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Following the September 11, 2001, attacks on New York City's World Trade Center, the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers *(SEI/ASCE),* in association with New York City and several other federal agencies and professional organizations, deployed a team of civil, structural, and fire protection engineers to study the performance of buildings at the World Trade Center (WTC) site.

Founded in 1852, ASCE represents more than 125,000 civil engineers worldwide and is the country's oldest national engineering society. ASCE members represent the profession most responsible for the nation's built environment. Our members work in consulting, contracting, industry, government and academia. In addition to developing guideline documents, state-of-the-art reports, and a multitude of different journals, ASCE, an American National Standards Institute (ANSI) approved standards developer, establishes standards of practice such as the document known as ASCE 7 which provides minimum design loads for buildings and other structures. ASCE 7 is used internationally and is referenced in all of our nation's major model building codes.

The events of following the attacks in New York City were among the worst building disasters and resulted in the largest loss of life from any single building event in the United States. Of the 58,000 people estimated to be at the WTC Complex, over 3,000 lives were lost that day, including 343 emergency responders. Two commercial airliners were hijacked, and each was flown into one of the two 110-story towers. The structural damage sustained by each tower from the impact, combined with the ensuing fires, resulted in the total collapse of each building. As the towers collapsed, massive debris clouds, consisting of crushed and broken building components, fell onto and blew into surrounding structures, causing extensive collateral damage and, in some cases, igniting additional fires and causing additional collapses. In total, 10 major buildings experienced partial or total collapse and 30 million square feet of commercial office space was removed from service, of which 12 million belonged to the WTC complex.

Scope of the study

The purpose of the FEMA/ASCE was to see what could be learned to make buildings safer in the future. Building performance studies are often done when there is major structural damage due to events such as earthquakes or blasts. A better understanding of how building respond to extreme forces can help us design safer structures in the future.

Specifically, the scope of the FEMA/ASCE study was to:

- review damage caused by the attack;
- assess how each building performed under the attack;
- determine how each building collapsed;
- collect and preserve data that may aid in future studies; and
- offer guidelines for additional study.

The team examined:

- The immediate effects of the aircraft impact on each tower;
- The spread of the fire following the crashes;
- The reduction in structural strength caused by the fires;
- The chain of events that led to the collapse of the towers; and
- How falling debris and the effects of the fires impacted the other buildings at the World Trade Center complex.

The team recommendations are presented for more detailed engineering studies, to complete the assessments and produce improved guidance and tools for building design and performance evaluation.

<u>World Trade Center 1 and World Trade Center 2</u>

As each tower was struck, extensive structural damage, including localized collapse, occurred at the several floor levels directly impacted by the aircraft. Despite this massive localized damage, each structure remained standing. However, as each aircraft impacted a building, jet fuel on board ignited. Part of this fuel immediately burned off in the large fireballs that erupted at the impact floors. Remaining fuel flowed across the floors and down elevator and utility shafts, igniting intense fires throughout upper portions of the buildings. As these fires spread, they further weakened the steel-framed structures, eventually triggering total collapse.

The collapse of the twin towers astonished most observers, including knowledgeable structural engineers, and, in the immediate aftermath, a wide range of explanations were offered in an attempt to help the public understand these tragic and unthinkable events. However, the collapse of these symbolic buildings entailed a complex series of events that were not identical for each tower. To determine the sequence of events, likely root causes, and methods or technologies that may improve or mitigate the building performance observed, FEMA and ASCE formed a Building Performance Study (BPS) Team consisting of specialists in tall building design, steel and connection technology, fire and blast engineering, and structural investigation and analysis.

The SEI/ASCE team conducted field observations at the WTC site and steel salvage yards, removed and tested samples of the collapsed structures, viewed hundreds of images of video and still photography, conducted interviews with witnesses and persons involved in the design, construction, and maintenance of each of the affected buildings, reviewed available construction documents, and conducted preliminary analyses of the damage to the WTC towers.

With the information and time available, the sequence of events leading to the collapse of each tower could not be definitively determined. However, the following observations and findings were made:

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

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

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

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

What caused the collapse of the towers?

Our analysis showed that the impact alone did not cause the collapse of the towers, but instead, left the towers vulnerable to collapse from any significant additional force, such as from high winds, an earthquake, or in the case of the Twin Towers, the fires that engulfed both buildings. Without that second event, the team believes the towers could have remained standing indefinitely.

Although steel is very strong, it loses some of its strength when heated. To prevent that loss of strength, structural steel is protected with fireproofing and sprinkler systems. In the towers, fires raged throughout several floors simultaneously, ignited by the jet fuel and fed by a mixture of paper and furniture. The impact dislodged some fireproofing on the structural beams and columns, which made them vulnerable to fire damage. With the sprinkler systems disabled, the fires raged uncontrollably, weakening the steel and leading to the collapse of the buildings.

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

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

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

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems;
- use of impact-resistant enclosures around egress paths;

- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards; and
- grouping emergency egress stairways in the central building core as opposed to dispersing them throughout the structure

Building Codes

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

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

Surrounding Buildings

Several other buildings, including the Marriott Hotel (WTC 3), the South Plaza building (WTC 4), the U.S. Customs building (WTC 6), and the Winter Garden, experienced nearly total collapse as a result of the massive quantities of debris that fell on them when the two towers collapsed. The St. Nicholas Greek Orthodox Church just south of WTC 2 was completely destroyed by the debris that fell on it.

WTC 5, WTC 7, 90 West Street, 130 Cedar Street, Bankers Trust, the Verizon building, and World Financial Center 3 were impacted by large debris from the collapsing twin towers and suffered structural damage, but arrested collapse to localized areas. The performance of these buildings demonstrates the inherent ability of redundant steel-framed structures to withstand extensive damage from earthquakes, blasts, and other extreme events without progressive collapse.

The debris from the collapses of the WTC towers also initiated fires in surrounding buildings, including WTC 4, 5, 6, 7; 90 West Street; and 130 Cedar Street. Many of the buildings suffered severe fire damage but remained standing. However, two steel-framed structures experienced fire-induced collapse. WTC 7 collapsed completely after burning unchecked for approximately 7 hours, and a partial collapse occurred in an interior section of WTC 5. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. The collapse of WTC 7 caused damage to the Verizon building and 30 West Broadway. The partial collapse of WTC 5 was not initiated by debris and is possibly a result of fire-induced connection failures. The collapse of these structures is particularly significant in that, prior to these events, no protected steel-frame structure, the most common form of large commercial construction in the United States, had ever experienced a fire-induced collapse. Thus, these events may highlight new building vulnerabilities, not previously believed to exist.

In the study of the WTC towers and the surrounding buildings that were subsequently damaged by falling debris and fire, several issues were found to be critical to the observed building performance in one or more buildings.

General Observations Findings and Recommendations

These issues above fall into several broad topics that should be considered for buildings that are being evaluated or designed for extreme events. It may be that some of these issues should be considered for all buildings; however, additional studies are required before general recommendations, if any, can be made for all buildings. The issues identified from this study of damaged buildings in or near the WTC site have been summarized into the following points:

a. Structural framing systems need redundancy and/or robustness, so that alternative paths or additional capacity is available for transmitting loads when building damage occurs.

b. Fireproofing needs to adhere under impact and fire conditions that deform steel members, so that the coatings remain on the steel and provide the intended protection.

c. Connection performance under impact loads and during fire loads needs to be analytically understood and quantified for improved design capabilities and performance as critical components in structural frames.

d. Fire protection ratings that include the use of sprinklers in buildings require a reliable and redundant water supply. If the water supply is interrupted, the assumed fire protection is greatly reduced.

e. Egress systems currently in use should be evaluated for redundancy and robustness in providing egress when building damage occurs, including the issues of transfer floors, stair spacing and locations, and stairwell enclosure impact resistance.

f. Fire protection ratings and safety factors for structural transfer systems should be evaluated for their adequacy relative to the role of transfer systems in building stability.

What significant recommendations does the team make in its report?

What may be most important is that the BPS Team does not recommend any immediate changes to building codes. The Team believes that there are a number of areas that need further study, and that there are some things that building designers could do to improve safety for occupants in buildings that might be possible terrorist targets.

In general terms, the FEMA/ASCE report suggests that critical building components such as the structural frame, the sprinkler system or the exit stairwells be designed to be more redundant, more robust, or both. Redundancy means, for example, that if some structural columns were shattered, the building would be designed to transfer the weight to other columns. Robustness means making the builder stronger and better able to resist impact without collapse.

The team is also strongly urging additional study of the collapse of the buildings.

What key findings impact all existing buildings?

The team found that some connections between the structural steel beams failed in the fire. This was most apparent in the collapse of World Trade Center Building 5, where the fireproofing did not protect the connections, causing the structure to fail.

The team is calling for more research and analysis of the how the connections weakened and how best to strengthen their resistance to future fires. Typically, fire resistance tests are limited to steel members, not to the steel connections. Furthermore, fireproofing is sprayed on the connections the same way it is applied to the trusses, though the steel in the trusses and joints may be made of different alloys.

<u>Specific Observations, Findings, and Recommendations</u>

The following sections present observations, findings, and recommendations specifically made in each chapter of the FEMA/ASCE report, including the discussion of building codes and fire standards and the limited metallurgical examination of steel from the WTC towers and WTC 7.

Building Codes and Fire Standards

Observations and Findings

a. The decision to include aircraft impact as a design parameter for a building would clearly result in a major change in the design, livability, usability, and cost of buildings. In addition, reliably designing a building to survive the impact of the largest aircraft available now or in the future may not be possible. These types of loads and analyses are not suitable for inclusion in minimum loads required for design of all buildings. Just as the possibility of a Boeing 707 impact was a consideration in the original design of WTC 1 and WTC 2, there may be situations where it is desirable to evaluate building survival for impact of an airplane of a specific size traveling at a specific speed. Although there is limited public information available on this topic, interested building owners and design professionals would require further guidance for application to buildings.

b. The ASTM E119 Standard Fire Test was developed as a comparative test, not a predictive one. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions, not to predict performance in real, uncontrolled fires.

World Trade Center 1 and World Trade Center 2

Observations and Findings

a. The structural damage sustained by each of the two buildings as aircraft impacted them during the 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.

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

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

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

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

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

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

h. Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These include the following:
   - robustness and redundancy of the steel framing system;
   - presence of adequate egress stairways that were; and
   - the conscientious implementation of emergency exiting training programs for building tenants.

i. Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:
   - the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems;
   - use of impact-resistant enclosures around egress paths;

- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards; and
- grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure.

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

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

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

a. During the course of this study, it was not possible to determine the condition of the interior structure of the two towers, after aircraft impact and before collapse. Detailed modeling of the aircraft impacts into the buildings should be conducted in order to provide understanding of the probable damage state immediately following the impacts.

b. Preliminary studies of the growth and heat flux produced by the fires were conducted. Although these studies provided useful insight into the buildings' behavior, they were not of sufficient detail to permit an understanding of the probable distribution of temperatures in the buildings at various stages of the event and the resulting stress state of the structures as the fires progressed. Detailed modeling of the fires should be continued and should be combined with structural modeling to develop specific failure modes likely to have occurred.

c. The floor framing system for the two towers was very complex and substantially more redundant than typical bar joist floor systems. Detailed modeling of these floor systems and their connections should be conducted to understand the effects of localized overloads and failures to determine ultimate failure modes. Other types of common building framing should also be examined for these effects.

d. The fire-performance of steel trusses with spray-applied fire protection, and with end restraint conditions similar to that present in the two towers, is not well understood, but is likely critical to the building collapse. Studies of the fire-performance of this structural system should be conducted.

e. Observations of the debris generated by the collapse and of damaged adjacent structures suggests that spray-applied fireproofing may be vulnerable to mechanical damage from blasts and impacts. This vulnerability is not well understood. Tests of these materials should be conducted to understand how well they withstand such mechanical damage and to determine whether it is appropriate and feasible to improve their resistance to such damage.

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

World Trade Center 3

Observations

WTC 3 was subjected to extraordinary loading from the impact and weight of debris from the two adjacent 110-story towers. It is noteworthy that the building resisted both horizontal and vertical progressive collapse after the collapse of WTC 2. The overloaded portions were able to break away from the rest of the structure without pulling it down and the remaining structural system was able to remain stable and support the debris load. The structure was even capable of protecting occupants after the collapse of WTC 1.

Recommendations

WTC 3 should be studied further to understand how it resisted progressive collapse.

World Trade Center 7

Observations and Findings

a. This office building was built over an electrical substation and a power plant, comparable in size to that operated by a small commercial utility. It also had a significant amount of diesel oil storage and had a structural system with numerous horizontal transfers for gravity and lateral loads.

b. The loss of the east penthouse on the videotape records suggests that the collapse event was initiated by the loss of structural integrity in one of the transfer systems. Loss of structural integrity was likely a result of weakening caused by fires on the 5th to 7th floors. The specifics of the fires in WTC 7 and how they caused the building to collapse remain unknown at this time. Although the total diesel fuel on the premises contained massive potential energy, the best hypothesis has only a low probability of occurrence. Further research, investigation, and analyses are needed to resolve this issue.

c. The collapse of WTC 7 was different from that of WTC 1 and WTC 2. The towers showered debris in a wide radius as their external frames essentially "peeled" outward and fell from the top to the bottom. In contrast, the collapse of WTC 7 had a relatively small debris field because the facade came straight down, suggesting an internal collapse. Review of video footage indicates that the collapse began at the lower floors on the east side. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. Loss of strength due to the transfer trusses could explain why the building imploded, with collapse initiating at an interior location. The collapse may have then spread to the west, causing interior members to continue collapsing. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building, including the cantilever transfer girders along the north elevation, the strong diaphragms at the 5th and 7th floors, and the seat connections between the interior beams and columns at the building perimeter.

Recommendations

The scope of this study was not intended to include in-depth analysis of issues. Certain issues should be explored before final conclusions are reached and additional studies of the performance of the WTC 7 building and related building performance issues should be conducted. These include the following:

a. Additional data should be collected to confirm the extent of the damage to the south face of the building caused by falling debris.

b. Determination of the specific fuel loads, especially at the lower levels, is important to identify possible fuel supplied to sustain the fires for a substantial duration. Areas of interest include storage rooms, file rooms, spaces with high-density combustible materials, and locations of fuel lines. The control and operation of the emergency power system, including generators and storage tanks, needs to be thoroughly understood. Specifically, the ability of the diesel fuel pumps to continue to operate and send fuel to the upper floors after a fuel line is severed should be confirmed.

c. Modeling and analysis of the interaction between the fire and structure are important. Specifically, the anticipated temperatures and duration of the fires and the effects of the fires on the structure need to be examined with an emphasis on the behavior of transfer systems and their connections.

d. Suggested mechanisms for a progressive collapse should be studied and confirmed. How the collapse of an unknown number of gravity columns brought down the whole building should be explained.

e. The role of the axial capacity between the beam-column connection and the relatively strong structural diaphragms may have had in the progressive collapse should be explained.

f. The level of fire resistance and the ratio of capacity-to-demand required for structural members and connection deemed to be critical to the performance of the building should be studied. The collapse of some structural members and connections may be more detrimental to the overall performance of the building than other structural members. The adequacy of current design provisions for members whose failure could result in large-scale collapse should also be studied.

Recommendations for Future Study

The Building Performance Study Team has developed recommendations for specific issues, based on the study of the performance of the WTC towers and surrounding buildings in response to the impact and fire damage that occurred. These recommendations have a broader scope than the important issue of building concepts and design for mitigating damage from terrorist attacks, and also address the level at which resources should be expended for aircraft security, how the fire protection and structural engineering communities should increase their interaction in building design and construction, possible considerations for improved egress in damaged structures, the public understanding of typical building design capacities, issues related to the study process and future activities, and issues for communities to consider if they are developing emergency response plans that include engineering response.

National Response. Resources should be directed primarily to aviation and other security measures rather than to hardening buildings against airplane impact. The relationship and cooperation between public and private organizations should be evaluated to determine the most effective mechanisms and approaches in the response of the nation to such disasters.

Interaction of Structural Elements and Fire. The existing prescriptive fire resistance rating method (ASTM E119) does not provide sufficient information to determine how long a building component can be expected to perform in an actual fire. A method of assessing performance of structural members and connections as part of a structural system in building fires is needed for designers and emergency personnel.

The behavior of the structural system under fire conditions should be considered as an integral part of the structural design. Recommendations are to:

- Develop design tools, including an integrated model that predicts heating conditions produced by the fire, temperature rise of the structural component, and structural response.
- Provide interdisciplinary training in structures and fire protection for both structural engineers and fire protection engineers.

Performance criteria and test methods of fireproofing materials relative to their durability, adhesion, and cohesion when exposed to abrasion, shock, vibration, rapid temperature rise, and high temperature exposures need further study.

Interaction of Structural and Fire Professionals in Design. The structural, mechanical, architectural, fire protection, blast, explosion, earthquake, and wind engineering communities need to work together to develop guidance for vulnerability assessment, retrofit, and design of concrete and steel structures to mitigate or reduce the probability of progressive collapse under single- and multiple-hazard scenarios.

An improved level of interaction between structural and fire protection engineers is encouraged. Specific recommendations are to:

- Consider behavior of the structural system under fire as an integral part of the design process.
- Provide cross-training of fire protection and structural engineers in the performance of structures and building fires.

Fire Protection and Engineering Discipline. The continued development of a system for performance- based design is encouraged. This involves the following:

- Improve the existing models that simulate fire and spread in structures, as well as the impact of fire and smoke on structures and people.
- Improve the database on material burning behavior.

Building Evacuation. The following topics were not explicitly examined during this study, but are recognized as important aspects of designing buildings for impact and fire events. Recommendations for further study are to:

- Perform an analysis of occupant behavior during evacuation of the buildings at WTC to improve the design of fire alarm and egress systems in high-rise buildings.

- Perform an analysis of the design basis of evacuation systems in high-rise buildings to assess the adequacy of the current design practice, which relies on phased evacuation.
- Evaluate the use of elevators as part of the means of egress for mobility impaired people as well as the general building population for the evacuation of high-rise buildings. In addition, the use of elevators for access by emergency personnel needs to be evaluated.

Emergency Personnel. One of the most serious dangers firefighters and other emergency responders face is partial or total collapse of buildings. Recommended steps to provide better protection to emergency personnel are:

- Have fire protection and structural engineers assist emergency personnel in developing broader pre- plans for buildings and structures to include more detailed assessments of hazards and response of structural elements and performance of buildings during fires, including identification of critical structural elements.
- Develop training materials and courses for emergency personnel with regards to effects of fire on steel.
- Review collaboration efforts between the emergency personnel and engineering professions so that engineers may assist emergency personnel in assessments during the time of the incident.

Education of Stakeholders. Stakeholders (e.g., owners, operators, tenants, authorities, designers) should be further educated about building codes, the minimum design loads typically addressed for building design, and the extreme events that are not addressed by building codes. Should stakeholders desire to address events not addressed by the building codes, they should have a basic understanding of developing and implementing strategies to mitigate damage from extreme events.

Stakeholders should also be educated about the expected performance of their building when renovations, or changes in use or occupancy, occur and the building is subjected to different floor or fire loads. For instance, if the occupancy in a building changes to one with a higher fire hazard, they should review the fire protection systems to ensure there is adequate fire protection. Or, if the structural load is increased with a new occupancy, the structural support system should be reviewed to ensure it can carry the new load.

Study Process. The report benefited from a tremendous amount of professional volunteerism due to the unprecedented level of national disaster. Improvements can be made that would aid the process for any future efforts. Recommendations are to:

- Provide resources that are proportional to the required level of effort.
- Provide better access to data, including building information, interviews, samples, site photos, and documentation.

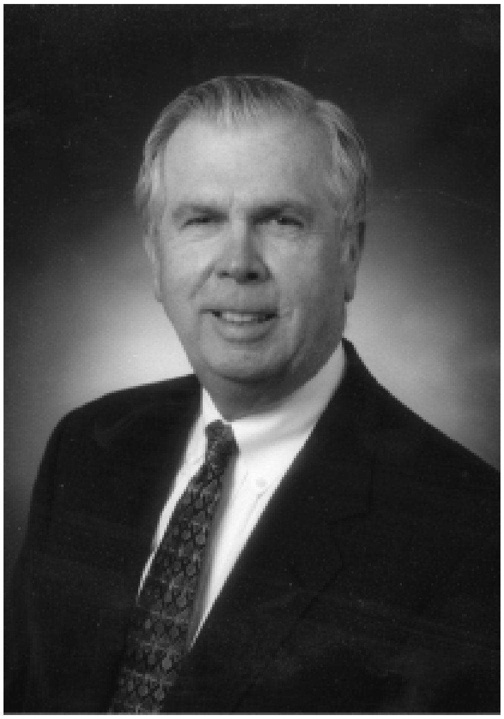
Archival Information. Archival information has been collected and provides the groundwork for continued study. It is recommended that a coordinated effort for the preservation of this and other relevant information be undertaken by a responsible organization or agency, capable of maintaining and managing such information. This effort would include:

- cataloging all photographic data collected to date;
- enhancing video data collected for both quality and timeline;
- conducting interviews with building occupants, witnesses, rescue workers and any others that may provide valuable information; and
- initiating public requests for information.

Conclusion

ASCE is proud of the work done by the BPS Team, but strongly believes that the follow up studies recommended by the FEMA/ASCE Report are critical to obtaining the technical knowledge needed by engineers for future building design.

Thank you for the opportunity to express ASCE's views. We offer you and all of the agencies involved in the recovery efforts ASCE's full resources to manage the nation's critical infrastructure needs. We are ready to help in any way possible, and are eager to hear from you regarding ways that ASCE's Critical Infrastructure Response Initiative can support you as you examine our infrastructure needs in the coming months.



W. Gene Corley
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Educational Background •
University of Illinois
B.S. Civil Engineering, 1958
M.S. Structural Engineering, 1960
Ph.D. Structural Engineering, 1961

Registration •
Licensed Structural Engineer - Illinois
Licensed Professional Engineer - Illinois
Registered Civil Engineer - California, Hawaii
Registered Professional Engineer - Alabama, Florida, Kansas, Louisiana, Michigan, Mississippi, Missouri, Pennsylvania, South Dakota, Tennessee, Texas, Utah, Virginia, Washington
Chartered Engineer, FI Struct E, UK

CTL Experience • Dr. Corley has served as CTL Vice President since 1987. In this position, he serves as CTL's managing agent for professional and structural engineering and leads structural evaluation projects related to industrial, transportation and parking facilities, bridges and buildings. He also is active in projects related to earthquake engineering. His wide range of experience includes evaluation of earthquake and blast damaged buildings and bridges; investigation of distress in prestressed concrete structures; repair of parking garages damaged by corrosion; evaluation and repair of high rise buildings, stadiums, silos and bridges; design and construction of repairs for prestressed and conventionally-reinforced, precast and cast-in-place concrete and structural steel facilities. In 1995, Dr. Corley was selected by ASCE to lead a Building Performance Assessment Team investigating the bombing of the Murrah Federal Building in Oklahoma City.

Prior Experience • After receiving his B.S. degree, Dr. Corley worked for the Shelby County, Illinois highway department where he designed highways and bridges. He then returned to the University of Illinois as a research assistant and National Science Foundation teaching fellow while pursuing his graduate studies.

Upon completion of his Ph.D., he served as a commissioned officer in the U.S. Army from 1961 until 1964. During this period, Dr. Corley was a research and development coordinator with the U.S. Army Corps of Engineers at Fort Belvoir, Virginia. His duties included bridge design, acceptance testing of mobile floating assault bridge equipment, design of tank launched bridges and fatigue testing of bridges fabricated from high strength steel, aircraft aluminum and titanium alloys.

In 1964, Dr. Corley began work as a development engineer with the Portland Cement Association. While serving in successively more responsible positions, he was directly involved in the development of improved design procedures for structural concrete, concrete pavement, railroads and structures subjected to fire loads. In addition, he served on an earthquake damage investigation team, carried out investigations of damaged or deteriorated structures and developed repair procedures for numerous buildings and bridges.

Publications and Professional Activities • W. Gene Corley has authored more than 150 technical papers and books. He frequently lectures to technical and non-technical groups on the subjects of prevention of failures, effects of earthquakes and design and repair of structures. He regularly presents training courses on reinforced concrete design and teaches the seismic design portion of a refresher course to candidates for the Illinois Structural Engineering License examination.

Dr. Corley chaired ACI Committee 318 for six years as the committee developed the 1995 Building Code Requirements for Structural Concrete. He also serves on several other national and international committees that prepare recommendations for structural design and for design of earthquake resistant buildings and bridges. His professional activities resulted in his receiving 11 national awards including the Best Structural Publication Award from NCSEA, Outstanding Paper from the ASCE Journal of Performance of Constructed Facilities, the Wason Award for research from ACI, the T.Y. Lin Award from ASCE and the Martin Korn Award for PCI. He also has received several regional awards, including the UIUC Civil Engineering Alumni Association's Distinguished Alumnus Award, the SEAOI Service Award, Illinois ASCE Structural Division's Lifetime Achievement Award, the Henry Crown Award, and the SEAOI John Parmer Award.

Dr. Corley serves or has served in leadership roles for numerous professional organizations, both national and international, including the following:

American Society of Civil Engineers (Fellow)
National Society of Professional Engineers (Member)
National Council of Structural Engineers Associations (Founding Member, Board of Direction, Former President)
American Concrete Institute (Fellow) Former Chairman, Committee on Standard Building Code
American Railway Engineering Association (Member)
Building Seismic Safety Council (Former Vice-Chairman and Founding Member, Board of Direction)
Chicago Committee on High Rise Buildings (Member and Former Chairman)
Earthquake Engineering Research Institute (Member and Former President, Great Lakes Chapter)
Institution of Structural Engineers, UK (Fellow)
International Association for Bridge and Structural Engineering (Member)
National Academy of Engineering (Member)
National Association of Railroad Safety Consultants and Investigators (Member)
NACE International (Member)
Prestressed Concrete Institute (Member)
RILEM (Member)
Post Tensioning Institute (Member)
Transportation Research Board (Member)
Structural Engineers Association of Illinois (Member, Former President)
Governor's Earthquake Preparedness Task Force (Illinois)