DISSECTING THE COLLAPSES

The September 11 terrorist attacks on the World Trade Center horrified the civilized world. An estimated 2,830 human lives were extinguished by these attacks-the second greatest number of lives ever lost in a single event in the United States. These attacks also resulted in extensive damage to a large number of buildings at the World Trade Center complex and within the vicinity of the complex. In the aftermath of the events, the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE)—in association with several other federal agencies and professional organizations-dispatched a team of civil, structural, and fire protection engineers to study the performance of the buildings at the site. These experts in tall building design, steel structure behavior, fire protection engineering, blast effects, and structural investigations were impaneled on a building performance assessment team (BPAT). This BPAT was sponsored by a partnership of FEMA, SEI/ASCE, the state

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of New York, the New York City Department of Design and Construction, and the Structural Engineers Association of New York. The team was also supported by the National Council of Structural Engineers Associations, the National Fire Protection Association, the Society of Fire Protection Engineers, the American Concrete Institute, the American Institute of Steel Construction, the Masonry Society, the Council on Tall Buildings and Urban Habitat, and the National Institute of Standards and Technology.

The BPAT was to review the damage caused by these events, collect available data, develop understanding of the performance of each affected building, determine the causes of observed behavior, and reveal the need for any further studies that should be performed. In particular, the team studied the immediate effects of the aircraft impact on each tower, the spread of fire following the crashes, the reduction in structural strength caused by the fire, and the mechanism that led to the collapse of each tower. Additionally, the performance of buildings in the immediate vicinity of the towers was studied to determine the effects of damage from falling debris and fires.

A draft of the team's report, World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations—a copy of which was obtained by Civil Engineering—was completed in March; the final report is scheduled for release by FEMA on April 30. What follows is essentially a distillation of portions of the draft that focus on the twin towers.

September 11, 2001, 8:46:26 A.M. EDT—A hijacked 767-200 ER commercial airliner-American Airlines flight 11, which originated in Boston, was bound for Los Angeles, and then was commandeered by terrorists—is flown into the north face of the north tower of New York City's World Trade Center (WTC 1) at a speed of 470 mph. The plane is carrying 92 people—and roughly 10,000 gal of jet fuel. The photographic record of this event will reveal that the entire plane penetrates the north facade before there is visual evidence of flames or an explosion. The fireball that erupts a split second later—sparked by the ignition of a vapor cloud of jet fuel—consumes between 1,000 and 3,000 gal of fuel; the remainder of the burning fuel flows across the impact floors—like an immense spill of lighter fluid on fire—then down the face of the building and down through elevator and utility shafts. It will subsequently be believed that this fuel burned off within a few minutes of impact; however, as it washes across the impacted floors it ignites intense fires that are fed by office furnishings, computers, paper files, and anything else that is combustible—including the flammable contents of the aircraft—and these fires spread through the upper portions of the building. Debris from the aircraft is propelled through the south facade: life jackets and portions of seats will subsequently be found on the roof of the Bankers Trust Building, which is located just south of the World Trade Center complex, between Greenwich and Washington streets, and landing gear will be found at the corner of West and Rector streets, five blocks south of the complex. The passage of this debris through the building causes some degree of damage across the floor plate—damage to perhaps the interior framing, core columns, and framing at the east, south, and west walls; the full extent of the damage inflicted by this passage will never be known, however.

The world's attention is riveted on this scene: What is happening?

The second plane hits.

At 9:02:54 A.M. EDT another hijacked 767-200 ER commercial airliner—United Airlines flight 175, which also originated in Boston, was bound for Los Angeles, and also was commandeered by terrorists—is flown into the south face of the south tower of the World Trade Center (WTC 2) at a speed of 586 mph. This plane is carrying 65 people and, like the plane that has just struck WTC 1, about 10,000 gal of fuel. The photographic record will reveal that this plane penetrates the south facade before there is visual evidence of flames or an explosion; however, this catastrophe unfolds so rapidly that to those observing it firsthand the crash and eruption of the fireballs appear to occur simultaneously. Because of the extraordinary speed at which this plane is traveling, it acts like a gigantic plow, scooping up material as it tears through the building, depositing it in the northeast corner of the structure, and propelling a section of the fuselage, a wheel, and a portion of its landing gear through the north facade and into the streets below.

Here, too, burning fuel flows across the impact floors, down the face of the building and down through elevator and utility shafts, igniting intense fires. And here, too, the movement of debris through the building no doubt causes some degree of damage—possibly to the interior framing, core columns at the southeast corner of the core, and framing at the north, east, and west walls.

The first aircraft struck WTC 1 roughly between the 94th and 98th floors, inflicting extensive damage to the north face of the tower in this area. At least five of the prefabricated, three-column sections that formed the exterior walls broke off in the area where the airplane fuselage and engines impacted, and parts of these sections were thrust inside the building envelope by the impact. Floors locally supported by these exterior wall sections appeared to partially collapse, losing their support along the exterior wall. In areas struck by the outer wing structures, the exterior columns fractured upon impact. Subsequent interpretation of photographic evidence will suggest that between 31 and 36 columns on the north facade were destroyed over portions of a four-story area and that a partial collapse of floors in this area appears to have occurred over a horizontal length of wall of approximating 65 ft; floors in other portions of the building will appear to have remained intact.

The second aircraft struck the eastern half of the south face of WTC 2 approximately between the 78th and 84th floors. Massive damage was inflicted on the south face of the building in the zone of impact. Within the central zone of impact, where the airplane fuselage and engines struck, six of the prefabricated, three-column sections that formed the exterior walls were broken loose of the structure, and some of the building elements were apparently thrust inside the building envelope. As in the impact of the plane on WTC 1, the floors supported by these exterior wall sections appear to have partially collapsed, losing their support along the exterior wall. In the areas impacted by the outer wing structures, the exterior steel columns were fractured on impact. Photographic evidence will subsequently suggest that between 27 and 32 columns along the south building face were destroyed over portions of a five-story range. Partial collapse of floors in this zone appears to have occurred over a horizontal length of wall of approximately 70 ft; floors in other portions of the building appear to have remained intact. It is probable that the columns in the southwest corner of the core also experienced some damage because they would have been in the direct path of the fuselage and port engine.

Subsequent interviews of people who were located on the 91st floor at the time the plane struck will reveal that a significant—but undefined—degree of damage was sustained by framing at the central core. The descriptions these people will provide of the damage they saw at the 91st floor suggest that there was relatively slight damage at the exterior wall of the building and progressively greater damage to the south and east. In particular, they observed extensive debris in the eastern portion of the central core, making it impossible for them to exit from the easternmost stairway. Their observations will suggest the possibility of the immediate partial collapse of framing in the tower's central core. They will also observe debris in the stairways located farther to the west, suggesting the possibility of some structural damage in the northwestern portion of the core framing.

> *Each of the fireballs expanded to its maximum diameter within about two seconds as the expelled fuel dispersed and flames traveled through the resulting fuel/air mixture. If an explosion or detonation had occurred, this expansion would have taken place in microseconds. Preliminary calculations suggest that the resulting overpressures were less than 1 lb per square inch (PSI). Although this pressure was sufficient to extensively break windows on the affected floors, it should not have resulted in significant structural damage.*

The impacts from the aircraft have substantially degraded the towers' ability to withstand additional loading and have increased the susceptibility of the structures to fire-induced failure. It is likely that the force of the impact and the speed with which debris traveled through the structures compromised the sprayed—on fire protection of some of the steel members in the immediate areas of the impact. Additionally, some of the columns are now experiencing elevated stress due to the transfer of load from destroyed and damaged elements, and portions of the floor framing directly beneath the partially collapsed areas are carrying a substantial degree of additional weight from the resulting debris—in some cases, carrying greater weight than they were designed to resist.

The fires spread, and there are significant temperature variations throughout those areas where the fires are located, depending on the type and arrangement of combustible material being consumed and the availability of air supporting combustion. The advancing fires elevate the temperature within the tower. Future estimates will place it between 1,700º and 2,000ºF—further stressing the structure. At the 80th floor of WTC 2—in the northeast corner, where office furnishings had been deposited by the rapid path of the plane—the fire burns at such a high temperature that a stream of molten metal begins to pour over the side of the tower. The heat output from these fires will later be estimated to have been comparable to that produced by a large nuclear generating station. Over a period of many minutes, this heat induces additional stresses on the damaged structural frames while simultaneously softening and weakening these frames.

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Damage inflicted by the impacts and the rapid movement of debris through the impacted floors has most likely impaired the sprinkler and fire standpipe systems, thus preventing the effective operation of both the manual and automatic fire-suppression systems. However, even without this damage these systems would have rapidly depressurized as a result of the opening of numerous sprinkler heads initiated by the flash fires of jet fuel, rendering them ineffective.

As the fires rage throughout the upper reaches of both towers, the evacuation of the structures progresses as successfully as thought possible given the nature of these incidents. Several building features will be identified as key to the towers' ability to remain standing for as long as they did, enabling most of the buildings' occupants to escape. These include the robustness and redundancy of the steel framing system, the presence of adequate egress stairways that are well marked and lighted, and the rigorous emergency egress training programs provided for building tenants. It will ultimately be determined that 99 percent of the occupants of the floors below the areas of impact survived, largely because the stairways at these levels remained intact and passable. Tragically, those occupying floors within and above the impact areas cannot escape because the stairways in the impact areas have been destroyed. The high percentage of those able to escape may also be attributed—at least in part—to the fact that some physical changes and training programs were put in place following the 1993 bombing of WTC 1. These physical modifications included the placement of photoluminescent paint on the egress paths to assist occupants during egress and the installation of emergency lighting in the stairways. Additionally, some of the occupants of WTC 2 vacate that tower upon learning of the crash of the first plane into WTC 1. The world would later learn the devastating news that a number of survivors who had occupied WTC 2 reported that a message was broadcast over the building's loudspeaker system indicating that WTC 2 was secure and that occupants should return to their offices. While many people did not heed this announcement, there were those who did. The decision would cost them their lives.

It is impossible to extinguish the infernos in both towers, and thus both structures are subjected to severe loading events.

> *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, secondary 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, potentially including buckling in columns or failure of floors.*

> *As the temperature of floor slabs and support framing increases, these elements can lose rigidity and bow into catenary action. As*

catenary action progresses, horizontal framing elements and floor slabs become tensile elements, which can cause failure of end connections 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. 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 a length of several stories.

As the temperature of column steel increases and the modulus of elasticity degrades, the critical buckling strength of the columns will decrease, potentially initiating failure, even if lateral support is maintained. This effect is most likely to have been significant in the failure of the interior core columns.

At 9:59:04 A.M. EDT, WTC 2 begins to collapse. Future review of video footage of the event will suggest that the collapse was probably initiated by a partial collapse of the floor in the southeast corner of the building at approximately the 80th floor. This appears to have been followed rapidly by the collapse of the entire floor level along the east side, as evidenced by a line of dust seen blowing out of the side of the building. Once collapse is initiated, the impact of the rapidly accelerating mass of the top part of the structure effects 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 fail, the mass associated with each of these floors joins

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At the 80th floor of WTC 2--in the northeast corner, where office furnishings had been deposited by the rapid path of the plane--the fire burns at such a high temperature that a stream of molten metal begins to pour over the side of the tower.

Large quantities of energy were stored in the buildings during their construction. For example, the construction of WTC 1 resulted in the storage of more than 3×10^{12} J of potential energy over the 1,360 ft height of the structure. Of this, approximately 7×10^{10} J of potential energy was stored in the upper part of the structure—above the impact floors—relative to the lowest point of impact. Once collapse was initiated, this energy was rapidly released and converted into kinetic energy—in the form of the rapidly accelerating mass of the top part of the structure. The impact of this rapidly moving mass onto 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, unleashing further destructive energy on the floors immediately below. This initiated a chain of progressive failure until total collapse of the building ensued.

Subsequent review of aerial photographs of the site taken after the collapse, as well as subsequent 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). The debris pattern spread laterally up to 500 ft from the base of the structure.

At 10:28:31 A.M. EDT, WTC 1 begins to collapse. Future review of videotapes of the event will reveal that the television 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 described of the debris patterns on the 91st floor. It will later be estimated that, prior to the impact from the aircraft, core columns were loaded to approximately 60 percent of their theoretical ultimate capacities. As some exterior and core columns were damaged upon 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 against failure. 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 impact of the aircraft could easily have brought several of these columns close to their ultimate capacity, and thus relatively little additional effect from the fires would have been required to initiate the collapse.

Once movement begins the entire portion of the building above the area of impact falls in a unit, pushing a cushion of air below it. As this cushion of air is pushed through the impact area, fires burning in that area are fed by new oxygen and are pushed outward, creating the illusion of a secondary explosion. Although the tower appears to collapse in its own footprint, subsequent review of aerial photographs of the site after the collapse—as well as damage to adjacent structures—will suggest 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. The debris field extended as far as 500 ft from the tower base.

> *The structural damage sustained by each of the two buildings as aircraft impacted them 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 massive damage, are generally not considered in building design, and the fact that these structures were able to successfully withstand such damage is noteworthy.*

> *Preliminary analyses of the damaged structures, together with the fact that the structures remained standing for an extended period of time, suggest that absent severe loading events, such as a windstorm or earthquake, the buildings could have remained standing in their damaged states indefinitely. However, the structures were subjected to a severe loading event in the form of the fires caused by the aircraft impacts.*
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> *The ability of the two towers to withstand aircraft impact without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse as 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.*

The BPAT determined that 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 identical for both towers, but the timing was not. In each case the first event was the initial impact of a Boeing 767-200 ER series commercial aircraft into the building combined with a fireball resulting from immediate rapid ignition of the fuel on board the aircraft. Boeing 767-200 ER aircraft have a maximum rated takeoff weight of 395,000 lb, a wingspan of 156 ft 1 in., and a rated cruise speed of 530 mph. The aircraft are capable of carrying up to 23,980 gal of fuel, and it is estimated that at the time of impact, each aircraft had approximately 10,000 gal of unused fuel on board.
In each attack the aircraft impacts resulted in severe structural damage, including some localized partial collapse, but that damage did not result in the initiation of global collapse. In fact, WTC 1 remained erect for a period of approximately 1 hour and 42 minutes following the impact of the aircraft; WTC 2 remained standing for approximately 57 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 loss of strength leading to a progressive sequence of failures—the third event—which culminated in the total collapse of both structures.

Collapse of the twin towers astonished most observers, including many knowledgeable structural engineers. These were structures notable for their robust, redundant framing systems. Many believed that their structural anatomy would have enabled them to withstand the attacks. The twin towers of the World Trade Center were the primary components of the seven-building World Trade Center complex, and although they were similar, they were not identical. Each of the towers encompassed 110 stories above grade and 6 levels below. WTC 1 had a roof height of 1,368 ft; WTC 2 was nearly as tall, with a roof height of 1,362 ft. WTC 1 also supported a 360 ft tall television and radio transmission tower. Each building had a square floor plat 207 ft 2 in. long on a side. Corners were chamfered 6 feet 11 in. Nearly 1 acre of floor space was provided at each level. A rectangular service core with overall dimensions of approximately 87 by 137 ft was present at the center of each building, housing three exit stairways, 99 elevators, and 16 escalators.

The service core in WTC 1 was oriented east to west; the core in WTC 2 was oriented north to south. In addition to these basic differences in configuration, the presence of each building affected the wind loading on the other structure, resulting in a somewhat different distribution of design wind pressures and, therefore, somewhat different structural design of the lateral-force-resisting system. In addition, tenant improvements over the years resulted in the removal of portions of floors and the placement of new, private stairways between floors, in a somewhat random pattern.

The towers' signature architectural design feature was the vertical fenestration, the predominant element of which was a series of closely spaced tubular columns. At typical floors, a total of 59 of these perimeter columns were present along each of the flat faces of the building. These tubular columns were built up by welding four plates together to form a section approximately 14 in. square spaced at 3 ft 4 in. on center. Adjacent perimeter columns were interconnected at each floor level by spandrel plates with a typical depth of 52 in. 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.

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 that were interconnected by the spandrel plates using all-welded construction. Cap plates were provided at the tops and bottoms of each column to permit bolted connections to the modules above and below. Access holes were provided at the inside face of the columns to permit these high-strength bolted connections to be made. Connection strength varied throughout the building, ranging from four bolts at upper stories to six bolts at lower stories. Supplemental welds were also utilized near the building base.

Side joints of adjacent modules consisted of high-strength bolted shear connections between the spandrels at midspan. Except at the base of the structures, horizontal splices between modules were staggered in elevation so that no more than one-third of the units were spliced in any one story. In those cases where the units were all spliced at a common level, supplemental welds were used to improve the strength of these connections. At the building base, adjacent sets of three columns tapered to form a single massive column in a forklike formation.

Twelve grades of steel, varying in yield strength from 42 to 100 kips per square inch (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 along the building perimeter—to accommodate the predicted loads and minimize differential shortening of columns across the floor plate. In the upper stories of the building, the plate thickness in the exterior wall was generally 1/4 in. At the base of the building, plates as thick as 4 in. were utilized.

Once movement begins the entire portion of the building above the area of impact falls in a unit, pushing a cushion of air below it. As this cushion of air is pushed through the impact area, fires burning in that area are fed by new oxygen and are pushed outward, creating the illusion of a secondary explosion.

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, a consequence of the combined effects of the short spans and significant depth, made for a structural system that was rigid 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 sidewalls acted as the webs of the tube and transferred shear between the windward and leeward walls through Vierendeel action. As a result of this behavior, the structural frame is considered to constitute a tubular system.

Floor construction typically consisted of 4 in. of lightweight concrete fill on 11/2 in., 22-gauge corrugated metal deck. Outside the central core, the floor deck was supported by a series of composite floor trusses that spanned the distance between the central core and the exterior wall. Detailing of these trusses was similar to that employed in open-web joist fabrication; in fact, the trusses were manufactured by a joist fabricator. However, the floor system design was not typical of open-web joist floor systems and was considerably more robust. Trusses were placed in pairs, with a spacing of 6 ft 8 in. and spans of approximately 60 ft to the sides and 35 ft at the ends of the central core. The metal deck spanned parallel to the joists and was directly supported by continuous transverse trusses spaced at 13 ft 4 in. and bridging spaced at 6 ft 8 in. The combination of main trusses, transverse trusses, and bridging enabled the floor system to act as a continuous flat plate to distribute load to the various columns.

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 tied the pairs of joists 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.

Floors were designed for a uniform live load of 100 psf over a 200 sq ft area with allowable live-load reductions elsewhere.

At approximately 10,000 locations in each building, viscoelastic dampers extended between the lower chords of the joists and gusset plates mounted on the exterior columns beneath the stiffened seats. These dampers, the first application of this technology in a high-rise building, were intended 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 joists.

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

Between the 106th and 110th floors 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. Altogether, 10 outrigger truss lines were present in each building, 6 extending across the long direction of the core and 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 designed to support such a tower.

A deep subterranean structure was present beneath the WTC plaza 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 along the extended alignment of West

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Broadway on the east, was 70 ft deep and had six subterranean levels. The structure housed a shopping mall as well as building mechanical and electrical plant, 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, placed over a period of several hundred years to displace the adjacent Hudson River shoreline and create additional usable land area. When the decision was made to build the World Trade Center complex, the eventual perimeter walls for the subterranean structure were built using the slurry wall technique. After the concrete wall was cured and had 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 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 then 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 granite 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.

Damage inflicted by the impacts and the rapid movement of debris through the impacted floors has most likely impaired the sprinkler and fire standpipe systems, thus preventing the effective operation of both the manual and automatic fire-suppression systems.

In its analysis of the performance of WTC 1, the BPAT noted that the building's structural system, which comprised the exterior load-bearing frame, the gravity-load-bearing frame at the central core, and the system of deep outrigger trusses in the upper stories, was highly redundant. This enabled the building to limit the immediate zone of collapse following the impact of the aircraft to the area where several stories of exterior columns were destroyed by the initial impact. Following the impact, floor loads originally supported by the exterior columns in compression were successfully transferred to other load paths. Most of the load supported by the failed columns is believed to have been transferred to adjacent perimeter columns through the Vierendeel behavior of the exterior wall frame. Preliminary 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 columns appear to have had substantial overstrength for gravity loads. Neglecting the potential loss of lateral support resulting from collapsed floor slabs, the most heavily loaded columns were probably at—but not over—their ultimate capacity. Columns located farther from the impact zone remained substantially below their ultimate load levels. 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 stress from P-delta effects. Also, exterior columns above the zone of impact were to some extent 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 and was transferred back to the interior core columns. The outrigger trusses would also have been capable of transferring some of the load carried by damaged core columns to adjacent core columns.

Following the impact of the aircraft the structure was able to successfully redistribute the building weight to the remaining elements and to maintain a stable condition. However, the structure's strength was severely degraded. Although the structure could have remained standing in this weakened condition for an indefinite period, it had limited ability to resist additional loading and could have collapsed as a result of any severe loading event, such as that produced by high winds or earthquakes. In this case, the first extreme event encountered was that of the fires that followed the impact of the plane.

> *Buildings are designed to withstand loading events that are deemed credible hazards and to protect the public safety during such events. Buildings are not designed to withstand all events that could ever conceivably occur. Any building can collapse if subjected to a sufficiently extreme loading event. Communities adopt building codes to assist building designers and regulators in determining load events that should be considered in the design process. These building codes are developed by the design, regulation, and public policy communities 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. Consequently, building codes do not require that such events be considered in building design. Nevertheless, at the owner's request design of the WTC towers did include some consideration of an aircraft impact, albeit by a somewhat smaller and slower-moving aircraft than those actually involved in the September 11 events. This consideration of aircraft impact did not include consideration of any postcrash fire.*

Building codes do regard fire as a credible hazard and include extensive requirements to control the spread of fire throughout buildings, to facilitate the safe egress of building occupants in a fire event, and to delay the onset of fire-induced structural collapse. For fire-protected steel-frame buildings such as WTC 1 and WTC 2, these code requirements had been deemed effective. Prior to September 11, there was no record of fire-induced collapse of such structures, despite some very large uncontrolled fires. However, these other buildings did not suffer extensive structural damage.

The ability of the WTC towers to withstand aircraft impacts without immediate collapse was a direct result of their design and construction characteristics. These characteristics also explained their vulnerability to collapse as a result of the combined effects of the impacts and ensuing fires. Many buildings would have been more vulnerable to collapse than the two towers, and few would have been less vulnerable.

The building features identified as key to the towers' ability to remain standing as long as they did and to allow the evacuation of most building occupants have been discussed. Similarly, several design features have been identified that may have played a role in the towers' mode of collapse and the inability of occupants at and above the impact floors to safely exit. These features should be regarded neither as design deficiencies nor as features that should be prohibited in future building codes. Rather, they should be subjected to a careful evaluation to understand their contribution to the performance of these buildings and how they may perform in other buildings. The features in question include the following:

- Steel floor trusses used as the primary horizontal framing elements for floor systems outside the structural core and their structural robustness and redundancy compared with other construction;
- Gypsum-board-sheathed walls in stairwells and shafts for impact resistance and as vertical fire separation between building floors;
- Spray-applied fire protection materials on steel framing and the adequacy of these materials to provide protection for the steel frame;
- Emergency egress stairways grouped in the central building core, as opposed to being dispersed throughout the structure.

During the course of this study, the question whether building codes should be changed in some way to make future buildings more resistant to airplane attacks was frequently explored. It may be technically feasible to develop design provisions that would reliably enable structures to survive the effects of impacts by aircraft, as well as the ensuing fires, without collapse. The likelihood of such attacks on most buildings, however, is deemed sufficiently low by the BPAT that inclusion of such

The ability of the WTC towers to withstand aircraft impacts without immediate collapse was a direct result of their design and construction characteristics. These characteristics also explained their vulnerability to collapse as a result of the combined effects of the impacts and ensuing fires.

requirements in building codes is not recommended. However, some individual building developers may wish to consider provisions for improved redundancy and robustness for such hazards, particularly for buildings that by the nature of their design or occupancy may be especially susceptible to such incidents. No other particular changes to the building codes to make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study. Future building code revisions may be considered once the technical details of the collapses and other building responses to damage are better understood. The scope of this study was not without limits, and many issues should be explored before final conclusions are reached. Additional study of the performance of WTC 1 and WTC 2 during the events of September 11, 2001, is warranted, together with an investigation of related building performance issues. In any such studies attention should be given to the following points:

1. 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 on each building should be conducted in order to better understand the probable damage state immediately following the impacts.
2. Preliminary studies of the growth of the fires and of their heat flux have been carried out. Although these studies provided useful insight into building behavior, they were not of sufficient detail to permit an understanding of the probable distribution of temperatures in the building as the fires progressed and of the resulting stress state of the structure. Detailed modeling of the fires should be continued and should be combined with structural modeling to develop a more detailed understanding of the likely failure models.
3. The floor framing system for the two towers was very complex and substantially more redundant and robust than typical joist-framed floor systems. Detailed modeling of these floor systems and their connections should be conducted to understand the effects of localized failures and overloads in the floor system and to identify likely ultimate failure modes for this system.
4. The performance during the fire of light steel trusses with spray-applied fire protection and the end restraint conditions typical of the towers is not well understood but is probably critical to the ultimate building failure. A study of the fire
performance of this structural system is definitely in order.
5. Observation of the structural damage to the towers and of their subsequent collapse suggests that the damage to floors reduced the lateral support provided to columns

for structural stability. It is a typical design practice to specify three-hour fire protection and two-hour fire protection for floor members because a floor member failure may result in localized damage but a column failure will affect structural stability. A study should be conducted to determine appropriate levels of fireproofing for members or diaphragms that provide lateral support to column members.

6. Observation of the debris generated by the collapse 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 spray-applied fireproofing materials should be conducted to understand their resistance to mechanical damage and to determine if it is appropriate and feasible to improve their resistance to such damage.
7. Tall buildings have occasionally been damaged in the past, typically by earthquakes, and have experienced partial collapse within the damaged zones. Those structures were able to arrest the collapse before it became total. The World Trade Center towers were also able to resist the initial impact of the aircraft without collapse, but they were unable to do this under the combined effects of fire, structural damage, and damage to fire protection systems. Studies should be conducted to determine whether, given the great size and weight of such buildings, there are feasible design and construction features that would arrest or limit a collapse.

Resources should be directed to airplane security rather than to hardening buildings against airplane impact.
