The Fall of Skyscrapers

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Editor's Note: This article first appeared in American Scientist*, Volume 90, January-February 2002. It is reprinted here with permission. Copyright, Henry Petroski, 2002. The article is reprinted as written earlier this year. In the ensuing months, many investigations have been performed, and the level of understanding of some of the technical aspects of the World Trade Center collapse have increased. The results of the FEMA investigation discussed in this article are now available at www.house.gov/science/hot/wtc/wtcreport.htm*

Figure 1. With the collapse of the World Trade Center towers, the fate of future skyscraper projects has come into question.

The terrorist attacks of September 11, 2001, did more than bring down the World Trade Center towers. The collapse of those New York City megastructures, once the fifth and sixth tallest buildings in the world, signaled the beginning of a new era in the planning, design, construction and use of skyscrapers . For the foreseeable future, at least in the West, there are not likely to be any new super-tall buildings proposed, and only those currently under construction will be added to the skylines of the great cities of the world. Even the continued occupancy of signature skyscrapers may come under scrutiny by their prime tenants.

Since two hijacked airplanes loaded with jet fuel were crashed within about 15 minutes of each other into the two most prominent and symbolic structures of lower Manhattan, the once reassuringly low numbers generated by probabilistic risk assessment seem irrelevant. What happened in New York ceased being a hypothetical, incredible or ignorable scenario. From now on, structural engineers must be prepared to answer harder questions about how skyscrapers will stand up to the impact of jumbo jets and, perhaps more important, how they will fare in the ensuing conflagration. Architects will likely have to respond more to questions about stairwells and evacuation routes than to those about facades and spires. Because of the nature of skyscrapers, neither engineers nor architects will be able to find answers that will satisfy everyone.

Inclination, Not Economy

Although the idea of the skyscraper is modern, the inclination to build upward is not. The Great Pyramids, with their broad bases, reached heights unapproached for the next four millennia. But even the great Gothic cathedrals, crafted of bulky stone into an aesthetic of lightness and slenderness, are dwarfed by the steel and reinforced concrete structures of the 20th century. It was modern building materials that made the true skyscraper structurally possible, but it was the mechanical device of the elevator that made the skyscraper truly practical. Ironically, it is also the elevator that has had so much to do with limiting the height of most tall buildings to about 70 or 80 stories. Above that, elevator shafts occupy more than 25 percent of the volume of a tall building, and so the economics of renting out space argues against investing in greater height.

The World Trade Center towers were 110 stories tall, but even with an elaborate system of local and express elevators, the associated sky lobbies and utilities located in the core still removed almost 30 percent of the towers' floor area from the rentable space category. By all planning estimates, the World Trade Center towers should have been viewed as a poor investment and so might not have been undertaken as a strictly private enterprise. In fact, it was the Port of New York Authority, the bi-state governmental entity now known as the Port Authority of New York and New Jersey, that in the 1960s undertook to build the towers. With its ability to issue bonds, the Port Authority could afford to undertake a financially risky project that few corporations would dare.

Sometimes private enterprise does engage in similarly questionable investments, balancing the tangible financial risk with the intangible gain in publicity, with the hope that it will translate ultimately into profit. This was the case with the Empire State Building, completed in 1931 and now the seventh tallest building in the world. Although it was not heavily

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occupied at first, the cachet of the world's tallest building made it a prestigious address and added to its real-estate value. The Sears Tower stands an impressive 110 stories tall, the same count that the World Trade Center towers once claimed. This skyscraper gained for its owner the prestige of having its corporate name associated with the tallest building in the world. The Sears Tower, completed in 1974, one year after the second World Trade Center tower was finished, held that title for more than 20 years-until the twin Petronas Towers were completed in Kuala Lumpur, Malaysia, in 1998, emphasizing the rise of the Far East as the location of new megastructures.

Building Innovation

It is not only the innovative use of elevators, marketing and political will that has enabled super-tall buildings to be built. A great deal of the cost of such a structure is in the amount of materials it contains, so lightening the structure lowers its cost. Innovative uses of building materials can also give a skyscraper more desirable office space. Now more than 70 years old, the steel frame of the Empire State Building has closely spaced columns, which break up the floor space and limit office layouts. In contrast, the World Trade Center employed a tubular-construction principle, in which closely spaced steel columns were located around the periphery of the building. Sixty-foot-long steel trusses spanned between these columns and the inner structure of the towers, where further columns were located, along with the elevator shafts, stairwells and other non-exclusive office space. Between the core and tube proper, the broad columnless space enabled open, imaginative and attractive office layouts.

The tubular concept was not totally new with the World Trade Center, it having been used in the diagonally braced and tapered John Hancock Center, completed in Chicago in 1969. The Sears Tower is also a tubular structure, but it consists of nine 75-foot(23-meter)-square tubes bundled together at the lower stories. The varying heights of the tubes give the Sears Tower an ever-changing look, as it presents a different profile when viewed from the different directions from which one approaches it when driving the city's expressways. When new to the Manhattan skyline, the unrelieved 209-foot(64-meter)-square plans and unbroken 1,360-foot(415-meter)-high profiles of the twin World Trade Center buildings came in for considerable architectural criticism for their lack of character. Like the Sears Tower, however, when viewed from different angles, the buildings, especially as they played off against each other, enjoyed a great aesthetic synergy. The view of the towers from the walkway of the Brooklyn Bridge was especially striking, with the stark twin monoliths echoing the twin Gothic arches of the bridge's towers.

Although the World Trade Center towers did look like little more than tall prisms from afar, the play of the ever-changing sunlight on their aluminum-clad columns made them new buildings by the minute. From a closer perspective, the multiplicity of unbroken columns corseting each building also gave it an architectural texture.

The tubular concept was not totally new with the WTC

The close spacing of the columns was dictated by the desire to make the structure as nearly a perfect tube as possible. A true tube, like a straw, would be unpunctured by peripheral openings, but since skyscrapers are inhabited by people, windows are considered a psychological must. At the same time, too-large windows in very tall buildings can give some occupants an uneasy feeling. The compromise struck in the World Trade Center was to use tall but narrow windows between the steel columns. In fact, the width of the window openings was said to be less than the width of a person's shoulders, which was intended by the designers to provide a measure of reassurance to the occupants. Since the terrorist attack, however, one of the most haunting images of those windows is of so many people standing sideways in the openings, clinging to the columns and, ultimately, falling, jumping or being carried to their death.

Failure Analyses

Terrorists first attempted to bring the World Trade Center towers down in 1993, when a truck bomb exploded in the lower-level public garage, at the base of the north tower. Power was lost in the tower and smoke rose through it. It was speculated that the terrorists were attempting to topple the north tower into the south one, but even though several floors of the garage were blown out, the structure stood. There was some concern among engineers then that the basement columns, no longer braced by the garage floors, would buckle, and so they were fitted with steel bracing before the recovery work proceeded. After that attack, access to the underground garage was severely restricted, and security in the towers was considerably increased. No doubt the 1993 bombing was on the minds of many people when the airplanes struck the towers last September.

As they had in the earlier bombing, the World Trade Center towers clearly survived the impact of the Boeing 767 airliners. Given the proven robustness of the structures to the earlier bombing assault, the thought that the buildings might actually collapse was probably far from the minds of many of those who were working in them on September 11. It certainly appears not to have been feared by the police and fire fighters who rushed in to save people and extinguish the fires. Indeed, the survival of the World Trade Center after the 1993 bombing seems to have given an unwarranted sense of security that the buildings could withstand even the inferno created by the estimated 20,000 gallons (76,000 liters) of jet fuel that each plane carried. (That amount of fuel has been estimated to have an energy content equivalent to about 2.4 million sticks of dynamite.)

The survival of the WTC after the 1993 bombing seems to have given an unwarranted sense of security

Steel buildings are expected to be fireproofed, and so the World Trade Center towers were. However, fireproofing is a misnomer, for it only insulates the steel from the heat of the fire for a limited period, which is supposed to be enough time to allow for the fire to be brought under control, if not extinguished entirely. Unfortunately, jet fuel burns at a much higher temperature than would a fire fed by normal construction materials and the customary furniture and contents found in an office building. Furthermore, conventional fire-fighting means, such as water, have little effect on burning jet fuel. The World Trade Center fire, estimated to have produced temperatures as high as of the order of the melting point of steel, continued unabated. It has been speculated that some of the steel beams and columns of the structure that were not destroyed by the impact eventually may have been heated close to if not beyond their melting point, but this appears to have been unlikely.

Even if it did not melt, the prolonged elevated temperatures caused the steel to expand, soften, sag, bend and creep. The intense heat also caused the concrete floor, no longer adequately supported by the steel beams and columns in place before the impact of the airplane, to crack, spall and break up, compromising the synergistic action of the parts of the structure. Without the stabilizing effect of the stiff floors, the steel columns still intact became less and less able to sustain the load of the building above them. When the weight of the portion of the building above became too much for the locally damaged and softened structure to withstand, it collapsed onto the floors below. The impact of the falling top of the building on the lower floors, whose steel columns were also softened by heat transfer along them, caused them to collapse in turn, creating an unstoppable chain reaction. The tower that was struck second failed first in part because the plane hit lower, leaving a greater weight to be supported above the damaged area. (The collapse of the lower floors of the towers under the falling weight of the upper floors occurred for the same reason that a book easily supported on a glass table can break that same table if dropped on it from a sufficient height.)

Within days of the collapse of the towers, failure analyses appeared on the Internet and in engineering classrooms. Perhaps the most widely circulated were the mechanics-based analysis of Zdenek Bazant of Northwestern University and the energy approach of Thomas Mackin of the University of Illinois at Urbana-Champaign. Each of these estimated that the falling upper structure of a World Trade Center tower exerted on the lower structure a force some 30 times what it had once supported. Charles Clifton, a New Zealand structural engineer, argues that the fire was not the principal cause of the collapse. He thinks that it was the damaged core rather than the exterior tube columns that succumbed first to the enormous load from above. Once the core support was lost on the impacted floors, there was no stopping the progressive collapse, which was largely channeled by the structural tube to occur in a vertical direction. In the wake of the World Trade Center disaster, the immediate concerns were, of course, to rescue as many people as might have survived. Unfortunately, even to recover most of the bodies proved an ultimately futile effort. The twin towers were gigantic structures. Each floor of each building encompassed an acre, and the towers enclosed 60 million cubic feet each. Together, they contained 200,000 tons of steel and 425,000 cubic yards (325 cubic meters) or about 25,000 tons of concrete. The pile of debris in some places reached as high as a ten-story building. A month after the terrorist attack, it was estimated that only 15 percent of the debris had been removed, and it was estimated that it would take a year to clear the site.

Forensic Engineering

Among the concerns engineers had about the clean-up operation was how the removal of debris might affect the stability of the ground around the site. Because the land on which the World Trade Center was built had been part of the Hudson River, an innovative barrier had to be developed at the time of construction to prevent river water from flowing into the basement of the structures. This was done with the construction of a slurry wall, in which the water was held back by a deep trench filled with a mudlike mixture until a hardened concrete barrier was in place. The completed structure provided a watertight enclosure, which came to be known as the "bathtub" within which the World Trade Center was built. The basement floors of the twin towers acted to stabilize the bathtub, but these were crushed when the towers broke up and collapsed into the enclosure. Early indications were that the bathtub remained intact, but in order to be sure its walls do not collapse when the last of the debris and thus all the internal support is removed, vulnerable sections of the concrete wall were being tied back to the bedrock under the site even as the debris removal was proceeding.

Atop the pile of debris, the steel beams and columns were the largest and most recognizable parts in the wreckage. The concrete, sheetrock and fireproofing that were in the building were largely pulverized by the collapsing structure, as evidenced by the ubiquitous dust present in the aftermath. (A significant amount of asbestos was apparently used only in the lower floors of one of the towers, bad publicity about the material having accelerated during the construction of the World Trade Center. Nevertheless, in the days after the collapse, the once-intolerant Environmental Protection Agency declared the air safe.) The grille-like remains of the buildings' facades, towering precariously over what came to be known as Ground Zero, became a most eerie image. Though many argued for leaving these cathedral wall-like skeletons standing as memorials to the dead, they posed a hazard to rescue workers and were in time torn down and carted away for possible future reuse in a reconstructed memorial. As is often the case following such a tragedy, there was also some disagreement about how to treat the wreckage generally. Early on, there was clearly a need to remove as much of it from the site as quickly as possible so that what survivors there might be could be uncovered. This necessitated cutting up steel columns into sections that could fit on large flatbed trucks. Even the disposal of the wreckage presented a problem. Much of the steel was marked for immediate recycling, but forensic engineers worried that valuable clues to exactly how the structures collapsed would be lost.

All of the speculations about the mechanism of collapse are in fact hypotheses

All of the speculations of engineers about the mechanism of the collapse are in fact hypotheses, theories of what might have happened. Although computer models will no doubt be constructed to test those hypotheses and theories, actual pieces of the wreckage may provide the most convincing confirmation that the collapse of the structures did in fact progress as hypothesized. Though the wreckage may appear to be hopelessly jumbled and crushed, telltale clues can survive among the debris. Pieces of partially melted steel, for example, can provide the means for establishing how hot the fire burned and where the collapse might have initiated. Badly bent columns can give evidence of buckling before and during collapse. Even the scratches and scars on large pieces of steel can be useful in determining the sequence of collapse. This will be the task of teams of experts announced shortly after the tragedy by the American Society of Civil Engineers and the Federal Emergency Management Agency. Also in the immediate wake of the collapse, the National Science Foundation awarded eight grants to engineering and social science researchers to assess the debris as it is being removed and to study the behavior of emergency response and management teams.

Analyzing the failure of the towers is a Herculean task, but it is important that engineers understand in detail what happened so that they incorporate the lessons learned into future design practices. It was the careful failure analysis of the bombed Federal Building in Oklahoma City that led engineers to delineate guidelines for designing more terrorist-resistant buildings. The Pentagon was actually undergoing retrofitting to make it better able to withstand an explosion when it was hit by a third hijacked plane on September 11. Part of the section of the building that was struck had in fact just been strengthened, and it suffered much less damage than the old section beside it, thus demonstrating the effectiveness of the work.

Understanding how the World Trade Center towers collapsed will enable engineers to build more attack-resistant skyscrapers. Even before a detailed failure analysis is completed, however, it is evident that one way to minimize the damage to tall structures is to prevent airplanes and their fuel from being able to penetrate deeply into the buildings in the first place. This is not an impossible task. When a B-25 bomber struck the Empire State

Building in 1945, its body stuck out from the 78th and 79th floors like a long car in a short garage. The building suffered an 18-by-20-foot (5.5-by-6-meter) hole in its face, but there was no conflagration, and there certainly was no collapse. The greatest damage was done by the engines coming loose and flying like missiles through the building. The wreckage of the plane was removed, the local damage repaired and the building restored to its original state. Among the differences between the Empire State Building and World Trade Center incidents was that in the former case, relatively speaking, a lighter plane struck a heavier structure. Furthermore, the propeller-driven bomber was on a short-range flight from Bedford, Massachusetts to Newark airport and

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so did not have on board the amount of fuel necessary to complete a transcontinental flight or to bring down a skyscraper.

Modern tall buildings can be strengthened to be more resistant to full penetration by even the heaviest of aircraft. This can be done by placing more and heavier columns around the periphery of the structure, making the tube denser and thicker, as it were. The ultimate defense would be to make the facade a solid wall of steel or concrete, or both. This would eliminate windows entirely, of course, which would defeat some of the purpose of a skyscraper, which is in part to provide a dramatic view from a prestigious office or board room. The elimination of that attraction, in conjunction with the increased mass of the structure itself, would provide space that would command a significantly lower rent and yet cost a great deal more to build. Indeed, no one would likely even consider building or

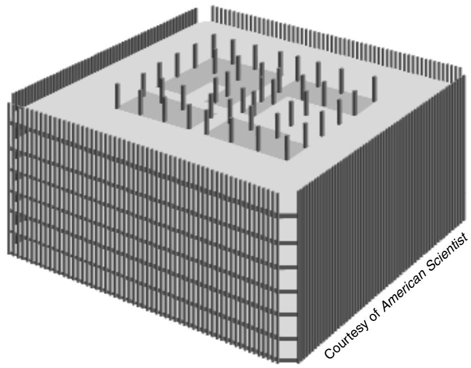

Figure 2. Structural design of the World Trade Center towers was a tube with a central core.

renting space in such a building. Hence, the solution would be a Pyrrhic victory over terrorists.

The World Trade Center towers might have stood after the terrorist attack if the fires had been extinguished quickly. But even if the conventional sprinkler systems had not been damaged, water would not have been effective against the burning jet fuel. Perhaps skyscrapers could be fitted with a robust fire-fighting system employing the kind of foam that is laid down on airport runways during emergency landings, or fitted with some other oxygen-depriving scheme, if there could also be a way for fleeing people to breathe in such an environment. Such schemes would need robustness and redundancy to survive tremendous impact forces, so any such system might be unattractively bulky and prohibitively expensive to install. Other approaches might include more effective fireproofing, such as employing ceramic-based materials, thus at least giving the occupants of a burning building more time to evacuate.

The evacuation of tall buildings will no doubt now be given much more attention by architects and engineers alike. Each World Trade Center tower had multiple stairways, but all were in the single central core of the building. In contrast, stairways in Germany, for example, are required to be in different corners of the building. In that configuration, it is much more likely that one stairway will remain open even if a plane crashes into another corner. But locating stairwells in the corners of a building means, of course, that prime office space cannot be located there. In other words, most measures to make buildings safer also make them more expensive to build and diminish the appeal of their office space. This dilemma is at the heart of the reason why the future of the skyscraper is threatened.

It is likely that, in the wake of the World Trade Center collapses, any super-tall building currently in the development stage will be put on hold and reconsidered. Real-estate investors will want to know how the proposed building will stand up to the crash of a fully fueled jumbo jet, how hot the ensuing fire will burn, how long it will take to be extinguished and how long the building will stand so that the occupants can evacuate. The investors will also want to know who will rent the space if it is built.

Potential tenants will have the same questions about terrorist attacks. Companies will also wonder if their employees will be willing to work on the upper stories of a tall building. Managers will wonder if those employees who do agree to work in the building will be constantly distracted, watching out the window for approaching airplanes. Corporations will wonder if clients will be reluctant to come to a place of business perceived to be vulnerable to attack. The very need to have workers grouped together on adjacent floors in tall buildings is also being called into question.

After the events of September 11, the incentive to build a signature structure, a distinctive super-tall building that sticks out in the skyline, is greatly diminished. In the immediate future, as leases come up for renewal in existing skyscrapers, real-estate investors will be watching closely for trends. It is unlikely that our most familiar skylines will be greatly changed in the foreseeable future. Indeed, if companies begin to move their operations wholesale out of the most distinctive and iconic of super-tall buildings and into more non-descript structures of moderate height, it is not unimaginable that cities like New York and Chicago will in time see the reversal of a long-standing trend. We might expect no longer to see developers buying up land, demolishing the low-rise buildings on it, and putting up a new skyscraper. Instead, owners might be more likely to demolish a vacant skyscraper and erect in its place a building that is not significantly smaller or taller than its neighbors. Skylines that were once immediately recognizable even in silhouette for their peaks and valleys may someday be as flat as a mesa.

There is no imperative to such an interplay between technology and society. What really happens in the coming years will depend largely on how businesses, governments and individuals react to terrorism and the threat of terrorism. Unfortunately, the image of the World Trade Center towers collapsing will remain in our collective consciousness for a few

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generations, at least. Thus, it is no idle speculation to think that it will be at least a generation before skyscrapers return to ascendancy, if they ever do. Developments in micro-miniaturization, telecommunications, information technology, business practice, management science, economics, psychology and politics will likely play a much larger role than architecture and engineering in determining the immediate future of macro-structures, at least in the West.

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