Executive Summary

Following the September 11, 2001, attacks on New York City's World Trade Center (WTC), 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 WTC site.

The events following the attacks in New York City were among the worst building disasters in history and resulted in the largest loss of life from any single building collapse in the United States. Of the 58,000 people estimated to be at the WTC Complex, 2,830 lost their lives that day, including 403 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 fires and causing additional collapses. In total, 10 major buildings experienced partial or total collapse and approximately 30 million square feet of commercial office space was removed from service, of which 12 million belonged to the WTC Complex.

The purpose of this study was to examine the damage caused by these events, collect data, develop an understanding of the response of each affected building, identify the causes of observed behavior, and identify studies that should be performed. The immediate effects of the aircraft impacts on each tower, the spread of fires following the crashes, the fire-induced reduction of structural strength, and the mechanism that led to the collapse of each tower were studied. Additionally, the performance of buildings in the immediate vicinity of the towers was studied to determine the effects of damage from falling debris and fires. Recommendations are presented for more detailed engineering studies, to complete the assessments and produce improved guidance and tools for building design and performance evaluation.

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 leading to total collapse.

The collapse of the 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 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 Team conducted field observations at the WTC site and steel salvage yards, removed and tested samples of the collapsed structures, viewed hundreds of hours of video and thousands of still photographs, conducted interviews with witnesses and persons involved in the design, construction, and maintenance of each of the affected buildings, reviewed 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 ability of these structures 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, causing simultaneous fires across several floors of both buildings. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial power 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 the resulting 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 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 buildings 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.

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
- adequate egress stairways that were well marked and lighted
- 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
- grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure

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 all 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 code revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

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 severe damage 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, the Bankers Trust building, the Verizon building, and World Financial Center 3 were impacted by large debris from the collapsing 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, and 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.

These issues 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 are 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.

The BPS 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 when 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 in a structural system 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 for 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 Professions in Design. The structural, fire protection, mechanical, architectural, blast, explosion, earthquake, and wind engineering communities need to work together to develop guidance for vulnerability assessment, retrofit, and the 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. 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 Engineering Discipline. The continued development of a system for performance-based design is encouraged. Recommendations are to:

- 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 to:

- Have fire protection and structural engineers assist emergency personnel in developing 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 concerning the 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 an 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 included in the building codes, they should understand the process 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, stakeholders should have the fire protection systems reviewed 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. This report benefited from a tremendous amount of professional volunteerism in response to this unprecedented 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 who may provide valuable information
- initiating public requests for information

SEAoNY Structural Engineering Emergency Response Plan. As with any first-time event, difficulties were encountered at the beginning of the relationship between the volunteer engineering community and the local government agencies. Lessons learned in hindsight can be valuable to other engineering and professional organizations throughout the country. Appendix F presents recommendations that can be used as a basis for the development of other, similar plans.