Comparison of Structural Performance of Multi-Story Buildings Under Extreme Events

Nestor Iwankiw, P.E., Ph.D.
Hughes Associates, Inc.

Lawrence G. Griffis, P.E.
Walter P. Moore & Associates, Inc.

American Institute of Steel Construction, Inc.
Chicago, Illinois

Report

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for

American Institute of Steel Construction, Inc.
Chicago, Illinois

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By

Nestor Iwankiw, P.E., PhD
Hughes Associates, Inc.

Lawrence G. Griffis, P.E.
Walter P. Moore and Associates, Inc.

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Table of Contents

EXECUTIVE SUMMARY

The purpose of this report is to provide a unified structural engineering review and objective assessment of the structural performance of major multi-story building collapses in the U.S. due to the extreme exposures of blast, impact, and fire from the following terrorist events:

- The 1993 bombing of the World Trade Center (WTC) towers in New York City
- The 1995 bombing of the Murrah Federal Building in Oklahoma City
- The September 11, 2001 attacks on the World Trade Center towers and collateral damage of surrounding buildings in New York City
- The September 11, 2001 attack on the Pentagon in Washington DC

For the purposes of this report, a multi-story building is defined as a building with four or more stories. In addition, a historical survey on the performance of multi-story buildings under normal fires has been presented for comparison to these extreme events. This Report was completed without the benefit of any new information that may have been developed or discovered during the course of the currently ongoing NIST WTC investigation. NIST is expected to finish this work and release its findings by the end of in early 2005.

The survival of the WTC to its 1993 bombing demonstrated the excellent resilience of the building's steel framing to an extreme and totally unexpected design scenario without any fire effects. Based on the evidence presented, it is believed that no new design requirements are warranted for blast effects on such steel structures. No related recommendations for steel framing design changes were issued at that time or subsequently. Meanwhile, the almost immediate progressive collapse of a significant portion of the Murrah Federal Building in its 1995 bombing resulted in the recommendation for use of special moment frame seismic detailing in reinforced concrete frames for blast effects, and other similar demands, as well as the newer structural integrity detailing provisions in ACI 318.

Extreme care must be taken to avoid over reaction in changing existing design standards and provisions of building codes. While the events of these terrorist attacks should provoke additional study into the behavior of buildings to better resist such abnormal loads, the real conclusion may be that security measures need to be taken that avoid such incidents, rather than to add additional design requirements for some, or all, buildings.

Comparable fire risks exist across the available building materials. The 2002 NIST survey (Iwankiw and Beitel, 2002) revealed that no one type of construction material or occupancy type was more prone to a fire-induced structural collapse than any other. The conclusion to be reached from this historical data is that fire effects are equally damaging to all building materials and types. This may be self-evident to some as presenting merely a confirmation of the importance of prevailing fire protection and fire resistance code provisions. Nevertheless, it is also a reminder that well-designed steel buildings are no more vulnerable to fire than those well designed and constructed of any other noncombustible material. The comparable performance of the WTC buildings and the Pentagon on September 11, 2001 further substantiates this conclusion.

Similar structural distress mechanisms for fire in combination with impact damage exist for steel and reinforced concrete buildings. The structural stability and integrity of the greatly damaged WTC 1 and 2, standing for 102 minutes and 56 minutes after jet impact, respectively, permitted the safe evacuation of many thousands of their occupants and those from the entire WTC complex. The Pentagon's secondary partial collapse was delayed for 20 minutes after jet impact, and this time also allowed for many to successfully evacuate. The final distress mechanism for all three of these buildings was identical in nature: fire degradation of an impact damaged structure. Loss of both spray-applied fire protection on the steel and concrete cover to reinforcing was critical to the fire-induced secondary collapses of these weakened structures.

The more conservatively designed Pentagon building experienced the less severe impact conditions on Sept. 11, 2001. The WTC impact conditions were more severe than those for the Pentagon relative to impact elevation, jet weight and on-board fuel of the colliding jets. The WTC towers and the Pentagon were entirely different building types; the latter was an institutional type building with heavy design live loads (150 psf unreduced) and the former a speculative office building with much lower design live loads (100 psf reduced). Thus, the Pentagon's initial structural design was more conservative than that for the WTC.

During the Sept. 11, 2001 events, longer survival times until secondary collapse were evidenced for the WTC towers. The stability of the damaged two WTC towers and the Pentagon until secondary collapses occurred was crucial in saving numerous lives. In view of the initial and impact conditions that favored a longer survival time for the Pentagon, it is surprising that both WTC towers avoided secondary collapse for substantially longer times than did the Pentagon. A part of this answer may be the dual purpose for reinforced concrete cover in columns (fire resistance and load-bearing capacity), and the correspondingly greater structural effects of its loss after impact and under fire conditions than for steel spray-applied fire protection, which does not contribute to its load-bearing strength.

The importance of architectural layout (building footprint and height) was apparent from the WTC and Pentagon attacks. The number of casualties and collapsed floors in the affected buildings on September 11, 2001 are principally dependent on the original architectural layout (building height and floor plans) of the individual buildings. Consequently, it can be postulated that taller and sleeker buildings, with relatively fewer columns subjected to heavier loads, will be more vulnerable to catastrophic collapse and to more numerous casualties under similar abnormal hazards, regardless of construction material and framing type, than flatter and more expansive mid-rise buildings, with all else being equal. Thus, enlargement of the building footprint to more widely distribute its occupancy and weight in the horizontal plane, with accompanying increase in number of columns but decrease in number of floors, is one strategy to minimize the potential fatalities and destruction from extreme events. However, the scarcity and premium for available open land for new construction, especially in the U.S. and the world's major urban areas, will probably render this alternative solution to be difficult for implementation in many cases.

One measure of framing redundancy is the "leaning" gravity index with a higher number indicating an increased relative risk of vulnerability. A simple set of objective functions for optimizing performance under extraordinary conditions is to maximize building footprint, minimize height, and minimize gravity only ("leaning") columns and simple framing. Other comparative risk indices could be similarly defined and used for all types of buildings and construction materials. Certain critical elements of taller structures, such as transfer girders/trusses and their supporting columns, also may warrant additional design consideration for increased strength and reliability.

There are changing magnitudes and nature of abnormal structural demands during and after the extreme loading period. A general problem with such extraordinary conditions is that structural member and connection demands often change quite radically during the course of the event, not just in the higher magnitude of applied loading and stresses, but also in the nature of this loading and stress reversal. One such example is floor beams and slabs which, though primarily designed for flexural resistance due to ordinary gravity loads, can be subjected to uplift from blast pressures and tension due to catenary action under fire. This can also occur with the failure of other supporting elements. The variety of potential alternate load paths that may be necessary to maintain structural integrity for each conceivable emergency scenario realistically cannot be fully defined, analyzed or constructed. FEMA 277, FEMA 403, and ASCE-SEI (2003) all discuss these phenomena and their effects.

Building Performance Reports for extraordinary events should be standardized in format, and the reports should be factual, objective, and address all relevant items.

New standards need to be developed in design for abnormal loads applicable to all types of building materials and construction. Such standards need to define a cost/benefit ratio for the particular risk addressed in the design. The cost of construction of ordinary buildings should not be unduly penalized.

It is expected that the observations cited will stimulate further responsible and professional discourse on the issues discussed with accompanying progress toward solving the problems raised. However, while important, undue over-reaction to the events themselves or any single issue is not warranted.

1. INTRODUCTION

Perceptions in the US of personal safety and security have changed dramatically since the September 11, 2001 terrorist attacks in New York and Washington, DC. New feelings of domestic vulnerability and vigilance have replaced the tranquility resulting from the end of the Cold War era with the USSR. Beyond merely emotional changes, these events have had some real effects on the daily lives of most individuals. As a nation, we have reacted to these events with new policies and regulations such as the mobilization of a new homeland security department, implementation of heightened airport restrictions and inspections, improvements and expansions of federal, state and local emergency plans, deployment of our military forces in Middle Eastern countries, among other actions.

Although the events of September 11, 2001 are certainly most vivid, the actual transition to this new state of existence began as early as February 26, 1993, when the first bombing attack on the World Trade Center (WTC) in New York City occurred. This event dramatically shattered the post-Cold War euphoria and produced the first explicit evidence that a new insidious threat had begun to emerge within the world and the United States (US) itself. Little more than two years later, the nation was shocked by the tragedy of the April 19, 1995 Murrah Federal Building bombing in Oklahoma City. Several deadly terrorist attacks on US facilities abroad followed during the intervening years: Khobar Towers in Saudi Arabia on June 26, 1996; US Embassies in Kenya and Tanzania on August 7, 1998, and the Navy ship USS Cole in Yemen on October, 12, 2000. Thus, the terrorist attacks of September 11, 2001 in New York City and Washington DC represent the critical focus of concern, rather than the beginning, of the new world realities and potential for threats to domestic public safety.

Even more so than natural hazards from wind and earthquakes, the extreme blast, aircraft impact, fire or other exposures associated with terrorist activities carry great potential to be high-consequence events. Yet blast, impact and fire loading from terrorist events are not typically included as design criteria in building codes in the US for normal civilian construction and occupancies. Rather than a design load, fire is typically addressed in US codes by prescriptive rules for building frame protection. In buildings where it is either required or desired, the capability exists, through specialty consulting practice, to incorporate such additional effects into design. However, the engineering and construction cost to incorporate these extreme abnormal loadings in the building design may be quite significant.

Much has been written and said about each of the aforementioned terrorist incidents separately, or within an overall geo-political context. However, there has been no systematic or relative evaluation of structural building performance across these various events. This report will attempt to provide such an evaluation. In addition, it will provide an historical overview of the effects of normal fires on the collapse of multi-story buildings. Several observations and recommendations are given for future building performance studies, damage assessment, and failure reports in order to supplement the previous narrower focus on any single event. It is anticipated that this report will provide a catalyst for additional related studies, professional activities, dialogue and eventually, new building standards, on how to improve building performance under the action of these extreme loads.

2. SCOPE

The objective of this report is to provide a unified structural engineering review and assessment of the structural performance of major multi-story building collapses in the US due to the extreme exposures of blast, impact, and fire from the following terrorist events:

- The 1993 bombing of the World Trade Center towers in New York City
- The 1995 bombing of the Murrah Federal Building in Oklahoma City
- The September 11, 2001 attacks on the World Trade Center towers and collateral damage of surrounding buildings in New York City
- The September 11, 2001 attack on the Pentagon in Washington DC

For the purposes of this report, a multi-story building is defined as a building with four or more stories.

In addition, an historical survey on the performance of multi-story buildings under normal fires will be presented for comparison to these extreme events (Iwankiw and Beitel, 2002). Because each of these hostile terrorist acts on American soil and their consequences are well documented in available references, only key background highlights and facts will be repeated here. The focus of this report will be to provide an objective comparison of structural performance similarities and differences among them and some specific recommendations for the future. This Report was completed without the benefit of any new information that may have been developed or discovered during the course of the currently ongoing NIST WTC investigation. NIST is expected to finish this work and release its findings by the end of 2004.

Earthquake and wind-induced failures are not considered in this report. Similarly, failures due to other conventional loadings or construction issues are not considered. These aspects of building performance are already quite mature and active knowledge areas within the profession.

This work was funded and reviewed by AISC, which the authors gratefully acknowledge.

3. MULTI-STORY BUILDING COLLAPSE FROM TERRORIST EVENTS

3.1. The 1993 World Trade Center Bombing in New York City

On February 26, 1993, a van containing about 1,500 lbs of explosives was detonated in Level B2 of the underground parking garage below the North Tower (also known as WTC 1) and adjacent Vista Hotel (also known as WTC 3) in New York City. The bomb created a large bowl-shaped crater in the parking garage that measured about 180 ft in diameter. Six people were killed and over 1,000 injured, but the remaining tens of thousands of occupants in the WTC complex were safely evacuated.

The floor opening on the B2 level, where the bomb detonated, was roughly 125 ft wide by 135 ft deep. The damage included the five sub-grade reinforced concrete floors below the Plaza, which ranged in thickness from 12 in. to 24 in., numerous below-grade walls and elevator shafts, and several steel column braces and connections (Ramabhushanam and Lynch, 1994). The damaged floor slabs total about 80,000 ft^2 in area.

Figure 1 shows the sub-grade hole created by this bomb blast, which compromised the lateral bracing of several steel columns by eliminating the floor slabs. The high-rise tower remained stable even though the explosion and loss of the floor slabs left seven of the main WTC building columns laterally unbraced for distances up to 60 ft. at these lower levels (Tarricone, 1993). This unbraced length translates to about four times their original design length.

This 110-story WTC 1 building, and its companion the south WTC 2 Tower were constructed in the early 1970’s as steel framed “tubes”, with core and perimeter columns only, that enabled open long-span floors that were column free up to 60 ft. The plan floor area for each tower was 207 ft square, with the exterior perimeter consisting of closely spaced steel box columns connected by spandrels at each floor level. The structural framing system for the towers extended through the sub grade parking and mechanical levels.

Elastic buckling strength of longer slender columns is an inverse quadratic function of their unbraced length, but shorter and stockier columns are governed by inelastic bucking that is relatively less sensitive to changes in member length. Under the assumed idealization that the blast damage increased the column unbraced length from about 15 ft to 60 ft, such a quadrupling of the column length is estimated to have effectively reduced the column strength of the affected members to approximately 33-67% of their pre-existing condition, with an assumption of initially stocky column slenderness ratios of 20-30. The overall structure remained standing through alternative load paths, which likely included whatever degree of lateral support was provided by the debris piles and remaining fire-protective concrete column encasement.

Supplemental bracing of the blast-damaged columns became the first repair priority in the repair effort. Steel hollow structural sections (HSS) were connected horizontally and diagonally as temporary replacement for the failed floor slabs on an emergency basis in five days, after which the many other repairs and clean up could then safely proceed.

Figure 1. Destruction of Floor Slab Bracing and Weakened Lower Columns in WTC 1 after February 1993 Explosion (from Bureau of ATF 1993 explosives incident report)

Figure 2. Alfred P. Murrah Federal Building in Oklahoma City Before Explosion

Throughout this entire blast event and subsequent repairs to the widespread sub-grade damage, the 110-story tower did not experience any other structural deterioration or progression of failures. Even though burning fires were not identified as a problem, the smoke damage and containment from the blast throughout the entire tower was also a major issue that was satisfactorily resolved.

The building was successfully restored to full service, with the return of tenants started within one month from the date of the bombing. In the aftermath of this 1993 bombing, main attention was directed at improved security and egress measures. The enhanced security measures served to minimize the potential blast threat within, or adjacent, to the structure. The enhanced egress measures included stairwell lighting, signage and smoke control features that made a significant difference for the occupants below impact levels on the later September 11, 2001 attack.

3.2. The 1995 Murrah Federal Building Bombing in Oklahoma City

The Alfred P. Murrah Federal Building in Oklahoma City, shown in Figure 2, was a 9-story office building, built between 1974 and 1976. It was designed as an ordinary moment frame of reinforced concrete for the GSA Public Building Service, occupying a plan footprint of approximately 100 ft by 220 ft within a complex that also included adjacent one-story buildings and a multi-level parking garage. A regular 20 ft by 35 ft floor bay pattern was used throughout the major office space on the third floor and above.

A bomb, estimated to be about 4,000 lbs TNT equivalent, was detonated on April 19, 1995. It immediately failed parts of three of the building's columns stacks and four levels of floor bays on the north face, as shown in Figure 3. The detonation occurred about 16 ft from column G20, and caused a crater approximately 28 ft in diameter and 6.8 ft in depth. The initial blast damage area in the Murrah Federal Building can be estimated to have totaled about 11,200 ft^2 of floor area. Approximately three seconds after this blast detonation, a progressive collapse ensued that brought down almost the entire northern half of the 9-story building, as shown in Figure 4. The term progressive collapse, as used herein, is generally defined as one which the failure is significantly disproportionate to the initial triggering event. The ratio of the final collapsed floor area to that originally damaged by the blast is roughly four, which would qualify the Murrah Federal Building collapse to be considered a progressive, or disproportionate, collapse.

While the total number of deaths from this disaster is not given in the FEMA 277 Report, Hinman and Hammond (1997) indicated a total of 167 casualties. FEMA 277 does cite that about 90 percent of the casualties occurred due to crushing from the building's progressive collapse and falling debris.

The Alfred P. Murrah Federal Building's typical one-way concrete floor slab was 6 in. thick, with temperature steel only in the north-south direction and #4 bottom bars at 9 in. on center spanning in the east-west direction. T-beams spanned 35ft. in the N-S direction at the column lines with E-W spandrel beams present at each floor level. Its north side reinforced concrete columns at the first floor were 20 in. by 36 in. The reinforced concrete transfer girder at the third floor measured 5 ft deep by 3 ft wide, while other typical floor girders were about 3 ft deep by 1½ ft wide.

Once the three columns on lines G16, G20, and G24 were initially damaged by the blast at the second level to effectively sever their vertical gravity load paths, the rest of the northern half of the frame was unable to redistribute these loads to the remaining members, and progressive collapse ensued. Simply put, given the initial blast damage and member failures, particularly the critical loss of the lower column G20, the remaining structure of girders and columns had inadequate flexural continuity to support the existing building loads.

FEMA 277 attributes the causes of this progressive collapse to several factors. One factor was the lack of continuity reinforcement in the transfer girders and floor slabs, which was not required by code for a concrete Ordinary Moment Frame. A second factor was the ordinary detailing provisions for the concrete columns did not provide for the redundancy and ductility necessary for additional column demands, which would have been present with spiral and shear reinforcement. The absence of these features contributed to the original blast damage in the columns, and subsequently did not allow for a beneficial secondary bending mechanism to develop in the floor spans between the surviving columns. This led to the final catastrophic failure. FEMA 277 concludes and recommends that seismic detailing, as required for a concrete Special Moment Frame, would have mitigated much of the primary and secondary structural damage for this type of explosion. The American Concrete Institute (ACI) has since introduced reinforcing detailing requirements for structural integrity, currently contained in Section 7.13 of ACI 318-02. These requirements are general prescriptive criteria intended to provide some nominal continuity of reinforced concrete joists, beams and two-way slabs for cases of limited unexpected structural damage, such as failure of one support.

Apart from repairs required to maintain safety for the emergency search and rescue work after the explosion, no repairs on the Murrah Federal Building were attempted. The damaged building was demolished.

3.3. The September 11, 2001 World Trade Center and Pentagon Attacks

At the time of their design and construction, the WTC and Pentagon buildings were state-of-the-art landmarks. On September 11, 2001, they were subjected to a combination of extraordinary loads under severe conditions that went far beyond normal design criteria.

The 110-story WTC towers had long-span floors allowing column-free areas up to 60 ft, which were designed for 100 psf live load, reduced as allowed by code with live-load reductions for tributary area. Additionally, significant value engineering efforts in the finalization of the design led to the selection of a unique floor system composed of two-way composite steel trusses topped with 4 in. of lightweight concrete on 1½ in. deep, 22-gauge non-composite steel deck. The floor system was a part of the lateral system because of the presence of viscoelastic dampers at the bottom chords of many of the trusses, which were intended to reduce wind-induced building motions. The WTC footprint for each tower was a 207 ft square and totaled about 4.7 million ft^2 of office space.

The 5-story Pentagon, built between 1941 and 1943, is a cast-in-place reinforced concrete structure with regular short spacing of spirally reinforced concrete columns at 10 ft to 20 ft on center throughout the outer ring building. Thus, the floor spans were relatively short, with a 5½-in. thick slab generally spanning to beams at 10 ft on center. Each of the five exterior building faces measures 922 ft in length and 372 ft in width with five circumferential ring subdivisions, to total about 6.6 million ft^2 of office space. Such an enormous amount of office space makes the Pentagon the largest office building in the world. The Pentagon has exterior concrete walls nominally 10 in. thick with regularly spaced window openings. It possessed the additional beneficial features of spirally reinforced concrete columns, enhanced floor slab reinforcement continuity for two-way bending action and extension of bottom reinforcement of beams and girders through their supports. The building was designed for a higher than normal 150 psf floor load, with no live-load reductions taken for tributary area. The perimeter wall at the impact area Ring E was faced with 5 in. thick limestone backed by 8 in. of unreinforced brick infill within the concrete frame.

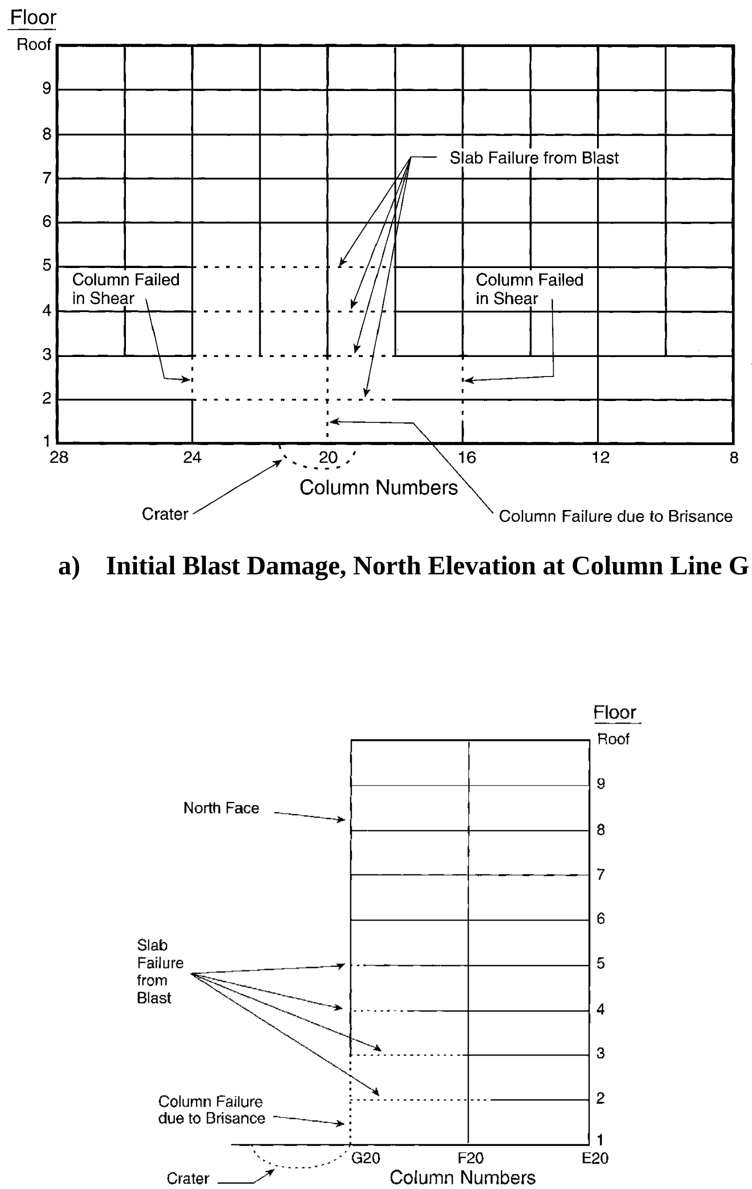
The attacks in New York City and Washington DC on September 11, 2001 have been well documented in FEMA 403 (2002) and ASCE-SEI (2003). More extensive information on these events can be found therein. Tables 1 and 2 summarize the pertinent facts of that catastrophic day drawn from these two sources, and Figures 5 and 6 show their representative visual images.

The two WTC towers and Pentagon were all designed to be of fire resistive, protected, noncombustible construction. The Pentagon building had been undergoing an extensive renovation and upgrading, which was nearly completed in the "Wedge1" section adjacent to the September 11, 2001 impact area. Consequently, it is reasonably assumed that there was much lower occupancy of the Pentagon in and near this construction zone than normal; this is significant in that it reduced the number of individuals at risk in and above the impact area. In fact, of the 189 total casualties in the Pentagon, 64 were aboard the hijacked aircraft, and the remaining 125 were occupants in the building. The deaths of the building occupants were attributed to either fire causes, or a combination of impact and fire. The estimated occupancy of the two WTC Towers at the time of the attacks was also lighter than normal and much less than full capacity for a variety of reasons.

Two other buildings in the World Trade Center complex experienced partial or total collapses on September 11, 2001:

- The 9-story WTC 5 building suffered extensive structural damage and fire ignition from the WTC 1 collapse debris that fell on it. Partial collapse of four intermediate floors occurred in an area below the roof which remained intact. Interior steel floor beam splices between supporting tree-column stubs were identified as the point of failure of these several floor bays. Splice failure has been attributed to probable fire-related causes.
- The full collapse of the 47-story steel-framed WTC 7 building occurred approximately seven hours after the collapse of WTC 1. WTC 7 was placed into service in 1987 with conventional structural steel framing and fire protection. The lower floors were framed using an interior braced core with a number of transfer trusses and two-story belt trusses. Above this, the structural system was a perimeter steel moment frame. The floors consisted of standard steel beams with composite deck and concrete topping, and the structural steel was protected by spray-applied fire proofing material to provide the necessary fire-resistive construction required by the code. The building also had automatic sprinklers of typical "light hazard" design for office occupancy. Although WTC 7 was not directly impacted by either of the jets, the building experienced some undetermined degree of impact damage from the falling WTC Tower debris, as well as disruption of the water supply for its automatic sprinklers. The eventual collapse of WTC 7 was also significantly influenced by the continuity of its fires, which were uncontrolled and likely fed by some existing fuel sources in the lower levels of the building. FEMA 403 noted that continuing fires

were observed in several areas of WTC 7, particularly near the transfer trusses, from the time of the collapse of the WTC Towers through the time of its own collapse.



a) Initial Blast Damage, North Elevation at Column Line G

b) Elevation Section of Blast Failures

Figure 3. Immediate Blast Damage to Murrah Federal Building

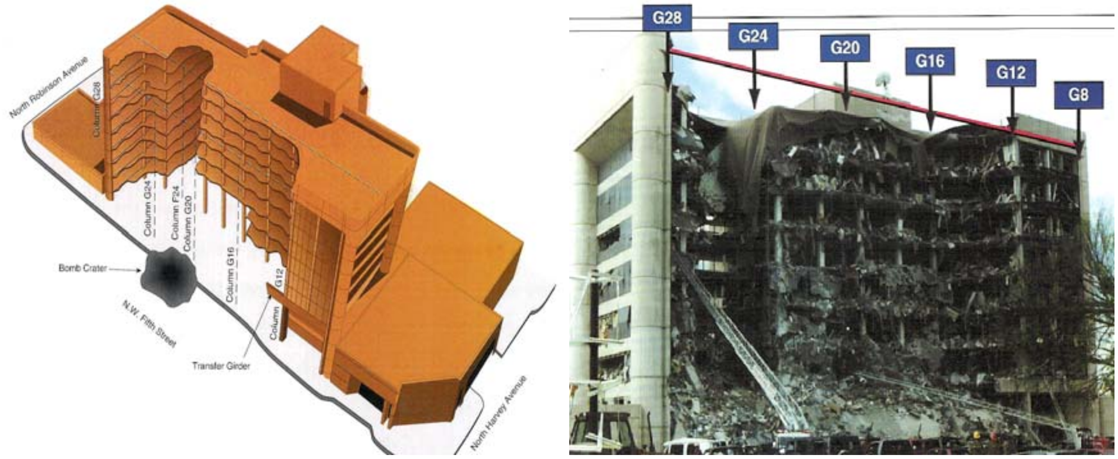


Figure 4. Progressive Collapse of North Side of Building

Figure 5. WTC 2 Fireballs – Second Jet Impact on September 11, 2001

Figure 6. Pentagon Crash Site After Sept. 11, 2001

Table 1. Comparisons of Pentagon and WTC Disasters of Sept. 11, 2001

BUILDING	**Pentagon**	**WTC 1**	**WTC 2**
Number of stories	5	110	110
Plan area and total office space	Five 922 ft long sides with 5 circumferential rings, 372 ft wide, 6.6 million ft^2	207 ft by 207 ft 4.7 million ft^2	207 ft x 207 ft 4.7 million ft^2
Footprint area	1.32 million ft^2	42,800 ft^2	42,800 ft^2
Structural framing	Reinforced concrete	Steel tube (perimeter and core columns)	Steel tube (perimeter and core columns)
Typical size of office floor bays	Regular 10 ft to 20 ft column spacing grid	Clear spans of up to 60 ft between perimeter and core	Clear spans of up to 60 ft between perimeter and core
AIRCRAFT	**Boeing 757-200**	**Boeing 767-200ER**	**Boeing 767-200ER**
Estimated jet impact gross weight and speed	181,520 lbs at 530 mph	274,000 lbs at 470 mph (FEMA 403)	274,000 lbs at 590 mph (FEMA 403)
Estimated aviation fuel onboard	36,200 lbs (5,300 gal)	68,300 lb (10,000 gal)	68,300 lb (10,000 gal)
Estimated fireball size	200 ft diameter	Greater than 200 ft	Greater than 200 ft
Number of Fireballs	1	3	3
Estimated amount of fuel consumed in initial fireball(s)	720 gal (4,900 lbs)	3,000 gal (20,400 lbs)	3,000 gal (20,400 lbs)
Estimated Initial Serious Damage Characteristics			
Number of severed, or structurally impaired, column lines	50	50 (30 perimeter and 20 in core) [2]	35 (30 in perimeter and 5 in core)[2]
Width	90 ft	65 ft	70 ft
Length	300 ft	100 ft to 150 ft	100 ft
Height	25 ft	65 ft	65 ft
Avg. Damage Volume	506,000 ft^3	528,000 ft^3	455,000 ft^3
Number of deaths	189 (active office, but with reduced occupancy for area under construction)	Approx. 2,800[1](active office buildings, but at much less than full capacity during impacts)	
Actual time from impact to secondary structural collapse	20 minutes (partial-all five levels of outer Ring E between col. lines 11-18)	102 minutes (full)	56 minutes (full)

[1]Total for entire WTC site
[2]Structural impact damage only for perimeter columns from FEMA 403, core column structural damage from Silverstein, Inc. (2002)

Table 2. Selected Information on Two Large Commercial Aircraft

Specification	Boeing 757-200	Boeing 767-200ER
Wingspan	125 ft	156 ft
Body Length	155 ft	159 ft
Tail height	45 ft	53 ft
Maximum takeoff weight	255,000 lb	395,000 lb
Maximum fuel capacity	11,275 gal	24,000 gal

4. MULTI-STORY BUILDING COLLAPSES FROM NATURAL FIRES

Information on fires in multi-story buildings around the world was compiled as part of a recently completed NIST project to assess the needs and existing capabilities for full-scale fire resistance testing. A report (Iwankiw and Beitel, 2002) was issued that included the survey results of past multi-story building collapses, either partial or total, that were directly caused by fires. For this study, multi-story buildings were defined as those with four or more stories. This historical survey of "normal" fires in such buildings and their structural consequences helps to put the extreme events of September 11, 2001 into better perspective. As significant as these events were, they were also clearly not representative of the "normal", mostly accidental, effects of fire on building structures.

A total of 22 such cases were identified after extensive searches of the literature including news sources and other contacts. The September 11th disasters were counted as five of these incidents (WTC 1, 2, 5 and 7, and the Pentagon). The cases identified occurred not just in the US and North America, but also internationally as well. This NIST survey data, summarized in Table A1 of the Appendix A, demonstrated that buildings of all types of construction and occupancies from all over the world are susceptible to fires and potentially to fire-induced collapse. Older buildings and those that may be undergoing construction, renovations or repairs seemed to be slightly more vulnerable, as will be discussed later. The total fatalities were dominated by the September 11th WTC and Pentagon disasters. These incidents were unique, as previously described, in that they were precipitated by terrorist attacks that substantially damaged the building's structural framing and destroyed their fire protection systems prior to the fire spread.

Fortunately, "normal" accidental fires in tall buildings do not often lead to partial or total collapse, as evidenced in these 22 documented cases. In addition, all of the fire-induced collapses were not nearly as catastrophic as the September 11th disasters. However, even in those fires that do not trigger structural collapse, the fire and smoke by themselves can cause many deaths in a densely occupied building, as well as significant fire damage and monumental property losses over many floors. For example, the 1980 fire in the unsprinklered MGM Grand Hotel in Las Vegas killed 84 people, injured another 679, and caused hundreds of millions of dollars in property damage (Clark County Fire Department, 1981). If the building is relatively vacant, or under construction, the probability of human fatalities is markedly decreased, but the resulting fire damage, even without collapse, can be significant.

In the US, the 1988 62-story First Interstate Bank fire in Los Angeles burned out four floors (Klem, Thomas J., 1988) and the 38-story One Meridian Plaza, 1991 fire in Philadelphia burned out nine floors (Klem, Thomas, J., 1991). In the UK, the 12-story Mercantile Credit Insurance Building fire in 1991 burned out three floors and the 14-story Broadgate, Phase 8 fires with its unprotected steel beams and columns during erection (Newman, G.M. et al, 2000) are notable examples of excellent structural integrity under adverse fire conditions. However, some casualties and major economic losses were still incurred in these steel-framed buildings. In each of these cases, complete burnouts of several floors destroyed the interior contents and caused substantial and permanent floor sagging and steel beam distortions, as would be expected after a long and severe fire exposure. In the One Meridian Plaza, main support beams deflected as much as 18 in., and one entire area of the 22nd floor had deformed as much as 4 to 5 ft!

Nevertheless, all of these buildings, except One Meridian Plaza, were repaired and returned to service. After extensive investigations and economic studies, it was decided to dismantle One Meridian Plaza rather than to conduct the repairs that could have returned it to service.

Sao Paulo, Brazil had two major high-rise fires in the 1970's in buildings that were constructed of reinforced concrete (Willey, Elwood A., 1972). The 31-story Andraus Building fire on Feb. 21, 1972 resulted in 16 casualties, while the 25-story Joelma fire caused 189 deaths on Feb. 1, 1974. The fires caused severe spalling of large portions of the exterior concrete walls, joists, and columns and exposure of the reinforcing steel, due to the severe fire and resulting high temperatures. Both the Andraus and Joelma Buildings remained standing and they were subsequently repaired and returned to service.

Past experience, confirmed by this recent NIST collapse survey, shows that fires, and the related damage, deaths, casualties and any collapses, are essentially rare and random events. The ultimate effects depend highly on the time, nature and circumstances of the fire occurrence. Therefore, based on this evidence, it cannot be concluded that any one building material (steel or concrete), building type or occupancy in multi-story buildings is more or less susceptible to fire-induced collapse. Consequently, fires represent a hazard to all building types, materials, and occupancies. Likewise, the added fire-fighting difficulty in all taller buildings is recognized, given the longer times needed to escape or access the higher floors. Many of the past major fires in tall buildings fortunately occurred in the evenings or weekends, when the office buildings were almost vacant, thus minimizing their potential dangers to human life. Automatic sprinkler systems are a very effective means to suppress a fire, but if the system is under repair, or is non-existent or non-functional for other reasons, the threat of fire spread increases significantly. For example, the One Meridian Plaza building was undergoing a sprinkler installation retrofit from the top floor down at the time of its 1991 fire. The 9-story fire was halted at the first level at which sprinklers had been installed and operational. Quite probably, the outcome of this major fire would have been radically different if functional sprinkler protection had existed throughout the building.

The NIST survey of 22 fire-induced building collapses since 1970 involved a variety of conditions, materials, locations, and buildings. Fifteen cases were from the US, two from Canada, and five from Europe, Russia and South America. The numbers of fire collapse events can be categorized by building material as follows:

- Concrete: 7 (including one in Pentagon September 11, 2001 event)
- Structural steel: 6 (including four in September 11, 2001 WTC event)
- Brick/masonry: 5
- Unknown: 2
- Wood: 2

Three of these events were from the 1970's, another three from the 1980's, four from the 1990's, and twelve from 2000 and beyond. This temporal distribution is skewed towards more recent occurrences, as expected, both due to the magnitude of the WTC (counted as 4 events) and Pentagon (1 event) disasters of September 11, 2001 and also the available information in news media searches.

The collapse distribution by building story height was as follows:

- 4-8 stories: 13 cases
- 9-20: 3 cases
- 21 or more: 6 cases

Almost 60 percent of the cases are in the 4-8 story range, with the remainder affecting much taller buildings. Six collapses occurred in buildings over 20 stories, but three of these were the WTC buildings (1, 2 and 7).

At least four of these fire collapses occurred during construction or renovations of some kind, where the usual expected architectural, structural and fire protection functions were still incomplete or temporarily disrupted and/or potential new fire sources were introduced. These include such items as electrical and gas line repairs, welding, and the presence of other flammable supplies and/or equipment. Partial collapses (14 events) were the most frequent occurrences, and the WTC disasters (listed as four separate events, with three full collapses) dominated the full collapse event total of eight cases. Office and residential were the primary types of occupancy in these 22 buildings, as would be expected in multi-story construction, with the occupancy distribution being as follows:

- Office: 9
- Residential: 8
- Commercial: 3
- Combined commercial/residential: 2

The September 11, 2001 collapses of the WTC 1, 2, and 7 buildings have been well covered in many other sources. Three much less known examples of multi-story buildings that were not of steel construction and that suffered fire-induced collapses are summarized herein. On May 21, 1987, Sao Paulo had one of the biggest fires in Brazil, which precipitated a substantial partial collapse of the central core of the tall CESP Building 2 (Berto, Antonio Fernando and Tomina, Jose Carlos, 1988). This was a 21-story office building, headquarters of the Sao Paulo Power Company (CESP), after whom the building was named. Buildings 1 and 2 of this office complex were both reinforced concrete frames with ribbed floor slabs. Approximately two hours after the beginning of the fire in CESP 2, its structural core area collapsed throughout the full building height. This collapse was attributed to the thermal expansion of the horizontal concrete T-beam frames under the elevated fire temperatures, which led to the fracture of the vertical framing elements and their connections in the middle of the building, and the consequent progressive loss of gravity load-carrying capacity (see Figure 7).

A partial roof and column collapse of the Military Personnel Record Center occurred on July 12, 1973. This was a large 6-story office building of reinforced concrete construction located in Overland, MO and built in the late 1950's. The building plan area covered 282 ft by 729 ft. The building had fire extinguishers, but sprinklers were present only on the first and second levels. A 1974 Fire Journal article (Sharry, Culver, et al) on this event reported that the fire started at midnight on the 6th floor and burned out of control for 20 hours, due to a very high fuel load of 21.7 million record files stored on the

6th floor. The roof collapse began after about 12 hours of fire exposure, and was concentrated in the 30 percent of the roof slab above the estimated point of origin of the fire. Subsequent to this, most of the remaining freestanding columns on the sixth floor toppled over. Almost no fire damage was experienced below the 6th floor. The collapse and damage were attributed to the large horizontal expansion of the 7-in.-thick, conventional concrete roof slab that was supported by 16-in. square tie-reinforced concrete columns. There were no expansion joints in the floors or roof. Lateral roof displacements of almost 2 ft occurred in one corner. Figure 8 shows the extent of the sixth floor horizontal deformation and damage to the concrete columns due to this roof thermal expansion. These failures appear to be similar to the column failures that have often occurred during earthquakes.

Two large department store fires occurred in Athens, Greece in 1980 (Papaioannoa, 1986). These fires began at 3 AM on Dec. 19, 1980, with arson being suspected as the cause. The Katrantzos Sport Department Store was an 8-story reinforced concrete building. Its fire started at the 7th floor and rapidly spread throughout the building, due to lack of vertical or horizontal compartmentalization and the absence of sprinklers. Evidence collected indicated that the fire temperatures reached 1000°C over the 2-3 hour fire duration, and the firefighters concentrated on containing the fire spread to the adjacent buildings. Upon later inspection, it was discovered that a major part of the 5-8th floors had collapsed. Various other floor and column failures throughout the Katrantzos Building were also observed (see Figure 9). The cause of these failures was considered to be restraint of the differential thermal expansion of the structure that overloaded specific elements or connections.

Figure 7. CESP 2 Core Collapse in Sao Paulo, Brazil

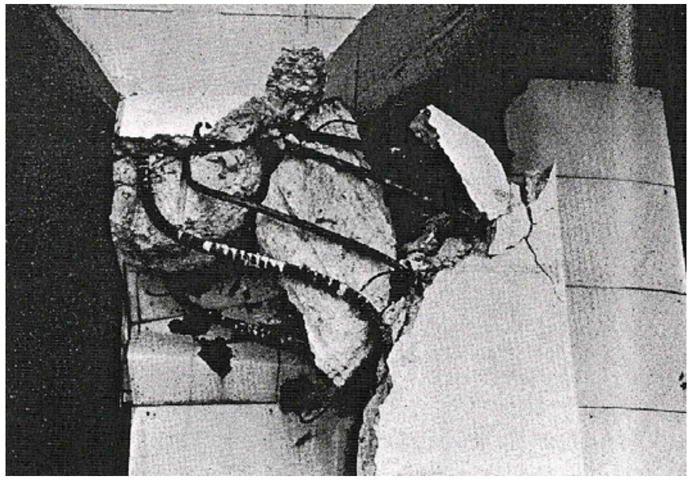


Figure 8. Large Lateral Deformations and Failure of Columns at Sixth Floor of Military Personnel Records Center

Figure 9. Katrantzos Building in Athens, Greece After 1980 Fire

5. OBSERVATIONS OF MULTI-STORY BUILDING COLLAPSES FROM TERRORIST EVENTS AND NATURAL FIRES

5.1. 1993 World Trade Center Bombing and 1995 Murrah Federal Building Bombing

These two tragic incidents from the 1993 and 1995 bombings are compared, since they both involved vehicle bombs detonated near similar vintage multi-story buildings that were designed for the basic code criteria, without seismic detailing and with conventional construction materials. The high-rise nature of its steel framing design provided the WTC Towers with additional reserve strength and redistribution capabilities compared to a more conventional mid-rise concrete building, such as the Murrah Federal Building. The WTC Tower lateral load system design had been originally checked for its strength to withstand an accidental Boeing 707 jet impact, but without consideration of related damage and fire effects. The WTC Towers also possessed proportionally bigger columns than the Murrah Building in the lower levels, with their resulting increased local strength to resist the unexpected blast pressures.

Table 3 summarizes the salient facts relevant to the assessment of the initial conditions and structural building performance. The respective blast effects dominated the structural behavior of both bombings. It should be noted that a subsequent fire was not a factor in either case. Much of the data in Table 3 shows that the structural building response and aftermath to these generally similar blast events in the 1993 and 1995 bombings were substantially different. The most critical distinguishing characteristic was the ability of the WTC towers to sustain a major weakening of seven critical columns due to the destruction of adjacent floor slabs without any local failures or subsequent progression of collapse. With these lower level columns severely compromised beneath the entire 110-story high rise, the WTC tower framing proved capable of redistributing the enormous loads above through alternative load paths to other members.

In contrast, the similarly ordinary detailing of the Murrah Federal Building suffered essentially immediate partial progressive collapse after three of its columns, and several floor slabs, failed due to the blast. A large portion of the remaining structure was unable to support the load from the six stories of superstructure above. In fact, most accounts of the 1995 Oklahoma City bombing have not distinguished between the comparatively limited initial blast damage and the more widespread, ensuing progressive collapse and related casualties.

FEMA 277 recommended that the special seismic detailing requirements are warranted to provide concrete moment frames with the needed ductility and redundancy to form alternate load paths in the event of a localized structural failure. Based upon the relative performance, and in view of the similarities in blast effects and level of detailing in the systems, it does not appear that a similar recommendation would need to be made for the steel construction framing used in the WTC Towers.

It is unknown what the performance of a comparable and conventional 9-story steel-framed building would have been in a similar bombing. However, such a hypothetical simulation and analysis might be worthwhile. Harris and Manzouri (2001) have already conducted a small pilot study for AISC of a 7-story prototype steel-framed building to predict what might happen if certain columns were removed due to blast effects. Further studies were recommended.

Table 3. Facts from 1993 WTC and 1995 Murrah Attacks

	1993 WTC 1	**1995 MURRAH**
Year building construction completed	1971-73	1974-76
Number of stories	110	9
Approximate office plan area	207 ft by 207 ft	100 ft by 220 ft
Structural framing	Steel-framed tube (perimeter and core columns only)	Ordinary reinforced concrete moment frame
Typical column layouts of office floors	Clear spans of up to 60 ft between perimeter and core columns	Columns on grid for 20 ft by 35 ft bays
Amount of Explosive Detonated (TNT equivalent)	1,500 lbs	4,000 lbs
Initial primary blast damage to structure	5 levels of sub grade parking floors totaling 80,000 ft^2, major weakening of seven steel columns over 60 ft of length	3 columns and 4 levels of floor slabs totaling 11,500 ft^2
Secondary collapse	None	Partial, covering almost entire north half of building about 3 seconds after blast
Number of reported deaths	6	167
Number of reported injuries	Over 1,000	601
Structural recommendations	None	Use special seismic detailing for blast damage mitigation
Final Disposition	Repaired in about 1 month and returned to service	Remains demolished for new building

5.2. World Trade Center and Pentagon Attacks

5.2.1. General Observations

In contrast to the attacks in 1993 and 1995, the WTC Towers and Pentagon buildings were all first significantly damaged by the impact of the airplanes that were deliberately flown into them. Each building was also further damaged by the fireballs that ensued shortly thereafter, igniting massive instantaneous fires. These fires weakened each structure until collapse occurred.

Of significance, these three buildings were the first to be subjected to such an extraordinary combination of maximum lifetime effects in combination: extensive structural damage combined with extraordinary fire exposures. Neither of these effects is anticipated or addressed in building codes or routine design practice. While fire protection is a design requirement in building codes, code requirements do not anticipate the nature of fire ignition, propagation and simultaneous systematic destruction of fire protection and suppression systems experienced in the WTC Towers and Pentagon building on September 11, 2001. Most of these fire safety requirements are prescriptive and intended for "normal" fire occurrences.

The eventual structural collapse times after impact of the Pentagon and WTC Towers are given as part of Table 1. In all three cases, immediate collapse beyond the directly damaged areas was avoided. Both WTC Towers suffered a total progressive collapse after 56 and 102 minutes, as shown, due to extensive and continuous fires burning within severely damaged structures. For the identical reasons, the Pentagon had a partial secondary collapse of its outer ring segment above the jet impact area after 20 minutes.

The effects on the fire protection and suppression systems in these three buildings were also very similar. In the WTC towers, the spray-applied fire protection materials were likely damaged and/or destroyed by the impact and debris wave during impact. In the Pentagon, the fire-protective concrete cover on the reinforced concrete beams, columns and slabs, was damaged and/or destroyed. In all three cases, there was similarly extensive destruction of the other life-safety systems, such as stairwells, partitions and sprinkler systems.

No active fire suppression in either WTC 5 or WTC 7 by the fire department was attempted under the dire circumstances, and it is likely that the buildings' sprinkler systems were also totally inoperative because of the surrounding severe damage to the WTC complex infrastructure and water supply. There were no known casualties from either the WTC 5 or WTC 7 collapses, since the entire WTC complex had been already fully evacuated. Neither WTC 5 nor WTC 7 experienced direct impacts from the hijacked jets. Because of these facts, coupled with the as yet relatively sparse factual information and substantiation of cause and effect on the performance of both WTC 5 and WTC 7, the remainder of this report will deal only with WTC 1 and 2.

The September 11, 2001 attacks in both New York City and Washington DC vividly demonstrated that a combination of extreme events can have devastating consequences. It also highlights the very specific nature of the criteria used in the design and construction of buildings. As an example, the building code requirements for fire protection and/or design envision none of this kind of damage inflicted on September 11, 2001 to the WTC Towers and the Pentagon. The building structure is not assumed to be weakened in its pre-fire state and the fire protection, detection, and many other life safety measures are assumed to be operational.

Given these facts, partial and/or total collapse under such extreme conditions should not be surprising. Perhaps we should be more surprised that structural collapse beyond the initial impact damage was beneficially delayed for periods of time from 20 through 102 minutes in each of these three directly impacted structures. As previously described, the WTC complex had been previously attacked with a bomb detonation in 1993, and survived this earlier blast with no secondary collapses.

The actual weight, speed, size, and flight orientation of the missile or the size, nature, and location of the explosive charge, the type of structure and the particular area affected will determine both the extent of the resulting immediate damage, and potential and time for secondary collapse. The greater the size, reserve strength, density, and ductility of structural elements that are in the flight path of the projectile, or close to the blast detonation, the greater is the likelihood that the direct physical damage will be contained to a smaller building area.

Even though WTC 1 and 2 were high-rise buildings with 110 stories, their total office space per tower was actually much less – about 30 percent less – than that contained in the sprawling 5-story Pentagon. The Pentagon’s total footprint area of 1.32 million ft^2 dwarfs each Tower’s 42,800 ft^2 footprint by more than an order of magnitude – about 31 times more. Figure 10 shows a scaled comparison of the relatively small WTC Tower square footprint (207 ft sides) superimposed within the Pentagon’s huge plan area in the vicinity of the Pentagon’s impact damage and collapse. Each of the WTC tower’s total height, or number of stories, is more than tenfold greater than the Pentagon’s – about 22 times more. Based solely upon these purely geometric comparisons, it can be seen that the Pentagon and WTC 1 and 2 are each very unique buildings, with the wide range of common multi-story buildings falling in between these two extremes.

The most important difference between the Pentagon and the WTC towers is in the architectural design. The building weight and space in the WTC is distributed vertically, while in the Pentagon they are spread horizontally. It is unlikely that any single commercial building would have a footprint area as large as the Pentagon’s.

Some distinct differences in structural damage patterns can be observed between the WTC and the Pentagon, due to their unique building construction and impact conditions. These provide important data on the local resistance of these elements to the initial impacts and the resulting structural conditions in each building as a precursor to the subsequent secondary collapses.

- The jet colliding with the Pentagon was very close to the ground and roughly parallel to it. Thus, its low and horizontal flight direction immediately damaged only the two lower floors, but affected a relatively longer skewed travel distance of 310 ft (ASCE/SEI, 2002).
- In contrast, the collisions with the steel-framed WTC 1 and 2 high-rise towers were at higher altitudes in the upper floor levels (between the 94^{th} and 98^{th} floors in WTC 1 and between the 78^{th} and 84^{th} floors in WTC 2), with the jets seemingly intentionally banked to hit multiple floor levels. About half of the columns in one face of each tower were thereby destroyed over 4-6 floors. There was no indication that either of the two jets was able to entirely penetrate through the 207 ft. width of either tower, apart from some of their engine fragments, landing gear and similar debris. Hence, the jet impact travel length was roughly estimated to be between 100 ft and 150 ft.

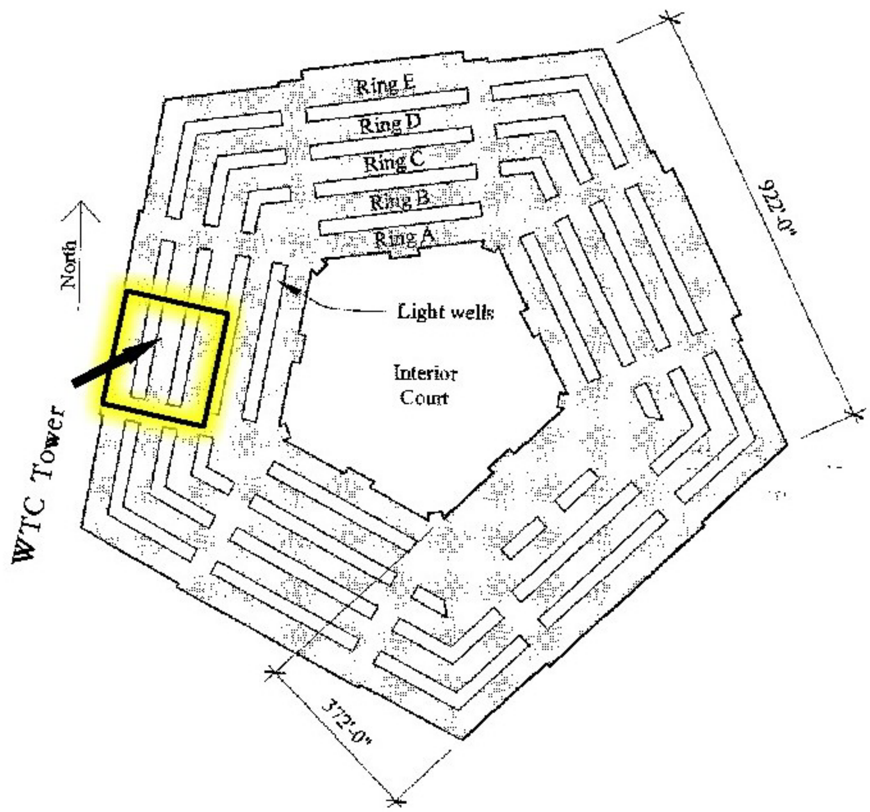


Figure 10. Scale Plan View of WTC Tower Footprint Superimposed on Pentagon

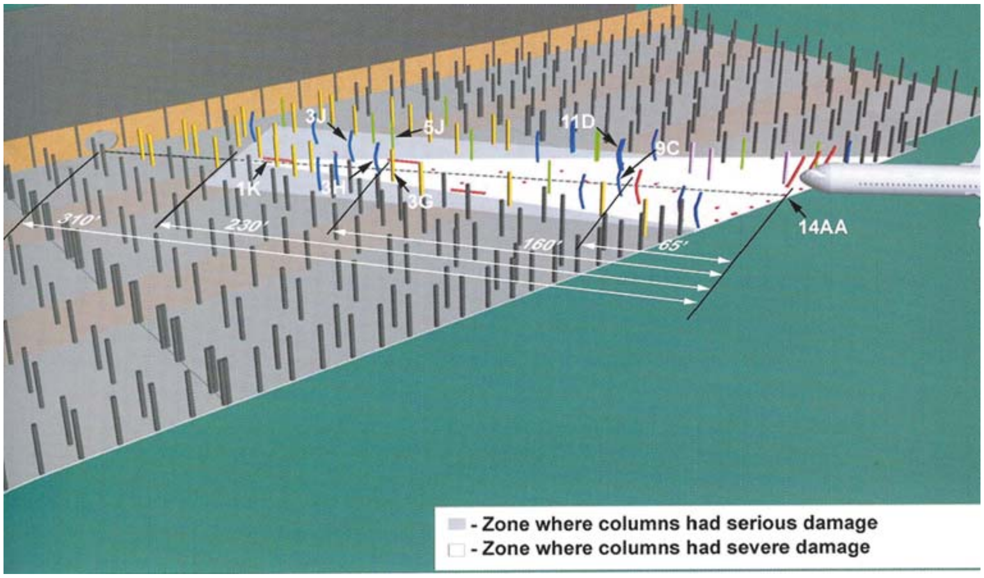


Figure 11. First Story Impact Damage in the Pentagon

Figure 12. Impact Exit Hole at AE Drive Wall in Pentagon

The impact damage documented in ASCE-SEI (2003) to the Pentagon's first floor is summarized in Table 1 and shown in Figure 11. It illustrates the depth of the jet's penetration and resulting extent of column damage to the building's outer ring. About 50 reinforced concrete columns were destroyed, or significantly impaired, with the jet piercing through a 120 ft width of the nominally 13-in.-thick perimeter exterior wall, and its parts or debris exiting through an approximately 6-ft-diameter hole punched out in the AE drive wall between Rings B and C, as shown in Figure 12. In the process, a corridor of major damage measuring approximately 90 ft to 45 ft in width, 250 ft in length, and 25 ft in height (1-2 stories) along the impact trajectory was mapped.

Much of the jet collision damage information with the WTC towers was initially grossly idealized in FEMA 403, especially relative to the post-impact conditions of the Tower core area, which was assumed to be intact. Since the interior damage to the floors and core area was obscured from outside views and the towers collapsed without interior inspection, this was, at the time, thought to be the best and reasonable assumption. However, more recent and in-depth analyses (Silverstein Properties, Inc., 2002) concluded that significant damage to the WTC core columns did very likely occur. Figure 13 is a schematic of the postulated interior floor plan damage, both structurally and from a loss of steel fire protection, on many columns over multiple floors of both towers. This projected impact damage to the steel core columns is included in Table 1. This latter study also slightly revised the impact speeds of the colliding aircraft to 500 mph (from 470 mph) and 550mph (from 590 mph) for Towers 1 and 2, respectively, as compared to the information given in FEMA 403.

Similar to the Pentagon damage and collapse area, the WTC columns were weakened by the initial impact of the plane and debris wave and/or high-temperature exposure. Loss of floor diaphragm bracing for the steel columns provided another source of the eventual instabilities that led to the total collapses. A scaled schematic drawing comparing the relative sizes of the overlayed damage areas is given in Figure 14 for comparison, with the longer narrow band representing the damage path in the Pentagon. This enlarged view of Figure 10 also helps to illustrate that the estimated total 310 ft jet travel distance into the Pentagon is slightly larger than the full diagonal 293 ft. dimension of the WTC Tower footprint.

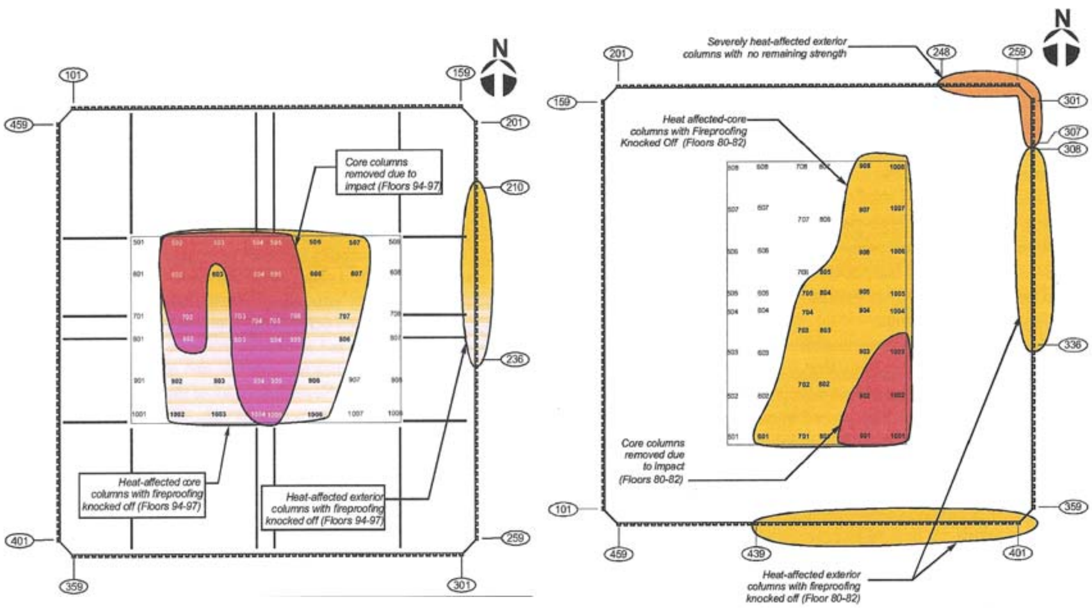


Figure 13. Expected Impact Damage to Columns of WTC Towers 1 and 2

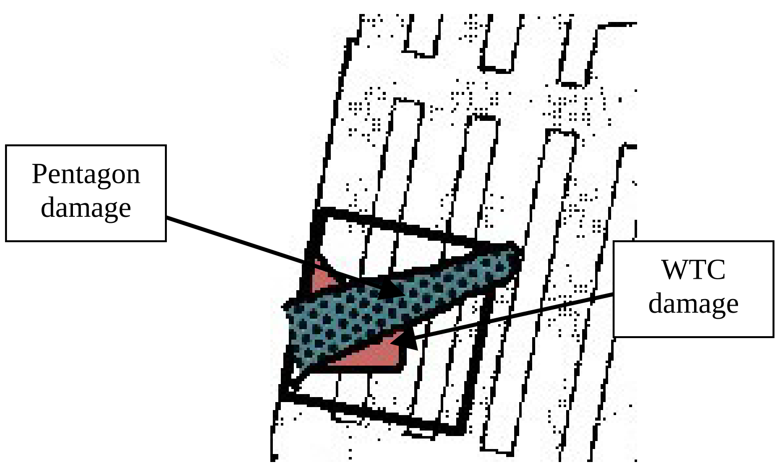


Figure 14. Scaled Overlay of WTC and Pentagon Impact Damage Areas

One simple measure of estimated impact damage is the spatial volume enveloping the most seriously damaged areas. This volume is calculated from the approximated length, width, and height distances. Using the average spatial volume of the damage paths given in Table 1, it can be seen that the initial damage patterns are roughly equivalent (within 10 percent) in each of the three targeted buildings at about 500,000 ft^3. Essentially, the lower depth of impact damage to the Pentagon relative to the WTC is offset by its longer depth of penetration. Also, a count of the impact damaged column lines in Table 1 is about the same (a total of 50) between the Pentagon and WTC 1, without consideration of the steel columns that only lost spray-applied fire protection material from the impacts. The total number of seriously damaged column lines in WTC 2 was slightly lower (about 35) but their asymmetry (see Figure 13) was a factor in the secondary collapse.

FEMA 403 listed several possible failure hypotheses, while Silverstein Properties Inc. (2003) concluded that column instability was the primary reason for the WTC 1 and 2 collapses.

Records show that almost all occupants of the WTC Towers below the impact zones were safely evacuated from these fully active offices. As previously mentioned, the Pentagon was under reconstruction near the impact area, with reduced occupancies that likely mitigated the number of deaths at this site.

One of the Observations and Findings of FEMA 403 on the WTC disasters was:

> *The structural damage sustained by each of these 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.*

The ASCE-SEI (2003) Report has a similar appraisal of the Pentagon's performance:

> *The BPS team concluded that the impact of the aircraft destroyed or significantly impaired approximately 50 structural columns. The ensuing fire weakened a number of other structural elements. However, only a relatively small segment of the affected structure collapsed, approximately 20 minutes after impact. The collapse, fatalities, and damage were mitigated by the Pentagon's resilient structural system.*

The National Institute for Standards and Technology (NIST) is currently completing a more comprehensive technical investigation of the WTC 1, 2 and 7 collapses on September 11, 2001. The results are expected to be released by the end of 2004. (NIST Special Publication 1000-3, 2003)

5.2.2. Different Impact Hazards

One important difference between the Washington DC and New York terrorist attacks is the size and weight of the hijacked aircraft used as the missiles. As shown in Tables 1 and 2, the two Boeing 767-200ER jets that were flown into WTC 1 and 2 were slightly bigger in size, and substantially heavier, than the Boeing 757-200 that was flown into the Pentagon. The Boeing 767-200ER was reported to be about 50 percent heavier, and carried almost twice as much aviation fuel as the Boeing 757-200. The larger onboard fuel contents could have accounted for the occurrence of three separate fireballs in each of the WTC tower impacts, as opposed to only a single one in the Pentagon crash.

It was also reported in ASCE-SEI (2003) that the Boeing 757-200 heading on its low altitude collision approach to the Pentagon hit several ground-based objects, including a generator building, several light poles, and a vehicle, and may have glanced off the ground itself before final impact with the target building. These a priori collisions would have partially damaged this aircraft and possibly reduced its speed somewhat, thereby lessening the impact delivered to the Pentagon. The impacting jets into WTC 1 and 2 both were both flown at higher altitudes and did not strike any intermediate objects in route. However, given the inherent variations in estimation accuracy, the three reported attacking aircraft speeds can be considered the same -- approximately 500 mph – for practical purposes. Nevertheless, the reported initial jet conditions and their respective flight paths indicate that the actual impact energy and fuel delivered to each of the WTC towers was substantially greater than that delivered to the Pentagon.

5.2.3. Height and Building Floor Plan Effects

Another marked difference between the attacks on the WTC towers and Pentagon lies in their respective building heights and floor size configurations. While all three of these buildings are considered as multi-story having four or more above-grade levels, the structural design, construction and response characteristics of the horizontally distributed 5-story Pentagon complex are all vastly different than those for the vertically distributed 110-story WTC towers. The Pentagon's total office space of 6.6 million ft^2 is substantially greater than the 4.7 million ft^2 in either of the WTC towers. The configuration being horizontal rather than vertical and the earlier comparisons of total building height and footprint area clearly show these dramatic layout differences.

Moreover, the particular jet impact elevations and height/weight of the superstructure above the originally damaged areas are variables that affected structural response. To avoid collapse, the surviving framing, in each case, was required to redistribute its existing loads in order to sustain the remaining superstructure above the initially damaged area. The much shorter Pentagon building had most of three floors left unsupported above the damaged outer impact zone, while the high-rise WTC had most of twelve and twenty-six floors unsupported above, respectively, for Towers 1 and 2.

Therefore, in concept, the secondary failures in both the WTC and Pentagon buildings of the impact damaged structure subjected to fires were very similar in nature, and with equivalently dire consequences for the stability of the affected structure and the safety of its occupants.

The WTC and Pentagon collapses, as well as the earlier 1995 Murrah Federal Building collapse, again demonstrate that columns carrying all of the upper accumulated tributary floor areas and weights are the most critical structural members. Bazant and Zhou (2001) explain this further in assessing the collapse mechanism of the WTC, along with the associated dynamic effects of the secondary failure. The force of gravity and weight of a building are the dominant natural factors that are acting on a damaged structure. If these large gravity loads from numerous floor levels above the ground cannot be satisfactorily resisted, collapse in inevitable. Accordingly, the key for mitigation of progressive collapse in taller buildings starts with the columns and continues into the other framing to ensure that a local instability does not become a global instability.

Bazant and Zhou (2001) approximated the tremendous amount of residual structural resistance that would be needed in taller buildings to be able to arrest progressive collapse once a major portion of its gravity system has been impaired. How large in size and how much of an overload should tall building columns, of any material and framing, safely accommodate in order to contain a gravity failure to a localized region? Given this significant structural issue, the risk, engineering, and cost relationships between flatter low-rise and mid-rise buildings versus taller high-rise construction to provide a certain amount of required building space become paramount. Besides such structural redundancy questions, taller buildings also present an easier target for airborne missile attacks and greater emergency egress issues, relative to shorter and more horizontally expansive ones.

Thus, the original architectural layout of the building for height and footprint area is probably the most important decision in any properly designed, conventional building to mitigate potential dangers from exposures that go beyond building code design criteria. Some private building owners, developers, and tenants have recently been sensing these types of concerns, with subsequent predispositions towards shorter buildings. Some very simple numerical indexes (all normalized by the building footprint area) that could be used for such comparative purposes are:

- total building weight per footprint area
- total number of building occupants per footprint area
- total number of columns per footprint area

Lower weight or occupant density indexes, or a higher column density, would signal the more favorable safety conditions for extreme events. Either a larger plan footprint or a shorter building height will lead to these more favorable density indexes.

However, this convenient ranking methodology does not account for structural framing system redundancies, such as the distribution of gravity only ("leaning") columns and simply supported framing, which are more susceptible to progressive failures than a stiffer and continuous lateral system. Two adjacent simple spans will become inadequate if their interior middle support fails, and the remaining end negative moment resistance becomes necessary to prevent further collapses. By definition, an essentially statically determinate member, or one with only nominal end fixity, is non-redundant and has very limited load redistribution capabilities. One easy way to approximate and rank this redundancy effect is to identify the largest area grouping of gravity only columns and simply-supported framing that are bounded by the more continuous, stiffer and stronger lateral system, (i.e. braced frame, moment frame, or shear wall systems), and multiply the total building tributary building weight carried over this area by the number of stories. This "leaning", or gravity load index could be compared for different buildings or framing plans, with a larger numerical index (more simple framing carrying more weight) signaling a greater relative vulnerability risk for the building. Other similar indexes for these ranking purposes could be identified.

With all other things being assumed equal, the lighter dead weight of the steel building superstructure compared to concrete buildings is a positive variable in terms of loading demands and mitigation of progressive collapse, similar to seismic design. On the other hand, larger size and mass are important factors for local blast and impact resistance of individual structural elements that might be targeted, such as lower level columns, wherein reinforced concrete or composite construction could prove to be advantageous.

5.2.4. Stair Enclosures

While stairway enclosures are not normally a structural topic, but rather one of fire and smoke protection, questions have been raised regarding their impact resistance. Critical remarks have been made in technical and public forums about the damage inflicted on the WTC tower shaft walls in the stairway and elevator core enclosure. These walls were constructed of multiple layers of fire resistant gypsum board. Because this system failed to remain intact and protect the egress routes at the locations of the airplane penetrations of the buildings, suggestions have been made that a stair shaft enclosure should be constructed of an alternate harder, heavier, and stronger material, such as concrete masonry units or reinforced concrete. FEMA 403 also recommends considering such alternatives for "impact-resistant enclosures around egress paths".

In this context, it is worth again reviewing the widespread impact damage sustained in the Pentagon on September 11, 2001, as well as the 1995 blast effects on the Murrah Federal Building, and its subsequent collapse. Even the thick masonry and concrete walls of the conservatively designed Pentagon building were unable to prevent the intrusion of the high-speed and heavy aircraft projectile and debris wave that caused the destruction of large interior members and areas. Both the 13 inch perimeter exterior wall at entry and the AE drive wall for exit, and about 50 reinforced concrete column lines (21 in. square in cross section) were penetrated by the projectile. And, as mentioned previously, the Boeing 757-200 jet used to attack the Pentagon was substantially lighter than either of the two that crashed into the WTC towers. Consequently, it is doubtful that any conventional material and design for a stairway exit shaft would be sufficiently impact resistant to appreciably improve emergency egress under similar catastrophic conditions, unless it was specifically designed for that purpose. Nevertheless, use of harder, stronger, denser, and/or stiffer materials for stair enclosures would be expected to lead to incremental benefits in resistance to incidental abrasion and damage for the more normal service conditions.

5.2.5. Building Performance

The use of hijacked commercial aircraft as coordinated missile attacks on these symbolic landmark US buildings has inextricably linked them together on this tragic date. The previously discussed events and facts of these tragedies lead to the following observations.

1. While the mode of delivery of the impacting destruction and fire ignition to the WTC towers and the Pentagon were similar, the actual size, weight and onboard fuel of the aircraft were quite different. The Boeing 767-200ER jets that were flown into WTC 1 and 2 were larger, about 50 percent heavier with almost twice as much onboard aviation fuel than the Boeing 757-200 that struck the Pentagon.

2. The greater weight, fuel contents, and higher altitude flight paths of the Boeing 767-200ER aircraft translate into a correspondingly larger impact hazard for the each of the two targeted WTC towers than for the Pentagon.

3. The substantially disparate impact elevations, building heights, and architectural floor space distribution of the targeted buildings in New York City and Washington DC placed much greater structural strength and stiffness demands on the damage-impaired WTC 1 and 2 framing to support a 12-story and 26-story superstructure, respectively, above the damaged area compared to the more horizontally localized three levels of affected floors in the Pentagon. The differences in number of casualties and magnitude of destruction among these incidents is probably due most to this horizontally oriented, campus-like layout of building space in the Pentagon versus the vertical high-rise construction of the WTC.

4. The original structural design intent and requirements for the floor systems were quite different between the WTC towers and Pentagon. One building was a heavy institutional type design while the other was a speculative office building design. Thus, the more conservatively designed Pentagon floors were well beyond building code and minimum ACI 318 code requirements compared to those floors in the WTC towers which were designed for a much lighter floor loading.

    a. In the Pentagon, a larger floor loading (150 psf unreduced vs. 100 psf reduced in the WTC), two-way action, and detailing (reinforcement continuity over supports for the beams and girders) were employed. All these requirements were beyond the typical minimum ACI criteria at the time of its construction, and beyond those for the modern ordinary frame designed in accordance with ACI 318-02.
    b. In contrast, the floors in the WTC towers were optimized for weight and cost efficiencies, using a lighter minimum loading of 100 psf, with allowable area reductions, as a baseline distributed load. A streamlined steel floor truss system, with typical simple end connections, was the final result of this value engineering

process, in contrast to the higher performance-level floor intentionally designed for the Pentagon.

5. Both the WTC towers and Pentagon columns possessed some intentionally designed reserve strength beyond the minimum requirements for ordinary loadings.

   a. The multi-story reinforced concrete columns in the Pentagon building had spiral reinforcement, also in excess of the minimum ACI criteria that permitted ordinary tied reinforcement.
   b. The lateral framing of the WTC towers was designed as a high-rise frame for control of drift and perception to motion; it was also checked for strength to survive an accidental jet collision of a Boeing 707 with a gross weight of 263,000 lbs at a flight speed of 180 mph.

6. Given the widespread initial damage sustained to the reinforced concrete construction in the Pentagon on September 11, 2001 and in the Murrah Federal Building in 1993, it is unlikely that the use of any conventional material and design for a stairway exit shaft enclosure would alone provide adequate impact resistance for either a blast or a high-speed impact of a heavy attack projectile. The only plausible recourse to provide measurable impact resistance in a stair shaft, or other applications, for such extreme conditions is to select the specific design criteria needed and to design the stairway enclosures for those criteria.

7. Under the highly adverse and extreme exposures of the WTC towers and Pentagon to the terrorist attacks of September 11, 2001, the structural performance of these three buildings should be viewed as similar. Immediate progressive collapse upon the initial jet impacts was prevented, thereby allowing for the massive evacuations of the building occupants in all three cases. This structural performance aspect was the most important and commendable one in saving many thousands of lives.

8. Secondary collapses occurred subsequently in each of the three buildings. These were precipitated by the fires’ eventual weakening of the already damaged structures. The losses of steel spray-applied fire protection (WTC) and concrete cover (Pentagon) from the impacts were identically critical to the more rapidly deteriorating fire resistance of these buildings compared to their as-designed conditions. The incremental time to the secondary full collapse of either WTC 1 or 2 was significantly greater than that of the Pentagon. This occurred despite the WTC towers being subjected to greater jet impact and fire hazards, and containing a floor system that was less conservatively designed than that in the Pentagon.

9. Even though the partial collapse in the Pentagon affected only the three remaining stories above the damaged area, this is only because there were only three stories above the damaged area. Hence, irrespective of similar initiating mechanisms, the increased vulnerability of taller buildings, and their interdependent gravity load-carrying systems, appears to be the principal issue relative to flatter and shorter mid-rise construction. The risks of potentially more devastating progressive collapses

under extreme conditions in all high-rise buildings due simply to layout need to be more fully addressed.

10. NIST is conducting a follow-up engineering investigation of only the WTC attacks, without inclusion of the Pentagon event. A systematic study and better understanding of building performance of both affected sites would have been desirable for the general public and professional interest, not just the New York City buildings. It is recommended that the ongoing NIST investigation of the WTC collapses, and other post-disaster research, more thoroughly study all the building performance issues raised in this report.

5.3. Multi-story Building Collapses from Natural Fires

Past experience and the recent NIST collapse survey (Iwankiw and Beitel, 2002) confirm that fires and the damage, deaths, and injuries they cause are rare and random events. Their effects depend not on type of material or occupancy, but on the time, nature and circumstances of the fire occurrence. Likewise, the added fire-fighting difficulty in all taller buildings is recognized, given the longer times needed to escape or access the higher floors. Many of the past major fires in tall buildings fortunately occurred in the evenings or weekends, when the office buildings were almost vacant, hence, minimizing their potential dangers to human life.

In summary, this recent survey of fire incidents in multi-story buildings shows that the type of building occupancy, material, and construction appear to have little, or no, correlation with actual fire occurrences, subsequent partial or total collapses, and fatalities.

6. FIRE PROTECTION IN REINFORCED CONCRETE AND STRUCTURAL STEEL BUILDINGS

Many of the Pentagon's damaged beams and columns had their steel reinforcement directly exposed to the subsequent fires upon loss of the concrete cover due to the airplane impact and debris wave. Figure 15 from ASCE-SEI (2002) shows a schematic drawing of the typical concrete column detail and the condition of one column after impact and fire. The columns were originally designed to be of square cross section, varying in size from 14 in. by 14 in. to 21 in. by 21 in., with from the minimum 1½ in. at the mid-sides to almost 6 in. at the corners of clear cover distance to its spiral reinforcement. After impact, many of the Pentagon's columns in the lower level impact area, as shown in Figure 14, and adjacent floor beams were reported to be stripped of their concrete cover that is intended to protect the steel reinforcing from fire effects, and to participate in supporting member loads. What was once a square column was effectively reduced to only its circular core within the spiral reinforcement, with all 1½ to almost 6 in. of concrete cover lost over much of the floor height.

This substantial impairment of the reinforced concrete structure, both structurally and for fire endurance at elevated temperatures resulted in the secondary collapse of the Pentagon building 20 minutes after jet impact. Analyses by the ASCE-SEI (2003) report team confirmed these observations for such damaged beam and column members. The WTC towers experienced an identical distress mechanism. The spray-applied fire protection material was damaged and came off the structural steel framing due to the initial jet impacts that exposed the underlying bare steel to the ignited fires.

Concrete cover and spray-applied fire protection material serve the very same fire resistance purpose – to insulate the steel from the degrading effects of high temperatures. (ACI 216.1-97 and ASCE/SFPE 29-99) The size and type of the member, type of concrete aggregate, and cover distance to the steel reinforcing are the key parameters that affect the fire resistance of structural concrete members and assemblies. Damage to, or loss of, either concrete cover or spray-applied fire protection leads to similar adverse consequences during subsequent fire exposures. In both cases, the steel becomes unprotected and fully exposed to the fire. For reinforced concrete columns, the loss of concrete cover also represents an additional loss of structural section, with a corresponding reduction in compressive capacity of the member. For structural steel members, fire protection materials, aside from composite design with concrete, are not load-bearing elements.

FEMA 403 clearly raises concerns about the impact resistance of spray-applied fire protection material for steel framing. ASCE-SEI (2003) is silent on the parallel danger that prior destruction or spalling of concrete cover over steel reinforcement brings in the event of a fire, not to mention the loss of section effects on reduction of the compressive strength capabilities of the concrete member. The importance of maintaining adequate fire protection and fire resistance for reinforced concrete construction under extreme conditions appears to have not been as widely acknowledged as it has been for structural steel framing. Harder and stronger materials, such as concrete, will usually offer more durable fire protection to the structural framing for typical service conditions. However, under high impact and blast exposures, it is probable that all normal fire protection, such as conventional concrete cover, spray-applied materials, and gypsum board in buildings will suffer some degree of damage that will compromise its performance for any subsequent fire exposure.

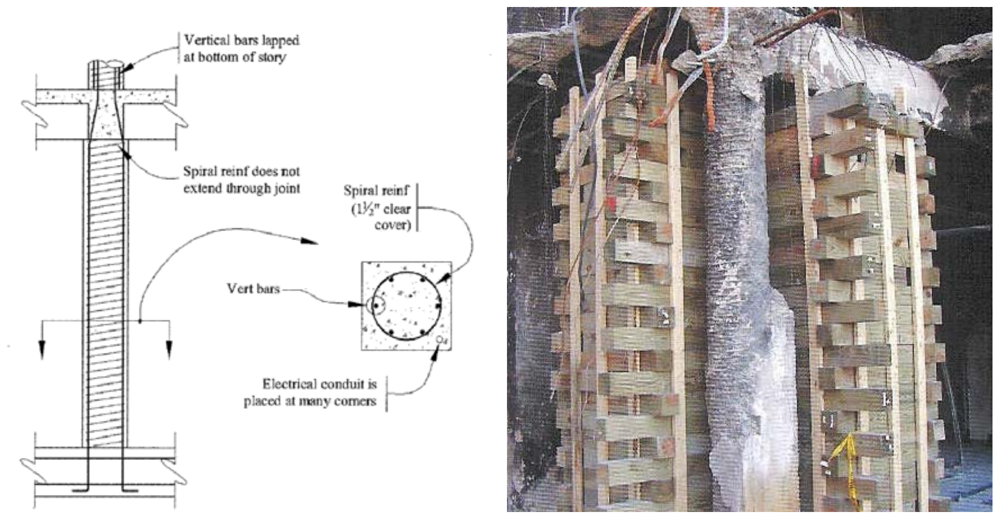


Figure 15. Original Detail and Post-impact Condition of Pentagon Column

7. THE ROLE OF BUILDING PERFORMANCE REPORTS

7.1. Format and Style of Existing Reports

The editorial style, titles, and content of each of the three major building performance reports (1995 Murrah Federal Building bombing, 2001 WTC and 2001 Pentagon disasters) were quite different for generally similar terrorist attacks and catastrophic consequences. There was no similar formal study or report issued on the first 1993 WTC bombing. Relative “successes”, as well as “failures”, under abnormal conditions can yield valuable lessons, and both should be covered and studied. These kinds of performance reporting differences could be potentially misleading to readers and subject to misinterpretations.

Perhaps these inconsistencies in determining when an event warrants further official study and reporting, how it is to be done and by whom, and the nature of the final report itself can be partially attributed to the dawning of a new era of terrorist threats to the US mainland. Regardless of possible past factors and considerations in this regard, NIST has now been given the official responsibility by the National Construction Safety Team Act (HR 4687-5) to be the lead organization to conduct such technical investigations and to issue public reports for various safety-related events. Thus, such matters should be properly, objectively and consistently handled. Similar work by the National Transportation Safety Board (NTSB) on transportation accidents and incidents could serve as a good model to emulate in this regard.

7.2. Report Recommendations

It is recommended that all extreme exposures (blast, impact and/or fire) in multi-story buildings with critical life safety ramifications be adequately documented and their public report format and content be standardized. The following report guidelines are suggested to enable such desired consistency and uniformity in format and style:

- Common standard title, with only name of subject building or site to be changeable
- Chronology of causative event(s)
- Complete technical documentation of relevant site and building characteristics
- Damage and casualties from event
- Documentation of damage or failure area(s), both immediate and secondary, if any
- Hypotheses for observed building performance
- Policy on use of restricted or classified information
- Recommendation for future research needs - short and long-term
- Complete photographs and illustrations
- Any immediate implications for design and construction practice
- Limited to available factual data
- Consistent editorial style throughout (use of neutral adjectives, avoidance of hyperbole and judgmental words, such as “safe” or “unsafe”, “compliant” and “noncompliant”, avoidance of other subjective connotations)

With such publication guidelines, the resulting building performance reports would be expected to look and read similarly, as an intended part of an on-going archival technical series, and not as ad-hoc stand-alone publications.

8. NEW STANDARDS OF BUILDING DESIGN FOR ABNORMAL EVENTS

8.1. Recommendations

Current codes and structural design practice for conventional civilian buildings do not regularly entail explicit consideration of such extreme events as heavy projectile impacts, blast, and fire, acting alone or in combination. Extensive knowledge bases in these areas do exist, but they are not readily available to, or usable by, the majority of design professionals. Thus, in view of the events of the previous 10 years and prognoses for continuing terrorist threats in the future, it may be desirable to develop a suitable model standard, or guideline, for design under abnormal loads. Such a document would enable a performance-based design for such abnormal conditions, if so authorized at the discretion of a given owner or required by a certain occupancy or nature of building.

It is recommended that if this document were to be initiated, it would be developed in a consensus manner to cover the use of all conventional building materials and common construction types. Both the elementary prescriptive countermeasures that would enhance performance under some general conditions, and the more refined and rigorous methods for other and more specific exposures should be provided. Much of this development work would probably include assimilation and technology transfer of the relevant criteria from unclassified Department of Defense information, such as the Tri-Services Design Manual. Perhaps, it makes sense to include these abnormal event considerations into a multi-hazard mitigation framework with the environmental loads of earthquakes, fire, snow and wind. The suggested, or required, limited set of building types, heights, and occupancies for which the additional provisions would apply must be as carefully considered as the provisions themselves. The largest landmark and/or historic buildings might continue be the primary targets for terrorist attacks. Thus, these provisions should not be necessary or mandated for all, or even most, building construction, which will continue to subjected to less risk.

During the development period and before issuance, serious professional debate and public policy decisions on associated risks and benefits must be undertaken to ensure that the document provisions are actually expected to provide incremental life safety at a reasonable and affordable cost. Broadly based input and consensus from the public and private sectors including industry, engineering and business communities, and the general public is vital in this process.

The relative importance of, and reliance on, security and military countermeasures, both national and local, to mitigate such potential abnormal threats versus enhanced structural design for them must be weighed. During the recently concluded Cold War era, it was just such a combination of diplomatic, security, military and defensive actions of the western world, led by the US, that successfully contained, neutralized and eventually diffused the possible horrific dangers from nuclear long-range missiles. Within that period, there was no effort made to structurally upgrade civilian buildings for the hazards of these nuclear weapons. During that period, as now, there was strong public opposition to drastically changing the country's life style, our open society, general civil liberties, building architecture, and area mobility. This experience may provide an equally valid model to follow for today's emerging terrorist threats, in that little, or no, building design changes may be the most appropriate course of action.

Additional considerations in formulating such new guidelines or code provisions are many and they are difficult. Can a substantial enough range of extreme building hazards be realistically identified and quantified to envelop a meaningful structural design for their effects? If a structure is designed to resist a particular threat, such as a single high-speed impact and subsequent fire with a given commercial aircraft, what happens when that design event threat substantially changes, such as occurrence of two attacking aircraft or when a larger and/or faster aircraft serves as the attack missile? Similarly for blast effects, the design loading for weight and type of explosive charge, and its distance, must be somehow bounded. If the blast is outside of this expected matrix, under what conditions will the building still be able to survive? For what types of buildings and occupancies will these apply? While security cannot eliminate all possible threats, it should serve to discourage and prevent most in order to relegate these to very low probability occurrences, with high return periods. In such a case, perhaps only some nominal structural integrity provisions for some types of buildings may be adequate, in the rational context of our society's general risk tolerances. These are all very complex and highly sensitive issues that need to be more fully explored and debated, with sound information and an open perspective, and without preoccupation on any single topic.

Building codes and standards certainly need close scrutiny in the wake of research results coming out of these studies on terrorist events. However, the profession must not over react to these events by incorporating expensive and unnecessary design requirements on normal buildings. The cost/benefit ratio needs to be examined closely for each risk to ensure that the cost of construction is not unduly penalized.

8.2. Efforts Currently Under Way

Since shortly after September 11, 2001 there has been a keen interest in the design of buildings for abnormal loads and the resistance of buildings to progressive collapse. Numerous articles and short courses have begun to appear within the profession, and many new standards and design guides are under development. Some of these efforts will be identified herein.

The following documents have recently become available:

- "Design of Buildings to Resist Progressive Collapse", Unified Facilities Criteria UFC 4-023-03, Department of Defense, approved for public release, distribution unlimited, July, 2004.
- "Design and Analysis of Hardened Structures to Conventional Weapons Effects", Unified Facilities Criteria (UFC) 3-340-01, Department of Defense, for official use only, June, 2002.
- "DoD Minimum Anti-Terrorism Standards Buildings", Unified Facilities Criteria (UFC) 4-010-01, approved for public release, October, 2003.
- "DoD Minimum Anti-terrorism Standoff Distances for Buildings", Unified Facilities Criteria (UFC) 4-010-10, for official use only, July, 2002.
- "Primer for the Design of Commercial Buildings to Mitigate Terrorist Attacks", FEMA 427, June, 2003.

- “Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings”, FEMA 427, June, 2003.
- “Best Practices Guidelines for the Mitigation of Progressive Collapse” by Robert Smilowitz, NIBS working document, presented at the 2/17/04 NIST Workshop.

AISC is developing a “Blast and Progressive Collapse – Facts for Steel Buildings”. In addition, there are plans for a follow-up AISC design guide. A new Appendix on structural steel design for fire conditions has been developed for the pending 2005 AISC Specification that is nearing approval and release. ASCE/SEI, through its Blast Standard Committee, is currently at work on a proposed design standard to be called “ASCE/SEI Standard for Blast Protection of Buildings”.

It is hoped that these various committees and organizations will consolidate their efforts so that duplicate standards, guidelines, or conflicting criteria are avoided.

9. Summary and Conclusions

The scope of this report has been limited to the review and assessment of multi-story building performance when subjected to the extreme exposures of fire, blast, and impact. The major high profile building disasters precipitated by terrorist acts in the US since 1993 were addressed, as were the past collapses from "normal", mostly accidental fires. It is expected that the observations cited will stimulate further responsible and professional discourse on the issues discussed with accompanying progress toward solving the problems raised. However, while important, undue over-reaction to the events themselves or any single issue is not warranted.

The following conclusions can be made as a result of this study:

- *No new design requirements have been recommended to date for blast effects on steel structures.* In events without fire effects, the survival of the WTC to its 1993 bombing demonstrated the excellent resilience of the building's steel framing to an extreme and totally unexpected design scenario. No related recommendations for steel framing design changes were issued at that time or subsequently.
- *Extreme care must be taken to avoid over reaction in changing existing design standards and provisions of building codes for abnormal demands.* While the events of these terrorist attacks should provoke additional study into the behavior of buildings to resist such abnormal loads, the real conclusion may be that security measures need to be taken that avoid such incidents rather than require some, or all, buildings be designed for them.
- *Comparable fire risks exist across building materials.* The recent 2002 NIST survey revealed that no multi-story (defined as having four or more levels) building, type of construction material or occupancy type was more prone to a fire-induced structural collapse than any other. The conclusion to be reached from this historical data is that fire effects are equally damaging to all building materials and types. This may be self-evident to some as presenting merely a confirmation of the importance of prevailing fire protection and fire resistance code provisions. Nevertheless, it is also a reminder that well-designed steel buildings are no more vulnerable to fire than those constructed of any other noncombustible material. The comparable performance of the WTC buildings and the Pentagon on September 11, 2001 further substantiates this conclusion.
- *Similar structural distress mechanisms for fire in combination with impact damage exist for steel and concrete buildings.* The structural stability and integrity of the greatly damaged WTC 1 and 2 standing for 102 minutes and 56 minutes after jet impact, respectively, permitted the safe evacuation of thousands of its occupants and those from the entire WTC complex. The Pentagon's secondary partial collapse was delayed for 20 minutes after jet impact, and this time also allowed for many to successfully evacuate. The final distress mechanism for all 3 of these buildings was identical in nature: fire degradation of an impact damaged structure. Loss of both spray-applied fire protection on the steel and concrete cover to reinforcing was critical to the fire-induced secondary collapses of these weakened structures.
- *The more conservatively designed Pentagon building experienced the less severe impact conditions on Sept. 11, 2001.* The WTC impact conditions were more severe

than those for the Pentagon relative to impact elevation, weight and on-board fuel of the colliding jets. The WTC towers and the Pentagon were entirely different building types; one was an institutional type building with heavy live loads (150 psf unreduced) and the other a speculative office building with much lower live loads (100 psf reduced). In addition, it has been demonstrated that the Pentagon's initial structural design was more conservative than that for the WTC.

- *Longer survival times until secondary collapse were evidenced for the WTC towers.* The stability of the damaged two WTC towers and the Pentagon until secondary collapses occurred was crucial in saving numerous lives. In view of the initial and impact conditions that favored a longer survival time for the Pentagon, it is surprising that both WTC towers avoided secondary collapse for substantially longer times than did the Pentagon. A part of this answer may be the dual purpose for reinforced concrete cover (fire resistance and load-bearing capacity), and the correspondingly greater structural effects of its loss after impact and under fire conditions than for steel spray-applied fire protection, which does not contribute to its load-bearing strength.
- *The importance of architectural layout (building footprint, height, and critical elements) was apparent from the WTC and Pentagon attacks.* The number of casualties and collapsed floors in the affected buildings on September 11, 2001 are principally dependent on the original architectural layout (building height and floor plans) of the individual buildings. Consequently, it can be postulated that taller and sleeker buildings, with relatively fewer columns subjected to heavier loads, will be more vulnerable to catastrophic collapse and to more numerous casualties under similar abnormal hazards, regardless of construction material and framing type, than flatter and more expansive mid-rise buildings, with all else being equal. This is due to the normal heavy concentration in a high-rise of both its occupants and building weight within a limited plan footprint. Simple weight, occupancy or column density indexes, normalized to the plan footprint area, can be easily used to quantify these general characteristics for different buildings, with lower occupancy and weight, and higher column density indexes being the more desirable ones for this type of risk reduction. Thus, enlargement of the building footprint to more widely distribute its occupancy and weight in the horizontal plane, with accompanying increase in number of columns but decrease in number of floors, is one strategy to minimize the potential fatalities and destruction from extreme events.

  The replacement construction for the destroyed Murrah Federal Building in Oklahoma City was, in fact, selected to be a more horizontally distributed, campus-style footprint than its predecessor. However, the scarcity and premium for available open land for new construction, especially in the US and the world's major urban areas, will probably render this alternative solution to be difficult for implementation in many cases.

  One measure of framing redundancy is the "leaning" gravity index previously defined, with a higher number indicating an increased relative risk of vulnerability. A simple set of objective functions for optimizing performance under extraordinary conditions is to maximize building footprint, minimize height, and minimize gravity only ("leaning") columns and simple framing. Other comparative risk indexes could be similarly defined and used for all types of buildings and construction materials.

Certain critical elements of taller structures, such as transfer girders/trusses and their supporting columns, also may warrant additional design consideration for increased strength and reliability

- *There are changing magnitudes and nature of abnormal structural demands during and after the extreme loading period.* A general problem with such extraordinary conditions is that structural member and connection demands often change quite radically during the course of the event, not just in the higher magnitude of applied loading and stresses, but also in the nature of this loading and stress reversal. One such example is floor beams and slabs which, though primarily designed for flexural resistance due to ordinary gravity loads, can be subjected to uplift for blast pressures and tension due to catenary action under fire. This can also occur with failure of other supporting elements. The variety of potential alternate load paths that may be necessary to maintain structural integrity for each conceivable emergency scenario realistically cannot be fully defined, analyzed or constructed. The dynamic impulsive nature of blast or impact loads, and its high strain-rate effects on materials, also become important factors. FEMA 277, FEMA 403, and ASCE-SEI (2003) all discuss these phenomena and their effects.
- *Building Performance Reports should be standardized in format and content outline for extraordinary events, and they should be factual, objective, and complete to address all relevant items*
- *New standards applicable to all types of materials and construction need to be developed in the design for abnormal loads.* Such standards need to define a cost/benefit ratio for the particular risk addressed in the design. The cost of construction for ordinary buildings should not be unduly penalized.

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APPENDIX A

Table A1. Summary of Multi-Story Building Fires With Collapses (buildings with 4 or more stories)

Building and Location	Construction Type, Material, and Fire Resistance	Floors, Occupancy	Date, Time to Collapse; References	Nature and Extent of Collapse (Partial or Total)
Santana Row, Bldgs. 7 San Jose, CA, USA	Wood frame, still under construction, fire protection and sprinklers not completed or functional	5, Commercial Residential	August 19, 2002; Chui; Gathright	Total collapse and destruction
Apartment block St. Petersburg, Russia	Reinforced concrete	L9, Residential	June 3, 2002, starting at 1 hour fire duration; BBC News Online	Total
Jackson Street Apartments Hamilton, Ontario Canada	Reinforced concrete	21, Residential	February 8, 2002; News reports	Partial collapse of concrete floor-ceilings
WTC 7 New York, NY, USA	Steel moment frame with composite steel beam and deck floors; fire resistive with sprinklers	47, Office	Sept. 11, 2001; fire burned uncontrolled for more than 8 hours FEMA 403	Total
WTC 2 New York, NY, USA	Structural steel tube lateral system with composite floor truss system; fire resistive with retrofitted sprinklers	110, Office	Sept. 11, 2001, after 1 hour of fire following jet impact and damage; FEMA 403	Total
WTC 1 New York, NY, USA	Structural steel tube lateral system with composite floor truss system; fire resistive with retrofitted sprinklers	110, Office	Sept. 11, 2001, after 1.5 hours of fire following jet impact and damage; FEMA 403	Total
WTC 5 New York, NY, USA	Steel moment frame with composite steel beam and deck floors; fire resistive with sprinklers	9, Office	Sept. 11, 2001, unknown time, fire burned uncontrolled for more than 8 hours; FEMA 403	Partial collapse of 4 stories and 2 bays
Pentagon Washington, DC, USA	Reinforced concrete	5, Office	Sept. 11, 2001, 20 minutes after jet impact; ASCE-SEI (2003)	Partial collapses of floors and members in outer Ring
Faces Nightclub and Memories Lounge Bar Motherwell, Lanarkshire UK	Unknown	4, Commercial Residential	February 27, 2001, after 2 hours; News reports	Total
Textile Factory Alexandria, Egypt	Reinforced concrete. no sprinklers	6, Commercial	July 21, 2000, after 9 hours of fire; Reuters News	Total

Building and Location	Construction Type, Material, and Fire Resistance	Floors, Occupancy	Date, Time to Collapse; References	Nature and Extent of Collapse (Partial or Total)
Apartment in Vandergrift Pittsburgh, PA, USA	Wood	6, Residential	May 7, 2000, few hours after fire started; News reports	Back wall fell, initiating progressive collapse
Commercial complex (near Chestnut Hill Mall) Newton, MA, USA	Brick/masonry	4, Commercial	February 9, 2000, after slightly more than a 1 hour fire; News reports	Collapse started at upper story and progressed
Effingham Plaza Nursing Home . Portsmouth, VA, USA	Unknown	Multi-story, Residential	April 6, 1998, fire started on top floor ; News reports	Roof collapsed in places
Coeur de Royale Condominium I-270 and Olive Blvd. Creve Coeur, MO, USA	Unknown	4, Residential	August 25, 1994; News reports	Partial collapses of roofs
Apartments, Brooke Ave and 138th St. Bronx, NY, USA	Brick	5, Residential	April 5, 1994; News reports	Rear of the building collapsed.
Central Square Apt. Massachusetts Ave. and Douglas St. Cambridge, MA, USA	Brick	8, Residential	October 1, 1993; News reports	Collapse of several floors
CESP, Sede 2 Sao Paulo, Brazil	Reinforced concrete frame, with ribbed slabs; no sprinklers	21, Office	May 21, 1987, after 2 hour fire; Berto and Tomina	Partial, full height interior core collapse
Alexis Nihon Plaza Montreal, Canada	Steel frame with composite steel beam and deck floors; fire resistive without sprinklers	15, Office	Oct. 26, 1986, after 5 hour fire, which then continued for 13 hours; Isner, NFPA Fire Investigation Report	Partial 11th floor collapse
Katrantzos Sport Department Store Athens, Greece	Reinforced concrete	8, Commercial	Dec. 19,1980; Papaioannou	Partial collapses of 5-8th floor, together with various other members, during a 2-3 hour fire
Military Personnel Record Center Overland, MO, USA	Reinforced concrete, without expansion joints, no sprinklers above 2nd floor	6, Office	July 12, 1973; 1974 Fire Journal	Roof and supporting columns partially collapsed 12 hours after fire began
Hotel Vendome Boston, MA, USA	Masonry with cast iron	5-6, Residential	June 17, 1972, after almost a 3-hour fire; News reports	All five floors of a 40 by 45 ft section collapsed
One New York Plaza New York, NY, USA	Steel framing with reinforced concrete core, fire resistive with no sprinklers.	50, Office	August 5, 1970; Abrams	Connection bolts sheared during fire, causing several steel filler beams on the 33-34th floors to fall and rest on the bottom flanges of their supporting girders.

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