material should take care to obtain the proper codes and design documents. This case study was previously published (Delatte 2005).

The World Trade Center Attacks

The response of reinforced concrete buildings to terrorist attacks is discussed in Chapter 5, with the cases of the Oklahoma City Murrah Federal Building and of the Pentagon attack on September 11, 2001. The collapse of the twin World Trade Center (WTC) towers on September 11, 2001, provides some insight into the vulnerabilities of steel structures against such attacks. After the event, the Federal Emergency Management Agency (FEMA) conducted an investigation (2002).

Design and Construction

The two World Trade Center towers were the tallest of six buildings on the WTC Plaza Complex in New York City. Construction started on August 5, 1966, and steel erection began in August 1968. The north tower (WTC-1) was occupied starting in December 1970, and the south tower (WTC-2) in January 1972. Each tower was 110 stories tall (FEMA 2002, p. 1-2).

The towers were of similar height, 417 m (1,368 ft) for WTC-1 and 415 m (1,362 ft) for WTC-2 at the roof. WTC-1 also supported a 110-m (360-ft) television and radio transmission tower. The buildings were square, a little more than 63 × 63 m (207 × 207 ft) on a side, providing almost 0.4 hectare (1 acre) of floor space on each level. Each building also had a rectangular service core at the center, 26.5 × 42 m (87 × 137 ft), housing three exit stairways, elevators, and escalators. The service core in WTC-1 was oriented east to west, and that in WTC-2 north to south (FEMA 2002, p. 2-1). Figure 6-6 shows a typical floor plan.

The basic structural form for the building was a tube of closely spaced box columns, with about 59 per face of the building. At each floor, they were connected by 1.3-m (52-in.) deep spandrel plates. The outer steel frame was made of overlapping three-story-tall segments. Splices between segments were staggered, so that no more than one-third of the splices were on any one story. Plate thicknesses and grades of steel were varied to accommodate different loads. Under wind loading, the tube acted similarly to a box beam in flexure, with windward and leeward walls acting as compression and tension flanges connected by a Vierendeel truss web (FEMA 2002, pp. 2-2–2-3). Figure 6-7 shows the outer steel frame, and Fig. 6-8 shows the structural behavior under lateral loading.

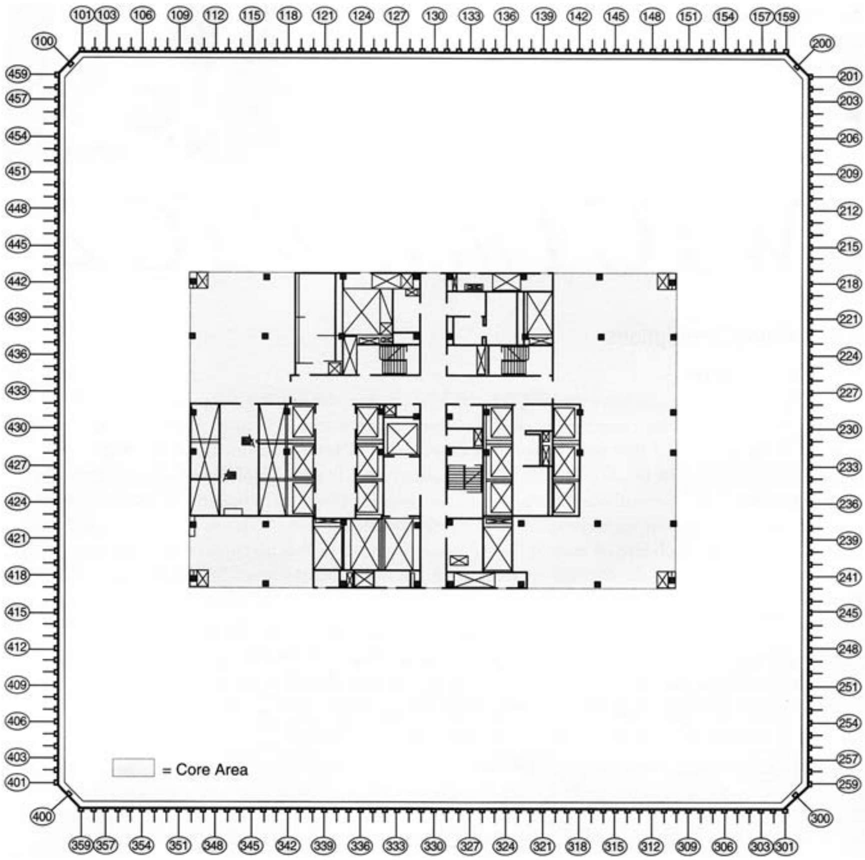

Figure 6-6. WTC typical floor plan.
Source: FEMA (2002).

The floor slab and framing system connected the outer tube to the inner core. The floor was 100-mm (4-in.) thick lightweight concrete on 38-mm (1½-in.) noncomposite steel deck. The floor rested on a series of composite floor trusses. The trusses were similar to open web joists but had more redundancy and better bracing. They were placed in pairs, approximately 2 m (6 ft 8 in.) apart. Transverse trusses ran between these main trusses. Truss spans were approximately 18 m (60 ft) to the sides and 10.7 m (35 ft) to the ends of the central cores. The truss top chords were supported at the outer wall in bearing by seats attached to alternate columns, and on seats at the central core (FEMA 2002, pp. 2-3–2-4). Figure 6-9 shows the trusses and end connection details.

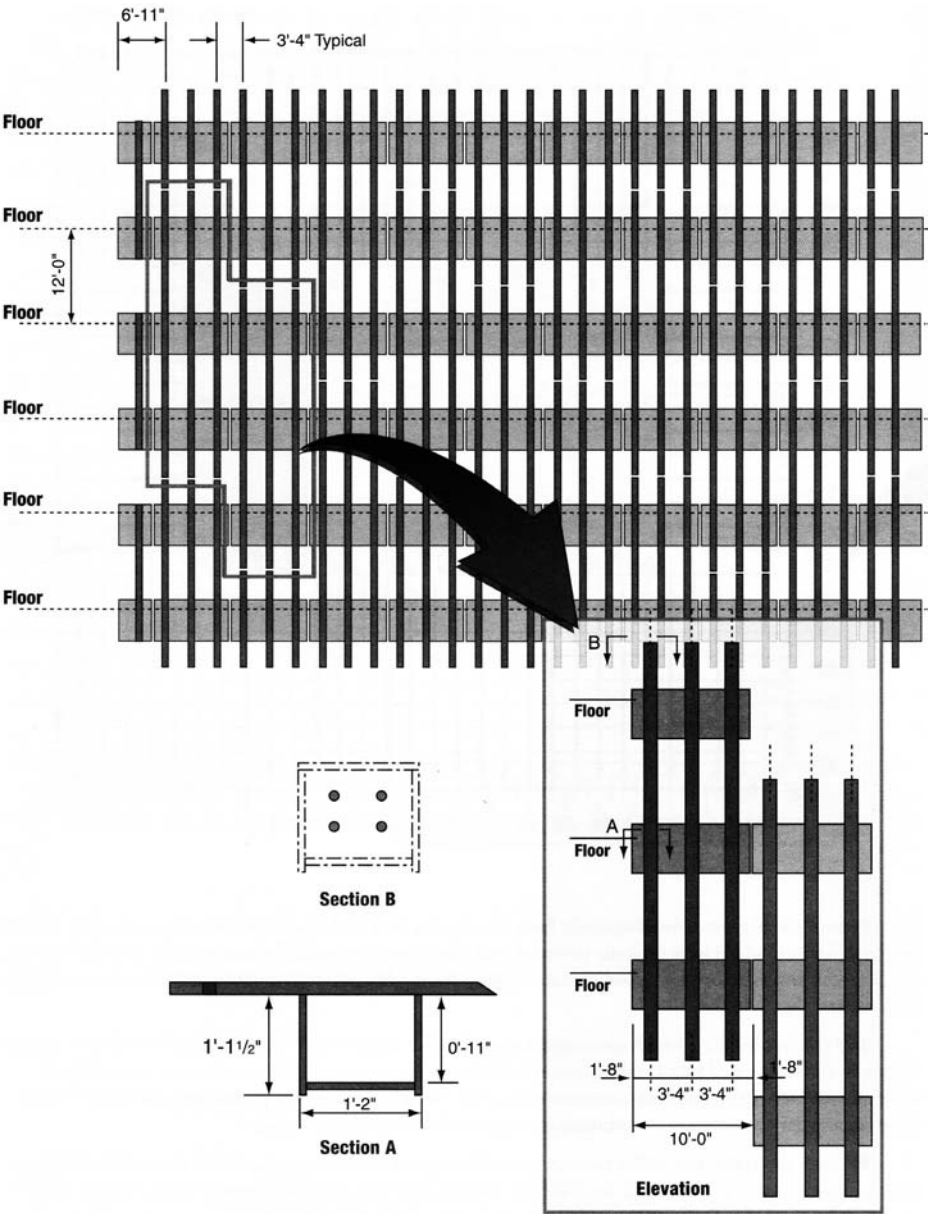

Figure 6-7. WTC bearing wall steel frame.
Source: FEMA (2002).

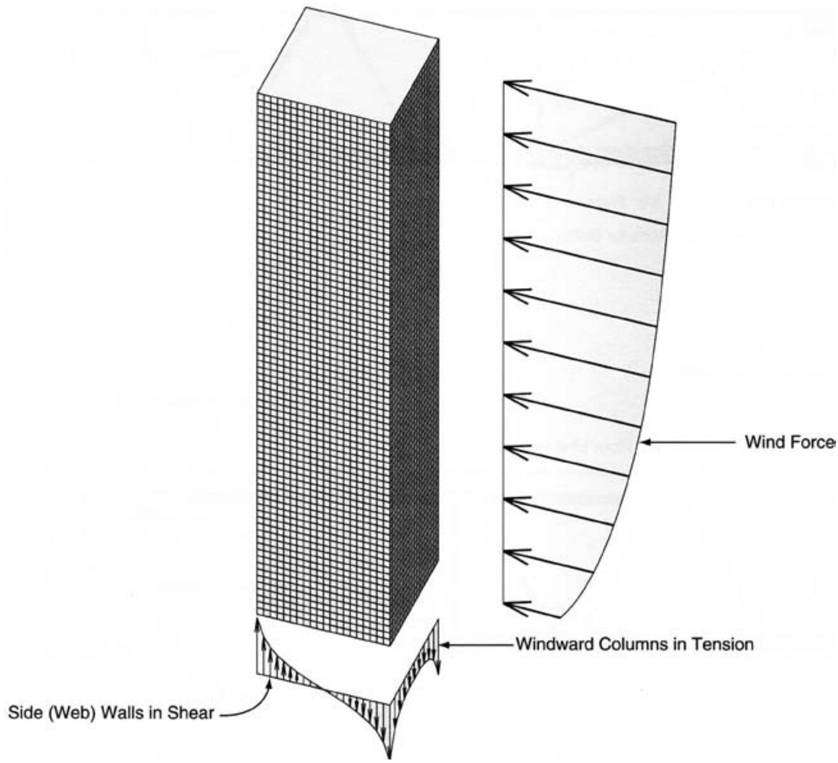

Figure 6-8. WTC structural behavior under lateral loading.
Source: FEMA (2002).

The building was stiffened further against wind loads by a diagonal brace truss system between the 106th and 110th floors. This system coupled the outer tube and the core. On WTC-1, the truss also supported the transmission tower (FEMA 2002, pp. 2-5–2-10).

For most tall buildings, wind forces are the controlling design issue. Ordinary structures are designed using code-proscribed wind loads. However, for important tall buildings, wind tunnel studies are often performed to predict more accurately the wind loads. WTC-1 and WTC-2 were among the first structures designed using wind tunnel studies (FEMA 2002, p. 1-15).

Model design codes do not consider loads that occur because of acts of war or terrorism (FEMA 2002, p. 1-15). In the wake of Oklahoma City and the September 11 incidents, these types of attacks are likely to be considered in the future for some government buildings, particularly overseas, and other potential highly important targets.

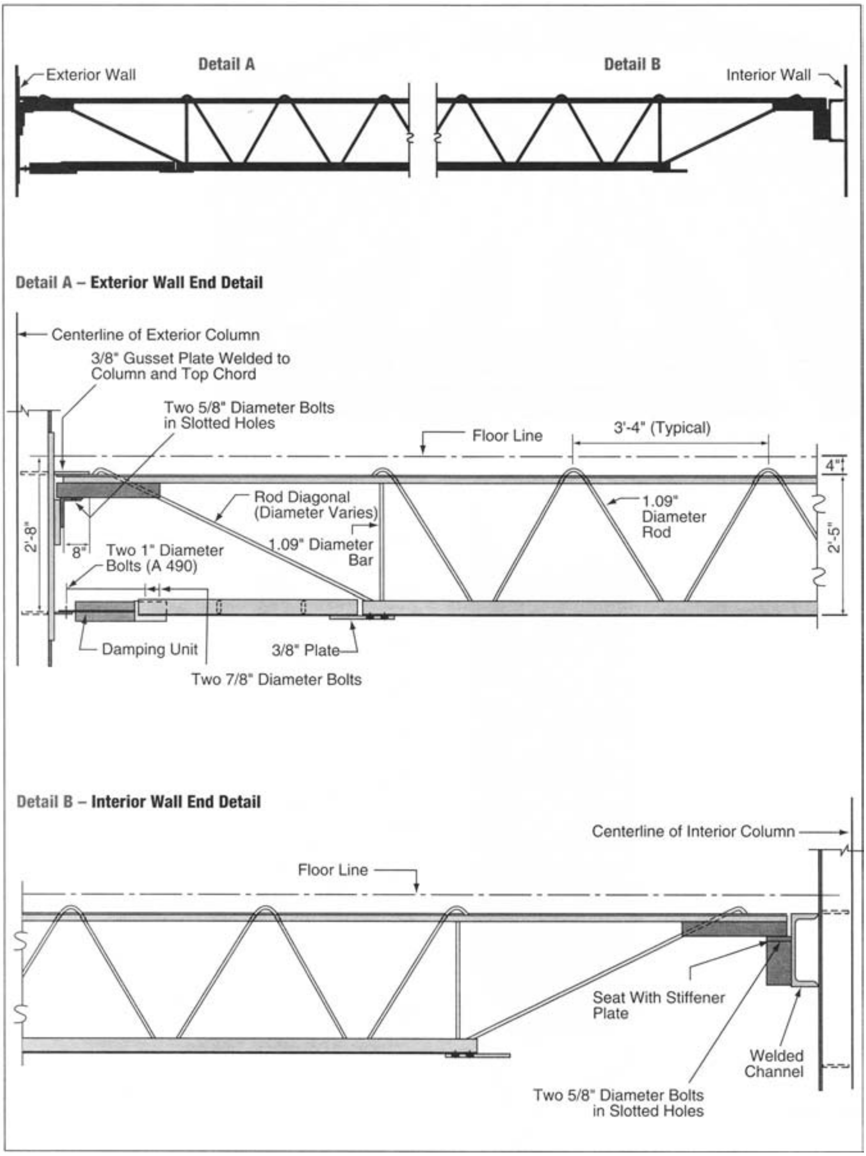

Figure 6-9. WTC trusses and end connection details.
Source: FEMA (2002).

Fire protection is an important element of buildings codes. The first line of defense is automatic sprinkler systems, which are effective for small fires but less so for larger fires, such as those that engulfed WTC-1 and WTC-2 after the aircraft impacts. The second line of defense is firefighters. The effectiveness of firefighting efforts is reduced if fires are high up in the building or if elevators are damaged. The final defense is the inherent fire resistance of the building materials themselves. In particular, the fire resistance of the structural steel is important for preventing collapse during fire. All of these defenses were overwhelmed by the scale of the attack on WTC-1 and WTC-2 (FEMA 2002, p. 1-16).

In WTC-1, a spray-applied fireproofing product containing asbestos had been used up to the 39th floor. The asbestos was later replaced or encapsulated. On the other floors of WTC-1 and throughout WTC-2, an asbestos-free mineral fiber spray product was used. The initial thickness was 19 mm (¾ in.), which was scheduled for upgrade starting in the mid-1990s to 38 mm (1½ in.) as individual floors became vacant. However, at the time of the incident, only 31 floors had been upgraded. Spandrels and girders were specified to have a three-hour fire protection rating, and stair and elevator shafts and stairwells a two-hour rating. The towers had originally been built without sprinkler systems, which were installed starting in 1990. Tanks on the 41st, 75th, and 110th floor provided water into the standpipe system (FEMA 2002, pp. 2-12–2-13).

The towers had actually been designed for an aircraft impact.

> The WTC towers were the first structures outside of the military and the nuclear industries whose design considered the impact of a jet airliner, the Boeing 707. It was assumed in the 1960s design analysis for the WTC towers that an aircraft, lost in the fog and seeking to land at a nearby airport, like the B-25 Mitchell bomber that struck the Empire State Building on July 28, 1945, might strike a WTC tower while low on fuel and at landing speeds. However, in the September 11 events, the Boeing 767-200ER aircraft that hit both towers were considerably larger with significantly higher weight, or mass, and traveling at substantially higher speeds. The Boeing 707 that was considered in the design of the towers was estimated to have a gross weight of [1.16 MN/119 Mg] 263,000 pounds and a flight speed of [290 km/h] 180 mph [mi/h] as it approached an airport; the Boeing 767-200ER aircraft that were used to attack the towers had an estimated gross weight of [1.22 MN/124 Mg] 274,000 pounds and flight speeds of [756 to 950 km/h] 470 to 590 mph on impact. (FEMA 2002, p. 1-17)

The kinetic energy that is transferred to the structure on impact is $\frac{1}{2}mv^2$. With the small increase in mass and considerable increase in velocity, the kinetic energy of the Boeing 767-200ER aircraft was 7 to 11 times that assumed in the design for a slow-moving Boeing 707. Calculations of impact forces are discussed in Chapter 2.

A deep foundation extended under WTC-1 and WTC-2 and the rest of the WTC plaza. The western part, under the towers, was 21 m (70 ft) deep with six underground levels. It was surrounded by a slurry wall, which formed a bathtub to keep water from the Hudson River out. The slurry wall was stabilized by tieback anchors. The subterranean floor slabs provided lateral support to the bathtub structure (FEMA 2002, pp. 2-10–2-11).

The Attack

The FEMA report describes the attack:

> On the morning of September 11, 2001, two hijacked commercial jetliners were deliberately flown into the WTC towers. The first plane, American Airlines Flight 11 . . . crashed into the north face of the north tower (WTC 1) at 8:46 A.M. The second plane, United Airlines Flight 175 . . . crashed into the south face of the south tower (WTC 2) at 9:03 A.M. (FEMA 2002, p. 1-4)

The north tower was hit by a jetliner traveling at approximately 756 km/h (470 mi/h) between floors 94 and 98. The impact caused a huge fireball, spreading jet fuel and igniting fires over several floors. The north tower burned until it collapsed at 10:29 A.M., or 1 hour and 43 minutes after the impact (FEMA 2002, p. 1-4).

The south tower was hit by a jetliner traveling at approximately 950 km/h (590 mi/h) between floors 78 and 84. Thus, the impact on WTC-2 was faster and lower in the structure than that on WTC-1. The south tower also caught fire and collapsed first, at 9:59 A.M., or 56 min after impact. It was estimated that the complex held about 58,000 people at the time of the collapse, and almost everyone below the impact areas was able to escape. The total loss of life was 2,830, including 2,270 building occupants, 157 in the aircraft, and 403 emergency responders (FEMA 2002, p. 1-4).

The collapse of the two structures also severely damaged other nearby buildings, as well as underground services and utilities. One nearby building, the 47-story WTC-7, caught fire and collapsed after burning for seven hours (FEMA 2002, p. 1-8).

The FEMA Investigation and Results

The FEMA Building Performance Study (BPS) team investigation examined the evidence and sequence of events and thoroughly reviewed the structural performance of WTC-1 and WTC-2 during the event, as well as that of other nearby buildings.

Damage and Response of WTC-1

Each tower was subjected to three loading events: the initial aircraft impact, the simultaneous ignition and growth of fires over several floors of the building, and, finally, a progressive sequence of failures leading to total collapse. The impact to WTC-1 broke loose at least five of the three-column assemblies. An estimated 31–36 columns were destroyed over four stories of the building. It also appears clear that the building core experienced significant but undetermined damage. Some aircraft debris passed completely through the structure (FEMA 2002, pp. 2-15–2-16).

Because of the structure's high degree of redundancy, the area of immediate collapse was limited to the general area of the impact. The loads previously carried by the destroyed columns were transferred to alternate load paths, through the Vierendeel truss. The most heavily loaded columns were probably near, but not over, their ultimate capacities. The inherent robustness of the structural system allowed it to remain standing for 1 hour and 43 minutes after the impact (FEMA 2002, pp. 2-16–2-21).

The fires, however, would prove fatal. Each of the aircraft contained approximately 38,000 L (10,000 gal) of jet fuel at the time of impact. Some of the fuel was consumed in a huge fireball on impact, and some remained within the building to fuel the fires. Damage from the impact created openings that provided oxygen for the fires. The impact probably also damaged and disrupted sprinkler and fire standpipe systems. At any rate, so many sprinklers were opened by the fires that the system would have quickly depressurized and become ineffective (FEMA 2002, pp. 2-21–2-23).

The fires imposed structural effects on the damaged building. It is likely that the impact knocked off and damaged some of the insulation protecting the structural steel. As mentioned earlier, some columns were heavily loaded because of the redistribution of forces after the impact. Also, some of the floor framing beneath the partially collapsed area was probably carrying considerable additional weight from the debris (FEMA 2002, p. 2-24).

The specific chain of events leading to the structural collapse will probably never be known, but certain structural effects of fire are likely to have played a part:

- As the floor framing and slabs were heated, they expanded. This effect alone may have caused some structural members or connections to fail.
- With increasing temperature, the floor and slab assemblies became less stiff and sagged into catenary action. Loading from debris would have increased the forces caused by sagging. The sagging imposed tensile forces on horizontal framing and floor elements, possibly causing end connections to fail. Because the floor and slab assemblies braced the exterior columns, as these connections failed, the unbraced length of the columns would have increased and their buckling loads would have decreased substantially.
- As the temperature of steel increases, its yield strength and modulus of elasticity decrease. Therefore, the elastic and inelastic buckling strength is decreased (FEMA 2002, pp. 2-24–2-25).

The final structural collapse was rapid. Although much of the debris stayed within the building footprint, some was scattered as far as 120–150 m (400–500 ft) from the tower base and heavily damaged some adjacent structures (FEMA 2002, p. 2-27).

Damage and Response of WTC-2

WTC-2 was subjected to the same loading events as WTC-1, but it collapsed more quickly. At the location of impact, six three-column assemblies were broken loose. An estimated 27–32 columns were destroyed over five stories of the building on the south building face, with more perhaps at the southeast corner as well. As with WTC-1, some aircraft debris passed completely through the structure, and the building core may also have been badly damaged. The building stood for 56 minutes after the impact (FEMA 2002, pp. 2-27–2-31).

There were, however, important differences between the aircraft impacts on WTC-2 and WTC-1. The higher speed of the aircraft hitting WTC-2 imposed about 60% more energy to the structure, which would have resulted in more severe damage. Also, the area of impact was closer to the corner of the building, and thus damaged two adjacent faces. In addition, the impact on WTC-2 was about 20 stories lower than that on WTC-1, so the columns were carrying substantially higher gravity loads. As a result, the overall structural effect of the impact on WTC-2 was more severe (FEMA 2002, pp. 2-31–2-32).

Before the impact, the outer columns of WTC-2 were estimated to be loaded to 20% of capacity because of gravity loads, and the interior columns to 60%. Wind and deflection were the design considerations for the outer structural frame, not gravity loads. After impact, fires spread through WTC-2 in a similar manner to those in WTC-1 (FEMA 2002, pp. 2-33–2-34).

Damage to Substructure

With the collapse of the two buildings, almost 600,000 tonnes (600,000 tons) of debris fell. The impact punched through the plaza and several of the six levels of substructure, which was partially filled with debris. The damage degraded the support provided to the slurry wall bathtub by the floor slabs. A significant engineering effort proved necessary to tie back and stabilize the wall during debris removal (FEMA 2002, pp. 2-35–2-36).

Overall FEMA Study Findings

The FEMA report assessed overall performance:

> 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. (FEMA 2002, p. 2-36)

Although the buildings withstood the initial attack, they were not able to withstand the severe structural effects caused by the fire loading. The burning fuel was not enough by itself to cause the buildings to collapse, but this fire ignited the building contents. The burning building contents, over time, combined with the structural damage to cause the collapses (FEMA 2002, pp. 2-36–2-37).

Some features of the building design helped the buildings stand long enough and aided the evacuation of most of the inhabitants. These features were the overall robustness and redundancy of the steel frames; the provision of adequate, well lighted and marked egress stairways; and prior emergency exit training for the building occupants (FEMA 2002, p. 2-38).