A SunCam online continuing education course

9/11 Attacks | WTC 1 & 2
Engineering Analysis

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Introduction

On September 11, 2001, the United States suffered a devastating attack in an act of terrorism, and one of the worst building-related disasters in American history, killing nearly 3,000 people. Four commercial airliners were hijacked and flown into both World Trade Center 1 & 2, the Pentagon, and a fourth, presumed to be targeting the White House or Capitol Building, crashed in Pennsylvania before reaching the destination. On an unprecedented scale, the terrorists exposed a weakness in security that had previously been overlooked, and certainly unexpected. The blow they dealt caused destruction and terror not seen on American soil. However, it also caused the US to be strengthened by hardening infrastructure, improving aviation security, and increasing public awareness of terrorism.

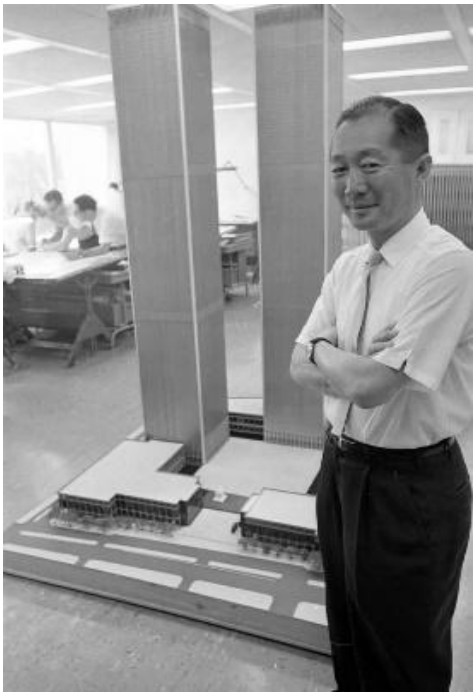
Now, nearly a quarter of a century later, 9/11 is a distant memory. Regardless, an indelible mark was made in history on that day. While the September 11 attacks were intentional and certainly not an accident, the engineering of the structures played a role in how the towers reacted to the impacts and subsequently collapsed. The architects and engineers who designed the WTC undoubtedly never imagined these buildings would be subject to an attack with the magnitude seen in 2001. However, their decisions played distinct roles in the effects of that day, and influenced the course of many people's lives.

This analysis examines the destruction of World Trade Center 1 & 2 in New York City. It covers the history of the WTC and the Twin Towers, and the details about the structural design, including integrated safety measures that were in place before the terrorist attacks. The following sections cover the impact of the aircraft and the extent of the instantaneous damage, followed by the subsequent collapses of the buildings and the evacuation effort. Finally, there is a review of the lessons learned from 9/11 and how modern buildings are reinforced against similar scenarios.

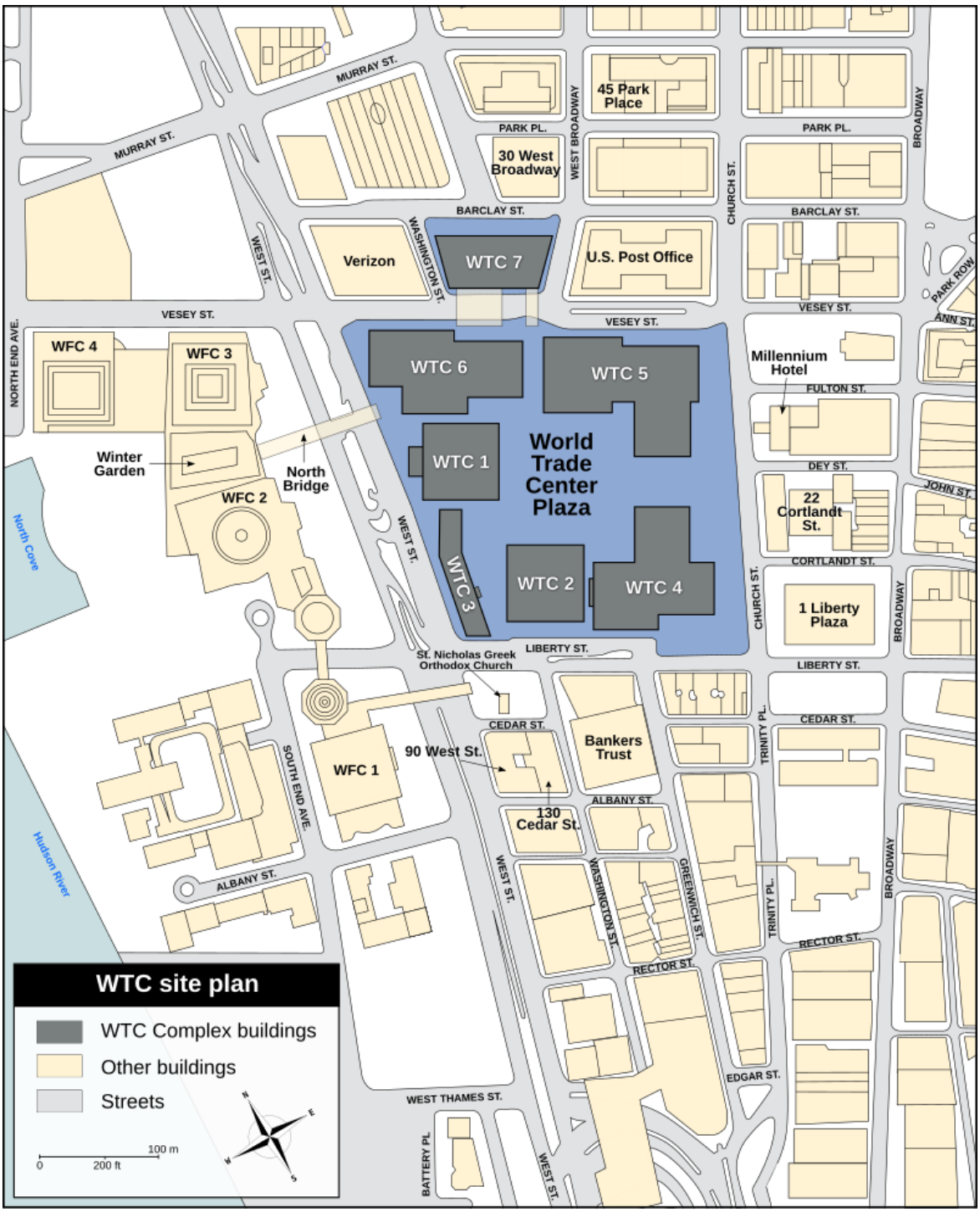
Not covered in this analysis are the political, economic, religious, and cultural motives or results of the attacks, the military response, rescue and recovery efforts, and non-engineering aspects of the buildings. Also, the damage inflicted on the Pentagon, the collapse of WTC 7, and damage to other surrounding buildings is not covered.

History of the World Trade Center

Discussions about a world trade facility began in the 1950s, in the shadow of the Cold War, in part as a spotlight on the strength of the American economic system, and as a symbol of globalization. The Port Authority of New York and New Jersey commissioned the project, and construction began in 1966. The architect, Minoru Yamasaki, was a Japanese American who specialized in the art of combining aesthetics and functional efficiency. His concept was seven buildings to form the trade center, with two tall towers dominating the skyline. Although subject to initial criticism, the Twin Towers became iconic NYC attractions. Construction of the towers saw completion and dedication in 1973. Weighing in at more than a combined 1.5 million tons, the two towers boasted 10 million square feet of floor space, 43,600 windows, and 194 passenger elevators. At approximately 208 feet per side, the towers reached over 1300 ft high and had 110 stories. The cost by the time the towers were finished reached $900 million.

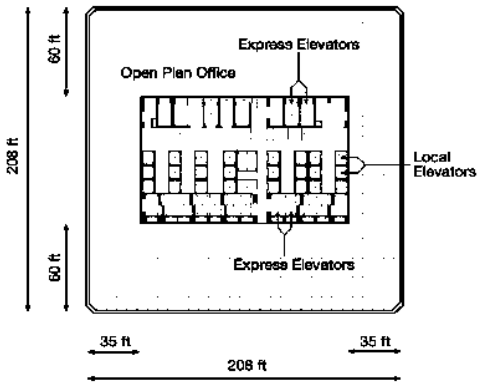


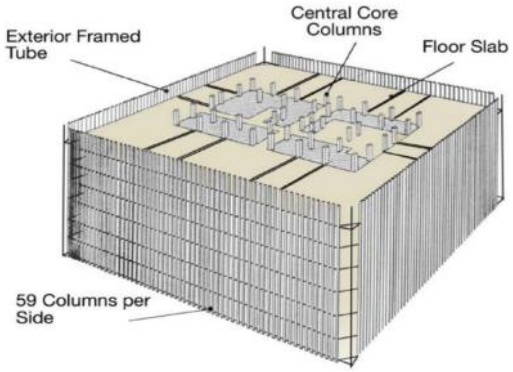
The following image is a map of the western side of Lower Manhattan, and the arrangement of the World Trade Center before 9/11:



WTC Structural Design

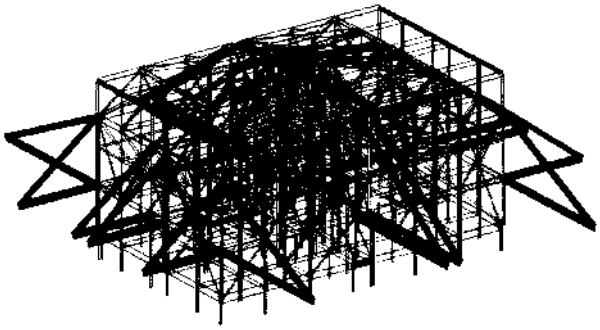
The structural system of WTC 1 & 2 was that of framed-tube design, developed in the 1960s (new at the time) and permitted a modern, open-floor design via a steel core and perimeter columns. The open floor was a revolutionary plan, offering vast, uninterrupted office space.

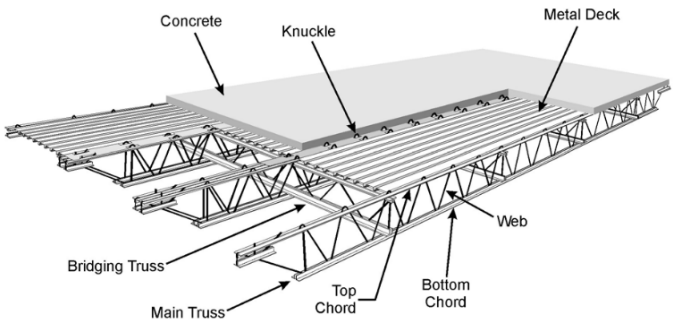


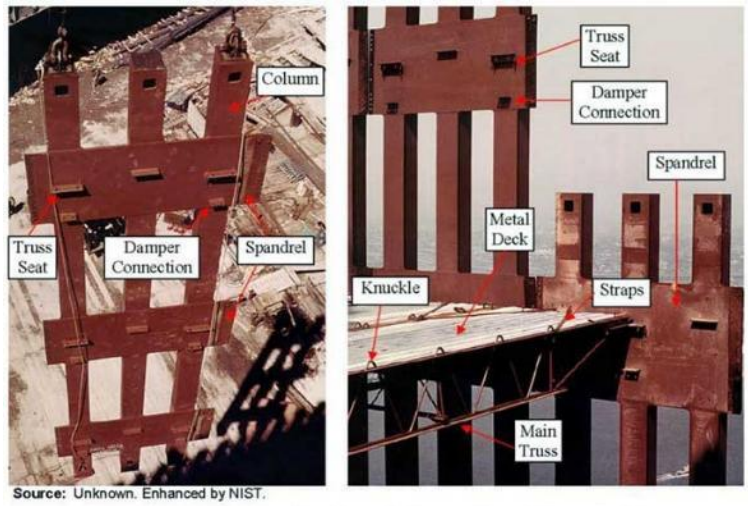


Each tower had 59 perimeter columns per side (40” on center, 236 total) to form a rigid wall that resisted the lateral loads and partially bore the gravity loads. These exterior columns were prefabricated into wall sections, three columns each, connected by spandrel plates. The spandrel plates were located at each floor and transmitted the shear stress between columns. Vertically staggered joints between sections allowed the floors to be interconnected with column joints at varying elevations, forming a strong external structure. At the outer wall, floor trusses were connected to steel brackets welded to the columns. Hat trusses at the top of the tower connected the central core to the perimeter columns, helping to stiffen the building and redistribute loads. The combination of external columns and internal core allowed the towers to have a relatively lightweight structure, and be more flexible than traditional masonry buildings, such as the neighboring Empire State Building.

The 47 internal core columns rose from the bedrock to the top of each tower. Each floor spanned the opening between exterior and the core by floor trusses on 6’8” centers. The floors were 4” reinforced lightweight concrete slabs cast on a steel deck, supported by open web joists spanning the distance between the exterior tube structure and interior core columns. Wind analysis and wind tunnel testing verified the amount of sway that was permissible for occupants and structure alike.







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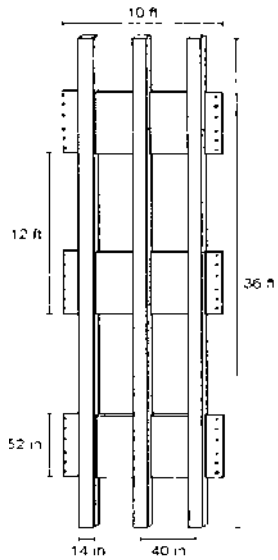
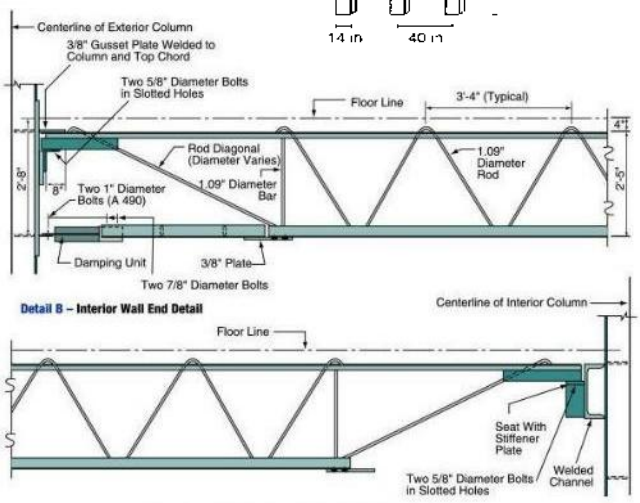


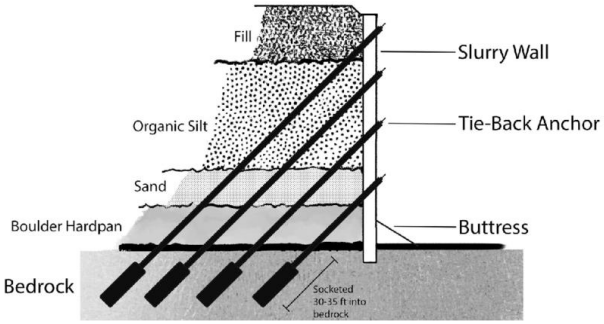


Under the towers, a six-story subterranean structure created the foundation for the skyscrapers. Geotechnical testing revealed that the site contained layers of marginal soil. Bedrock lay between 65-80 feet below street level. The ground water table was only a few feet below street level. Additionally, two subway tubes for the Port Authority Trans-Hudson (PATH) rail line lay buried in the site location. With potential for the Hudson River breaching the excavation, major geotechnical and civil engineering challenges were encountered.

Deep foundations were deemed too risky and expensive, so the Port Authority design teams selected large excavations to place the foundations directly on the bedrock. To do so, a perimeter cutoff wall had to be constructed to dewater the site and permit soil to be excavated within the site. This occurred in the form of a slurry wall. To build a slurry wall, a trench is dug in the location of the perimeter foundation walls and bentonite slurry is pumped into the trench, permitting the trench to effectively be shored against collapse and maintain a water-resistant barrier. Rebar is lowered into the trench, and concrete is poured to displace the slurry which creates a reinforced wall around the perimeter. Once the concrete is cured, the substructure excavation begins. Over 1 million cubic yards of soil and rock was excavated from the WTC site. This was transported to the adjacent bank of Manhattan Island across West Street, which created 23

acres of new land for future real estate development, and eventually became the site of the World Financial Center (now Brookfield Place).

To prevent deflections and movement of the wall, tieback reinforcement was necessary. Sleeves were installed in rows, and drills advanced through the exposed concrete wall diagonally into the bedrock below. Each tieback was grouted in place and tensioned to hold against lateral earth pressure, creating a robust and stable foundation system. Approximately 1,500 tiebacks were installed at the WTC site and were considered temporary and were eventually replaced by floor slabs that provided lateral wall support.



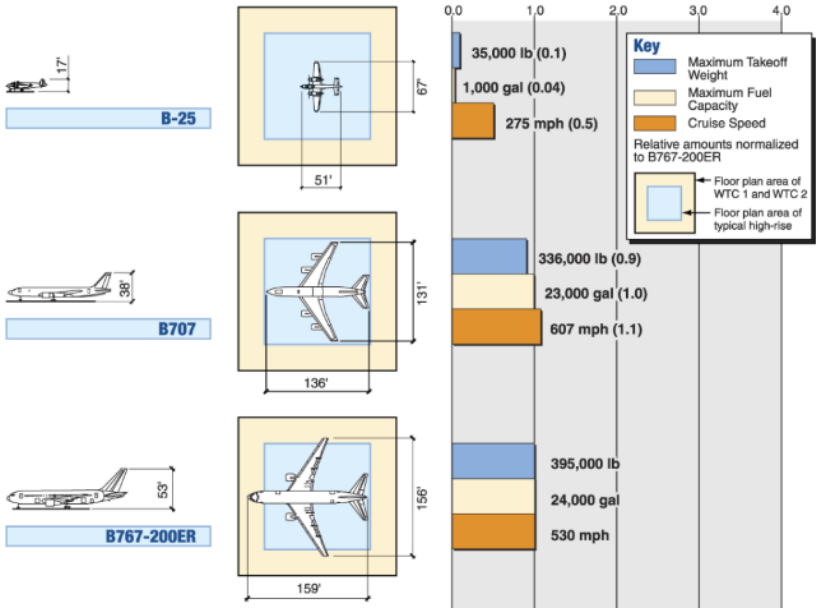
WTC Slurry Walls & Tiebacks

Integrated Safety Measures

Although engineers design buildings for gravity, wind, and earthquake loads, a myriad of other protection and safety systems are integrated into a building design (fire protection, egress, sprinklers, alarms, special hazard mitigation, etc.) Particularly in high-rise buildings, fire safety requirements are prescribed to maintain the integrity of the structure by controlling the intensity of the fire and providing adequate structural strength during fires. This is accomplished via sprinklers, manual firefighting, and fire-resistant building materials and construction. In the case of the WTC, all three of these defenses were overwhelmed.

While reports indicate that an aircraft impact was considered during the design of the WTC Towers, building codes did not require building designs to consider aircraft impact at the time of the WTC construction. In fact, national model building codes still do not include requirements for design for loads that might be imposed due to acts of war or terrorism (additional security and defense measures are generally at the discretion of the owner). Furthermore, the aircraft at the time of construction (1960s) were smaller and carried less fuel than modern airliners. The Boeing 707 was considered in 1964 as the likely airplane to crash into a tower, presumably by accident, not intentionally. Nevertheless, the WTC towers were the first structures outside of the military or nuclear industries whose design included the impact of a jet airliner. Post-crash fires were not considered. However, the then-recent B-25 crash into the Empire State Building must have influenced the minds of the designers as a potential scenario.

Note: on July 28, 1945, a B-25D Mitchell bomber crashed into the north side of the Empire State Building between the 78th-80th floors while flying in thick fog and attempting to land at LaGuardia. 14 people, including the crew, were killed. The building's structure was not compromised. The resulting fire due to the crash is still the highest structural fire brought under control by FDNY. For reference, a B-25 has approximately 4% of the fuel capacity of a 767-200ER and about 10% of the maximum takeoff weight:



The World Trade Center bombing event that occurred in 1993 prompted additional safety measures to be installed in the WTC complex. A 1,300-pound bomb in a van located in the underground parking garage detonated with the intent to topple the North Tower, and also cause the South Tower to collapse. While the bomb caused damage to the structure and killed 6 people, it failed to cause a collapse. This event prompted additional security measure implementation: physical defenses such as anti-ram barriers at parking ramps, security screening, access control systems for subgrade entries, and other measures. Additionally, 1,600 emergency lights were installed in stairways, lobbies, and elevators. Secondary backup generators, exit signs, command & control stations, fire alarm systems, FDNY radio antennas, backup PA systems, and battery backup systems all contributed to the upgrades.

Sprayed fire-resistant material (SFRM) installed in the original WTC structures were applied to steel framing with the intent to temporarily provide fire resistance and lengthen evacuation time, not prevention against prolonged fires and total collapse. Fire-protection of a truss-supported floor system with spray-on fireproofing was innovative and not consistent with then-prevailing practice. Asbestos-containing types (mineral wool, Portland cement, and chrysolite) were installed on lower core columns, exterior walls, and floor trusses. Asbestos-free types (mineral wool, and glass fiber) were installed on upper floors, in addition to gypsum plaster and board. Original coating thicknesses ranged from ½" – ¾", and were later upgraded in part to nearly 2-1/2" thick. Note: ½" thickness was specified when WTC towers were built to maintain Class 1-A fire rating requirement of the NYC Building Code.

Much analysis and speculation occurred in the time following 9/11, with some varying opinions. For example, no evidence that full-scale fire resistance tests of the WTC floor system were conducted to determine the required fireproofing thickness; in 1966, the Architect of Record and, in 1975, the Structural Engineer of Record stated that the fire rating of the WTC floor system could not be determined without testing. An engineering study from 2002 states that "no fireproofing is designed to withstand such devastating impacts."

In summary, the WTC towers were well designed with a reasonable amount of safety measures in place. It seems unlikely that the designers would have considered that terrorism in the form of a hijacked aircraft would eventually cause the demise of the architectural masterpieces. And, to their credit, even if they did foresee such tragedy, it's fair to say they couldn't have anticipated exactly what kind of threat would be a possibility. The WTC towers withstood tremendous impact loads for enough time to permit a large-scale evacuation, which no doubt saving many lives.

Summary of the 9/11 Attacks

On the morning of 11 September 2001, 19 terrorists from the Islamist extremist group al Qaeda hijacked four commercial aircraft and crashed two of them into the North and South Towers of the World Trade Center complex in New York City. A third plane crashed into the Pentagon in Arlington, Virginia. After learning about the other attacks, passengers on the fourth hijacked plane, Flight 93, fought back, and the plane was crashed into an empty field in Pennsylvania about 20 minutes by air from Washington, D.C. In all, the 9/11 terrorism events were the most devastating attack on American soil since the Japanese attacked Pearl Harbor in 1941. This brief summary recaps the events and the timeline of occurrences:

American Flight 11 (Boeing 767-200ER, Boston-LA) took off at 7:59 AM with 81 passengers.

United Flight 175 (Boeing 767-200ER, Boston-LA) took off at 8:14 AM with 56 passengers.

American Flight 77 (Boeing 757-200, DC-LA) took off at 8:20 AM with 58 passengers.

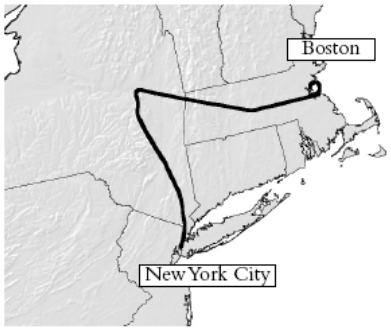
United Flight 93 (Boeing 757-200, Newark-San Francisco) took off at 8:42 AM with 37 passengers.

American 11 is hijacked around 8:14 AM by five al-Qaeda terrorists.
United 175 is hijacked around 8:45 AM by four al-Qaeda terrorists.
American 77 is hijacked around 8:51 AM by five al-Qaeda terrorists.
United 93 is hijacked around 9:28 AM by four al-Qaeda terrorists.

American 11 crashes into 1 WTC (North) at 8:46 AM.
United 175 crashes into 2 WTC (South) at 9:03 AM.
American 77 crashes into the Pentagon at 9:37 AM.
United 93 crashes into a field in Shanksville, PA at 10:03 AM.

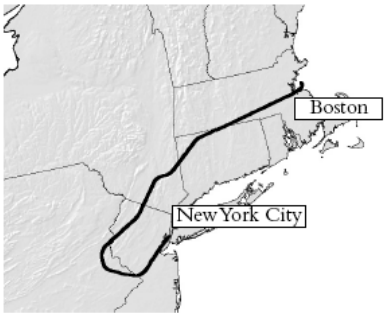
2 WTC collapses at 9:59 AM, after burning for 56 minutes.
1 WTC collapses at 10:28 AM, after burning for 1 hour 42 minutes.

American Airlines Flight 11 (AA 11)
Boston to Los Angeles



7:59	Takeoff
8:14	Last routine radio communication; likely takeover
8:19	Flight attendant notifies AA of hijacking
8:21	Transponder is turned off
8:23	AA attempts to contact the cockpit
8:25	Boston Center aware of hijacking
8:38	Boston Center notifies NEADS of hijacking
8:46	NEADS scrambles Otis fighter jets in search of AA 11
8:46:40	AA 11 crashes into 1 WTC (North Tower)
8:53	Otis fighter jets airborne
9:16	AA headquarters aware that Flight 11 has crashed into WTC
9:21	Boston Center advises NEADS that AA 11 is airborne heading for Washington
9:24	NEADS scrambles Langley fighter jets in search of AA 11

United Airlines Flight 175 (UA 175)
Boston to Los Angeles



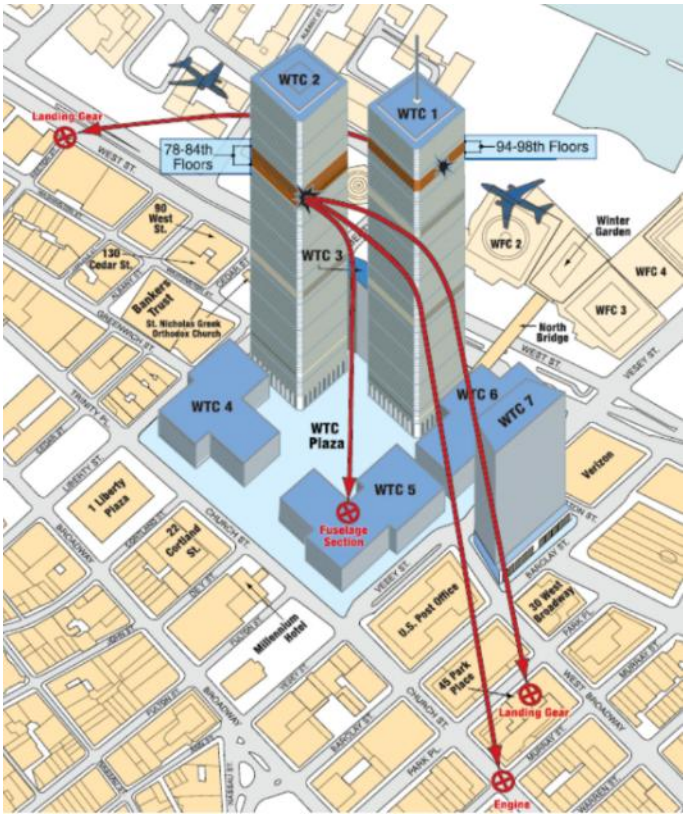
8:14	Takeoff
8:42	Last radio communication
8:42-8:46	Likely takeover
8:47	Transponder code changes
8:52	Flight attendant notifies UA of hijacking
8:54	UA attempts to contact the cockpit
8:55	New York Center suspects hijacking
9:03:11	Flight 175 crashes into 2 WTC (South Tower)
9:15	New York Center advises NEADS that UA 175 was the second aircraft crashed into WTC
9:20	UA headquarters aware that Flight 175 had crashed into WTC

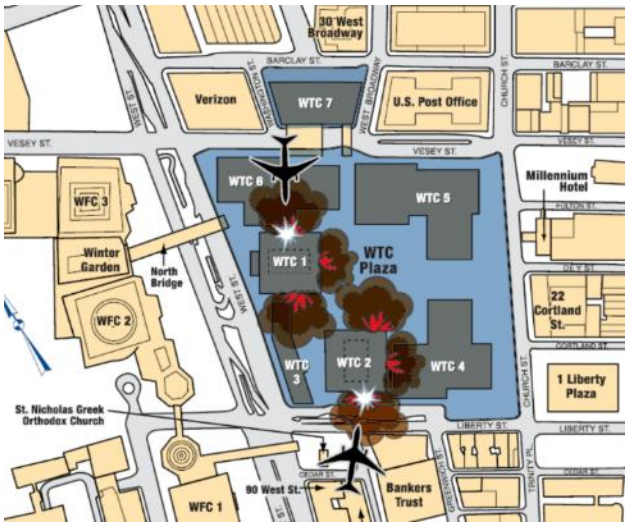
Impact Damage

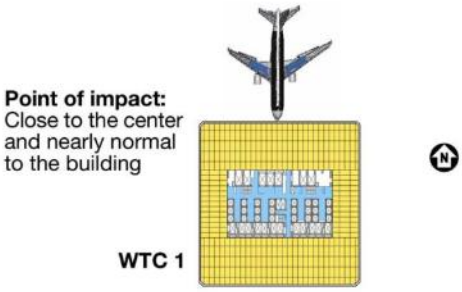
When the hijacked aircraft struck the towers, they were still heavily loaded with fuel, as they were both destined for a cross-country flight to LA. The estimated speed at impact into the North tower was 410 knots (470 mph) and 510 knots (590 mph) into the South Tower. The kinetic energy alone is approximately 2 GJ per aircraft, an incredible amount of energy, approximately equal to a 1,000-lb. TNT blast. However, it is important to note that the primary damage to the towers that lead to their collapse came not just from the impact energy, but rather the long-duration fires started by the tremendous amount of chemical energy from the jet fuel (estimated to be several thousand giga-joules per aircraft).

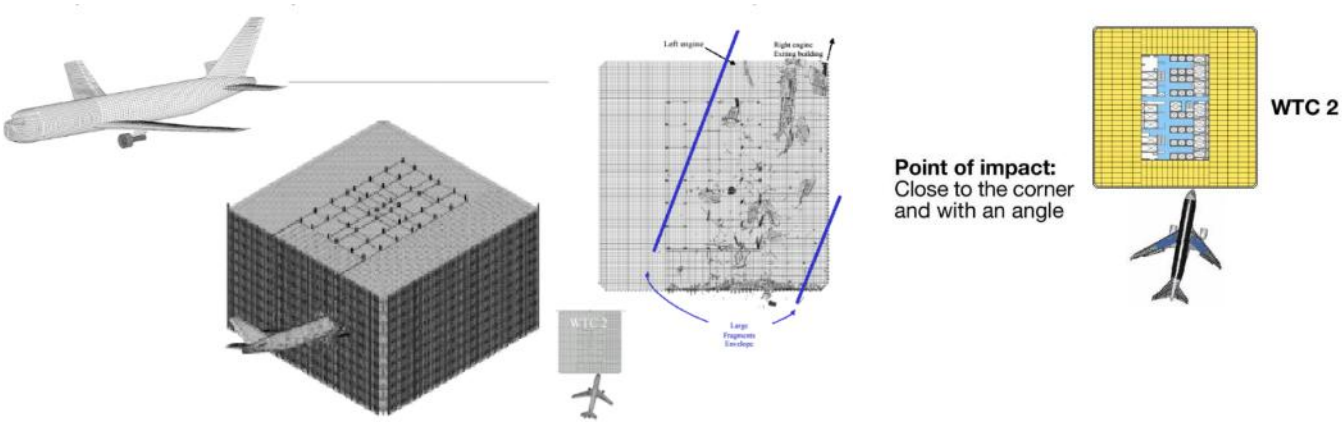
American 11 crashed into WTC 1 between the 93th-99th floors, and was essentially centered on the building's north face. United 175 crashed into WTC 2 between the 77th-85th floors, and was offset toward the east side of the south face.

Larger aircraft components such as landing gear, fuselage sections, and engines continued through the towers and landed on the streets below, some distance away.



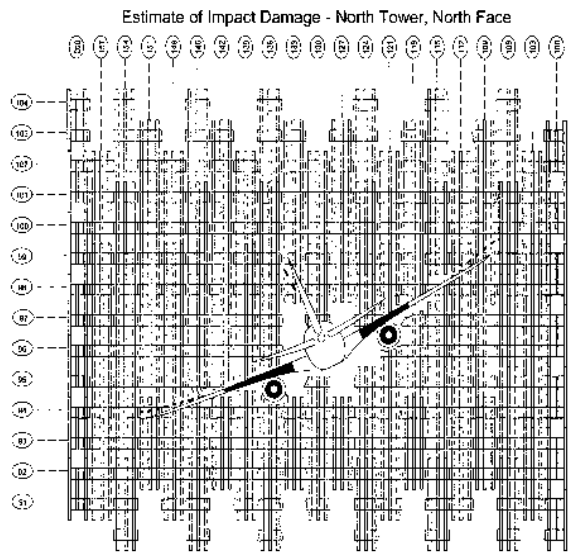


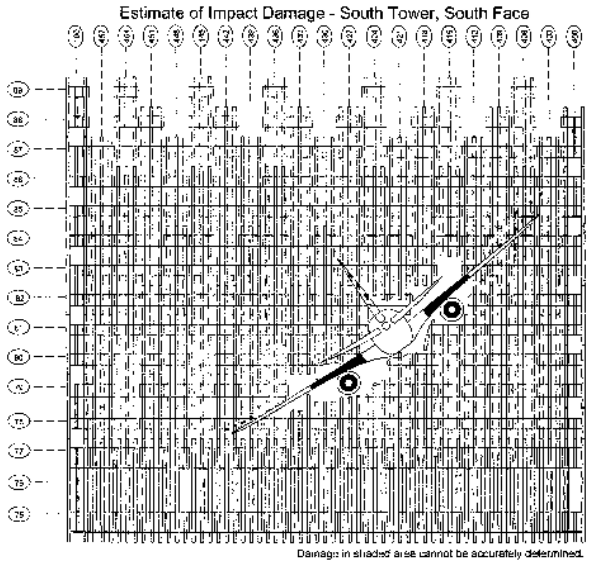




Computer Simulation Model of Impact

The images below show an overlaid 767 outline and the floor levels of impact on each tower. The following pictures are actual images of the same vicinity soon after the crashes occurred. The initial collisions into the WTC towers severely damaged the structure, compromising many of the exterior columns, collapsing a large area of the floor slabs near the entry points, and causing structural harm to the core columns. Damage patterns were asymmetric, and extended sideward and up/down into adjacent floors.





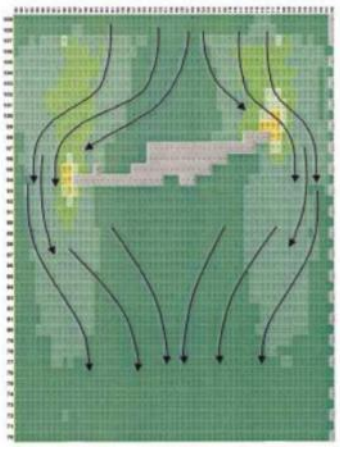
The fireballs that erupted in and around the towers immediately after impact resulted from aviation fuel igniting inside the tower, and then rapidly forcing large volumes of unburned fuel through openings created by impact and overpressure generated by the fire itself. Most of the fuel likely was atomized leaving the building, and burned when it mixed with air outside of the building. It's estimated that approximately 10,000 gal of fuel was on board Flight 11 and 9,100 gal on Flight 175 at impact, but only about one-third of the fuel burned in the initial fireball outside of the building, which lasted only a short time. The remaining fuel burned quickly inside the building, and the majority of the dust cloud and fire died down within the first 30-45 seconds. This is consistent with fire behavior that causes available oxygen to be rapidly consumed and subsequently depleted.

The fires that burned for almost the entire time that the buildings remained standing were due mainly to remaining burning building contents and, to a lesser extent, aircraft contents, not jet fuel. No structural component, however, was subject to intense fires for the entire period of burning. The duration of intense burning impacting any specific component was controlled by the availability of combustible materials, fuel gases released by those combustibles, and combustion air in the specific area. The typical floor had on average about 4 PSF of combustible materials on floors. The mass of the aircraft's solid combustibles was significant in the immediate impact region of both WTC towers. The 1968 NYC Building Code required buildings like the WTC towers to have 1-hr fire rated tenant separations, but the code did not impose any minimum compartment requirements to mitigate the spread of fire in large open floor plan buildings.

Photos show large amounts of debris and dust falling from the impacts. Some of this debris is higher than the impact floors, indicating that initial debris was expelled from the building and carried upward by the fireballs. Closeups also show the air surround the towers to be filled with thousands of sheets of paper floating down. After the largest flames were extinguished, the heated gases rose, and formed a mushroom cloud of smoke and dust.

Post-analysis of photos and videos show that both towers swayed heavily (possibly several feet, even up to 10 feet) due to the aircraft impact. Original design permitted structural deflections of up to 12 inches during high wind loads, incorporating the effects of viscoelastic dampers. While relatively insignificant for such a tall tower, even that much would be enough to feel. On 9/11, witnesses inside the tower during the initial impacts reported explosion and violent jolts, followed by the sensation of falling or tipping over. The excessive movement caused physical damage within the structures, such as ceiling panels falling, windows shattering, and door frames twisting. After the initial sway, the buildings stabilized; yet another testament to their structural design and resilience.

The impacts destroyed 33 out of 59 perimeter columns in the north face of WTC 1, and 29 out of 59 perimeter columns in the south face of WTC 2. Computer models showed further that the planes also destroyed approximately 15 out of 47 columns in the center of the core of Tower 1, and approximately 10 out of 47 columns in the southeast corner of the core of Tower 2. Because the towers were designed with a redundant system of perimeter and core columns, connected at the top with a steel hat truss, the loads meant to be carried by the impact-damaged columns were redistributed to the remaining columns. This load redistribution allowed the towers to remain standing for as long as they did.



Towers Collapse

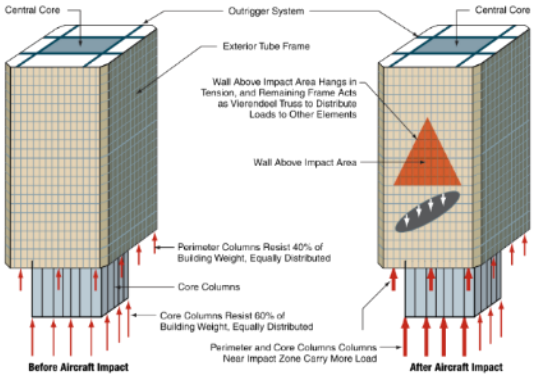
Terrorism aside, the collapse of the World Trade Center structures following the terrorist attacks on 9/11 was one of the worst-ever building disasters in recorded history. More than 400 fire and emergency responders were among those killed, the largest loss of life for this group in a single incident. Although evacuation was well underway, many people were still trapped in the building without a way of escape. Major devastation to Lower Manhattan occurred with dozens of adjacent structures being damaged or destroyed by debris. The toxic dust was dispersed throughout NYC which plagued residents for a long time after.

As the fires continued to burn inside the towers, the structural weakening became critical. The initial impacts of the aircraft knocked loose much insulation that could have protected the steel structure for a time. Post-damage analysis concluded that were it not for prolonged fire damage, the towers would not have collapsed. This quote from an engineer from the firm that conducted investigations after 9/11 stated that: *"The fact that Tower 1 stood for 103 minutes after losing approximately 53 column lines and that Tower 2 stood for 56 minutes after losing approximately 34 column lines is a testament to the strength of the buildings and the skill of Leslie Robertson and the other engineers who designed them. I believe that few, if any, other buildings could suffer that amount of damage and not collapse immediately."*

Further study indicates that the tremendous force of each airliner crashing into a tower not only fractured columns outright but also shook loose the column fireproofing. No fireproofing is designed to withstand such devastating shock as an airliner crash. The loss of fireproofing left those columns vulnerable to the aviation fuel fires, which eventually caused them to fail. Those models identify the failure of columns that either lost fireproofing or were destroyed on impact as the specific cause of the collapse of each tower. Failure of the floor trusses was shown not to have had any significant role in the initiation of the collapses.

Progressive building collapse is a chain-reaction failure in which the loss of one structural element—such as a column, connection, or floor—triggers the failure of adjoining components, ultimately causing a large portion or the entirety of the structure to collapse. It typically begins when a building is subjected to an extreme event beyond its design capacity, such as an explosion, fire, impact, or major design or construction flaw. When a critical load-bearing element can no longer support the weight it carries, that load must redistribute to neighboring elements; if those components are not sufficiently redundant or robust, they too fail, accelerating the collapse. Modern engineering and building codes aim to prevent this phenomenon by requiring improved fireproofing, stronger connections, better load-path continuity, and structural redundancy, ensuring that localized damage cannot propagate into a total structural failure.

After burning for only 56 minutes, the South Tower began a progressive collapse. Because Tower 2 was hit off center, it was left without one of its corner columns in the core of the building and, like a table losing one of its legs, had less ability to redistribute the weight that was meant to be carried by the weakened or lost columns. Large portions of the perimeter columns and core columns were left without support, and soon the local area of impact began to catastrophically fail as the columns yielded and buckled due to the prolonged heat. The hat truss at the top of the tower shifted loads to the perimeter columns as the core columns weakened. Simultaneously, the floor trusses began to buckle, pulling the perimeter walls toward the center of the tower. The floors above the impact zone fell freely onto the structure below. This sudden gravity load was more than any one story could take, and thus the sequence began until there was no more building to collapse.



The initial collapse caused the upper stories to tilt, but the remainder of the tower collapsed virtually straight down, in a progressive manner. As the rubble fell, it pushed the perimeter walls outward, causing the rubble to spread as the building rapidly disassembled itself. The sudden compressing of the building created high pressure air which blew out windows below the destruction above. The result was an enormous dust cloud and incredible debris pile, amid widespread chaos and terror.

WTC Tower 2 Collapses: 9:59 AM

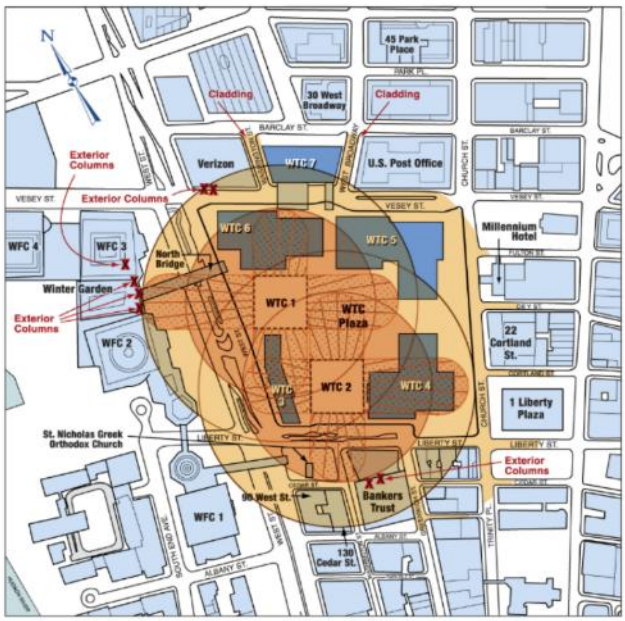
The North Tower burned longer (1 hr. 42 min) and thereby fell after the South Tower, even though it was struck 17 minutes sooner. The reason it stood longer is that the Flight 11 impact zone was more central to the tower's face, and consequently left more structure intact and prevented an eccentric imbalance. It also

hit higher on the tower, thereby significantly reducing the gravity load on the affected stories. The core of the North Tower retained its corner columns and, like a table with all four of its legs, it was better able to redistribute the weight meant to be carried by lost columns. Similar to the South Tower, the North Tower experienced prolonged fire and therefore loss of steel strength due to elevated temperature, in combination with the loss of structural integrity due to distortion of the steel. The impact zones compromised the columns, and again the structure became critical. NYPD airborne helicopter pilots reported that the North Tower was leaning, followed by confirmation that a corner of the building was beginning to buckle and the roof looked unstable. Shortly after, WTC 1 collapsed.

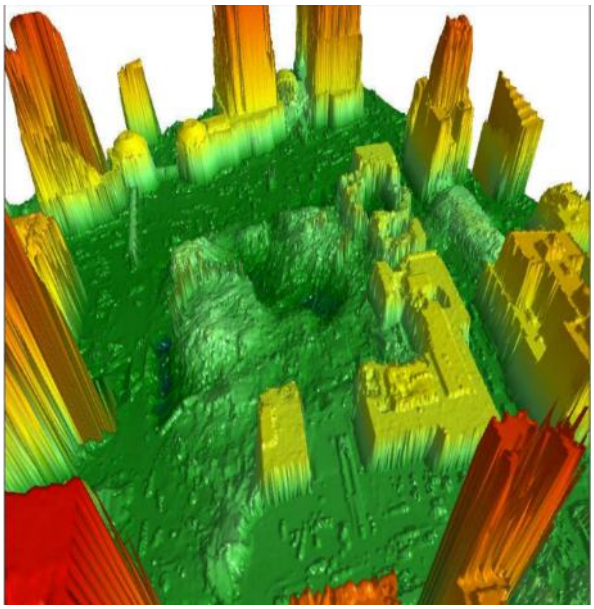
WTC Tower 1 Collapses: 10:28 AM

At that point, less than 2 hours since the first airplane struck the building, both towers were destroyed. To date, this catastrophe is the largest single building collapse in US history (by loss of life), and one of the largest building disasters in history, uniquely so due to fire-induced progressive collapse. It is an interesting point to consider that it took from 1966 to 1973 to construct the World Trade Center towers, and they each fell in less than 10 seconds

Post-analysis established that the collapse of Tower 2 did not cause any significant structural damage to Tower 1. Because the towers were offset, Tower 1 stood out of the way of the falling Tower 2 walls, and debris only superficially damaged Tower 1. Studies also showed that each collapse was initiated separately by a combination of the immediate damage from the impact of an airliner and the resulting fires on the floors that were struck.



Debris Affected Areas



Topographical Debris Image

Evacuation

It is estimated that about 17,000 occupants were present in the WTC towers on the morning of September 11, 2001. Approximately 87% of the WTC tower occupants, including more than 99% of those below the floors of impact, were able to evacuate successfully. Functioning elevators allowed many (roughly 3,000) survivors to self-evacuate WTC 2 during the 16 minutes prior to aircraft impact. The egress capacity (number and width of exits and stairways) was adequate to accommodate survivors who were seeking and able to reach and use undamaged exits and stairways. A full capacity evacuation of each WTC tower with 25,000 people—three times the number present on 9/11—would have required about 4 hours and likely resulted in the loss of 14,000 lives. The average surviving occupants moved down stairs at about half the slowest speed previously reported for non-emergency evacuations. Many occupants were largely unprepared for the physical challenge of evacuation.

Post-Event Assessments

In the days following September 11, teams of structural engineers began helping with the rescue and recovery efforts by assisting contractors to remove debris, providing descriptions of structures, and offering recommendations on structure stability. They provided warnings of possible hazards and advised on equipment selection and placement. In total, more than 10,000 engineering hours were recorded for this effort in the first 30 days after the attack. Subsequent efforts included engineering evaluation of damaged buildings for future occupation, and identification of structural hazards that could cause further harm.

The structural integrity of the slurry wall is a testament to the design and construction, which was severely put to the test on 9/11. When the towers collapsed, the floors that had resisted lateral loads no longer existed. This put the slurry wall at risk of collapse; not only causing risk of flooding the entire NY subway system (via PATH tunnels), but the possibility of the Hudson River breaching the site and flooding Lower Manhattan. Portions of the wall deflected more than 4 feet; but amazingly, the wall held. Temporary structural efforts prevented further risk and bolstered the remaining infrastructure so rescue and recovery work could be done in relative safety. A portion of the original slurry wall is now preserved and visible in the 9/11 Memorial Museum.

In 2002, the Congress passed the National Construction Safety Team (NCST) Act, giving NIST authority to investigate building failures, similar to the NTSB and transportation failures. Thereby, NIST investigated the WTC Towers collapse following the aircraft impact, with the objectives including why and how the towers collapsed, the number of injuries specific to location, practices and procedures during construction and operation of the WTC, and identify national building and fire codes that warrant revision.

The following excerpts from the NIST report's findings include:

- The two large, fuel-laden aircraft hit the towers at high speed and did significant damage to principal structural components (core columns, floors, and perimeter columns) that were directly impacted by the aircraft or associated debris.

- The towers withstood the impacts and would have remained standing if not for the dislodged insulation (fireproofing) and the subsequent multi-floor fires. The amount of insulation dislodged by the aircraft impact was sufficient to cause the structural steel to be heated to critical levels.

- The robustness of the perimeter frame-tube system and the large size of the buildings helped the towers withstand the impact. The structural system redistributed loads from places of aircraft impact, avoiding larger scale damage upon impact.

- The hat truss, a feature atop each tower which was intended to support a television antenna (and to connect the core to the perimeter steel framing), prevented earlier collapse of the building core. In each tower, a different combination of impact damage and heat-weakened structural components contributed to the abrupt structural collapse.

- In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. The floors pulled the heated south perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the south wall buckled. The top section of the building tilted to the south and began its descent.

- In WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors. The steady burning fires on the east side of the building caused the floors there to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the east wall buckled. The top section of the building tilted to the east and to the south and began its descent.

- The WTC towers likely would not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11, 2001, if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

- NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photographs and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

- Because of the Port Authority's establishment under a clause of the United States Constitution, its buildings were not subject to any state or local building regulations. The buildings were unlike any others previously built, both in their height and in their innovative structural features. Nevertheless, the actual design and approval process produced two buildings that generally were consistent with nearly all of the provisions of the New York City Building Code and other building codes of that time that were reviewed by NIST. The wind loads used for the WTC towers, which governed the structural design of the external columns and provided the baseline capacity of the

structures to withstand abnormal events … significantly exceeded the requirements of the New York City building code and other building codes of the day that were reviewed by NIST.

- Approximately 87% of the estimated 17,400 occupants of the towers and 99% of those located below the impact floors, evacuated successfully. A principal factor limiting the loss of life was that the buildings were one-third to one-half occupied at the time of the attacks.

Studies after the event refute speculation that the fireproofing in the Twin Towers had not been properly monitored. While maintenance records were destroyed in the collapses, inspection reports for the Twin Towers were located and analyzed. A study of those reports confirmed that fireproofing on the structural steel was regularly examined. The researchers concluded that the structural integrity inspection program conducted by the Port Authority represented a greater standard of care than is generally followed for high-rise office buildings in New York City. The studies also showed that fireproofing was stripped from the structures only in the paths of the aircraft debris.

The following is a list of factors that enhanced the buildings' performance during the 9/11 attacks and prolonged the time between impact and collapse.

- The unusually dense spacing of perimeter columns, coupled with deep spandrels, that was an inherent part of both the architectural and structural design of the exterior walls, resulted in a robust building that was able to redistribute loads from severed perimeter columns to adjacent intact columns.

- The wind loads used for the WTC towers, which governed the design of the perimeter frame-tube system, significantly exceeded the prescriptive requirements of the New York City building code and selected other building codes of the era (Chicago, New York State), including the relevant national model building code.

- The robustness of the perimeter frame-tube system and the large dimensional size of the WTC towers helped the buildings withstand the aircraft impact.

- The composite floor system with open-web bar joist elements, framed to provide two-way flat plate action, enabled the floors to redistribute loads without collapse from places of aircraft impact damage to other locations, avoiding larger scale collapse upon impact.

- The hat truss resisted the significant weakening of the core, due to aircraft impact damage and subsequent thermal effects, by redistributing loads from the damaged core columns to adjacent intact columns and, ultimately, by redistributing loads to the perimeter walls from the thermally weakened core columns that lost their ability to support the buildings' weight.

- As a result of the above factors, the buildings would likely not have collapsed under the combined effects of aircraft impact and the subsequent jet-fuel ignited multi-floor fires, if the fireproofing had not been dislodged or had been only minimally dislodged by aircraft impact. The existing condition of the fireproofing prior to aircraft impact and the fireproofing thickness on the WTC floor system did not play a significant role in initiating collapse on September 11, 2001.

Preventing High-Rise Failures

In 2002, the US National Institute of Standards & Technology (NIST) launched a 6-year investigation of the WTC collapses, on the premise that the WTC Towers and WTC 7 were the only known cases of total structural collapse in high-rise steel framed buildings where fires played a significant role, which was subsequently concluded by the NIST investigation. The following are reasons why high-rise collapses do not occur due to fire alone:

1. Fires alone are typically too short in duration and not hot enough to cause steel structural members to yield. This depends on the factor of safety used in the design (i.e. a higher safety factor means additional material to heat up, and therefore more energy required to raise temperatures to critical levels). While far from melting, steel retains structural capacity up to about 600 °F, and only loses about 50% of its strength by 1100 °F. For design purposes, it is usually assumed that all capacity is lost at around 2200 °F, even though melting doesn't occur until 2700 °F. *Note: AISC's general structural steel rule of thumb is "if steel is still straight after fire exposure, it's probably OK".*

2. Fire suppression systems are integrated into high-rises per building code, to prevent fire from releasing energy that could heat the steel to a critical state.

3. Fireproofing structural members prevent them from reaching high temperatures, averting loss of strength capacity within specific time periods. For example, a certain fireproofing material may only be useful during the first hour of a fire, after which its ability to insulate is lost.

4. High-rises are supposed to be redundant structural systems, and localized failure should not result in the collapse of the entire building.

High rises are often designed to allow only a low percentage of their column's load capacity used for gravity loads, to permit additional resistance to lateral loads. In the case of the WTC towers, the exterior columns only used about 20% of their strength for gravity loads, leaving 80% capacity for wind and seismic loads. On September 11, the weather was clear with no high winds and no earthquake occurred. Thus, the aircraft impact was the only significant lateral load, leading to surprise that this alone caused the buildings to collapse.

In summary, the 9/11 attack on the Twin Towers highlighted both the strength and the vulnerabilities of the original design, created by structural engineers who pioneered the framed-tube system of closely spaced perimeter columns and a robust central core to resist wind loads and even a hypothetical aircraft strike. While this innovative engineering helped the towers withstand the initial impacts on September 11, 2001, the combination of dislodged fireproofing, the extensive structural damage, and prolonged high-temperature fires led to progressive collapse. In the aftermath, engineers and building-code officials drew critical lessons from the event, prompting major advancements in fireproofing materials, structural redundancy, egress design, communications systems, and overall high-rise fire resilience. These changes have informed modern skyscraper standards worldwide, aiming to prevent similar catastrophic failures and improve occupant safety in extreme conditions.

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