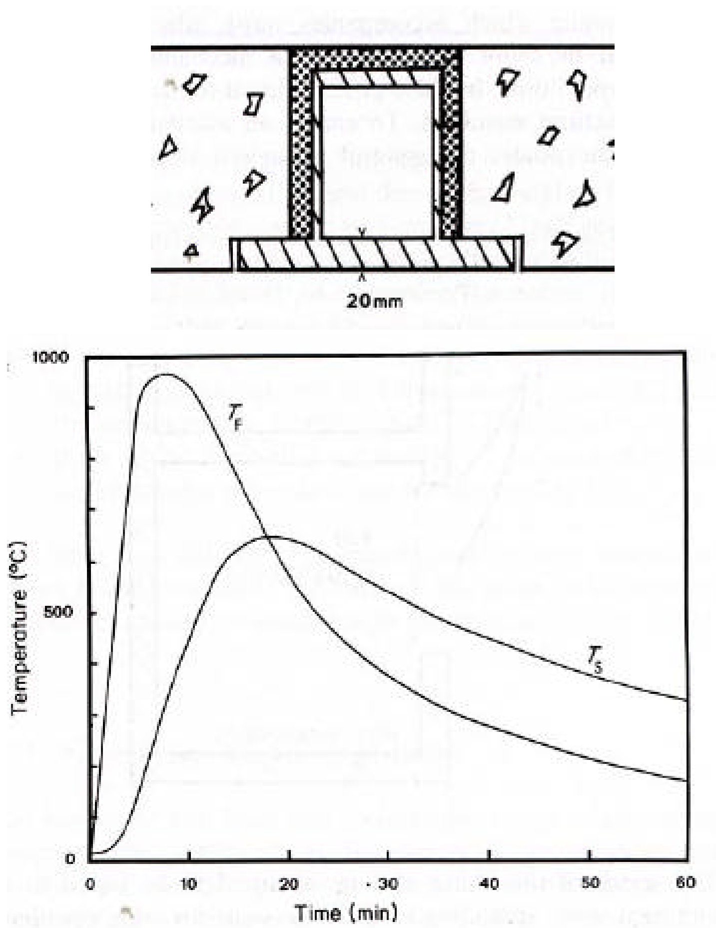

Fig. 7: Temperature history of the fire, measured at the ceiling steel bean. The fire load is 100 MJ/m^2, and the opening factor is 0.08 $m^{1/2}$, subscripts f and S correspond to fire, and steel Reproduced with permission from [2].

When calculating the history of the fire temperature, it is important to remember that what matters for the structural integrity of buildings, in this case the WTC Towers, is the time history of temperature of the steel columns and floor trusses, which were initially protected by fireproofing materials, but in time lost this protection. Input to these structural elements is the total heat flux, composed of radiative and convective fluxes, which they receive from the radiation and convective fluxes that may be very significant if the fire is raging in the immediate vicinity of the structural elements. Calculations show that steel may reach temperature close to 550° C in 15-17 minutes following the start of a fire, when exposed to a standard fire source. More significantly, a steel girder exposed to a fire of 100 MJ/m^2 and an opening factor of 0.08 reaches 650° C during the first 15 minutes, and remains at temperatures higher than the fire from then on, because steel loses heat slowly by convection while the fire runs out of fuel and its temperature decays fast. Given the current lack of data describing in sufficient detail the conditions inside the Towers, it is not possible to apply similar analysis to them, e.g., the interior steel columns that constituted the core structure of the Towers, or the structural elements of the upper floors. Figure 7 shows an example of the temperature history in a fire occurring in a compartment whose ceiling is made of steel girder carrying precast concrete floor units on the bottom flange [2]. The figure shows the relative rise time of the fire and steel column temperatures, and that while the steel temperature is below that of the fire at the early stages, it stays higher at the later stages.

6. Conclusions

The analysis presented here was based on simplifying assumptions that reduced the problem to that of a compartment fire, albeit of a much larger scale than anything that has been analyzed before. Further simplifications have been applied to estimate the values of the various parameters that appear in compartment fire models, and allowed estimates for the burn rate and the temperatures to be obtained. Preliminary results, based on approximate estimates of the fire conditions following the crash of the planes into the WTC Towers and the initial damage caused by the impact, shows that the fires generated very significant heat release rates and the fire temperatures were likely to have exceeded 1000° C. Given the amount of fuel available at the moment of the crash, such temperatures are likely to have lasted long enough to raise the temperature of the building material to dangerously high levels, and hence for the fires to have contributed significantly to the weakening of the towers structures and their collapse, contrary to some early speculations.

The next step in assessing the contribution of the fire to the collapse of the Towers is to define the fire conditions more precisely, e.g., the initial size of the exterior wall opening created by the crash, the volume and surface area of the initial impact zone, the initial distribution of the jet fuel and other combustible material, and the fraction that participated in the initial fireball, etc. Conditions must have changed rapidly due to the further weakening of the structure, the caving-in of the floors and the seepage of the jet fuel downward, which must have also changed the fire conditions and have strengthened the fire as more air was fed through the damaged exterior walls. Results of a study of the crash and the dynamics of the structural failure that followed can provide the necessary input to update the fire conditions and will lead to better estimates of the temperature history of the fire and the surrounding structures. The strong coupling between the progress of the fire and the further damage to the structure should be considered next, in a modeling analysis in which a two-way interaction is maintained. Such complex analysis must rely on powerful computational models, running on state of the art computational facilities of very high sustained speeds.

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Materials and structures

Oral Buyukozturk
Professor of Civil & Environmental Engineering, MIT

Franz-Josef Ulm
Esther and Harold E. Edgerton Associate Professor of Civil & Environmental Engineering, MIT

Abstract

The collapse of the World-Trade Center towers, on September 11, 2001, has raised questions about the design principles in high-rise buildings. In this article, we first consider the likely failure mechanisms that may have ultimately led to the collapse of the Twin towers. This analysis is based on a materials-to-structures approach, in which we look both at the characteristic behavior of the construction materials and the design details of the buildings. The very fact that the buildings survived the crash of the planes into the buildings suggests that a time dependent behavior at the material level affected the structural stability of the structure to the point of failure. On the other hand, the failure per se reveals the existence of a weakest link in the structural system, which ultimately failed because of a lack of redundancy. We then turn to the question whether —from an engineering point of view— skyscrapers will continue to have a future in the 21st century despite the increased vulnerability of our mega-cities. New materials-to-structures engineering solutions are also discussed, which in time could provide a new technology of redundancy to ameliorate the vulnerability of critical engineering structures.

Introduction

The terrorist attack of September 11, 2001 at New York's World Trade Center towers (WTC) (Figure 1) was the first attack on a mega-city in the 21st century. The collapse of the towers revealed the vulnerability of a mega-city to terrorist attacks at multiple scales, from the level of structural components to the collapse of the towers, from the scale of individual heroic rescue operations to the scale of mass evacuation and emergency operations, from the interruption of local transportation systems to the freeze of air traffic nation wide. Everyone who lived through the day at Ground Zero can continue the list: This was not a day for business as usual!

Figure 1: World Trade Center Towers (Photo from AP)

As the WTC towers sunk to Ground Zero and below, the logic of a world collapsed: a building designed to rocket into the sky, imploded into the ground. Ever since that day, structural engineers all over the world seek for explanations as to how and why the towers collapsed, and how to prevent such failures in the future. Of course, in theory, it is possible to engineer a structure to withstand a devastating attack whether accidental or intentional. For instance, eight years before, on February 26, 1993, a bomb detonating in the parking area of the WTC did not challenge the stability of the structure, unlike the event of September 11. Roughly two hours after the impact of two planes into the towers, the icons of strength and prosperity of New York that had been standing there for almost three decades, disappeared almost instantly from the Manhattan skyline, transforming the 110-story towers into a big pile of debris a few stories high. Ever since, the question is raised whether our skyscrapers are safe considering the events which proved the limits of predictability, anticipation and prevention. To answer this question, from a structural engineering point of view, we first need to reconstruct, as much as possible, the sequence of events that led to the collapse of the towers.

How did the towers collapse?

Initial assessment of the collapse

On September 11, the first Boeing 767-200 aircraft hit the North Tower at 8:46am, near the center of the North face at about the 96th floor. The South Tower was hit at 9:03am by another Boeing 767-200 aircraft near the southeast corner of the building at about the 80th floor (Figure 2). In both cases, the planes appeared to have sliced into the buildings and exploded immediately after penetration. Smoke clouds discharged heavily from the impact face as well as the side faces of the buildings. In both cases, destruction looked local, and appeared at first not to have challenged the structural stability. People tried to escape from the impact area, while some were unfortunately trapped in the floors above the impact zones due to damaged egress routes and/or raging fuel fire.

The South Tower collapsed suddenly at 9:59am, 56 minutes after the impact. Tilting occurred in the upper portion (Figure 3), which was immediately followed by a total collapse top down in about 10-12 seconds. The North Tower collapsed at 10:28am in a very similar fashion, 102 minutes after the impact. Figure 4 shows the collapsed building with the perimeter

Figure 2: Boeing 767 aircraft approaching the South Tower (www)

Figure 3: Progressive collapse of the South Tower (Photos from AP)

steel columns several stories high still linked together at the lower levels. In the collapse of the two WTC towers, a three-step failure mechanism may have been involved at different scales:

Step 1 – Impact of the airplane:
The buildings had been designed for the horizontal impact of a large commercial aircraft. Indeed, the towers withstood the initial impact of the plane. This is understandable when one considers that the mass of the buildings was about 2500 times the mass of the aircraft, and that, as has been reported, the buildings were designed for a steady wind load of roughly 30 times the weight of the plane. The impact of the plane was instantaneously followed by the ignition of perhaps 40 m^3 of jet fuel. While a fully fueled Boeing 767-200 can carry up to 90 m^3 of fuel, the flights initiated from Boston may have carried perhaps half of this amount, comprising about one-third of the airplane's weight. The impact and the ensuing fireball definitely caused

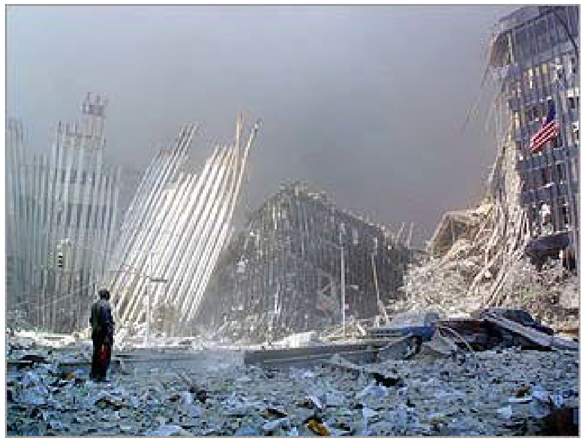


Figure 4: Collapsed tower with perimeter columns still linked at the bottom floors (www)

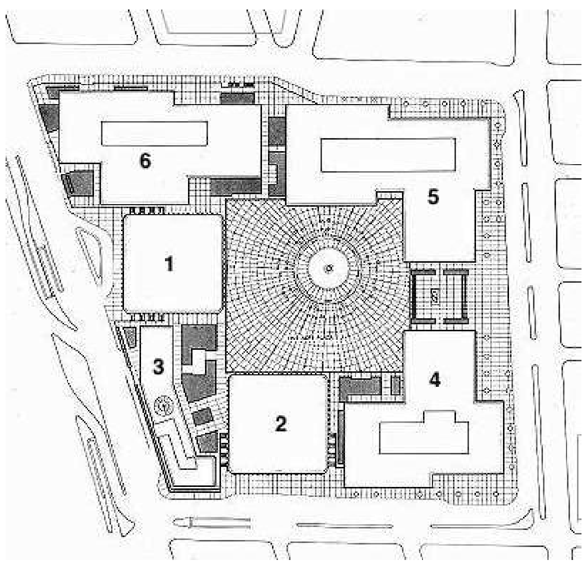
severe local damage to the building and, in fact, destroyed some perimeter and core columns across multiple floors. It has been argued that the damage to several floors should have overloaded the remaining intact columns in the damaged floors affecting their resistance to buckling. Yet, their resistance was sufficient to carry the loads of the upper floors almost one hour in the South Tower and almost double that much in the North Tower.

Step 2 – The failure of an elevated floor system:
The fireball following the impact may have destroyed some of the thermal insulation of the structural steel members. The burning of the jet fuel may have easily caused temperatures in the range of 600°C-800°C in the steel. Under these conditions of prolonged heating, structural steel looses rigidity and strength. This may have caused further progressive local element failures, in addition to those failed from the initial impact, leading to a greater reduction of resistance of the connected two to three floor structural system. The load to which the column bracing system was subjected to was the weight transferred from the upper floors. At a certain stage, after some 50 minutes in the South Tower and some 100 minutes in the North Tower, the buckling resistance of the columns was reached and collapse of the columns became inevitable. Preceding this progressive failure within the damaged column-bracing system, the floor decking system may have failed first in a brittle way, releasing explosively the energy stored in the system. It has also been argued that the failure may have initiated by shearing of a critical floor from the floor-external/internal column connections. In reality, combinations of floor failure with that of column buckling may have occurred simultaneously. In fact, failure of a floor system would result in an instant loss of lateral column bracing, leading in turn to loss of column stability. The tower with the higher load on top (the South Tower) collapsed first; but both towers exhibited nearly identical failure mechanism.

Step 3 – Dynamic crash of the structure:
The failure of the floor system led to a free fall of a mass of approximately 30 stories and 14 stories onto the 80 and 96, respectively, floor structure below. The enormous kinetic energy released by this 2-3-floor downfall was too large to be absorbed by the structure underneath. The impact effect generated from this upper part onto the lower part was surely much higher than the buckling resistance of the columns below, which to this point may have been

essentially undamaged and were not affected by fire. The impact caused explosive buckling, floor after floor, of the WTC towers with the debris of the upper floors wedging with the lower part of the structures. As the floors failed, the collapse of the building accelerated downwards with the accumulation of the falling mass and the dynamic amplification of its impact on to the lower structure. Similar to a car crash in a wall, the towers crashed into the ground with a velocity close to that of a free fall.

While the first and the third step to failure are focus of two other contributions in this book, the initiation of the collapse of the WTC is still not clear. More precisely, the two key observations that deserve more attention are (1) the time elapsed between airplane impact and collapse, and (2) the abrupt failure of the structure with little warning. The first suggests that there was a time dependent mechanism involved, at the material and/or structural level. The second indicates a structural stability problem, which is always associated with an abrupt



1 WTC – North Tower
2 WTC – South Tower
3 WTC – Hotel
4 WTC – South Plaza Building
5 WTC – North Plaza Building
6 WTC – US Customs House

Figure 5: Plan of the World Trade Center complex (www)

failure, in contrast to a ductile failure. Understanding the combination of these two phenomena appears to be the key to explaining the collapse of the towers. This requires, first, a look into the structural system and construction materials employed in the structure.

Overview of the WTC

The world trade center was developed and constructed by the Port Authority of New York and New Jersey to serve as the headquarters for international trade. The center was located on Church St. in Manhattan of New York City. The complex consisted of two 110-story office towers (WTC-1 and WTC-2), a 22-story luxury hotel (WTC-3), two 9 story buildings (WTC-4 and WTC-5), an eight story US Customs house (WTC-6) and 47 story office building (WTC-7). The complex was bound by West Street to the west, Vesey and Barkley streets to the north, Church street to the east and Liberty street to the south. (Figure 5). Having a rentable space of more than 12 million square feet, the complex was housing more than 450 firms and organizations and more than 60,000 people working in these firms. About another 90,000 people were visiting the complex each day, with the shopping mall located below the plaza being the main interior pedestrian circulation level of the complex.

The complex was designed by Minoru Yamasaki and Associates of Troy, Michigan, and Emerith Roth and Sons of New York. The structural engineers were John Skilling and Leslie Robertson of Wortington, Skilling, Helle, and Jackson. The site excavation had begun in 1966 and construction of the towers started two years later. The first tower (WTC-1) was completed in 1970 and the second tower (WTC-2) was completed in 1972. Figure 6 shows one of the towers under construction.

Figure 6: Towers under construction (www)

Figure 7: View of the bathtub (www)

The WTC buildings were supported by gigantic foundations. They rested on bedrock 21m (70ft) below ground. In the area that contained the twin towers, more than a million cubic yards of earth and rock were removed to place a basement that was 299m $\times$ 155m $\times$ 21m (980ft $\times$ 510ft $\times$ 70ft). The basement housed a commuter rail station, a 2000 car parking area, mechanical equipment rooms, and storage. Prior to excavation, underground walls were built all the way down and into the bedrock to withstand the external water and earth pressure, and

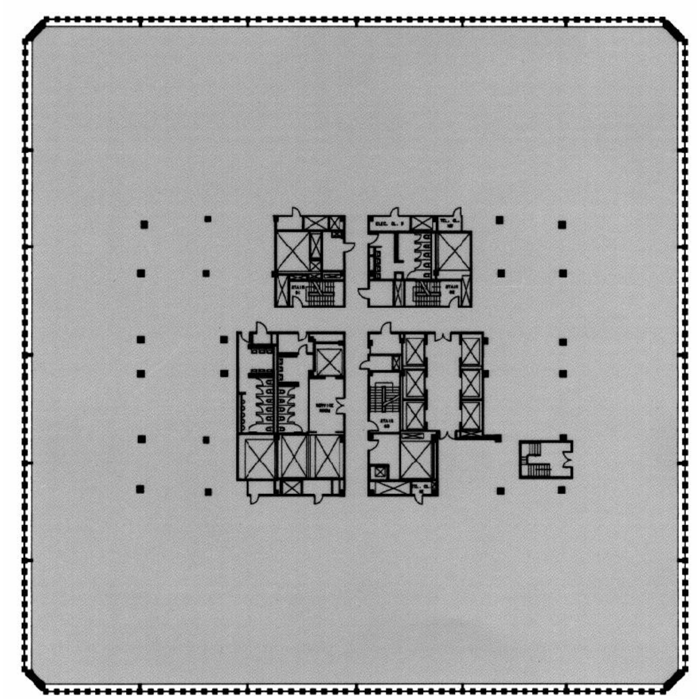


Figure 8: Typical floor plan (Hart et al., 1985)

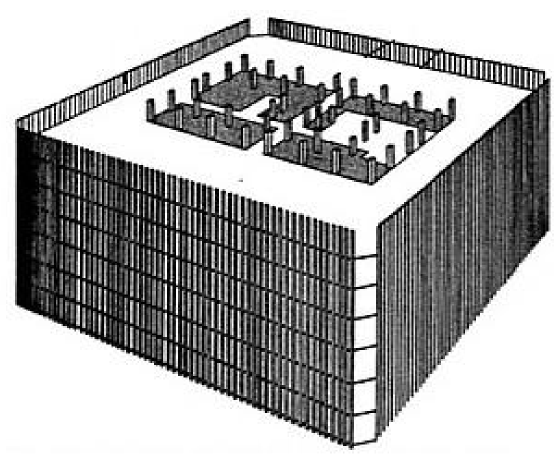


Figure 9: A conceptual view of the structural system (Hart et al., 1985)

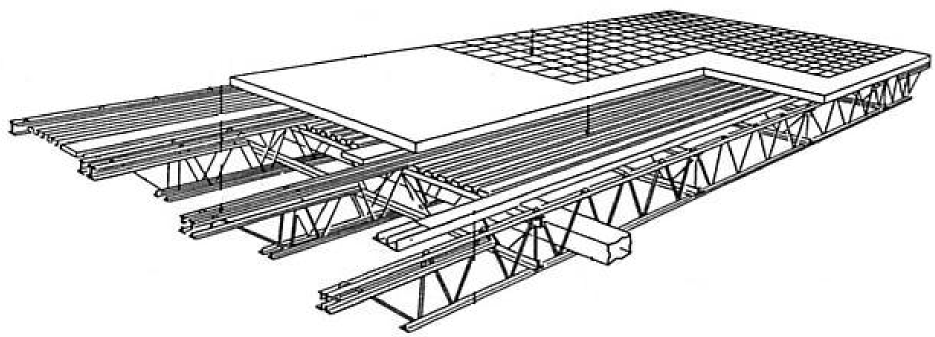


Figure 10: Conceptual view of floor system (Hart et al., 1985)

to prevent the undermining of adjacent buildings and streets. These walls were 7 story high, heavily reinforced concrete walls. The completion of the walls around the entire eight-block area resulted in a cutoff boundary around the site to be excavated. The excavated area, which is generally referred to as the "bathtub", is shown in Figure 7.

Structural system

The twin towers were built as a steel tubular structural system that differed radically from other structures of that time. The exterior walls were built of closely spaced steel columns to perform as load bearing walls and the interior columns were located only in the core area containing the elevators. The outer walls carried the vertical loads and also provided resistance to lateral effects such as wind, earthquake, and impact. Figure 8 shows a view of the exterior wall.

The towers were square in plan with sides of 63.7m (209ft). The structural height of each tower was 415m (1362ft). The height to the top floor was 411m (1348ft). The towers were built as framed tube cantilever structures with 0.45m wide built-up box columns (Figure 9) tied with 1.3m deep spandrel beams in the perimeter. The beams and columns were pre-fabricated into panels and assembled on site in a staggered fashion by bolting and welding. The perimeter member assembly made of 59 columns over the 63.7m-wide façade ensured the load bearing capacity of the outer skin for gravity load, lateral load, and torsional effects. The columns were spaced 1m apart and spandrels 3.6m apart. The 24m $\times$ 42m core was composed of 44 box columns. The core comprises steel beams and columns with reinforced concrete infill panels designed to share part of the gravity loads. The core was designed to resist vertical loads and was not assumed to transfer any lateral loads. The perimeter columns were tied to the core only by the truss-slab system and the horizontal forces were assumed to be resisted by the perimeter columns and their connecting spandrel beams. A typical floor plan is shown in Figure 10. The isometric view shown in Figure 11 helps conceptualizing the structural system.

The slab system consisted of primary vertical bar trusses spaced 2m apart spanning 20m from the core to the perimeter (connected to every other column). These primary trusses were braced by orthogonal secondary trusses. Figure 12 shows the original drawing of the floor system details. A conceptual view of the floor system is shown in Figure 13. All trusses were built up by four angle sections to form a top cord, two to form a bottom cord, and bent round bars to form the diagonals of a classic warren truss. The bars were sandwiched between and welded to the angles. The bent bars protruded above the upper angle sections and into the 10 cm thick concrete floor to act as a shear key. Trusses were connected at their ends by bolts.

The connection of each truss to the external columns was made by means of a truss seat (Figure 14), which was connected to the box columns. The truss seat was a built up section onto which the two angles of the top chord were bolted with two bolts. Connection of the truss to the core was made by bolting the bottom chord angle to a channel section, which was connected to the interior columns (Figure 15). The bolted connections were of friction (or slip-critical) type, 16mm – 19mm (indicating diameter of the bolt) A325 bolts possessing a tensile strength of about 110ksi were used. Corrugated steel decks were then secured on the orthogonal trusses, and 10cm lightweight concrete topped the decks to complete the slab. The corrugated steel decking acted as permanent formwork and as a composite with the concrete to support the floor loads. It is noted that at a later stage, viscoelastic dampers were attached to the ends of each floor truss connecting the lower truss chords to the perimeter box columns in order to reduce wind induced vibrations.

Structural and fireproofing materials

The major structural material employed in the towers was A36 structural steel, although higher strength steel was used in the lower elevations of the structure. Except for some selected floors, for which normal strength concrete was employed, the composite slabs were made of a 21MPa (3ksi) lightweight concrete.

Fire resistance of the perimeter columns was provided by a layer of sprayed concrete around the three sides of each column. The concrete layer had a thickness of about 5cm and included ceramic fibers in the mix. The interior face of each column was fire protected with approximately 5cm thick layer of vermiculate plaster (Figure 16). The exterior sides of each perimeter column were covered by aluminum to which the window frames were fixed. It has been reported that passive fire protection was provided to the underside of the floor systems by a fire rated suspended ceiling. Specifics of fireproofing implemented on these buildings including which structural members were treated and to what level of fire resistance are still being investigated.

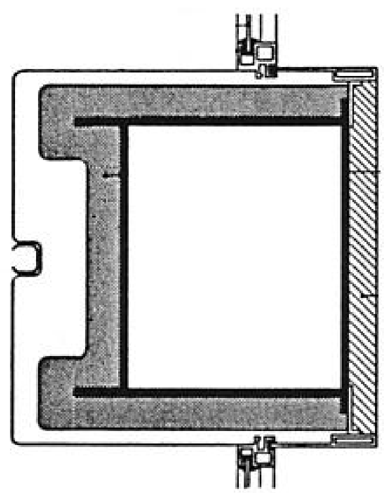


Figure 11: Fire proofing of external columns (Hart et al., 1985)

Could the impact have been the primary source for the collapse?

The penetration of the two aircraft into the towers seems to suggest that the primary source of the collapse of the building was the impact of the airplanes. There are several indications that support this view.

The first point relates to the load for which the structure was designed. According to Leslie E. Robertson Associates, the structural engineering consultant who engineered the buildings, both towers were designed to resist the impact of a Boeing 707. Such design was deemed necessary for the skyscrapers due to the possibility of having an aircraft crashing into them under inclement weather conditions. This was not without precedence; a B-25 bomber crashed into the Empire State Building in 1945 on a foggy morning. It has been argued that the damage inflicted by the Boeing 767 was far more substantial than the one of a Boeing 707, for which the building was designed. Indeed, while both planes have a similar take-off weight, the design scenario of a lost airplane is quite different from that of a suicide plane intentionally hitting a building. The speed of the planes and severity of the impact, the level of penetration, the excess weight of the aircraft on the slabs after penetration, the fireball following the collision, and the weight of debris accumulating on lower levels are among the factors not considered in the design of the towers for aircraft impact.

A second argument that might be given is a structural one, relating to the specific framed tube cantilever structures of the towers. Indeed, such a structural system is based on the premise that the perimeter columns and spandrel members resist gravity and lateral loads. These loads are transformed into axial, bending, shear, and torsion stresses and deformations. The function of the core is only to share part of the gravity loads carried by and transferred from the slab system. In order to have all the members function properly as designed, continuity has to be maintained at all times so that loads can be transferred from one member to another and eventually carried down to the foundation. The impact and penetration of the airplanes disrupted the continuity of the force flow in the outer skin; and floor trusses, slabs, and core columns in the vicinity of the impact were substantially deformed and destroyed. This disruption of continuity was confirmed by people who successfully escaped and who reported having seen widening of cracks in the stairwells during evacuation. From a structural mechanics point of view, these observations indicate that a significant stress distribution took place from damaged members to undamaged parts, establishing a new force balance. As the absence of equilibrium is associated with failure, this overall force balance was maintained during the time to failure, that is the 56 minutes and 102 minutes the towers still stood after the impact of the plane. It should also be noted that the buildings, which were approximately 95% air, could not tip over as a result of the initial impact, and they essentially imploded onto themselves at a later stage. In conclusion, we can state that, although the initial impact must have caused significant local damage to several floors by the impacting aircraft slicing through the perimeter frames, the impact alone falls short as a sole explanation of the towers' collapse.

Why did the towers collapse?

Weakest link theory

A fundamental principle of engineering design theory is that a structure is only as stable as the weakest link in a chain of elements. This weakest link may exist at a material or structural level, and affects the entire structural system stability if no provisions for redundancies have been implemented in the system. In the collapse of the twin towers there is no doubt that there were many interacting factors involved that lead to the catastrophic failure. However, it can be argued that perhaps a weakest link may have played a critical role in the initiation of the failure process.

A key element in the failure process of the tower buildings was the time elapsed between the impact and the collapse, which indicates a detrimental role of a physical phenomenon that depends on time. The obvious one is related to the heat effects that started with the fireball and continued until failure. In the days following September 11, it was argued that the fire was the ultimate cause of the collapse of the towers, since it is known that steel looses strength and stiffness at high temperatures. But one can learn more by trying to reconstruct the different levels at which high temperature played an important role in the initiation of failure and the collapse mechanism.

Fire

There has been speculation with respect to the magnitude of temperature that may have resulted from burning of the jet fuel possibly leading to the melting of the steel in the WTC fire. It has been noted (Eagar and Musso, 2001) that although heat and temperature are related they should not be confused. Temperature is an intensive property, meaning that it does not vary with the quantity of the material, while the heat is an extensive property, which varies with the material volume. The two quantities are related through the heat capacity and the density. On the other hand, the dispersal of the jet fuel over several floors of the WTC did not necessarily imply an unusually hot fire. While burning hydrocarbons (jet fuel) using pure oxygen may reach approximately 3000°C, the same material burning in air produces about one third of that; that is, 1000°C. Thus the temperature experienced by the steel as a result of the fire may have been in the range of 750°C to 800°C, which is not sufficient to melt the steel. Typical value of steel melting temperature is in the range of 1400°C-1500°C. However, this level of temperature has significant effect on the structural behavior.

Behavior of steel under high temperature

Generally, unprotected steel in a high temperature environment does not perform well as a structural material due to the fact that steel has a high thermal conductivity and the members made of steel usually have thin cross sections. Typical fire proofing materials for steel structures are sprays (mineral fiber, vermiculite plaster), boards (fiber-silicate or fiber-calcium-silicate, gypsum plaster), and compressed fiber boards, (mineral wool, fiber-silicate). Typical thicknesses of insulating materials generally vary from 15mm to 50mm. Figure 17 shows two standard fire curves corresponding to combustible cellulosic material and a material of petrochemical origin. Steel temperatures for a structural beam for unprotected and protected steel together with a standard fire temperature is shown in Figure 18 (ISO, 1975; Buchanan, 2001).

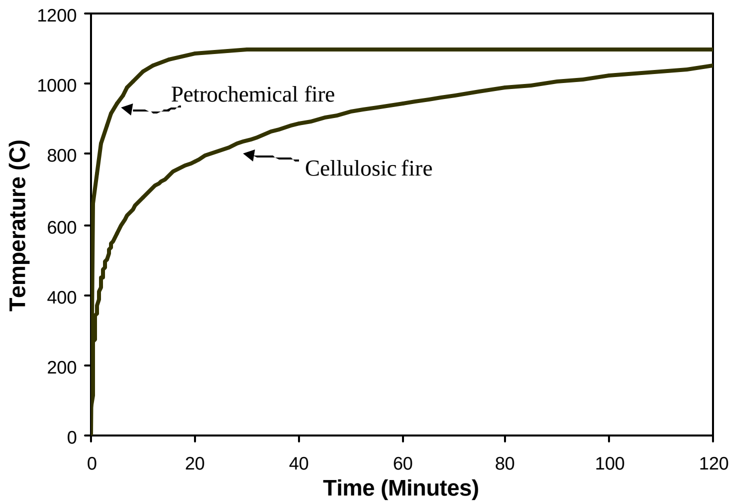


Figure 12: Fire curves (ISO, 1975)

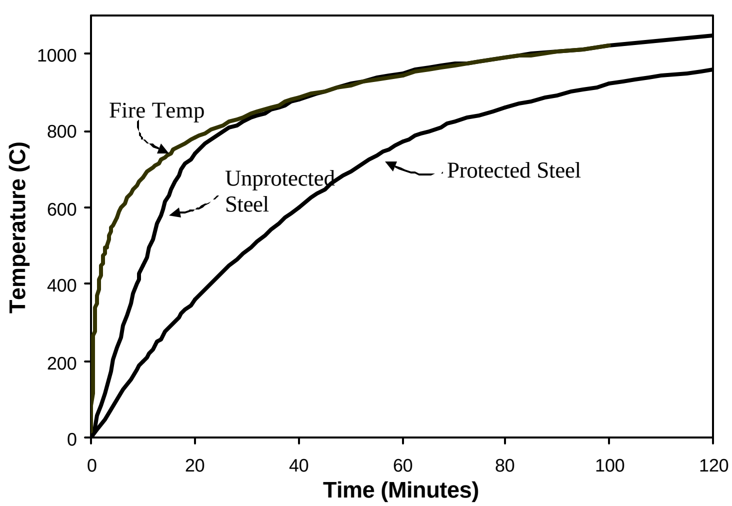


Figure 13: Temperatures for protected and unprotected beams exposed to fire (Buchanan, 2001)

We already mentioned the important role that the sustained temperature may have played during the time elapsed between the impact and the collapse in the failure process of the tower buildings. Considering the behavior of steel under high temperature one can now reconstruct the different levels at which the high temperature may have affected the building behavior.

Material level: thermal softening and thermal creep

Steel subjected to high temperature undergoes a substantial loss of strength and stiffness at a temperature level far below the melting temperature, which is referred to as thermal softening and thermal damage, respectively. By loss of stiffness (thermal damage), we mean an increase of the deformability of the material under load. A part of this increased deformability is known as thermal creep, and results from the higher agitation of the atoms of steel at high temperatures, which increases the susceptibility to and likelihood of deformation. Figure 19

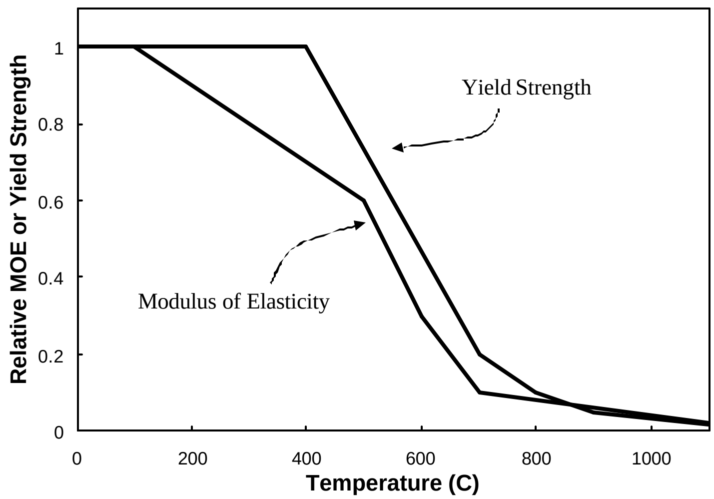


Figure 14: Reduction in yield strength and modulus of elasticity of steel as a function of temperature (EC3, 1995)

shows the relative strength and stiffness degradation upon increasing temperature. At a temperature level of about 600°C-700°C, which corresponds roughly to one half of the melting temperature of steel, strength and stiffness of steel are reduced to 50% and 30%, respectively, of the initial value. Still, we should note that the temperature dependence of strength and stiffness of steel is a material property, which only affects the structural response if the member is heated. This involves at least two further physical processes: heating rate and heat diffusion.

Structural level: heating rate and heat diffusion

Standard fire curves, shown in Figure 17, do not consider the initial explosion at impact. However, they can be considered as a first approximation to the rapid temperature rise to which the structural members in the towers could have been subjected after the impact. Given the rapid burning of the jet fuel, a temperature of 600°C-700°C (corresponding to about one half of the steel melting temperature) could have been reached essentially in a matter of minutes. Any structural steel member without or insufficient fireproofing (destroyed e.g. by the impact, and thus directly exposed to the high temperature) would have undergone substantial thermal damage and thermal softening. On the other hand, the fireproofing increases the thermal inertia of the member by delaying the heat diffusion into the material. It is likely that this heat diffusion, slowed down by fireproofing, was one of the rate determining mechanisms that delayed the collapse initiation in time. In fact, it can be shown, from dimensional analysis, that the critical time span t during which a steel member of thickness H with a fireproofing at its surface of thickness e, is protected by fireproofing (see Figure 20) is scaled by:

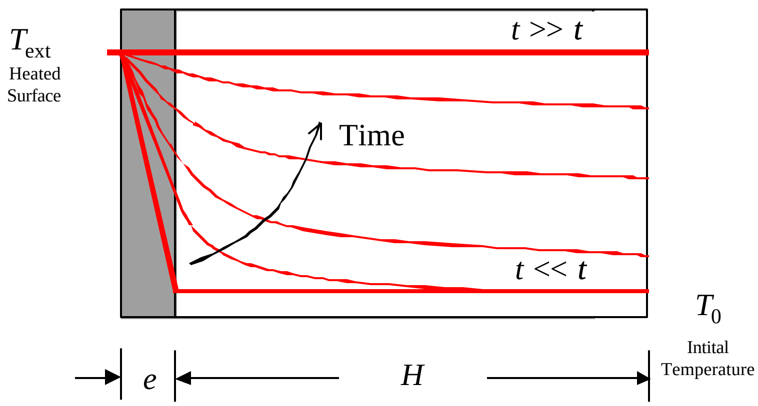


Figure 15: Temperature Profiles Through a Cross Section with a Fire Proofing Layer

$$t = \frac{H^2}{D} \times F\left(\frac{e}{H}, \frac{H}{k/l}\right) \qquad 1)$$

where F is a dimensionless function of the arguments e/H and Hl/k; $D = k/(rc)$ is the thermal diffusivity of steel, k the thermal conductivity, c the specific heat capacity, r the mass density; and l the thermal exchange coefficient of the fire proofing. The smaller l, the more efficient the fireproofing. For times $t << t$ the steel member, coated by a fire proofing layer, will not feel the external temperature, but for $t>>t$, the steel over its entire thickness will be at the external temperature. This time is inverse proportional to the heat diffusivity of steel. Note that k/l has the dimension of length, which needs to be compared to the structural dimension H. In fact, for a given steel member of size H and conductivity k, an efficient fireproofing must be such that $l << H/k$. Hence, the smaller H and the higher the conductivity, the smaller the required fireproofing heat exchange coefficient. The high heat diffusivity of steel, which is 5 times that of air, and the high conductivity of steel, which is some 20,000 times that of air (see Table 1), combined with the generally small characteristic dimensions of steel members, highlights the high vulnerability of steel members to high temperatures.

Structural performance of columns and slabs under high temperature

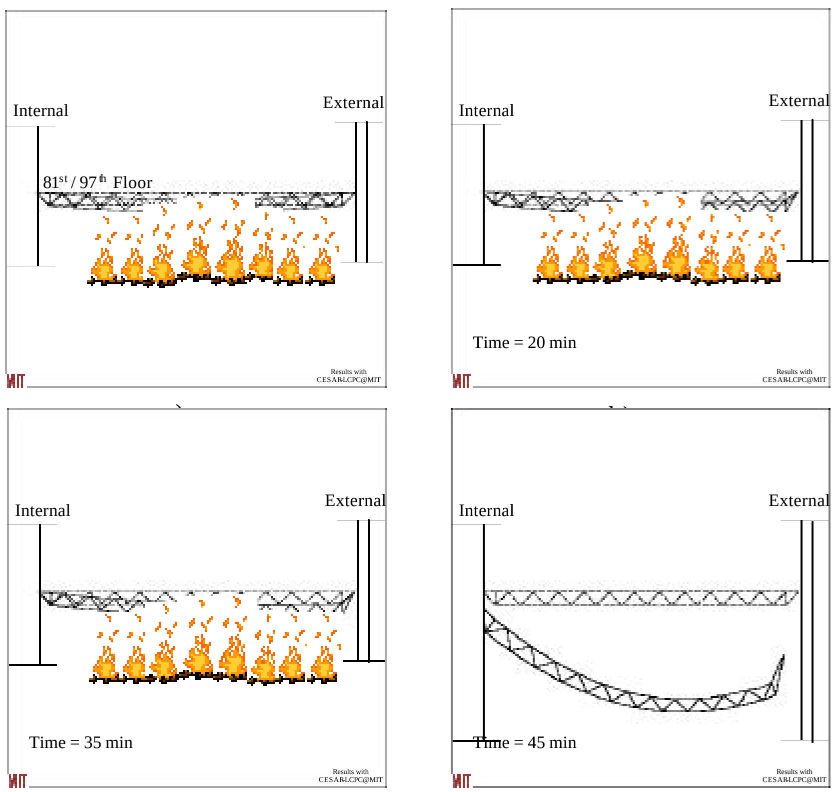
Thermal damage and thermal softening are material properties, and heat diffusion occurs at the sectional level of the steel member. The missing link in the initiation of the collapse is the

Table 1: Physical parameters of materials at 20°C

Material	r [kg m^{-3}]	k [W m^{-1}K^{-1}]	c [W s kg^{-1}K^{-1}]	D [m^{2}s^{-1} $\times$ 10^6]
Steel	7,800	45	420–510	11.3 – 13.7
Concrete	2,500	6–8	840–1,000	2.4 – 3.8
Air	1.2	0.0026	717–1,005	2.1 – 3.0

structural performance of the structural members subjected to heating. To this end, at the member level, we shall distinguish the slab system from the columns.

The slab system carries the load primarily in bending. From past-fire experiences in factories and buildings, it is well known that bending members subjected to fire undergo large deformations. Such a ductile response is readily understood from the fact that in steel, the loss of strength occurs faster than the reduction in stiffness. In other words, with heating, the structural member reaches the yield limit of the steel faster, and as a result, undergoes a large plastic deformation. Such a ductile deformation mode, involving large plastic deformation, could hardly have occurred in the towers. In fact, such a ductile deformation mode would have further delayed the structural collapse, or would have even prevented it. By way of conclusion, it appears that the slab could not have undergone a uniform thermal softening and thermal damage, which would have essentially led to a ductile failure of the slab system.



c) d)

Figure 16: Finite element simulation of the floor collapse from end joints

Figure 21 (a), (b), (c), and (d) displays the results of finite element simulations of the slab truss system subjected to non-uniform heating. This non-uniform heating may have resulted from locally damaged or insufficient fireproofing and the higher thermal damage of the high-strength bolt connections with the outer façade. In the numerical study, the non-uniform heating effect is taken into account by a 100 times higher thermal exchange coefficient (see eq. (1)) of the end diagonal truss at the external façade, thus considerably reducing the fire protection time. As the results show, this weak point in the fireproofing system could actually be the weakest link of the entire system: while uniform heating would have led to a uniform bending and yielding (see Figure 21 (a)), an increased local thermal damage of one structural element leads to a rigid body motion of the statically determinate truss system (see Figure 21(c)), which ultimately causes failure of the truss system. This weakest link situated at the end supports, to which the steel truss system was mounted by bolts, may explain the failure of the truss system in a shorter time span than the nominal fireproofing time. This finding based on model-based simulation is consistent with forensic studies carried out on the WTC-site after Sept 11, which showed that several of the end supports were either strongly deformed (indicating exposure to very high temperatures), or perforated by the bolts.

With still limited knowledge, the most likely scenario that may have triggered the collapse of the WTC towers is the local failure of the support structures of the slab, initiated most probably through an insufficient fireproofing or a higher thermal damage and softening of the bolts. The local failure of one or several supports could have caused a zipper effect leading to the loss of the slabs load bearing capacity. Upon failing of a floor system, the lower floor had to carry the additional weight. While the trusses may well have been able to carry the load, the supports are typically designed for twice or three times the nominal weight. Hence, if we assume that one or two floor systems were already destroyed by the impact, it suffices one additional floor failure, and/or the dynamic amplification effect, to make the lower floor fail. However, this is not yet the complete scenario leading to total collapse.

The last missing link is the failure behavior of the supporting core column system. These core columns were designed primarily to carry the vertical load from the slabs to the ground. In the absence of horizontal forces, columns are designed in a way that the applied normal force N is always smaller than the maximum admissible (buckling) force F^b, at which the column looses (almost) instantaneously its capacity to carry load. From classical column stability problem, expressed in terms of a safety factor $\gamma = F^b/N$, the structure will keep its load bearing capacity provided that:

$$g = \frac{EI}{a^2 L^2 N} > 1 \qquad (2)$$

where E is the elasticity modulus, I the moment of inertia of the column section, L is the length of the column between two horizontal supports provided by the intact bracing slab systems, and $\alpha \in [0.5,2]$ is a coefficient relating to the end bearing conditions of the slabs. The length magnitude (αL) is generally referred to as “effective length”. At the level of impact, it is likely that γ was much larger than unity, typically 5–10. The three factors that may have affected the collapse are, with decreasing importance:

- The increased effective length of the columns: Once a slab system failed, the distance between the horizontal supports by the slabs doubles, thus decreasing γ by (at least) a factor of 4 for the first slab, 9 for the second slab, and so on. Failure of two or three floors would be sufficient to bring the column load to the critical buckling value, that is $\gamma = 1$, leading to the collapse of the columns.
- The initial load in the columns: The axial force in the columns at the impact floor is roughly proportional to the load of the floors above the impact floor. Thus, the axial force at the 80th floor of the South Tower having 30 floors above was roughly twice as much as the one at the 96th floor in the North Tower (with 14 floors above). With regard to this initial load, the additional load due to failing slab system is quite small (roughly 1/14th of the initial force in the South Tower, 1/30th in the North Tower), and can be excluded as a major contributor to the buckling failure.

- The thermal damage of the columns: the reduction of elastic stiffness, as a function of temperature, T, i.e. $E=E(T)$ linearly decreases the safety factor γ.

In addition to these factors, the important effect of dynamic amplification of the impact loads should be considered. This aspect is covered elsewhere in this book.

Given the higher initial load of the South Tower columns, it is likely that the longer time to failure of the North Tower of 102 min (versus 56 min of the South Tower) may have well involved some substantial thermal damage of the columns prior to failure. But it is more likely that an additional failure of one slab system occurred. Indeed, for all structural and material parameters constant, buckling in the North Tower will occur, theoretically, for a buckling length of $L_{North}/L_{South} = (N_{South}/N_{North})^{1/2} \approx 1.4$, where L_{South} is the buckling length which made the South Tower fail first, and $N_{South}/N_{North} = 2$ is the axial load ratio between South and North Towers. Thus, the lower initial load in the North Tower, which translates into a higher buckling length, made the North Tower gain 46 minutes of time for evacuation. These 46 minutes compare well with the characteristic time scale of failure of one slab system due to heat effects at the end supports (see Figure 21(a), (b), (c), and (d)). It then appears, indeed, that the North Tower collapsed once an additional floor had failed, indicating some redundancy of the failure mechanism. This confirms that the key to understanding the failure is the time dependence of the failure mechanism of the weakest link in the system.

Could the collapse of the buildings have been prevented?

The world trade towers were ingeniously designed for the physical and social reality prior to September 11, 2001. In fact, it appears to us that the structure as a general system was built with high level of redundancy against failure. The towers did not significantly tilt throughout the failure which no doubt avoided an even greater catastrophe and destruction far beyond lower Manhattan. They withstood both the initial impact of the aircraft and the resulting fire balls. The preceding analysis indicated that the collapse mechanism of the towers involved failure of the floor system from heat affected joints with the ensuing domino effect of progressive collapse, one could cite the perceived weaknesses at several levels: a) the end joints of the floor systems, which involved rather simple bolt connections, b) the fire proofing of the joints of the floor trusses, c) the transfer of internal forces among the elements, (lateral and vertical members) within the external tube system.

The tower structures were built with a breakthrough innovation, given the physical and social realities at the time of their construction, in creating a highly redundant and efficient system for external effects. It is ironical that 30 years later the very same structures had to collapse by imploding onto themselves through primarily a local mechanism within the strong external envelope.

Could the use of concrete have prevented the collapse?

The answer to this question requires, first, an analysis of different levels at which collapse was initiated. Concrete is non-combustible, and has a low thermal conductivity compared to steel; but this alone does not explain the better fire performance of concrete compared to that of steel.

In fact, on a purely material level, thermal damage and softening of normal concrete is quite similar for concrete and steel, although the involved chemo-physical mechanisms are quite different. In contrast to steel, the thermal damage of concrete is due to several sources: a differential thermal expansion behavior between the cement paste matrix and the aggregate inclusion, thermal instability of some mineral components of hydrated cement at some 400°C, transformation of aggregates at some 800°C, and so on. The thermal softening of concrete results in addition from a dehydration of concrete, leading to a loss of strength of the material. Typical curves of thermal damage and thermal softening for steel are shown in Figure 19 and thermal damage and thermal softening of concrete are shown in Figure 22 and Figure 23,

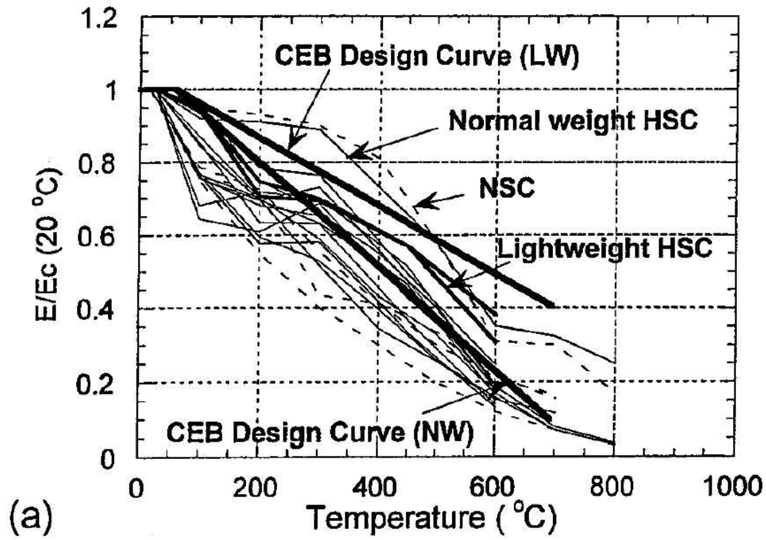


Figure 17: Thermal damage of concrete: loss of stiffness at high temperature
(from the compilation of data by Phan, 1997)

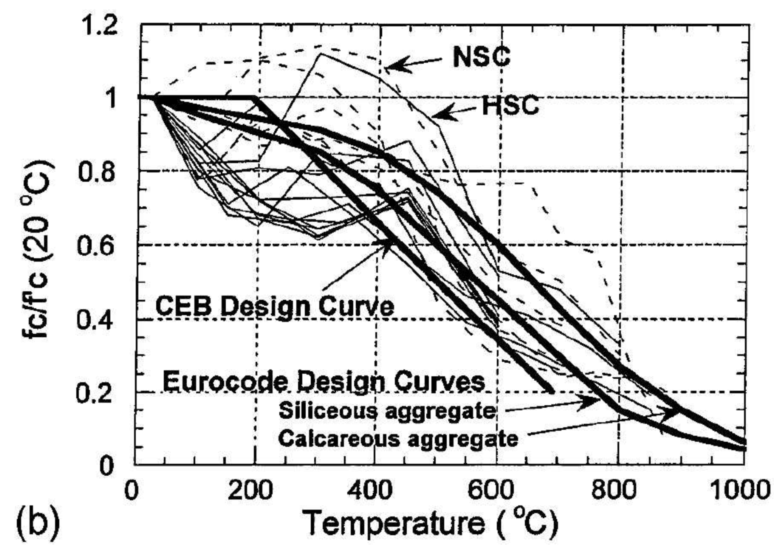


Figure 18: Thermal softening of concrete: loss of strength at high temperature
(from the compilation of data by Phan, 1997)

respectively. Figure 24 shows the combination of these two effects as design curves. A comparison of these four figures shows that there is indeed little difference between concrete and steel on a material level.

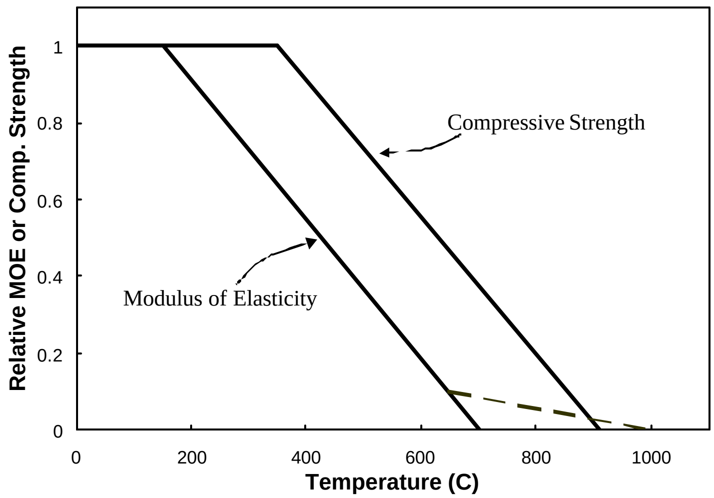
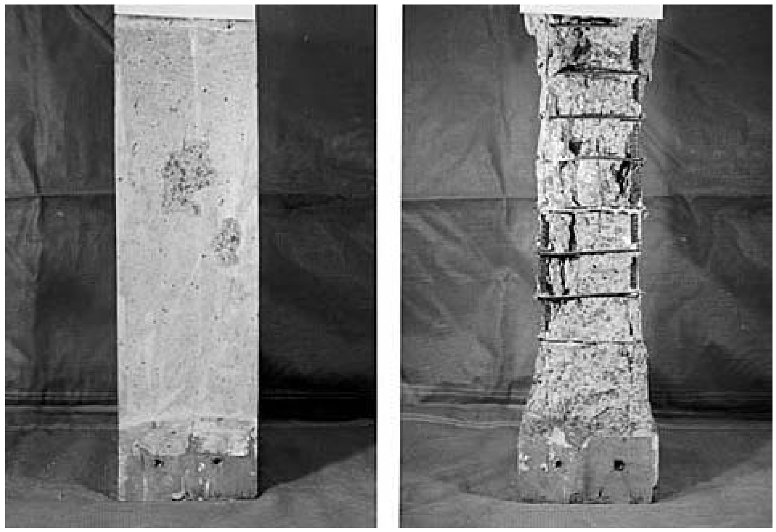


Figure 18: Idealized curves for thermal damage and thermal softening of concrete at high temperature (BSI, 1985)

However, several other mechanisms enter when one considers the behavior on a section member level. First, we should note that concrete material in the context of structures is generally used in conjunction with reinforcing bars. The concrete cover, that is the distance between the fire exposed surface and the steel reinforcement, needs to be designed so to protect the steel reinforcement over sufficient time. Furthermore, the mechanism of failure of concrete members under high temperature is different than that of steel, as it involves spalling of thin layers of concrete from the face of the concrete. The first aspect relates to the heat propagation properties of concrete, the second to stress and pressure build-up in structural members.

Table 1 compares the physical values of heat propagation of steel and concrete. Use of these values in eq. (1) shows that for a given fireproofing (same value of l) and same structural dimension H, the fire protection time t of concrete is at least 5 times the one of steel. Furthermore, the characteristic size H of concrete members is generally much larger than the one of steel. Therefore, a combination of these two effects explains why fireproofing is generally not required for concrete. Indeed, because of its low heat conductivity, concrete in different forms is commonly employed as fireproofing material. For instance, shotcrete (that is a sprayed concrete) has been employed in the WTC for fireproofing the façade columns.

On the other hand, concrete members subjected to high temperatures exhibit a very particular behavior, known as spalling, that is the successive disintegration of surface layers of a concrete member similar to the peeling of an onion. Figure 25 displays spalling of the concrete cover of a reinforced concrete column subjected to heating. Spalling is an interesting phenomenon that is known to be related to the types of constituent materials, thermal stress concentrations, and is dependent of the behavior of the cement paste. The two physical mechanisms that affect the thermal stability of concrete members with regard to spalling are:



a) b)

Figure 19: Effect of heat on concrete after 2 hours of exposure to 1000°C Fire
(a) Fiber reinforced concrete and (b) Ordinary reinforced concrete
(Takenaka Co, 2000)

The compressive stress build-up due to restrained thermal expansion, which is readily understood as a combination of the low heat diffusivity of concrete and its thermal expansion behavior. Like most materials, concrete subjected to heating undergoes a thermal expansion. Because of the low diffusivity, the temperature rise is not uniform over the structural member, but restricted to a surface layer that is scaled in time by $x \propto \sqrt{Dt}$, while the rest of the section remains close to the initial temperature. Since a structural member cannot expand in a non-uniform fashion without disintegrating, the expansion in the surface layer is restrained, which induces high compressive stresses in the surface layer, on the order of the compressive strength of concrete per 100 Kelvin of temperature rise [Ulm et al., 1999a]. The stresses in the surface layer, therefore, reach quickly the compressive strength of concrete, which in turn is subjected to thermal softening (see Figure 23). Concrete, under such compressive stresses, typically fails in planes parallel to the surface.

The vapor pressure build-up due to vaporization of free water or moisture in concrete at high temperature. Concrete is made of cement, water and aggregates, and the material hardens by chemical reactions between cement and water. After hardening, part of the initial water remains in the pores of the material and is subjected, under normal conditions, to a very slow drying process, roughly 300 years for 1m of concrete. Hence, there is always some water left in concrete. At 100°C the liquid water becomes vapor, expanding in the pore space previously occupied by water. While the water–vapor phase change is an endothermic reaction, reducing a small part of the heat during vaporization, the vapor cannot expand within concrete or to the outside. Therefore, the vapor pressure increases, exerting an increasing pressure on the solid part of the concrete. This pressure reduces the confinement of the solid generated by the thermal compressive stresses, and increases the susceptibility of concrete to spalling, particularly in concrete with high moisture content.

A combination of these two phenomena leads to the spalling of the concrete surface layers with a rate of roughly 3 mm/min: The compressive stresses in the surface layer generated by restrained thermal expansion are released by explosive spalling of the surface layer, which disintegrates from the remaining section triggered by the vapor pressure. However, in contrast to steel, concrete sections in general are large, and therefore deterioration in layers from the fire exposed faces of a cross-section does not lead to a rapid catastrophic failure of the entire section. The remaining section remains intact, providing a built-in redundancy for the structural load bearing capacity. This built-in redundancy ensured, for instance, the stability of tunnel liners in recent long-term tunnel fires in several transport tunnels in Europe, such as the 1996 fire in the Channel tunnel, the 35 km tunnel connecting England with France [Ulm et al., 1999b]. Clearly, as far as material and structure is concerned, concrete is less sensitive to fire than steel, and therefore performs well in fires.

But, perhaps what is more important is that concrete, in contrast to steel, comes today in an almost infinite variety of mixes, that can be fine-tuned to generate a new material with a high degree of built-in redundancy. For instance, addition of polypropylene fibers to concrete mix is known to improve material behavior under fire by reducing spalling. This is because the fibers melt under high temperatures, leading to the increased porosity through which water vapor can escape. Figure 25 shows the stunning effect of such fibers on the thermal stability of a reinforced concrete member.

Still, we should note that this built-in redundancy on a material level affecting the structural performance of a member, becomes only efficient as part of a global structural system with built-in redundancies at multiple scales. Indeed, the use of reinforced concrete for the column cores in the WTC would have surely improved the thermal stability of the columns. However, prevention of the failure of the slab system would still require implementation of redundant end joint connections with respect to structural and fire proofing and perhaps, also provision of a reinforced concrete core tube system well integrated with the lateral load transfer mechanism within the building structure. Thus, a materials-to-structural sequence of failure highlights the necessity of redundancy at different scales, from the material level to the structural level, and beyond.

New technology of redundancy

We believe that a built-in redundancy in design and operation of mega-cities and society at large could significantly reduce vulnerability. Redundancy of a system may be defined as a provision of multiple added failure mechanisms that prevent the total system from collapse upon failure of single or several of its components. Therefore, implementation of redundancy in a system will improve its reliability. Redundancy in a system can be defined as that of the active type or the standby type. In the active redundancy all components of the system are simultaneously contributing to the system stability at all times. On the other hand, in the standby redundancy, some of the elements of the redundancy may be generally inactive and become active when some of the active redundancy components fail. Generally, redundant structural systems are examples of the active redundancy type. In the structural context, redundancy may be provided at the material as well as at the system level.

Fiber-reinforced material systems: a multiscale redundant system

A material possesses redundancy if it responds to the same action using more than one mechanism. Below we will illustrate this concept via the fire resistant mechanism of fiber reinforced cementitious composites, a high performance material that has gained increasing popularity in tall building as well as other infrastructure construction.

Recent advances in concrete science and engineering provide the basis for a fine tuned material design of concrete materials, which overcome the traditionally weaknesses of concrete-type materials, that is brittleness and low compressive strength compared to steel (steel typically has a strength that is 10 times higher than that of standard concrete). This brought about a totally new generation of High Performance Cementitious Composites (HP2C), which are based upon the optimization of both the packing density of the cementitious matrix, and the length-diameter spectrum of the reinforcing fibers. In comparison with ordinary concrete, HP2C materials have enhanced microstructural material properties and an enhanced material ductility obtained by incorporating small-sized steel or organic fibers. A typical HP2C mix-composition gives a mean 28 days cylinder compressive strength of 190 MPa, and a ductile tensile strength of 10-15 MPa. The high compressive strength-to-low mass density of this material makes it an ideal material for skyscrapers, in which weight is always a limiting factor. In fact compared to steel, HP2C is 30 to 50% more efficient in terms of strength-to-weight. Furthermore, the ductile tensile strength of HP2C is sufficiently large that one can employ this material without steel reinforcement. As to the fire performance, this is a first advantage of this material in comparison with standard concrete materials. But the real built-in redundancy with regard to fire resistance is that the polypropylene fibers in the material, which contribute in service to the ductile tensile behavior, melt under high temperatures, offering to the vapor an additional connected expansion space to escape. This second function of the fibers, which is only activated in the extreme case of a fire, reduces the susceptibility to spalling of the structural member, thus providing a superior structural performance of the structure under high temperature.

Furthermore, this new generation of high performance materials may well serve, in the future, for the retrofitting of existing structures. The low heat diffusivity combined with the high strength and low weight (compared to steel) of this new class of materials make it an ideal material for structural fireproofing in skyscrapers, which can fulfill more than one function: (1) increase of thermal inertia (like standard fire proofing materials), (2) increased mechanical resistance to blast loading, (3) structural load bearing capacity when the steel member thermally softens. The multi-functionality of this new class of materials can provide, if employed properly for retrofitting of steel members at a material to structural level, a built-in redundancy similar to a second or third airbag built into a car, which would inflate if the first ever failed. This built-in redundancy is a general principle of a sound engineering design, and encompasses materials and structures.

Acknowledgements

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Escaping with your life

John E. Fernandez
Assistant Professor of Architecture, Building Technology Program, MIT

Abstract

Of the many horrors of September 11, 2001, the sight of people falling and jumping to their deaths from the Towers of the World Trade Center will not be soon forgotten by anyone watching. The sight brutally expressed the desperation of those trapped above the raging fires, unable or unwilling to descend through the wounded structures. Even in light of the eventual collapse of the structures, the terrible situation above the crash locations made very clear a fundamental failing of escape strategies of all tall and supertall buildings. In the event of a catastrophic compromise of the emergency fire stairs, people trapped above the disaster have no options for escape. Rescue from above is dangerous and extremely time-consuming and waiting for fire suppression can risk many lives and cause unimaginable suffering. Also, in light of the recent collapse of the World Trade Center towers in New York City, it is clear that there may arise situations in which the amount of time necessary for a full evacuation of a tall building exceeds the amount of time that the structure can resist instability and collapse. Therefore, there is an existing need to investigate building systems that provide augmented means that substantially increase the efficiency with which people may be evacuated and protected during these catastrophic events. This article proposes several augmentations of existing egress systems while accepting current net to gross floor area ratios necessary for these types of buildings to remain economically and operationally practical. Under moderate emergency conditions, such as small and localized fires, emergency systems in tall buildings have performed well. However, during catastrophic events tall buildings are challenged with exceedingly difficult egress scenarios, fire suppression demands and structural performance requirements. As a result of very large occupancies, limited floor space and the increasing heights of the most recent tall buildings, the challenge of quickly and completely evacuating the interior spaces of these types of buildings should again be addressed. Building codes, both local and national have established a high level of design and specification for fire ratings, alarms, communication systems, suppression technologies and evacuation plans that address the life-threatening conditions of a tall building emergency. This paper does not intend to question the effectiveness of these existing regulations. This proposals contained within are assessed in terms of their potential effectiveness in alleviating current problems during emergency situations as well as the practicality of their inclusion in both new designs and existing buildings.

1.1 Introduction

The modern tall building is one of only a select few architectural types that can legitimately claim a decidedly American origin. During the late 19th and early 20th centuries several buildings in the United States signaled a new age of structural engineering and architectural form at the service of increasingly dense and intense central business districts. The Carson Pirie Scott Department Store (Chicago, 1894), the Guaranty Building (Buffalo, 1895), and the Reliance Building (Chicago, 1895), among others, initiated the entry of the tall building into urbanism as a viable economic response to the pressures of the densification of modern central business districts. The first tall buildings were massive masonry structures with bearing walls that reached a thickness of 6-8 feet at their lowest levels. However, the rise of the tall building, as a new type of urban structure, truly began with the first steel structural frames [1][2][3]. The Woolworth Building (New York, 1913), one of the earliest structural steel frames, retained its title as world's tallest building for 17 years until the construction of the Chrysler Building. Eventually, engineers invented any number of structural technologies that made very tall buildings possible. A very tall building is normally referred to as *supertall* when it reaches 80 stories or more.

In concert with the development of structural technologies and safe elevators to lift occupied space ever higher into the sky came building systems to support and protect life. These systems include the strategies and technologies necessary for aiding in the safe and quick evacuation of people from a building that has become dangerous to its occupants. The regulation of the design of these structures, as with any legally occupied building, has been the mandate of the national and local building codes. However, because of the performance requirements of these specialized buildings, the designers, both architects and engineers, have consistently specified systems that have exceeded required code expectations. It is important to note that the performance demands that structural engineers have asked of their frames has often far exceeded the stated structural codes under which the design work was regulated. One reason for this is the obvious need to insure an extra level of care in responding to the demands of a building type so heavily occupied and affected by factors such as earthquakes and the variability of the lateral wind load. Many designs have exceeded the stiffness stipulated under building codes specifically to establish a generally accepted level of comfort for those working and living in very tall buildings. During the design of the World Trade Center, Leslie Robertson took into account detailed studies that stipulated the proportion of the building population adversely affected by various levels of lateral acceleration due to wind load. In other words, the culture of structural and life safety design for tall buildings has been one of innovation and specification that goes well beyond the legally regulated performance requirements of these types of buildings.

However, in response to the recent tragedy in New York City, the terrible collapse of not one but two of the largest structures in the world and the largest in the city, another round of evaluation needs to occur to continue innovation of emergency systems for tall buildings. This need is particularly pressing because of the anticipated new crop of supertall buildings to be built around the world. In the aftermath of the WTC collapse, some projects in their financing and planning stages may be postponed indefinitely, however many other projects will undoubtedly continue through design and construction. Currently, projects being planned include the Shanghai World Financial Center at 1,509 feet, the Center of India Tower in Katangi at 2,222 feet and 7 South Dearborn in Chicago at 2,000 feet. The World Trade Centers extended to the height of 1,420 feet (1,350 feet above grade + 70 feet below). If only these three planned towers are built, they would collectively accommodate a total population of something like 120,000 people.

1.2 Working assumptions of egress for tall buildings

Innovation in architectural technologies may be characterized as following a fitful series of small breakthroughs that lead to occasional paradigm shifts. With the invention of ever-higher structures has come a steady stream of improvement that has allowed designers to periodically discount any notion of an upper height limit. The recent few decades have shown that the actual limit to the height and bulk of tall buildings has been the amount of capital available for investment in such large projects - not the technology necessary to realize them.

Emergency systems have also evolved alongside the structure, exterior envelope, mechanical, vertical transportation, and interior partition and finishing systems of these large towers. Even though these systems have performed well, it is understood that these buildings are designed under certain fundamental assumptions that may not be compromised and are particular only to tall buildings. We will consider two primary assumptions here:

1. during an emergency event, the vertical egress path – the path of safe escape from the building - may not be critically compromised; that is, this egress path is the only route provided to persons that need to evacuate the building, Figures 1 and 2, and
2. the amount of space allocated to the egress path is sufficient, and therefore the amount of time for egress is not excessive, either for the structure to maintain its integrity as a load bearing and transfer system, or for any other necessary building system to perform properly to sustain life in the building.

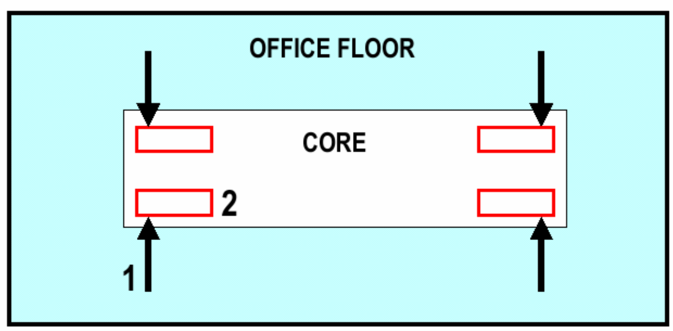


Figure 1: Typical tall building egress strategy

1: Egress entry
2: Rated fire stair

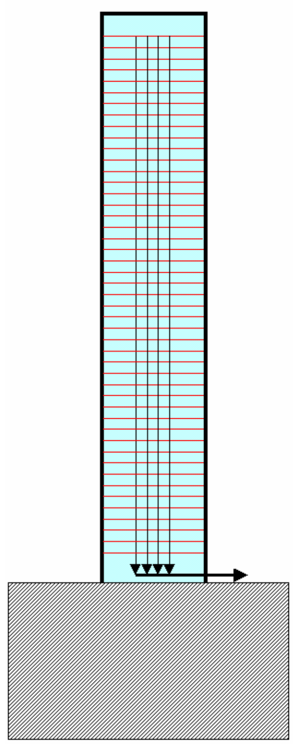
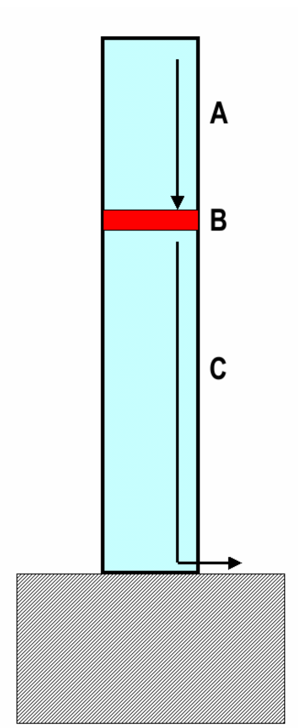


Figure 2: Typical tall building egress strategy

This paper specifically addresses these two assumptions by noting that very tall buildings may not sufficiently provide adequate egress space or alternative paths for evacuation given that the amount of time necessary for a full evacuation has been known to exceed 2, 3 and sometimes 4 hours. In addition, it is obvious that there always exists the potential for the vertical path to be severed. In that case, there is currently no good solution for quick evacuation of trapped persons. This is the issue that this paper addresses.

It is obvious that a tall building is like no other contemporary building type in that a significant amount of the volume of the building, usually the vast majority, occurs at heights that often far exceed the reach of even the tallest evacuation ladders. In any supertall building, at an average floor to floor height of 12 ft. 4 inches, the 80th floor is at a height of approximately 980 feet above grade. Even assuming that those at and below 80 floors could be rescued somehow, even if the regular egress path was compromised, those above 80 floors do not have an alternative path of travel to safety. Given the average level of occupation per floor of many supertall towers, this may leave many hundreds, if not thousands, of people trapped if the regular egress path is rendered, or perceived to be, impassable. Therefore, those above the emergency have little ability to evacuate. Ron Hamburger, chief structural engineer for ABC Consulting New York and a member of the performance-review team assigned by the Federal Emergency Management Agency to review the collapse of the World Trade Center, has stated that this particular situation requires attention [4]. In addition, augmented egress was identified as a primary concern by the FEMA team in its report to Congress submitted in May of 2002 [5].



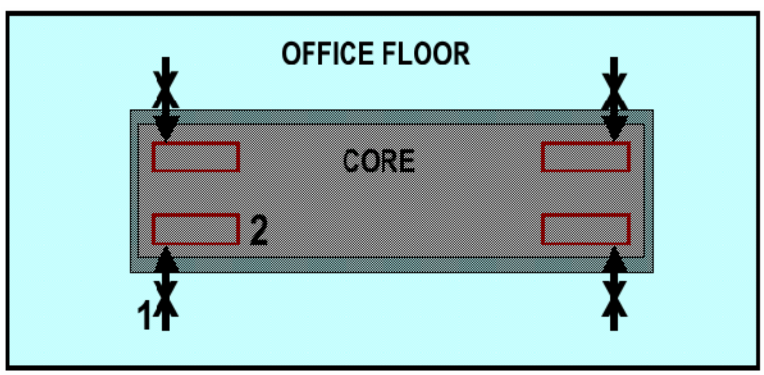


Figure 3: Compromised building egress within zones A and B

1: Egress entry
2: Rated fire stair

Figure 4: Building Zones

A: Above Event Zone
B: Event Zone
C: Below Event Zone

1.3 The Event Zone

For the purpose of addressing these issues, the study poses the following scenario in which an emergency event occurs within the shaft of a supertall structure.
In Figure 4, zone B designates the Event Zone; the volume of one or more floors in which a catastrophic event is occurring. Zone A corresponds to those occupied floors above the Event Zone. Zone C designates those floors below the Event Zone. In the event that zone B has become an impassable obstacle within the building, those persons above this area have very limited possibilities for quick evacuation. For the most part, accepted rescue strategy entails first the evacuation of individuals en masse, and then, treatment of the event zone by emergency personnel. Under these conditions, it is also possible to evacuate people within zone A from the roof with a helicopter. However, this strategy is risky and can only move a small number of people in discrete increments. In any case, those in zone A will not have the option of a quick evacuation. The occupied floors within zone B may or may not have the option of evacuation. The possibility for escape within this volume is highly dependent on the nature of the event and the status of the vertical egress volumes of the fire stairs and exits at each floor in this zone. Those in zone C may proceed to evacuate the building in the usual way. It is also possible for there to be an obstruction that prevents occupants of any particular floor to access the emergency stairs, Figure 3. In this case again, the occupants have no options for alternative evacuation.

Let us return to the two assumptions that we are addressing.

The first assumption is that the vertical egress circulation system, the fire stairs and the rated corridors leading to them, will not be compromised. These fire-rated enclosures are the designated paths for leaving the building under the protection of the shaft from higher temperatures, smoke and fumes. Those in the building that find themselves below the location of an emergency are in the best position to simply descend through the egress path and out into the public way. Those located above or at the same level as the event may or may not find that their path vertically downward is still intact. If the path is compromised, currently there is no good solution to this difficult situation. It is now clear that during the attacks on September 11, the vertical paths from those floors above the crash locations were either critically compromised or perceived to be impassable. Those above the crash location could not or did not feel that they could evacuate before the collapse of the buildings occurred. It is clear they either did not have this egress option or perceived it to have been rendered impassable. Given the severity of the explosion it is likely that the fire-rated shafts of many of the egress stairs were completely destroyed and rendered impassable. The strongest evidence of this are the telephone calls received from inside the building that suggest that those above the crash site knew that escape downwards was no longer possible. However, four people from above the crash locations made their way down the fire stairs. It is clear now that there still existed a single and possibly several egress stairs that were passable. The critical element in restricting people from using these stairs was the perception of impassability.

In addition, the stairs were all located in the central core of the building and it was a reasonable assumption to believe that the core, in its entirety, had been destroyed. There is no better proof of the desperation of those trapped above the crash locations than the horrific choice made to jump from the windows of the towers.

The second assumption is that the amount of space provided for egress has been sufficient for the quick and efficient evacuation of tall buildings. Again, indications from the recent events in New York and also from the bombing of those same buildings on February 26, 1993, seem to indicate that the space required for egress in tall buildings is simply inadequate for the rapid evacuation of the enormous population attempting to leave the buildings. There is the need to provide both a greater number of egress paths that contribute a substantial increase in the available egress path width over and above current practice. In addition, there is a need to provide for egress paths that provide an alternate route away from a damaged core. Finally, the strategy of phased evacuation of tall buildings needs to be revisited.

2.0 Redundant and Complementary Systems

In the days following the collapse of the towers, a number of articles were written in the popular press that speculated on ways in which to better evacuate persons trapped in tall buildings and fortify the structure of these types of buildings. While there have been opinions stated in and outside of the design and engineering professions that the future of the tall building [6] has dimmed significantly, the overriding reaction has been to acknowledge that tall buildings will continue to be built; as tall and taller than ever. The discussion has now shifted toward strategies in which to make the structures and evacuation systems of these buildings more robust. Various types of technologies have been cited as having a potential to improve the egress situation. While several of those technologies are mentioned here, the following sections are meant to emphasize the need for a reevaluation of the emergency egress systems that assist people during an emergency situation.

2.1 System 1: Alternate Egress Systems

It has been shown in a study by Fahy and Proulx [7], that the overall response to emergency situations is a complex combination of seemingly unpredictable human behavior, actions based on previous training, imperfect and conflicting information and many other factors often uniquely particular to the building and situation itself. The researchers identified 6 meaningful stages of response in the 1993 bombing of the World Trade Centers:

1. Investigate
2. Seek information
3. Alert or report
4. Assist others
5. Seek refuge
6. Wait

These stages suggest that the decision by each individual to evacuate is far from instantaneous. The decision to leave the building is arrived at after having considered various pieces of information from as many sources as possible. In 1993, the amount of time between the initial blast and leaving the building ranged from a few minutes to 4.8 hours in Tower 1 and again from a few minutes to 3.8 hours in Tower 2, as recorded in the study [7]. The study also recorded mean times of 11.3 and 25.4 minutes and median times of 5 and 10 minutes respectively. Clearly, the decision to evacuate was neither instantaneous nor unanimous.

Since the 1993 bombing the conditions within the fire stairs had been improved, with better lighting and signage. However, the evacuation of the towers was still not accomplished with the speed necessary to fully empty the buildings before their collapse. In 1993, over 70% of those from Tower 2 (in which accurate responses were received [7]), reported leaving the building in an hour or less. Only 40% of the respondents from Tower 1 were able to leave in an hour or less. Many of those that took longer to evacuate delayed in leaving the buildings after the initial blast. Egress strategies should begin to address this lag in the decision to evacuate by offering alternate routes in which to exit quickly by relieving pressure on the primary egress path. There is no doubt that evacuation times were improved during the recent partial evacuation of the towers. Within a very short time, most occupants of the tower that could evacuate did.

Even though egress times for the recent tragedy at the WTC were vastly reduced from the 1993 bombing, we can safely assume that this can be attributed, to some extent, to the increase in training that workers received after that attack. This heightened level of experience and training is not something that we can safely assume for all supertall buildings.

Most contemporary buildings designed in the U.S. are required to document a well-conceived egress strategy. The egress components, in outline, consist of the following elements [8]:

1. means of egress: a continuous and unobstructed path of travel from any point in a building or structure to a public way,
2. corridor: an enclosed passageway which limits the means of egress to a single path,
3. common path of travel: that portion of exit access which the occupants are required to traverse before two separate and distinct paths of travel to two exits are available,
4. exit: that portion of a means of egress which is separated from all other spaces of a building or structure by construction and opening protectives as required for exits to provide a way of travel to the exit discharge,
5. exit access: that portion of a means of egress which leads to an entrance of an exit,
6. exit discharge: that portion of a means of egress between the termination of an exit and a public way.
7. exit, horizontal: A way of passage from one building to an area of refuge in another building on approximately the same level.

All of these components together form the path of travel from any space inside the building to a public way. The egress path down through a tall building essentially consists of the path to the fire rated enclosure of the stair and the descent, within this rated volume, down to the public way. As buildings exceed 50 stories a substantial percentage of the floor space is consumed by the necessary shaftways for elevators and mechanical components as well as bathrooms and other service spaces. Therefore, the path to the fire stair is often easily made. However, once inside a stairwell the path down 50 or more stories is a long and arduous journey, made slower, in a building-wide evacuation, with congestion from the large population of the building. In addition, while the width of the stair may not decrease, by law, it is clear that the stair width does not increase enough for the accommodation of a variety of rates of descent. The slower evacuees necessarily substantially determine the rate of descent for all. To provide for an dramatically increasing stair width in proportion to the number of people in tall buildings would very quickly become a prohibitive incursion into the usable net office space of the building and render the building types uneconomical. As a result, tall buildings have come to accept a lower level of accommodation in minimum required egress dimensions as a necessary functional demand of the building type. Therefore, there exists a critical need to reexamine the possible ways in which a tall building may provide for the necessary width of egress travel appropriate for the population of the building. The following sections describe three types of ideas to enhance egress:

1. interior egress paths: using existing shafts to accommodate vertical egress paths systems,
2. exterior egress paths: using the exterior wall assembly to support additional egress systems, and
3. adjacent building egress paths: using adjacent buildings as an alternate path by bridging over to their exterior walls, roofs and accessing the adjacent building's interior egress paths.

All three types of additional paths are meant to provide a significant increase in egress area far beyond what can currently be proposed for tall buildings, for both complete building evacuation and the circumvention of localized failures in the primary egress path. These strategies will not impose a prohibitive incursion into the net area of the building's floor space.

2.1.1 Interior Egress Paths

Using various continuous interior volumes that are commonly found in all tall buildings, new and old, additional interior egress may be provided. Currently, fire rated stair shafts are the only path of egress in an overwhelming majority of tall buildings. This first proposal identifies the elevator shafts in tall buildings as additional egress pathways. These shafts are continuous volumes that currently sit idle during a fire. With the exception of the use of elevators by emergency rescue personnel, the elevators themselves are not operated during an emergency because of the risk to occupants.

Tall buildings may devote 10-15% of gross floor area to elevator shafts. The numbers of elevators necessary to practically service the population of the building particularly encumbers buildings above 50 stories. Elevators are available to be devoted to providing additional egress by containing, within their rated shafts, a folding stair that may be placed into service for use by the occupants during an emergency. In addition, one of these shaftways could be devoted to providing mechanisms for lowering disabled and physically compromised people down to the ground. The situation of a disabled person trapped in a tall building needs to be better addressed both for the individual and those that are encumbered to assist the person down stairs. This would free up further primary egress space for evacuation and also allow a separation between circulation devoted to emergency personnel and that dedicated to egress.
Other systems may also provide an alternative way in which to bring people down to the ground faster. Fire rated shoots made of fire resistant textiles can be placed within elevator shafts and quickly deployed to allow an alternate route down for people.

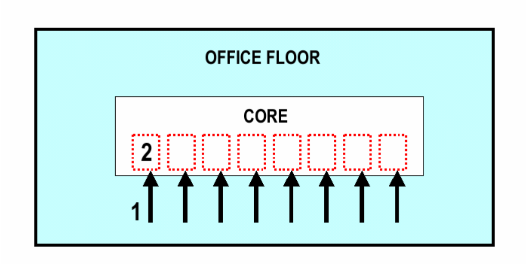


Figure 5: Elevator Shaft Egress Strategy

1: Egress Entry
2: Rated Elevator Shaft

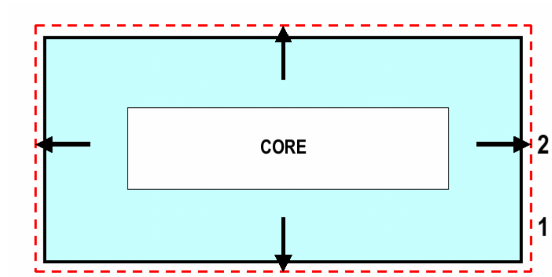


Figure 6: Exterior Wall Egress Strategy

1: Egress Path, across and down
2: Egress Entry

Another set of continuous shaft spaces are the mechanical servicing shafts for the building, but because these shafts are permanently occupied with air distribution ductwork and plenums and other equipment, these shafts are not practical volumes to be used for alternative egress paths. In addition, very tall buildings often contain more than one mechanical plant. These plants are distributed through the building on various floors making the shafts that are distributed from each not continuous throughout the entire building.

This particular augmentation of the vertical volume available for egress does not offer a solution to the situation in which all elements within the critical zone have been compromised. In that scenario, the elevator shafts would also become impassable. In Figure 4, the elevator shafts are assumed to be impassable as the emergency stairs are. In this scenario, that of a catastrophic severing of the egress path, additional strategies need to be employed to bypass the event zone. Any strategy that uses th core as the location for an egress path may risk becoming unworkable in the event that the core is severely compromised. Additional strategies are, therefore, required.

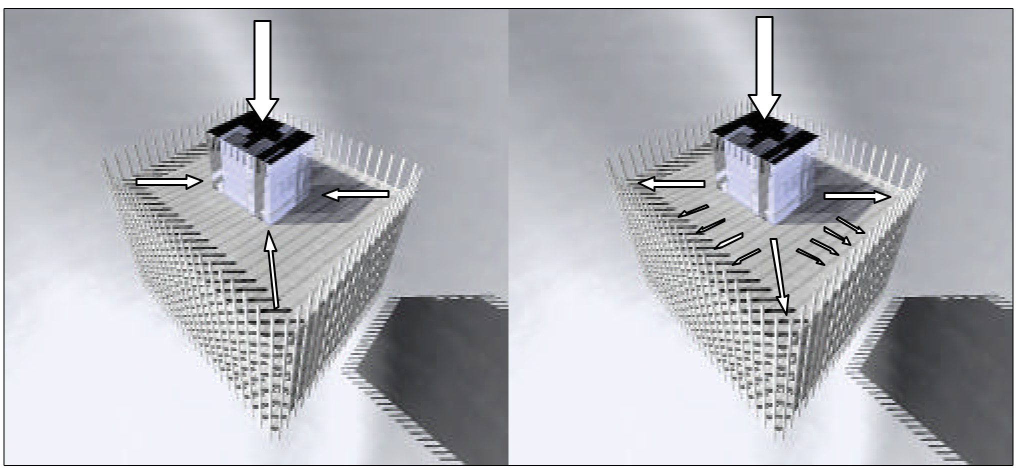


Figure 7: Egress concentrated at core

Figure 8: Egress also available at perimeter wall

2.1.2 Exterior Egress Paths

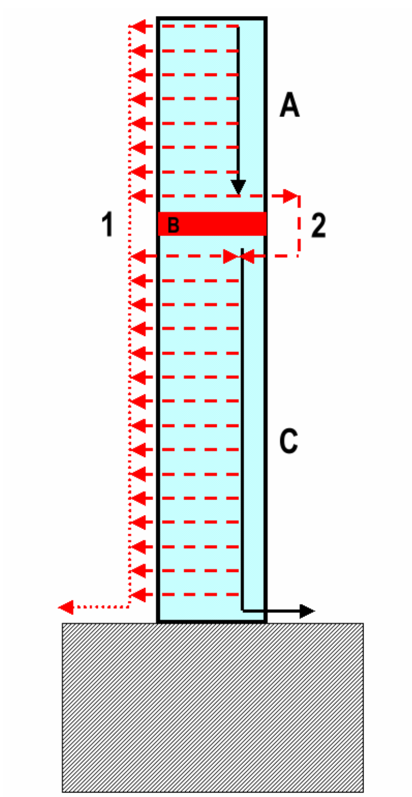
The exterior perimeter surfaces of tall buildings also offer a structural armature for the support of evacuation systems that could form an augmented egress strategy for tall buildings, Figure 8. This alternative egress provides additional paths to be used in the event of an emergency. These paths could be used in two modes depending on the need:

1) increased egress routes supplementing uncompromised egress paths, and
2) alternate egress routes in the event that the internal rated stair paths have been compromised.

The exterior (perimeter wall) egress system could provide a path down the full length of the building; Figure 9, path 1, or in the case of the second mode, as a path to circumvent the floors that have been rendered impassable within the event zone; Figure 9, path 2. In this second case, an exterior egress system serves as an emergency backup when the normal egress path is too dangerous to follow. In very tall buildings, this is a possible solution to a very real need that has not been addressed; the case of those persons caught above an imp assable event zone. The most reasonable application of this system will be at those heights above the reach of ladder trucks.

2.1.3 Adjacent-Building Egress Paths

In situations of extremely high urban density, alternate escape routes need to be coordinated between adjacent existing and new buildings. These alternate paths would require only that a continuous route be provided from one tower over to another. In the case of many tall buildings, this strategy makes the most sense as restricted to the upper floors of the buildings thus providing an alternative to those that would require the most amount of time to egress the structure, see Figure 10.



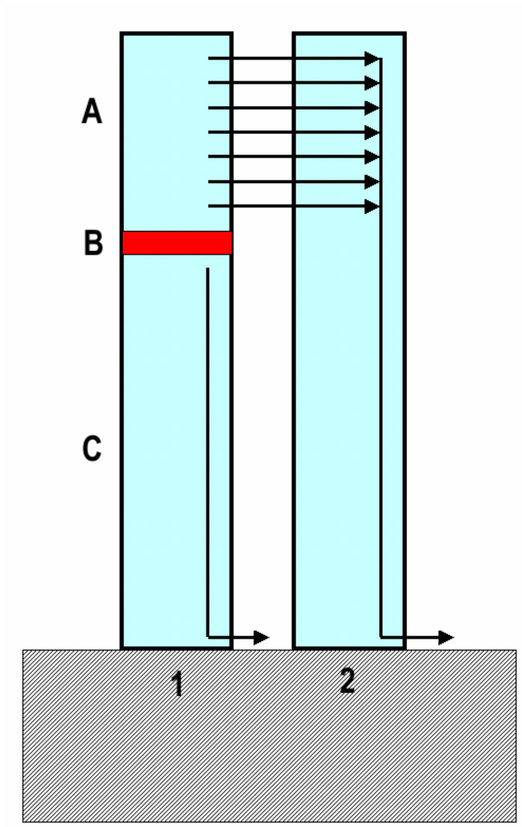


Figure 9: Exterior Egress Path

Figure 10: Egress path through an adjacent building

1. Building-wide alternate path
2. Event zone bypass

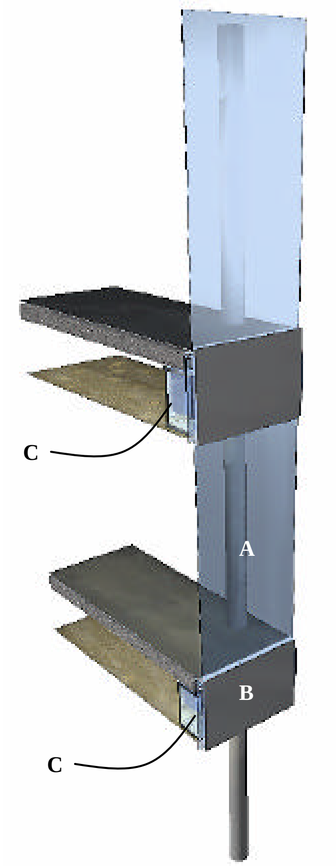


Figure 11: Section of curtainwall with integral perimeter wall escape mechanism.

A. Glazing system
B. Spandrel panel
C. Deployable escape device

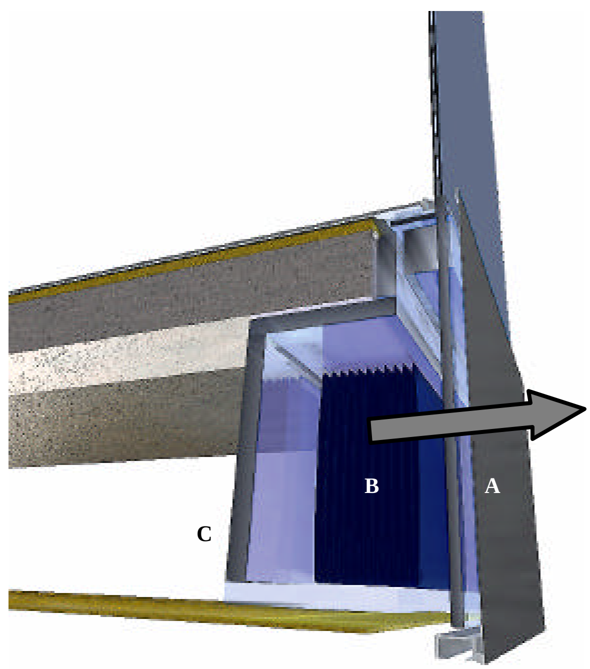


Figure 12: Detail at spandrel panel

A. Removable spandrel panel
B. Stored deployable escape device
C. Fire-protected enclosure

Three distinct configurations of the adjacent-building egress path are illustrated in Figures 13 A, B and C. These conditions are also illustrated to show that the more highly dense cities of the world already contain numerous opportunities for making links between buildings. As these cities become denser, these opportunities will only increase and the planning for cooperation between buildings will become more important.
The images shown are all taken in New York City.

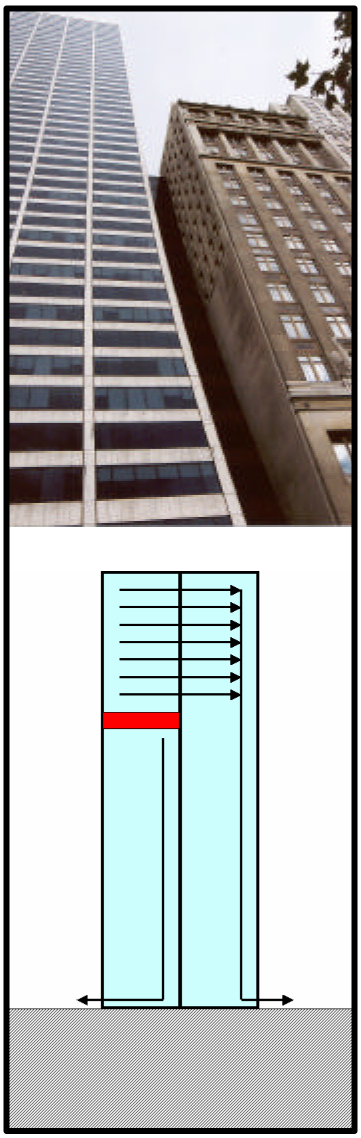


Figure 13A: Adjacent Building Egress

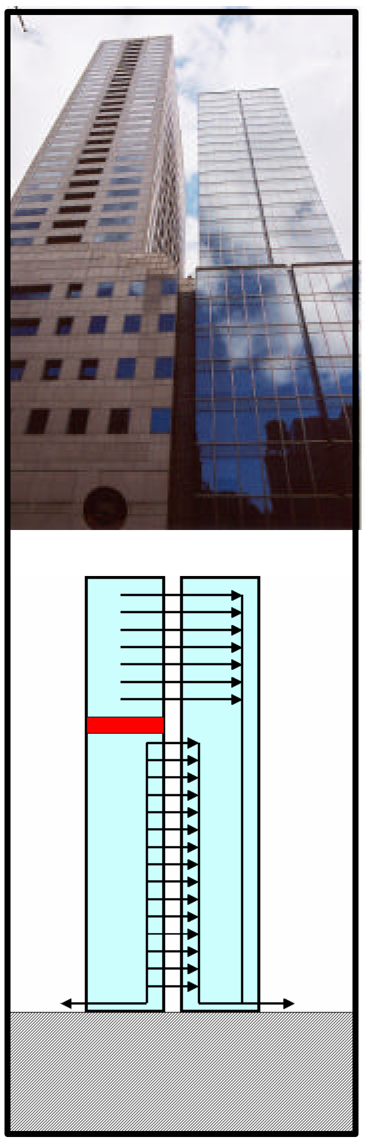


Figure 13B: Adjacent Building Egress

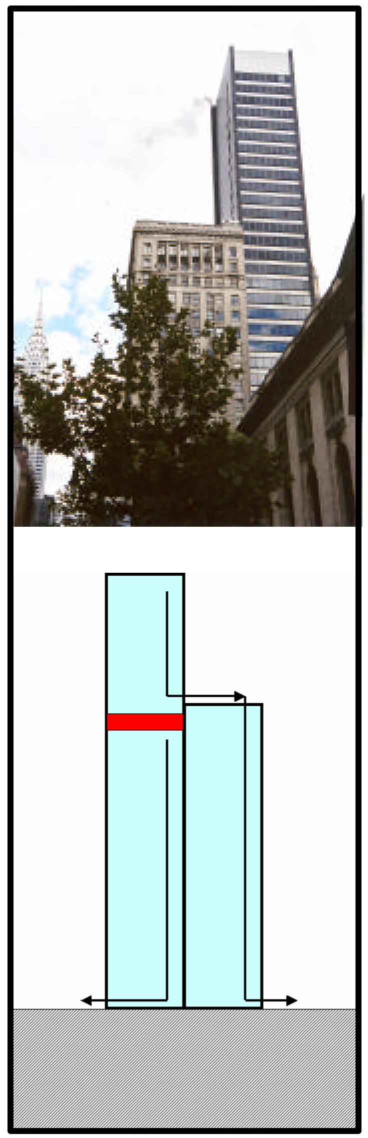


Figure 13C: Adjacent Building Egress

The bypass of the event zone requires devices that can be easily deployed and operated such that persons trapped under dire conditions can avail themselves of this alternate egress path. The materials best suited for this kind of device are fire resistant textiles of high tensile strengths and high impact tolerance. The best textile assembly would most likely involve several layers engineered to deliver and protect individuals from one floor to the next. For the sake of economy and the minimization of storage space necessary in the undeployed state, these types of devices may be best suited to delivery of individuals at maximum distances of several floors, say three or four floors at the most. Most fires in tall buildings have not extended much beyond several floors. In addition, there is also the possibility of linking individual lengths of escape chutes to make longer runs if necessary.

As shown in Figures 11 and 12, the material may be gathered and contained within the spandrel panel of the exterior curtainwall system. This space is typically free of mechanical ductwork, lighting and structure. Inserting a fire resistant cavity between the finish ceiling and the underside of the structural slab would be a relatively easy process, both in new designs and retrofits for existing buildings. The deployment of the system could be achieved manually, thus not relying on continuous power during an emergency. The fabric would drop down and out quickly assuming a tube form that would allow one to descend several floors at a time as shown below in Figures 14 and 15.

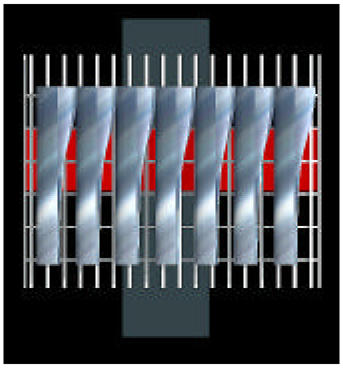


Figure 14: Elevation showing egress chutes deployed

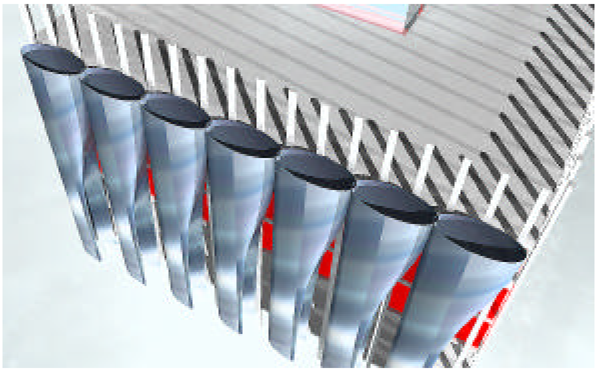


Figure 15: View from above

Several designs are shown for illustration purposes only in Figures 16 - 19. The images show deployable systems in different geometric configurations. The implications of such an approach are numerous and will require substantial further study. However, the intent can be clearly described as a non-centralized, manually deployed egress armature that contains either a tensile fabric that works by acting as an escape chute or contains within it a folding lightweight stair that is supported by the fabric membrane. The advantages of a fire-resistant fabric material are the ability to be easily deployed, lightweight and foldable. In addition, the space contained within the fabric enclosure may be pressurized from the ground and therefore smoke may be removed.

In addition, Figure 20 shows the side of a tower covered in an alternate egress system as shown deployed.

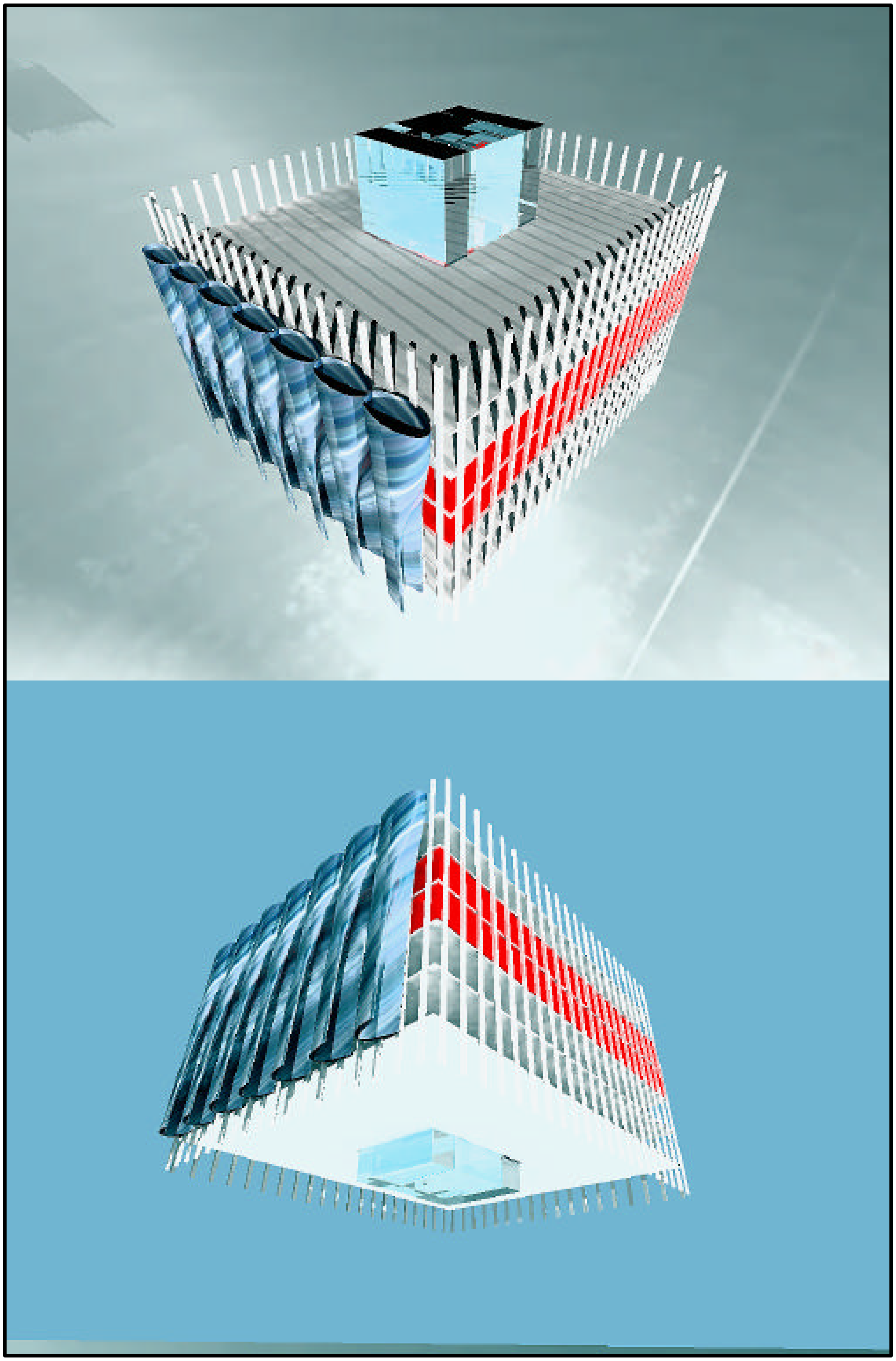


Figure 16: Deployed fire-resistant textile egress chute.

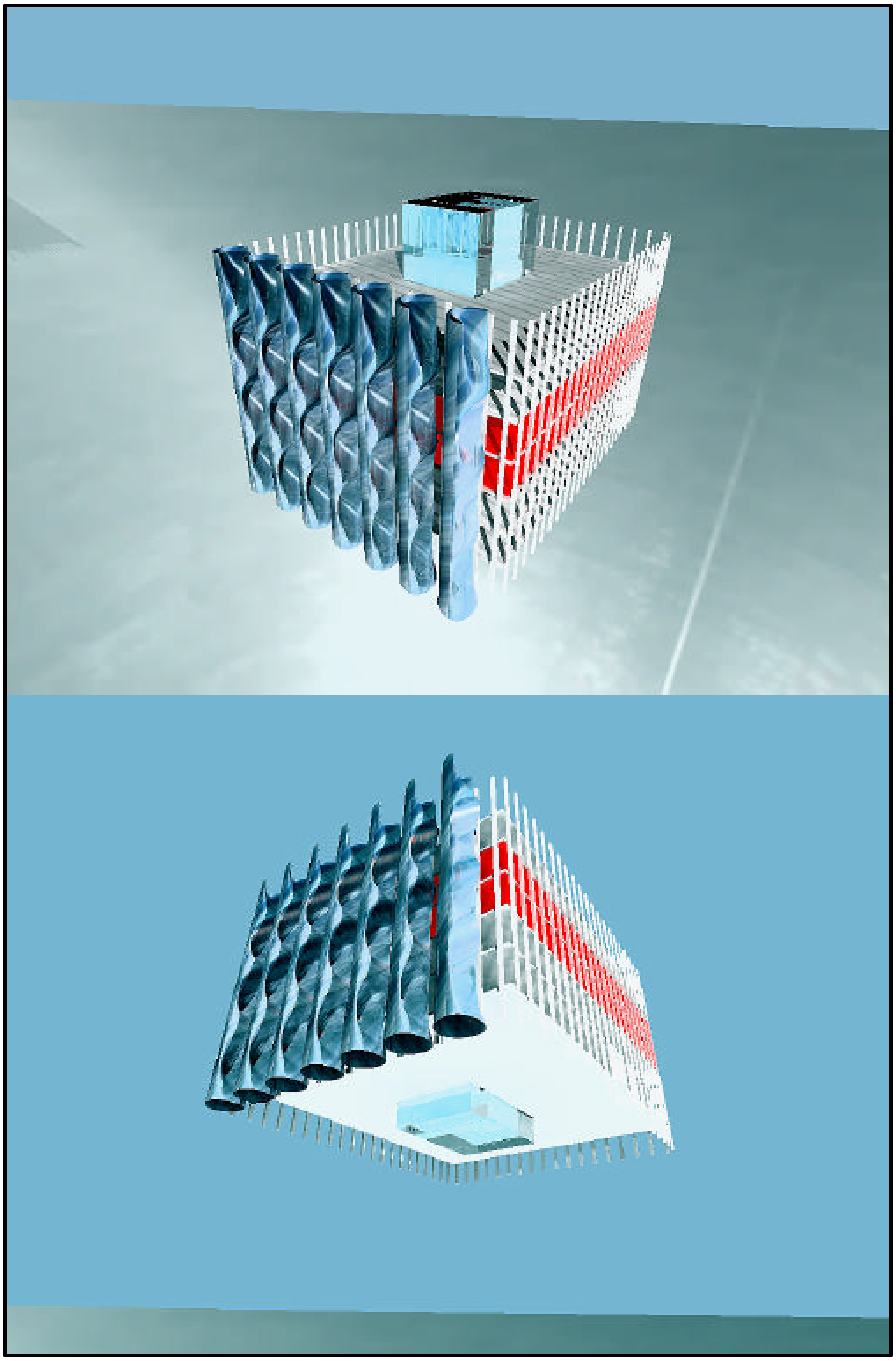


Figure 17: Deployed fire-resistant textile egress chute.

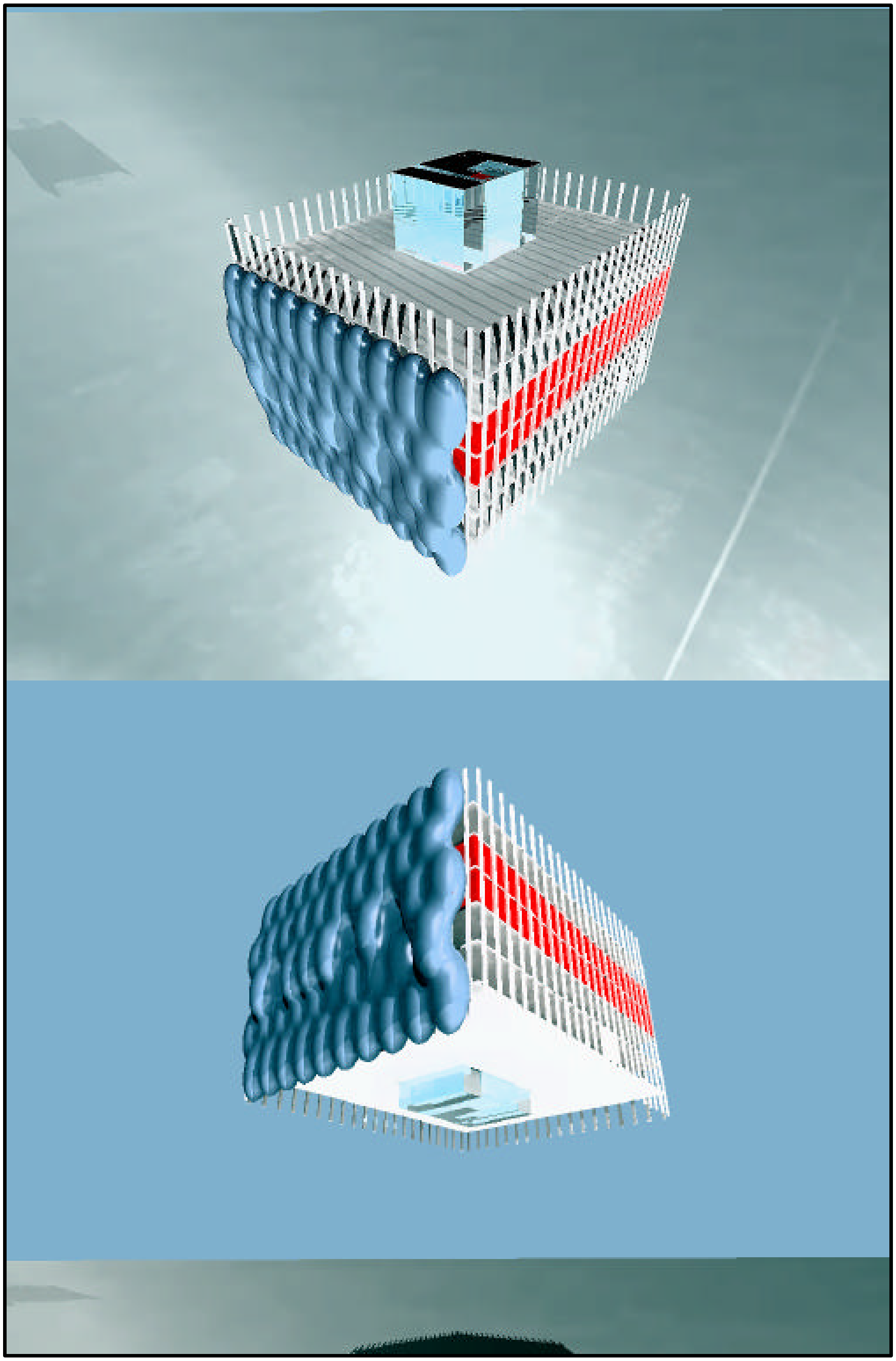


Figure 18: Deployed fire-resistant textile egress chute.

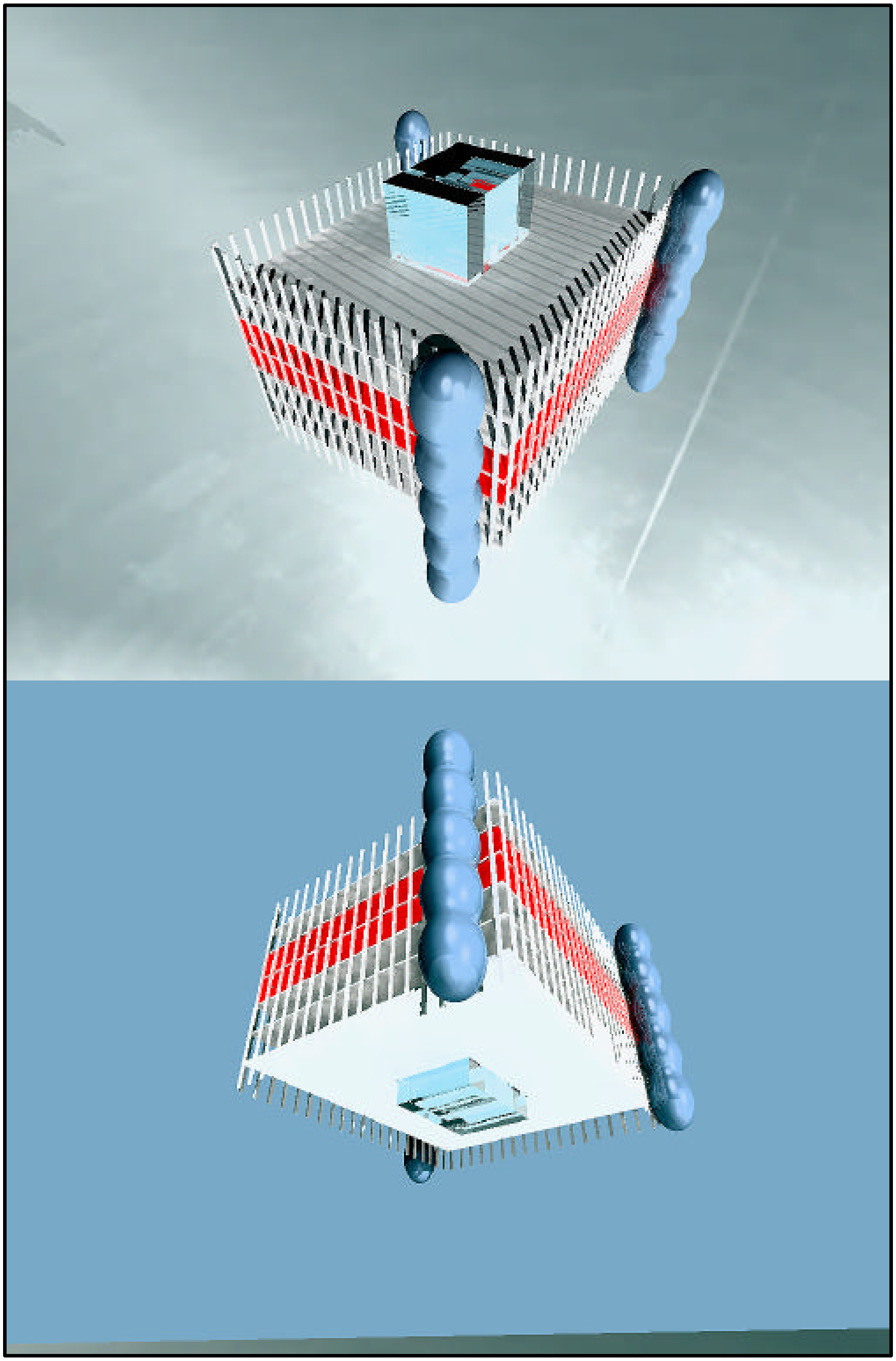


Figure 19: Deployed fire-resistant textile egress chute.

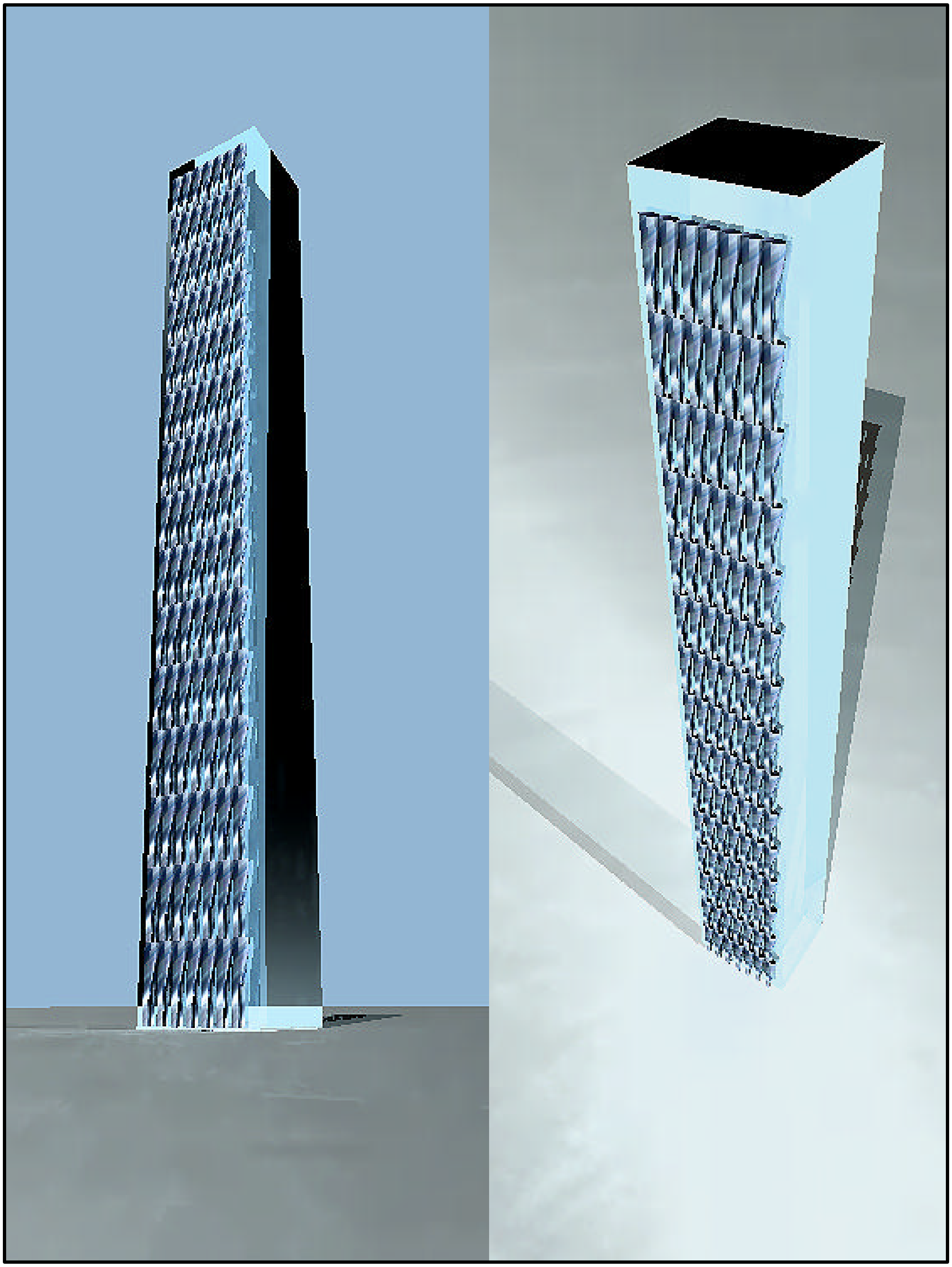


Figure 20: Deployed fire-resistant textile egress chute.

3. Experimental Rescue Devices

In contrast to the strategies mentioned above, several alternative technologies have been receiving some attention in the popular press [9][10][11]. These technologies include the following:

- ladders: deployable climbing devices for lowering oneself down to the ground,
- rope and pulley systems: especially relevant in the case of handicapped or otherwise incapacitated person rescue,
- escape shoots: woven fabric shoots that may be deployed for descent either to an adjacent building or down to the street below and while the limit is dependent on the manufacturer there is at least one company that markets a shoot that extends 15 floors or more,
- perimeter wall rescue vehicles: the adaptation of a common technology for the maintenance of the exterior envelope, platforms that descend from an armature secured to the building could provide a method for collecting and lowering trapped persons,
- rescue vehicles: a reexamination of rescue helicopters is being reconsidered and hovering platforms are also being investigated as ways in which to provide an exterior escape route that is completely independent of the building itself,
- emergency building escape parachute systems: individual low-altitude deployment parachutes used as a last resort in exiting a building.

Of these six alternatives, the fourth - perimeter wall rescue vehicles - would seem to hold the most promise because of existing perfected technology for automatic window washing and the ease of incorporating such a system into the exterior envelope of a tall building. The adaptation of such a platform would be a relatively trivial task. Furthermore, the rescue vehicle could be automated and deployed on any side of the building thereby avoiding parts of the exterior wall that may be engulfed in flames. Such a system could also be used to shuttle firefighters and their equipment up to locations in the building without the need for climbing stairs and without traveling through egress stairways being used by people trying to leave the building. In contrast, both the escape shoot and the independent rescue vehicle (helicopter or flying platform) engender far greater risks in transfer, balance and ultimately successful rescue of persons. Finally, the perimeter envelope rescue vehicle would require the least amount of physical agility of its users and would therefore accommodate the widest possible population of trapped persons. It could even be designed to assist with the rescue of those trapped in wheelchairs.

Ladders and rope and pulley systems are less attractive solutions because of the relatively high level of physical agility needed for each. In some circumstances however, the use of a rope and pulley system may assist in the delivery of handicapped persons down to the ground, as mentioned earlier.

While it is true that three people had successfully parachuted from the World Trade Towers in separate stunts over the years, the risks inherent in parachute systems are extremely high and can only be considered as an absolute last resort.
However, all of these ideas should be investigated for their possible utility in addressing the conditions of a catastrophic emergency.

4. Conclusions

A suite of egress strategies has been presented for the augmentation of safety systems for tall buildings. These ideas are meant to promote a general reevaluation of the methods and standards by which tall buildings are designed for egress in the event of a catastrophic event. The strategies presented here are intended to provide two things:

1. alternate paths of egress in the case of the critical compromise of the primary path, and
2. additional paths of egress to alleviate congestion in the primary path and provide a more efficient evacuation sequence for the entire building.

While there are numerous egress technologies that are receiving attention, the addition of redundant and complementary egress paths and their configurations, such that they may allow for passage around a critically damaged portion of the building, may substantially increase the safety of tall buildings under catastrophic emergency conditions. Further study is needed to develop those systems - lightweight deployable kinetic stairs, rescue vehicles and chutes - that may be incorporated into the exterior envelope and elevator shafts of existing and future supertall buildings. In any case, the issue of efficient passage to safety from any location in a tall building needs to be comprehensively addressed and a greater variety of egress options should be developed.

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Supply chains and terrorism

Yossi Sheffi
Professor of Civil and Environmental Engineering

Abstract

On the morning of September 11th, 2001 the United States and the Western world entered a new era – one in which indiscriminate terrorist acts of all kinds must be expected. Many, if not most, of the expected consequences of the new era will be reflected in supply chain management challenges: relations with suppliers and customers, transportation difficulties and revised inventory management strategies.

This article looks at the twin corporate challenges of preparing for new terrorist attacks, and of operating under heightened security resulting in less reliable lead times and less certain demand scenarios. In addition it looks at how companies should organize to meet those challenges efficiently and the new role that public-private partnerships are likely to play.

To prepare for terrorist attacks, firms should revise their inventory management posture and keep strategic inventory on hand. This does not mean that they should abandon just-in-time principles since JIT brought about better quality, higher accountability and better productivity, in addition to reduction in inventory carrying cots. Instead, firms should manage the strategic inventory in a JIT fashion. Similarly, firms should not abandon offshore procurement. Instead, they should organize to run dual procurement systems where the bulk of the material is bought from inexpensive and innovative offshore suppliers, and at the same time, a portion of the business is given to a local supplier who can pick up the slack in case an attack disrupts transportation lanes. Both of these examples can be analyzed in the context of real options where the dual supplier or the extra inventory buys the firm the ability to continue manufacturing after an attack.

To keep operating in an environment where security measures mean less reliable lead times, supply chain managers should focus on methods that they have always used to deal with uncertain supply chain. These include investments in better visibility measures, configuration of manufacturing systems for postponement and make-to-order, and the use of risk pooling strategies.

In preparation for another attack and as part of the effort to foil it, companies should redesign their systems with security in mind. Thus this article calls for the establishment of a Chief Security Officer and for the creating of a security culture similar to the sales culture of the 1970-s and the quality culture of the 1980-s and 1990-s. In addition the article calls for a public-private partnership focused on sharing data and knowledge at all levels.

1 The challenge

Shortly after the September 11th 2001 terrorist attack, many manufacturers experienced disruptions to the flow of raw material and parts into manufacturing plants. For example, Ford had to idle several of its assembly lines intermittently in the days following the attack, as trucks loaded with parts destined to these production plants were delayed at the Canadian and Mexican borders. As a result, Ford lost 12,000 units of production. And as reported by the wall Street Journal (Ip 2001), Toyota came within 15 hours of halting production at its Sequoia SUV plant in Princeton, IN, since one of its suppliers was waiting for steering sensors, normally imported by plane from Germany, and air travel was shut down.

The reason that Ford, Toyota, and other leading manufacturers were vulnerable to transportation disruptions is that they operate a "Just-in-Time" (JIT) inventory discipline, keeping just enough material on hand for only a few days and sometimes only a few hours of operation. The system requires frequent deliveries of material and a reliable transportation system.

It is instructive to note that these disruptions were not caused by the attack itself but by the US Government response to the attack: closing borders, shutting down air travel, and evacuating buildings all over the country. The US Government is now in the process of getting its thinking, its institutions, its communications strategy, its military response, and its domestic defense strategy ready for a challenge that is likely to last a long time. Thus, we have entered a new era during which there are likely to be continuous hostilities between the US and its allies on the one side, and various terrorist group and governments who support them, on the other. A "win" will be a long period of unsuccessful terrorist activity and one will never know whether the US has achieved it or not, since the "win" can be reversed in a single act by a small number of people.

This article focuses on how corporations should prepare and change so they can continue operating in the face of the new realities, since "living well is the best revenge" and getting back to economic growth is the job of the private sector.

As companies organize to face the new world order, manufacturers, distributors, retailers and other entities involved in the handling of physical goods are faced with four challenges:

1. How to be prepared for another attack? Assuming that some attacks will be successful, companies have to prepare to operate in the aftermath. It should be noted that companies are vulnerable not only to attacks on their own assets, but also to attacks on their suppliers, customers, transportation, and communication lines and other elements in their eco-system.
2. How to manage supply chains under increased uncertainty? The measures taken by the US and other governments aimed at better homeland defense and higher scrutiny of international movements have burdened the world's transportation system, thus creating longer and less reliable lead times. In addition, even small terrorist events, which have little economic consequences, can have unexpected effects on demand.
3. How to manage the relationship with the government. The war on terrorism will bring about a new era of public-private cooperation in which companies will rethink their relationships with the government. Unlike any prior wars, all US citizens and US institutions, in particular private enterprises, will have to be part of this war.
4. How to manage the increased costs of security measures?, Taking precautions to defend employees, physical assets and intellectual property, will take resources. Companies need to determine what has to be done, and how to do it in the most efficient manner, balancing the need for security against other corporate goals.

Sections 2, 3, 4 and 5 of this article, respectively, describe the steps companies should undertake to position themselves for success in the new environment.

2 Getting ready

The analysis of preparedness and the extent that companies should invest in it, maybe best conducted in the context of real options theory.[1]

An option represents an opportunity — the right but not the obligation — to take action in the future. In the financial markets, options are contracts representing the right to buy or sell an asset at a given price under certain conditions (such as on a given date, or when a certain event takes place). Option contracts are, therefore, a mechanism for handling risk,[2] since they can be activated (or not) if a certain outcome takes place.[3] Since options represent a right that can be exercised (or not) at the discretion of the option holder, their value is higher when the range of underlying possible outcomes is wider. In other words, the option holder should not mind if a bad outcome is very bad, especially if a good outcome may be very good – since the option would not be exercised in case of a bad outcome regardless of its magnitude. The option price is the amount a buyer will have to pay for the option (i.e., for the opportunity represented by the option).[4]

Unlike financial options, real options deal with physical entities. Since any investment that a company may undertake entails risk, and it may open for the company a range of investment opportunities that will not be otherwise available, option theory provides a natural framework for analyzing capital investments; and as many authors argue, it leads to better decisions than traditional methods.

While traditional investment criteria are based on the Net Present Value (NPV) rule, in many cases they fail to take into account the value of creating opportunities or *options* for future actions. An investment that appears uneconomical when subtracting its discounted costs from its discounted benefits, as the NPV rule prescribes, may be viewed differently if the company can take into account other investments and projects that will be open to it (but it will not be obliged to undertake) if the first investment is made. For example, Dixit and Pindyck (1996) make the point that by not accounting properly for the options that research and development (R&D) may open up, naïve NPV analysis may lead companies to under-invest in R&D.

One of the main tenants of preparedness is the investment in redundancy, which can hardly be justified on the basis its positive NPV. Instead, we use real options framework to

[1] For more detailed explanation of real option analysis, see, for example, Luenberger, (1998); and Amran and Kulatilaka, (1999).
[2] Note that people use option in everyday life to manage risk – DeNeufville (2001) make the point that insurance is a form of option. The insurance premium gives an automobile owner the right to "sell" the car to the insurance company at a certain price (its market value) regardless of its actual shape (say, following an accident). In practice, the automobile owner does not really sell the car but simply receives payment for the losses.
[3] Most high technology employees are familiar with company stock options, which give the holder the right to buy the underlying stock at a certain ("exercise") price. The value of the option stems from the fact that the employee may be able to "exercise the option" (i.e. buy the underlying stock) when the market price of the stock is higher than the exercise price (i.e., the option is "in the money"), pocketing the difference between the market price and the exercise price. If the stock price is not above the exercise price, the employee does not have to exercise and thus does not have to take a loss.
[4] Note that the option price is different from the exercise price. The former is the (usually upfront) price that a buyer pays to purchase the option, while the latter is part of the contract represented by the option.

analyze these investment which fall into three main categories: (i) supplier relationships and awards, and (ii) inventory management criteria, and (iii) knowledge and process backup.

2.1 Supplier relationships

In the last decade many companies have moved to limit the number of their suppliers, developing "core supplier" programs in order to create stronger relationships with fewer, key suppliers. A counter trend took hold in the late 1990-s with the Internet boom. New procurement tools and services have enabled companies to conduct on-line auctions and participate in commodity exchanges.

Security considerations are likely to push more companies to abandon public Internet exchanges in favor of private auctions (where only known and pre-screened suppliers are allowed to participate), or to abandon auctions altogether in favor of long-term relationships with suppliers. The latter types of relationships are more prevalent in Europe and the Far East and in some cases were viewed suspiciously in the US.[5] In the new environment, however, companies may worry that their suppliers might start rationing their products in case of difficulties due to a local terrorist attack, a problem with one of their own suppliers, transportation difficulty, or another disruption. Clearly suppliers are likely to allocate products first to their long-term customers, with whom they have stronger relationships, giving more impetus to this type of relationships.

Following the September 11 attack, many US companies started re-considering the wisdom of using overseas suppliers. The choice is between a close-by US suppliers and international (mostly but not exclusively third world) suppliers. Offshore suppliers may be less expensive but require longer lead-time and may be susceptible to disruptions in the international transportation system. Local suppliers may be more expensive but closer (and, arguably, less vulnerable) and therefore able to respond faster.

Instead of choosing one alternative over another, the solution may include both – using offshore suppliers for the bulk of the procurement volume while making sure that a local supplier has the capability to fill the needs, by giving it a fraction of the business.

Thinking in terms of real options - the incremental cost of using the local supplier for the fraction of the business is the price of the option. Consider the following example: a high technology company sells medical devices made by a contract manufacturer in Malaysia. The Malaysian supplier is contracted to deliver the devices at $100 a piece and the devices are sold by the US company at $400 each. The fixed costs involved in marketing and channel setup have been estimated at $200 per device. Thus, the company expects a profit of:

$$P_1 = \$400 - \$100 - \$200 = \$100 \text{ per device.}$$

The company estimates, however, that there is a 1% probability that the Malaysian supplier will be disrupted and will not be able to deliver for an extended period. Taking this into account, the expected profit when using the Malaysian supplier is:

$$P_2 = 0.99*(\$400 – \$100) - \$200 = \$97 \text{ per device,}$$

[5] Clearly, many US companies -- for example, Chrysler -- have developed deep relationships with key suppliers – looking for low costs through stable relationships and joint product development, while others (such as General motors under "Procurement Czar" I. Lopez) looked for low costs through whip-sawing suppliers against each other to get the lowest bids.

since in case of a disruption the company will have no sales but he fixed costs will still be there. A local supplier can deliver the same devices for $150 a piece. Under a dual supply arrangement the local supplier may be given, say 20% of the business so it will have the capability to supply all of the company's requirements should the need arise. If there is no disruption, then, the expected profit when using dual manufacturing will be:

$$P_3 = \$400 - (0.8*\$100 + 0.2*\$150) - \$200 = \$90 \text{ per device}$$

If there is a disruption, the local vendor will supply all the devices and the company's profit will be:

$$P_4 = \$400 - \$150 - \$200 = \$50 \text{ per device}$$

Taking into account both eventualities, the expected profit when operating with dual suppliers is:

$$P_5 = 0.99* P_3 + 0.01* P_4 = \$89.6 \text{ per device}$$

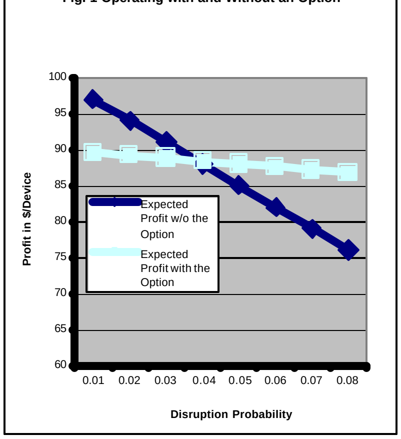
Thus, the price of the option that the company bought, looking at the expected value of the lost profit, is:

$$P_6 = P_2 – P_5 = \$97 - \$89.6 = \$7.4 \text{ per device}$$

Naturally, if there is no disruption, the company has spent $P_1 – P_3$ = $10 to be able to call upon the local supplier and avoid a loss of $200 per device when no supply is available.

Clearly this simplistic example ignores the time value of money, possible penalties for not delivering and many other aspects of reality. It demonstrates, however, the value of creating a real option. By establishing the relationships with the local supplier, the company has the right to procure the devices from it. It has no obligation to procure the devices from it (beyond the 20% required to keep the supplier's capability). And it will use its right in case of a disruption to the main supply flows.
Note that as DeNeufville (2001) points out, such an option is more valuable the more uncertain the reliability of the supply chain becomes. As Figure 1, the difference between the expected profits when using the option to the expected profit when operating without using an option grows as the probability of disruption grows.

Fig. 1 Operating with and Without an Option



Thus, one can expect some jobs to be moving back into the US as companies trade off lower parts costs against delivery reliability and adding local sources to their mix. This, however, is likely to be neither a large shift nor an immediate one. It is not going to be large since it is not likely that companies will forgo the benefits of low cost, high quality offshore manufacturing altogether, but rather only hedge their bets with local suppliers. It will also take time since companies sourcing decisions are made, in many cases, several years in advance of product launch. The first signs of such strategies should be seen in the high technology sector with its short product life cycle and high traditional reliance on offshore contract manufacturing.

Dual supply sources are not a new idea and they have general merits beyond responding to terror. For example, Billington and Johnson (2000) describe how Hewlett Packard has used "dual response manufacturing" to supply inkjet printers to North America for several years. Initially this was done using a combination of high volume, low cost production resources in Singapore and higher cost, shorter lead-time production resources in Vancouver, Washington. It used the Vancouver supplier to launch the product and deal with demand peaks, while the Singaporean supplier handled most of the stable production.

Another example is the Pentagon's concern about the availability of high quality design and manufacturing of weapon systems in the US. This concern has been used to justify many weapons contracts by the need to keep design and manufacturing capacity alive, even when the need for a specific weapon system is not clearly justified by the services' immediate needs.[6]

2.2 Inventory

Following the terrorist attack of September 11th, many companies started questioning the wisdom of "lean operations" using just-in-time" (JIT) processes. The temptation is to start accumulating inventories "just-in-case" something happens again. Some companies are looking to ordering parts in larger quantities and creating new safety stocks to keep their assembly lines moving in case their inbound transportation is disrupted. In addition, they plan to keep more finished goods on hand so their customers can be supplied even when the manufacturing process is disrupted.

The benefits of JIT manufacturing, however, have been immense – manufacturers who adopted the system saw not only their inventory carrying costs go down -- even more importantly, they saw their *product quality* improve dramatically. The reason is that having large inventories on hand creates complacency, which masks quality problems in the manufacturing, procurement, and other processes. Rather than fix these problems, it used to be easy and tempting to discard defective parts and replace them with parts from stock. With a JIT system, such quality difficulties are apparent and lead to fixing the problem at its source. This discipline is one of the underlying principles of the Toyota Manufacturing System, which propelled the company to its current leadership position, and was adopted, in one form or another, by leading manufacturers in every industry.

The challenge, then, is to ensure that supply lines are intact while not incurring the high costs of extra inventory. A possible solution, which can again be analyzed by using the notion of real options, is to separate the normal business uncertainties from the risk associated with another possible terrorist attack, creating, in fact, a "dual inventory" system. Under this system, normal forecasting discrepancies and business fluctuations should be covered by safety stock, which should be set using existing methods, based on the lead time and required service levels (see section 3 for a discussion of mitigating forecast challenges).

To create a dual inventory system logistics managers should designate a certain amount of inventory as "Strategic Emergency Stock." This stock should not be used to buffer the day-to-day fluctuations of the processes it feeds. Instead, it should be managed using an

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[6] Even the 2002 controversial tariffs on imported steel were justified, in part, by the need to keep steel production capabilities in the US in case of war (Will, 2002).

inventory discipline that can be summarized as: "Sell-One-Store-One" ("SoSo.") With this discipline the reorder quantity of the items in the strategic emergency stock is raised by the number of item required in this inventory. Then this inventory is managed in JIT fashion – when an item is drawn upon, it is replenished immediately regardless of changing daily needs. Furthermore, this inventory can be drawn upon only in case of an extreme disruption, possibly requiring approval at a high level of authority within the organization.

Using the real option terminology, the costs of the extra inventory represent the price of the option, or insurance policy, that the organization invests in.

Clearly, it is difficult to expect managers to ignore this inventory when a service failure is about to take place in normal times. To make sure, however, that the organization will not simply get used to the higher level of inventory, reaching the strategic inventory level should be treated as a stock-out situation. In other words, such occurrences should get top management attention and the root causes fixed at the source.

Such a discipline is difficult to implement since the temptation will be to always draw on existing inventory, especially since it is physically indistinguishable from any other inventory the company may keep and the separation between the two types of inventory takes place in the database and not on the floor. However, this discipline, while increasing inventory carrying costs some, may save manufacturers the considerable costs of low quality associated with "Just-in-Case" inventory management.

The concept of Strategic Emergency Stock is similar to the philosophy that led the US to keep Strategic Oil Reserves. Such reserves are intended to buffer the US in case of a sever disruption in the flow of oil. When these reserves were dipped into occasionally due to price fluctuations, they were replenished immediately.

Manufacturers and distributors of medical supplies keep a similar "strategic inventory" for military needs. In the early 1990-s, the Department of Defense (DOD) discontinued the practice of holding emergency medical supply inventory in special depots (where they would get outdated) in favor of two cooperative industry programs:

- Corporate Exigency Contracts (CEC). Established in the early 1990-s, this program requires manufacturers to keep certain amount of inventory, which the DOD has already paid for, as part of their regular safety stock.[7] Thus, if the re-order point of a certain item is say, 100 units and the DOD requires 50 units in its emergency inventory, the re-order point would be raised to 150 units. Furthermore, a stock level of 50 units is treated as a "stock out" where shipments to all commercial customers are canceled. In consultation with DOD, however, this inventory can be released.[8]
- Prime Vendor Contracts (PVC) with distributors. Established in 2001, this program is similar but is based on the inventory kept by distributors near urban areas. This is usually the first line of response as distributors are required to ship supplies to hospitals within 12 hours (while manufacturers have to be ready to ship their emergency inventory in 24 to 48 hours, depending on the item).

The medical supply industry is, naturally, more attuned to emergency response considerations than other industries, but the philosophy behind the handling of their emergency inventory is applicable to all industries.

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[7] The DOD also pays the manufacturers inventory carrying coats and handling costs for this inventory.

[8] For example, the DOD approved shipments of emergency inventory from Johnson and Johnson plants to New York in the aftermath of September 11th, even though the inventory was originally slated for the use of the military.

2.3 Knowledge

The preparations involved in protecting companies' knowledge involve three main efforts:

1. Developing backup processes
2. Backing up the company's knowledge
3. Backing up the company's relationships

Process documentation and backup

Many companies have long understood their total reliance on their information technology infrastructure. Consequently, they have set up backup sites for the information technology infrastructure of each enterprise, ensuring appropriate backup of critical applications and data.

Consider, for example Solomon Smith Barney. The giant financial services firm had 7,000 workers in one of the towers of the Word trade center. Luckily, they all got out in time. What was not due to luck but to massive preparations, was that the firm had its trading desks backed up by complete information technology infrastructure, ready to operate on the afternoon of September 11. As it turns out the company kept a set of back up systems in a New jersey site and was able to be up and running in very little time. The company was able to move very quickly because in addition to *systems*, it also had emergency backup processes in place.

Fewer companies, however, had worried about the development of such backup emergency <u>business</u> processes. Such process should spell out communications protocols, authority, and decision-making procedures in case of a breakdown in communication as a result of another terrorist attack.

Knowledge backup

More generally, however, the most precious resource of every company is the knowledge of its workers. Since companies cannot afford to keep redundant employees around "just in case," companies should make sure that the knowledge is backed up. This means that critical processes should be documented and that access to these documents is available. When appropriate, cross training should be part of any preparedness effort.

Interestingly, many companies document business process when such processes are designed. They fail to keep up, however, with the ever-changing nature of such processes in the business world. This need may be the nucleus of a much better set of software applications, which support both processes and their continuous documentation.

Relationships backup

In addition to business processes, companies need to be able to salvage customer and supplier relationships. These can be salvaged if all interactions with customers have been documented in a Customer Relationships Management (CRM) system. Relationships should be thought of as just as important as data and processes. Documenting all customer interactions can help companies pick up after a disaster a lot faster than otherwise.

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All these backup activities are a form of insurance premium or the price of a real option that companies should pay in order to be able to exercise them when the need arises.

Not every preparedness action, however, involves a premium. Some strategies are beneficial to the business at any time but take on extra significance when looked upon from the perspective of preparedness. One such notion is standardization. One of the most important tools in creating redundancy and the ability to recover quickly is standardization of business processes and practices across the enterprise. To this end, corporations with several warehouse management systems, multiple order entry systems, several incompatible manufacturing and financial systems, are much more vulnerable than companies who standardized their operations and can move personnel and processes between locations if a single location goes down.

Standardization, in effect creates the option of letting managers from different places to move around the enterprise and use their expertise elsewhere in case part of the enterprise is inoperable.

3 The basics: better supply chain management

For many nations and peoples, terrorism is not a new phenomenon – the people of Belfast, Jerusalem, Spain's Basque region, Kashmir, and elsewhere had to endure terrorist actions for many years. And they had to keep operating their enterprises under these conditions, putting the proper security measures in place as well as making contingency plans.

The supply chain of any manufactured good involves the network of enterprises and processes which take a combination of raw materials and turn them into a finished product at the consumer's hands. Most of the expected impact of the new security measures will be reflected in supply chain management challenges, which are likely to be less reliable.

Longer supply lines and uncertain deliveries are not new for supply chain managers. The globalization of manufacturing, the explosion of new products, and the short life cycle of many products have burdened logistics managers with long supply lines and significant uncertainty in forecasting of demand. In that sense the new world order does not represent a fundamentally new challenge and thus the basic problem can be tackled by refocusing on known solutions, and adopting new technology to this end as it become available. Some of the most basic strategies include (i) improvements in-shipment visibility, (ii) improved collaboration between trading partners and across enterprises, and (iii) better forecasting through risk pooling methods.

3.1 Shipment visibility

Many logistics managers are still describing the transportation system they are dealing with as a "black hole" – shipments disappear when tendered to the carrier and no information is available to either shipper or consignee until the shipment is delivered. Shipment visibility tools allow shippers to track the progress of their shipments in the same way that consumers can track the flow of their UPS or FedEx shipments. Tracking industrial shipments has proved to be a significantly more challenging problem – it involves multiple carries and 'hand-offs," and it requires integration with manufacturing, inventory and purchasing -- since logistic managers need to know not only what is in-transit, but also what is available in stock and what is on-order, and when orders will be available from suppliers. And they deal with thousands of items every day.

Lack of visibility can aggravate the well-known "bullwhip" phenomenon in supply chains (see, for example, Lee *et al*, 1997).[9] This phenomenon describes how demand information becomes increasingly distorted as it moves away from the actual consumers; from retailers to distributors, wholesalers, manufacturers and suppliers along the supply chain. Such distortion leads to forecasting errors, excessive inventory, erratic order patterns, and unavailable products to fill orders – all leading to higher costs and poor customer service.[10] One of the principal ways of mitigating the bullwhip effect is by sharing data about actual end-consumer demand, inventory levels and incoming shipments throughout the supply chain. In other words, by providing visibility to all participants in the supply chain.

Thus data visibility allows manufacturers to avoid plant shutdown due to part shortages and allows retailers to avoid turning customers away due to unavailability of goods. At the same time, good visibility also allows all the players in the supply chain to keep lower safety stocks since both the demand pattern they experience will be more stable and their suppliers will be more consistent.[11] The costs savings associated with better forecasting and smoother operations include not only lower inventory carrying costs, and the avoidance of expedited shipments; it also means that warehousing facilities can be downsized and a significant amount of administrative overhead associated with unscheduled activities can be avoided.

There are several partial technology solutions available today for helping shippers find out where their shipments are, as well as helping them decide what action to take in case a shipment is late, misrouted, damaged, or otherwise in trouble. Some of these solutions are available from carriers who are tracking better their own conveyance movements, while others are available from software providers who are attempting to aggregate the information from many carriers and present it to shippers in integrated fashion.[12]

To date, most of the shipment tracking information is based on tracking the conveyance that a shipment is using or the environment it is in. Thus, it depends on timely reporting from the carriers hauling the shipment, the warehousemen storing it, or the distributors handling it. New technology using tags which can communicate directly with low-earth-orbiting-satellite (LEOS) systems offers the promise of freeing shippers from their

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[9] The first model characterizing the bullwhip effect was built by Forrester (1958). His model consisted of a four stage supply chain, where each stage ordered on its immediate upstream neighbor who only ship those orders (plus those in backlog).

[10] The information distortion gets more pronounced as one moves "upstream" in the supply chain due to "system dynamic" effects – see Sterman (1989a, 1989b), who conducted human-subject experiments to demonstrate that the sources of oscillation and increase in variability were managers' misperceptions of feedback and their inability to account for the supply line of orders as suggested by Forrester

[11] Note that there are other factors that contribute to the bullwhip effect, including long and uncertain lead times, promotions, order and shipment batching, and order inflation during shortage periods. All these factors should be addressed when striving for better supply chain operations, as mentioned in Sec 3.2.

[12] Many of the impediments to full visibility for shippers are not technological. Some leading carrier refuse to let shippers "see" where their trucks are, even though the carriers have the information. To understand the reason, consider, for example, a large truckload carrier who may have at any point in time 10,000 trucks on the road. The carrier's own tracking system may indicate that as many as 1,000 of those are behind schedule. The carrier knows, however, that through a combination of mitigation techniques (driver switching, assigning tractors with team drivers, etc.), only 50 or so will end up actually late. It does not know which 50, though. Opening the tracking system to customers is likely to generate an avalanche of frantic phone calls, which may hamper the work of dispatchers and the relationships with the customers. Instead, carriers usually notify customers that something is late only when they are convinced that they cannot fix the problem. In many cases this notification comes too late for the shipper to avoid service failure to its customer or a disruption to a production line.

reliance on carriers and other suppliers by allowing direct communications with the shipment.[13]

As lead times are becoming longer and less consistent, shippers should mitigate the problem by investing in visibility tools. Even in cases in which such these tools provide only a partial coverage, they help moderate the problems.

3.2 Collaboration

The term "supply chain" describes the movement of material from raw material to finished good at the end-consumer's hands.[14] Thus, while the logistics function within the enterprise is concerned with the inbound and outbound movements to and from manufacturing and storage facilities and the accompanying movements of information and cash, supply chain management is focus on such movement between enterprises. Thus, collaboration among different enterprises is what binds supply chains to make them integrated systems.

In general, one can distinguish between two types of business collaboration:

- Horizontal collaboration – between firms at the same stage of the supply chain. For example, among different retailers or different OEMs. Sometimes the collaborating companies are competitors in certain parts of their business. In the past such cooperation involved working together on the development of standards for commercial transactions, lobbying the government on industry issues, cross selling, and other forms. The new environment will require companies to share knowledge with other enterprises in their industry, including competitors, to develop secure processes.
- Vertical collaboration – between suppliers and their customers and the third parties involved in commercial transactions: transportation carriers, financial institutions, infrastructure operators, etc. This type of collaboration is aimed directly at improving visibility and reducing lead times by letting suppliers and customer collaborate in a structured fashion, which is standard across all industry participants. This is what industry initiatives such as co-managed inventory (CMI),[15] Collaborative Planning, Forecasting and Replenishment (CPFR)[16] processes are currently attempting to accomplish.

Vertical collaboration is aimed square at mitigating the bullwhip effect. By creating mechanisms for trading partners to work together on reconciling their forecasts of sales and

[13] An intermediate step between bar code identification systems and satellite-based system are radio frequency tags, which allow more remote and automatics readings of shipment identification, thus aiding carriers, warehouse operators and distributors to keep better tabs on items under their control. These systems, however, still rely on supplier reporting.
[14] Some authors also include the "reverse logistics" (dealing with returns) and "green logistics' (the disposal of packaging material and discarded products).
[15] CMI grew out of the practice of vendor-managed inventory which many retailers adopted
[16] CPFR is a process by which retailers and their suppliers are sharing data regarding future sales and promotions, allowing retailers to keep less inventory and provide higher availability of products to consumers, while allowing manufacturers to tailor their production schedules to the exact needs of the retailers, leading to lower inventories and higher availability at the manufacturing echelon.

orders, they are much less likely to over-react, independently, to demand signals and order too much or too little, thereby magnifying the demand signal, leading to the bullwhip effect.

Since the middle of the 1980-s, American companies have devised many cooperative schemes to improve supply chain operations. These include Vendor-Managed-Inventory (VMI) and Co-Managed Inventory (CMI) in the retail industry, Efficient Consumer Response (ECR) in the grocery industry, Quick Response (QR) in the textile industry, Just-In-Time (JIT) in manufacturing, JIT II in procurement and lately, Collaborative Planning, Forecasting and Replenishment (CPFR) in the consumer packaged goods industry and Collaborative Transportation Management (CTM) in the transportation industry. These and dozens of other such initiatives are aimed at ensuring that trading partners coordinate their forecasts, orders, thus avoiding the bullwhip effects.

The Internet and electronic commerce in particular have enabled new collaboration methods between companies with the development of new standards (such as XML[17]), which allow more flexible and general computer-to-computer communications than older electronic data interchange (EDI) standards. The new technologies also gave rise to new breeds of application software that are housed by third party providers and allow many trading partners to access them simultaneously (rather than having one trading partner using an application developed by another).

As lead times are becoming more variable, companies should counter this by redoubling their collaboration efforts. The basic reason is that if the consignee knows about a problem early enough, it can take corrective measures (such as expedite shipment, go to an alternative source, adjust its own customer's expectations, etc.)

Security collaboration

In addition to working on collaboration in order to improve supply chain operations, companies should work both with trading partners (vertical collaboration) and with industry groups (horizontal collaboration) to develop best practices and share relevant knowledge. More than ever, corporations should realize that their long-term fate is intertwined with that of their suppliers, customers, corporations in other sectors of the economy, and even their competitors. Such collaboration has many precedents and is not limited to collaboration among US companies or any other nation's enterprises. For example, when the Japanese figured out the lean manufacturing and Just-in-Time system, leading Japanese manufacturers, such as Toyota, not only allowed researchers from the world over to study their methods, they allowed other companies, including other automobile companies to visit their plants and study their manufacturing system, including their system of collaborating (vertically) with their suppliers. This is an example of collaboration that will be required in the coming era.

Both types of collaboration are important in allowing supply chains to function better. A new type of collaboration – with government is discussed in section 4.

3.3 Risk pooling

One of the fundamentals of forecasting is that it is always easier to forecast more aggregate phenomena.[18] For example, it is easier to forecast the number of Ralph Loren's men's blue blazers size 44R that will be sold nationwide, than the number that will be sold in a particular

[17] Extended markup language

[18] The reason for this, in simplified terms, is that when the number of items one is dealing with is large and varied, it is likely that errors will cancel each other – thus if the forecast is too high for a particular store, or item, or day, it may be lower for another store, or item, or day. And thus the larger the universe of units one is dealing with, the smaller the forecast error is likely to be.

store. And it is easy to forecast the monthly sales than the sales during a particular day.[19] To take advantage of this, companies can employ a variety of strategies such as:

- Postponement. By delaying the time that product have to be committed to a particular destination (customer, location, etc), companies can reduce the forecasting error. For example, Billinton and Johnson (2000) report that Hewlett-Packard cut printer supply costs by 25 percent with modular design and postponement. Generic printers are shipped to local distribution centers worldwide, where local customization (involving local transformers, power cords, and instruction manual in local language) take place once firm orders are at hand.[20] Thus HP has to forecast the aggregate demand for the generic printers, while requiring a disaggregate forecast only for the local parts. These parts are not only less expensive to stock, but can also be manufactured with short lead-time (as compared to the whole printer).
- Build-to-order. The ultimate postponement strategy is to build items only after customer orders are known. Dell Computer has used this strategy to become the world's dominant PC maker. But even automobile manufacturers are embracing the strategy. For example, VW now delivers many of its models to German customers within two weeks of ordering. This means that VW has very few built cars waiting for customers in dealers' showrooms.[21]
- Product variability reduction. Some manufacturers have combated forecasting difficulties by reducing the number of options and items they are producing. For example, many automobile manufacturers stopped long ago offering all possible combinations of features on their products and offer "packages" of features instead, thus reducing the number of options, reducing costs, and improving the forecasts of the packages desired by customers. This improvement is possible since the smaller number of option allows for better risk pooling, lower variability and thus better forecasts.
- Centralized inventory management. By managing inventory centrally, companies can use surpluses in one area of the country to cover for deficits in others. This is another example of risk pooling (in this case - geographical aggregation). Thus the trend towards reducing the number of warehouses and other inventory stocking location may accelerate as part of companies' learning to operate in even more uncertain times.[22]

4 Public-private partnership

Most executives in US corporations look at the government as a hindrance to the smooth functioning of the economy. Defense, however, is one of the few roles that even Libertarians

[19] More accurately, the *coefficient of variation (the ratio of the standard deviation to the mean forecast)* of an aggregate forecast is never higher than the coefficient of variation for a disaggregate forecast. In other words, the relative accuracy of an aggregate forecast is always at least equivalent and in most cases higher.
[20] Using postponement, HP has become number one worldwide in Q3, 2001 in inkjet printer market share, in photo-quality inkjet printers, in all-in-one products, and in large-format inkjet printers
[21] Over 80% of the cars VW sells in Germany are built to order rather than to dealers' stock.
[22] Note that increasingly stringent level of service requirements may limit the use of centralized physical inventory.

believe is the proper role of government. In fact, the creation of an Army and a Navy were contemplated in the US constitution itself.

The US government has taken the first step in organizing for the new environment by establishing the office of homeland defense. At this point, the office is charged with coordinating the efforts of the various defense, intelligence, emergency response, health services and many related agencies. The challenge facing the US government is enormous, but the government is slowly rising to this challenge. Protecting private interests, however vital to the nation, is still the purview of the owners of those private assets.

4.1 Sharing information

Recognizing the important role that government will play in the new era, and recognizing that government cannot do it alone, corporate executives need to adjust their thinking and start considering the government, both Federal and local, as a partner in certain aspects of corporate life. Some possible collaborative avenue include the following:

- Use of the vast government know-how on the nature of threats and ways to deal with them. At the same time, corporations who may be subject to attacks have an obligation to inform local law enforcement and rescue agencies about their vulnerabilities. Companies who are in particularly sensitive businesses, such as Nuclear power generation and chemical manufacturing are already subject to laws that require them to do so, but in the new era, corporate executives should think about new possible threats and work with local authorities over and above the legal obligations.[23]
- Many American corporations have operations all over the world and may possess information that is important to the national defense. Following the Cold War tradition, many corporations and individual executives may increase the level of information sharing with the US government.

4.2 Taking on certain security tasks

Immediately following the September 11 attack the US had a somewhat uncoordinated response, marked by closed airports and borders. Conflicting government calls to be on the alert, while leading normal life, followed this. In the months following the attack The US has started to settle into the long-term reality. This reality is marked by added security costs, added administrative costs, and longer, as well as less certain transportation times due to security checks. Currently, however, the nation has not yet developed the new long-term procedures that will be necessary to deal with the threats efficiently. The delays shippers and carriers experience in the months following September 11 will be reduced as the US develop a more sustainable security system.[24] Thus, firms should not yet over-react to current transportation delays and added administrative costs.

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[23] One area of possible coordination is the transportation of hazardous materials, which is described in section 4.3.

[24] Clearly, short-term government responses to specific attack may still disrupt product flows, but even these may be tempered if the threat of terrorist attacks becomes a way of life. For example, immediately after American Airlines flight 587 crashed into the neighborhood of Belle Harbor, Queens, NY, on November 12, 2001, the city closed all bridges and tunnels in and out of Manhattan for several hours. The economic costs of such disruptions are very large and in the future such actions might be avoided.

At this point, the philosophy behind cargo security checks mirrors airport checks in the US – inefficient and not very effective. By and large, US checkers at airports give the same level of attention to every passenger who goes through the system. By contrast, leading airports in Europe and Israel have always used an advanced "profiling" system to pre-screen, conduct quick interviews and then check more thoroughly certain passengers, while letting others go through.[25]

Similarly, many of the current processes used to insure the security of freight flows are inefficient and do not "scale" up. This will become more and more evident as the economy will start to get out of the current recession. For example – checking every truck getting into Manhattan or crossing the Mexican border is impractical – the cost it imposes on the economy is too high. Furthermore, such security regime is less effective; it means that security checks become more "routine" and checkers tend to become more complacent when every vehicle is examined.

The freight equivalent of "profiling" is the use of "known shippers" and "certified carriers." In other words, a new certification program will have to be put in place – this will probably be a government certification of carriers, based on training and a prescribed set of security processes. An important part of such certification will be the need to create a class of "known shippers" who have done business with the carrier for a long time and have their own security measures in place. Thus, for example, trucks owned by "certified carriers" hauling shipments from "known shippers" coming into Manhattan, may be waved through (or just spot-checked).

A version of this idea is included in FAA Directive 108-01-10 and its more recent "Cargo Revised Emergence Amendment." The FAA attempts to distinguish between "known shippers" and "unknown shippers" in setting up procedures for acceptance of cargo by air carriers. The FAA does not address carrier certification since it is already familiar with all the air carriers. The problem of certifying carriers is most acute in the trucking industry.

This means that corporations will have to take upon themselves some of the burdens of security provision. Shippers will have the responsibility to check and seal trailers at the origin, as well as to check the background of their transportation managers and warehouse and dockworkers. Transportation carriers will have to develop security procedures for routing and scheduling sensitive cargo as well as to check the background of all their employees. In addition, certified carriers will have the ability to track their vehicles at any point through its journey[26] and to be automatically alerted if the journey pattern changes.

Leading carriers and shippers should work with the government on the creation of the certification programs and the guidelines for who is a "known shipper." Such certification programs are similar in nature to the ISO 9000 programs used to certify quality. In fact, the government may choose to relegate the certification to private organizations, creating a structure similar to the quality programs.[27]

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[25] The US is using such profiling only to check the luggage of "flagged" passengers.

[26] Most trucking companies can track shipments from origin to destination using satellite communications systems such as Qualcomm's OmniTrack. The system is still vulnerable, however, when cargo has to change hands, as it is transfered between modes of transportation, and in local pickup and delivery operations. The software applications that companies use to track their equipment will have to be augmented in order to detect suspicious patterns.

[27] In a speech at an importers conference on November 27, 2001, Customer Commissioner Robert Bonner laid out a vision of exactly such system. He even suggested a government security certification program similar to the ISO 9000 quality certification process. Companies will be able to use a "fast lane" to enter the US if, for example, they will have certifiably secure processes at their loading docks and their offshore suppliers plants, if they share the cargo information with the custom service in a timely fashion, if they use electronic seals on their containers, etc.

Interestingly, US Customs Commissioner Robert Bonner laid out a vision of a similar system in a speech at an importers conference on November 27, 2001. He suggested a government security certification program similar to the ISO 9000 quality certification process. Companies will be able to use a “fast lane” to enter the US if, for example, they will have certifiably secure processes at their loading docks and their offshore suppliers plants, if they share the cargo information with the customs service in a timely fashion, if they use electronic seals on their containers, etc. (see O’Reiley, 2001).

4.3 Hazardous materials

More than 800,000 hazardous materials shipments are transported every day in the US alone, 94% of which are moved by truck.[28] While many transportation movements may be subject to terrorist threats, the transportation of hazardous materials deserves special attention. Not only is it important to strengthen the security of hazardous material transportation and handling, but also the infrastructure that was already put in place to deal with hazardous materials (especially if it is strengthened) can be the basis for a more comprehensive security program. The main elements of the existing system are:

- The Emergency Planning and Community Right-to-Know Act requires that detailed information about hazardous substances in or near communities be available at the public's request.
- The U.S. Department of Transportation employs a labeling and placarding system for identifying the types of hazardous materials that are transported along the nation's highways, railways, and waterways. This system enables local emergency officials to identify the nature and potential health threat of chemicals being transported.
- In 1986, Congress passed the Superfund Amendments and Reauthorization Act (SARA) of 1986. Title III of this legislation requires that each community establish a Local Emergency Planning Committee (LEPC) to be responsible for developing an emergency plan for preparing for and responding to chemical emergencies in that community. The LEPC is required to review, test, and update the plan each year.

The systems that are in place are aimed at efficient response to an accident involving hazardous material. Proposed new legislation increases fines for non-compliance and strengthens the US Department of Transportation inspectors’ authority to inspect cargo in transit. Separate legislation is aimed at tightening the rules for obtaining commercial drive licenses.

These legislative moves are appropriate and timely. The threat of terrorism calls for further control of the movements of hazardous materials so that the authorities can react after a trailer-load or a rail car loaded with hazardous materials is reported missing but before it is used in a terrorist attack. To this end the US may create a “HazMat Transportation Control System” similar to the air traffic control. Before trucks or rail cars will be allowed to depart they will have to file a “flight plan” and then tracked to that plan throughout their journey. Any deviations from the plan will be checked.

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[28] About 5% of the shipments are moved by air, and the rest by rail and pipeline. Note, however, that rail and pipelines move a much larger share of the tonnage of hazardous materials (O’Reilly, 2001).

Food supplies

The nation's food supply may also be a target of a terrorist act and, as with hazardous materials, food inspection services can also be used as part of the model and the infrastructure for creating a secure distribution system. In that case there are many Federal and State agencies involved, including the Federal Drug Administration (FDA), the Food Safety and Inspection Service (FSIS), the Environmental Protection Agency (EPA) and the National Marine Fisheries Services (NMFS). In addition, every state has several agencies responsible for public health, agricultural products and meat and poultry inspections.

In refocusing many of these agencies on the threat of terrorism, the main challenge is to coordinate the work of these agencies and make sure that information keeps flowing freely among all the agencies involved.

* * *

In both of these instances – hazardous materials handling and transportation, and food processing and transportation – there is an infrastructure and a tradition of public-private partnerships to ensure safety. In both cases there are many Federal, state and local agencies involved with private industry. And both cases can serve as a basis for a more comprehensive system that will deal with security threats.

4.4 Direct emergency assistance

Modern, large corporations have been in existence only since the second part of the 18th century, with the emergence of the American railroads and Germany's Deutsche Bank. Since then they have developed resources, which in many cases rival public resources and are used in case of war.

For example, US strategy for sea lift in case of war includes the use of The Merchant Marine, which is the fleet of ships that carries imports and exports during peacetime and becomes a naval auxiliary during wartime to deliver troops and war materiel. According to the Merchant Marine Act of 1936: "It is necessary for the national defense... that the United States shall have a merchant marine of the best equipped and most suitable types of vessels sufficient to carry the greater portion of its commerce and serve as a naval or military auxiliary in time of war or national emergency..." The Civil Reserve Air Fleet (CRAF) was similarly established to organize civilian airliners to augment regular military airlift capability in a military emergency.

The specter of continued terrorist attacks means that corporations should get ready to join in the national defense and in the rescue and recovery efforts, which will follow. And the corporate function, which can most likely provide help, is logistics and transportation management. Logistics professional should organize in every area on the US to prepare and help FEMA, the Red Cross and the many other agencies that may be working to alleviate emergencies and rebuild affected communities. Most of these preparedness efforts involve the creation of local databases regarding the availability of transportation capacity to haul people and materiel; heavy earth moving and construction equipment; warehouse space and shipping and handling equipment; computers and communication hardware; etc.

Interestingly, during the meeting of the World Economic Forum in New York in 2002, several construction and logistics enterprises have come together to create an informal network for disaster relief. Their objective is to help governments worldwide to mitigate the effects of disasters, whether they are natural or man-made.[29]

5 Organizing to meet the challenge

The demands of the new world reality will require enterprises to add another dimension to the set of objectives and criteria by which they manage their operations: *security*. Many of the actions required for security and preparedness, however, are in conflict with traditional corporate goals and processes. Consider, for example, the following trade-offs:

- Repeatability vs. unpredictability. In order to be successful and reduce the cost of performing their everyday activities, companies establish repeatable processes. Doing the same task over and over again means that workers are getting good at it, it is easy to measure and "perfect," it is easy to cost, and easy to manage. In fact, when processes differ from the norm, companies generate another process to deal with exception – this is an attempt to standardize even the outliers. Many aspects of security, however, require that companies will be less predictable. For example, daily changes the route that a truck carrying hazardous material is using, or frequent changes to password systems and other entry control systems to computers and facilities, increases security.
- The lowest bidder vs. the known supplier. Section 2.1 mentioned that companies may choose to deal with fewer suppliers on a long-term basis. One should not forget, however, that there might be substantial costs involved. Not only can new suppliers be more competitive price-wise, but also they may bring with them new ideas and processes that may help innovation. The same rationale applies to the choice of local vs. overseas suppliers discussed in that section.
- Centralization vs. dispersion. One of the points argued in Section 2.2 is that in order to pool the forecasting risk, companies should manage inventory centrally. Indeed, many corporate activities, from the provision of information technology, to office work, are conducted better in central location. Security considerations, however, call for dispersion of both assets and personnel in order to mitigate the effect of any local terrorist attack.
- Redundancy vs. efficiency (or security vs. value delivery). Another way to look at the same point mentioned above. All the preparatory steps that corporations may be taking regarding procurement policies, inventory management and knowledge backup (see section 2), involve the creation of redundancies in the system – be it extra supplier capacity, extra inventory, backup equipment and processes, etc. Such redundancies are, by their very nature, in direct conflict with the concept "lean operations." The latter calls for "just in case" mentality of preparations while modern operations are organized around "just in time" systems. As argued in section 2.2, the challenge in creating the required redundancies (which can be looked upon as insurance or real options) is to minimize their adverse effects and possibly, use them to create value.
- Collaboration vs. secrecy. Section 3.2 argued for increased collaboration among enterprises as a way to manage supply chains more efficiently and avoid some of the increased costs of longer and less certain lead times and demand patterns. One of the

[29] The effort is coordinated by the Fritz Institute in San Francisco.

tenants of security, however, is secrecy. Thus, while corporations maybe exposing more of their data and internal workings to others and even sharing information about security measures with other corporations, they have to do it in a way that does not compromise security.

- Government cooperation vs. direct shareholder value. US executives are conditioned to put shareholders value, above all other considerations. The new environment may create situation where cooperation with government and the companies, including competitors, may be required, even at the expense of short term profit and therefore shareholder value.

To organize for dealing with the threats, companies will need to create a new function headed by a "Chief security Officer" (CSO) that may join the executive team. The CSO will have to be, first and foremost, a *businessperson* who is familiar with the enterprise and in getting things done in a corporate environment. The reason is that every person and organization is subject to a strong temptation to return to normalcy; return to the days when nobody had to worry about terrorism and bio-attacks. The CSO and the security organization will have to continuously fight this temptation. They will face many of the trade-offs mentioned above on daily basis, and will have to create the constituency to follow through with the required investments and changes to corporate life. By and large, military or other security agency background may not be enough for CSO candidates since they will be quickly marginalized in a corporate environment, unless they can understand the business trade-offs and argue for just the required measures and no more, while taking into account the normal business mission and objectives..

In addition, the CSO office is likely to be the only place in the organization where the various security schemes will be coordinated and tested. This is the function that will not only have to make sure that the enterprise can continue after an attack, but that the emergency processes complement each other. For example, while it is clear that dispersion of work and personnel is a reasonable strategy to avoid a large damage due to physical terrorist attack, this strategy makes the enterprise more vulnerable to an Internet virus or worm attack that will slow down and even shut down sections of the Internet. The CSO will also have to be part of the team that will determine not only the priorities under various scenarios but also the procedures to set such priorities when the unexpected happens.

The CSO task, however, is much bigger. In the 1970-s and 1980-s corporations tried to instill in their employees that "everyone is a salesperson." In other words, every employee has to worry about sales and the customers, not only the marketing and sales people. In the 1980 and the 1990-s corporations realized that every employee had to be quality-conscious. It was not enough to add an executive in charge of quality; high quality was the result of entire organizations changing the way they do business to "get it right the first time." The security challenge is similar. No Chief Security Officer or security organization will be successful unless the culture of the enterprise adds security consciousness to its daily life. Thus, companies that will best survive terrorist attacks will be those where employees have internalized both a set of intelligent applications of security measures and the need backup emergency processes.

Another reason for the CSO to be a businessperson is that many of the efforts aimed at security can actually improve corporate performance and the preparation should be put in place with an eye towards reaping such "collateral benefits." For example, better security measures can help reduce theft, embezzlement, and loss of intellectual property. Participation in community-wide efforts can also help the image of many corporations as good citizens. Beyond the image, however, such efforts can empower employees and inject new meaning to their jobs as strong corporations will be seen not only as a source of economic security to individuals but also as contributors to the greater good of the nation.

6 Summary and conclusions

Terror is not a new phenomenon and the US itself was no stranger to either suicide bombing or terrorist plots or attacks even before September 11th, 2001:

- On February 26, 1993 a minibus containing 1,100 pounds of explosives detonated in the garage beneath the World Trade Center complex, killing six people. (Investigation of the WTC bombing reveals that it was only a small part of a massive attack plan that included hijacking a plan and crashing it into the CIA headquarters.)
- On August 7th, 1998 the US embassies in Kenya and Tanzania were bombed (killing 224, including 12 Americans).
- In December 1999, authorities arrested an Algerian trying to enter the U.S. from Canada and foiled a plot to detonate a bomb at Los Angeles International Airport in the days before January 1, 2000.

The September 2001 attack highlights a fundamental difference between past and future terrorist acts, which should be looked upon in a historical context.[30] Violent battles for control of people by one group over others have characterized the human race since it began forming societies. Entire populace possessed by a collective anger and hatred, threatening their neighbors and demanding hegemony are as ancient as Biblical histories and as modern as the late 20th century. They always had justification for violence – be it economic conquest, religious domination, righting ancient wrongs, cultural threat, whatever.

Never before, however, has the risk arising from violent social confrontation been as large for a greater number of people. The increased risks cropped up out of the confluence of increased destructive power of weapons and the rise of cheap, instant communications. Together these factors allow, for the first time, ordinary people to gain access to tools of mass destruction and to spawn well coordinated, geographically distributed networks of soldiers ready to use those tools.

The scope of the risk may be nothing less than the survival of humanity. Based on several thousand years of human history, the likelihood that some number of the world's six billion people will from time to time want to spread their influence through violence is 100%. The likelihood that some group will do so in a way that adversely affects a significant portion of the world's population depends only on the vigilance with which the rest of the world (i) defends against the possible violence and (ii) seeks out its roots and cleans away the intolerance of those groups seeking to control others through violence. The United States, with the help of a few other nations, notable Great Britain, may have started to face the threat.

The upcoming period of struggle, however, will challenge not only the US armed forces and its intelligence and police institutions. It will lead to a change in the way US citizens lead their lives and in the way US corporations conduct their business. This article had focused on the last point – getting back to business in the new environment: creating redundancies do that enterprises can withstand new attacks; cooperating with the government and adding security measure in order to prevent such attacks from taking place; and changing corporate processes to cope with the heightened security environment.

[30] The following three paragraphs are taken from a private communication from D. Dolgin to the author.

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The Reflecting Wall at MIT, a 12-by-25-foot wooden replica of a fragment of the wall of the World Trade Center installed next to the MIT Chapel, was proposed and designed by Assistant Professor of Architecture John Fernandez in the days immediately following the disaster in New York. He conceived it as a temporary space where people could pause to reflect on the nearly 3,000 people who died in New York, Virginia and Pennsylvania after terrorists piloted hijacked airplanes.

Fernandez proposed an actual-size wall fragment, abstracted to wood rather than aluminum, of "the icon of New York" in memory of all victims of the Sept. 11 terrorist actions. At the dedication ceremony, he said one of the images that stayed in his mind was that of the people inside who pressed against the skyscraper's windows, trying to escape the flames. "This is the first project I've ever worked on that I wish that it had never been built," Fernandez said. "But after Tuesday, it had to be built." One feature that wasn't in the original wall are the slots below the window ledges, which were requested by students for letters, notes and memorabilia.

The Wall was dedicated Friday September 14, 2002 in the afternoon when 400 students, faculty and staff laid roses, candles and notes on the structure. The dedication ceremony at the Reflecting Wall by the walkway to the chapel began at 5:15 p.m. on Sept. 14, just over 48 hours after the request was first voiced.