



# 8 *Observations, Findings, and Recommendations*

The observations, findings, and recommendations of this building performance study are summarized in three sections:

- Summary of Report Observations, Findings, and Recommendations
- Chapter Observations, Findings, and Recommendations
- Building Performance Study (BPS) Recommendations for Future Studies

## 8.1 **Summary of Report Observations, Findings, and Recommendations**

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.

## 8.2 Chapter Observations, Findings, and Recommendations

The following sections present observations, findings, and recommendations specifically made in each chapter of this report, including the discussion of building codes and fire standards in Chapter 1 and the limited metallurgical examination of steel from the WTC towers and WTC 7 in Appendix C.

### 8.2.1 Chapter 1: 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.

### 8.2.2 Chapter 2: WTC 1 and WTC 2

#### 8.2.2.1 Observations and Findings

- a. 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.
- 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, 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.

- d. Because the aircraft impacts into the two buildings are not believed to have been sufficient to cause collapse without the ensuing fires, the obvious question is whether the fires alone, without the damage from the aircraft impact, would have been sufficient to cause such a collapse. The capabilities of the fire protection systems make it extremely unlikely that such fires would 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 just described failed. In the incident of September 11, not only did the aircraft impacts 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 disabled 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 buildings would have responded to an extremely severe fire in a situation where there was no prior structural damage. Such simulations were not 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 regulatory 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, the 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 consider 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 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.
- 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 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
- 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
  - 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 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.

#### **8.2.2.2 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 conducted and combined with structural modeling to develop specific failure modes likely to have occurred.
- c. The floor framing system for the two towers was 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 those 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. Observation of the debris generated by the collapse of the towers 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 fires when combined with the impact effects of the aircraft attacks. 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.

### 8.2.3 Chapter 3: WTC 3

#### 8.2.3.1 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 when subjected to debris from 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 on lower floors after the collapse of WTC 1.

#### 8.2.3.2 Recommendations

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

### 8.2.4 Chapter 4: WTC 4, 5, and 6

WTC 4, 5, and 6 have similar design features, although their building configurations are somewhat different. Because WTC 5 was the only building accessible for observation, most of the following discussion focuses on this building. However, the observations, findings, and recommendations are assumed to be applicable to all three buildings.

#### 8.2.4.1 Observations and Findings

- a. All three buildings suffered extensive fire and impact damage and significant partial collapse. The condition of the stairways in WTC 5 indicates that, for the duration of this fire, the fire doors and the fire protective covering on the walls performed well. There was, however, damage to the fire side of the painted fire doors, and the damage-free condition on the inside or stairwell side of those same doors indicates the doors performed as specified for the fire condition that WTC 5 experienced. These stairway enclosures were unusual for buildings that have experienced fire because they were not impacted by water from firefighting operations. In addition, the stairway doors were not opened during the fire and remained latched and closed throughout the burnout of the floors. Therefore, general conclusions regarding the effectiveness of this type of stairway construction may not be warranted.
- b. The steel generally behaved as expected given the fire conditions in WTC 5. Many beams developed catenary action as illustrated in Figure 4-14. Some columns buckled, as shown in Figure 4-17. The one exception is the limited internal structural collapse in WTC 5. The fire-induced failure that led to this collapse was unexpected. As in the rest of the building, the steel beams were expected to deflect significantly, yet carry the load. This was not the case where the beam connections failed. The failure most likely occurred during the heating of the structure because the columns remained straight and freestanding after the collapse.
- c. The structural redundancy provided by the exterior wall pipe columns helped to support the cantilevered floors. This was important because it kept the cantilevers from buckling near the columns as might be expected.
- d. The limited structural collapse in WTC 5 due to fire impact as described in Section 4.3.2 appeared to be caused by a combination of excessive shear loads and tensile forces acting on the simple shear connections of the infill beams. The existence of high shear loads was evident in many of the column tree beam stub cantilevers that formed diagonal tension field failure mechanisms in the cantilever webs, as seen in Figure 4-19.
- e. The end bearing resistance of the beam web was less than the double shear strength of the high-strength bolts. An increased edge distance might have prevented this collapse by increasing the

connections' tensile strength. The failure most likely began on the 8th floor and progressed downward, because the 9th floor did not collapse. The 4th floor and those below remained intact.

- f. The 7th floor framing was shop-coated. In some locations, the paint appeared to be in good condition and not discolored by the fire. Paint usually blisters and chars when heated to temperatures of about 100 °C (212 °F). This indicates that the fire protection material remained on the steel during the early phase of the fire and may have fallen off relatively later in the fire as the beams twisted, deflected, and buckled. Additional measures for proper adhesion may be required when applying spray-on fire protection to painted steel.
- g. On the lower floors, the steel beams appeared to have heat damage from direct fire impact and there was little or no evidence of shop painting, indicating that fireproofing material was either missing before the fire or delaminated early in the fire exposure.
- h. In general, the buildings responded as expected to the impact loadings. Collapse was often localized, although half of WTC 4 and most of the central part of WTC 6 suffered collapse on all floors. The damage was consistent with the observed impact load.
- i. Reinforced web openings in steel beams performed well, as no damage or local buckling was observed at these locations.
- j. The automatic sprinkler system did not control the fires. Some sprinkler heads fused, but there was no evidence of significant water damage, due to a lack of water. This is consistent with the lack of water damage in the bookstore on the lower level and the complete burnout of the upper floors.

#### **8.2.4.2 Recommendations**

The scope of this study and the limited time allotted prevented in-depth analysis of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 4, 5, and 6 during the events of September 11, 2001, and related building performance issues should be conducted. These include the following:

- a. There is insufficient understanding of the performance of connections and their adequacy under real fire exposures as discussed in Appendix A. This is an area that needs further study. The samples discussed in Section 4.3.2 should be useful in such a study.
- b. A determination of the combined structural and fire properties of the critical structural connections should be made to permit prediction of their behavior under overload conditions. This can be accomplished with a combination of thermal transfer modeling, structural finite element modeling (FEM), and full-scale physical testing.

### **8.2.5 Chapter 5: WTC 7**

#### **8.2.5.1 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 stored a significant amount of diesel oil and had a structural system with numerous horizontal transfers for gravity and lateral loads.
- b. The loss of the east penthouse on the videotape 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 façade 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.

#### **8.2.5.2 Recommendations**

Certain issues should be explored before final conclusions are reached and additional studies of the performance of WTC 7, 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 fires and structural members 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 must 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 connections 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.

### **8.2.6 Chapter 6: Bankers Trust Building**

#### **8.2.6.1 Observations and Findings**

- a. An evaluation of the damage patterns revealed several interesting interpretations. The spandrels were sheared by the impactor, between column lines C and D, from the 23rd to the 19th floors. The D-8 column splices failed at the 18th floor and at the 16th floor, but there are no clues to indicate why



column splice tension overload occurred at this location. However, unlike the spandrels above, the girder-column connections at column lines C and D failed. Although severed from the column above and below, column D-8 remained suspended from the girders spanning between column lines E and D. These girders developed large vertical and lateral deformations (twisting). The twisting and bending of these girders may have extended the zone of collapse to bays bounded by column lines C and E. If the column splices had not failed at the 16th and 18th floors, it is possible the extent of collapse may have been limited to the single bay in the path of the impactor. This enlarged zone of damage continued until the collapse was arrested on the 8th floor. It is unlikely that dynamic effects caused the damage to column D-8 below the 16th floor; otherwise, the collapse should have progressed all the way to the ground. It is possible that the column splice failures and the resulting large deformations (twisting) of the spandrels caused the remaining portion of column D-8 to lose lateral bracing, and the collapse was not arrested until the energy of the impactor and debris pile was sufficiently diminished to halt the collapse. If this actually accounted for the enlargement of the damage zone, the restraint of the twisting deformations may have prevented the failure of column D-8.

- b. Although a considerable amount of debris fell from the upper floors onto the first-floor extension to the north, a two-story deep pile of debris accumulated on the 8th floor. By one estimate, although the debris distributed some of its weight by bridging action, the net effect would have been a 500-percent increase in dead load moment for the supporting beam. Based on the computed results, and in the absence of wind, it appears that the connections would have been able to support more than 500 percent of the estimated dead load moments before any hinging would occur. This may explain why multiple stories of debris came to rest at the 8th floor without incurring additional damage to the structure.
- c. Because column D-8 failed below the 16th floor, the beam-to-column moment connection was the single most significant structural feature that helped limit the damage. The portion of the building above the collapsed floors was held in place by frame action of the perimeter. Static elastic analyses of the moment frame show very high stress levels; however, there was a negligible deformation directly above the damaged structure. Furthermore, connections that enable the beams to develop some membrane capacity improve a structure's ability to arrest collapse. The typical floor beam end connections with their A307 bolts were overloaded in direct tension. High-strength bolts would have provided significantly greater tensile ability and possibly held more beams in place through catenary action. Inelastic analyses demonstrate the role of the weaker connections in the response of the structure. Finally, stronger column splices may have made it more difficult for the damaged column to separate from the upper column. Heavier column splices could have allowed the damaged column to function as a hanger and limit the amount of collapsed area, or they could have tended to pull more of the frame down.

#### **8.2.6.2 Recommendations**

It is difficult to draw conclusions and more detailed study is required to understand how the collapse was halted. As better descriptions of the structural details become available, the observed patterns of damage may provide useful information in the calibration of numerical simulation tools. Some issues requiring further study are:

- a. Whether the observed damage in the column flange, and not at the beam flange, of the moment frames top connection plates is due to high restraint in the welds.
- b. Why the bottom flange welded connection has typically failed at the fillet weld to beam interface and not at the fillet weld to seat plate interface.
- c. The impact response of various moment-connected details.

- d. Whether composite construction would reduce local collapse zones. (There were no shear connectors to provide composite action between the floor beams and slab. Composite construction would have increased the capacity of the members and may have dissipated more of the impact energy; however, it may have also pulled a greater extent of the adjoining regions into the collapse zone.)
- e. Whether perimeter rebar in the slabs could improve the structural response by providing catenary action and tensile force resistance in the slabs to reduce local collapse zones.
- f. Whether the partial-strength connections permitted members to break away from the structure, thereby limiting the extent of damage. (If the moment connections had been designed for the capacity of the sections [as opposed to fully rigid partial strength based on design load and stiffness requirements], the building performance is likely to have been different.)
- g. Whether the collapse zone would have been limited if the spandrels on the 16th, 17th, and 18th floors had not been so grossly distorted through twisting.

## 8.2.7 Chapter 7: Peripheral Buildings

### 8.2.7.1 Observations and Findings

- a. Steel-frame construction from the 1900s through the 1980s, though different in many details, performed well under significant impact loads by limiting impact damages and progressive collapse to local areas.
- b. Heavy unreinforced masonry façades were observed to absorb significant amounts of impact energy in the Verizon and 90 West Street buildings. Heavy masonry façades like those in the Verizon, 90 West Street, or even 130 Cedar Street buildings may also provide an alternative load path for a damaged structure.
- c. Older, early-century fireproofing methods of concrete-, brick-, and terra cotta tile-encased steel frames performed well, even after 90+ years, and protected the 90 West Street building from extensive structural damage.

### 8.2.7.2 Recommendations

The known data and conditions of the perimeter structures after the impact damage should be utilized as a basis for calibration, comparison, and verification of existing software intended to predict such behavior, and for the development of new software for the prediction of the ability of structures to sustain localized and global overload conditions.

## 8.2.8 Appendix C: Limited Metallurgical Examination

Two structural steel samples from the WTC site were observed to have unusual erosion patterns. One sample is believed to be from WTC 7 and the other from either WTC 1 or WTC 2.

### 8.2.8.1 Observations and Findings

- a. The thinning of the steel occurred by high temperature corrosion due to a combination of oxidation and sulfidation.
- b. Heating of the steel into a hot corrosive environment approaching 1,000 °C (1,800 °F) results in the formation of a eutectic mixture of iron, oxygen, and sulfur that liquefied the steel.
- c. The sulfidation attack of steel grain boundaries accelerated the corrosion and erosion of the steel.

- d. The high concentration of sulfides in the grain boundaries of the corroded regions of the steel occurred due to copper diffusing from the high-strength low-alloy (HSLA) steel combining with iron and sulfur, making both discrete and continuous sulfides in the steel grain boundaries.

#### **8.2.8.2 Recommendations**

The severe corrosion and subsequent erosion of Samples 1 and 2 constitute an unusual event. No clear explanation for the source of the sulfur has been identified. The rate of corrosion is also unknown. It is possible that this was the result of long-term heating in the ground following the collapse of the buildings. It is also possible that the phenomenon started prior to collapse and accelerated the weakening of the steel structure. A detailed study into the mechanisms of this phenomenon is needed to determine what risk, if any, is presented to existing steel structures exposed to severe and long-burning fires.

### **8.3 Building Performance Study Recommendations for Future Study**

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.

#### **8.3.1 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.

#### **8.3.2 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.

### 8.3.3 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.

### 8.3.4 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.

### 8.3.5 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.

### 8.3.6 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 with regard to 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.

### 8.3.7 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.

### 8.3.8 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.

### 8.3.9 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

### 8.3.10 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.