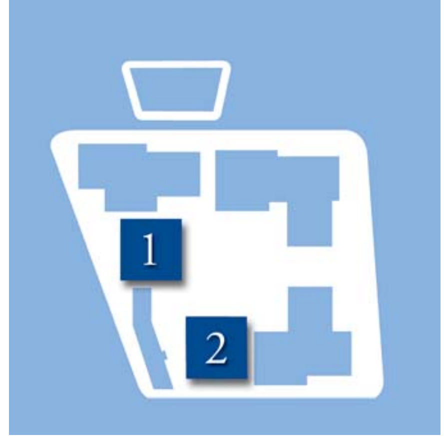


Ronald Hamburger
William Baker
Jonathan Barnett
Christopher Marrion
James Milke
Harold “Bud” Nelson

2 WTC 1 and WTC 2

2.1 Building Descriptions

2.1.1 General

The WTC towers, also known as WTC 1 and WTC 2, were the primary components of the seven-building World Trade Center complex. Each of the towers encompassed 110 stories above the Plaza level and seven levels below. WTC 1 (the north tower) had a roof height of 1,368 feet, briefly earning it the title of the world’s tallest building. WTC 2 (the south tower) was nearly as tall, with a roof height of 1,362 feet. WTC 1 also supported a 360-foot-tall television and radio transmission tower. Each building had a square floor plate, 207 feet 2 inches long on each side. Corners were chamfered 6 feet 11 inches. Nearly an acre of floor space was provided at each level. A rectangular service core, with overall dimensions of approximately 87 feet by 137 feet, was present at the center of each building, housing 3 exit stairways, 99 elevators, and 16 escalators. Figure 2-1 presents a schematic plan of a representative aboveground floor.

The project was developed by the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority), a bi-state public agency. Original occupancy of the towers was dominated by government agencies, including substantial occupancy by the Port Authority itself. However, this occupancy evolved over the years and, by 2001, the predominant occupancy of the towers was by commercial tenants, including a number of prominent financial and insurance services firms.

Design architecture was provided by Minoru Yamasaki & Associates, and Emery Roth & Sons served as the architect of record. Skilling, Helle, Christiansen, Robertson were the project structural engineers; Jaros, Baum & Bolles were the mechanical engineers; and Joseph R. Loring & Associates were the electrical engineers. The Port Authority provided design services for site utilities, foundations, basement retaining walls, and paving. Groundbreaking for construction was on August 5, 1966. Steel construction began in August 1968. First tenant occupancy of WTC 1 was in December 1970, and occupancy of WTC 2 began in January 1972. Ribbon cutting was on April 4, 1973.

2.1.2 Structural Description

WTC 1 and WTC 2 were similar, but not identical. WTC 1 was 6 feet taller than WTC 2 and also supported a 360-foot tall transmission tower. The service core in WTC 1 was oriented east to west, and the service core in WTC 2 was oriented north to south. In addition to these basic configuration differences, the presence of each building affected the wind loads on the other, resulting in a somewhat different distribution of design wind pressures, and, therefore, a somewhat different structural design of the lateral-force-resisting system. In addition, tenant improvements over the years resulted in removal of portions of floors and placement of new private stairways between floors, in a somewhat random pattern. Figure 2-2 presents a structural framing plan representative of an upper floor in the towers.

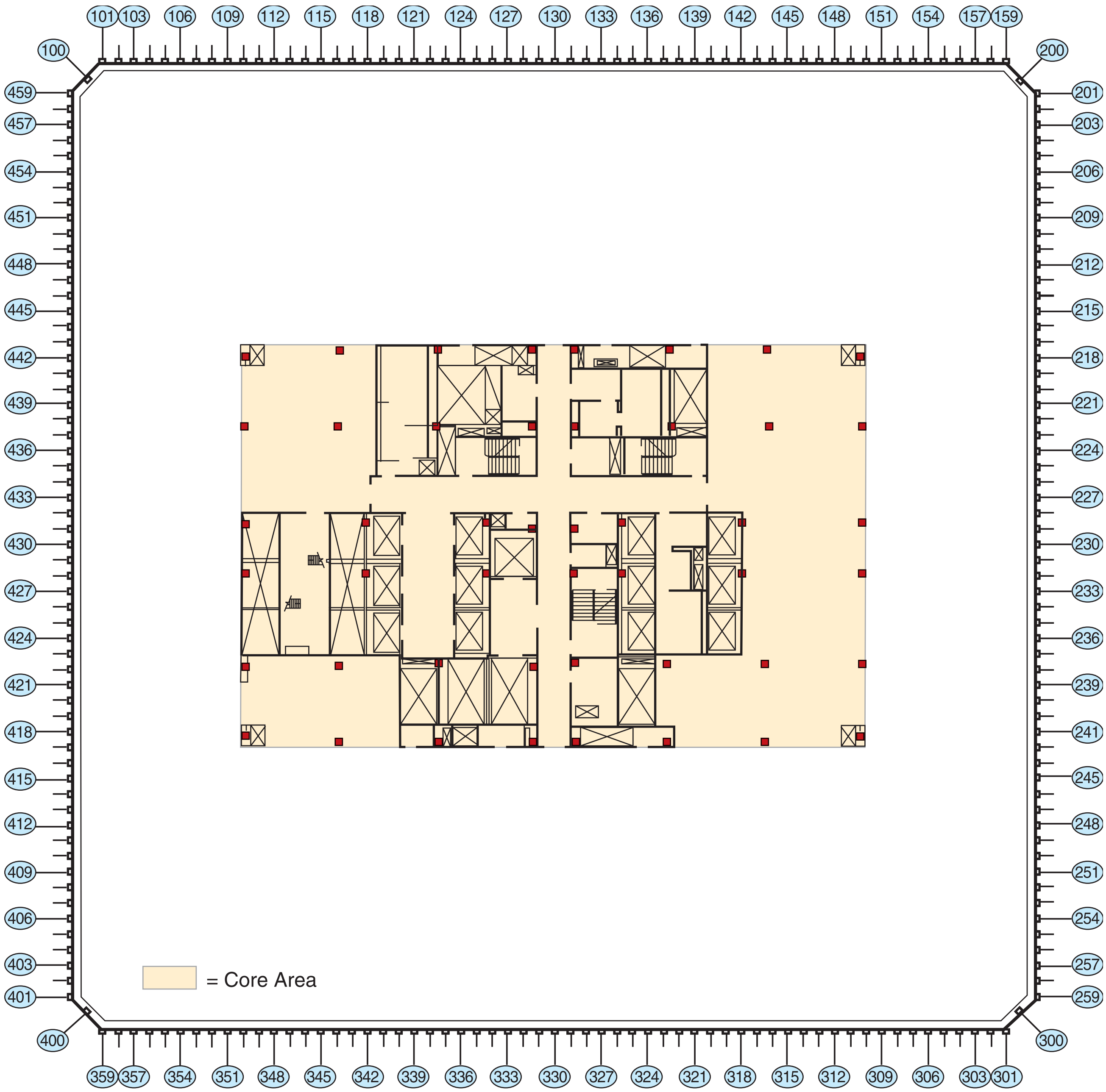


Figure 2-1 Representative floor plan (based on floor plan for 94th and 95th floors of WTC 1).

The buildings' signature architectural design feature was the vertical fenestration, the predominant element of which was a series of closely spaced built-up box columns. At typical floors, a total of 59 of these perimeter columns were present along each of the flat faces of the building. These columns were built up by welding four plates together to form an approximately 14-inch square section, spaced at 3 feet 4 inches on center. Adjacent perimeter columns were interconnected at each floor level by deep spandrel plates, typically 52 inches in depth. In alternate stories, an additional column was present at the center of each of the chamfered building corners. The resulting configuration of closely spaced columns and deep spandrels created a perforated steel bearing-wall frame system that extended continuously around the building perimeter.

Figure 2-3 presents a partial elevation of this exterior wall at typical building floors. Construction of the perimeter-wall frame made extensive use of modular shop prefabrication. In general, each exterior wall module consisted of three columns, three stories tall, interconnected by the spandrel plates, using all-welded construction. Cap plates were provided at the tops and bottoms of each column, to permit bolted connection to the modules above and below. Access holes were provided at the inside face of the columns for attaching high-strength bolted connections. Connection strength varied throughout the building, ranging from four bolts at upper stories to six bolts at lower stories. Near the building base, supplemental welds were also utilized.

Side joints of adjacent modules consisted of high-strength bolted shear connections between the spandrels at mid-span. Except at the base of the structures and at mechanical floors, horizontal splices between modules were staggered in elevation so that not more than one third of the units were spliced in any one story. Where the units were all spliced at a common level, supplemental welds were used to improve the strength of these connections. Figure 2-3 illustrates the construction of typical modules and their interconnection. At the building base, adjacent sets of three columns tapered to form a single massive column, in a fork-like formation, shown in Figure 2-4.

Twelve grades of steel, having yield strengths varying between 42 kips per square inch (ksi) and 100 ksi, were used to fabricate the perimeter column and spandrel plates as dictated by the computed gravity and wind demands. Plate thickness also varied, both vertically and around the building perimeter, to accommodate the predicted loads and minimize differential shortening of columns across the floor plate. In upper stories of the building, plate thickness in the exterior wall was generally 1/4 inch. At the base of the building, column plates as thick as 4 inches were used. Arrangement of member types (grade and thickness) was neither exactly symmetrical within a given building nor the same in the two towers.

The stiffness of the spandrel plates, created by the combined effects of the short spans and significant depth, created a structural system that was stiff both laterally and vertically. Under the effects of lateral wind loading, the buildings essentially behaved as cantilevered hollow structural tubes with perforated walls. In each building, the windward wall acted as a tension flange for the tube while the leeward wall acted as a compression flange. The side walls acted as the webs of the tube, and transferred shear between the windward and leeward walls through Vierendeel action (Figure 2-5). Vierendeel action occurs in rigid trusses that do not have diagonals. In such structures, stiffness is achieved through the flexural (bending) strength of the connected members. In the lower seven stories of the towers, where there were fewer columns (Figure 2-4), vertical diagonal braces were in place at the building cores to provide this stiffness. This structural frame was considered to constitute a tubular system.

Floor construction typically consisted of 4 inches of lightweight concrete on 1-1/2-inch, 22-gauge non-composite steel deck. In the core area, slab thickness was 5 inches. Outside the central core, the floor deck was supported by a series of composite floor trusses that spanned between the central core and exterior wall. Composite behavior with the floor slab was achieved by extending the truss diagonals above the top chord so that they would act much like shear studs, as shown in Figure 2-6. Detailing of these trusses was similar to that employed in open-web joist fabrication and, in fact, the trusses were manufactured by a joist fabricator, the LaClede Steel Corporation. However, the floor system design was not typical of open-web-joist floor systems. It was considerably more redundant and was well braced with transverse members. Trusses were placed in pairs, with a spacing of 6 feet 8 inches and spans of approximately 60 feet to the sides and 35 feet at the ends of the central core. Metal deck spanned parallel to the main trusses and was directly supported by continuous transverse bridging trusses spaced at 13 feet 4 inches and intermediate deck support angles spaced at 6 feet 8 inches from the transverse trusses. The combination of main trusses, transverse trusses, and deck support enabled the floor system to act as a grillage to distribute load to the various columns.

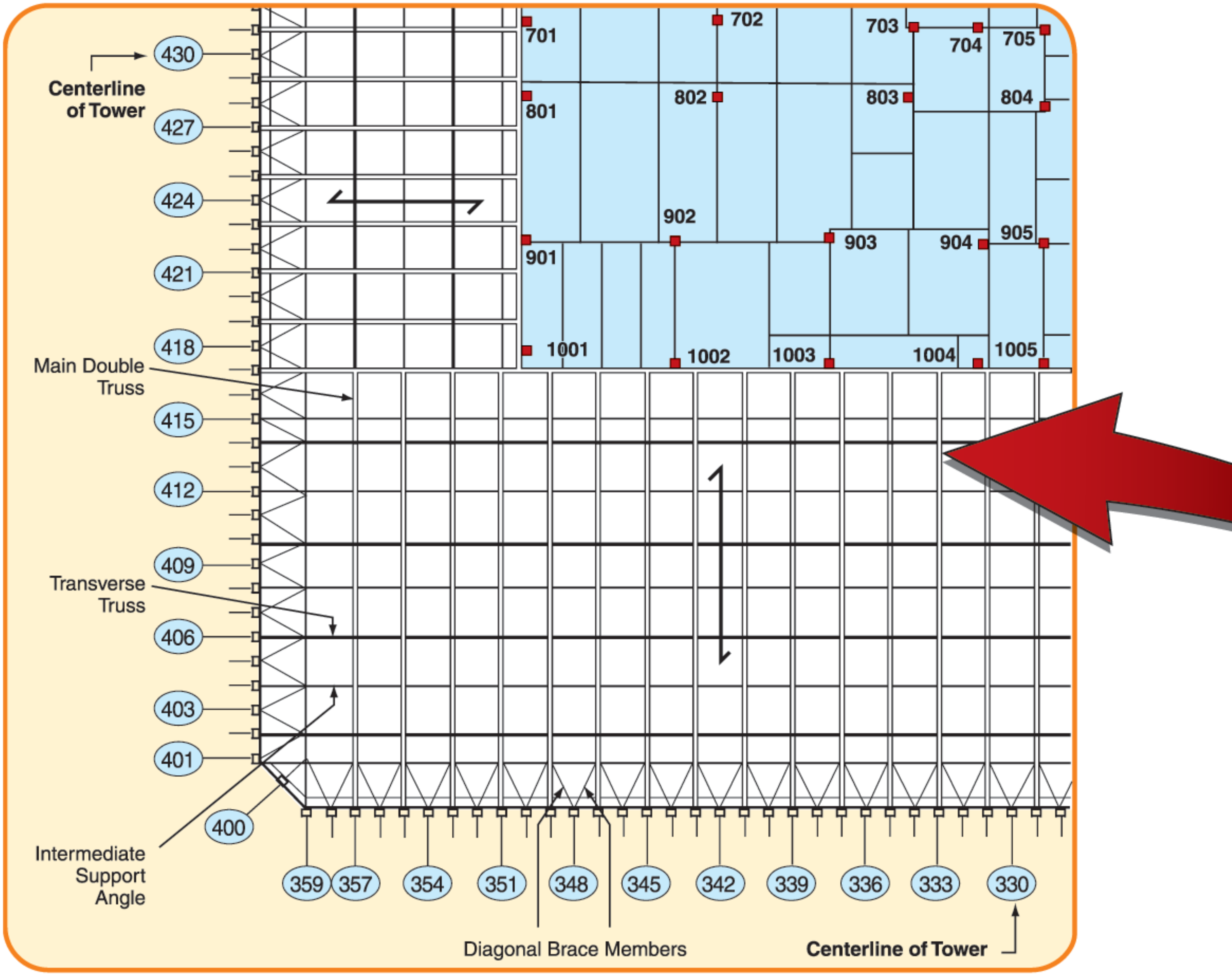
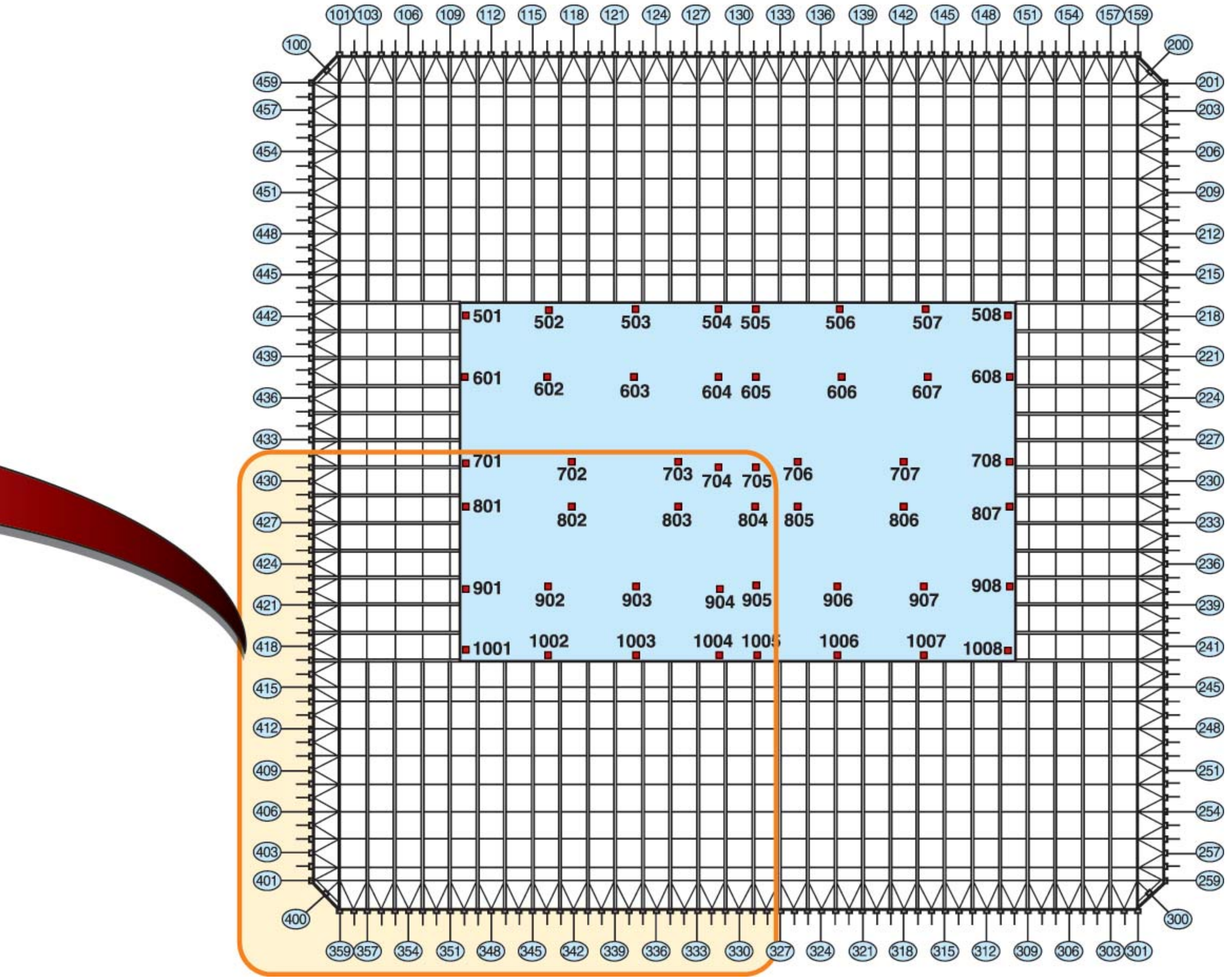


Figure 2-2 Representative structural framing plan, upper floors.

At the exterior wall, truss top chords were supported in bearing off seats extending from the spandrels at alternate columns. Welded plate connections with an estimated ultimate capacity of 90 kips (refer to Appendix B) tied the pairs of trusses to the exterior wall for out-of-plane forces. At the central core, trusses were supported on seats off a girder that ran continuously past and was supported by the core columns. Nominal out-of-plane connection was provided between the trusses and these girders. Figures 2-7 and 2-8 illustrate this construction, and Figure 2-9 shows a cross-section through typical floor framing. Floors were designed for a uniform live load of 100 pounds per square foot (psf) over any 200-square-foor area with allowable live load reductions taken over larger areas. At building corners, this amounted to a uniform live load (unreduced) of 55 psf.

At approximately 10,000 locations in each building, viscoelastic dampers extended between the lower chords of the trussess and gusset plates mounted on the exterior columns beneath the stiffened seats (Detail A in Figure 2-6). These dampers were the first application of this technology in a high-rise building, and were provided to reduce occupant perception of wind-induced building motion.



Pairs of flat bars extended diagonally from the exterior wall to the top chord of adjacent trusses. These diagonal flat bars, which were typically provided with shear studs, provided horizontal shear transfer between the floor slab and exterior wall, as well as out-of-plane bracing for perimeter columns not directly supporting floor trusses (Figure 2-2).

The core consisted of 5-inch concrete fill on metal deck supported by floor framing of rolled structural shapes, in turn supported by a combination of wide flange shape and box-section columns. Some of these columns were very large, with cross-sections measuring 14 inches wide by 36 inches deep. In upper stories, these rectangular box columns transitioned into heavy rolled wide flange shapes.

Between the 106th and 110th floors, a series of diagonal braces were placed into the building frame. These diagonal braces together with the building columns and floor framing formed a deep outrigger truss system that extended between the exterior walls and across the building core framing. A total of 10 outrigger truss lines were present in each building (Figure 2-10), 6 extending across the long direction of the core and

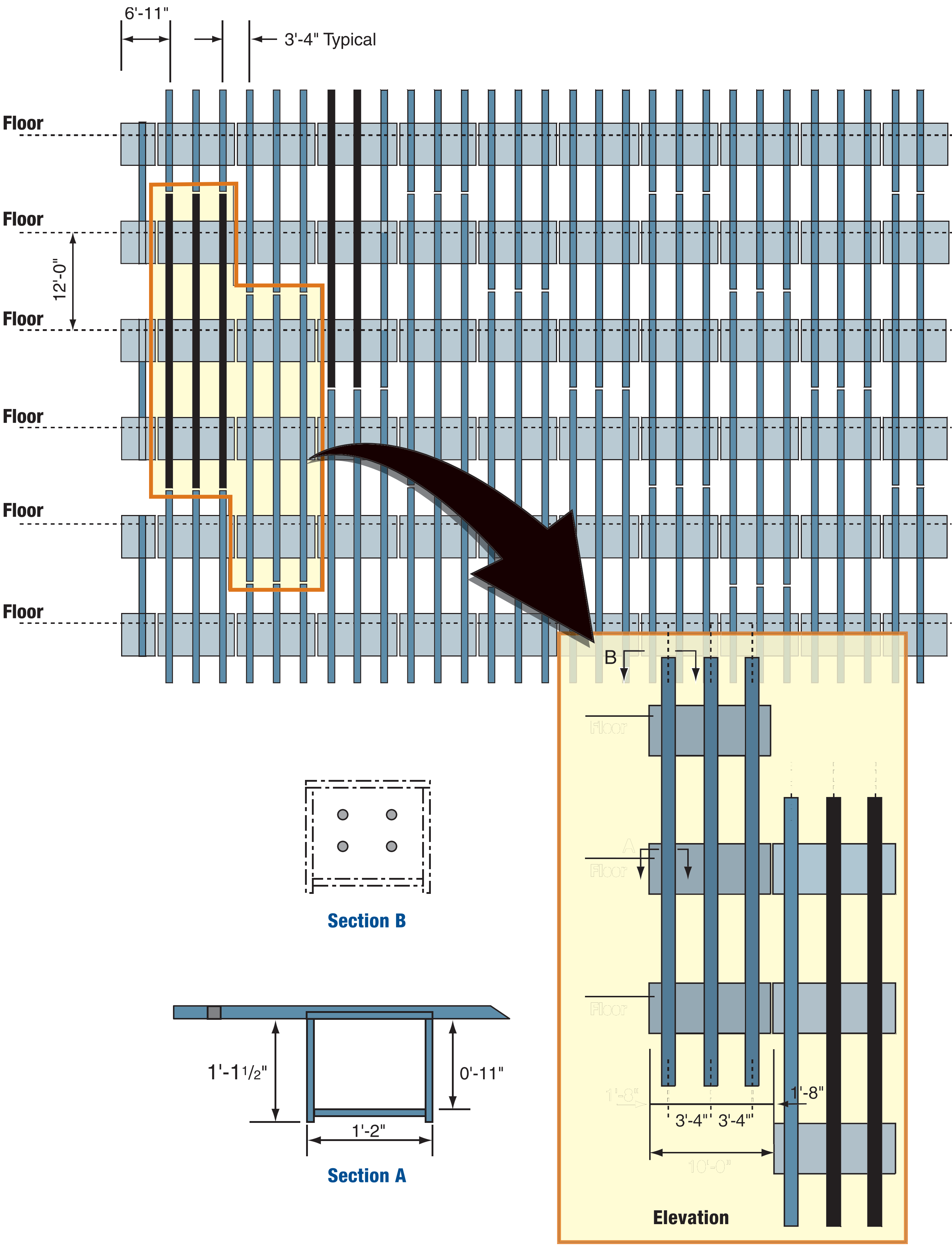


Figure 2-3 Partial elevation of exterior bearing-wall frame showing exterior wall module construction.

Figure 2-4 Base of exterior wall frame.

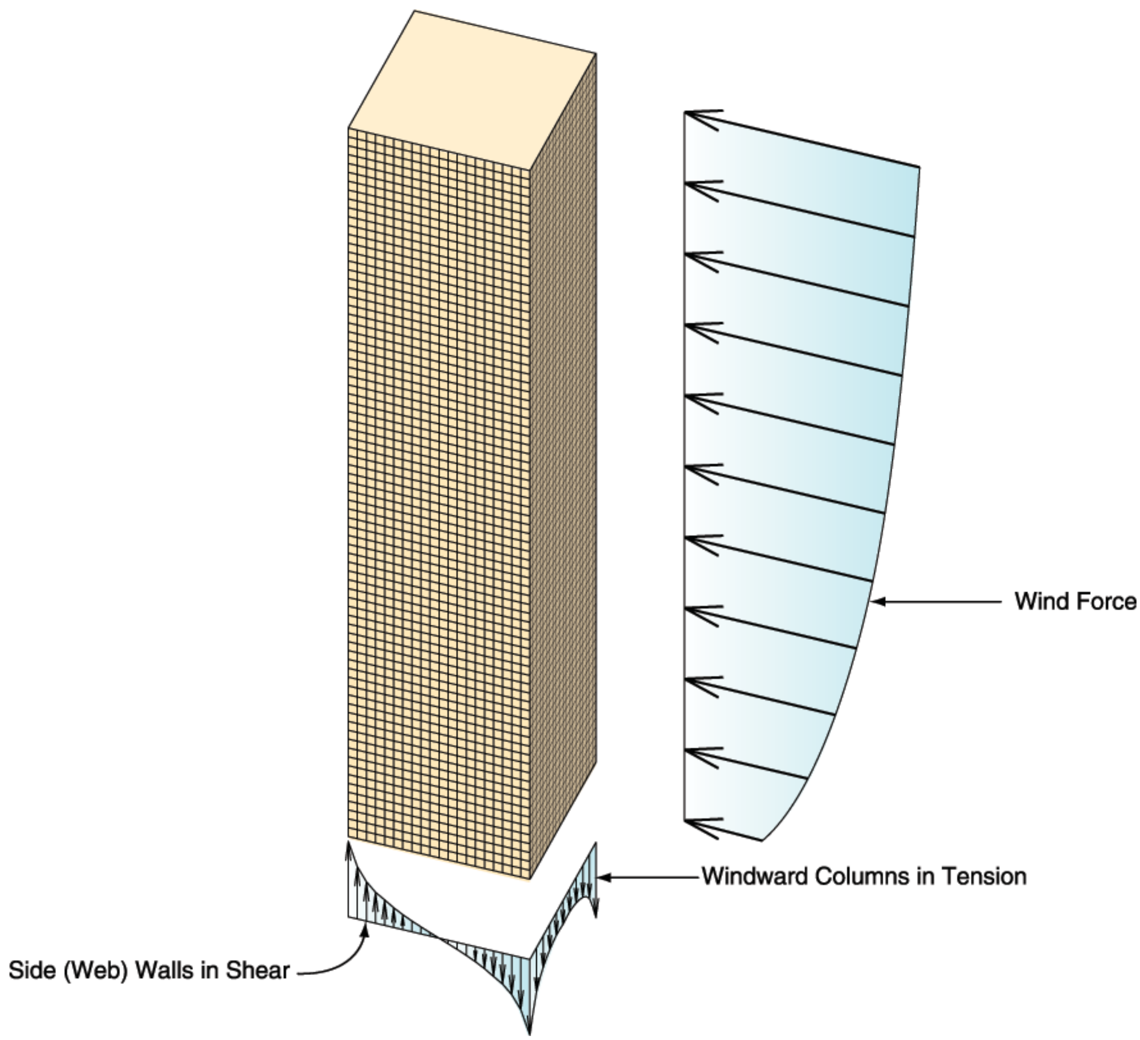


Figure 2-5 Structural tube frame behavior.

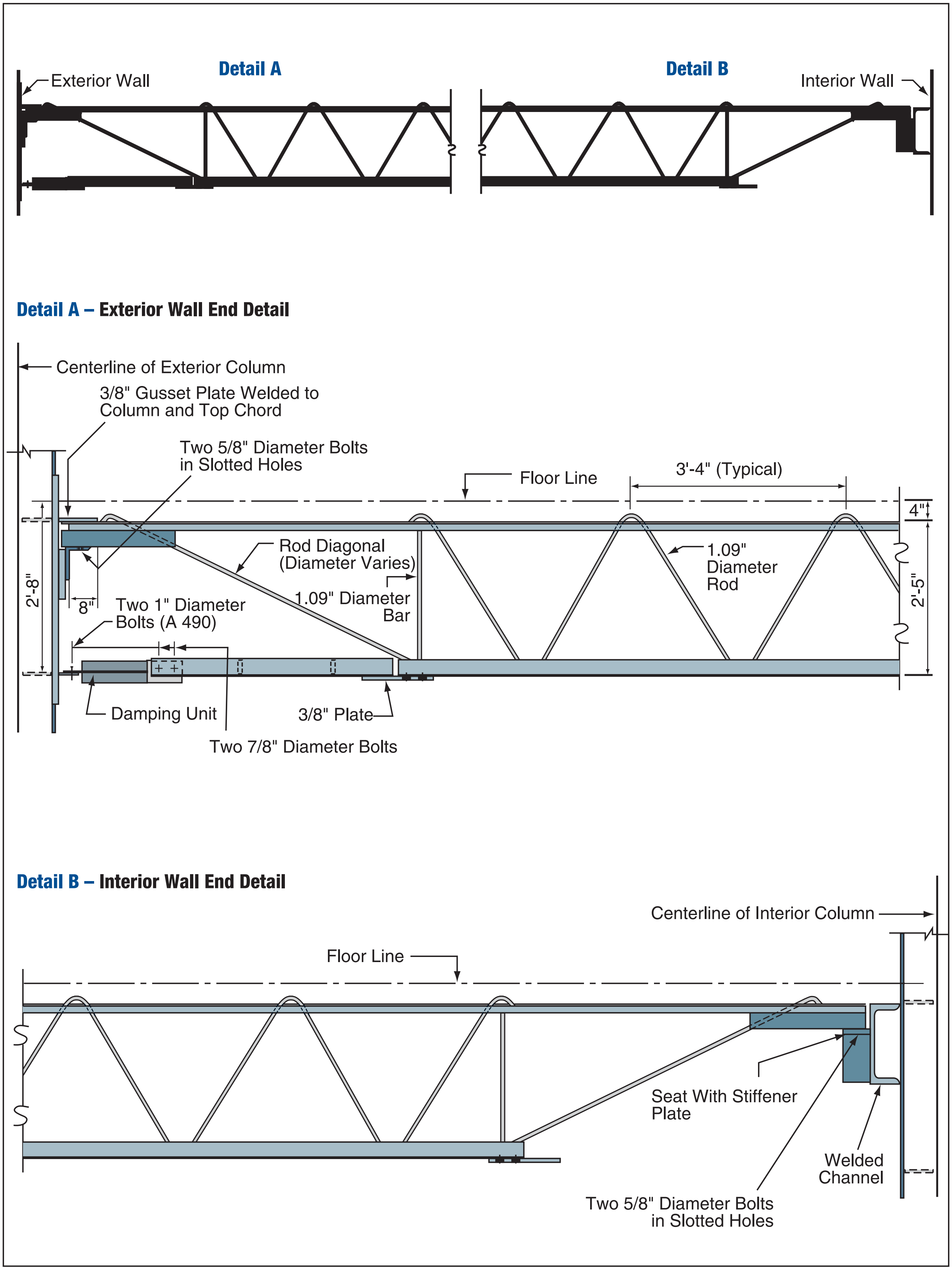


Figure 2-6 Floor truss member with details of end connections.

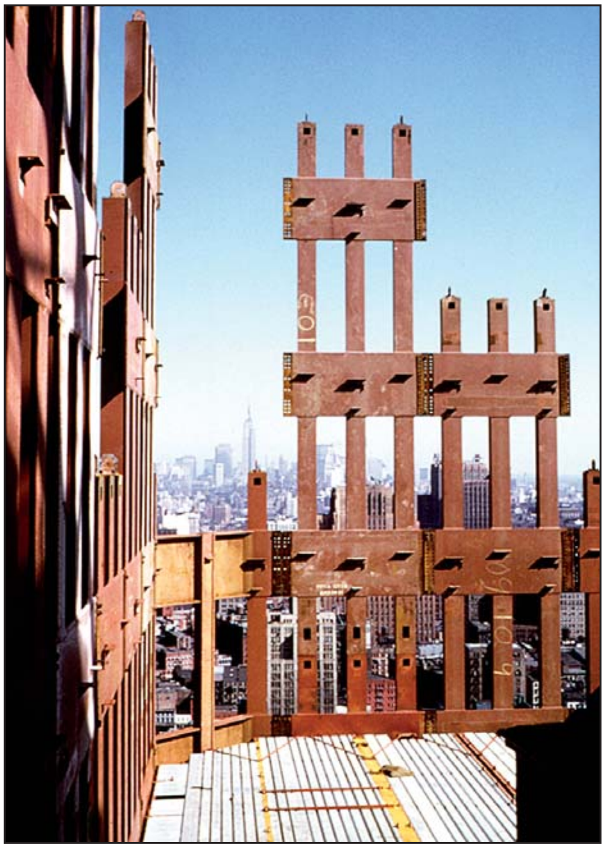


Figure 2-7 Erection of prefabricated components, forming exterior wall and floor deck units.

Figure 2-8 Erection of floor framing during original construction.

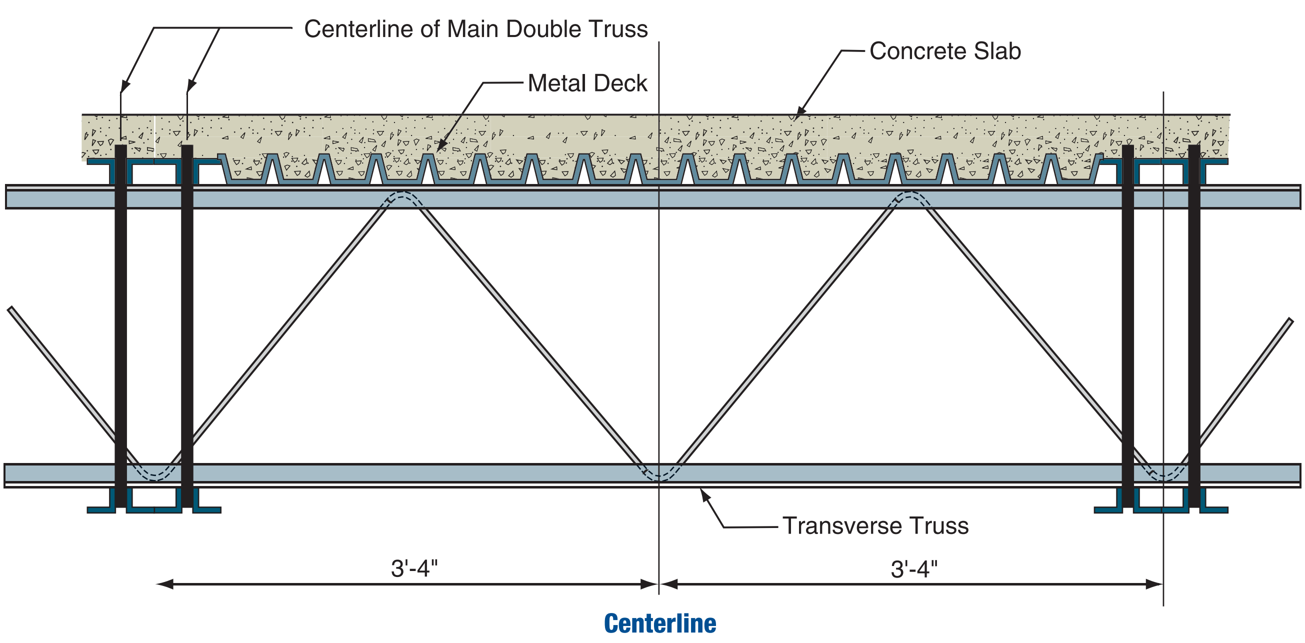


Figure 2-9 Cross-section through main double trusses, showing transverse truss.

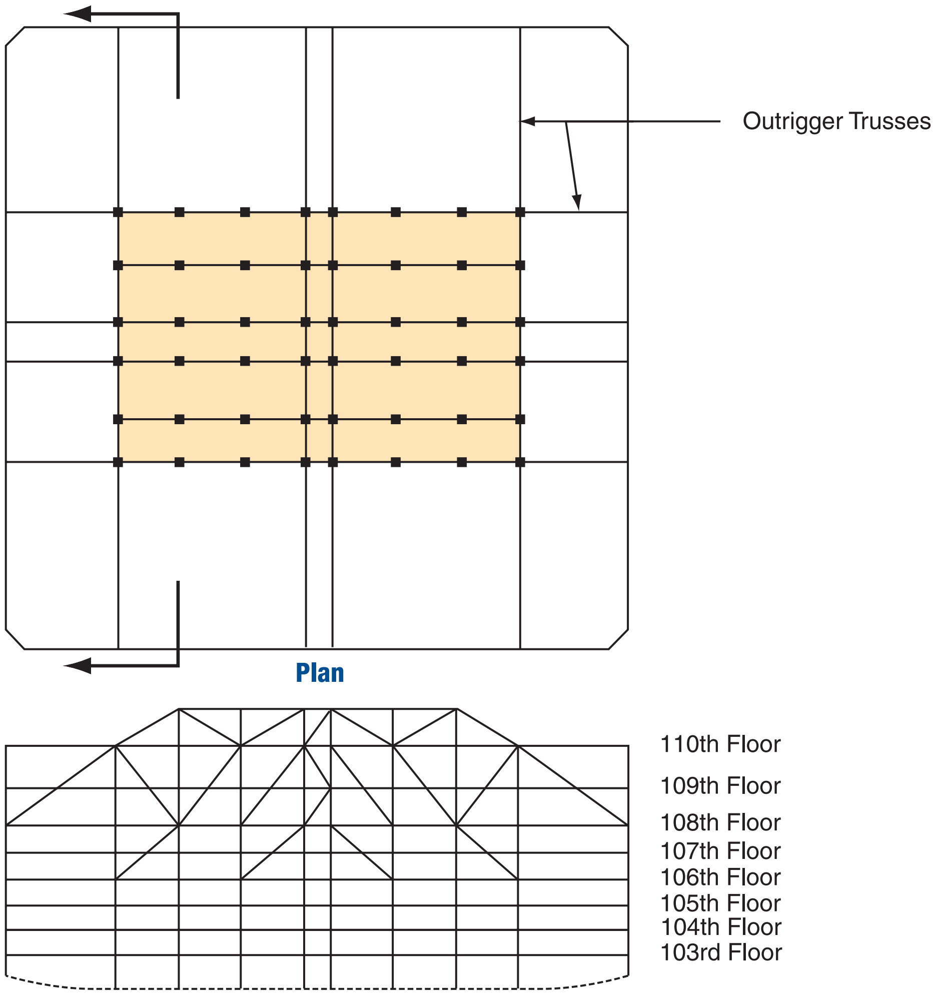


Figure 2-10 Outrigger truss system at tower roof.

4 extending across the short direction of the core. This outrigger truss system provided stiffening of the frame for wind resistance, mobilized some of the dead weight supported by the core to provide stability against wind-induced overturning, and also provided direct support for the transmission tower on WTC 1. Although WTC 2 did not have a transmission tower, the outrigger trusses in that building were also designed to support such a tower.

A deep subterranean structure was present beneath the WTC Plaza (Figure 2-11) and the two towers. The western half of this substructure, bounded by West Street to the west and by the 1/9 subway line that extends approximately between West Broadway and Greenwich Street on the east, was 70 feet deep and contained six subterranean levels. The structure housed a shopping mall and building mechanical and electrical services, and it also provided a station for the PATH subway line and parking for the complex.

Prior to construction, the site was underlain by deep deposits of fill material, informally placed over a period of several hundred years to displace the adjacent Hudson River shoreline and create additional usable land area. In order to construct this structure, the eventual perimeter walls for the subterranean structure were constructed using the slurry wall technique. After the concrete wall was cured and attained sufficient strength, excavation of the basement was initiated. As excavation proceeded downward, tieback anchors were drilled diagonally down through the wall and grouted into position in the rock deep behind the walls. These

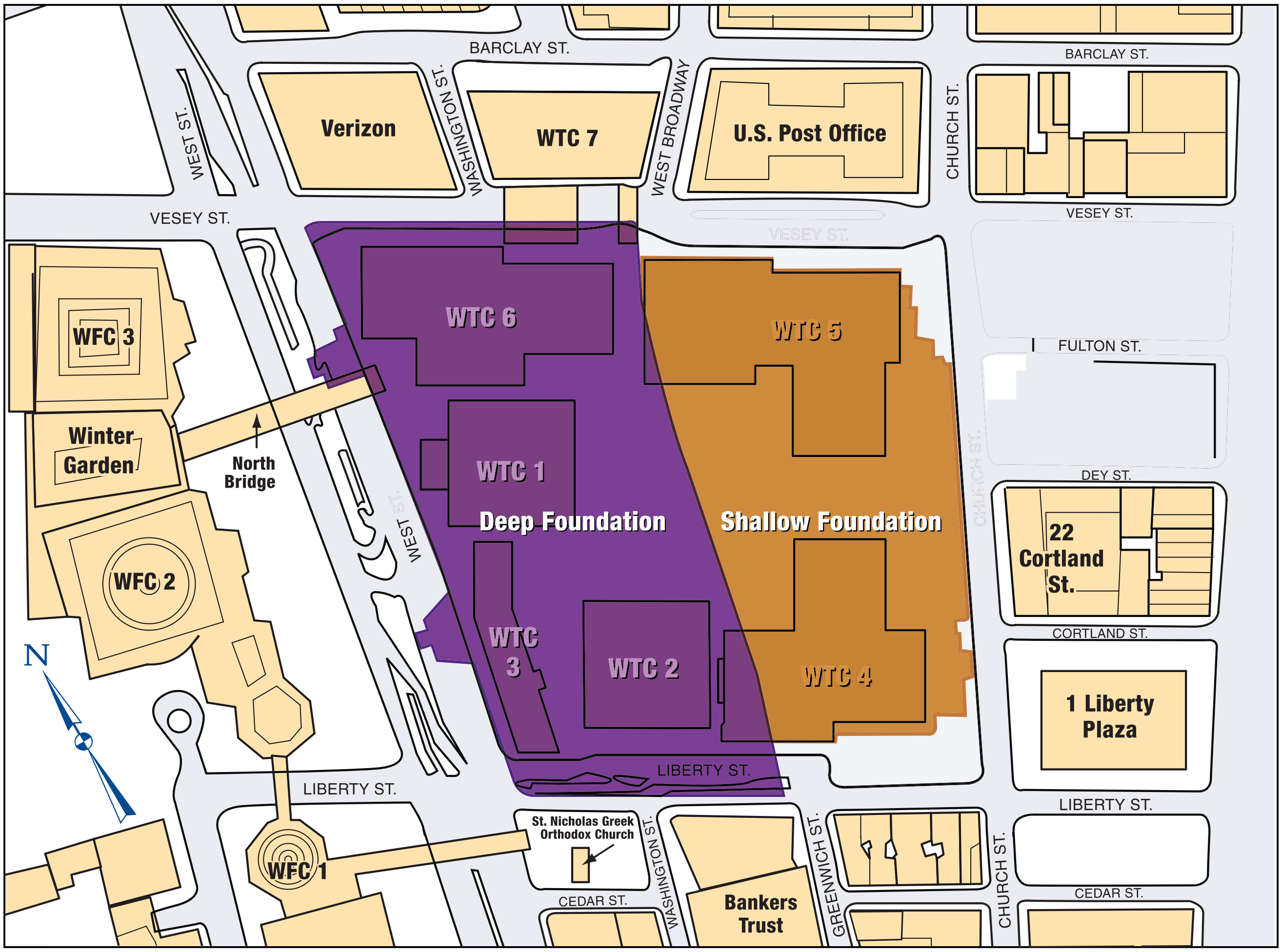


Figure 2-11 Location of subterranean structure.

anchors stabilized the wall against the soil and water pressures from the unexcavated side as the excavation continued on the inside. After the excavation was extended to the desired grade, foundations were formed and poured against the exposed bedrock, and the various subgrade levels of the structure were constructed.

Floors within the substructure were of reinforced concrete flat-slab construction, supported by structural steel columns. Many of these steel columns also provided support for the structures located above the plaza level. After the floor slabs were constructed, they were used to provide lateral support for the perimeter walls, holding back the earth pressure from the unexcavated side. The tiebacks, which had been installed as a temporary stabilizing measure, were decommissioned by cutting off their end anchorage hardware and repairing the pockets in the slurry wall where these anchors had existed.

Tower foundations beneath the substructure consisted of massive spread footings, socketed into and bearing directly on the massive bedrock. Steel grillages, consisting of layers of orthogonally placed steel beams, were used to transfer the immense column loads, in bearing, to the reinforced concrete footings.

2.1.3 Fire Protection

The fire safety of a building is provided by a system of interdependent fire protection features, including suppression systems, detection systems, notification devices, smoke management systems, and passive systems such as compartmentation and structural protection. The failure of any of these fire protection systems will impact the effectiveness of the other systems in the building.

2.1.3.1 Passive Protection

In WTC 1, structural elements up to the 39th floor were originally protected from fire with a spray-applied product containing asbestos (Nicholson, et al. 1980). These asbestos-containing materials were later abated inside the building, either through encapsulation or replacement. On all other floors and throughout WTC 2, a spray-applied, asbestos-free mineral fiber material was used. Each element of the steel floor trusses was protected with spray-applied material. The specific material used was a low-density, factory-mixed product consisting of manufactured inorganic fibers, proprietary cement-type binders, and other additives in low concentrations to promote wetting, set, and dust control. Air setting, hydraulic setting, and ceramic setting binders were added in varying quantities and combinations or singly at the site, depending on the particular application and weather conditions. Finally, water was added at the nozzle of the spray gun as the material was sprayed onto the member to be protected. The average thickness of spray-applied fireproofing on the trusses was 3/4 inch. In the mid-1990s, a decision was made to upgrade the fire protection by applying additional material onto the trusses so as to increase fireproofing thickness to 1-1/2 inches. The fireproofing upgrade was applied to individual floors as they became vacant. By September 11, 2001, a total of 31 stories had been upgraded, including the entire impact zone in WTC 1 (floors 94–98), but only the 78th floor in the impact zone in WTC 2 (floors 78–84).

Spandrels and girders were specified to have sufficient protection to achieve a 3-hour rating. Except for the interior face of perimeter columns between spandrels, which were protected with a plaster material, spray-applied materials similar to those used on the floor systems were used. The thickness of protection on spandrels and girders varied, with the more massive steel column sections receiving reduced fireproofing thickness relative to the thinner elements.

The primary vertical compartmentation was provided by the floor slabs that were cast flush against the spandrel beams at the exterior wall, providing separation between floors at the building perimeter. After a fire in 1975, vertical penetrations for cabling and plumbing were sealed with fire-resistant material. At stair and elevator shafts, separation was provided by a wall system constructed of metal studs and two layers of 5/8-inch thick gypsum board on the exterior and one layer of 5/8-inch thick gypsum board on the interior. These assemblies provided a 2-hour rating. Horizontal compartmentation varied throughout the complex. Some separating walls ran from slab to slab, while others extended only up to the suspended ceiling. A report by the New York Board of Fire Underwriters (NYBFU) titled *One World Trade Center Fire, February 13, 1975* (NYBFU 1975) presents a detailed discussion of the compartmentation features of the building at that time.

2.1.3.2 Suppression

When originally constructed, the two towers were not provided with automatic fire sprinkler protection. However, such protection was installed as a retrofit circa 1990, and automatic sprinklers covered nearly 100 percent of WTC 1 and WTC 2 at the time of the September 11 attacks. In addition, each building had standpipes running through each of its three stairways. A 1.5-inch hose line and a cabinet containing two air-pressurized water (APW) extinguishers were also present at each floor in each stairway.

The primary water supply was provided by a dedicated fire yard main that looped around most of the complex. This yard main was supplied directly from the municipal water supply. Two remotely located high-pressure, multi-stage, 750-gallons per minute (gpm) electrical fire pumps took suction from the New York City municipal water supply and produced the required operating pressures for the yard main.

Each tower had three electrical fire pumps that provided additional pressure for the standpipes. One pump, located on the 7th floor, received the discharge from the yard main fire pumps and moved it up to the 41st floor, where a second 750-gpm fire pump pushed it up to a third pump on the 75th floor. Each fire pump produced sufficient pressure to supply water to the pump two stages up from it in the event that any one pump should fail.

Several 5,000-gallon storage tanks, filled from the domestic water system, provided a secondary water supply. Tanks on the 41st, 75th, and 110th floors provided water directly to a standpipe system. A tank on the 20th floor supplied water directly to the yard main. Numerous Fire Department of New York (FDNY) connections were located around the complex to allow the fire department to boost water pressure in the buildings.

2.1.3.3 Smoke Management

A zoned smoke control system was built into each building's ventilation systems and was activated upon direction of the responding FDNY Incident Commander. The system was designed to limit smoke spread from the tenant areas to the core area, thereby assisting both individuals evacuating from an area and those responding to the scene by limiting smoke spread into the core.

2.1.3.4 Fire Department Features

At the time of the 1993 World Trade Center bombing, a centralized Fire Command Center (FCC) for the two towers was present at the Concourse level. This FCC was located in the B-1 level Operations Control Center (OCC). Following the 1993 bombing, additional FCCs were installed in the lobbies of each tower.

A Radiax cable and antenna were installed in the WTC complex to facilitate the use of FDNY radios in the towers. Fire department telephones were provided in both towers on odd floors in Stairway 3, as well as on levels B-1, B-4, and B-6.

The WTC had its own fire brigade, consisting of Port Authority police officers trained in fire safety, who worked with the FDNY to investigate fire conditions and take appropriate actions. The internal fire brigade had access to fire carts located on the Concourse level and on the 44th and 78th floor sky lobbies of each tower. These fire carts were equipped with hoses, nozzles, self-contained breathing apparatus, turnout coats, forcible entry tools, resuscitators, first-aid kits, and other emergency equipment. Typically, the WTC fire brigade would collect the nearest fire cart and set up operations on the floor below the fire floor.

The WTC complex had 24 Siamese connections located at street level for use by the FDNY apparatus. Each of these Siamese connections served various portions of the complex and was identified as such.

2.1.4 Emergency Egress

Each tower was provided with three independent emergency fire exit stairways, located in the core of the building, as indicated in Figure 2-12. Two of these stairways, designated Stairway 1 and Stairway 2, were 44 inches wide and ran to the 110th floor. The third stairway, designated Stairway 3, had a width of 56 inches and ran to the 108th floor. The stairways did not run in continuous vertical shafts from the top to the bottom of the structure. Instead, the plan location of the stairways shifted at some levels, and occupants traversing the stairways were required to move from one vertical shaft to another through a transfer corridor. Both Stairways 1 and 2 had transfers at the 42nd, 48th, 76th, and 82nd levels. Stairway 1 had an additional transfer at the 26th level and Stairway 3 had a single transfer at the 76th level. After the 1993 bombing, battery-operated emergency lighting was provided in the stairways and photoluminescent paint was placed on the edge of the stair treads to facilitate emergency egress.

There were 99 elevators in each of the two towers, including 23 express elevators; however, the express elevators were not intended to be used for emergency access or egress. There were also several freight elevators servicing groups of floors in the buildings. The several elevators that served each floor were broken into two groups that operated on different power supplies.

Upon alarm activation, an automatic elevator override system commanded all elevators serving or affected by a fire area to immediately return to the ground floor, or to their sky lobby (44th and 78th floors). From there, the elevators could be operated manually by the FDNY. Although many fire departments

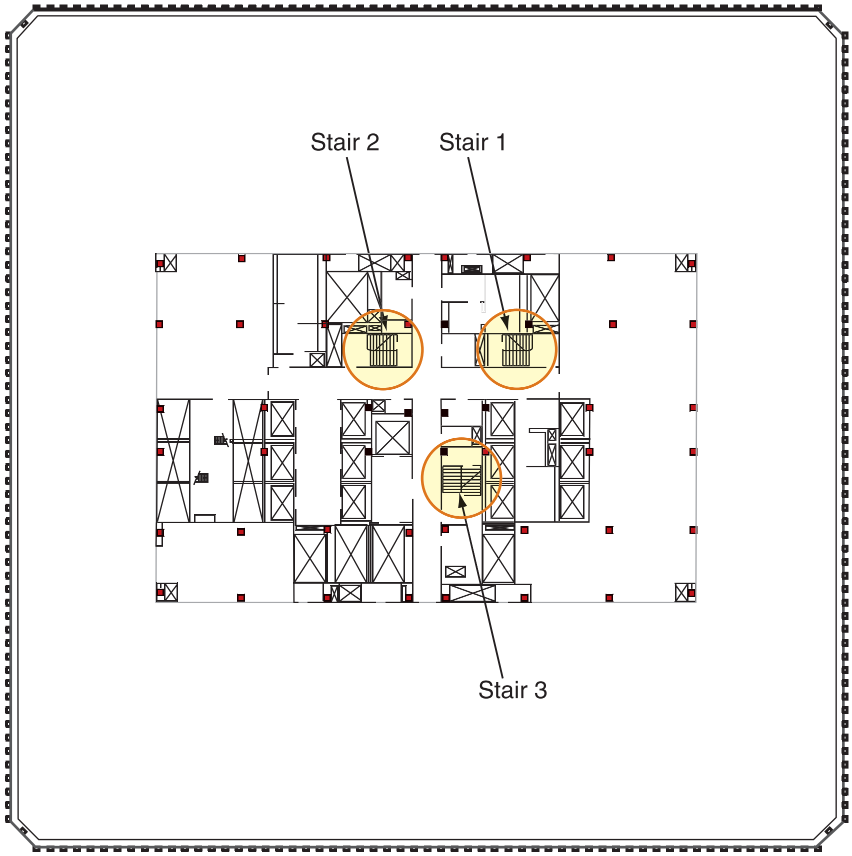


Figure 2-12
Floor plan of 94th and 95th floors of WTC 1 showing egress stairways.

routinely use elevators to provide better access in high-rise buildings, FDNY does not do this, because there have been fatalities associated with such use.

2.1.5 Emergency Power

Primary power was provided at 13.8 kilovolts (kV) through a ground level substation in WTC 7 near the Barclay Street entrance to the underground parking garage. The primary power was wired to the buildings through two separate systems. The first provided power throughout each building; the second provided power to emergency systems in the event that the primary wiring system failed.

Six 1,200-kilowatt (kW) emergency power generators located in the sixth basement (B-6) level provided a secondary power supply. These generators were checked on a routine basis to ensure that they would function properly during an emergency. This equipment provided backup power for communications equipment, elevators, emergency lighting in corridors and stairwells, and fire pumps. Telephone systems were provided with an independent battery backup system. Emergency lighting units in exit stairways, elevator lobbies, and elevator cabs were equipped with individual backup batteries.

2.1.6 Management Procedures

The Port Authority has a risk management group that coordinates fire and safety activities for their various properties. This group provided training for the WTC fire brigade, fire safety directors, and tenant fire wardens. The WTC had 25 fire safety directors who assisted in the coordination of fire safety activities in the buildings throughout the year. Six satellite communication stations, staffed by deputy fire safety directors, were spaced throughout the towers. In addition, each tenant was required to provide at least one fire warden. Tenants that occupied large areas of the building were required to provide one fire warden for every 7,500 square feet of occupied space. The fire safety directors trained the fire wardens and fire drills were held twice a year.

2.2 Building Response

WTC 1 and WTC 2 each experienced a similar, though not identical, series of loading events. In essence, each tower was subjected to three separate, but related events. The sequence of these events was the same for the two buildings, although the timing was not. In each case, the first loading event was a Boeing 767-200ER series commercial aircraft hitting the building, together with a fireball resulting from immediate rapid ignition of a portion of the fuel on board the aircraft. Boeing 767-200ER aircraft have a maximum rated takeoff weight of 395,000 pounds, a wingspan of 156 feet 1 inch, and a rated cruise speed of 530 miles per hour. The aircraft is capable of carrying up to 23,980 gallons of fuel, and it is estimated that, at the time of impact, each aircraft had approximately 10,000 gallons of unused fuel on board (compiled from Government sources).

In each case, the aircraft impacts resulted in severe structural damage, including some localized partial collapse, but did not result in the initiation of global collapse. In fact, WTC 1 remained standing for a period of approximately 1 hour and 43 minutes, following the initial impact; WTC 2 remained standing for approximately 56 minutes following impact. The second event was the simultaneous ignition and growth of fires over large floor areas on several levels of the buildings. The fires heated the structural systems and, over a period of time, resulted in additional stressing of the damaged structure, as well as sufficient additional damage and strength loss to initiate the third event, a progressive sequence of failures that culminated in total collapse of both structures.

2.2.1 WTC 1

2.2.1.1 Initial Damage From Aircraft Impact

American Airlines Flight 11 struck the north face of WTC 1 approximately between the 94th and 98th floors (Figures 2-13 and 2-14), causing massive damage to the north face of the building within the immediate area (Figure 2-15). At the central zone of impact corresponding to the airplane fuselage and engines, at least five of the prefabricated, three-column sections that formed the exterior walls were broken loose of the structure, and some were pushed inside the building envelope. Locally, floors supported by these exterior wall sections appear to have partially collapsed, losing their support along the exterior wall. Away from this central zone, in areas impacted by the outer wing structures, the exterior columns were fractured by the force of the collision. Interpretation of photographic evidence suggests that from 31 to 36 columns on the north building face were destroyed over portions of a four-story range. Partial collapse of floors in this zone appear to have occurred over a horizontal length of wall of approximately 65 feet, while floors in other portions of the building appear to have remained intact. Figure 2-16 shows the damage to the exterior columns on the impacted face of WTC 1.

In addition to this damage at the building perimeter, a significant but undefined amount of damage also occurred to framing at the central core. Interviews were conducted with persons who were present in offices on the 91st floor of the building at the north face of the structure, three floors below the approximate zone of impact. Their descriptions of the damage evident at this floor level immediately following the aircraft impact suggest relatively slight damage at the exterior wall of the building, but progressively greater damage to the south and east. They described extensive building debris in the eastern portion of the central core, preventing their access to the easternmost exit stairway. This suggests the possibility of immediate partial collapse of framing in the central core. These persons also described the presence of debris from collapsed partition walls from upper floors in stairways located further to the west, suggesting the possibility of some structural damage in the northwestern portion of the core framing as well. Figure 2-17 is a sketch made during an interview with building occupants indicating portions of the 91st floor that could not be accessed due to accumulated debris.

Figure 2-13 Zone of aircraft impact on the north face of WTC 1.

It is known that some debris from the aircraft traveled completely through the structure. For example, life jackets and portions of seats from the aircraft were found on the roof of the Bankers Trust building, located to the south of WTC 2. Part of the landing gear from this aircraft was found at the corner of West and Rector Streets, some five blocks south of the WTC complex (Figure 2-18). As this debris passed through the building, it doubtless caused some level of damage to the structure across the floor plate, including, potentially, interior framing, core columns, framing at the east, south, and west walls, and the floors themselves. The exact extent of this damage will likely never be known with certainty. It is evident that, despite this damage, the structure retained sufficient integrity and strength to remain globally stable for a period of approximately 1 hour and 43 minutes.

The building's structural system, composed of the exterior loadbearing frame, the gravity loadbearing frame at the central core, and the system of deep outrigger trusses in upper stories, was highly redundant. This permitted the building to limit the immediate zone of collapse to the area where several stories of exterior columns were destroyed by the initial impact and, perhaps, to portions of the central core as previously described. Following the impact, floor loads originally supported by the exterior columns in

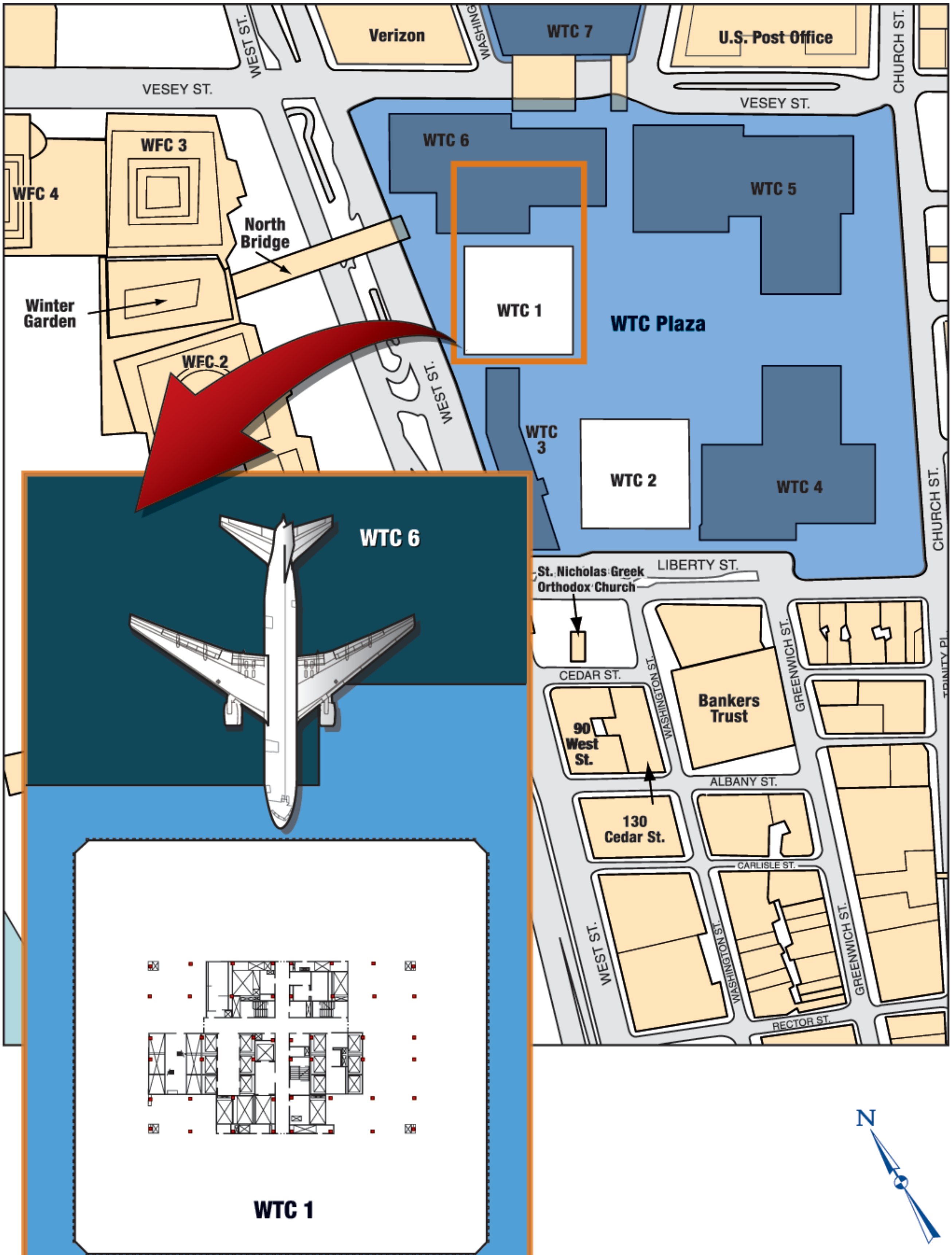


Figure 2-14 Approximate zone of impact of aircraft on the north face of WTC 1.

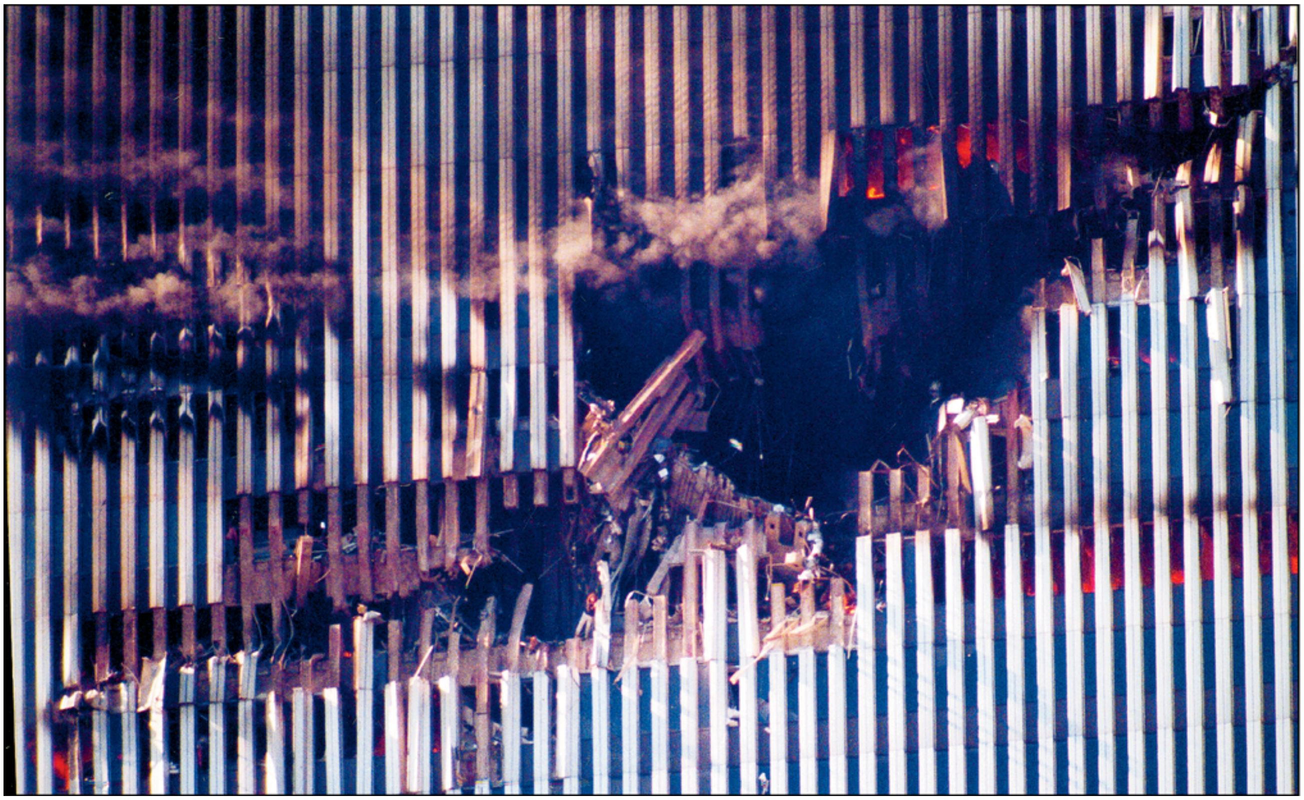
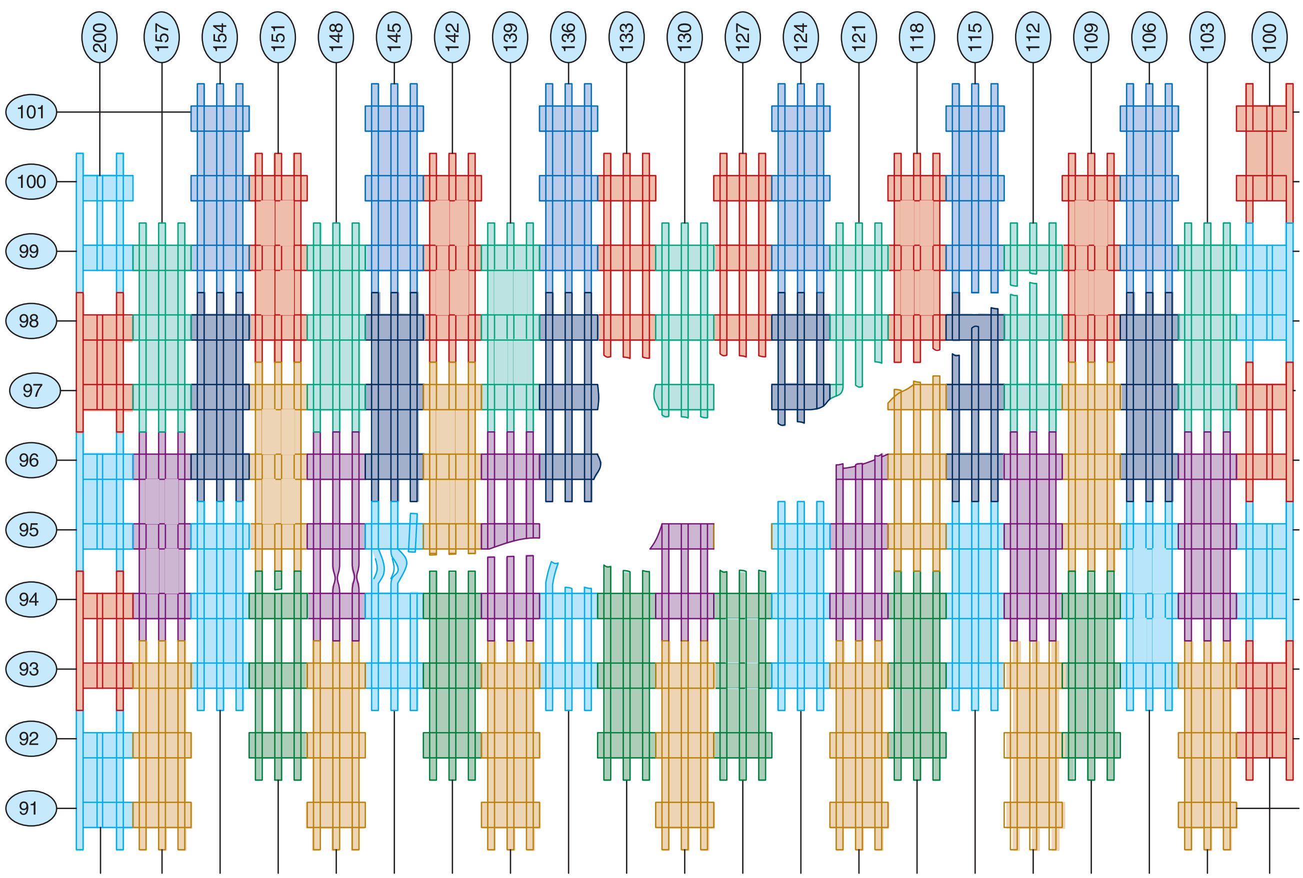


Figure 2-15 Impact damage to the north face of WTC 1.



GENERAL NOTES: (1) Column damage captured from photographs and enhanced videos. (2) Damage to column lines 111-115 at level 98 is estimated.

Figure 2-16 Impact damage to exterior columns on the north face of WTC 1.

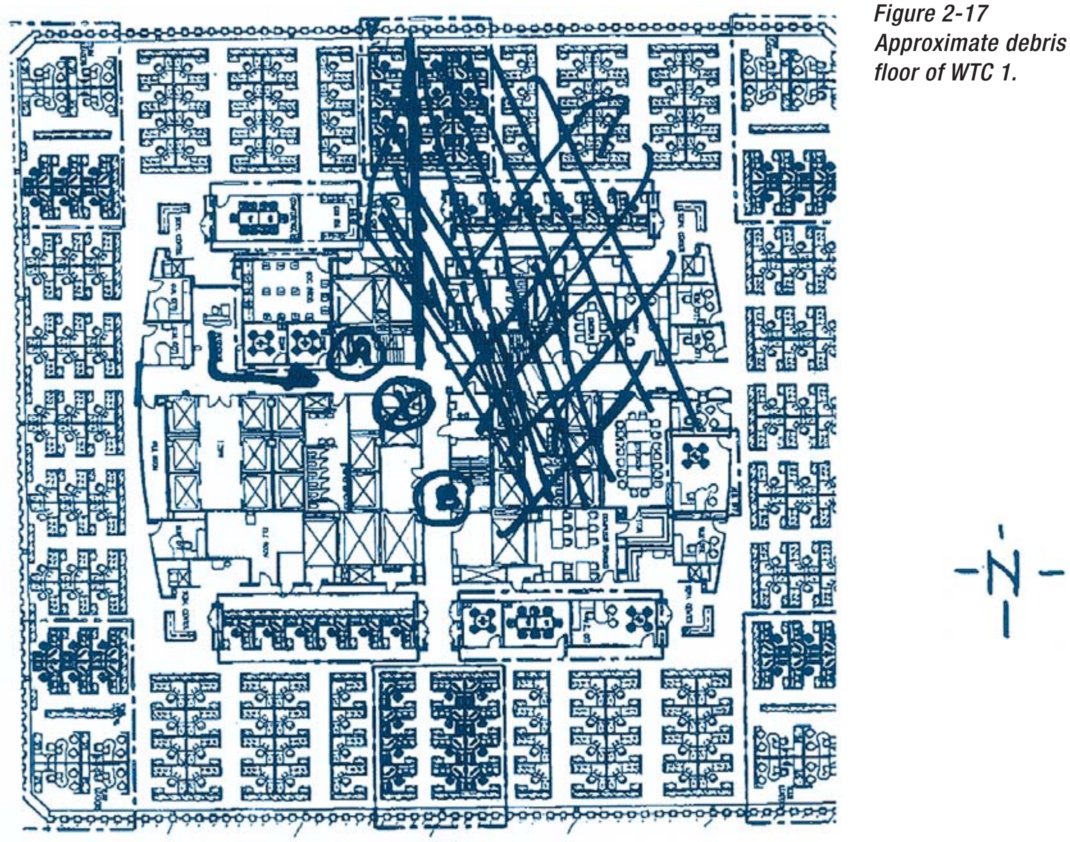


Figure 2-17
Approximate debris location on the 91st floor of WTC 1.

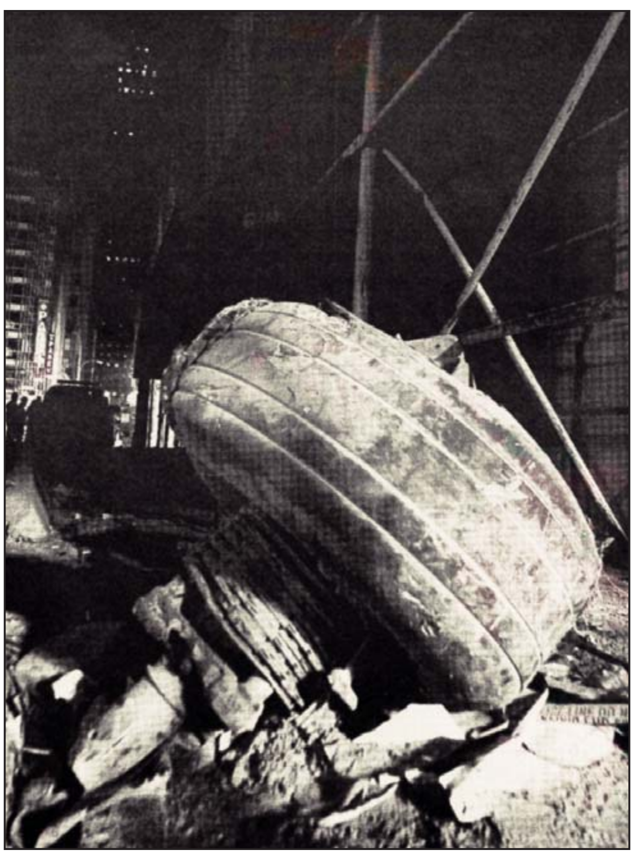


Figure 2-18
Landing gear found at the corner of West and Rector Streets.

compression were successfully transferred to other load paths. Most of the load supported by the failed columns is believed to have transferred to adjacent perimeter columns through Vierendeel behavior of the exterior wall frame. Preliminary structural analyses of similar damage to WTC 2 suggests that axial load demands on columns immediately adjacent to the destroyed columns may have increased by as much as a factor of 6 relative to the load state prior to aircraft impact. However, these exterior columns appear to have had substantial overstrength for gravity loads.

Neglecting the potential loss of lateral support resulting from collapsed floor slabs and any loss of strength due to elevated temperatures from fires, the most heavily loaded columns were probably near, but not over, their ultimate capacities. Columns located further from the impact zone are thought to have remained substantially below their ultimate capacities. The preliminary analyses also indicate that loss of the columns resulted in some immediate tilting of the structure toward the impact area, subjecting the remaining columns and structure to additional stresses from P-delta effects. Also, in part, exterior columns above the zone of impact were converted from compression members to hanger-type tension members, so that, in effect, a portion of the floors' weight became suspended from the outrigger trusses (Figure 2-10) and were transferred back to the interior core columns. The outrigger trusses also would have been capable of transferring some of the load carried by damaged core columns to adjacent core columns. Figure 2-19 illustrates these various secondary load paths. Section 2.2.2.2 provides a more detailed description of these analyses and findings.

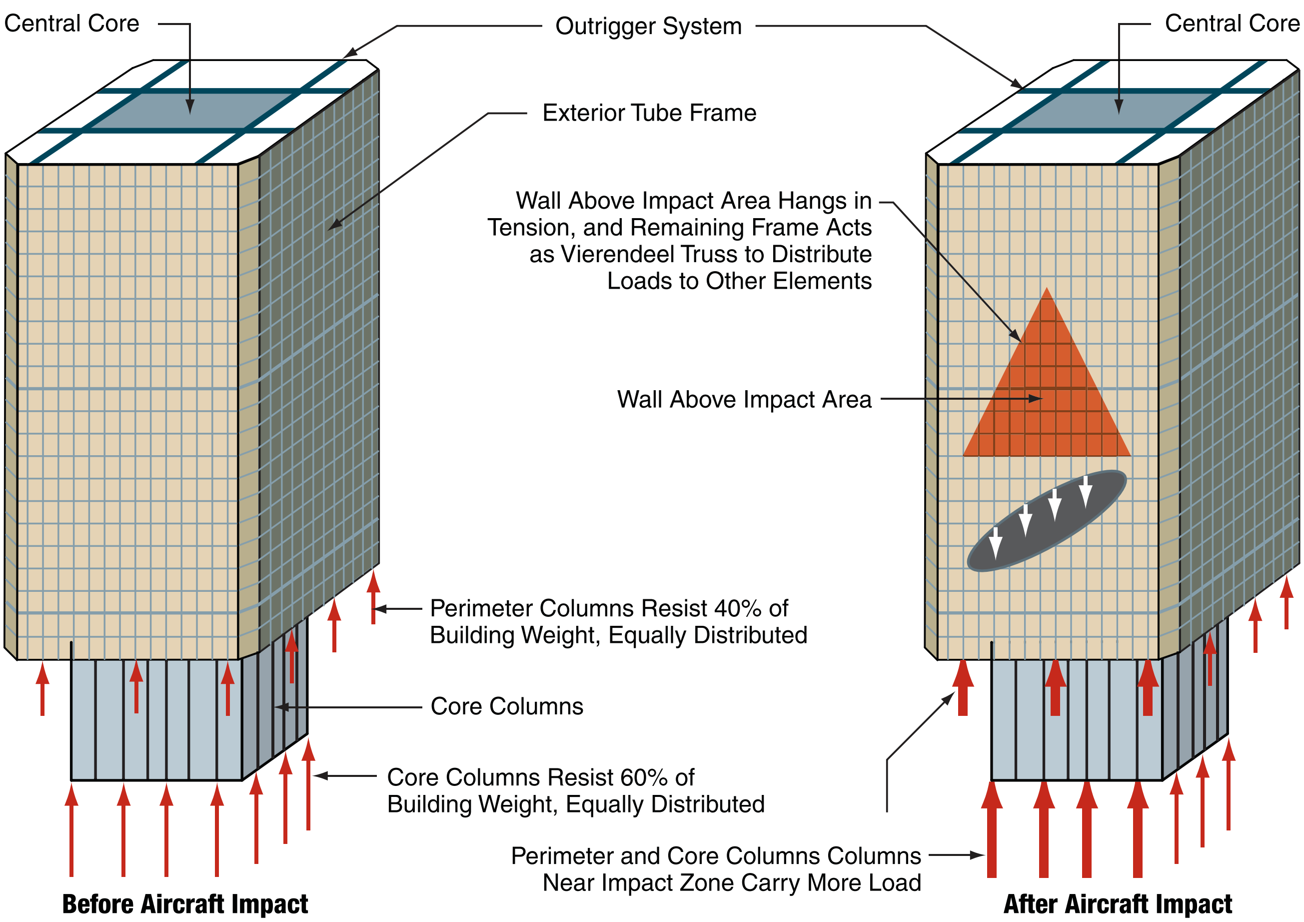


Figure 2-19 Redistribution of load after aircraft impact.

Following the aircraft impact into the building, the structure was able to successfully redistribute the building weight to the remaining elements and to maintain a stable condition. This return to a stable condition is suggested by the preliminary analyses and also evidenced by the fact that the structure remained standing for 1 hour and 43 minutes following the impact. However, the structure's global strength was severely degraded. Although the structure may have been able to remain standing in this weakened condition for an indefinite period, it had limited ability to resist additional loading and could potentially have collapsed as a result of any severe loading event, such as that produced by high winds or earthquakes. WTC 1 probably experienced some additional loading and damage due to the collapse of the adjacent WTC 2. The extent of such damage is not known but likely included broken window and façade elements along the south face. This additional damage was not sufficient to cause collapse. The first event of sufficient severity to cause collapse was the fires that followed the aircraft impact.

2.2.1.2 Fire Development

It is estimated, based on information compiled from Government sources, that each aircraft contained about 10,000 gallons of jet fuel upon impact into the buildings. A review of photographic and video records show that the aircraft fully entered the buildings prior to any visual evidence of flames at the exteriors of the buildings. This suggests that, as the aircraft crashed into and plowed across the buildings, they distributed jet fuel throughout the impact area to form a flammable "cloud." Ignition of this cloud resulted in a rapid pressure rise, expelling a fuel rich mixture from the impact area into shafts and through other openings caused by the crashes, resulting in dramatic fireballs.

Although only limited video footage is available that shows the crash of American Airlines Flight 11 into WTC 1 and the ensuing fireballs, extensive video records of the impact of United Airlines Flight 175 into WTC 2 are available. These videos show that three fireballs emanated from WTC 2 on the south, east, and west faces. The fireballs grew slowly, reaching their full size after about 2 seconds. The diameters of the fireballs were greater than 200 feet, exceeding the width of the building. Such fireballs were formed when the expelled jet fuel dispersed and flames traveled through the resulting fuel/air mixture. Experimentally based correlations for similar fireballs (Zalosh 1995) were used to estimate the amount of fuel consumed. The precise size of the fireballs and their exact shapes are not well defined; therefore, there is some uncertainty associated with estimates of the amount of fuel consumed by these effects. Calculations indicate that between 1,000 and 3,000 gallons of jet fuel were likely consumed in this manner. Barring additional information, it is reasonable to assume that an approximately similar amount of jet fuel was consumed by fireballs as the aircraft struck WTC 1.

Although dramatic, these fireballs did not explode or generate a shock wave. If an explosion or detonation had occurred, the expansion of the burning gasses would have taken place in microseconds, not the 2 seconds observed. Therefore, although there were some overpressures, it is unlikely that the fireballs, being external to the buildings, would have resulted in significant structural damage. It is not known whether the windows that were broken shortly after impact were broken by these external overpressures, overpressures internal to the building, the heat of the fire, or flying debris.

The first arriving firefighters observed that the windows of WTC 1 were broken out at the Concourse level. This breakage was most likely caused by overpressure in the elevator shafts. Damage to the walls of the elevator shafts was also observed as low as the 23rd floor, presumably as a result of the overpressures developed by the burning of the vapor cloud on the impact floors.

If one assumes that approximately 3,000 gallons of fuel were consumed in the initial fireballs, then the remainder either escaped the impact floors in the manners described above or was consumed by the fire on the impact floors. If half flowed away, then approximately 4,000 gallons remained on the impact floors to be consumed in the fires that followed. The jet fuel in the aerosol would have burned out as fast as the flame could spread through it, igniting almost every combustible on the floors involved. Fuel that fell to the floor and did not flow out of the building would have burned as a pool or spill fire at the point where it came to rest.

The time to consume the jet fuel can be reasonably computed. At the upper bound, if one assumes that all 10,000 gallons of fuel were evenly spread across a single building floor, it would form a pool that would be consumed by fire in less than 5 minutes (SFPE 1995) provided sufficient air for combustion was available. In reality, the jet fuel would have been distributed over multiple floors, and some would have been transported to other locations. Some would have been absorbed by carpeting or other furnishings, consumed in the flash fire in the aerosol, expelled and consumed externally in the fireballs, or flowed away from the fire floors. Accounting for these factors, it is believed that almost all of the jet fuel that remained on the impact floors was consumed in the first few minutes of the fire.

As the jet fuel burned, the resulting heat ignited office contents throughout a major portion of several of the impact floors, as well as combustible material within the aircraft itself.

A limited amount of physical evidence about the fires is available in the form of videos and still photographs of the buildings and the smoke plume generated soon after the initial attack. Estimates of the buoyant energy in the plume were obtained by plotting the rise of the smoke plume, which is governed by buoyancy in the vertical direction and by the wind in the horizontal direction. Using the Computational Fluid Dynamics (CFD) fire model, Fire Dynamics Simulator Ver. 1 (FDS1), fire scientists at the National Institute of Standards and Technology (NIST) (Rehm, et al. 2002) were able to mathematically approximate the size of fires required to produce such a smoke plume. As input to this model, an estimate of the openings available to provide ventilation for the fires was obtained from an examination of photographs taken of the damaged tower. Meteorological data on wind velocity and atmospheric temperatures were provided by the National Oceanic and Atmospheric Administration (NOAA) based on reports from the Aircraft Communications Addressing and Reporting System (ACARS). The information used weather monitoring instruments onboard three aircraft that departed from LaGuardia and Newark airports between 7:15 a.m. and 9:00 a.m. on September 11, 2001. The wind speed at heights equal to the upper stories of the towers was in the range of 10–20 mph. The outside temperatures over the height of the building were 20–21 °C (68–70 °F).

The modeling suggests a peak total rate of fire energy output on the order of 3–5 trillion Btu/hr, around 1–1.5 gigawatts (GW), for each of the two towers. From one third to one half of this energy flowed out of the structures. This vented energy was the force that drove the external smoke plume. The vented energy and accompanying smoke from both towers combined into a single plume. The energy output from each of the two buildings is similar to the power output of a commercial power generating station. The modeling also suggests ceiling gas temperatures of 1,000 °C (1,800 °F), with an estimated confidence of plus or minus 100 °C (200 °F) or about 900–1,100 °C (1,600–2,000 °F). A major portion of the uncertainty in these estimates is due to the scarcity of data regarding the initial conditions within the building and how the aircraft impact changed the geometry and fuel loading. Temperatures may have been as high as 900–1,100 °C (1,700–2,000 °F) in some areas and 400–800 °C (800–1,500 °F) in others.

The viability of a 3–5 trillion Btu/hr (1–1.15 GW) fire depends on the fuel and air supply. The surface area of office contents needed to support such a fire ranges from about 30,000–50,000 square feet, depending on the composition and final arrangement of the contents and the fuel loading present. Given the typical occupied area of a floor as approximately 30,000 square feet, it can be seen that simultaneous fire involvement of an area equal to 1–2 entire floors can produce such a fire. Fuel loads are typically described in terms of the equivalent weight of wood. Fuel loads in office-type occupancies typically range from about 4–12 psf, with the mean slightly less than 8 psf (Culver 1977). File rooms, libraries, and similar concentrations of paper materials have significantly higher concentrations of fuel. At the burning rate necessary to yield these fires, a fuel load of about 5 psf would be required to provide sufficient fuel to maintain the fire at full force for an hour, and twice that quantity to maintain it for 2 hours. The air needed to support combustion would be on the order of 600,000–1,000,000 cubic feet per minute.

Air supply to support the fires was primarily provided by openings in the exterior walls that were created by the aircraft impacts and fireballs, as well as by additional window breakage from the ensuing heat of the fires. Table 2.1 lists the estimated exterior wall openings used in these calculations. Although the table shows the openings on a floor-by-floor basis, several of the openings, particularly in the area of impact, actually spanned several floors (see Figure 2-17).

Sometimes, interior shafts in burning high-rise buildings also deliver significant quantities of air to a fire, through a phenomenon known as "stack effect," which is created when differences between the ambient exterior air temperatures and the air temperatures inside the building result in differential air pressures, drawing air up through the shafts to the fire area. Because outside and inside temperatures appear to have been virtually the same on September 11, this stack effect was not expected to be strong in this case.

Based on photographic evidence, the fire burned as a distributed collection of large but separate fires with significant temperature variations from space to space, depending on the type and arrangement of combustible material present and the available air for combustion in each particular space. Consequently, the temperature and related incident heat flux to the structural elements varied with both time and location. This information is not currently available, but could be modeled with advanced CFD fire models.

Damage caused by the aircraft impacts is believed to have disrupted the sprinkler and fire standpipe systems, preventing effective operation of either the manual or automatic suppression systems. Even if these systems had not been compromised by the impacts, they would likely have been ineffective. It is believed that the initial flash fires of jet fuel would have opened so many sprinkler heads that the systems would have quickly depressurized and been unable to effectively deliver water to the large area of fire involvement. Further, the initial spread of fires was so extensive as to make occupant use of small hose streams ineffective.

Table 2.1 Estimated Openings in Exterior Walls of WTC 1

Floor	North Wall		South Wall		East Wall		West Wall		Total Area	
	ft^2	(m^2)	ft^2	(m^2)	ft^2	(m^2)	ft^2	(m^2)	ft^2	(m^2)
92	743	(69)	0	(0)	1,572	(146)	0	(0)	2,314	(215)
93	958	(89)	0	(0)	1,356	(126)	0	(0)	2,314	(215)
94	592	(55)	54	(5)	1,163	(108)	0	(0)	1,808	(168)
95	1,055	(98)	54	(5)	0	(0)	420	(39)	1,528	(142)
96	797	(74)	151	(14)	0	(0)	1,518	(141)	2,465	(229)
97	926	(86)	151	(14)	0	(0)	1,798	(167)	2,874	(267)
98	1,335	(124)	0	(0)	0	(0)	0	(0)	1,335	(124)
TOTAL	6,405	(595)	409	(38)	4,090	(380)	3,735	(347)	14,639	(1,360)

NOTE: Differences in totals are due to rounding in the conversion of square meters to square feet.

2.2.1.3 Evacuation

Some occupants of WTC 1 and WTC 2 began to voluntarily evacuate the buildings soon after the first aircraft struck WTC 1. Full evacuation of all occupants below the impact floors in WTC 1 was ordered soon after the second plane hit the south tower (Smith 2002). As indicated by Cauchon (2001a), the overall evacuation of the towers was as much of a success as thought possible, given the overall incident. Cauchon indicates that, between both towers, 99 percent of the people below the floors of impact survived (2001a) and by the time WTC 2 collapsed, the stairways in WTC 1 were observed to be virtually clear of building occupants (Smith 2002). In part this was possible because conditions in the stairways below the impact levels largely remained tenable. However, this may also be a result of physical changes and training programs put into place following the 1993 WTC bombing. Important modifications to building egress made following the 1993 WTC bombing included the placement of photo-luminescent paint on the egress paths to assist in wayfinding (particularly at the stair transfer corridors) and provision of emergency lighting for the stairways. In addition, an evacuation training program was instituted (Masetti 2001).

Shortly before the times of collapse, the stairways were reported as being relatively clear, indicating that occupants who were physically capable and had access to egress routes were able to evacuate from the buildings (Mayblum 2001). People within and above the impact area could not evacuate, simply because the stairways in the impact area had been destroyed.

Some survivors reported that, at about the same time that WTC 2 collapsed, lighting in the stairways of WTC 1 was lost (Mayblum 2001). Also, there were several accounts of water flowing down the stairways and of stairwells becoming slippery beginning at the 10th floor (Labriola 2001).

Anecdotes indicate altruistic behavior was commonly displayed. Some mobility-impaired occupants were carried down many flights of stairs by other occupants. There were also reports of people frequently stepping aside and temporarily stopping their evacuation to let burned and badly injured occupants pass by (Dateline NBC 2001, Hearst 2001). Occupants evacuating from the 91st floor noted that, as they descended to lower levels of the building, traffic was considerably impaired and formed into a slowly moving single-file progression, as evacuees worked their way around firefighters and other emergency responders, who were working their way up the stairways or who were resting from the exertion of the climb (Shark and McIntyre 2001).

2.2.1.4 Structural Response to Fire Loading

As previously indicated, the impact of the aircraft into WTC 1 substantially degraded the strength of the structure to withstand additional loading and also made the building more susceptible to fire-induced failure. Among the most significant factors:

- The force of the impact and the resulting debris field and fireballs probably compromised spray-applied fire protection of some steel members in the immediate area of impact. The exact extent of this damage will probably never be known, but this likely resulted in greater susceptibility of the structure to fire-related failure.
- Some of the columns were under elevated states of stress following the impact, due to the transfer of load from the destroyed and damaged elements.
- Some portions of floor framing directly beneath the partially collapsed areas were carrying substantial additional weight from the resulting debris and, in some cases, were likely carrying greater loads than they were designed to resist.

As fire spread and raised the temperature of structural members, the structure was further stressed and weakened, until it eventually was unable to support its immense weight. Although the specific chain of events that led to the eventual collapse will probably never be identified, the following effects of fire on structures may each have contributed to the collapse in some way. Appendix A presents a more detailed discussion of the structural effects of fire.

- As floor framing and supported slabs above and in a fire area are heated, they expand. As a structure expands, it can develop additional, potentially large, stresses in some elements. If the resulting stress state exceeds the capacity of some members or their connections, this can initiate a series of failures (Figure 2-20).
- As the temperature of floor slabs and support framing increases, these elements can lose rigidity and sag into catenary action. As catenary action progresses, horizontal framing elements and floor slabs become tensile elements, which can cause failure of end connections (Figure 2-21) and allow supported floors to collapse onto the floors below. The presence of large amounts of debris on some floors of WTC 1 would have made them even more susceptible to this behavior. In addition to overloading the floors below, and potentially resulting in a pancake-type collapse of successive floors, local floor collapse would also immediately increase the laterally unsupported length of columns, permitting buckling to begin. As indicated in Appendix B, the propensity of exterior columns to buckle would have been governed by the relatively weak bolted column splices between the vertically stacked prefabricated exterior wall units. This effect would be even more likely to occur in a fire that involves several adjacent floor levels simultaneously, because the columns could effectively lose lateral support over several stories (Figure 2-22).
- As the temperature of column steel increases, the yield strength and modulus of elasticity degrade and the critical buckling strength of the columns will decrease, potentially initiating buckling, even if lateral support is maintained. This effect is most likely to have been significant in the failure of the interior core columns.

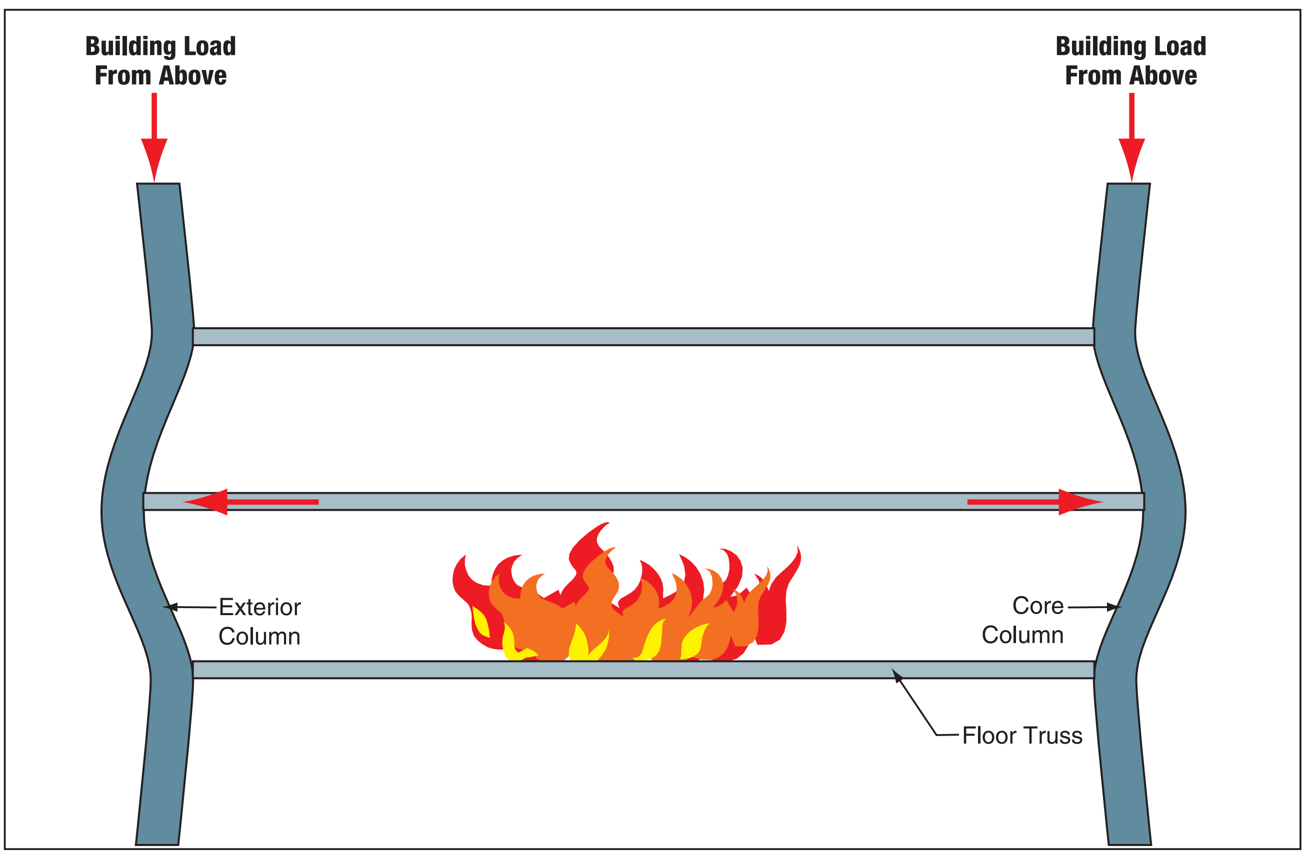


Figure 2-20 Expansion of floor slabs and framing results in outward deflection of columns and potential overload.

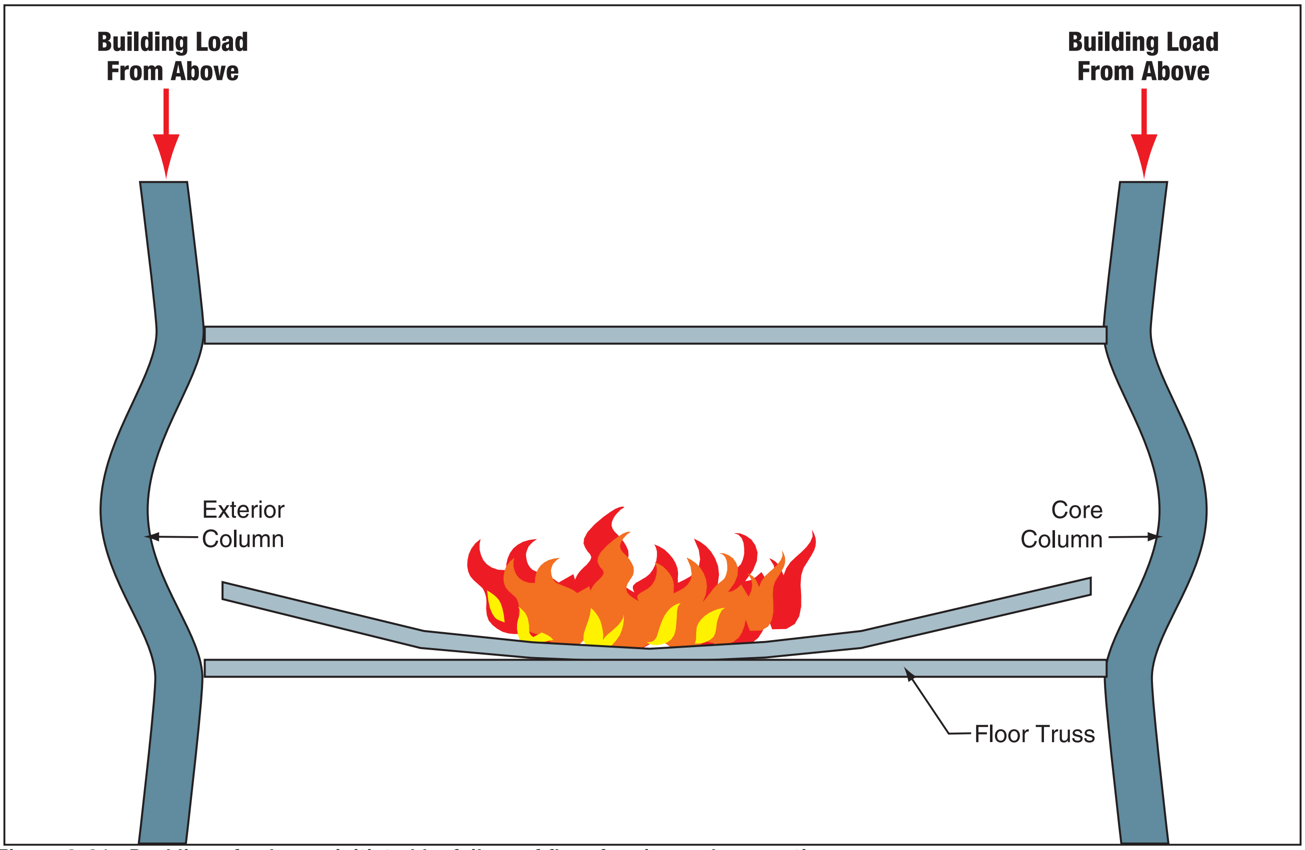


Figure 2-21 Buckling of columns initiated by failure of floor framing and connections.

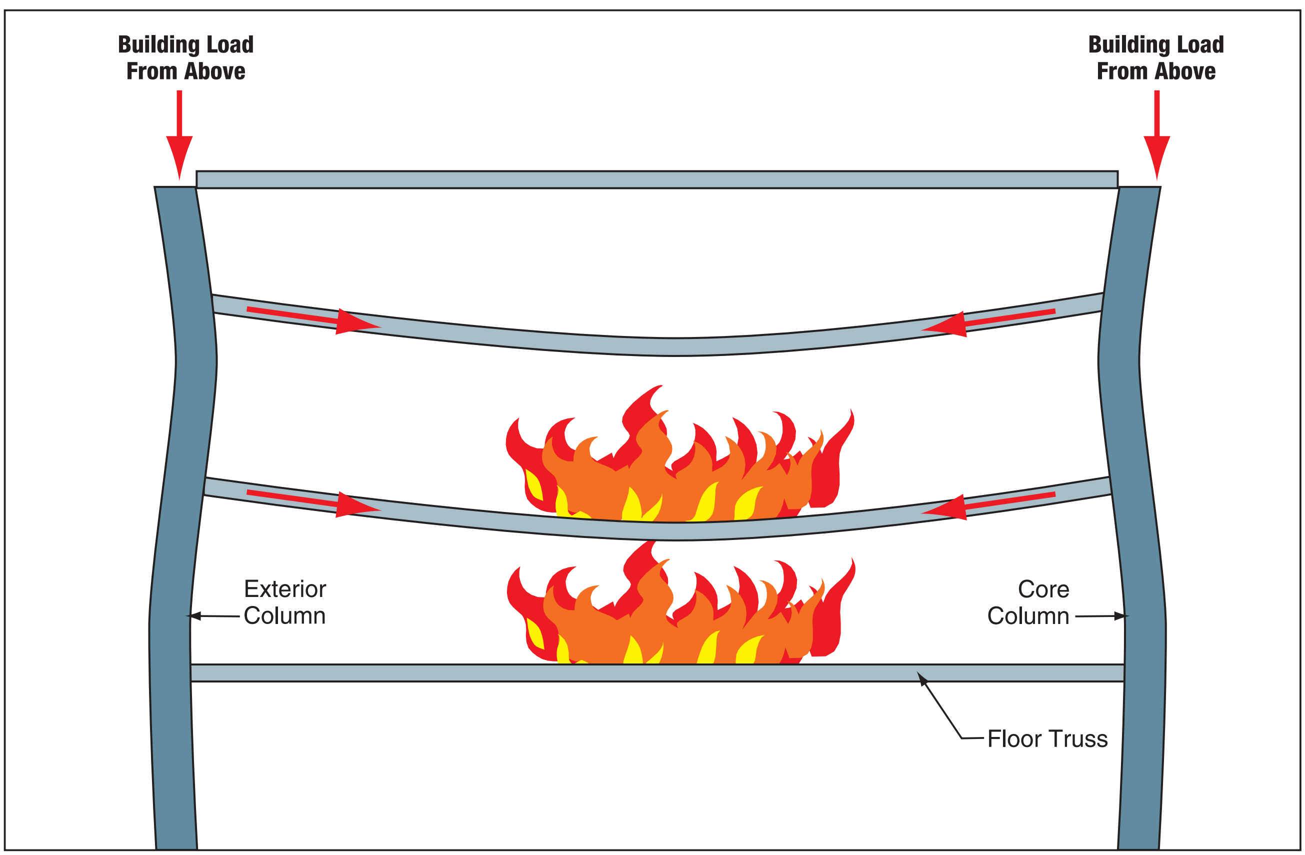


Figure 2-22 Catenary action of floor framing on several floors initiates column buckling failures.

2.2.1.5 Progression of Collapse

Construction of WTC 1 resulted in the storage of more than $4x10^{11}$ joules of potential energy over the 1,368-foot height of the structure. Of this, approximately $8x10^{9}$ joules of potential energy were stored in the upper part of the structure, above the impact floors, relative to the lowest point of impact. Once collapse initiated, much of this potential energy was rapidly converted into kinetic energy. As the large mass of the collapsing floors above accelerated and impacted on the floors below, it caused an immediate progressive series of floor failures, punching each in turn onto the floor below, accelerating as the sequence progressed. As the floors collapsed, this left tall freestanding portions of the exterior wall and possibly central core columns. As the unsupported height of these freestanding exterior wall elements increased, they buckled at the bolted column splice connections, and also collapsed. Perimeter walls of the building seem to have peeled off and fallen directly away from the building face, while portions of the core fell in a somewhat random manner. The perimeter walls broke apart at the bolted connections, allowing individual prefabricated units that formed the wall or, in some cases, large assemblies of these units to fall to the street and onto neighboring buildings below.

Review of videotape recordings of the collapse taken from various angles indicates that the transmission tower on top of the structure began to move downward and laterally slightly before movement was evident at the exterior wall. This suggests that collapse began with one or more failures in the central core area of the building. This is consistent with the observations of debris patterns from the 91st floor, previously discussed. This is also supported by preliminary evaluation of the load carrying capacity of these columns, discussed in more detail in Section 2.2.2.2. The core columns were not designed to resist wind loads and, therefore, had less reserve capacity than perimeter columns. As some exterior and core columns were damaged by the aircraft impact, the outrigger trusses at the top of the building shifted additional loads to the remaining core columns, further eroding the available factor of safety. This would have been particularly significant in the upper portion of the damaged building. In this region, the original design load for the core columns was less than at lower floors, and the column sections were relatively light. The increased stresses caused by the aircraft impact could easily have brought several of these columns close to their ultimate capacity, so that relatively little additional effects due to fire would have been required to initiate the collapse. Once movement began, the entire portion of the building above the area of impact fell in a unit, pushing a cushion of air below it. As this cushion of air pushed through the impact area, the fires were fed by new oxygen and pushed outward, creating the illusion of a secondary explosion.

Although the building appeared to collapse within its own footprint, a review of aerial photographs of the site following the collapse, as well as damage to adjacent structures, suggests that debris impacted the Marriott Hotel (WTC 3), the Customs House (WTC 6), the Morgan Stanley building (WTC 5), WTC 7, and the American Express and Winter Garden buildings located across West Street (Figure 2-23). The debris field extended as far as 400–500 feet from the tower base.

2.2.2 WTC 2

2.2.2.1 Initial Damage From Aircraft Impact

United Airlines Flight 175 struck the south face of WTC 2 approximately between the 78th and 84th floors. The zone of impact extended from near the southeast corner of the building across much of the building face (Figures 2-24 and 2-25). The aircraft caused massive damage to the south face of the building in the zone of impact (Figures 2-26 and 2-27). At the central zone of impact corresponding to the airplane fuselage and engines, six of the prefabricated, three-column sections that formed the exterior walls were broken loose from the structure, with some of the elements apparently pushed inside the building envelope. Locally, as was the case in WTC 1, floors supported by these exterior wall sections appear to have partially collapsed. Away from this central zone, in the areas impacted by the outer wing structures, the exterior steel columns

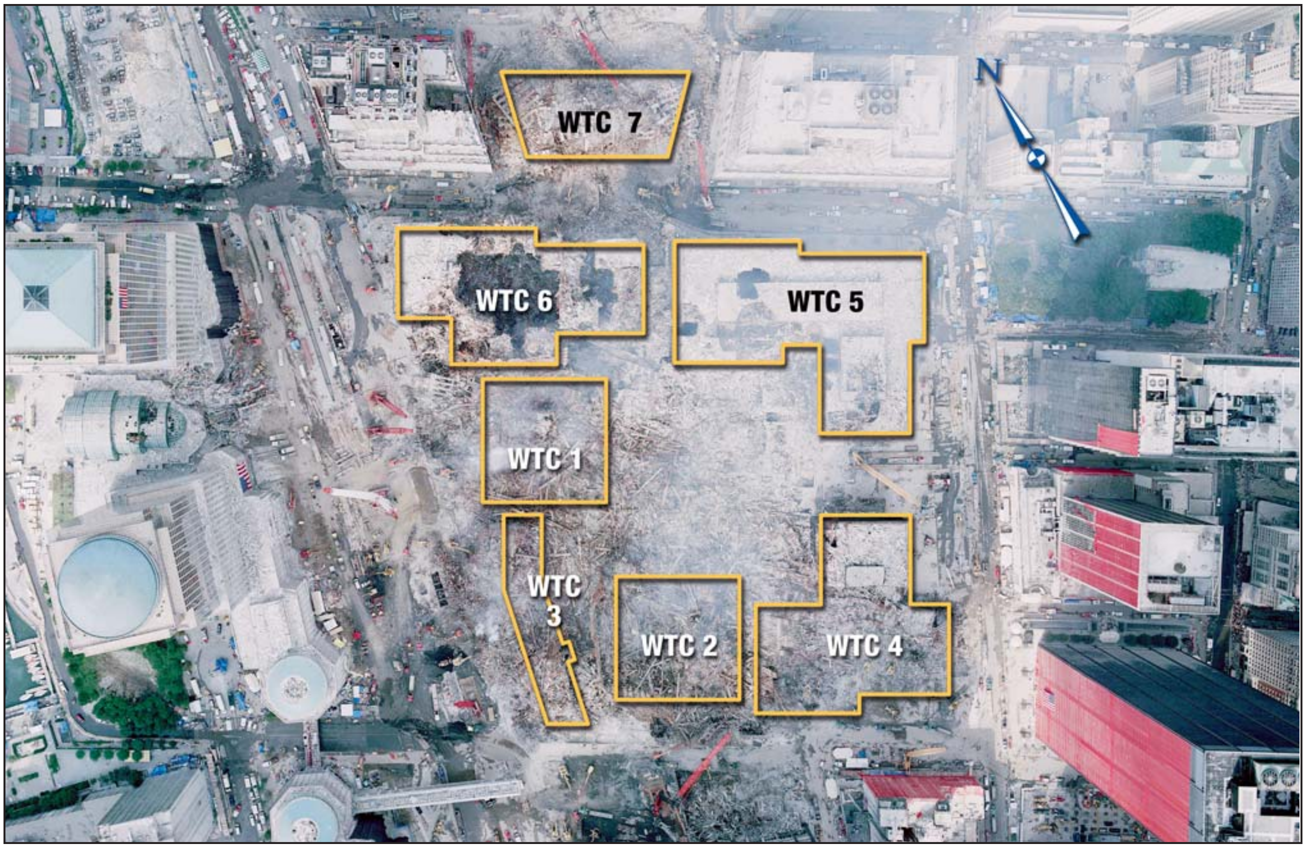


Figure 2-23 Aerial photograph of the WTC site after September 11 attack showing adjacent buildings damaged by debris from the collapse of WTC 1.

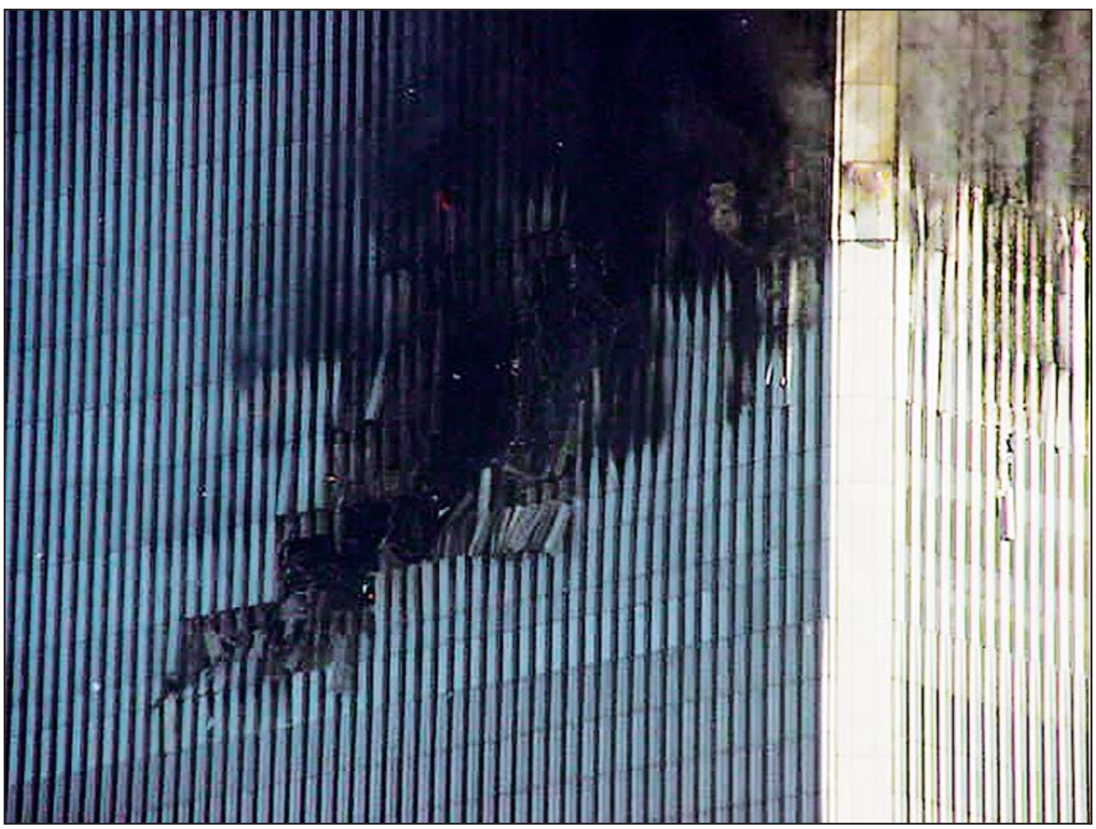


Figure 2-24 Southeast corner of WTC 2 shortly after aircraft impact.

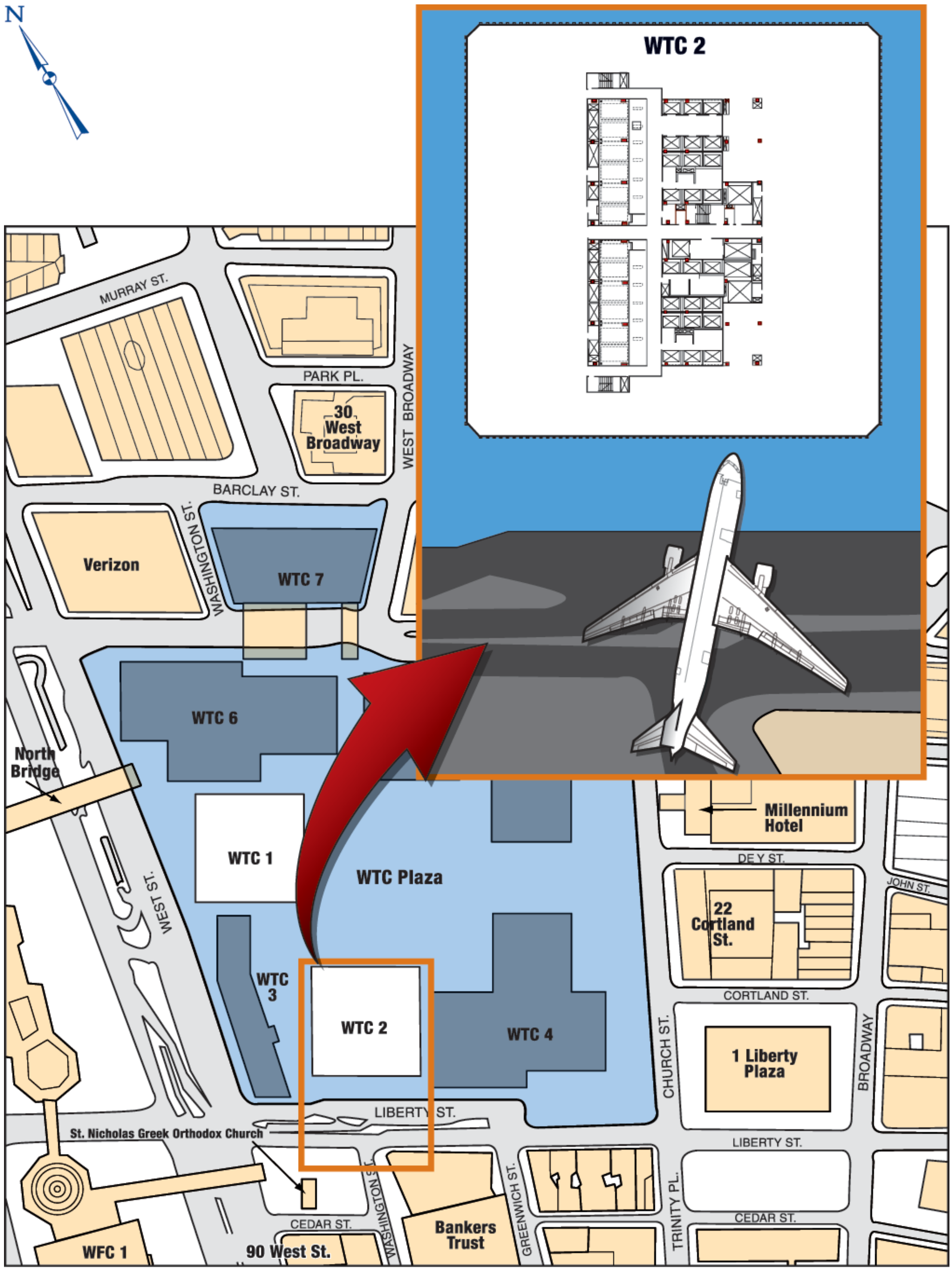
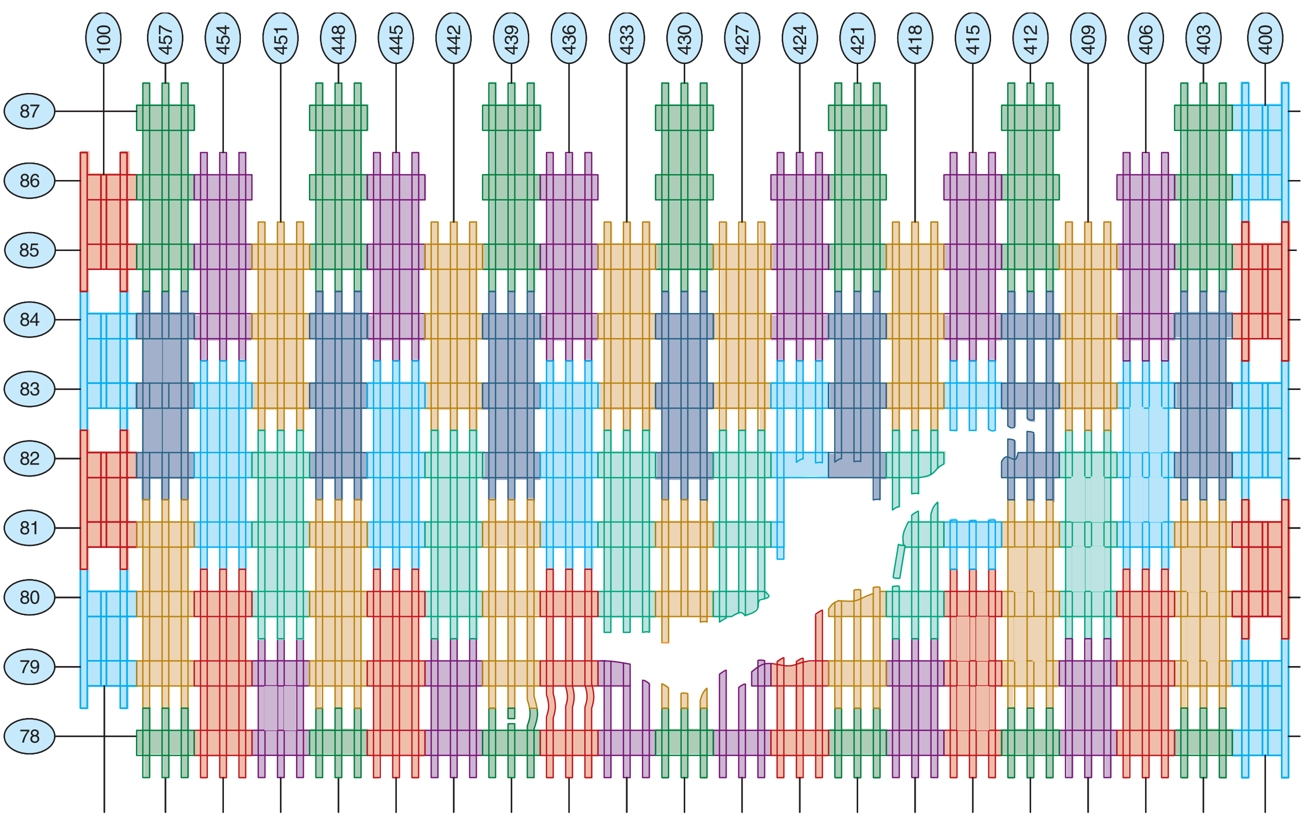


Figure 2-25 Approximate zone of impact of aircraft on the south face of WTC 2.

Figure 2-26 Impact damage to the south and east faces of WTC 2.



GENERAL NOTES: (1) Column damage captured from photographs and enhanced videos. (2) Damage to column lines 413-418 at levels 81 and 82 is estimated. (3) There is not sufficient information to detail damage to column lines 408-411 at levels 83-84.

Figure 2-27 Impact damage to exterior columns on the south face of WTC 2.

were fractured by the impact. Photographic evidence suggests that from 27 to 32 columns along the south building face were destroyed over a five-story range. Partial collapse of floors in this zone appears to have occurred over a horizontal length of approximately 70 feet, while floors in other portions of the building appeared to remain intact. It is probable that the columns in the southeast corner of the core also experienced some damage because they would have been in the direct travel path of the fuselage and port engine (Figure 2-25).

It is known that debris from the aircraft traveled completely through the structure. For example, a landing gear from the aircraft that impacted WTC 2 was found to have crashed through the roof of a building located six blocks to the north, and one of the jet engines was found at the corner of Murray and Church Streets. The extent to which debris scattered throughout the impact floors is also evidenced by photographs of the fireballs that occurred as the aircraft struck the building (Figure 2-28). Figure 2-29 shows a portion of the fuselage of the aircraft, lying on the roof of WTC 5.

As described for WTC 1, this debris doubtless caused some level of damage to the structure across the floor plates, including interior framing; core columns at the southeast corner of the core; framing at the north, east, and west walls; and the floor plates themselves. Figure 2-30, showing the eastern side of the north face of the WTC 2 partially hidden behind WTC 1, suggests that damage to the exterior walls was not severe except at the zone of impact. The exact extent of this damage will likely never be known with certainty. It is evident that the structure retained sufficient integrity and strength to remain globally stable for a period of approximately 56 minutes.

There are some important differences between the impact of the aircraft into WTC 2 and the impact into WTC 1. First, United Airlines Flight 175 was flying much faster, with an estimated speed of 590 mph, while American Airlines Flight 11 was flying at approximately 470 mph. The additional speed would have

Figure 2-28 Conflagration and debris exiting the north wall of WTC 2, behind WTC 1.

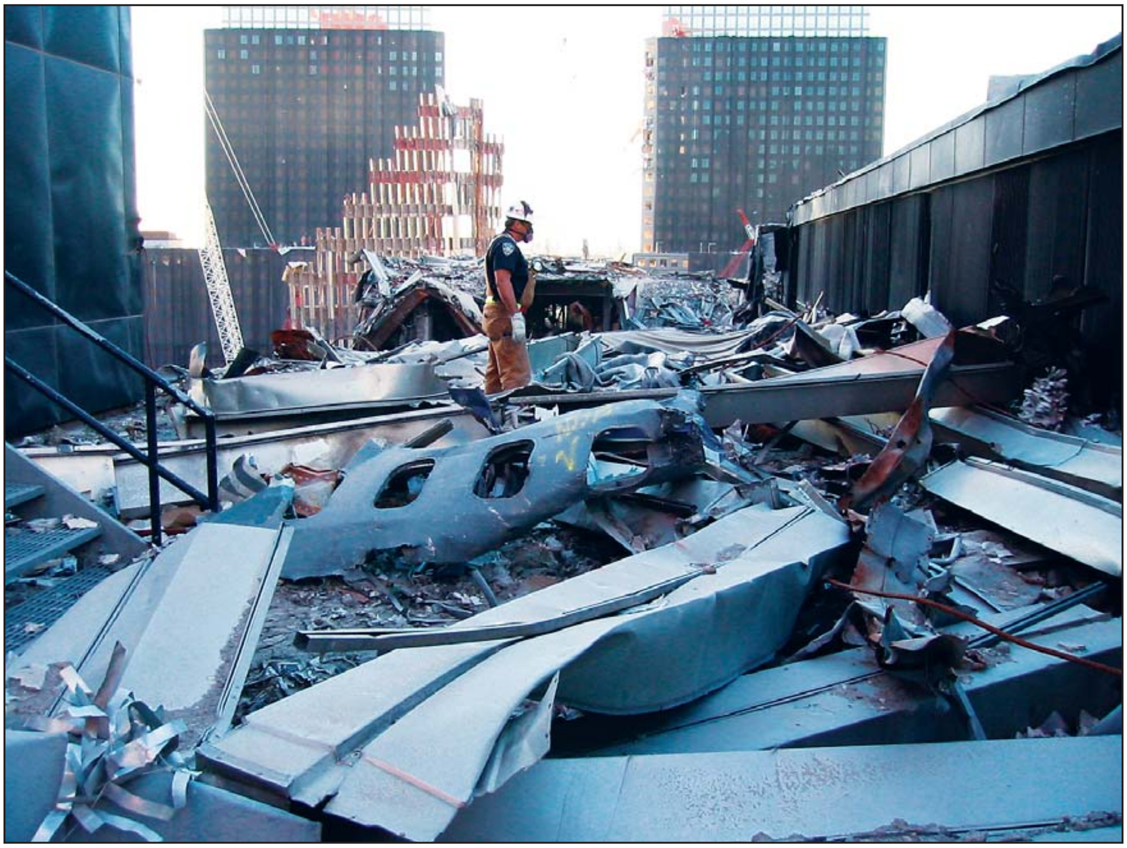


Figure 2-29 A portion of the fuselage of United Airlines Flight 175 on the roof of WTC 5.

given the aircraft a greater ability to destroy portions of the structure. The zone of aircraft impact was skewed toward the southeast corner of WTC 2, while the zone of impact on WTC 1 was approximately centered on the building's north face. The orientation of the core in WTC 2 was such that the aircraft debris would only have to travel 35 feet across the floor before it began to impact and damage elements of the core structure. Finally, the zone of impact in WTC 2 was nearly 20 stories lower than that in WTC 1, so columns in this area were carrying substantially larger loads. It is possible, therefore, that structural damage to WTC 2 was more severe than that to WTC 1, partly explaining why WTC 2 collapsed more quickly than WTC 1.

2.2.2.2 Preliminary Structural Analysis

An approximate linear structural analysis of WTC-2 was performed using SAP-2000 software (CSI 2000) to provide an understanding of the likely stress state in the building following the aircraft impact. The upper 55 stories of the building's exterior-wall frame were explicitly modeled using beam and column elements. This encompassed the entire structure above the zone of impact and about 20 stories below. The lower 55 stories of the exterior were modeled as a "boundary condition" consisting of a perimeter super-beam that was 52 inches deep and about 50 inches wide, supported on a series of springs. A base spring was provided at each column location to represent the axial stiffness of the columns from the 55th floor down to grade. The outrigger trusses at the top of the building were explicitly modeled, using truss-type elements. The interior core columns were modeled as spring elements.

An initial analysis of the building was conducted to simulate the pre-impact condition. In addition to the weight of the floor itself (approximately 54 psf at the building edges and 58 psf at the building sides), a uniform floor loading of 12 psf was assumed for partitions and an additional 20 psf was conservatively assumed to represent furnishings and contents. At the 80th floor level, exterior columns were found to be

Figure 2-30
North face of WTC 2 opposite the zone of impact on the south face, behind WTC 1.

approximately uniformly loaded with an average utilization ratio (ratio of actual applied stress to ultimate stress) of under 20 percent. This low utilization ratio is due in part to the unusually close spacing of the columns in this building, which resulted in a very small tributary area for each column. It reflects the fact that wind and deflection considerations were dominant factors in the design. Core columns were more heavily loaded with average calculated utilization ratios of 60 percent, which would be anticipated for these columns, which were designed to resist only gravity loads.

A second analysis was conducted to estimate the demands on columns immediately following aircraft impact and before fire effects occurred. Exterior columns were removed from the model to match the damage pattern illustrated in Figure 2-27. Although some core columns were probably damaged by the aircraft impact, the exact extent of this damage is not known and therefore was not considered in the model. As a result, this analysis is thought to underestimate the true stress state in the columns immediately after impact. The analysis indicates that most of the loads initially carried by the damaged exterior columns were transferred by Vierendeel truss action to the remaining exterior columns immediately adjacent to the impact area. If the floors at this level are assumed to remain intact and capable of providing lateral support to the columns, this raised the utilization ratio for the most heavily loaded column immediately adjacent to the damage area to approximately a value of 1.0. At a value of 1.0, columns would lose stiffness and shift load to adjacent columns. Based on this analysis, it appears that the structure had significant remaining margin against collapse. However, this analysis does not consider damage to the building core, which was likely significant. Columns located further from the damage area are less severely impacted, and columns located only 20 feet away from the damaged area experience almost no increase in demand at all. These data are plotted in Figure 2-31.

The columns immediately above the damage area are predicted to act as tension members, transferring approximately 10 percent of the load initially carried by the damaged columns upward to the outrigger trusses, which, in turn, transfer this load back to the core columns. Not considering any damage to the core columns, utilization ratios on these elements are predicted to increase by about 20 percent at the 80th floor level. In upper stories, where the core columns were more lightly loaded, the increase in utilization ratio is substantially larger and may have approached a value of 1.0. These conditions would have been made more severe by damage to one or more core columns.

2.2.2.3 Fire Development

Following the impact, fires spread throughout WTC 2, similar to the manner previously described for WTC 1. Extensive videotape of the fires' development through the building was recorded from various exterior vantage points. This videotape suggests that, in the minutes immediately preceding the collapse, the most intensive fires occurred along the north face of the building, near the 80th floor level. Just prior to the collapse, a stream of molten material—possibly aluminum from the airliner—was seen streaming out of a window opening at the northeast corner at approximately this level. This is of particular interest because, although the building collapse appears to have initiated at this floor level, the initiation seems to have occurred at the southeast rather than the northeast corner.

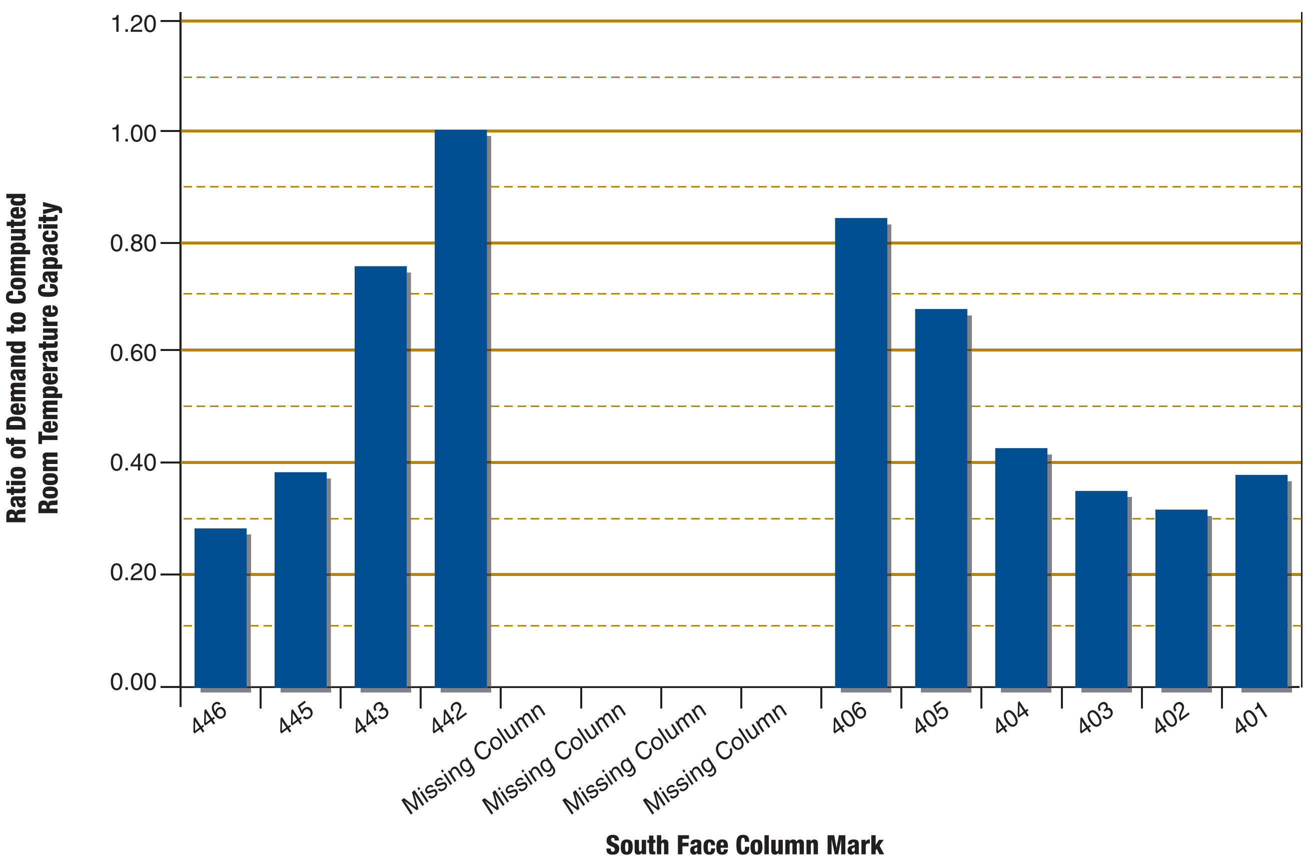


Figure 2-31 Plot of column utilization ratio at the 80th floor of WTC 2, viewed looking outward. (Conservatively assumes columns 407–411 and 440–441 to be missing.)

2.2.2.4 Evacuation

Although less time was available for evacuation of WTC 2 than for WTC 1, and the aircraft hit the building some 16 floors lower than in WTC 1, fewer casualties occurred within this building. The reduced number of casualties to building occupants in WTC 2 may be attributed to the movement of some of the building occupants immediately after the aircraft impact into WTC 1 and before the second aircraft struck WTC 2. Several survivors from WTC 2 stated that, following the impact of the aircraft into WTC 1, a message was broadcast over the loudspeaker system indicating that WTC 2 was secure and that occupants should return to their offices (Scripps 2001, BBC News 2001). Many of these survivors did not heed the announcement and continued to exit the building, using the elevators. Survivors also related reports of individuals who listened to the message, returned to their floors, and did not make it out after the second aircraft impacted WTC 2. Some survivors related that a small number of people traveled to the roof under the assumption that a helicopter rescue was possible (Cauchon 2001b).

2.2.2.5 Initiation of Collapse

The same types of structural behaviors and failure mechanisms previously discussed are equally likely to have occurred in WTC 2, resulting in the initiation of progressive collapse, approximately 56 minutes after the aircraft impact. Review of video footage of the WTC 2 collapse suggests that it probably initiated with a partial collapse of the floor in the southeast corner of the building at approximately the 80th level. This appears to have been followed rapidly by collapse of the entire floor level along the east side, as evidenced by a line of dust blowing out of the side of the building. As this floor collapse occurred, columns along the east face of the building appear to buckle in the region of the collapsed floor, beginning at the south side and progressing to the north, causing the top of the building to rotate toward the east and south and to begin to collapse downward (Figure 2-32). It should be noted that failure of core columns in the southeast corner of the building could have preceded and triggered these events.

2.2.2.6 Progression of Collapse

As in WTC 1, a very large quantity of potential energy was stored in the building, during its construction. Once collapse initiated, much of this energy was rapidly released and converted into kinetic energy, in the form of the rapidly accelerating mass of the structure above the aircraft impact zone. The impact of this rapidly moving mass on the lower structure caused a wide range of structural failures in the floors directly at and below the aircraft impact zone, in turn causing failure of these floors. As additional floor plates failed, the mass associated with each of these floors joined that of the tower above the impact area, increasing the destructive energy on the floors immediately below. This initiated a chain of progressive failures that resulted in the total collapse of the building.

A review of aerial photographs of the site, following the collapse, as well as identification of pieces of structural steel from WTC 2, strongly suggests that while the top portion of the tower fell to the south and east, striking Liberty Street and the Bankers Trust building, the lower portion of the tower fell to the north and west, striking the Marriott Hotel (WTC 3). Again, the debris pattern spread laterally as far as approximately 400–500 feet from the base of the structure.

2.2.3 Substructure

As first WTC 2, then WTC 1 collapsed, nearly 600,000 tons of debris fell onto the Plaza level, punching large holes through the Plaza and the six levels of substructure below, and partially filling the substructure with debris. This damage severely compromised the ability of the slabs to provide lateral bracing of the substructure walls against the induced lateral earth pressures from the unexcavated side. This condition was most severe at the southern side of the substructure, adjacent to WTC 2 and WTC 3. In this region, debris from the collapsed WTC 2 punched through several levels of substructure slab, but

Figure 2-32 The top portion of WTC 2 falls to the east, then south, as viewed from the northeast.

did not completely fill the void left behind, leaving the south wall of the substructure in an unbraced condition over a portion of its length.

In early October, large cracks were observed along Liberty Street, indicating that the south wall had started to move into the failed area under the influence of the lateral earth pressures. Mueser-Rutledge Engineers were retained to review the situation and make suitable recommendations. As a temporary measure, sand fill was backfilled against the inside face of the south wall to counterbalance earth pressures on the unexcavated side. Following temporary stabilization of the wall, tiebacks were reinstalled through the wall in a manner similar to that used to stabilize the excavation during the original construction of the development. After these tiebacks were installed, it was possible to begin excavation of the temporary sand backfill and the accumulated debris. Tiebacks were similarly installed at the other exterior substructure walls to provide lateral support as the damaged slabs and debris were excavated and removed from the site.

2.3 Observations and Findings

The structural damage sustained by each of the two buildings as a result of the terrorist attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the ability of these structures to successfully withstand such damage is noteworthy.

Preliminary analyses of the damaged structures, together with the fact the structures remained standing for an extended period of time, suggest that, absent other severe loading events such as a windstorm or earthquake, the buildings could have remained standing in their damaged states until subjected to some significant additional load. However, the structures were subjected to a second, simultaneous severe loading event in the form of the fires caused by the aircraft impacts.

The large quantity of jet fuel carried by each aircraft ignited upon impact into each building. A significant portion of this fuel was consumed immediately in the ensuing fireballs. The remaining fuel is believed either to have flowed down through the buildings or to have burned off within a few minutes of the aircraft impact. The heat produced by this burning jet fuel does not by itself appear to have been sufficient to initiate the structural collapses. However, as the burning jet fuel spread across several floors of the buildings, it ignited much of the buildings' contents, causing simultaneous fires across several floors of both buildings. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial power generating station. Over a period of many minutes, this heat induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and the resulting damage were sufficient to induce the collapse of both structures.

Because the aircraft impacts into the two buildings are not believed to have been sufficient to cause collapse without the ensuing fires, the obvious question is whether the fires alone, without the damage from the aircraft impact, would have been sufficient to cause such a collapse. The capabilities of the fire protection systems make it extremely unlikely that such fires would develop without some unusual triggering event like the aircraft impact. For all other cases, the fire protection for the tower buildings provided in-depth protection. The first line of defense was the automatic sprinkler protection. The sprinkler system was intended to respond quickly and automatically to extinguish or confine a fire. The second line of defense consisted of the manual (FDNY/Port Authority Fire Brigade) firefighting capabilities, which were supported by the building standpipe system, emergency fire department use elevators, smoke control system, and other features. Manual suppression by FDNY was the principal fire protection mechanism that controlled a large fire that occurred in the buildings in 1975. Finally, the last line of defense was the structural fire resistance. The fire resistance capabilities would not be called upon unless both the automatic and manual suppression systems just described failed. In the incident of September 11, not only did the aircraft impacts disable the first two lines of defense, they also are believed to have dislodged fireproofing and imposed major additional stresses on the structural system.

Had some other event disabled both the automatic and manual suppression capabilities and a fire of major proportions occurred while the structural framing system and its fireproofing remained intact, the third line of defense, structural fireproofing, would have become critical. The thickness and quality of the fireproofing materials would have been key factors in the rate and extent of temperature rise in the floor trusses and other structural members. In the preparation of this report, there has not been sufficient analysis to predict the temperature and resulting change in strength of the individual structural members in order to approximate the overall response of the structure. Given the redundancy in the framing system and the capability of that system to redistribute load from a weakened member to other parts of the structural system, it is impossible, without extensive modeling and other analysis, to make a credible prediction of how the buildings would have responded to an extremely severe fire in a situation where there was no prior structural damage. Such simulations were not performed within the scope of this study, but should be performed in the future.

Buildings are designed to withstand loading events that are deemed credible hazards and to protect the public safety in the event such credible hazards are experienced. Buildings are not designed to withstand any event that could ever conceivably occur, and any building can collapse if subjected to a sufficiently extreme loading event. Communities adopt building codes to help building designers and regulators determine those loading events that should be considered as credible hazards in the design process. These building codes are developed by the design and regulatory communities themselves, through a voluntary committee consensus process. Prior to September 11, 2001, it was the consensus of these communities that aircraft impact was not a sufficiently credible hazard to warrant routine consideration in the design of buildings and, therefore, the building codes did not require that such events be considered in building design. Nevertheless, the design of WTC 1 and WTC 2 did include at least some consideration of the probable response of the buildings to an aircraft impact, albeit a somewhat smaller and slower moving aircraft than those actually involved in the September 11 events. Building codes do consider fire as a credible hazard and include extensive requirements to control the spread of fire throughout buildings, to delay the onset of fire-induced structural collapse, and to facilitate the safe egress of building occupants in a fire event. For fire-protected steel-frame buildings, like WTC 1 and WTC 2, these code requirements had been deemed effective and, in fact, prior to September 11, there was no record of the fire-induced-collapse of such structures, despite some very large uncontrolled fires.

The ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse a result of the combined effects of the impacts and ensuing fires. Many buildings with other design and construction characteristics would have been more vulnerable to collapse in these events than the two towers, and few may have been less vulnerable. It was not the purpose of this study to assess the code-conformance of the building design and construction, or to judge the adequacy of these features. However, during the course of this study, the structural and fire protection features of the buildings were examined. The study did not reveal any specific structural features that would be regarded as substandard, and, in fact, many structural and fire protection features of the design and construction were found to be superior to the minimum code requirements.

Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These included the following:

- robustness and redundancy of the steel framing system
- adequate egress stairways that were well marked and lighted
- conscientious implementation of emergency exiting training programs for building tenants

Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems
- use of impact-resistant enclosures around egress paths
- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards
- grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure

During the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks was frequently explored. Depending on the size of the aircraft, it may not be technically feasible to develop design provisions that would enable all structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design intent practically infeasible.

Although the attacks on the World Trade Center are a reason to question design philosophies, the BPS Team believes there are insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes. Some believe the likelihood of such attacks on any specific building is deemed sufficiently low to not be considered at all. However, individual building developers may wish to consider design provisions for improving redundancy and robustness for such unforeseen events, particularly for structures that, by nature of their design or occupancy, may be especially susceptible to such incidents. Although some conceptual changes to the building codes that could make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study, the BPS Team felt that extensive technical, policy, and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building code revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

2.4 Recommendations

The scope of this study was not intended to include in-depth analysis of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 1 and WTC 2 during the events of September 11, 2001, and of related building performance issues should be conducted. These include the following:

- During the course of this study, it was not possible to determine the condition of the interior structure of the two towers, after aircraft impact and before collapse. Detailed modeling of the aircraft impacts into the buildings should be conducted in order to provide understanding of the probable damage state immediately following the impacts.
- Preliminary studies of the growth and heat flux produced by the fires were conducted. Although these studies provided useful insight into the buildings' behavior, they were not of sufficient detail to permit an understanding of the probable distribution of temperatures in the buildings at various stages of the event and the resulting stress state of the structures as the fires progressed. Detailed modeling of the fires should be conducted and combined with structural modeling to develop specific failure modes likely to have occurred.
- The floor framing system for the two towers was complex and substantially more redundant than typical bar joist floor systems. Detailed modeling of these floor systems and their connections should be conducted to understand the effects of localized overloads and failures to determine ultimate failure modes. Other types of common building framing should also be examined for these effects.
- The fire-performance of steel trusses with spray-applied fire protection, and with end restraint conditions similar to those present in the two towers, is not well understood, but is likely critical to the building collapse. Studies of the fire-performance of this structural system should be conducted.
- Observation of the debris generated by the collapse of the towers and of damaged adjacent structures suggests that spray-applied fireproofing may be vulnerable to mechanical damage from blasts and impacts. This vulnerability is not well understood. Tests of these materials should be

conducted to understand how well they withstand such mechanical damage and to determine whether it is appropriate and feasible to improve their resistance to such damage.

- In the past, tall buildings have occasionally been damaged, typically by earthquakes, and experienced collapse within the damaged zones. Those structures were able to arrest collapse before they progressed to a state of total collapse. The two WTC towers were able to arrest collapse from the impact damage, but not from the resulting fires when combined with the impact effects of the aircraft attacks. Studies should be conducted to determine, given the great size and weight of the two towers, whether there are feasible design and construction features that would permit such buildings to arrest or limit a collapse, once it began.

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