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Appendix L
INTERIM REPORT ON WTC 7

L.1 BUILDING DESCRIPTION

L.1.1 Purpose

Project 6 addresses the first primary objective of the technical investigation led by the National Institute of Standards and Technology (NIST) of the 47-story World Trade Center (WTC) disaster: to determine why and how WTC 7 collapsed. Specifically, the objective of this Project is to determine the response of structural components and systems to the impact damage and fire environment in WTC 7, and to identify probable structural collapse mechanisms.

L.1.2 Scope of Work

The structural response of WTC 7 to damage from debris and fires is being evaluated to identify possible collapse sequences and critical components that are consistent with the videographic and photographic records, interview accounts by individuals that were in or around WTC 7, and other available data. This work is being conducted in two tasks:

- Task 1, Structural response analysis to identify critical components
- Task 2, Structural analysis of possible collapse initiation hypotheses

The analytical work is being conducted with the assistance of Gilsanz Murray Steficek LLP.

The scope of work under Task 1 includes (a) develop a nonlinear global structural model of WTC 7 and evaluate its performance under design gravity loads, (b) identify credible failure sequences for the structural model with service loads and initial structural damage by analyzing the effect of component failures (that may have occurred directly or indirectly from fires) on the structural system stability, (c) identify dominant failure modes for critical components and subsystems determined in (b) for service loads and elevated structural temperatures, (d) conduct parametric studies of critical subsystems to identify influential parameters, and (e) develop approaches to simplify structural analyses for global modeling and analyses.

Selected technical results and finding for progress on Task 1 (a), (b), and (c) are presented in the following sections: a description of the WTC 7 structural design, observations of damage, fires, and the structural collapse, and the working collapse hypothesis developed to date.

L.1.3 Introduction

WTC 7 was a 47 story commercial office building, completed in 1987. Its location relative to the WTC Plaza is shown in Fig. L–1. It contained approximately 2 million ft^2 of floor area. The overall dimensions of WTC 7 were approximately 330 ft long, 140 ft wide, and 610 ft tall. The typical floor was similar in size to a football or soccer field (see Fig. L–2). The gross floor area was about 75 percent of that contained in the Empire State Building. The building was constructed over a pre-existing electrical substation owned by Con Edison. The original plans for the Con Ed Substation included supporting a high-rise building, and the foundation was sized for the planned structure. However, the final design for WTC 7 had a larger footprint than originally planned. Section L.1.4 describes the WTC 7 foundation.

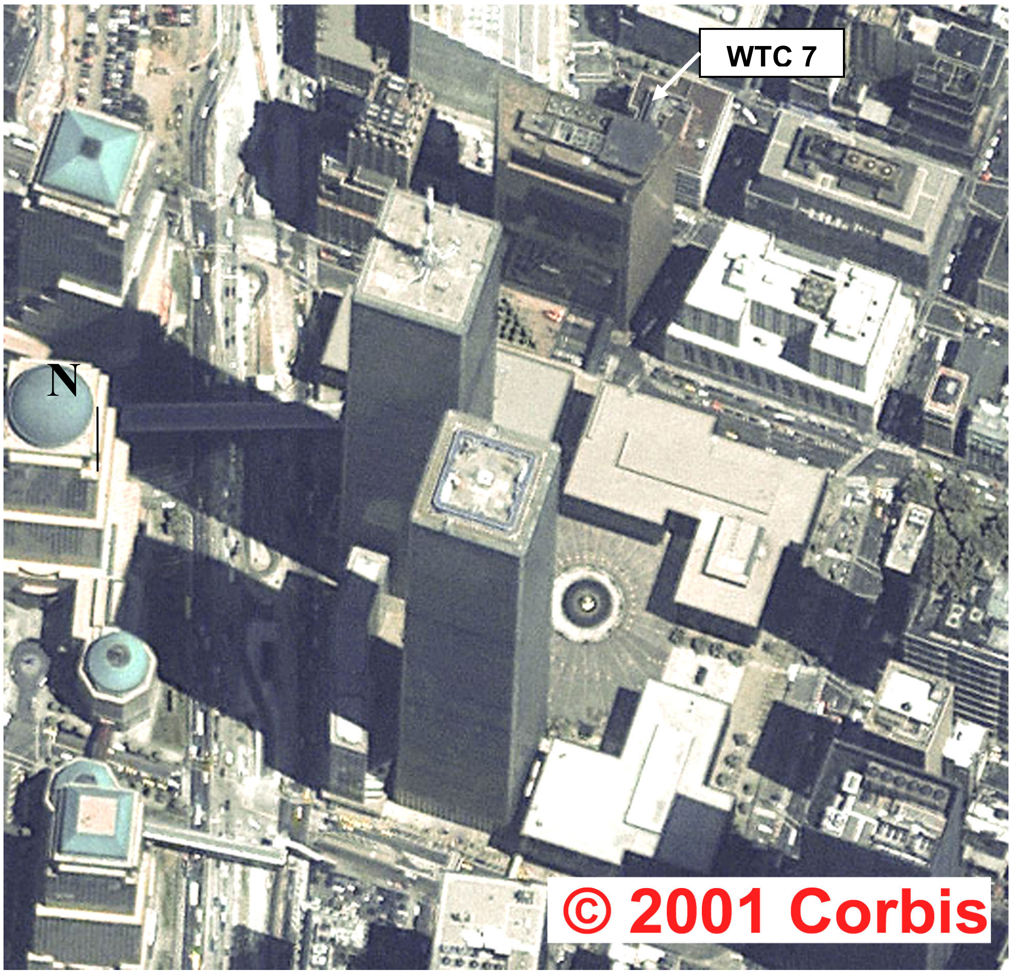
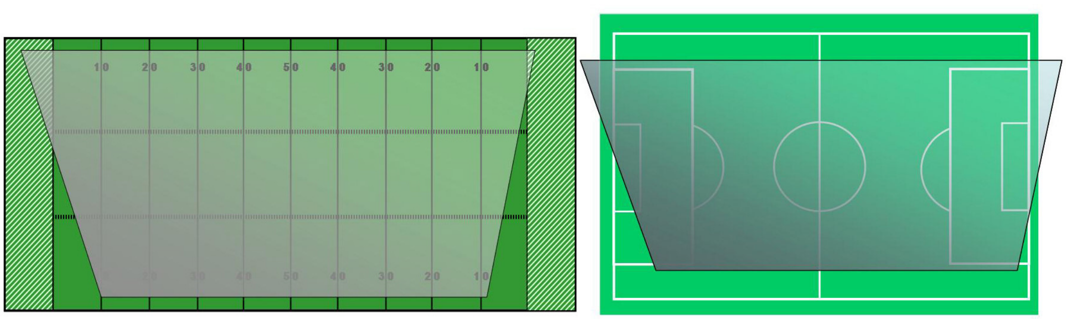


Figure L–1. WTC complex.



A. Comparison to Football Field B. Comparison to Soccer Field

Figure L–2. Size comparison of WTC 7.

WTC 7 was located immediately to the north of the main WTC Complex, approximately 350 ft from the north side of WTC 1. It occupied the block bounded by Vesey Street on the south, Barclay Street on the north, Washington Street on the west, and West Broadway on the east. It was connected to the WTC complex with a 120 ft wide elevated plaza at the Floor 3, and a 22 ft wide pedestrian bridge, also at Floor 3.

Above Floor 7, the building had typical steel framing for high-rise construction. The floor systems had composite construction with steel beams supporting concrete slabs on metal deck, with a floor thickness of 5.5 in. The core and perimeter columns supported the floor system and carried their loads to the foundation. The perimeter moment frame also resisted wind forces. Columns above Floor 7 did not align with the foundation columns, so braced frames, transfer trusses, and transfer girders were used to transfer loads between these column systems, primarily between Floors 5 and 7. Floors 5 and 7 were heavily reinforced concrete slabs on metal decks, with thicknesses of 14 in. and 8 in., respectively. The following sections describe the components and subsystems of WTC 7.

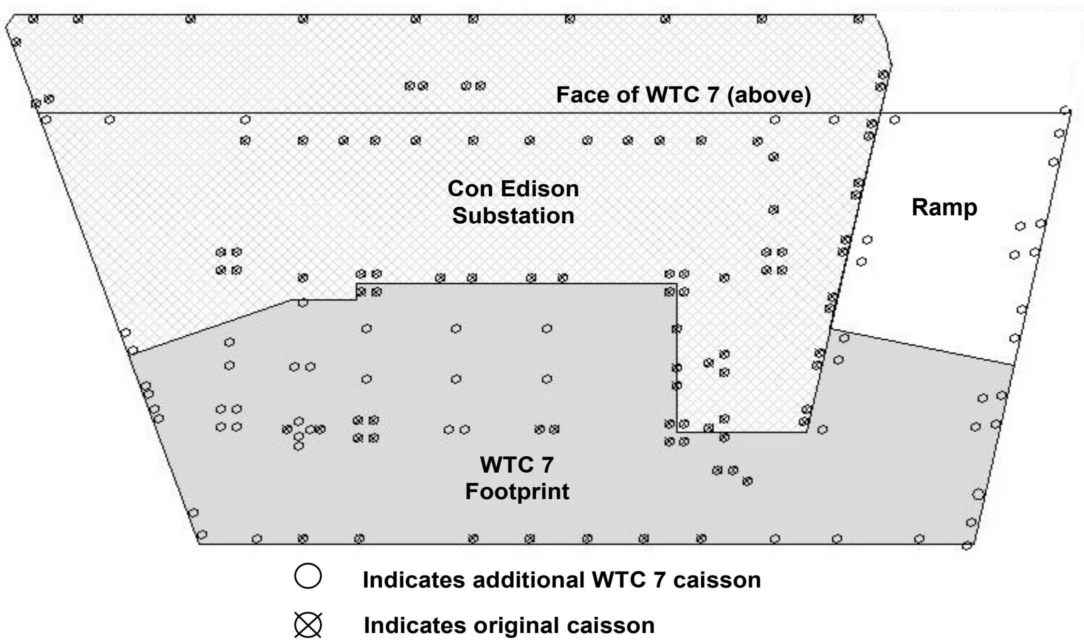
L.1.4 Foundations

WTC 7 and the electrical substation were supported on caisson foundations. When the substation was constructed in 1967, provision was made for a future office tower by including capacity to carry both the substation and the weight of a future building. Caissons were also installed in the property adjacent to the substation, for the proposed future building. When WTC 7 was constructed approximately 20 years later, it was significantly larger than the originally proposed building, and required additional caissons to be installed, as shown in Fig. L–3.

The typical caisson consisted of several components: a 30-in., 36-in., or 42-in. diameter steel casing, a heavy rolled or built-up steel core shape, vertical reinforcing bars, spiral rebar, and concrete fill. At the base of the caisson core, a pattern of shear studs was placed to help transfer the load from the steel caisson core into the encompassing concrete, from which it passed into the rock. The caissons extended through the soil, and were socketed (seated) in the bedrock, approximately 60 ft below the surface. There were vertical caissons as well as battered (or sloped) caissons to carry the lateral load. Above the caissons were heavy grillages composed of built up steel girders. Grillages transferred loads between the building columns and the caissons.

The distance between the caisson grillages and the first floor varied between 8 ft and 30 ft. This region was braced by reinforced concrete walls with thicknesses varying from 1 ft to 2.5 ft. Many of the WTC 7 steel columns were embedded in these walls, and supporting steel braces were made composite by the addition of shear studs along the height of embedment.

Areas between the concrete walls were backfilled with compacted gravel fill and then covered with a concrete slab on grade or framed slab to form closed cells and bring the structure up to the required elevation. In some cases, the area was left unfilled and used to house fuel tanks.



Source: McAllister 2002.

Figure L–3. WTC 7 to foundations.

L.1.5 Con Edison Substation

The Con Ed Substation was constructed in 1967 and consisted of a steel framed structure with cast-in-place concrete floors and walls. It was placed on the northerly portion of the site and extended approximately 40 ft north of the north facade of WTC 7, as shown in Fig. L–4. Its southerly boundary was irregular, but extended approximately one-third to two-thirds of the width of WTC 7. The Con Ed Substation was three stories in height.

The substation's lateral system consisted of a moment frame along the northern row of interior columns. Along the south edge of the substation there was a braced frame. This braced frame was coincident with the north side of the WTC 7 core, at columns 64, 67, 70, and 73. Lateral loads from WTC 7 were passed directly from the core above to the Con Ed braced frame below. There were also two moment frames within the substation oriented in the north-south direction, one on each end of the WTC 7 core.

The WTC 7 columns, which were within the perimeter of the substation, were supported by substation columns. During the construction of WTC 7, heavy plates were welded to the tops of the existing substation columns which then received the new building columns.

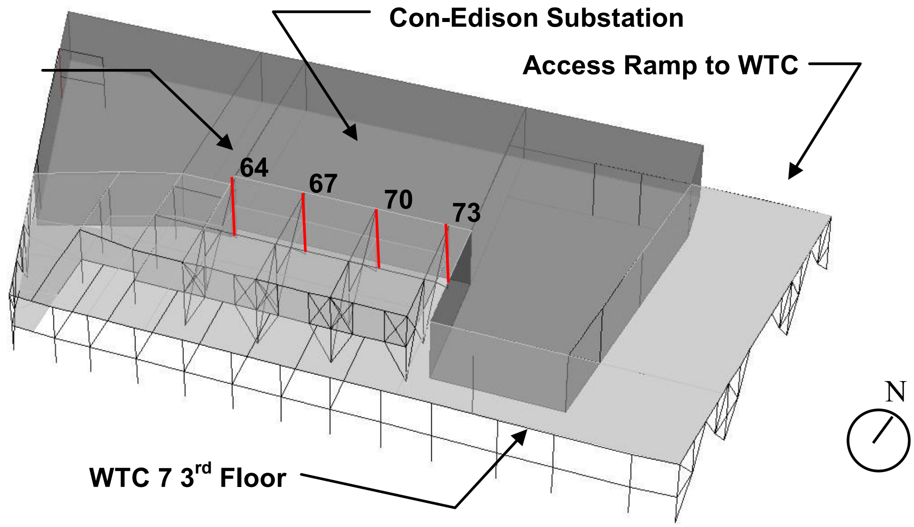


Figure L–4. Con Ed substation location relative to the WTC 7 building.

L.1.6 Floor Systems

Typical Floor Systems Above Floor 7

The typical floor framing system, shown in Fig. L–5, was composed of rolled steel wide-flange beams with composite metal decking and concrete slabs. Floors 8 through 45 had essentially the same framing plan, but the core layout varied over the height of the building.

Floors 8 through 45 had floor slabs that were composed of 3 in., 20 gage metal deck with 2.5 in., 3,500 psi normal weight concrete, for a total thickness of 5.5 in. There was one layer of 6x6 W1.4xW1.4 welded wire mesh within the concrete. The drawings show a second layer of mesh placed over girders at the slab edges. The fastening requirements for the metal deck are not shown on the drawings, but standard practice provides puddle welds 12 in. on-center at the beams and side lap welds, screws, or button-punching at 36 in. on-center between adjacent panels of deck. The drawings contain a note calling for 1.5 in., 20 gage deck with 4 in. concrete topping (5.5 in. total) in the elevator lobbies, where there was a 3 in. floor finish specified by the architect.

Typical floor framing for Floors 8 through 20 and Floors 24 through 45 consisted of 50 ksi wide-flange beams and girders. Between the core columns was a grid of beams and girders. Core girders ranged in size from W16x31 to W36x135, depending on the span and load. (W16x31 describes a steel wide-flange beam, sometimes referred to as ‘I’ beams; the nomenclature indicates the cross-section is nominally 16 in. deep and weighs 31 lb per lineal foot.) Beams spanned directly between the core and the exterior of the building, at approximately 9 ft on-center spacing. On the north and east sides, the typical beam was a W24x55 with 28 shear studs, spanning 53 ft. On the south side, the typical beam was a W16x26 with 24 shear studs spanning 36 ft. Between the exterior columns were moment connected girders that formed part of the lateral system of the building. On Floors 10, 19, and 20, a portion of the floor framing was

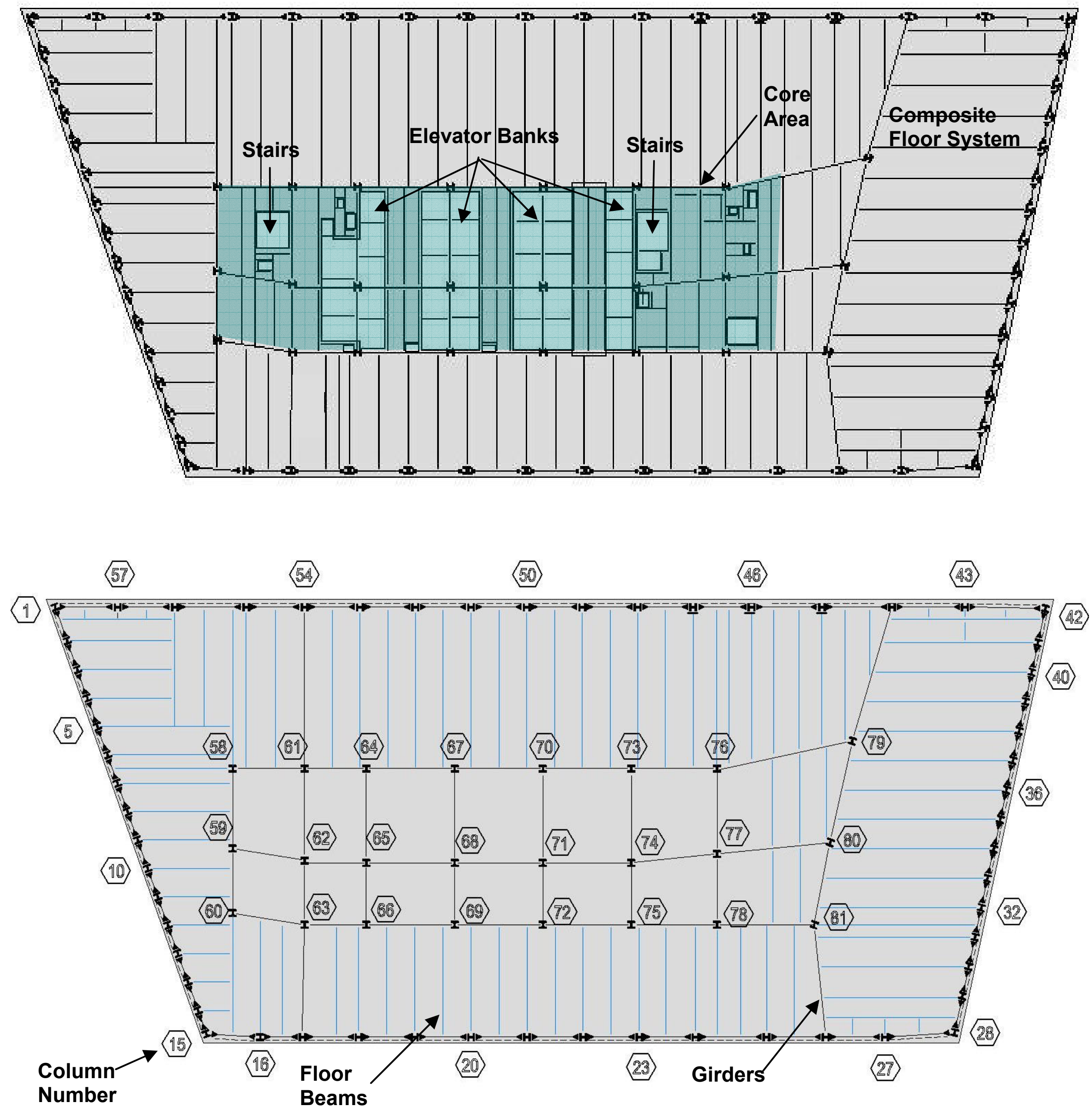


Figure L–5. Floors 8 to 45 plan.

reinforced with plates attached to the bottom flange. Certain connections at these floors were also reinforced.

Floors 21 to 23 had slightly heavier steel framing than the typical floors. Core girders were generally one size class larger than the typical floor; the beams between the core and the south facade were W16x31 instead of W16x26. There were additional studs on the W24x55 beams on the north and west sides.

Most of the beams and girders were made composite with the slabs through the use of shear studs. Typically, the shear studs were 0.75 in. in diameter by 5 in. long, spaced 1 ft to 2 ft on center. Studs were not indicated on the design drawings for many of the core girders. The design drawings specified design forces for connections and suggested a typical detail, but did not show specific connection designs; this is standard practice on the U.S. east coast. The erection drawings indicate that design shear forces for the typical beam and girder connections were to be taken from the American Institute of Steel Construction (AISC) beam design tables for beams without shear studs, using 1.5 times those forces for beams with shear studs.

According to a paper by Salvarinas (1986), who was the project manager for Frankel Steel, which fabricated the steel for WTC 7, the typical floor beam to girder and girder to core column connection was a single shear plate, although end plate and double angle connections were also used. The typical beam to exterior column connection was a seated connection. The typical bolt size for the simple shear connections is cited as 0.875 in. in diameter ASTM A325, where A325 is a standard specification for a structural bolt specified by ASTM International. The bolt size used for heavier brace and moment connections was 1 in. in diameter ASTM A490. Information on the specific connection details used is unavailable at this time.

Other Floors

The remaining floors, Floors 1 to 7 and Floors 46 to 47, were atypical and are described below and in Figs. L–6 through L–15.

Floor 1 was built adjacent to the substation and included the truck ramp for the WTC complex. The first floor is shown in Fig. L–6. The floor was framed with steel beams that were encased in a formed concrete slab. The floor slab was 14 in. thick, with typical #5 reinforcement bars (5/8 in. rebar) at a 10 in. to 12 in. spacing and #6 rebar at 9 in. spacing for the bottom reinforcement; #5 rebar at 12 in. spacing was used for temperature reinforcement. The southeast portion of the floor above the WTC truck ramp had a 6 in. formed concrete slab with #4 rebar at 12 in. spacing for top and bottom reinforcement; #4 rebar at 18 in. spacing was used for temperature reinforcement.

The floor slab for Floors 2, 3, 4, and 6 had a 3 in., 20 gage metal deck with 3 in. 3,500 psi normal weight concrete, for a total thickness of 6 in. Floors 2 and 3 were also partial floors adjacent to the substation. In addition, they had a floor opening on the south side to form the atrium above the ground level lobby (see Figs. L–7 and L–8). Floor 4 was above the substation and had a large opening over most of the south side of the building, to form a double-height space above the 3rd floor lobby (see Fig. L–9). Floor 6 had two openings on the floor to form a double-height mechanical space, one at the east side and the other one at the southeast corner (see Fig. L–12). Truss #2 and column 80 were located in this double-height mechanical space.

The 5th floor slab was 11 in. of 3,500 psi normal weight concrete on top of a 3 in., 18 gage composite metal deck for a total slab thickness of 14 in. The slab was heavily reinforced, with #7 rebar at 12 in. spacing for top reinforcement in both directions and #9 rebar at 12 in. spacing for bottom reinforcement that acted as additional diaphragm chord reinforcement in many areas. This floor also had 36 ksi steel WT sections (W, or wide-flange, sections cut in half to look like a ‘T’ section) embedded in the 11 in. concrete slab above the deck. The WT sections were designed to act as a horizontal truss within the plane of the floor between the perimeter and core columns (see Figs. L–10 and L–11).

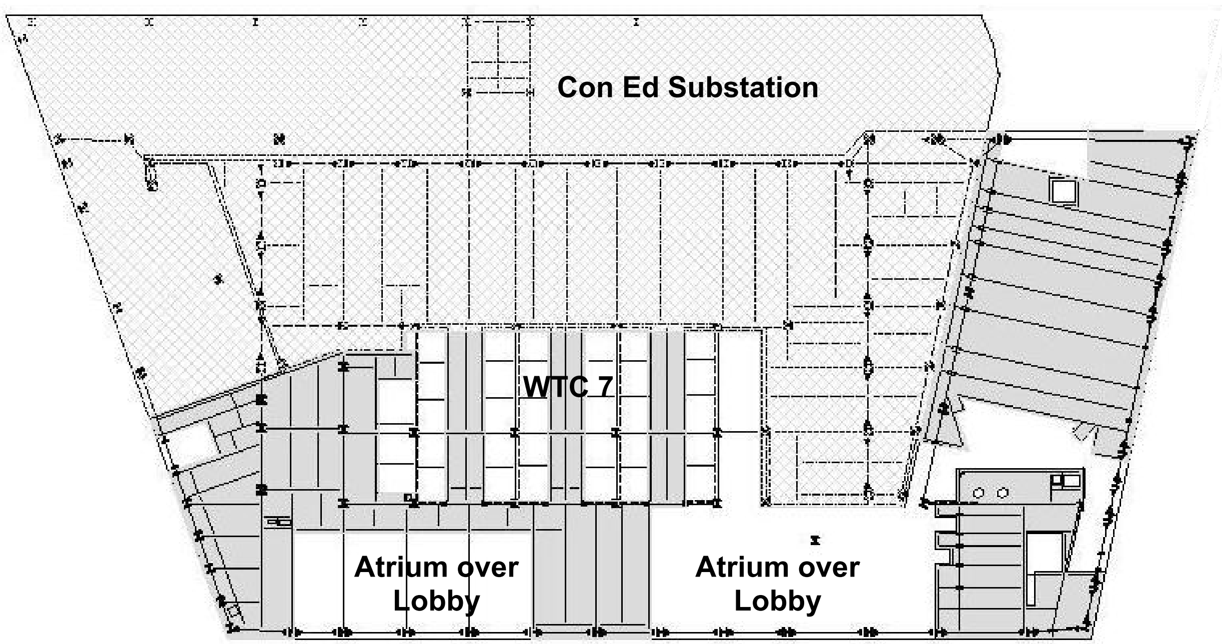


Figure L–6. Floor 1 plan.

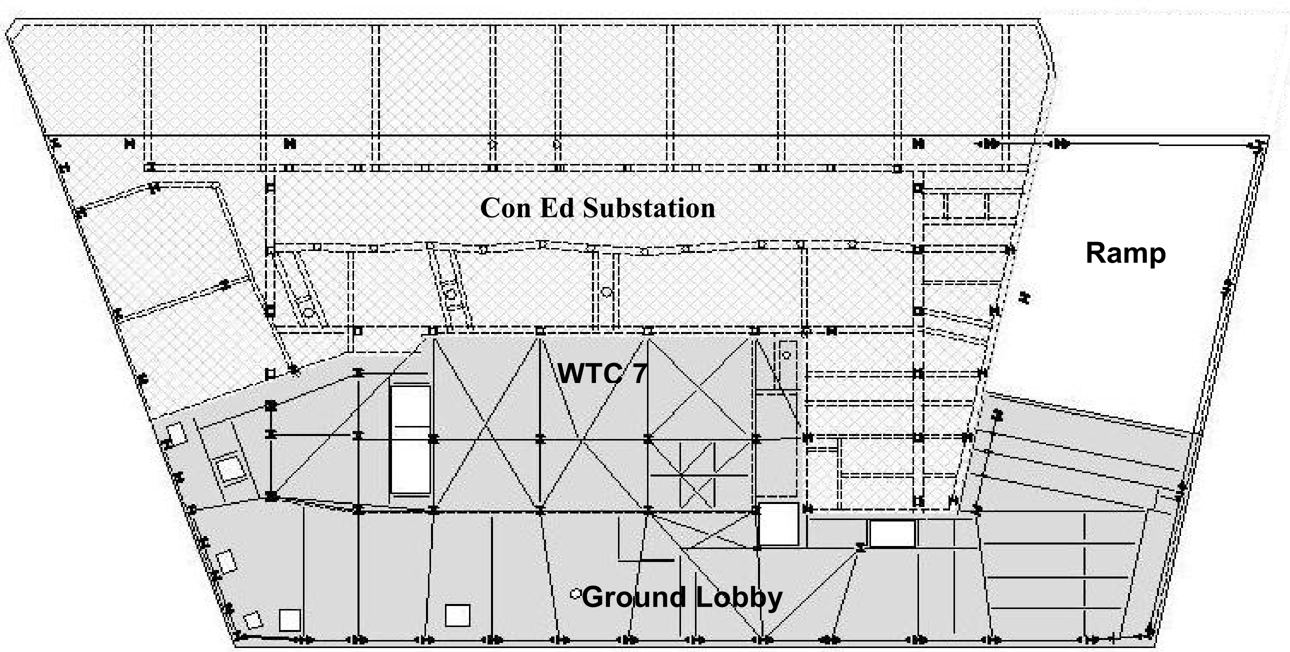


Figure L–7. Floor 2 plan.

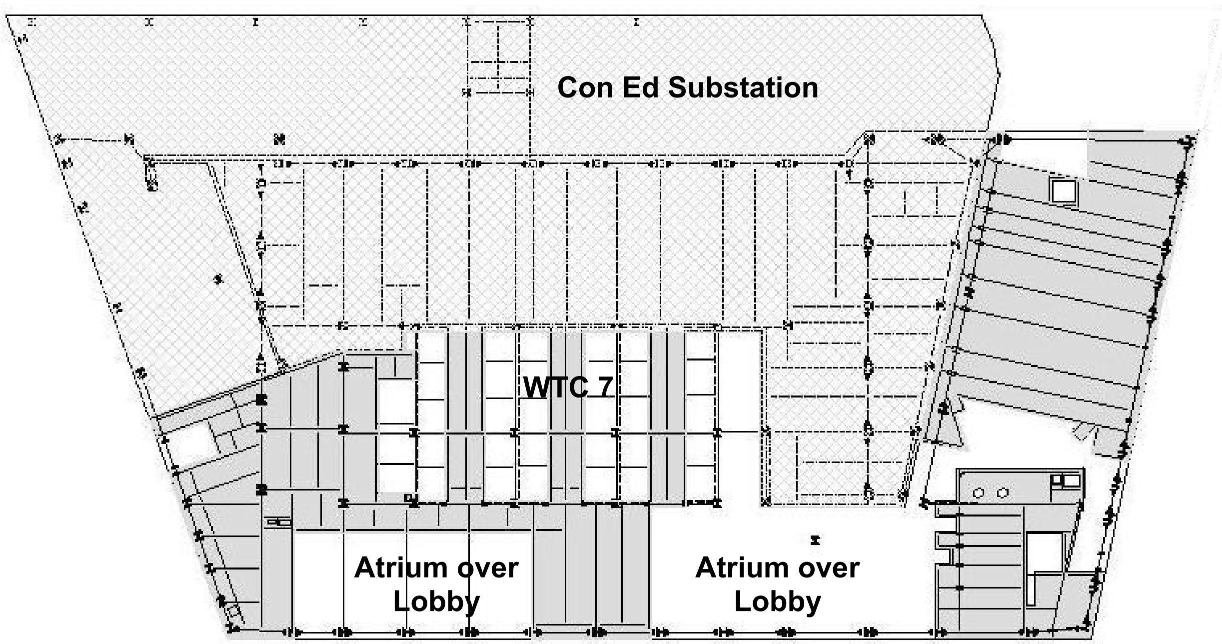


Figure L–8. Floor 3 plan.

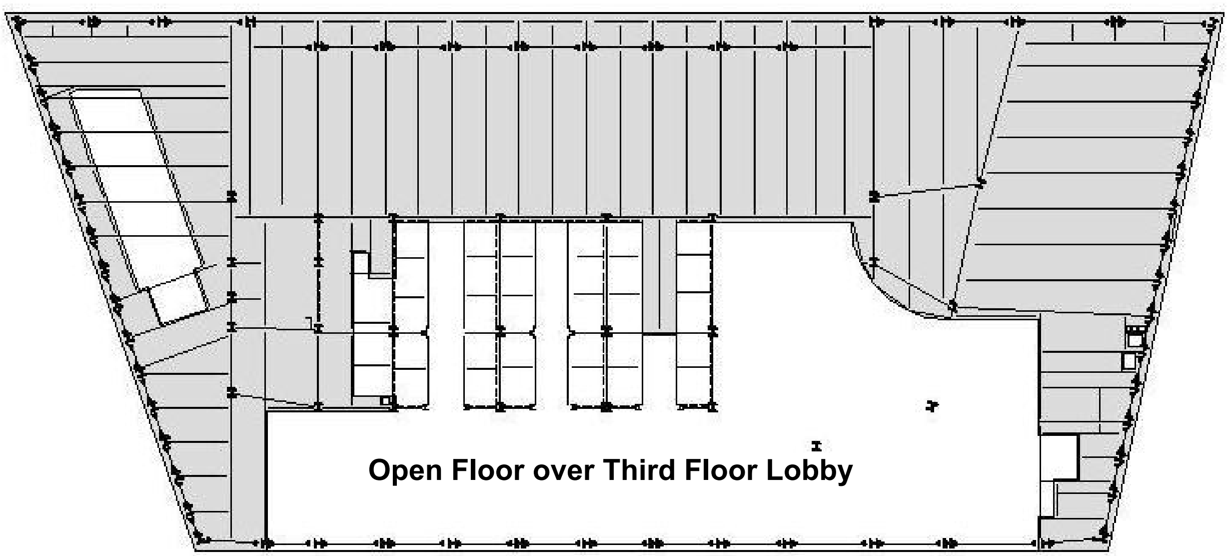


Figure L–9. Floor 4 plan.

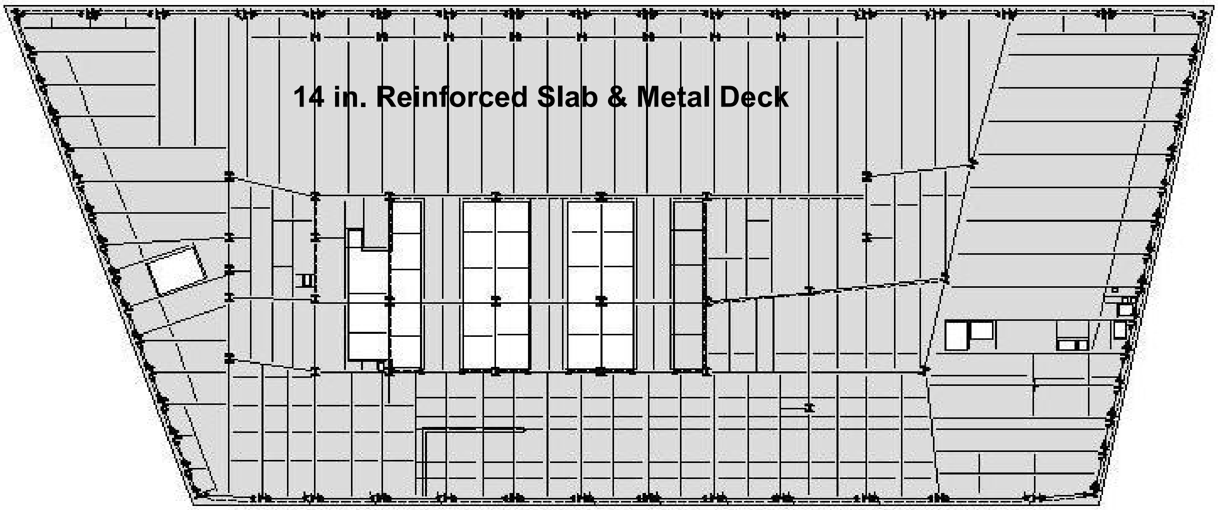


Figure L–10. Floor 5 plan.

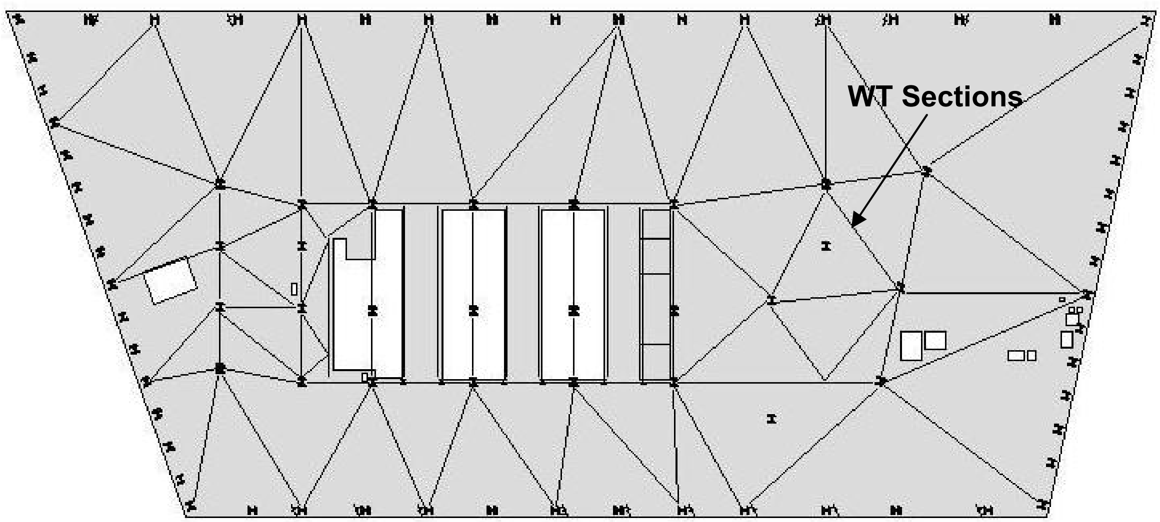


Figure L–11. Floor 5 diaphragm plan.

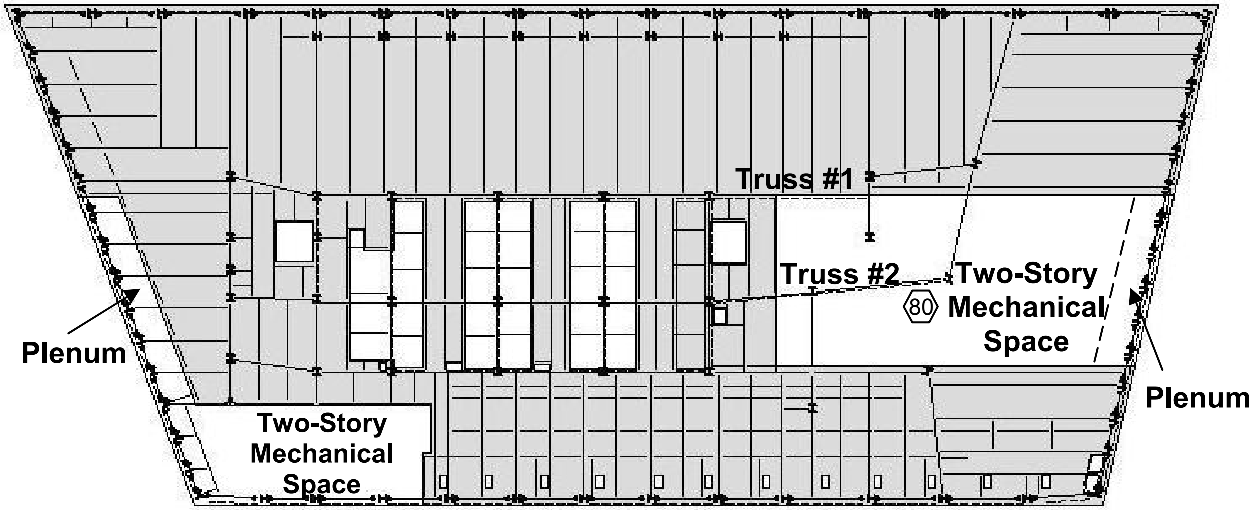


Figure L–12. Floor 6 plan.

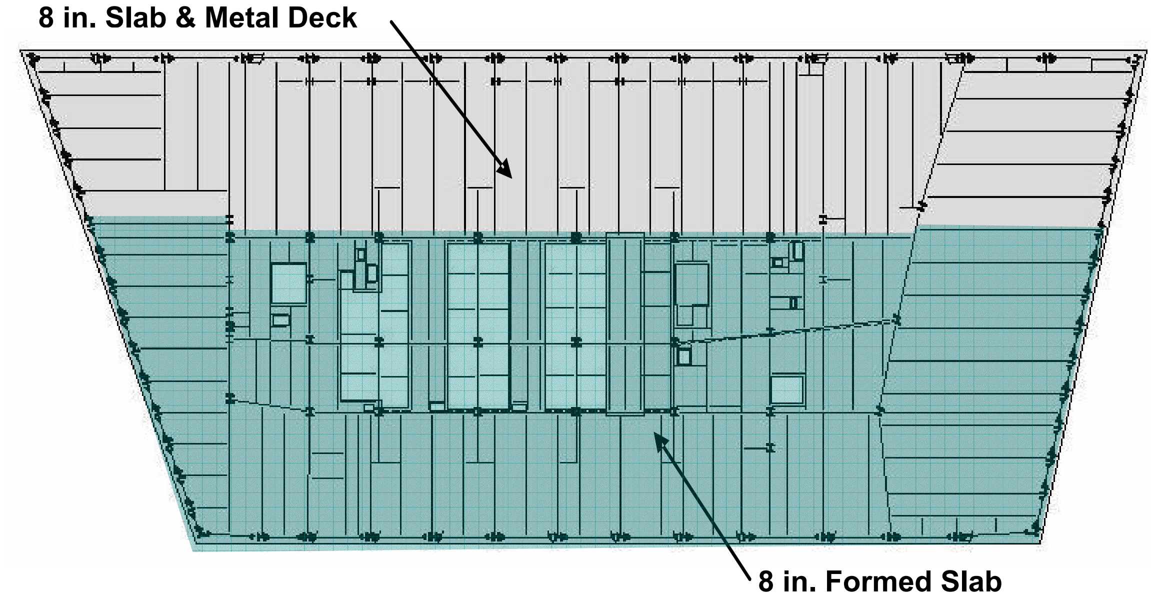


Figure L–13. Floor 7 plan.

The 7th Floor slab consisted of 5 in. of 3,500 psi normal weight concrete on top of 3 in., 18 gage composite metal deck, for a total thickness of 8 in. The slab was reinforced with #5 rebars at 6 in. on-center in both directions. Regions of the slab on the south side of the building had 8 in. of formed concrete without any metal deck. In these regions two layers of steel reinforcing were provided (see Fig. L–13).

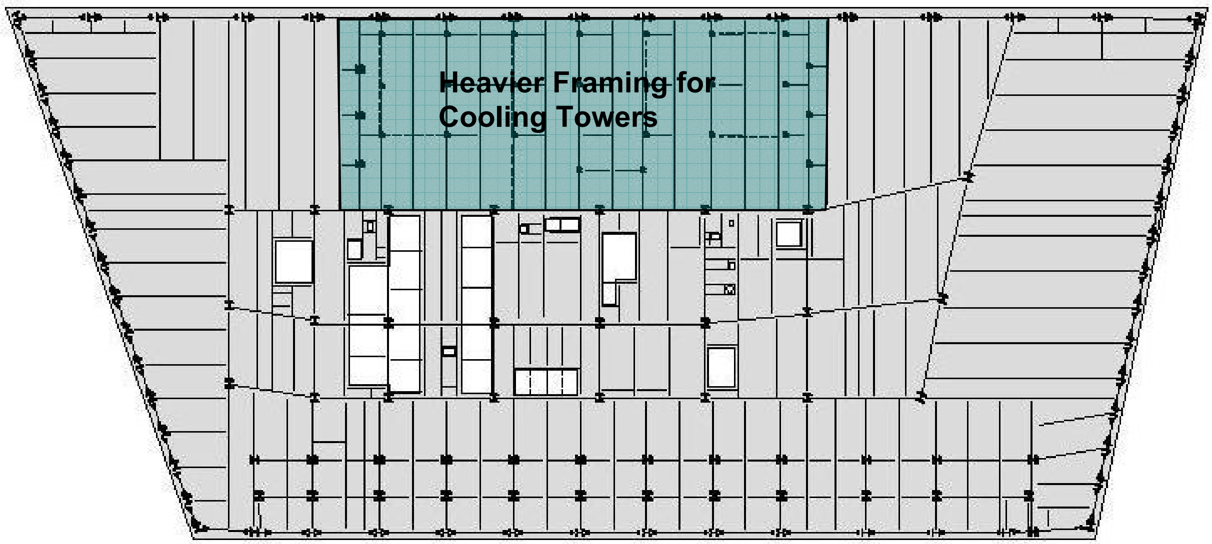


Figure L–14. Floor 46 plan.

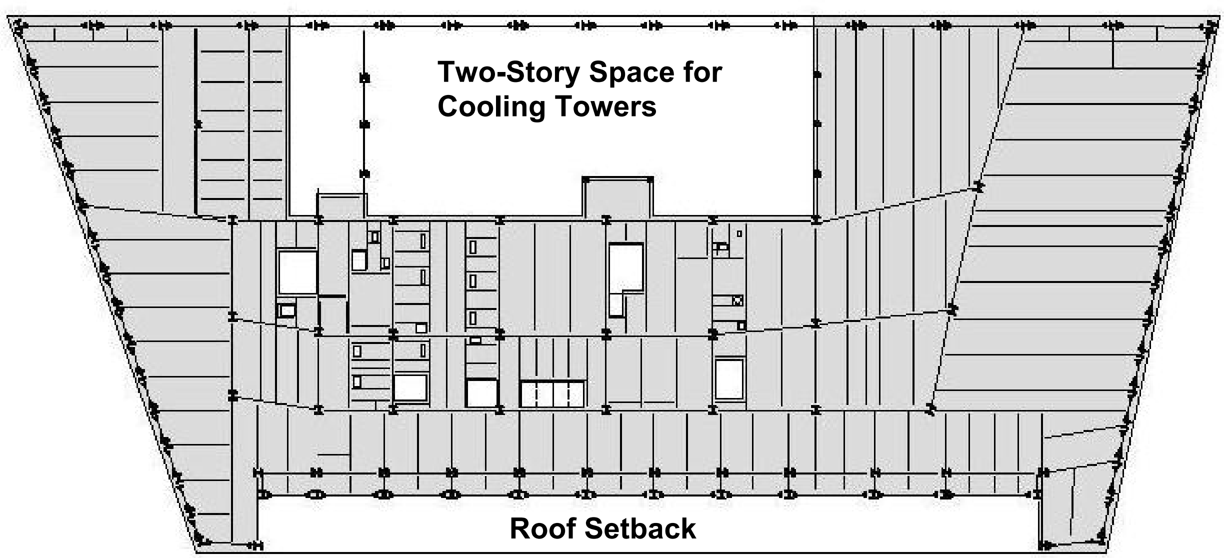


Figure L–15. Floor 47 plan.

Floors 41 and 43 had the east half removed to provide double height spaces. Columns in these areas and areas of Floors 40 and 42 had been reinforced to provide adequate capacity for the additional height and change in use by tenants. By 2001, Floors 41 and 43 had been reconstructed to provide full floor space. Specifics of this reconstruction are not available at this time.

The 46th Floor had heavier framing to support the cooling towers and dunnage on the north side, (alternating W36x150 with W36x260 under the posts) and the setback roof on the south side (alternating W21x44 with W36x150 under the posts). There was a 6 in. reinforced concrete slab in a portion of the core and under the cooling towers (see Fig. L–14).

Floor 47 had a double height space extending from the 46th Floor to the underside of the roof for the cooling towers on the north side. There was also a setback roof on the south side at Floor 46 (see Fig. L–15).

Roof and Penthouses

The roof had a concrete slab on metal deck, the top of which sloped 3 in., from an 8.5 in. thickness to a 5.5 in. thickness, to provide drainage. The wire mesh in this slab was 6x6 W2.4xW2.4, which was 70 percent heavier mesh than at the typical floor. There were slab openings for the cooling towers on the north and the setback roof on the south. The area above the cooling towers was framed in steel, with areas of grating spanning between the beams. A series of diagonal WT 6x9 members under the grating provided diaphragm action in this area. The east side of the floor was reinforced to carry the east penthouse and its contents. Specifics of this reinforcement are not available at this time.

The west penthouse roof was framed in steel with the floor slab increased to a 6 in. thickness. The framing and roof reinforcement for the east penthouse and the mechanical equipment screenwall are not available at this time. Layout of these areas has been determined from photographs, as shown in Fig. L–16.

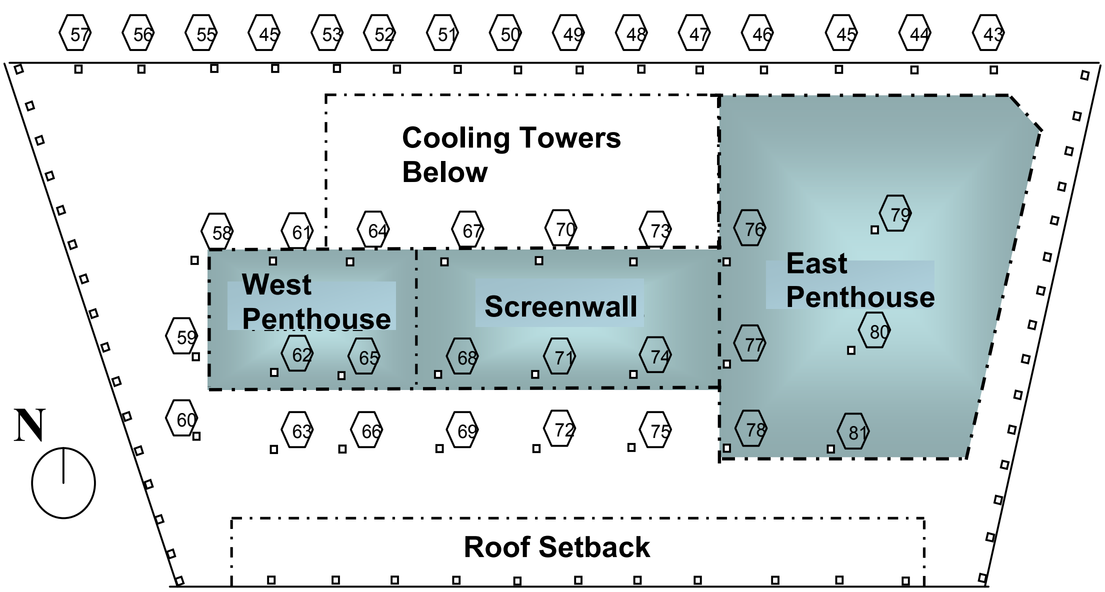


Figure L–16. Roof layout.

L.1.7 Columns

Core columns were primarily rolled wide-flange shapes of grade 36 or 50 steel. As the loads increased towards the base of the building, many of these column sizes were increased through the use of built-up shapes. These built-up columns had a W14x730 core with cover plates welded to the flanges (to form a box) or web plates welded between the flanges as shown in Fig. L–17. The reinforcing plate welds were specified to be continuous 0.5 in. fillet welds at the cover plates and 0.313 in. minimum at the web plates. Plate thickness ranged from 1.5 in to 8 in. Reinforcing plates were specified as follows:

Plate thickness t (in.):

2 < t < 4	ASTM A588 Grade 50
4 < t < 6	ASTM A572 Grade 42
t > 6	ASTM A588 Grade 42

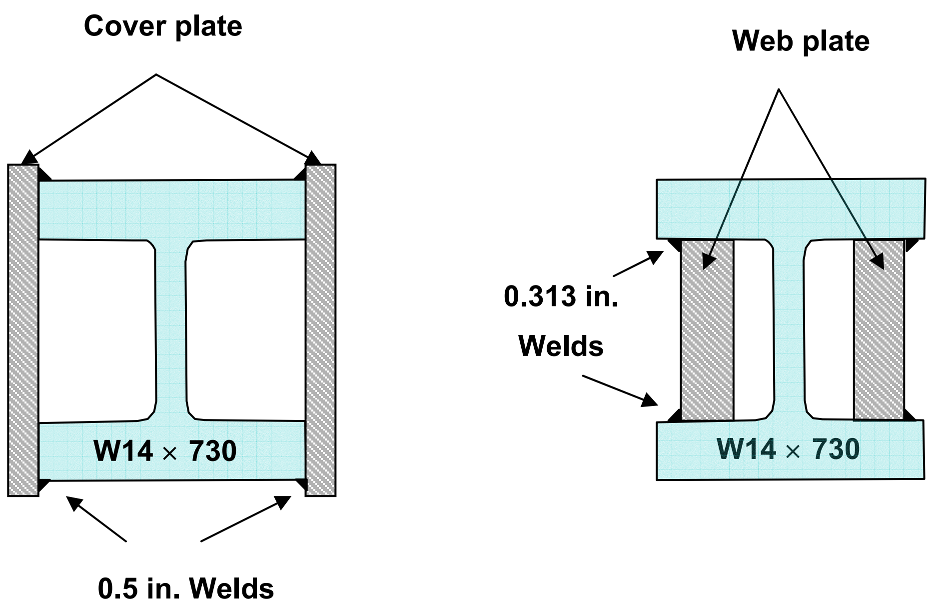


Figure L–17. Typical built-up column details.

Typical core column splices were shown on available erection drawings. The adjoining surfaces of columns were specified to be milled. The splice plates were welded or bolted to the outsides of the column web and flanges. Built-up columns were also milled at their bearing ends but the splice plates were fillet welded to the cover plates.

Perimeter columns were nominally 14 in. wide-flange shapes (W14) of ASTM A 36 steel. Perimeter column splices were similar to the core column splices.

L.1.8 Column Transfer Trusses and Girders

The layout of the substructure and Con Edison columns did not align with the column layout in the upper portion of WTC 7. Therefore a series of column transfers were constructed. These transfers occurred primarily between Floors 5 and 7. See Fig. L–18 for a schematic rendering of the transfers.

Columns 47 through 54, at the north facade, were transferred at Floor 7 by cantilever girders to bring them in line with the substation columns, offset 6 ft to 9 ft to the south. The back-span of these cantilevers was supported by the north side core columns. The eastern most cantilever girder was connected to truss #1, and the western most cantilever girder was connected to truss #3 (see Fig. L–18).

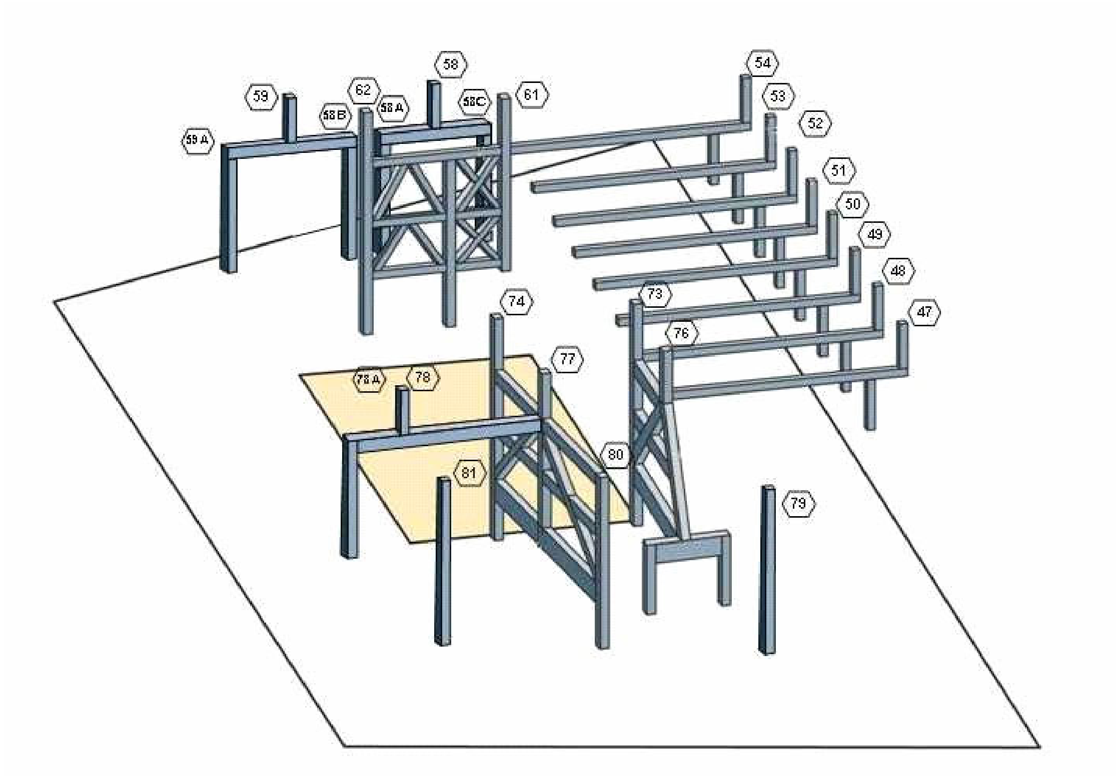


Figure L–18. 3D schematic view of transfer trusses and girders between Floors 5 and 7.

Column 76 was supported at Floor 7 by truss #1. The west side of truss #1 is supported by column 73, while the east side is supported by a transfer girder running north-south which is, in turn, supported by columns E3 and E4 at Floor 5.

Columns 58, 59, and 78 were transferred by simply supported girders at Floor 7. Column 78 was supported at Floor 7 by a transfer girder that was supported at its north end by truss #2. Column 77 was also supported by truss #2. Truss #2 was supported by column 74 at its west end and by column 80 at its east end.

Column 61 was supported by truss #3. Truss #3 runs north-south and was supported by columns 62 and 61A. Truss #3 has a 10 ft cantilever span between column 61 and column 61A and an 18 ft back span to column 62.

L.1.9 Lateral System

Above Floor 7, WTC 7 had a perimeter moment frame. Exterior columns were typically rolled W14 shapes of ASTM A36 grade steel. Column trees were fabricated for the east and west facades with field splices occurring every other story in the columns and at the spandrel beam midspan between columns, where the tree stubs were spliced with a bolted connection. On the north and south facades, the moment frames were constructed with spandrel connections at the face of the columns. Some column splices were shown on the erection drawings to be partial penetration groove welds between the column flanges.

At Floors 5 to 7 and Floors 22 to 24, there was a perimeter belt truss, shown in Fig. L–19. Below Floor 7, a combination of moment and braced frames around the perimeter and a series of braced frames in the core, is shown in Fig. L–20. The strong diaphragms of Floors 5 and 7 transferred load from the perimeter to the core. Above the loading dock at the south facade, two of the columns were hung from the belt truss at Floors 5 through 7. Above the Con Edison vault at the north facade, eight columns were also hanging from the belt truss between Floors 5 and 7.

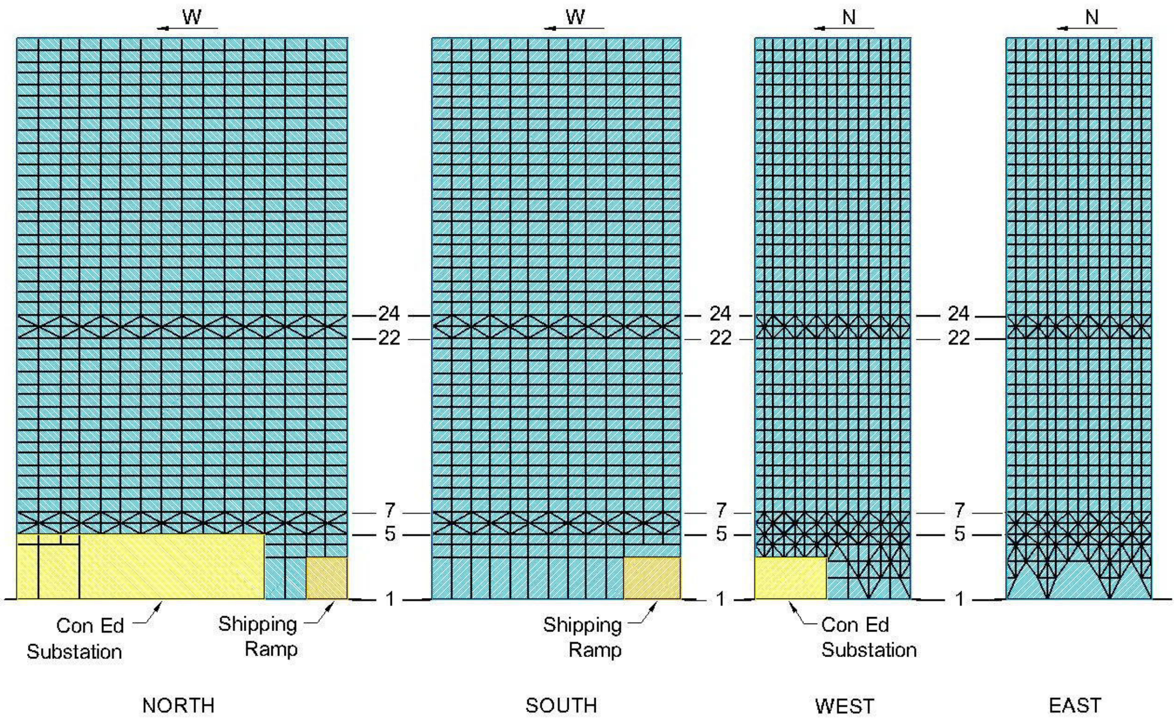


Figure L–19. Perimeter lateral system elevations.

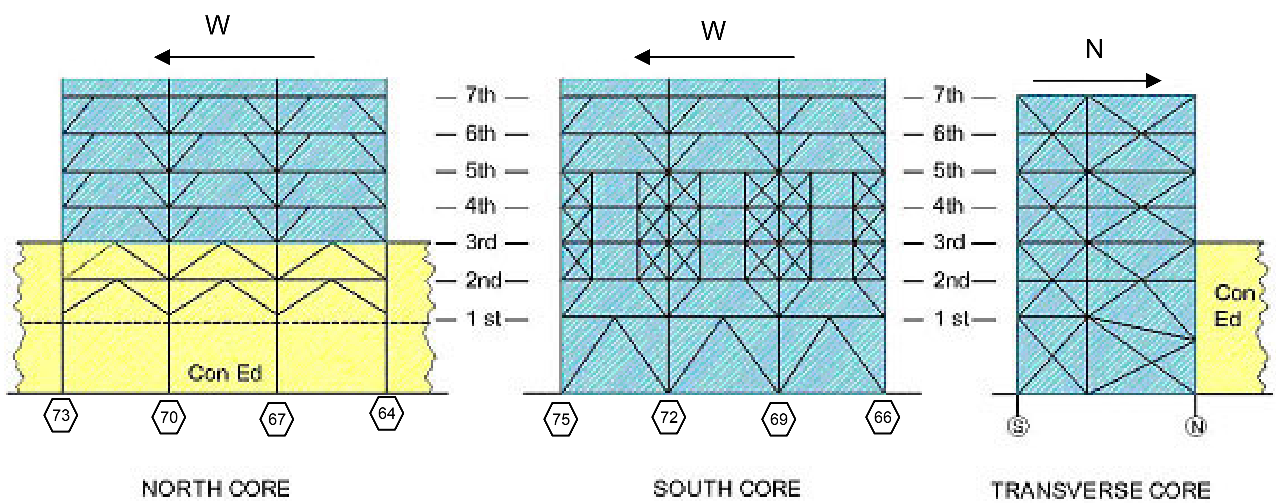


Figure L–20. Core lateral system.

L.2 OBSERVATIONS OF STRUCTURAL COLLAPSE

This section presents observed data and events from available drawings, photographic and videographic records, interviews, and other data sources for WTC 7 to identify damage and fire locations. Damage to WTC 7 from debris impact from WTC 1 and WTC 2 is summarized in Section L.2.2, followed by known fire growth and progression in Section L.2.3. The observed exterior sequence of collapse events from photographic and videographic records are described in Sections L.2.4 and L.2.5, where collapse observations are considered from the plan and elevation views of the structure, respectively. These observations have been used for developing possible collapse initiation locations and progression mechanisms, which are presented in Section L.3.

L.2.1 Damage from WTC 1 and WTC 2 Collapses

To place the events leading to the global collapse of WTC 7 into context, it is helpful to summarize the events of September 11, 2001:

8:46 a.m.	WTC 1 was struck by an aircraft
9:03 a.m.	WTC 2 was struck by an aircraft
9:59 a.m.	WTC 2 collapsed
10:28 a.m.	WTC 1 collapsed
5:21 p.m.	WTC 7 collapsed

After WTC 1 collapsed, the south face of WTC 7 was obscured by smoke, making direct observation of damage from photographs or videos difficult or impossible. The source of the smoke is uncertain, as large fires were burning in WTC 5 and WTC 6, as well as those noted below in WTC 7. The light but prevalent winds from the northwest caused the smoke to rise on the leeward, or south, side of the building. The following information about damage seen in WTC 7 was obtained from interviews of people in or near the building:

After WTC 2 collapsed:

- Some south face glass panes were broken at lower lobby floors
- Dust covered the lobby areas at Floors 1 and 3
- Power was on in the building and phones were working
- No fires were observed

Reported close to time of WTC 1 collapse:

- East stair experienced an air pressure burst, filled with dust/smoke, lost lights
- West stair filled with dust/smoke, lost lights, swayed at Floors 29 through 30, and a crack was felt (in the dark) on the stairwell wall between Floors 27 through 28 and Floors 29 through 30
- Floors 7 and 8 had no power, air was breathable but not clear

- Phone lights on Floor 7 were on but could not call out

After WTC 1 collapsed:

- Heavy debris (exterior panels from WTC 1) was seen on Vesey Street and the WTC 7 promenade structure at the third floor level
- Southwest corner damage extended over Floors 8 to 18
- Damage was observed on the south face that starts at the roof level and severed the spandrels between exterior columns near the southwest corner for at least 5 to 10 floors. However, the extent and details of this damage have not yet been discerned, as smoke is present.
- Damage to the south face was described by a number of individuals. While the accounts are mostly consistent, there are some conflicting descriptions:
  - middle one-fourth to one-third width of the south face was gouged out from Floor 10 to the ground
  - large debris hole near center of the south face around Floor 14
  - debris damage across one-fourth width of the south face, starting several floors above the atrium (extended from the ground to 5th floor), noted that the atrium glass was still intact
  - from inside the building at the 8th or 9th Floor elevator lobby, where two elevator cars were ejected from their shafts and landed in the hallway north of the elevator shaft, the visible portion of the south wall was gone with more light visible from the west side possibly indicating damage extending to the west

At 12:10 to 12:15 p.m.:

- Firefighters found individuals on Floors 7 and 8 and led them out of the building
- No fires, heavy dust or smoke were reported as they left Floor 8
- Cubicle fire was seen along west wall on Floor 7 just before leaving
- No heavy debris was observed in the lobby area as the building was exited, primarily white dust coating and black wires hanging from ceiling areas were observed

Photographs support some of these reports and show additional damage at the upper portions of the building. Figure L–21 is an aerial view of WTC 7 after the collapse of WTC 1. There is no visible debris on the roof; some minor damage is seen on the south side at the parapet wall. Figures L–22a and L–22b show the reported damage between Floors 8 to 18 at the southwest corner. Much of the damage above Floor 18 appears to be nonstructural. The black areas on the facade indicate areas of burned out fires. Note the heavy smoke obstructing any observations along the south face. Study of this photograph indicates that at least two exterior columns were severed. Figures L–23a and L–23b show the debris on Vesey Street in front of WTC 7 after the collapse of WTC 1. The pedestrian bridge (L–23a) and the promenade (L–23b) appear to be standing, although damaged. Exterior panels from WTC 1 can be seen on Vesey Street and on the promenade. The approximate extent of possible damage due to debris from WTC 1 is shown in Fig. L–23c.

Figure L–21. Photograph of roof after WTC 1 collapse.

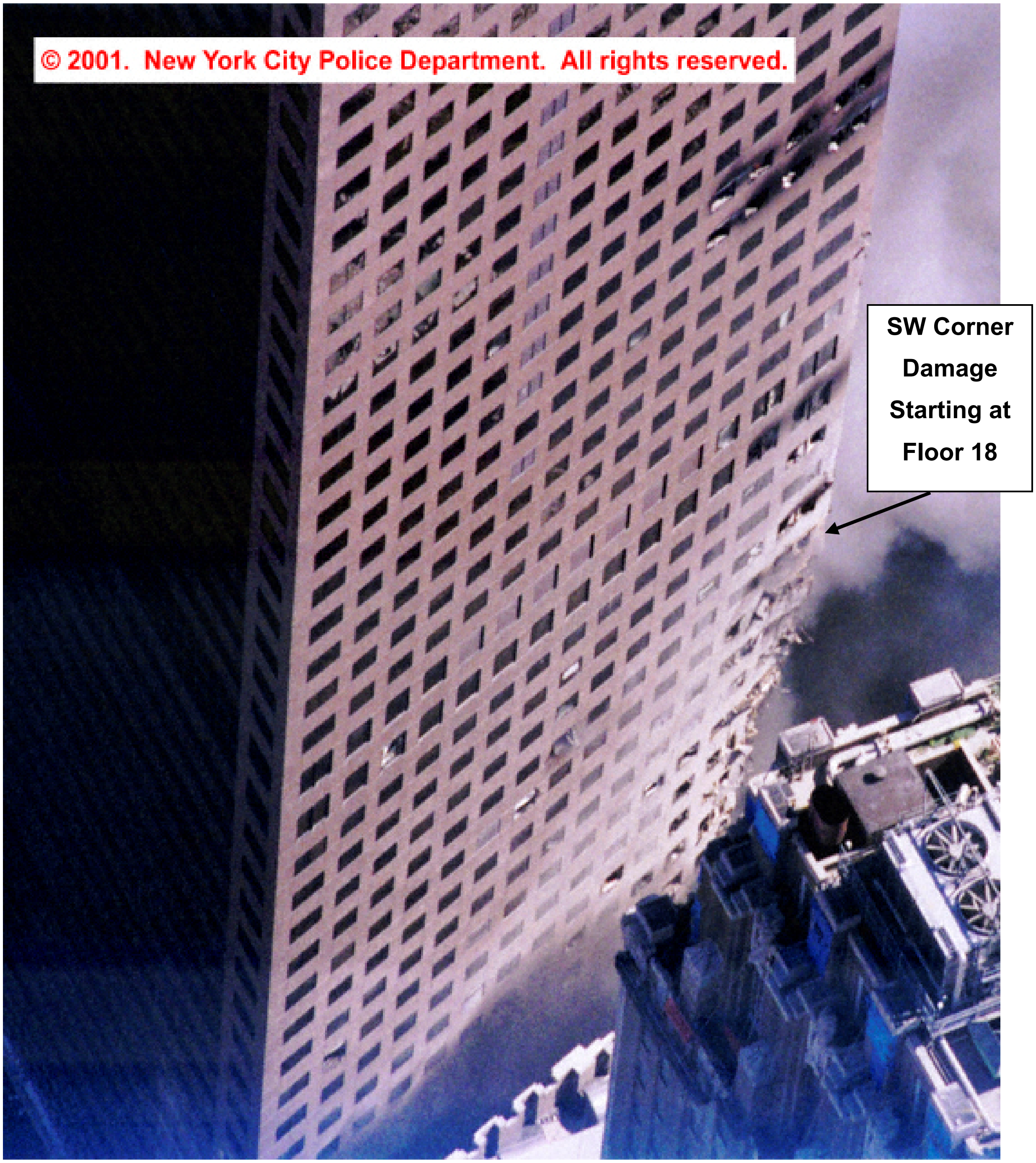


Figure L–22a. Debris damage around Floor 18 of the southwest corner.

Figure L–22b. Debris damage around Floor 8 of the southwest corner.

Figure L–23a. Pedestrian bridge and debris on Vesey Street after WTC 1 collapsed.

L.2.2 Observed Fire Locations

Photographs and videos were used to determine fire locations and movement within WTC 7. Most of the available information is for the north and east faces of WTC 7. Information about fires in other areas of the building was obtained from interviews, and is summarized as follows:

From 11:30 a.m. to 2:30 p.m.:

- No diesel smells reported from the exterior, stairwells, or lobby areas
- No signs of fire or smoke were reported below the 6th Floor from the exterior, stairwells or lobby areas
- In the east stairwell, smoke was observed around Floors 19 or 20, and a signs of a fully involved fire on the south side of Floor 23 were heard/seen/smelled from Floor 22.
- Interviews place a fire on Floor 7 at the west wall, toward the south side, at approximately 12:15 p.m.

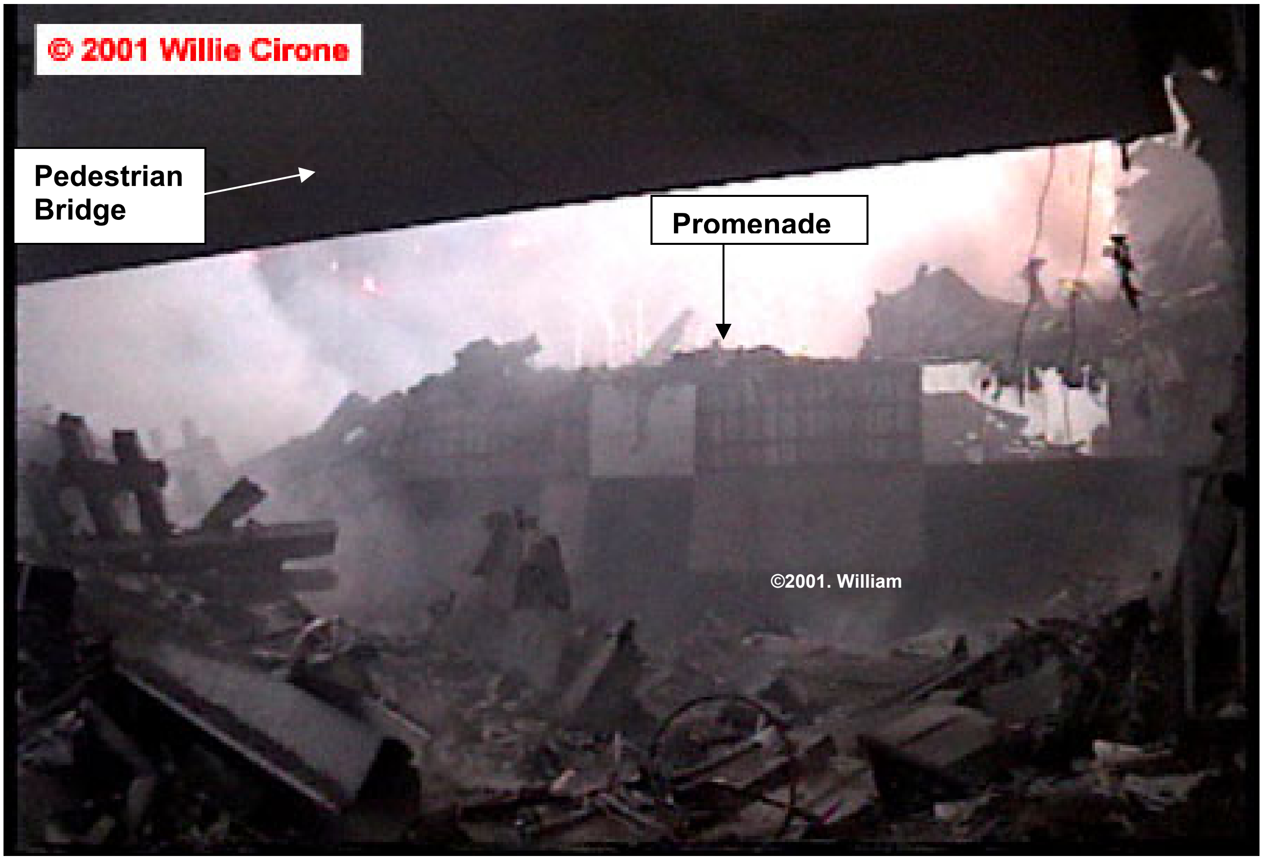


Figure L–23b. WTC 7 Promenade and debris on Vesey Street after WTC 1 collapsed.

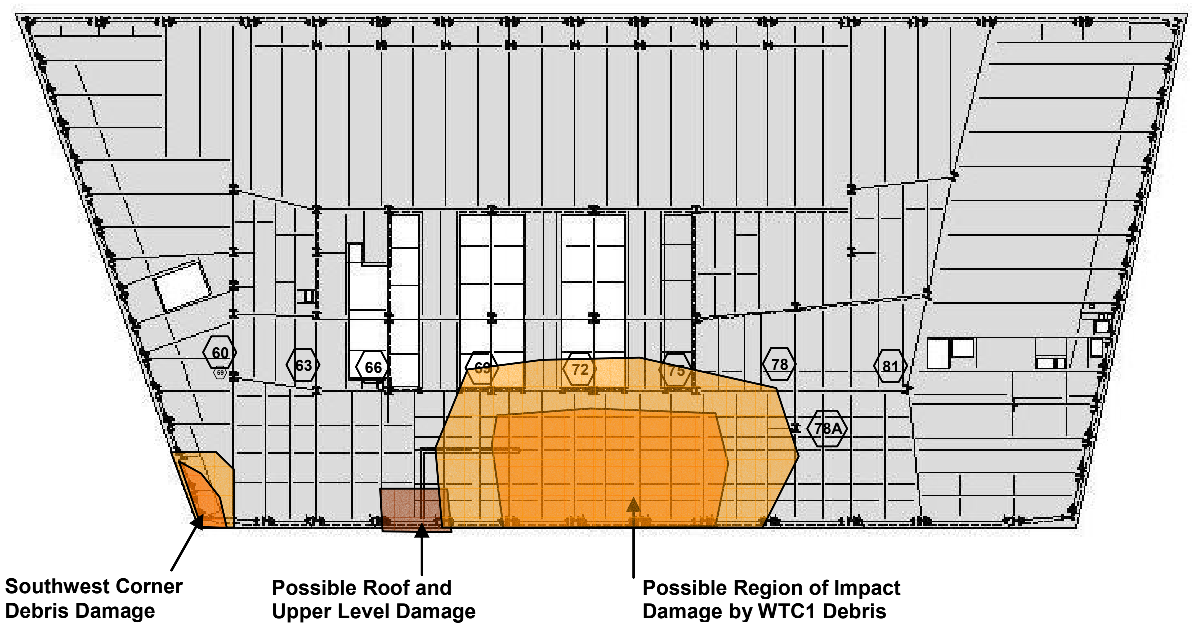


Figure L–23c. Possible extent of debris damage in plan.

- From West and Vesey Streets near the Verizon Building, fires were observed in floors estimated to be numbered in the 20s and 30s.

Looking from the southwest corner at the south face:

- Fire was seen in the southwest corner near Floor 10 or 11
- Fire was seen on Floors 6, 7, 8, 21, and 30
- Heavy black smoke came out of a large, multi-story gash in the south face

Looking from the southeast corner of the south face:

- Fire seen on Floor 14 (reported floor number) on south face; the face above the fire was covered with smoke
- Fire on Floor 14 moved towards the east face

Looking at the east face:

- Fire on Floor 14 (reported floor) moved along east face toward the north side

Photographs and videos were used with these interview accounts to document fire progression in the building. The fires seen in photographs and videos are summarized:

Before 2:00 p.m.

- Figures L–22a shows fires that had burned out by early afternoon on Floors 19, 21, 22, 29, and 30 along the west face near the southwest corner.

2:00 to 2:30 p.m.

- Figure L–24a shows fires on east face Floors 11 and 12 at the southeast corner. Several photos during this time show fires progressing north.

3:00 to 5:00 p.m.

- Around 3 p.m., fires were observed on Floors 7 and 12 along the north face. The fire on Floor 12 appeared to bypass the northeast corner and was first observed at a point approximately one third of the width from the northeast corner, and then spread both east and west across the north face.
- Some time later, fires were observed on Floors 8 and 13, with the fire on Floor 8 moving from west to east and the fire on Floor 13 moving from east to west. Figure L–24b shows fires on Floors 7 and 12.
- At this time, the fire on Floor 7 appeared to have stopped progressing near the middle of the north face.

Figure L–24a. Fires on Floors 11 and 12 on the east face.

Figure L–24b. Fires on Floors 7 and 12 on the north face.

- The fire on Floor 8 continued to move east on the north face, eventually reaching the northeast corner and moving to the east face.
- Around 4:45 p.m., a photograph showed fires Floors 7, 8, 9, and 11 near the middle of the north face; Floor 12 was burned out by this time.

L.2.3 WTC 7 Collapse Observations

The collapse of WTC 7 was recorded on several videos from locations northeast and northwest of the building. Study of these videos led to the development of the timeline in Table L–1, which lists the visible external sequence of events. Figures L–25 to L–28 are images from a CBS News Archives video that show key points observed during the collapse.

The deformed shape of the east penthouse roof shows that the middle fell before the sides (see Fig. L–25), as the whole penthouse drops into the main building (see Fig. L–26). This may imply that support initially remained on the east and west edges of the east penthouse. Therefore, the perimeter columns on the east side of the building which have not already been considered least likely, may be considered less likely locations for collapse initiation.

Table L–1. Timeline of WTC 7 collapse as observed from the northwest.

Time Interval (s)	Total Time (s)	Observation from CBS Video
0.0	0.0	- First movement of east penthouse roofline downwards
0.9	0.9	- East penthouse kink between columns 44 and 45 (Fig. L–25) - First 2 windows at Floor 40 fail between columns 44–45 (windows 9 and 11 from east end)
0.3	1.2	- 4 more windows fail at Floor 40 - East penthouse submerged from view (now inside building)
0.5	1.7	- 3 windows break at Floor 41, Floor 43, Floor 44
0.5	2.2	- East penthouse completely submerged (Fig. L–26)
1.8	4.0	- Windows break along column 46 at Floors 37 and 40
3.0	7.0	- West penthouse and screenwall begin to move downward into building - Movement of entire north face of WTC7 (visible above Floor 21)
0.2	7.2	- West end of roof starts to move
0.5	7.7	- East end of roof starts to move - Kink formed in north facade along column 46-47
0.4	8.2	- West penthouse and screenwall submerged - Windows fail between Floors 33–39 around column 55 - Global collapse initiates (Fig. L–27 and L–28)

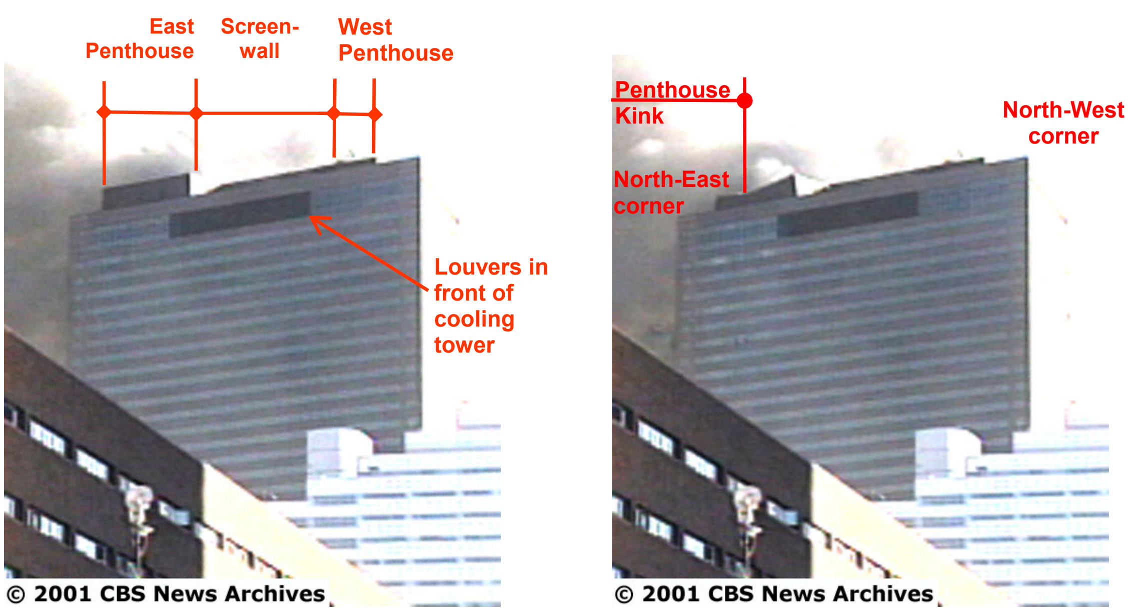


Figure L–25. East penthouse kink.

Figure L–26. East penthouse sinks (2.2 s).

Figure L–27. Center screenwall and west penthouse sink (7.9 s).

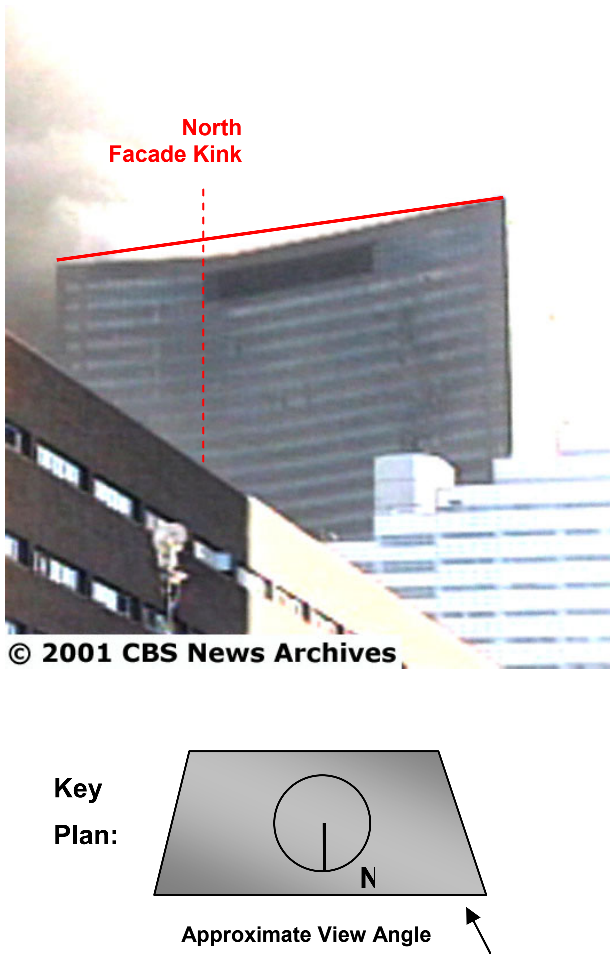


Figure L–28. Global collapse.

Possible Locations of Collapse Initiation

Columns 76, 77, 78, 79, 80, and 81 appear to have direct influence on the collapse initiation of the east penthouse. A failure of any of these columns, truss #1 or #2, or the east transfer girder, or some combination of these components, with possible contribution of adjacent framing and floor systems, could be considered possible locations of the initiating events that led to the observed collapse of the east penthouse.

L.2.4 Interpretation of Collapse Initiation Observations in Elevation

In addition to determining some possible locations of the collapse initiation locations within the plan of the structure, it is also helpful to use the available collapse documentation to identify possible locations in the building elevation for the initial failure.

Least Likely Locations of Collapse Initiation–Penthouse Failure Mechanism

Because the first visible failure is in the east penthouse, one possible collapse initiation mechanism involves a local failure of the penthouse framing, which then progressed down the structure with floors sequentially impacting upon those below. There are two reasons that this scenario may be considered unlikely.

First, there was no visible abnormal loading locally applied to cause a local failure at the East Penthouse. The photograph in Fig. L–21 shows the east penthouse sustained no damage due to the collapse of the WTC towers. The videographic records do not show any visible fire in or near the penthouse prior to collapse.

Second, Fig. L–25 shows a snapshot as the east penthouse starts to collapse. When the roof of the penthouse starts to fall, a line of windows (roughly in line with columns 79 to 81) has broken over the entire height of the visible region. In free fall, it would take 3 to 4 seconds for an object to fall from the roof elevation to the height of the bottom visible broken window, around Floor 33. Since the bottom window is broken nearly simultaneously when the kink is seen at the east penthouse, the initial failure may be assumed to have propagated upward from the lowest window breakage rather than propagated downward from the top of the building. Therefore, initial failure within the penthouse may be considered unlikely.

Less Likely Locations of Collapse Initiation–High Elevation Column Failure Mechanism

Another possible collapse initiation mechanism may be the failure of a column in the upper elevations of the building. The collapse could have progressed vertically upward by pulling down the floors above the failed column as debris landed on and sequentially crushed the floors below.

The timing required for this mechanism, in accordance with gravitational acceleration, requires that any column locations significantly above the 13th floor (the lowest visible floor in photographic and videographic records) may be considered unlikely failure initiation locations. The lack of observed fires in the floors above Floor 13 also reduces the likelihood of failure initiating in this region of the building.

Possible Locations of Collapse Initiation Mechanism

Based on review of the photographic and videographic records, a failure of any column within the plan area shown in Fig. L–29, and below Floor 13, likely contributed to the collapse initiation. This includes columns 76, 77, 78, 79, 80, and 81, truss #1, truss #2, column 78A, the east transfer girder and adjacent framing and floor systems within this region (see Fig. L–30).

L.2.5 Interpretation of Collapse Progression Observations

Interior columns 79, 80, and 81, were located directly below the east penthouse on the roof and supported large tributary areas. It appears that some sequence of component failures in the region identified in Figs. L–29 and L–30 led to the failure of one or more of these columns, as discussed above. The failure progressed vertically upward within the failed bay to the roof level, based upon observations of window breakage relative to failure of rooftop structures, and was first visible from the exterior when the east penthouse lost support (see Fig. L–26).

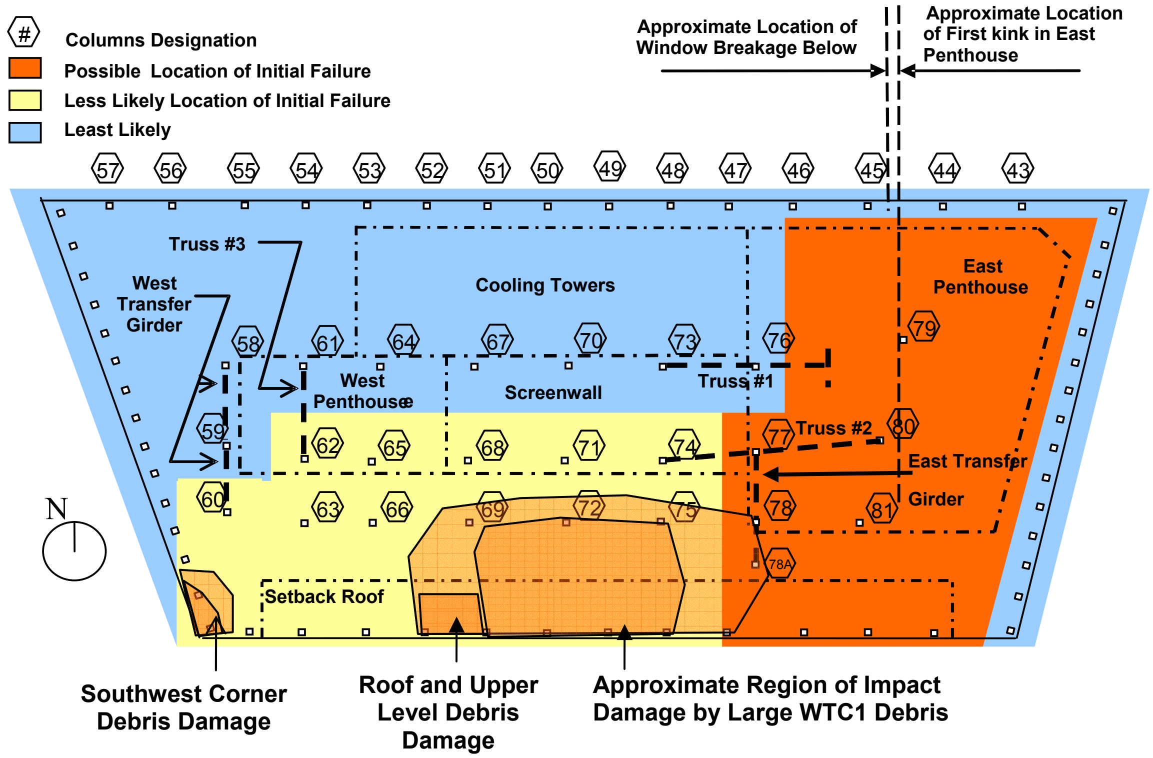


Figure L–29. Plan view of regions for collapse initiation.

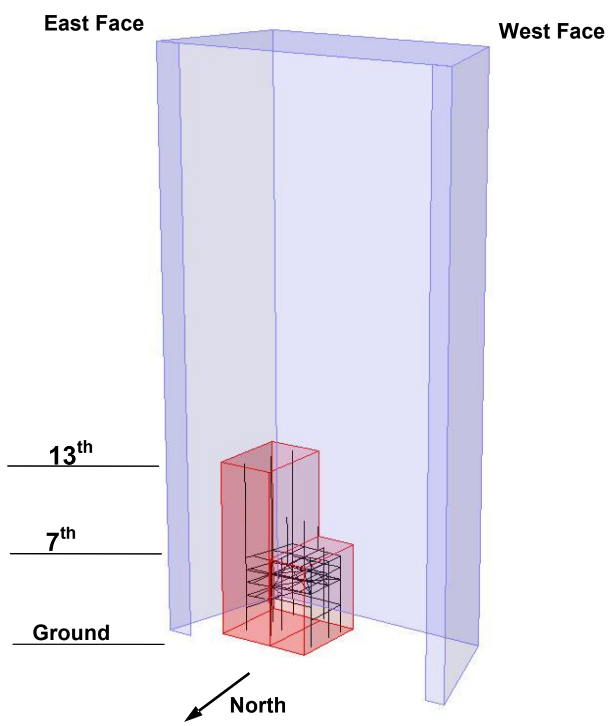


Figure L–30. Likely region of initiating component failures based on videographic and photographic records of fire and collapse.

The 5 s to 6 s delay between the failure of the east penthouse and the failure of the screenwall and west penthouse (shown in Fig. L–27) approximates the time it would take for the debris pile from the vertical failure progression on the east side of the building to reach Floors 5 to 7 and damage the transfer trusses and girders in this area.

A kink developed in the north facade approximately where column 76 projects to the north face. The kink may have formed in the plane of the north facade or it may represent a displacement in the structure along this line towards the south. The area of this kink correlates to the easternmost cantilever transfer at Floor 7. All of the Floor 7 cantilever transfer girders had back spans supported along the line of the north core columns, of which the easternmost one was supported by truss # 1. This north facade kink also coincides with the girders at the eastern edge of the cooling tower area at Floor 46.

When the screenwall and the west penthouse sank into the building, a line of windows broke from Floor 44 down to the bottom of the visible range, which is approximately at Floor 33 on the west side of the structure (see Fig. L–27). This area aligns with column 61, which is supported by the cantilevered end of transfer truss #3 between Floors 5 and 7, as shown in Fig. L–31. This suggests that the observed window breakage may be related to the failure of column 61 or truss #3.

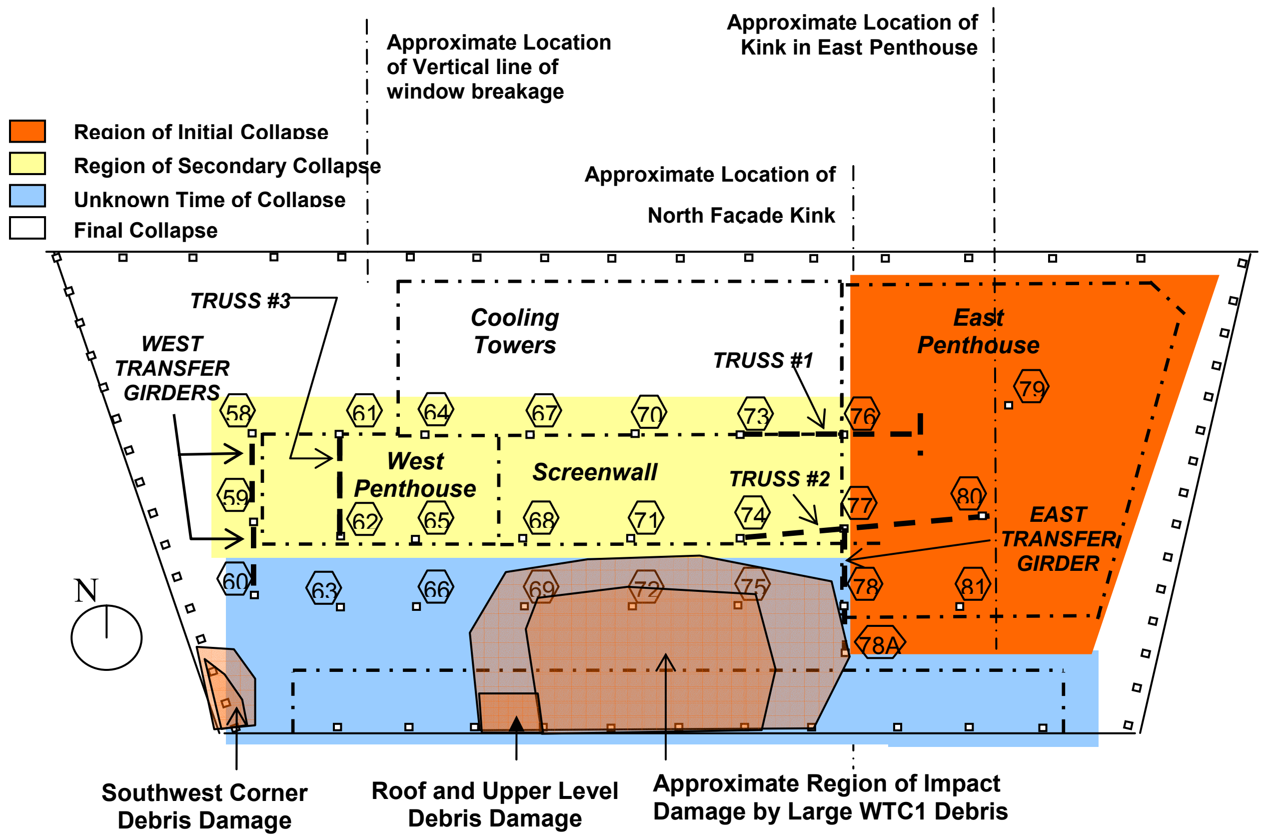


Figure L–31. Plan View of Collapse Progression.

The simultaneous failure of screenwall and west penthouse structures, window breakage on the west side of the north facade, and initiation of global collapse (see Fig. L–28) indicates that the building loads could no longer be supported. Horizontal progression of the collapse appears to have occurred after the vertical collapse on the east side of the building. The greater strength of Floors 5 and 7 relative to the other floors and the transfer trusses between these floors suggests that this region of the building played a key role in destabilizing the remaining core columns, and the global collapse occurred with few external signs prior to the system failure.

All of the photographic and videographic records show the north facade collapsing from below the visible area; the facade appears to sink into the ground without any sign of the other floors in the visible portion of the building collapsing. This may indicate that the collapse of the facade starts below the area visible in the photographic and videographic records.

L.2.6 Debris Field

The debris of WTC 7 was mostly contained within the original footprint of the building. From aerial photos, the debris visible on top of the pile is mostly façade structure. This failure sequence suggests that the interior of the building collapsed before the exterior. See Fig. L–32.

L.2.7 Summary

The possible region of collapse initiation and progression has been refined and can be limited based upon available data as follows:

- Based upon the observed fire locations, it appears that the initiating collapse event may have occurred on Floors 5 through 13.
- Due to the pattern of window breakage, it appears that the initiating collapse event may have occurred below Floor 13 and then progressed vertically upward to the east penthouse.
- Since the middle of the east penthouse roofline appears to fall first, it is possible that the initiating collapse event occurred at columns or transfer components with direct influence on the footprint of the east penthouse.
- The north facade kink and the window breakage on the west side of the north facade as the screenwall and west penthouse began to fall into the building core suggest that a horizontal collapse mechanism occurred between Floors 5 and 7, as there are vertical discontinuities in line with each of these elements between Floors 5 and 7.
- The relatively small debris field, with the exterior moment frame visible on top of the building debris, an internal collapse mechanism is likely.

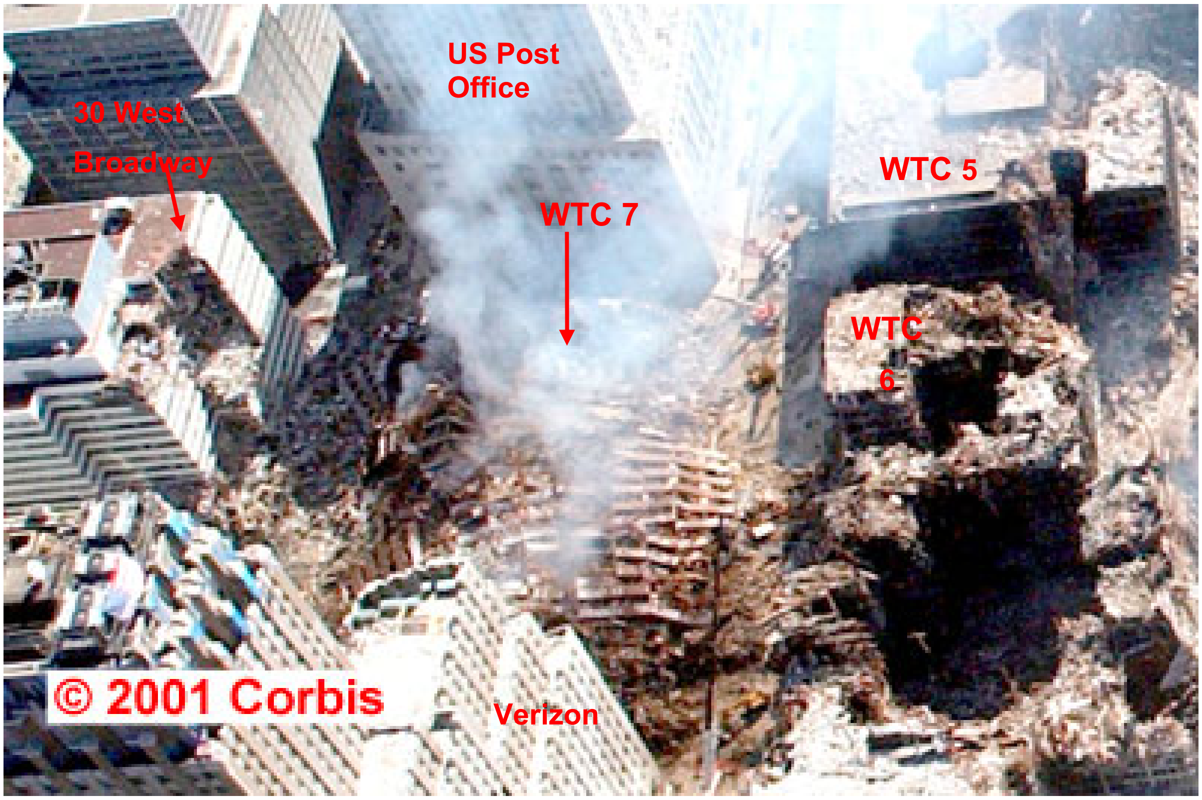


Figure L–32. Aerial view of WTC 7 after collapse.

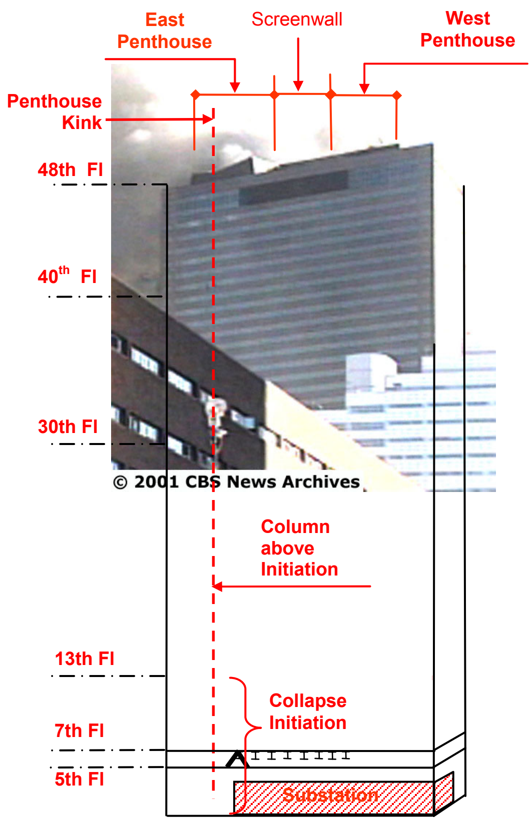
The working collapse hypothesis can be summarized in Figs. L–33 and L–34, which illustrate the components of the observed collapse event: collapse initiation and vertical progression, horizontal progression, and global collapse.

L.3 COLLAPSE HYPOTHESIS

L.3.1 Introduction

WTC 7 suffered a global collapse. The initiating cause or causes of this collapse, and its sequence of events, are still being investigated though fire appears to have played a key role and there may have been some physical damage on the south side of the building.

To develop a working hypothesis for the collapse sequence, it is useful to subdivide the problem into several phases. Many factors and structural components may have contributed to the start of the collapse, but there must have been an initiating event. After the collapse initiated, it progressed to other parts of the building, leading to their failure as well. From the observations of the collapse (see Section L.2), it appears that first there was a vertical failure progression, from some point in the lower eastern portion of the building up to the east penthouse. After a time lag of approximately five seconds, the screenwall and west penthouse were observed to begin sinking into the core area. This suggests that there was a horizontal progression of the collapse towards the west. Since the screenwall and west penthouse fell almost simultaneously, it is reasonable to assume that the horizontal progression captured all the columns that support these building parts.



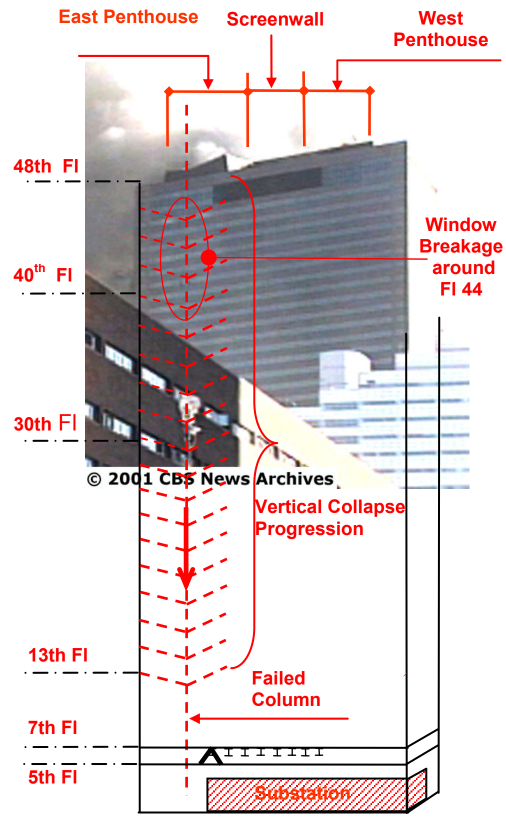
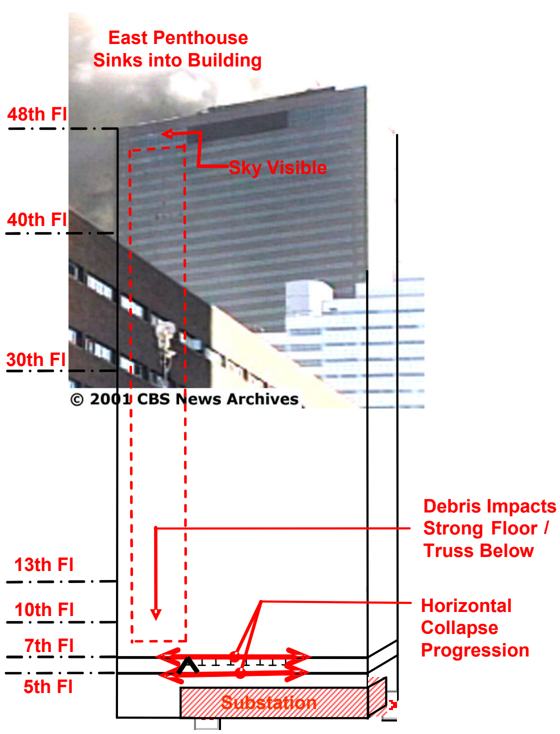


Figure L–33. Collapse initiation and vertical progression on the east side of WTC 7.



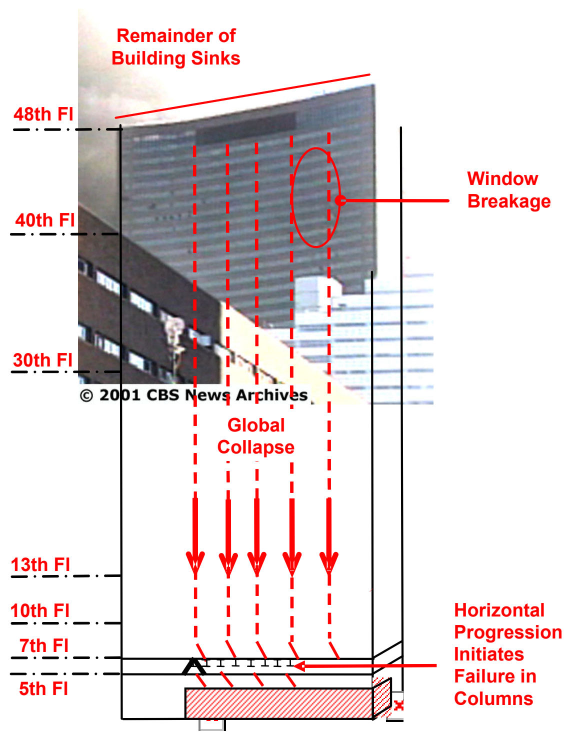


Figure L–34. Horizontal progression to the west side of WTC 7.

Within each phase of the collapse shown in Fig. L–35, the initiating event, vertical progression, horizontal progression, and global collapse, exist many possible scenarios. Scenarios have been developed from available observations of the collapse and are explored with event trees. Preliminary analyses, combined with the observations of collapse, can be used to prune the list of postulated scenarios to a relatively small number of possible collapse hypotheses. These possible hypotheses will then be analyzed in successive levels of detail to try to determine one or more probable sequence of events leading to the building collapse.

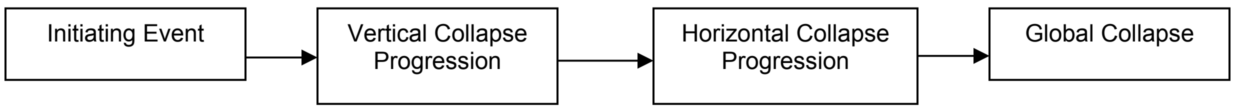


Figure L–35. Phases of WTC 7 building collapse.

L.3.2 Collapse Initiation Scenarios

For the collapse to have started, there must have been a component or group of components that failed first, referred to here as the initiating event, as shown in Fig. L–36. The initiating event may have included structural components severed or damaged by falling debris (I1.1) and/or structural components affected by fires (I1.2).

I1.1 Initiating Components Fail Due to Debris Damage From WTC 1 of WTC 2: The initiating components may have included perimeter or interior columns that were severed or damaged by falling debris from WTC 1 or WTC 2.

- **I2.1 Debris Damage to South Facade Columns:** Perimeter columns on the south face and the southwest corner were reported or observed in photographic and videographic records to have been severed or damaged after WTC 1 collapsed. If the initiating event was due to damage to the perimeter moment frame, then it would have started along the south or southwest facade. Photographic and videographic records show that columns on the north and east facades were undamaged by debris impact.

  – **I3.1 Perimeter Moment Frame Arrests Failure Progression:** Analysis of the global structure indicates that the structure redistributed loads around the severed and damaged areas. A progression of column failure to adjacent columns would have been arrested by the vierendeel action of the perimeter moment frame, which could span across a sizeable opening due to the strength and stiffness of the frame.

  – **I2.2 Debris Damage to Interior Columns:** Interior columns may have been severed or damaged by impacting debris.

  – **I3.2 Interior Columns Fail Immediately:** If interior columns had been severed or severely deformed, they may have failed immediately.

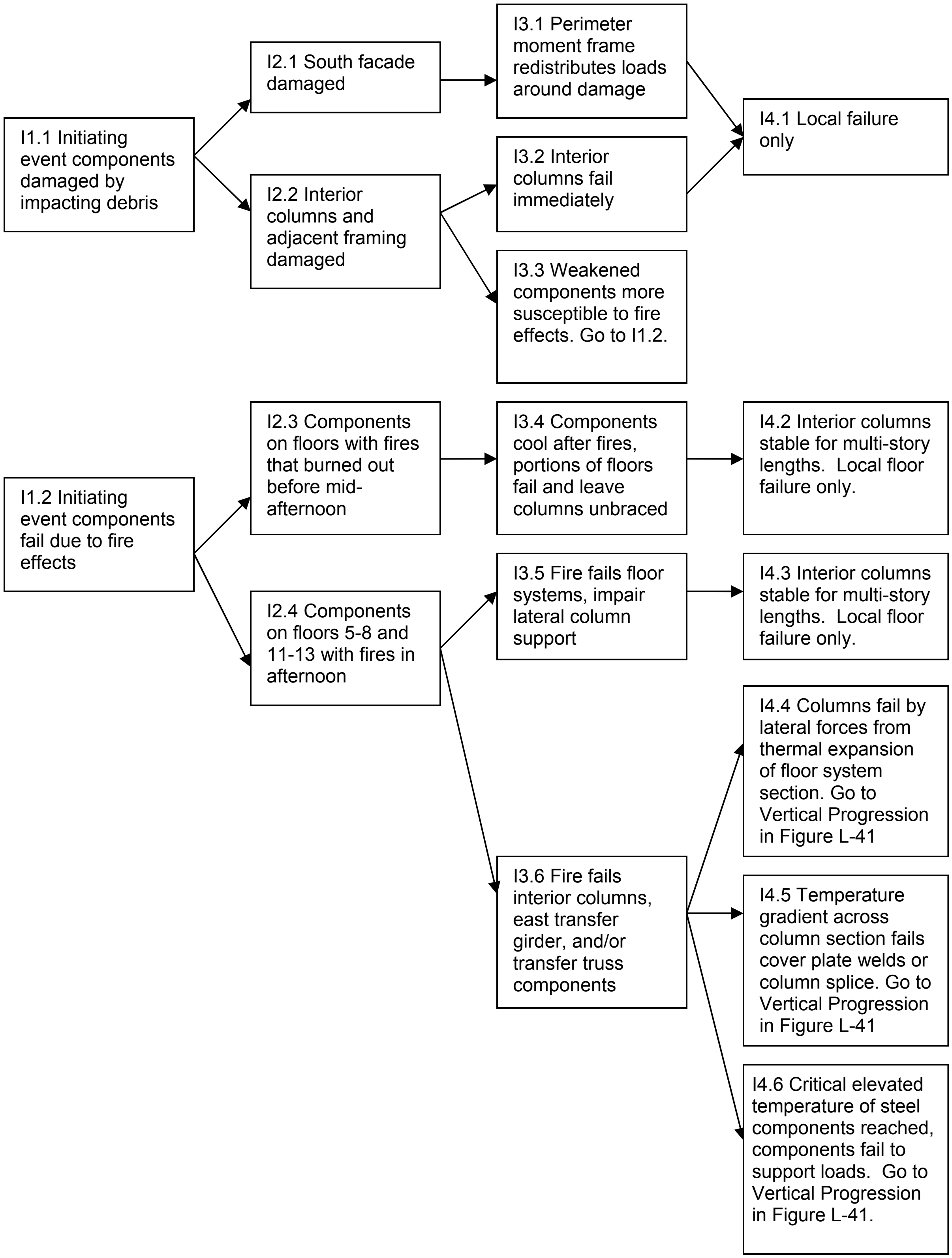


Figure L–36. Collapse initiation scenarios.

- **I4.1 Localized Failure at Interior Columns:** If the interior columns failed just after impact, this likely resulted in a local failure only, since the building continued to stand for almost 7 hours after WTC 1 collapsed. This failure could have progressed vertically upward to the roof level within the bays immediately adjacent to the failed columns, yet from the northern vantage point of the photographic and videographic observations, would not have been visible.

– **I3.3 Interior Columns Remain Standing But Damaged:** If interior columns were weakened by damage from debris, but retained sufficient capacity to carry their loads, then additional loading and/or fire effects would have been required to cause their failure. Debris impact may have damaged the structural steel fireproofing without significantly deforming the structural component.

I1.2 Initiating Components Fail Due to Fire Effects: Fires had been burning in WTC 7 for many hours, as observed in the photographic and videographic records (see section L.2). The initiating event may have been caused by fire effects on structural components.

- **I2.3 Components on Floors With Burned Out Fires:** If the initiating components failed from fire effects, then locations where fires had burned out by mid afternoon could possibly been affected by the cooling which occurs after a fire. No fire was observed or reported in the afternoon on Floors 1–5, 10, or above Floor 13.

– **I3.4 Floor Systems Fail:** The cooling that may have occurred as the fires burned out in an area may have generated thermal contraction forces, which may have induced tensile forces at floor-to-column connections.

- **I4.2 Unbraced Columns:** If floor systems failed, one or more columns may have lost lateral bracing. At a floor where fires were noted, interior columns were comprised of W14x730 cores and reinforcing plates, and could support several stories unbraced without failure. As an example, the column capacity curve of column 79 between Floors 5 to 9 is shown in Fig. L–37. Column load-carrying capacities shown in this figure are based on the AISC column capacity formulas (AISC 2001). The column is not very sensitive to the number of stories of unbraced column length, K. This column, which had a service load stress of approximately 21 ksi, would be approaching its load carrying capacity for an unsupported length of four stories if it was also subject to a uniform temperature of 500 °C.

- **I2.4 Components on Floors With Fire:** If the initiating components failed because of fire effects, then locations with uncontrolled fires would be more likely for the initiating event. From available data of fire locations in WTC 7, likely locations would include Floors 5, 6, 7, 8, 9, 11, 12, and 13. No fires were observed on Floor 5, but the lack of windows and the presence of fuel systems on the south, west, and north floor areas indicate that fire should be considered as a possibility on this floor.

– **I3.5 Floor System Failure:** The fires could have caused the failure of portions of one or more floor system and its framing connections.

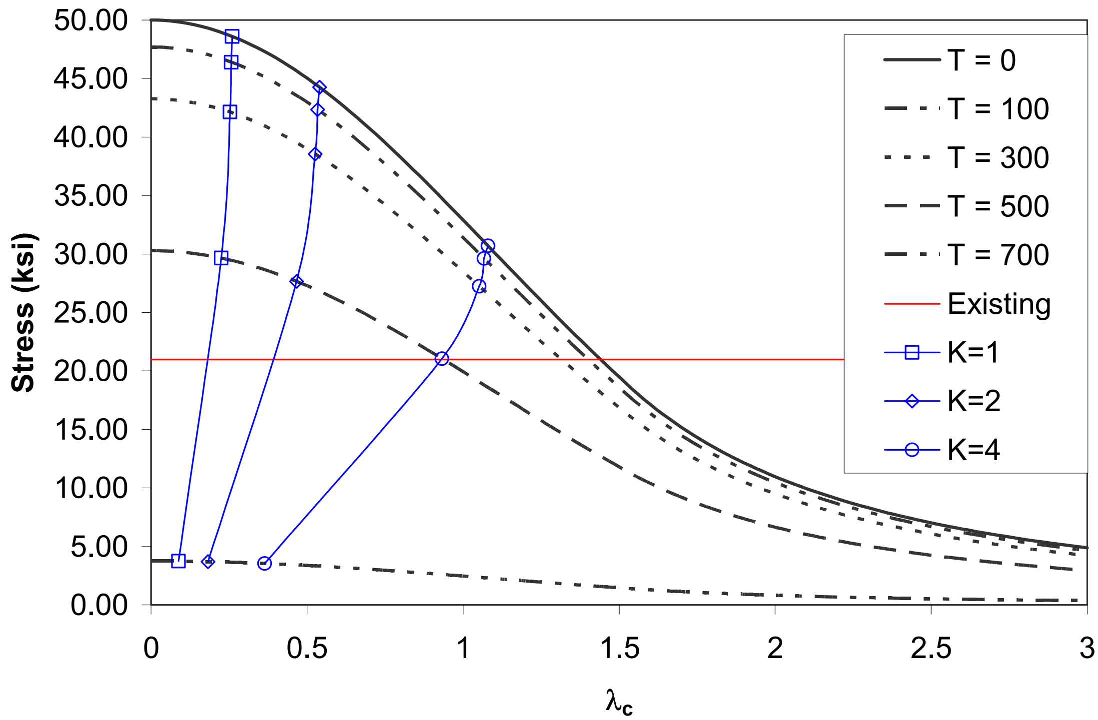


Figure L–37. Column 79 capacity versus temperature and unbraced length K.

- **I4.3 Unbraced Columns:** If floor systems failed, one or more columns may have lost lateral bracing. See I4.2 for discussion.

– **I3.6 Columns, Transfer Girders or Transfer Trusses Fail:** The fires could have failed interior columns, transfer girders, transfer trusses, or their framing connections.

- **I4.4 Lateral Displacements:** Fire effects may have caused column instability failure by lateral displacements from asymmetric thermal expansion of the floor system. Such thermally-induced displacements must overcome the restraining effect of the remaining floor system against further lateral deflection of the column.
- **I4.5 Temperature Gradients:** Fire effects may have caused the failure of columns and other components through the forces induced by temperature gradients through their cross section. Bending and shear forces may be induced that are sufficient to yield either the column splice or reinforcing plate welds. Analysis of a one-story segment of interior column 79 indicates that the cover plate weld would begin to yield at a mean temperature of 490 °C with a 200 °C gradient across the section, as shown in Fig. L–38. Other mean temperature and gradient combinations may also cause this type of failure.

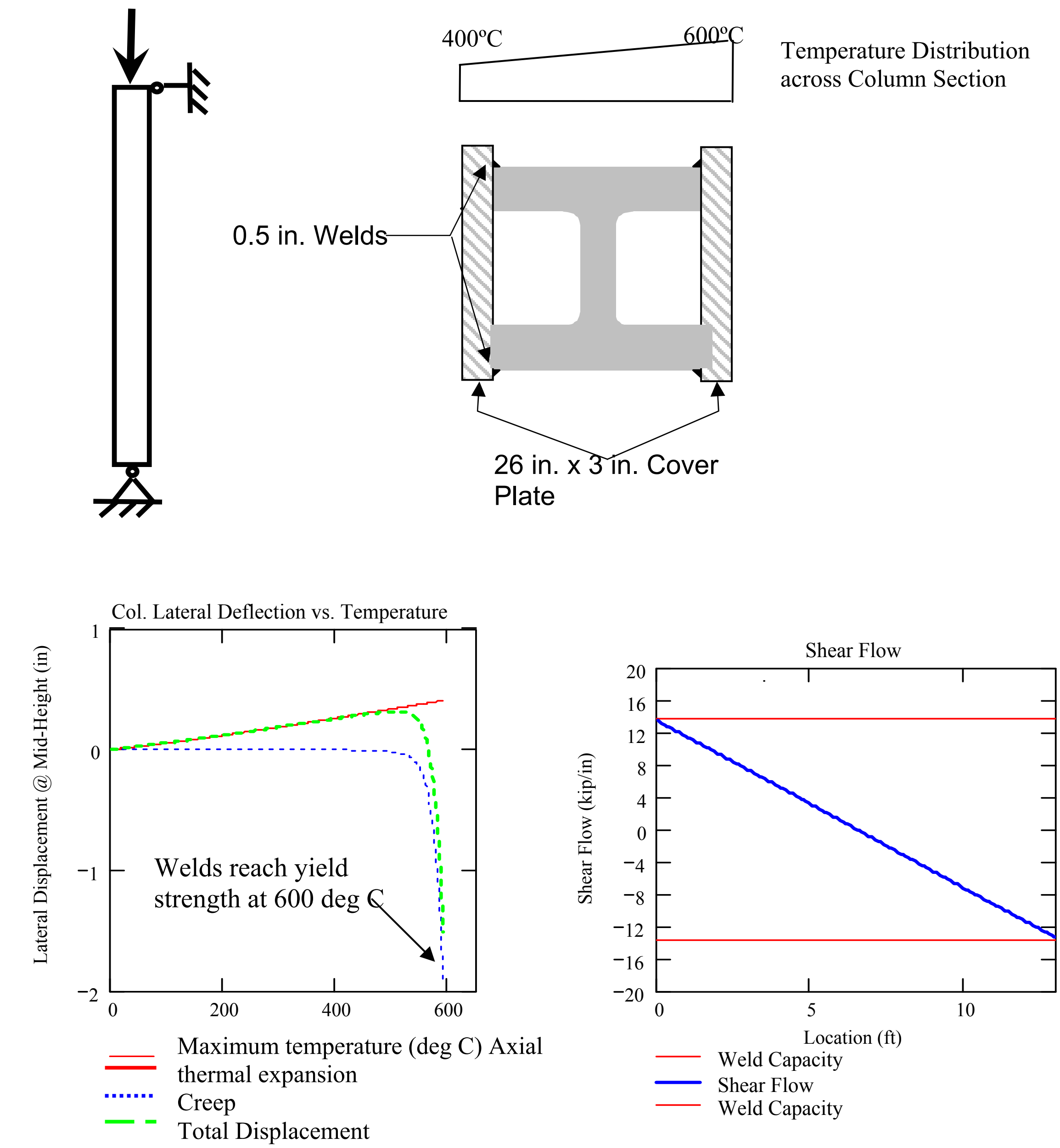


Figure L–38. Effects of temperature gradient on interior column 79.

- **I4.6 Uniform High Temperatures:** If initiating event components were sufficiently exposed to fire effects to be uniformly heated to elevated temperatures, the steel strength would be reduced below that required to support the load. Figure L–39 shows that for interior columns subject to service loads (shown as approximately 20 ksi of compressive stress), uniform steel temperatures of approximately 570 ºC would result in column failure.

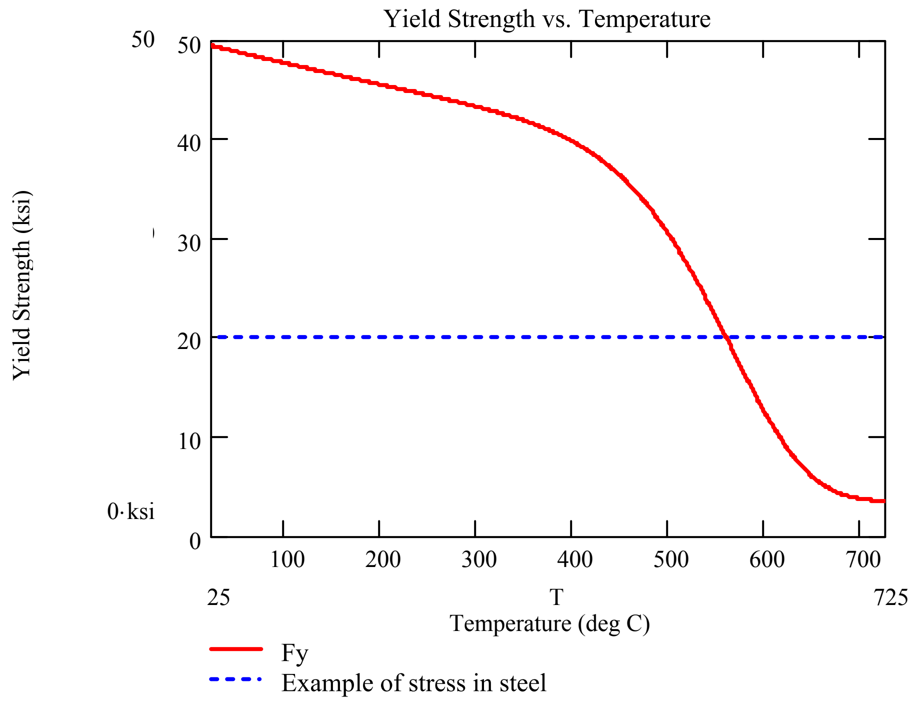


Figure L–39. Steel strength versus temperature.

L.3.3 Vertical Progression Scenarios

After the initiating component or components failed, there must have been a progression of the failure from the initiating event to other locations. To reflect the observed failure of the east penthouse, the failure likely progressed vertically upwards. Figure L–40 shows possible vertical progression scenarios. The initiating component could have failed by any of the failure sequences listed under the collapse initiation scenarios in Fig. L–36. This component could have been one of the columns under the east penthouse. It could also have been one of transfer trusses #1 or #2 under the east penthouse.

A collapse mechanism model was created to capture possible collapse initiation at the roof and the east penthouse. The model seeks to simulate only the kinematics of the collapse mechanism when columns are removed. Several columns were tested for removal. The resulting geometry change was then compared to the observed collapse of WTC 7.

V1.1 Perimeter Columns Fail: Had the initiating component been any perimeter column, most likely it would have been at floor levels with debris impact damage (possible range extends from the ground level up to floors 15 to 20) or the floors possibly experiencing fire (Floors 5, 6, 7, 8, 9, 11, 12, or 13).

- **V2.1 Collapse Does Not Progress:** If a group of perimeter columns failed, the perimeter framing above this area would have redistributed its loads, due to the redundancy of the moment frame.

V1.2 Core Columns Not Directly under East Penthouse Fail: Had the initiating component been a core column that was not under the east penthouse, most likely it would have been at floor levels with debris impact damage (possible range extends from the ground level up to Floors 15 to 20) or the floors

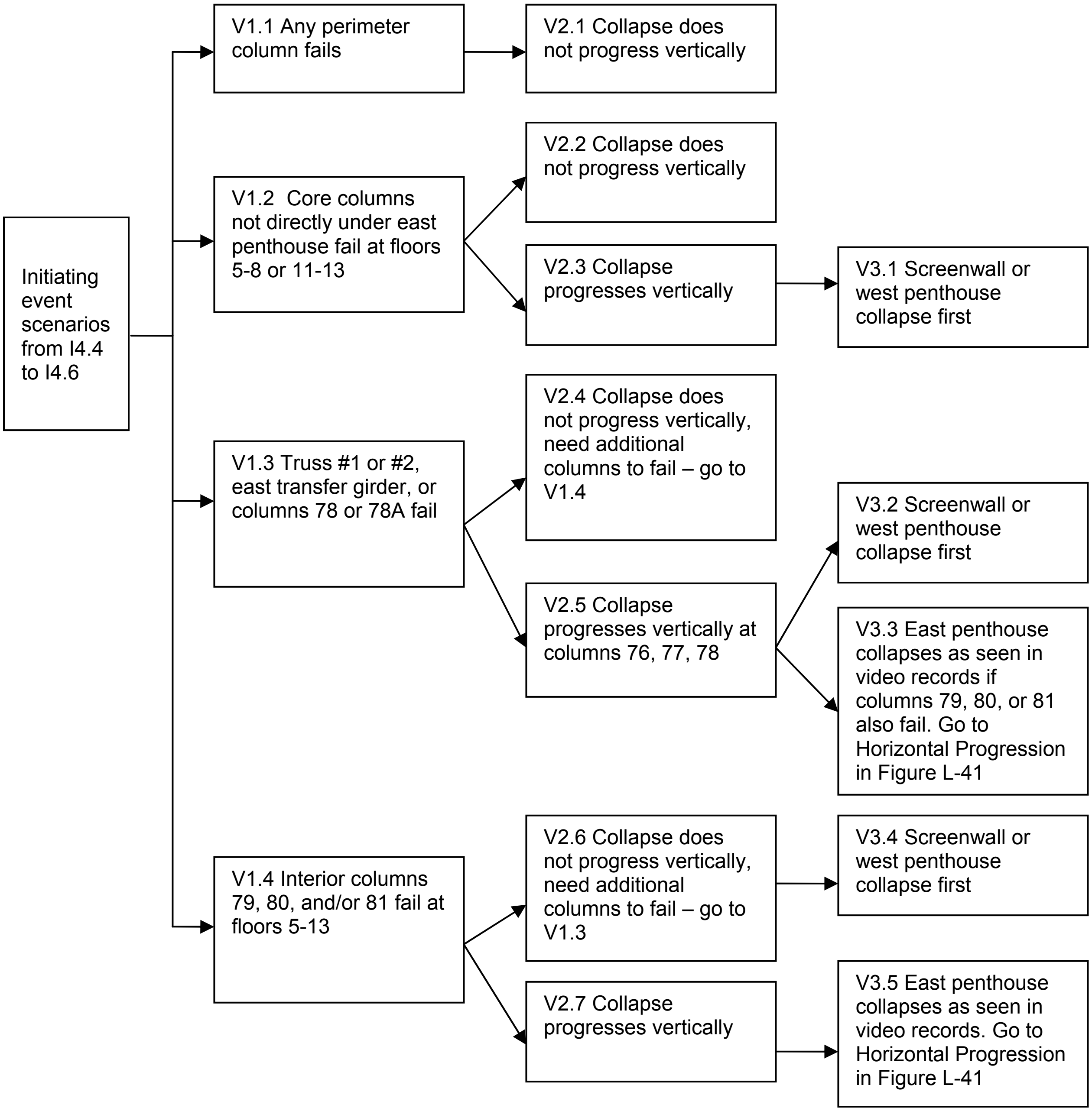


Figure L–40. Vertical collapse progression scenarios.

possibly experiencing fire (Floors 5, 6, 7, 8, 9, 11, 12, or 13). However, a core column may have failed following the failure of adjacent columns or framing members.

- **V2.2 Collapse Does not Progress:** If core columns failed, the loads above the failed columns may have been redistributed to adjacent columns through the core floor system. If the loads could not be redistributed, then additional failures in one or more components would have been necessary to progress the collapse.

- **V2.3 Collapse Progresses:** From this initial failure, the portion of the column above the failure could have fallen, progressing the failure vertically upwards.

- **V3.1 Something Else Besides East Penthouse Observed to Collapse First:** Had the failure of core columns progressed upwards, then the first exterior sign of the internal failure likely would have been seen in the screenwall or west penthouse, which are located above the core columns. A collapse mechanism analysis performed for the removal of columns 61, 64, 67, 70, and 73 produced geometry changes that differed from the observed collapse. For the scenario where each of these columns fails and the failure progresses upwards to the roof line as the adjacent floors cannot redistribute the loads, the screenwall or the west penthouse collapses, and no kink develops in the east penthouse (see Figs. L–41, L–42, and L–43).

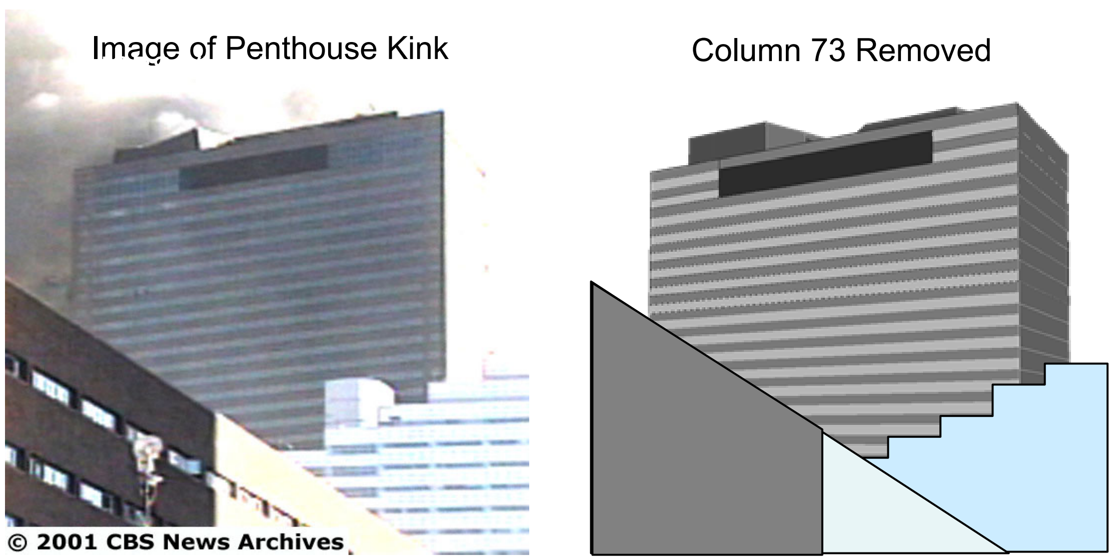


Figure L–41. Geometry changes for removal of column 73.

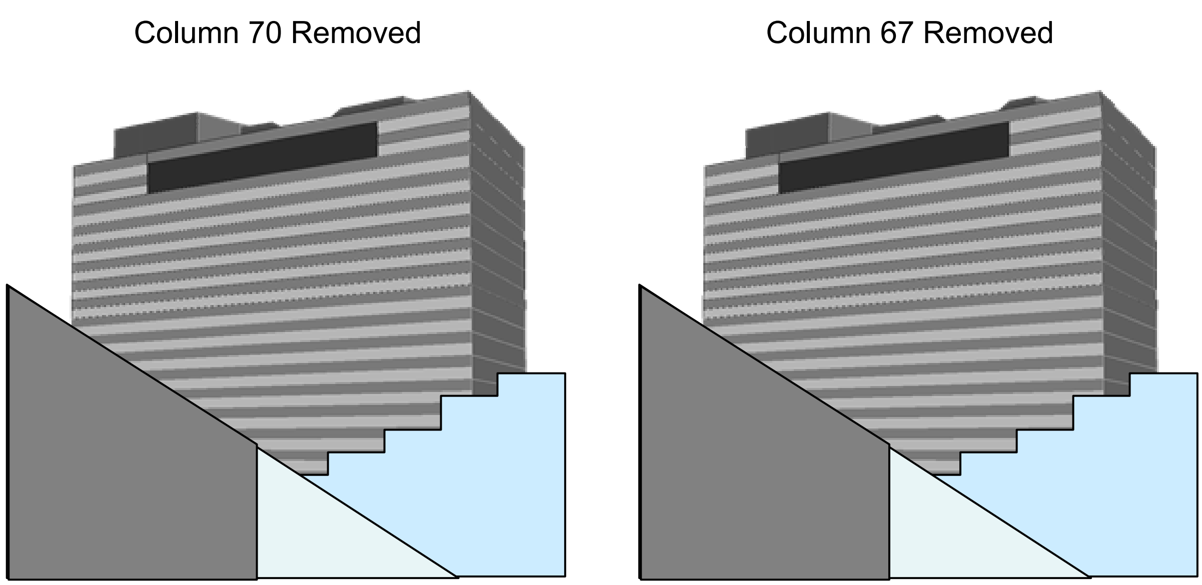


Figure L–42. Geometry changes for removal of columns 70 and 67.

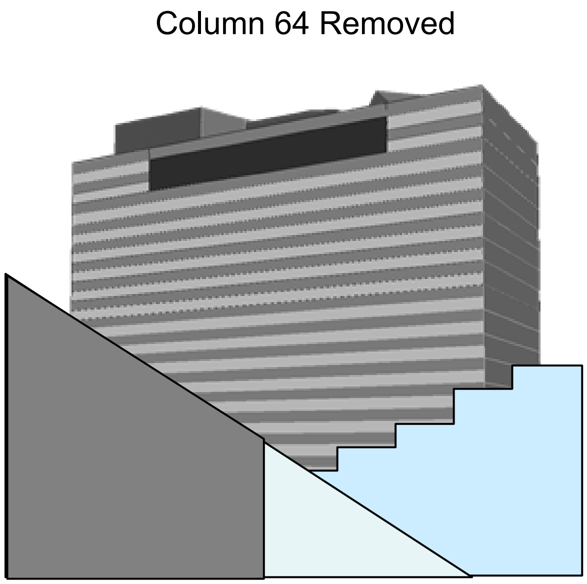


Figure L–43. Geometry changes for removal of columns 64 and 61.

V1.3 Truss #1 or Truss #2 East Transfer Girder, or Columns 78 or 78A Fail: Had the initiating component been truss #1 or truss #2, most likely there would have been debris impact damage or possibly fires at Floors 5 or 6. However, truss #2 failure could have followed the failure of the east transfer girder or columns 78 or 78A.

- **V2.4 Collapse Does Not Progress:** If truss #1 or #2 failed, the floor framing, including the Floor 7 diaphragm, may have redistributed the loads to adjacent columns. Had this occurred, additional failures in one or more components would have been necessary to progress the collapse. For instance, the columns 76, 77, 78, 79, 80, or 81 may also have failed, and the combined effect of both component failures could have been sufficient to overcome the supporting strength of the floor systems.

- **V2.5 Collapse Progresses:** If truss #1 failed, column 76 would lose its support at Floor 7, and the failure could have progressed vertically upwards if the floors could not redistribute column 76 loads. If truss #2 failed, columns 77 and 78 would lose their support at Floor 7, and the failure could have progressed vertically upwards if the floors could not redistribute the loads from columns 77 and 78.

    - **V3.2 East Penthouse Collapses Differently Than Observed:** If truss #1 or truss #2 failed and the failure progressed vertically upward to the roof level, the exterior deformations observed in the roof structures would be different from what was actually observed. Column 76 supported the west side of the east penthouse and the east end of the screenwall. A collapse mechanism analysis performed for the removal of column 76 produced a geometry change that shows the west side of the east penthouse and the east end of the screenwall deflecting downward (see Fig. L–44).

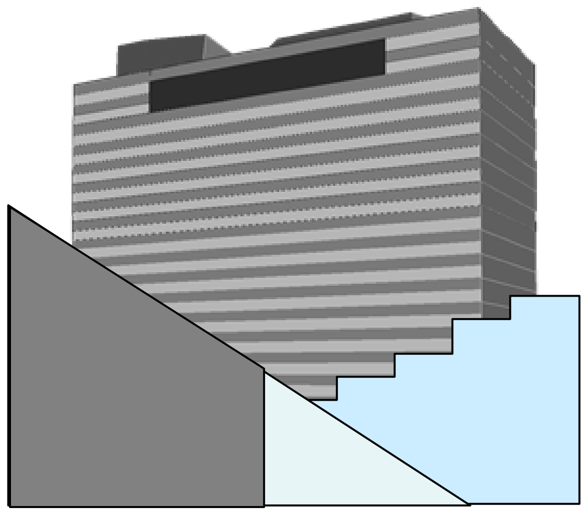


Figure L–44. Geometry changes for removal of column 76.

- **V3.3 East Penthouse Collapses as Observed:** Had the failure of columns 76 or 77 and 78 been followed by the failure of columns 79, 80, or 81, such that the failure of column 79, 80, or 81 progressed upwards, while the vertical progression of failure above columns 76, 77, and 78 was arrested, then the first exterior sign of the internal failures could have been observed at the center of the east penthouse roof.

V1.4 Interior Columns 79, 80 or 81: Had the initiating component been column 79, 80 or 81, most likely the failure would have occurred at the floors possibly experiencing fire (Floors 5, 6, 7, 8, 9, 11, 12, or 13).

- **V2.6 Collapse Does Not Progress:** If only one of columns 79, 80, or 81 failed, the floor systems above the failure area may have redistributed the column loads to adjacent columns. Had this occurred, additional failures in one or more components would have been necessary to progress the collapse vertically upwards. For instance, both columns 79 and 80 may have failed, and the loads of both columns could have been sufficient to overcome the supporting strength of the floor systems.

- **V2.7 Collapse Progresses:** If only one of columns 79, 80, or 81 failed, the floor systems above the failure area may have not been able to redistribute the column loads to adjacent columns. The floor system above Floor 7 had beams and girders, concrete slabs on metal deck, wire mesh in tenant floor areas, and rebar in the core area slabs. These floor systems do not appear to have sufficient bending or catenary action to redistribute loads for failure of column 79, 80, or 81. A calculation of the catenary action that might be developed by the beams and girders framing into column 79, assuming the floors try to redistribute the loads above the area of column 79 failure, found that the girder connections reach their capacity at approximately 10 percent of the estimated service loads and the connections probably fail at approximately 25 percent of the service loads. If the floor-to-column connections had not failed, the beams would have started to yield axially at approximately 40 percent of the service load present.

- **V3.4 East Penthouse Collapses Differently than Observed:** The collapse could have progressed upwards, but the failure caused in the east penthouse could be different than what was actually observed.
- **V3.5 East Penthouse Collapses as Observed:** Had the failure of the column progressed upwards, then it could have been reflected in the observed collapse of the east penthouse, which sits directly above columns 79, 80, and 81. Also, the kink observed in the roof of the east penthouse was in line with these columns. A collapse mechanism analysis performed for the removal of column 79 produced a deformed shape with a kink in the roof of the east penthouse (see Fig. L–45). This is a possible collapse scenario.

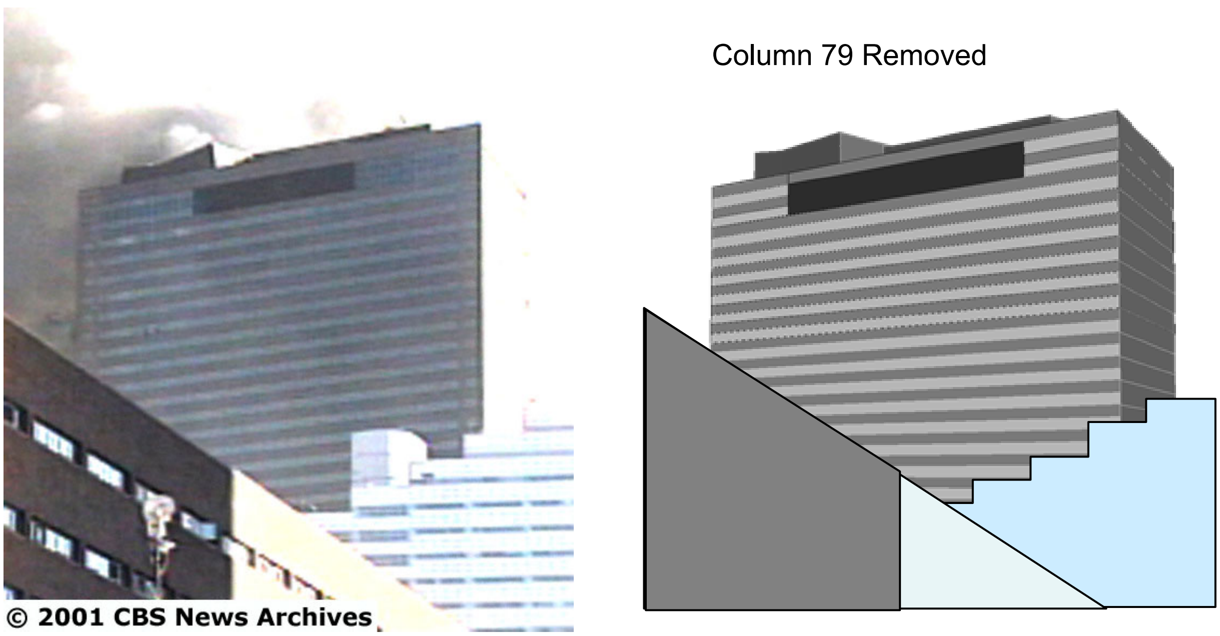


Figure L–45. Geometry change for removal of column 79.

L.3.4 Horizontal Progression Scenarios

After the east penthouse was observed to sink into the building core, approximately five seconds lapsed before the screenwall and west penthouse were observed to also sink into the building core. The screenwall and west penthouse movements occurred almost simultaneously with the global collapse of the structure. From these external observations, it appears that after the vertical progression failure on the east side of the building, the failure progressed horizontally across the core. The horizontal progression of the collapse could have started due to any of the likely vertical progression scenarios, which are shown in Fig. L–46.

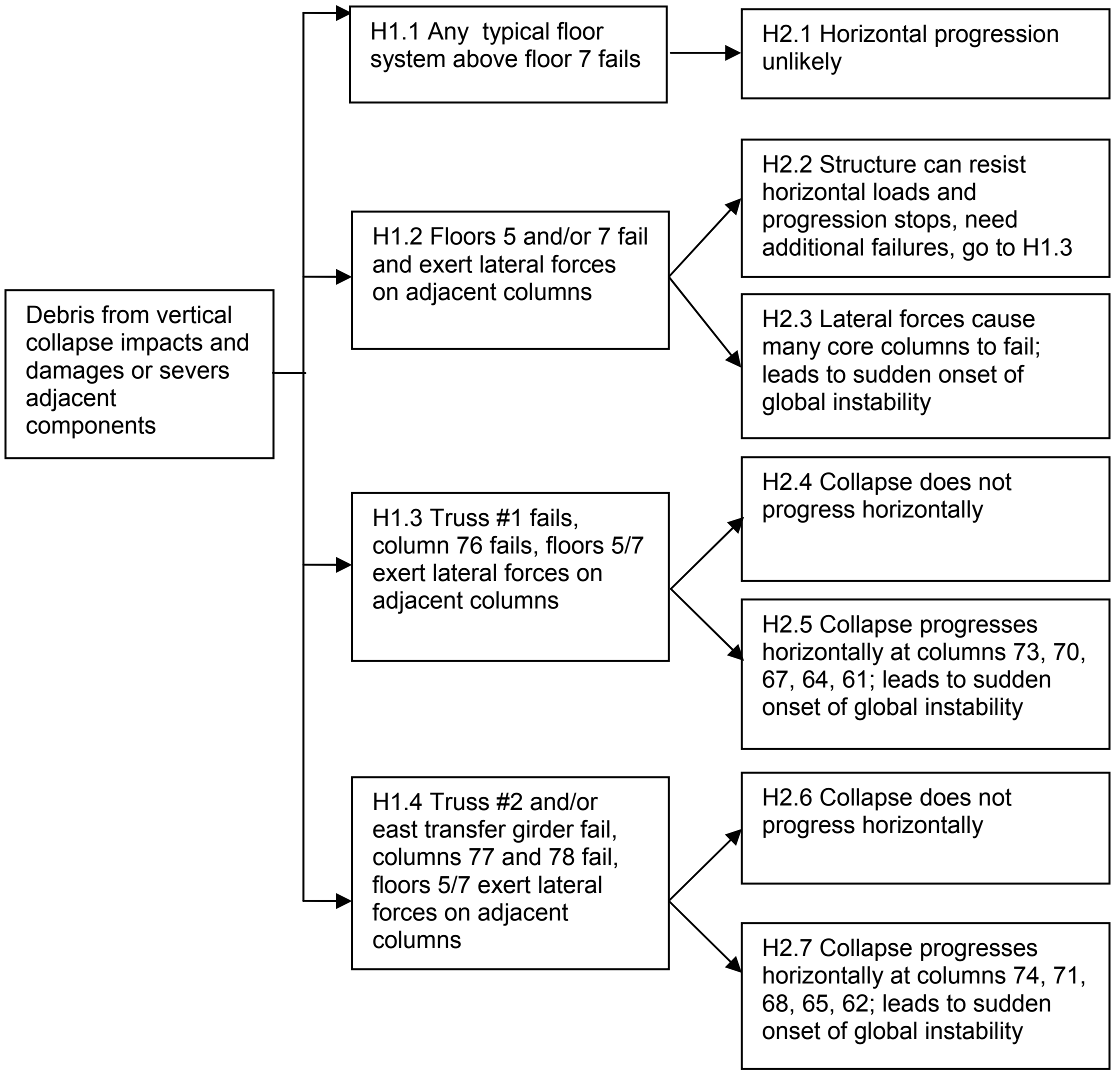


Figure L–46. Horizontal collapse progression scenarios.

The likely region in which the horizontal progression occurred is in the lower portion of the building, around Floors 5 and 7. Floor 5 had a 14 in. reinforced concrete slab on metal deck. The slab was heavily reinforced, and contained steel WT sections embedded in the slab. The WT sections were arranged in a diagonal pattern, like a horizontal truss, within the plane of the floor between the perimeter and core columns. Floor 7 had an 8 in. reinforced concrete slab on metal deck with rebar in each direction. The beams between interior columns at Floors 5 and 7 were much larger than at other floors, and the beam-to-column connections were able to transfer more of the beam axial and bending load capacity. These strong lateral ties between the interior columns may have been able to impose lateral displacements on adjacent columns. Transfer trusses and girders between Floors 5 and 7 transferred loads from the columns above Floor 7 to the foundation columns below Floor 5.

Assuming that a vertical collapse of one or more bays occurred over the height of the building, a large pile of debris would have fallen on Floor 7 and below. Such a large amount of debris is likely to have severed the Floor 7 slab and damaged or severed any transfer truss or girders in the vicinity. For a vertical collapse on the east side of the building, transfer trusses #1 and #2 and the east transfer girder may have been damaged, particularly the east diagonals of the trusses. The scenarios below describe possible responses of Floors 5 and 7 following a vertical collapse of one or more bays.

H1.1 Floor Systems above Floor 7: Typical tenant floors above Floor 7 were constructed with concrete slabs metal deck with wire mesh reinforcement. The steel framing connections were designed for shear loads only, though they could likely resist some degree of tensile catenary forces.

- **H2.1 Collapse Does Not Progress:** For any interior column failure above Floor 7, the tenant and core floor systems are not able to develop sufficient axial tensile loads for imposing lateral deflections on adjacent columns. It is likely that the floor system within a bay will fail before a column failure is propagated horizontally to adjacent columns.

H1.2 Floors 5 and 7: Floors 5 and 7 were thicker and more heavily reinforced than the typical floor systems, and may have been subjected to a large debris load from a vertical collapse within one or more bays.

- **H2.2 Collapse Does Not Progress:** Floors 5 and 7 may fail at connections to adjacent columns before developing any tensile forces large enough to cause other column failures through lateral displacements, halting the horizontal progression.

- **H2.3 Collapse Progresses:** Floors 5 and 7 may impose large tensile forces at the adjacent columns to cause lateral displacements that fail the columns. The failure mechanism could occur at the column splice, located just above Floor 5 and Floor 7, rather than through the column section. The simultaneous occurrence of column instability in many core columns would cause a sudden and large change in the structural system capacity.

H1.3 Truss #1: If one of the diagonals of truss # 1 (see Fig. L–47) was damaged or severed by collapse debris from the vertical progression, there would be a horizontal force developed in the Floor 7 slab as column 76 became unstable. The floor beam between column 76 and column 73 would try to restrain column 76 movement through tensile forces to column 73.

- **H2.4 Collapse Does Not Progress:** The horizontal tensile force would tend to pull the line of columns 73, 70, 67, 64, and 61 towards the east. The continuity of the Floor 7 slab and the presence of braced frames around the north core column line makes the simultaneous lateral displacement of the core columns less likely, as such displacements within a rigid slab may similarly displace other columns, including perimeter columns.

- **H2.5 Collapse Progresses:** The failure of column 76 may create its own vertical collapse, due to the inability of the floor systems above to redistribute the loads and fail at the column splices near Floors 5 and 7 as shown in Fig. L–48. If column 76 cannot be restrained and there is a vertical collapse of the surrounding bay, it would cause a debris pile at the lower floors which may then destabilize adjacent columns.

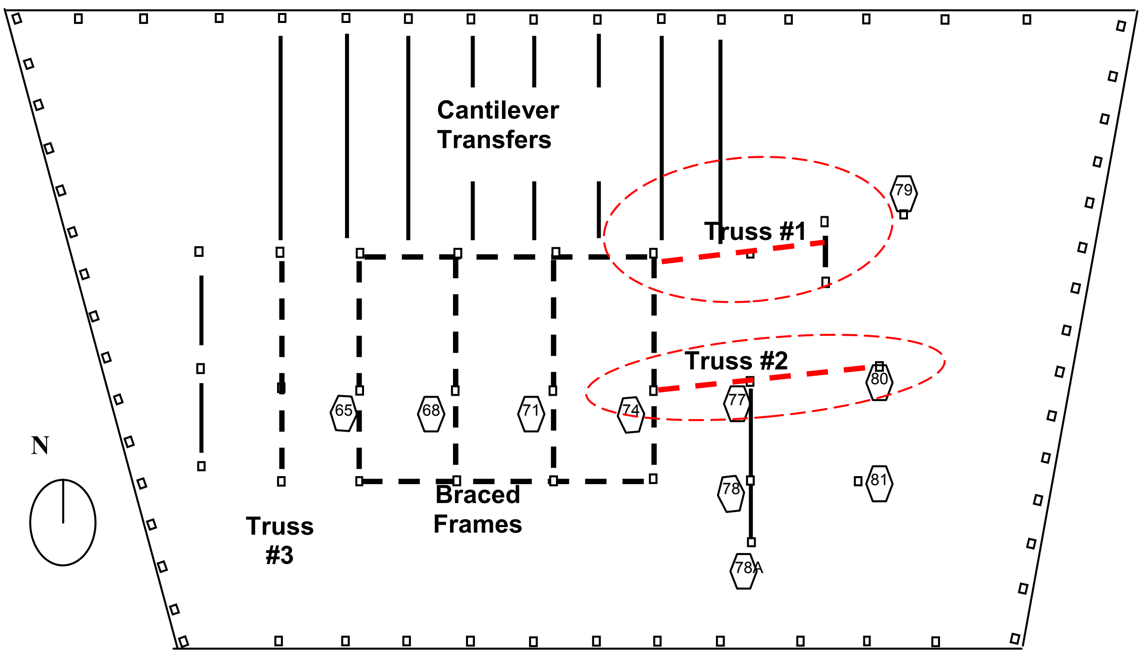


Figure L–47. Transfer components between Floors 5 and 7.

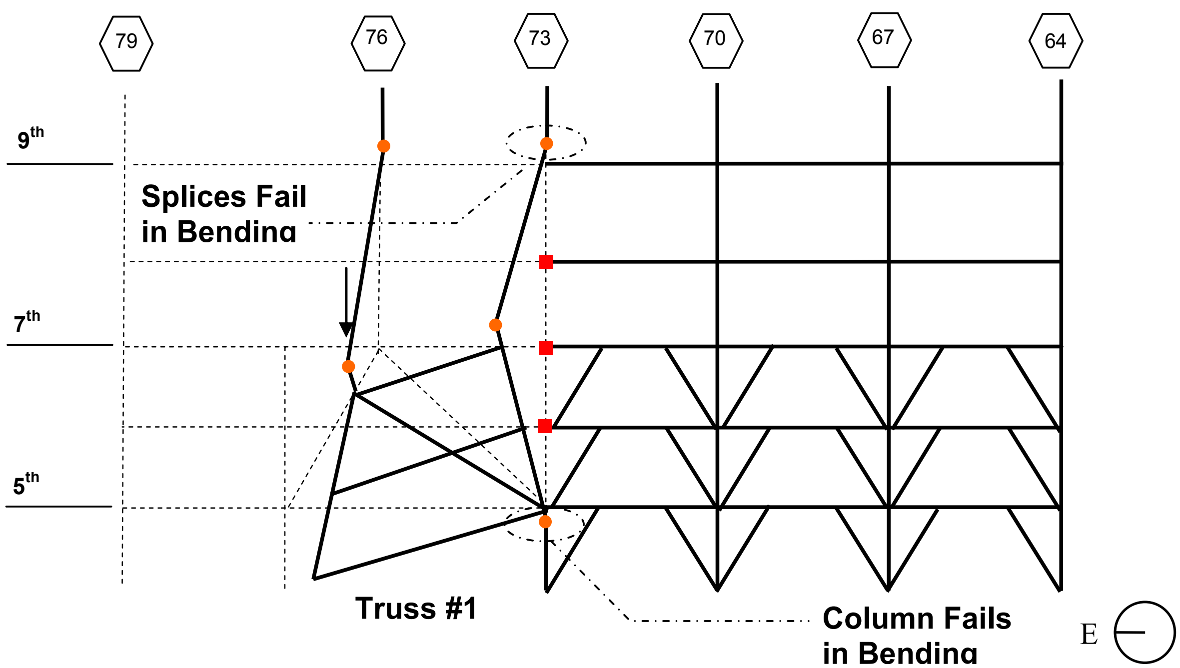


Figure L–48. Horizontal progression mechanism for truss #1 failure.

H1.4 Truss #2 and/or East Transfer Girder: If one of the diagonals of truss # 2 and/or the east transfer girder was damaged or severed by collapse debris from the vertical progression, there would be a horizontal force developed in the Floor 7 slab as columns 77 and 78 became unstable.

- **H2.6 Collapse Does Not Progress:** The Floor 7 slab may fail at adjacent columns prior to imposing lateral displacements sufficient to fail the columns or their splices.

- **H2.7 Collapse Progresses:** The horizontal tensile force would tend to pull the line of columns 74, 71, 68, 65, and 62 towards the east. The general absence of the Floor 7 slab and braced frames around the center core column line, due to the presence of elevators shafts, creates a more likely scenario for the simultaneous lateral displacement of the center core columns without similarly displacing other core columns. The possible result is a failure of all the columns at their splices, as shown in Fig. L–49.

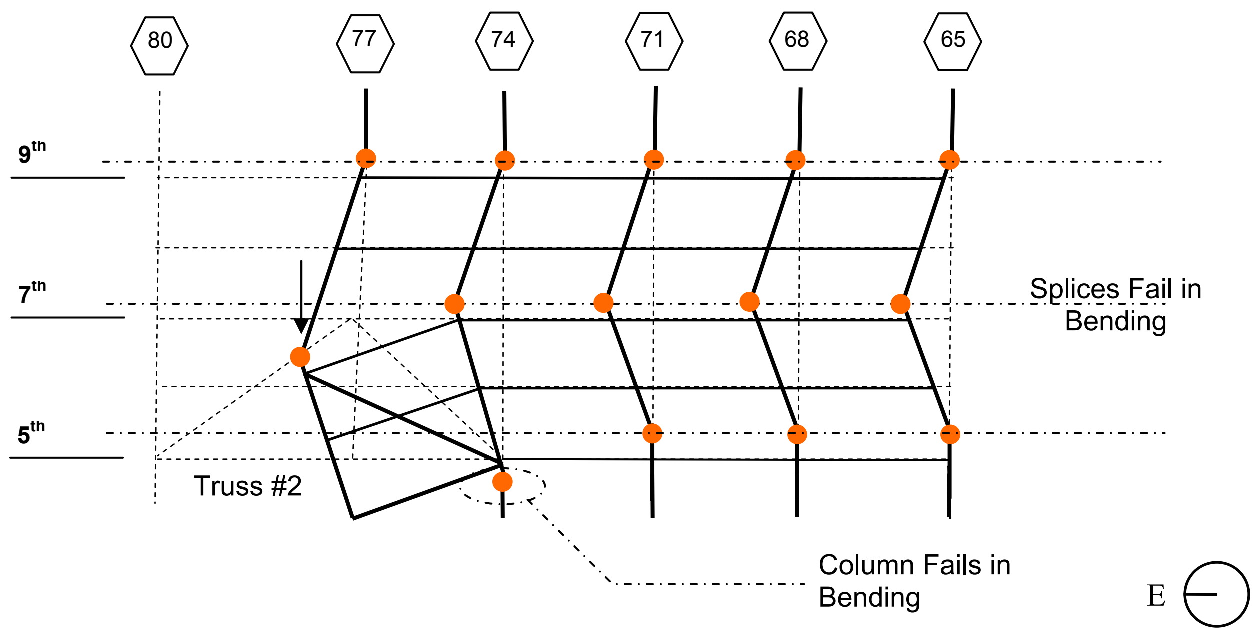


Figure L–49. Horizontal progression mechanism for truss #2 failure.

L.3.5 Summary of Working Collapse Hypothesis

The working collapse hypothesis has been developed around four phases of the collapse that were observed in photographic and videographic records: the initiating event, a vertical progression at the east side of the building, and a horizontal progression from the east to west side of the building, leading to global collapse.

From an analysis of the observed collapse sequence, the following general sequence of events appears possible:

1. Debris damaged the south face of the perimeter moment frame and some interior core framing on the south side. The debris impact severed approximately a quarter to a third of

the south face perimeter columns. The damaged floors are less certain, but reports indicate they occurred between the ground and up to Floors 15 or 20. The extent of damage, both structural and to fireproofing, of core framing is not known, but damage to elevator cars and shafts was reported to have occurred around columns 69 to 78 at Floors 8 or 9.

2. Fires were observed after the collapse of WTC 1. Fires were observed after 2 pm on Floors 7, 8, 9, 11, 12, and 13. Fires were not observed on Floor 5, but this may be due to the lack of windows. The presence of a fuel distribution system and the possibility of damage at the south face from WTC 1 debris impact, indicates that fires may have been present on Floor 5.

3. The initiating event may have included a number of structural components, though the relative role of impact damage and fire need further investigation. Possible components that may have led to the failure of columns 79, 80, and/or 81 include interior columns 69, 72, 75, 78, and 78A, the east transfer girder (which supports column 78A and frames into transfer truss #2), and adjacent framing and floor systems.

4. A vertical collapse appears to have occurred after interior columns 79, 80, and/or 81 failed. This failure mechanism would progress vertically upward within the failed bay to the roof level, as analysis indicates that the floors would not be able to redistribute their loads.

5. The debris from a 40-story vertical collapse on the east side of the building would fall down onto the strong diaphragms at Floors 5 and 7 and possibly onto transfer trusses #1 and #2, and/or the east transfer girder. Damage and loading on these floors and transfer components would generate lateral forces which would cause the failure of the remaining core columns. The horizontal progression requires further analysis and investigation, but observations indicate that the remaining core columns appeared to fail almost simultaneously, approximately 5 second after the east penthouse failed.

6. The core columns failed and redistributed loads until the building loads could no longer be supported. Once the core columns failed, the cantilever girders which supported the north facade also failed. The remaining perimeter columns at the east, south, and west facades were either left unsupported or were pulled down with the interior collapse. The global collapse occurred with few external signs prior to the system failure.

The working hypothesis, for the collapse of the 47-story WTC 7, if it holds up upon further analysis, would suggest that it was a classic progressive collapse that included:

- An initial local failure due to fire and/or debris induced structural damage of a critical column, which supported a large span floor area of about 2,000 ft^2, at the lower floors (below Floor 14) of the building,
- Vertical progression of the initial local failure up to the east penthouse bringing down the interior structure under the east penthouse, and
- Horizontal progression of the failure across the lower floors (in the region of Floors 5 and 7 that were much thicker and more heavily reinforced than the rest of the floors), triggered by

damage due to the vertical failure, resulting in disproportionate collapse of the entire structure.

The working hypothesis will be revised and updated as results of ongoing, more comprehensive analyses become available.

L.3.6 Technical Approach for Analysis of the Working Collapse Hypothesis

There are many possible collapse scenarios that have been postulated in the preceding section. Many of the scenarios will not produce the observed sequence of global collapse events and can be classified as unlikely. Likely collapse scenarios will be identified through analyses that test the postulated phases of collapse against observations. It is equally important to test scenarios that are not predicted to match the observed data. The testing of the postulated collapse scenarios will be conducted through hand calculations, simplified nonlinear thermal-structural analysis, and full nonlinear thermal analysis.

L.4 REFERENCES

American Institute of Steel Construction Inc., Manual of Steel Construction, Load and Resistance Factor Design, Third Edition, 2001. Chapter 16-E.

McAllister, T., ed. 2002. World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations. FEMA 403. Federal Emergency Management Agency. Washington, DC, May.

Salvarinas, John J. 1986. Seven World Trade Center, New York, Fabrication and Construction Aspects, *Proceedings of the 1986 Canadian Structural Engineering Conference*, Vancouver, Canadian Steel Construction Council, Ontario. February 24-25.