



The Multihazard Mitigation Council  
of the  
National Institute of Building Sciences

## **PREVENTION OF PROGRESSIVE COLLAPSE:**

### **REPORT ON THE JULY 2002 NATIONAL WORKSHOP AND RECOMMENDATIONS FOR FUTURE EFFORTS**

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# Chapter 1

## INTRODUCTION

### 1.1 Background of the Workshop

Consideration of how to prevent progressive collapse is not new to the structural engineering community. The subject has been discussed and studied in various ways for over three decades. Nevertheless, there remains confusion on what is progressive collapse and what is not. Recent incidents of structural damage leading to catastrophic failure may, at first, be categorized as progressive collapse, when, in fact they may involve much more. Generally speaking, progressive collapse is the result of a localized failure of one or two structural elements that lead to a steady progression of load transfer that exceeds the capacity of other surrounding elements, thus initiating the progression that leads to a total or partial collapse of the structure. Recent dramatic collapses of buildings due to blasts exemplified by the Murrah Federal Building in Oklahoma City in 1995 and the World Trade Center Towers in New York City on September 11, 2001, may not be examples of progressive collapse. Several countries have developed design procedures to prevent progressive collapse so that buildings are able to withstand the accidental removal of a single column. No codes or procedures currently exist to design commercial buildings against terror attacks or for war conditions, and the initial assaults described above caused substantially more damage than any current codes envisioned. Consequently, these examples that have focused national attention on progressive collapse are not representative of conventional risks. Indeed, if research on progressive collapse used these examples, there would be an expectation that the structural community could develop a solution and the public would expect a performance level that may be difficult to achieve and inappropriate for most buildings.

Defining and understanding progressive collapse is a noteworthy effort. Realizing there is a need to highlight this subject, collect the existing research and identify future efforts to mitigate the impacts of progressive collapse, led the National Institute of Standards and Technology (NIST) and the General Services Administration (GSA) to conduct a workshop in Oakland, California, on September 10, 2001. A summary report is provided in Appendix A. The purpose was to examine whether seismic rehabilitation technologies could be applied to mitigate blast-induced progressive collapse. The report on this workshop (see Appendix A) concluded:

It was the consensus of the participants that there is a need for a coordinated national effort to develop engineering tools to assist in designing structures to resist progressive collapse and to develop methods to rehabilitate structures that are vulnerable to progressive collapse. The later effort would be analogous to those that have been developed for seismic rehabilitation under the NEHRP program.

Needless to say, the tragic events of the following day highlighted the national awareness of catastrophic collapse of structures and begs the question whether anything can be done to minimize or at least reduce the destruction and possibly save lives in similar events.

Defining what is and is not progressive collapse may be more of a public relations issue than a structural engineering one. Further, it cannot be assumed that progressive collapse can be totally prevented. The earlier workshop in Oakland understood this reality and sculptured into the report text the need to “resist” progressive collapse, not necessarily to prevent it. Consequently, while all may not agree on methods or direction, most believe that engineering tools can be developed to improve building performance against progressive or catastrophic collapse.

Identifying the existing tools, collecting the work already performed, highlighting the need for additional research, developing an implementation strategy, and coordinating a national plan are large tasks that many feel will lead to better building performance both for new buildings and the rehabilitation of existing ones. Before one can weigh benefits versus costs, it is necessary to examine all aspects of the subject and determine if there are viable options available with some expectation that the benefits are worth the costs. Thus, the viability of prevention of progressive collapse should be examined and a determination made concerning whether additional discussion and research are necessary.

## **1.2 Organization of the Workshop**

In February 2002, NIST asked the Multihazard Mitigation Council (MMC) of the National Institute of Building Sciences (NIBS) to convene a steering committee (see Appendix B) to outline how a national standard for progressive collapse prevention should be developed. It was agreed that a workshop of national experts on the subject should be conducted. The committee then drafted an agenda for the workshop and determined that it should involve papers by professionals who have either conducted research or have developed positions from their practice on progressive collapse, several breakout sessions for debating specific topics, and a session for presentation of breakout session summaries and conclusions. The steering committee also drafted an initial list of paper topics and suggested authors as well as an initial list of recommended professionals to attend.

## **1.3 Conduct of the Project**

NIST, The Defense Threat Reduction Agency (DTRA), the GSA, and the U.S. Army’s Engineering Research and Development Center (ERDC) collectively sponsored the workshop, and NIST, acting as the lead activity, entered into a contract with the NIBS/MMC for conduct of the workshop and preparation of a workshop summary. Following the steering committee’s recommendations, 10 professionals were asked to develop and present their papers, chairmen and co-chairmen were identified to moderate the breakout sessions, and the list of invitees was expanded. As planning progressed, it was decided to have three breakout sessions. The first focuses on codes and standards, and was chaired by Bruce Ellingwood of Georgia Institute of Technology and co-chaired by Don Dusenberry of Simpson, Gumpertz, & Heger, Waltham, Massachusetts. The second session on structural systems and analytical tools was chaired by James Cagley of Cagley and Associates, Rockville, Maryland, and co-chaired by Robert Smilowitz of Weidlinger Associates, New York, New York. The third session on existing buildings was chaired by Larry Reaveley of the University of Utah and co-chaired by James Jirsa

of the University of Texas. As the papers were being developed, the participant list was finalized (see Appendix C). Each participant received the papers and agenda prior to the workshop.

The papers presented at the workshop were:

- Design Professional’s Concerns Regarding Progressive Collapse Design by James Cagley of Cagley and Associates
- Review of Existing Guidelines and Provisions Related to Progressive Collapse by Donald O. Dusenberry and Gunjeet Juneja, Simpson, Gumpertz & Heger
- United Kingdom and European Regulations for Accidental Actions by David B. Moore, Building Research Establishment, United Kingdom
- Load and Resistance Factor Criteria for Progressive Collapse Design by Bruce R. Ellingwood, Georgia Institute of Technology
- Structural Systems for Progressive Collapse Prevention by Joseph Burns, Thornton ■ Tomasetti Engineers
- Analytical Tools for Progressive Collapse Analysis by Robert Smilowitz, Weidlinger Associates, Inc.
- Applicability of Seismic Design in Mitigating Progressive Collapse by W. Gene Corley, Construction Technology Laboratories
- Fire Considerations in Progressive Collapse Design by David Scott, ARUP
- Retrofit Methods to Mitigate Progressive Collapse by John Crawford, Karagozian and Case
- Current Research on Progressive Collapse Resistance by Robert Hall, U.S. Army Corps of Engineers, and Young G. Sohn, Defense Threat Reduction Agency (presented by Jack Hayes)

The papers and associated workshop presentation slides are included as Appendix D of this report.

The National Workshop on the Prevention of Progressive Collapse was held in Chicago at the Gateway Sheraton Suites O’Hare Hotel in Rosemont, Illinois, from July 10-12, 2002. Approximately 60 attended and the dialog was open, enthusiastic and diverse. The make up of those attending included more than structural engineers and architects. The group included academics, material representatives, research professionals, government representatives, building and code officials, and association representatives.

Gerald Jones of the Multihazard Mitigation Council welcomed the workshop participants and H.S. Lew of NIST’s Building Fire and Research Laboratory (BFRL) described the workshops goals and objectives. S. Shyam Sunder of NIST’s BFRL then discussed NIST’s response to the

investigations of the World Trade Center disaster and the related research and development Program.

The presentation of the papers by their respective authors followed during the remainder of the first day of the workshop.

The three breakout sessions were conducted on the second day of the workshop. The codes and standards session had approximately 27 participants, structural systems and analytical tools had approximately 16, and existing buildings session had approximately 12.

On the final day, each breakout session chair presented a summary discussion focused on the breakout session conclusions. A final presentation was given by Mark Loizeaux of Controlled Demolition Inc. (CDI), who narrated a videotape showing several examples on how buildings are demolished using explosives.

## Chapter 2

# WORKSHOP CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

### 2.1 Workshop Conclusions

The codes and standards breakout group discussed the development of codes and guidelines for progressive collapse resistance. This led to consensus agreement on the need to study the issue and a discussion of the merits of direct and indirect design approaches. The group identified 14 areas in need of research. The cost estimates were supplied by the chair.

The structural systems and analytical tools breakout group reached several diverse conclusions. Since there are many different types of structural systems and analytical methods, research is needed to establish the accuracy of the various analytical assumptions. Research is also needed to determine appropriate performance criteria relating elastic response analyses to inelastic behavior. Real structures must be tested to validate the simplified methods and one way to collect empirical data is to provide instrumentation on controlled demolition projects. This can be estimated for future research.

During the third breakout session on existing buildings, two smaller working groups were formed. One focused on tools to assess vulnerability to progressive collapse of structural systems and the second discussed a systems approach to retrofit by examining strengthening methods to columns, beams, diaphragms, walls, and connections. Seven research tasks to be addressed over the short term (12-18 months).

The research needs identified by the three groups are presented below with some estimated cost data:

Item	Short Title	Cost Estimate (\$000)
<b>Codes and Standards Recommendations</b>		
1.	Establish the Need	\$200
2.	Investigate detailing used for seismic resistance	\$400
3.	Study buildings that have performed well	\$900
4.	Identify collapse initiation scenarios	\$200
5.	Accumulate and evaluate data on events that lead to extreme loads	\$200
6.	Investigate large deformation behavior through testing	\$1,500
7.	Consider probability-based risk analysis on certain structures	\$200
8.	Conduct thermal/structural analysis in fire conditions	\$600
9.	Monitor building in full scale fire tests to determine response to thermal loads and element deterioration	\$2,000
10.	Instrument, monitor, and study buildings being demolished	\$800

	to study collapse phenomenon	
11.	Install retrofit concepts in test buildings to verify performance	\$500
12.	Perform structural analysis for test buildings to determine ability to predict performance	\$1,000
13.	Assess construction costs to implement design changes.	\$400
14.	Develop and promote responsive code language to code-writing bodies for adoption in building codes.	\$400
	<b>Structural Systems and Analytical Tools Recommendations</b>	
15.	Establish accuracy of various simplifying assumptions on various types of structural systems and different analytical methods.	\$250
16.	Determine appropriate performance criteria relating elastic response analyses to inelastic behavior.	\$500
17.	Test real structures in order to validate the simplified methods.	\$50 to \$400/Test
18.	Provide instrumentation on pre demolition buildings to collect empirical data.	\$25 to \$100/Test
	<b>Existing Buildings Recommendations</b>	
19.	Review current state of practice for progressive collapse Assess procedure for structural integrity/progressive collapse	\$700
20.	Define causes of progressive collapse	\$200
21.	Conduct advanced assessment procedure for structural integrity/progressive collapse. <ul style="list-style-type: none"> <li>• Tier 2 specify if simple analysis, not threat specific, and use of new or adaptations of existing procedures.</li> <li>• Tier 3 specify higher level threats and defined threats</li> </ul>	\$400 \$200
22.	Develop techniques manual	\$500
23.	Test existing buildings to develop understanding of behavior	\$500/test
24.	General – Conduct component-based laboratory tests to support above items over long term	\$2,000/yr for 5 years

## 2.2 Recommendations for Future Research

*To be developed.*

## **Chapter 3**

### **WORKSHOP SUMMARY**

#### **3.1 Workshop Paper Summaries**

##### **3.1.1 The Design Professional's Concerns Regarding Progressive Collapse, James R. Cagley, Cagley and Associates**

Prevention of progressive collapse came to light in 1968 with collapse of the high-rise building in the United Kingdom called Ronan Point. Since that time there have been several examples of structures that are clear examples of progressive collapse or a combination of major failure coupled with progressive collapse. This has mobilized the structural engineering community to be more aware of this problem but there have been many obstacles to setting needed goals and standards to mitigate the impacts of progressive collapse. Several examples of progressive collapse have been the result of a blast and when associated with a military or other federal operation, the information from these occurrences is closely held and available to the engineering community as a whole to work towards mitigation on future efforts. Designers are not interested in the sources of the problems, but rather in the technical information that could lead to better building performance. Designers need to know the design loads from blast pressure, what expectations are needed of the building behavior, what load factors should be applied, what allowable stresses should be attributed to each material, and what type of inelastic behavior should be assumed.

With the above information available, designers could then analyze if existing procedures are adequate or if better tools are needed. The latter is more likely the case but there is still a need to examine all tools available as well as develop new ones. ASCE 7 and ACI 318 are good starting points but need additional work to meet the rising interest in blast design and the complexities of progressive collapse. Demystifying blast resistant design and the development of charts and design load tables would be a great help to the designers faced with this emerging requirement.

The author also believes that prescriptive as well as performance based design will be required in possible combination. Establishing prescriptive requirements in reference documents and developing "Life Safety" performance based standards, especially for unusual situations, are all necessary in the development of codes, standards, and guidelines.

##### **3.1.2 Review of Existing Guidelines and Provisions Related to Progressive Collapse, Donald O. Dusenberry and Gunjeet Juneja, Simpson Gumpertz & Heger Inc.**

The Ronan Point apartment building collapse in England in 1968 generated substantial interest in general structural integrity for buildings and in the prevention of progressive collapse. Many authoritative papers were prepared in the decades that followed that failure and subsequent failures of other buildings, and some building codes and reference standards have attempted to incorporate provisions to address the problem of progressive collapse by enhancing general structural integrity. This paper summarizes some significant technical papers and reference

documents on the subjects of progressive collapse and general structural integrity, and relevant provisions in codes of North America. Recommendations are included to guide the use of available information in codes and reference documents in the development of future code provisions to address the problem of progressive collapse of buildings and other structures.

### **3.1.3 The UK and European Regulations for Accidental Actions, D. B. Moore, BRE**

This paper presents the background to the recommendations for the disproportionate collapse of tall buildings (five storeys and over) given in the current UK Building Regulations and its associated Approved Documents and supporting material codes and standards. The proposed changes to these recommendations are also presented. Although the current recommendations have generally proved adequate there is a general belief that the recommendations for disproportionate collapse should be extended to all buildings. Consequently, a proposal to change the current recommendations has been developed by the UK's Department for Transport, Local government and the Regions (DTLR). This new approach is based on a risk and consequences approach and sub-divides building into four structural categories. The emerging European standards include a similar categorization and this is also presented. Unlike the guidance given in the UK, which provides rules for a general level of robustness the European standard gives guidance on specific hazards.

### **3.1.4 Load and Resistance Factor Criteria for Progressive Collapse Design, Bruce R. Ellingwood, School of Civil and Environmental Engineering, Georgia Institute of Technology**

A progressive collapse initiates from a local structural failure and propagates, by a chain reaction mechanism, into a failure that involves a major portion of the structural system. The aftermath of the Ronan Point collapse in 1969 saw numerous attempts in the 1970's to develop criteria for progressive collapse resistance. Improved building practices and design procedures to control the likelihood of progressive collapse are receiving renewed interest by standards organizations in the United States and elsewhere in the aftermath of the tragedy of September 11, 2001. Procedures for assessing the capability of a damaged structure to withstand damage without the development of a general structural collapse can be developed using concepts of structural reliability analysis and probability-based limit states design. This paper describes design strategies to minimize the likelihood of progressive collapse, and prospects for the implementation of general provisions in national standards such as ASCE Standard 7, *Minimum Design Loads for Buildings and Other Structures*.

### **3.1.5 Structural Systems for Progressive Collapse Prevention, Joseph Burns, John Abruzzo, and Mark Tamaro, Thornton-Tomasetti Engineers**

Structural Systems for Progressive Collapse Prevention is discussed in the context of their evolution in the United States. The GSA was the first to apply a rigorous methodology to the design of structures for Federal Government Buildings. The disasters of September 11, 2001 have raised public awareness of progressive collapse issues, and the extent to which non-governmental buildings are designed to resist accidental loading are being debated in the structural engineering profession. Examples of some design approaches in commercial buildings are included.

### **3.1.6 Analytical Tools for Progressive Collapse Analysis, Robert Smilowitz, Weidlinger Associates**

This paper focused on the tools that are available for progressive collapse vulnerability analysis and compare them in terms of capabilities and ease of use.

- What makes progressive collapse analysis different from routine structural analysis?
- What kinds of capabilities are needed in computational tools?
- Compare available tools
- Verification of predictive capabilities
- Research needs

### **3.1.7 Applicability of Seismic Design in Mitigating Progressive Collapse, W. Gene Corley, Senior Vice President, Construction Technology Laboratories, Inc.**

A Building Performance Assessment Team (BPAT) composed of American Society of Civil Engineers (ASCE) and Federal Government engineers investigated damage caused by the malevolent bombing of the Alfred P. Murrah Federal Building in Oklahoma City, Oklahoma. The purposes of the investigation were to review damage caused by the blast, determine the failure mechanism, and identify engineering strategies for reducing damage to new and existing buildings. Specifically, mechanisms for multi-hazard mitigation, including mitigation of earthquake effects, were considered. Among the strategies evaluated were use of seismic detailing for the structural concrete. This report describes results of the investigation, makes recommendations for design of buildings to be more blast-resistant, and discusses how these details might have changed results of damage in Oklahoma City. The paper also reviews requirements for structural integrity reinforcement after 1989, refers to a case study of blast-damage to the Murrah Federal Building in Oklahoma City, describes how earthquake detailing can reduce losses, and shows how the use of full capacity butt splices could have further reduced the casualties in that blast. Finally, it questions whether seismic detailing can protect buildings where brisance is the failure mode.

### **3.1.8 Fire Induced Progressive Collapse, David Scott, Barbara Lane, and Craig Gibbons, Arup**

This paper discusses issues related to fire induced progressive collapse of tall buildings in extreme events. It discusses current fire engineering practice, particularly as it relates to tall building design and the issues that need to be considered in the understanding and prevention of progressive collapse. This paper concentrates on the scenario where further to an extreme event active life safety systems are no longer effective. It proposes suggestions, subject to further research, as to what can be done to improve the performance of buildings against fire induced progressive collapse.

The paper recommends that Building Codes introduce some form of simple minimum design requirements that reduces the risk of progressive collapse for all buildings. For high-risk structures the paper recommends that a comprehensive performance based approach should be used to assess and mitigate the risk from extreme fire and impact loading. This approach

considers the whole performance of the building under extreme events and includes an assessment of the means of escape, fire fighting, active fire safety systems and passive fire protection, in combination with the performance of the structure and its behavior under extreme conditions.

### **3.1.9 Retrofit Methods to Mitigate Progressive Collapse, John E. Crawford, Karagozian & Case**

Certainly much more is needed in terms of retrofit technology and methods to address the varied needs presented by the progressive collapse problem related to existing structures, especially in those structures constructed with relatively weak lateral system with little continuity and capacity to redistribute load. However, maybe the biggest need for research and development effort is in the area of design infrastructure—the tools, methodologies, engineers, and professional standards by which designs are performed. Infrastructure is particularly important to retrofit design where determining the behavior of complex structures under complex conditions is the norm. Several suggestions for infrastructure improvements were provided in Sections 1.3 and 3.

In summary with respect to retrofitting buildings to prevent progressive collapse, much research is still needed, especially in the area of predicting the capability of damaged building systems to redistribute the load from failed columns.

### **3.1.10 Development of Progressive Collapse Analysis Procedure and Condition Assessment for Structures, Ted Krauthammer, Protective Technology Center, The Pennsylvania State University,**

**Robert L. Hall, Stanley C. Woodson, James T. Baylot, and John R. Hayes, U.S. Army Engineer Research and Development Center, and**

**Young Sohn, Defense Threat Reduction Agency**

The authors begin with a short history of progressive collapse and the difference with global collapse. With both, there are abnormal loads that need to be analyzed and various agencies within the federal government have made great efforts to define a practical procedure in the design process.

With the advancement of construction materials and procedures, designers have been able to construct structures with a smaller margin of safety. They can easily withstand normal loading but leave little reserve capacity for the abnormal loads that result from events that initiate global or progressive collapse. In the field of design, the approaches for reducing the risk of progressive collapse may be categorized as follows: (1) Event control; (2) indirect design; or (3) direct design. Each approach is defined and the research that is needed to expand on current knowledge and practice.

Research Strategy is next explained in three phases. The first is Progressive Collapse Analysis Methodology where the objective is to develop progressive collapse theories and to establish corresponding analysis procedures. It is broken down into 6 steps. They are: (1) Identify the

Problem; (2) Theory Review and Procedure Definition; (3) Numerical Approaches and Computer Code review; (4) Modify and/or Develop numerical Code; (5) Validation; and (6) Parametric Study. The second phase is System Identification and its objective is to establish relationships between the characteristics of progressive collapse and measurable parameters. It too has similar steps like phase 1 listed as follows: (1) Identify Behavioral Characteristics; (2) Theory review and Procedure definition; (3) Review Computer Codes; (4) develop Modify Numerical Codes; (5) Validation; and (6) Parametric Study. The third phase is Physical Tests that test the theoretical and numerical approaches outlined in the first two phases. The authors have outlined the following steps to implement this strategy as follows: (1) Structural Models; Structural prototypes; (2) Test; (3) System Identification; and (4) Test Data Analysis.

The results of this strategy when fully implemented leads to better protection of structures against progressive collapse and improves the life safety of those who occupy these structures.

## **3.2 Breakout Session Summaries**

### **3.2.1 Report of Codes and Standards Breakout Session, Donald O. Dusenberry, Simpson Gumpertz & Heger, Inc., and Bruce R. Ellingwood, Georgia Institute of Technology**

**Background:** In cooperation with the Multihazard Mitigation Council, the National Institute for Standards and Technology convened a workshop to discuss whether codes in the United States should include enhanced requirements to improve progressive collapse resistance in buildings, and to develop an action plan that would lead to best-practice guides and draft language for codes and standards. On the second day of the workshop, participants divided into three breakout groups to have focused discussions on specific, inter-related progressive collapse topics. The specific charge given by the workshop organizers to the Codes and Standards Breakout Group (Group 1) was to discuss an “action plan for the development of codes, standards, and best-practice documents for prevention of progressive collapse.” Participants in Group 1 discussed code attributes and the practical development and implementation of code provisions and guidelines. The participants are listed in an attachment to this report, which summarizes the product of this group’s discussions.

**Premises:** In the course of the breakout session, Group 1 developed consensus that there are basic principles that need to be addressed during the consideration of code provisions. These principles are as follows.

***Progressive collapse needs a consistent definition.*** Within the standards that already exist for increasing resistance to progressive collapse, universal agreement does not exist on the definition of progressive collapse or on the performance expectation for designs that are intended to limit collapse, given an initiating, structurally damaging event. Several reference standards are so vague that they simply include general statements that buildings should possess “structural integrity,” leaving it to a commentary or the individual engineer to determine whether this implies resistance to progressive collapse.

As progressive collapse resistance is analyzed for codification, it will be essential to extract a clear and consistent definition of progressive collapse and performance expectations for buildings that are deemed to be resistant to progressive collapse.

***Resistance to progressive collapse is a multi-hazard issue.*** Terrorism has brought attention to the potential for buildings to suffer disproportionate collapse, but malevolent assaults are not the only events that can trigger a massive failure. Fire, vehicular impact, ground subsidence, explosion, construction error, design error, occupant abuse, and many other sources of limited damage can convert a building's potential energy into kinetic energy, and set in motion inertial forces that can bring a structure to the ground. Many of these initiators can be assessed specifically on a site-by-site basis, whereas others are more random in nature. Some groups of causes have similar influence on a structure, whereas others affect structures in very different ways. In any case, the potential exists for all buildings to receive the damage that has potential to cause progressive collapse. On this basis, mitigation of progressive collapse should not be solely a response to current world events; rather, it is an issue of response to multiple hazards that present risk to nearly all buildings.

***Fire performance is a significant element of the issue.*** Fires cause many fatalities each year, and some of those losses occur when structures collapse during fires. Malevolent and accidental assaults on buildings can ignite fires at the same time that they compromise essential fire protection and fire suppression systems. For these reasons, the members of the breakout group concluded that fire alone, and fire in combination with structural damage from other causes, should be considered as models for the environment in which progressive collapse should be prevented.

***Education must accompany code provisions to prevent progressive collapse.*** Code provisions to address progressive collapse most probably will require engineers to pursue design approaches not now practiced, particularly with performance-based approaches. In addition, owners, building officials, insurers, and the general public will need to understand and appreciate the goals and expectations for design to prevent progressive collapse. For these reasons, implementation of new code provisions will require a concerted effort to educate design engineers, many of whom are not accustomed to thinking about what can go wrong in a building structure. Moreover, efforts must be undertaken to communicate fundamental issues regarding building performance and risk to stakeholders to the building ownership and to the public.

***There is a window of opportunity.*** The issue of progressive collapse prevention is not new. The profession has been discussing this phenomenon at least since the collapse of the Ronan Point apartment building in England in 1968. Over the past three decades, collapses of the Skyline Plaza at Baileys Crossroads, VA, the Hartford Civic Center roof, L'Ambiance Plaza, the Alfred P. Murrah building, and now the World Trade Center towers have raised attention to the catastrophic outcome possible when buildings receive extraordinary damage. While interest is high, progress can be made. For this reason, the profession should assess the problem now and evaluate means to improve performance.

***Importance factors/performance categories could be used to create thresholds for consideration of progressive collapse.*** It is not obvious that all buildings need to have the robustness that is necessary to prevent progressive collapse. Provisions that are proposed for

codes should include exemptions or thresholds based on occupancy, structure type or size, exposure, or other characteristics to separate buildings into categories that are used to prescribe the level of required protection. A near-term approach might be to adopt categorizations already used in codes of the United Kingdom or other jurisdictions.

***Simple detailing improvements can yield substantial improvement in performance.*** It is well known in the structural engineering profession that certain relatively straightforward, indirect approaches can increase robustness in buildings (e.g., ACI Standard 318, Section 7.13). Spiral reinforcement, perimeter ties, strong connections, and other detailing features allow structures to absorb energy and to redistribute forces within structural systems. Such requirements for indirect means to add robustness can be introduced to codes without requiring extensive supporting research or causing high construction costs.

***Frangibility analyses can balance design so that capacities are compatible and modes of failure are ductile.*** It will not be essential to upgrade all elements of a structure to enhance robustness. Each structure has weak links which, if strengthened, will add measurably to progressive collapse resistance without wholesale upgrades. One approach for enhanced robustness is to conduct relatively simple evaluations of component characteristics to identify the weaknesses in a structural system. This will likely require professional education for structural engineers not accustomed to thinking in such terms. Once identified, strengthening the weaknesses can elevate the expected overall performance without need for sophisticated progressive collapse analyses.

***Column confinement provides performance advantages without significant cost premium.*** Research has documented that effective column confinement, through use of spirals, enhances the ability of columns to absorb energy when deformed. While spiral reinforcement adds construction cost over ties for the same size column, it also allows for higher design capacities over columns with ties. Hence, columns designed with spirals often can be smaller than tied columns supporting the same forces. For this reason, the cost savings associated with the reduced required size of a spiral column might compensate for the field complications that accompany installation of spirals. This cost tradeoff, once verified, could justify near-term code changes to encourage the use of spirals in critical columns.

***Minimum standards for ties from beams to beams and columns provide alternate load paths.*** Collapses often progress vertically because the ties for beams in the vicinity of the initiating failure are not strong enough to transfer loads from the failure area to adjacent, intact areas. Upgrading continuity along beam lines and between beams and supporting vertical elements can establish secondary paths for support of loads. In many cases, simple measures such as increasing the edge distance for bolts or continuing beam bottom reinforcing steel through columns can establish the tensile capacity needed for catenary's action. Such changes in common practice can be implemented without extensive addition research.

***Appropriate treatment of framing arrangements can eliminate weaknesses.*** The behavior of transfer girders played an important role in the collapse of the Alfred P. Murrah building. Likewise, a transfer truss might have contributed to the collapse of the 47-story World Trade Center 7 building. Framing systems that include such elements have inherent weaknesses that make the buildings more vulnerable to disproportionate collapse. Structural systems for

buildings at risk in the future will benefit if the framing arrangements are evaluated for such weaknesses, and if those weaknesses are addressed either through elimination or by design to a higher importance factor. Code provisions to address this problem can be developed by relatively simple risk analyses that identify vulnerable structural systems, and result in corresponding classifications that force appropriate design approaches that address the weaknesses.

***Designing for notional removal of a structural element increases robustness.*** A common performance-based approach is to specify design for the removal of certain critical elements, with the expectation that the remaining structure will remain stable even though it might undergo large deformations as it develops resistance to the imposed forces. The appeal of this approach is that the stakeholders can visualize specific threats and, within the limits of analytical accuracy, specific performance expectations. However, it is not essential that the specified initiation scenarios replicate all potential threats to the structure. Structures that are designed for notional removal of structural elements will possess robustness that will enhance their resistance to threats that are not specifically within the design base.

***New load cases, with loads in directions not associated with the primary function for certain structural elements, can provide alternate load paths.*** Case studies of buildings that have sustained blast loads reveal that it is forces in directions opposite to the primary action of structural elements that often destroy key elements. This has led to the common belief that blast resistance can be enhanced if slabs are designed with continuous negative reinforcement to resist uplift loads. The concept that structural elements might be called to support forces in directions other than the directions of action for routine loads can be employed for general enhancement of structural robustness. Columns can act as hangers, beams sometimes experience positive moment at a support line, and infill walls that are designed for out-of-plane loads often function as webs of story-high beams when a structure has catastrophic damage. New load cases, which force a design engineer to add capacity in otherwise unconsidered directions, can yield strength and ductility that will enhance general robustness.

***Consider practices used by others.*** Codes in the public sector generally are not comprehensive in their coverage of progressive collapse prevention. Some federal guidelines (e.g., General Services Administration, Interagency Security Committee, and Department of Defense) and some foreign national codes (e.g., in Canada and United Kingdom) treat the issue more comprehensively. In the near-term, design guidance already in such codes and standards should be evaluated for adoption in part or in total in codes for the public sector.

***Plan layout, compartmentalization, and enclosure systems can reduce risk of progressive collapse.*** Basic principles for space programming and layout of structural systems can yield benefits in the reduction of damage, should there be an extreme event, and containment of collapse when key elements are damaged. Enlightened architectural and structural design can reduce the need for consideration of progressive collapse and for hardening of structures against extreme loadings.

## **Direct and Indirect Design Approaches**

The breakout group discussed the merits of direct and indirect approaches for increasing structural integrity. The principal topics are summarized below.

***Indirect design is threat-independent.*** Indirect design approaches provide detailing that increases robustness without the direct consideration of any particular threat. This eliminates the need to postulate conditions that might initiate a collapse, or to follow through with analyses to determine the existence of specific functional alternate load paths. The advantage is simplicity and versatility. The disadvantage is the indefinite articulation of design objective and an incomplete assessment of expectations for performance against any threat.

***Indirect design procedures can be implemented easily by most engineers.*** In most cases, indirect design approaches are implemented through prescriptive detailing standards that add ductility and the basic strength requirements that contribute to collapse prevention. As such, special design tools, dynamic or quasi-static design approaches, or other sophisticated analyses are not required. Satisfaction of the design intent can be accomplished without special training, and with design and analysis tools already in common use. Group 1 was of the opinion that in the short term, it is socially desirable to implement changes in codes and standards that would provide additional integrity in building design if such changes can be implemented with little impact on building cost.

***Performance-based engineering will be required for direct design to be fully effective.*** While indirect design can be implemented relatively easily by most engineers, this approach falls short of verification that a structure will survive any particular threat. Direct design, on the other hand, can be developed to demonstrate that a framing system can survive specific, prescribed threats. However, performance-based approaches are required to verify satisfaction of the design goals. With specific definitions of the end condition of the structure, the design engineer will have appropriate goals for the collapse restraint system.

***Special expertise is needed for direct design.*** Many engineers following a direct design approach will need to develop a new appreciation for the required design approaches and performance expectations. Depending on the specific requirements of the code, it might be necessary for practicing engineers to receive education and training in the implementation of direct design procedures.

***The fee structure must support direct design.*** Direct design for progressive collapse will require additional analyses and designs. As such, existing fee structures for structural engineering services most probably will be insufficient to cover the engineer's costs. The stakeholders in the process will need to develop an appropriate understanding about the increased costs for the necessary engineering.

***There is a need to communicate performance and risk to stakeholders.*** As is currently the case for design to resist seismic loads, the stakeholders will need to understand performance expectations for indirect and direct design approaches. Engineers, owners, insurers, and others will need to realize that structures that perform satisfactorily when designed for progressive collapse may nonetheless be severely damaged, should there be an initiating event. It might be necessary to demolish a building, even though it has satisfied the design intent. All stakeholders will need to appreciate this fact.

## **Performance-Based Design Approaches**

Given the premise that design codes eventually will address progressive collapse through performance-based design approaches, Group 1 discussed essential elements of this approach.

***Performance-based criteria should be for life safety.*** Group 1 discussed the goal for progressive collapse design. Upon consideration of options, the group concluded that life safety, rather than general collapse prevention, should be the principal goal. This is a restrictive goal that will require consideration of issues of access for emergency personnel, occupant egress, and other factors beyond structural performance.

***The basic premise is that the structure survives for the evacuation of the occupants and for protection of emergency personnel.*** With fire as an associated condition, the group considered time-dependent performance expectations. Given that fire might cause further deterioration of a structure damaged by a partial collapse, there is the potential that a structure may survive an initial collapse, but ultimately fail over time. Under this scenario, it is imperative that time before failure be long enough for occupants to exit and for emergency personnel to conduct basic response activities. Ultimately, should there be additional collapse, design should be to minimize risk of damage to neighboring structures.

***Consideration should be given to the survivability of buildings threatened by fire burn-out conditions.*** It is possible that an initial partial collapse will damage fire protection and fire suppression systems. This raises the possibility that fires will burn un-arrested until fuel is consumed. During the development of code provisions for progressive collapse, consideration should be given to this condition, with the intent to determine whether viable provisions can yield effective and economical designs to allow structures to withstand burn-out without collapse.

***Performance criteria need to address containment of fire-related collapse.*** Should it not be practical to design for burn-out conditions, performance criteria still should be developed to reduce the progression of collapse during a fire beyond the initiating failure. Under best-case conditions, the initial failure is the only failure, and subsequent fire-related deterioration does not lead to propagation of collapse. Depending on the occupancy of the building and the interests of the stakeholders, under some circumstances the ultimate performance goals during a fire might be the subject of discussions among the fully informed stakeholders. However, for critical structures and structures that present a hazard to other facilities, fire-related performance should not be subject to negotiation.

***Importance factors/performance categories should be used to create triggers for consideration of progressive collapse.*** It is unlikely that all structures will need to be designed to prevent progressive collapse. To establish the demarcation, code provisions will need categories to establish the performance goals for different types of structures. It also is possible to apply importance factors to building or component designs to address the risk associated with progressive collapse threats.

## **Technical Barriers and Research Needs**

Group 1 attempted to list principal tasks that must be performed before comprehensive code provisions can be developed. These tasks are listed below in descending order of priority. During the breakout session, the group did not discuss costs for studies and research. However, after the session the breakout group chair and co-chair attempted to assign approximate costs to each task identified during the breakout session. These cost opinions are shown in parentheses in each of the following sections. It should be noted that breakout group members and other workshop participants remarked during the closing session of the workshop that the costs listed below are too low.

***Establish the need (estimated cost -- \$200,000).*** While not specifically resolved by the breakout group, substantial discussion focused on the determination of the need for codes to include additional requirements to reduce the risk of progressive collapse in the general building inventory. Building performance history needs to be evaluated against costs to increase robustness and other social factors to determine whether the public's interests are served by increasing building structural integrity.

***Detailing used for seismic resistance should be investigated for application to mitigation of progressive collapse (estimated cost -- \$400,000).*** Some authoritative studies suggest that seismic detailing is beneficial for resistance to progressive collapse. This potential should be assessed to determine if detailing already in common practice can be applied to enhance general structural integrity.

***Buildings that have performed well under the influence of extreme loads should be studied to reveal benefits of detailing and systems (estimated cost -- \$900,000).*** The performance of the Pentagon during the terrorist attack of September 2001, the La Mirage Hotel during construction, and other structures that have experienced severe damage without collapse have demonstrated that buildings can perform well when exposed to extreme loading conditions. A selection of buildings that have withstood severe damage should be studied to reveal those design and construction details that contributed to the building's survival when tested to the limit. Practical applications could be developed to incorporate the demonstrated performance characteristics in new construction.

***Collapse initiation scenarios (structural damage) associated with extreme loads should be identified (estimated cost --\$200,000).*** For prescriptive designs to be responsive to the potential for progressive collapse, researchers will need to understand the range of collapse initiation scenarios. Data on past failures should be reviewed to characterize the types of physical damage that is most likely to be associated with progressive collapse potential. Generally, one would expect that these scenarios would involve low-probability (e.g., less than  $10^{-4}$ /yr) events. However, unless a full probabilistic approach is to be used to design for robustness, it is not necessary at this time to assign probabilities to the various collapse initiation conditions.

***Data on events (e.g., gas explosions, vehicle impacts) that lead to extreme loads need to be accumulated and evaluated (estimated cost -- \$200,000).*** As with structural damage that leads to collapse, the basic threats to buildings should be studied so that the population of initiation scenarios can be identified, and responsive designs can be developed. With a characterization of the risk potential, designs can be appropriately balanced to respond to those threats.

***Large deformation behavior should be investigated through testing to determine its effectiveness for prevention of progressive collapse (estimated cost -- \$1,500,000).*** Many concepts to arrest collapse require structural elements to undergo massive deformations that extend behavior far beyond limits normally associated with extremes of performance. Actual behavior in these post-failure modes has not been documented fully through tests and analyses. Reliable designs will be facilitated by better understanding of load-carrying and energy-absorbing ability of structural elements and systems taken to the extreme of their performance limits. The behavior of connections in the nonlinear range is particularly important to the development of alternate load paths and general structural integrity of the building system.

***Probability-based risk analysis should be considered for certain structures (estimated cost - \$200,000).*** The exercise should be completed for some exemplary structures to reveal the complexities of the process and the uncertainties associated with the prediction and mitigation of progressive collapse through different design strategies, ranging from LRFD-type checks to fully-coupled risk analysis of the building structural system.

***Thermal/structural analysis is needed to support analysis of structural resistance to progressive collapse in fire conditions (estimated cost -- \$600,000).*** Analytical tools presently are available to evaluate fire effects on structures. However, these tools are not comprehensive, nor are they integrated so they can be used as a continuous analysis stream from the fire ignition, growth, and spread to corresponding structural response. Analysis for progressive collapse will be enhanced if tools for structural response to fire conditions are extended and integrated.

***Buildings should be monitored during full-scale fire tests to determine response to thermal loads and element deterioration (estimated cost -- \$2,000,000).*** Tests have been performed recently in the United Kingdom to assess the actual performance of full-scale buildings during fire. Similar tests should be performed to augment the available data and to assess United States construction practice.

***Buildings should be monitored while being demolished to study collapse phenomenon (estimated cost -- \$800,000).*** Each year, several buildings are demolished by implosion. Each of these events represents an opportunity for the profession to study building performance under extreme structural demand. A research program should monitor a building during demolition to extract data that will yield a more precise understanding of building performance during progressive collapse. Impact from debris loads should be included in this research program.

***Retrofit concepts should be installed in test buildings to verify performance (estimated cost -- \$500,000).*** As part of full-scale testing for collapse and fire performance, retrofit concepts should be tested by adding appropriate construction to test structures. Within the constraints associated with such testing, it could be possible to extract data that will be useful in the evaluation of remediation methods.

***Structural analysis should be performed for test buildings to determine the ability to predict performance (estimated cost -- \$1,000,000).*** Analyses should be performed for selected buildings that are tested for progressive collapse performance or fire performance, and for selected buildings that have withstood severe damage without progressive collapse, to evaluate

analyses techniques and the accuracy with which performance can be predicted. An attempt should be made to identify relatively “simple” methods of analysis that would be suitable and easily utilized to check integrity of the majority of building structural systems, leaving the more “complex” methods for special structures or design cases.

***Construction costs to implement design changes should be assessed (estimated cost -- \$400,000).*** Once code provisions to prevent progressive collapse have been identified, construction costs should be estimated and evaluated against risks to determine whether proposed code changes are in economic balance with the benefits.

***Responsive code language should be developed and promoted to code-writing bodies for adoption in building codes for the public sector (estimated cost -- \$400,000).*** Upon completion of progressive collapse studies, specific code provisions need to be drafted and presented to authorities with responsibility for code development. Education and promotion activities will be necessary to implement such provisions through the voluntary consensus standard approval process and for the profession to accept new provisions that result from this effort.

## **Conclusions**

Group 1 discussed development of codes and guidelines for prevention of progressive collapse. This discussion led to consensus on the need to study the issue and on certain merits of direct and indirect design approaches. The breakout group concluded that some steps to improve codes, if warranted, can be taken in the near term, whereas other more comprehensive code development activities would involve sophisticated research, analyses, and tests. A controversial cost estimate, which was not tested for consensus within the breakout group, to pursue research and code language development for design to prevent progressive collapse is approximately \$9,300,000.

## **Participants in Codes and Standards Breakout Session**

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### **3.2.2 Report of Structural Systems and Analytical Tools Breakout Session, Robert Smilowitz, Weidlinger Associates, Inc., and James Cagley, Cagley and Associates**

While public safety was a concern to all the engineers at the session, it was not obvious that they all perceived the need for strong code requirements at this time. It was frequently expressed that Progressive Collapse is too rare an event to consider for general design requirements. Many people expressed the view that these code provisions would not have improved the resistance of the World Trade Center towers to collapse (the towers sustained considerably more damage than is postulated in the alternate path approach and remained standing for quite some time).

Before any meaningful discussion regarding protection to resist progressive collapse could begin, the group decided that it was important to establish a working definition of Progressive Collapse. The definition that emerged involved the disproportionality of failure relative to extent of initiating damage, the inadequate resistance to stall progression of collapse and the concept that one failure successively leads to another. However, when asked to cite specific examples of progressive collapse, the group was hard pressed to cite more than a dozen examples. Excluding terrorism as the cause, these examples all involved failure of designs and means & methods. Although this list was by no means exhaustive, it did indicate the relative rarity of a progressive collapse failure where terrorism or faulty construction techniques were not the cause. Furthermore, based on the observation of the controlled demolition experts, it was noted that most structures possess inherent redundancy to redistribute loads, with a few notable exceptions. These structures that are easiest to bring down include poorly Detailed Post-Tensioned Flat Plate, corners of buildings and transfer systems. Additional observations of the controlled demolition experts, which were also expressed by fire fighters witnessing the collapse of structures, indicated that greater continuity may actually increase likelihood of Progressive Collapse. If the diaphragms and frames of structures are too well tied together, a localized structural failure may actually pull down a greater portion of the building. This observation contradicts many engineering approaches to structural integrity and needs to be studied further.

The group then identified the need to catalog the hazards that cause the initiating damage before discussing the design solutions. It was generally agreed that more predictable protective design solutions may be developed for natural-hazards than for man-made hazards. The hazards that initiate progressive collapse may be categorized as: terrorism (Bomb Damage), fire damage, overload, abuse, accidental Explosions and strong Ground Motions that Initiate Localized Failure. Similarly, it was decided that the types of structures that required different types of guidelines may be identified as general Buildings, government facilities (DoD, GSA, etc) and stadiums and other large gathering places. Different design strategies for bridging over the damaged members may include hat or belt trusses or girders, highly redundant Vierendeel systems (such as the WTC type frame) and each floor may be designed to carry its own weight, spanning over removed column. However, the criticality of the individual structural members, and the severity of the requirements to which they should be designed, may be related to the tributary area they support. Furthermore, the connection details must be consistent with the analytical assumptions such that the large axial forces generated by catenary action can be resisted. This might involve increased edge distance on bolted connections to provide steel frame structures adequate capability to develop axial forces, tension splices to enable columns to hang from hat trusses or girders and adequate ties for precast panels. It was also noted that narrow structures, that contain one bay on either side of the core, may not be deep enough to resist the axial forces that might be generated when the beams develop catenary action. Nevertheless, prescriptive requirements may be available to eliminate problematic construction.

The three design approaches identified in ASCE 7-98 were summarized as the implicit method, the alternate path method and the method of specific local resistance. The implicit method prescribes the extent of strengthening & detailing similar to the ACI 318 section 7-13 that provides resistance without specifying load side of equation. The group generally agreed that this approach is adequate for most structures. Although the alternate path approach assumes the removal of a primary load-bearing member, it does not consider realistic damage patterns, which might correspond to diminishing degrees of damage sustained by adjacent elements.

Nevertheless, this approach may be effective in quantifying extent of Strengthening & Detailing required to arrest collapse and may provide more effective design than implicit method. However, this method may not be feasible for existing structures where as-built drawings and aged structural conditions may not be available. The method of specific local resistance may be the most effective where a threat is specified in that it averts the loss of critical elements that may otherwise precipitate a collapse. This approach may be the least intrusive for retrofit of existing structures.

A wide range of commercially available software was identified and the different analytical approaches for implementing the Alternate Path Approach were listed in successively increasing analytical rigor. These methods start with good engineering judgment, which brings experience and intuition into the design process, followed by hand calculations such as energy methods and limit state approaches. Static elastic frame analysis software is the most widespread computational method used by most engineering offices. Although this analytical approach will understate the damage state deformations and overstate the likely reaction forces and stress resultants, it provides a first order approximation to the likely response of the structure to the removal of a primary load-bearing member. Static analyses do not account for inertial effects, which may be associated with the sudden removal of the primary load-bearing members and these dynamic response characteristics are frequently represented with Dynamic Load Factors. The incremental elastic analysis, used in pushover analyses, allows the analyst to interactively and manually modify the structural representation as the plastic hinges form, thereby limiting the calculated forces and stress resultants to the yield levels while representing the amplified deformations associated with inelastic behavior. Static geometrically nonlinear elastic analyses couple the flexural and membrane stiffness while the structure develops catenary forces as the members undergo large displacements. Static geometrically nonlinear inelastic analyses couple the membrane and flexural stiffness while automatically tracking the development of plastic hinges and inelastic deformations. The dynamic geometrically nonlinear inelastic analyses, account for the dynamic, large displacement response in which members yield and plastic hinges form. These finite element models generally contain all the physics associated with the removal of the primary load-bearing members. A more thorough discussion of the different analytical methods for performing the alternate path method, with a comparison of results when these different methods are applied to a range of structural systems, is presented in the white paper “Analytical Tools for Progressive Collapse Analysis” submitted to the workshop.

Although the addition of each level of analytical rigor reduces the level of simplifying assumptions it increases the level of expertise required to model the structure. Conversely, the analytical results that are based on simplifying assumptions require the greatest interpretation on the part of the analyst. These simplifying assumptions include the idealization of connections, whether they be represented as pinned, fixed or partially fixed and the use of a Dynamic Increase Factor to represent a suddenly applied step load. The appropriate magnitude of these dynamic increase factors depend on the nature of the response motions and these factors may be determined from the response of single-degree-of-freedom systems using the methods documented in the textbook Introduction to Structural Dynamics by John Biggs. These responses may be shown to range from a maximum value of two, associated with a purely elastic response, to a factor of 1.25 for a modest level of inelastic deformation (ductility of 2.5). In addition to the simplifying assumptions that are used to characterize the structural resistance and the loading function, the analyst is required to interpret the results of the analyses. The use of linear elastic

material models requires a means of attributing inelastic response to the calculated deformations, forces and moments. This may be accomplished using demand capacity ratios, ductility limits or energy methods, however, the appropriate limiting values will depend on the type of structural system and material type (concrete, steel, masonry, etc).

Based on the different types of structural systems and the different types of analytical methods, research is needed to establish the accuracy of the various simplifying assumptions. Research is also needed to determine appropriate performance criteria relating elastic response analyses to inelastic behavior. Real structures must be tested in order to validate the simplified methods. The instrumentation of the pre-demolition tests conducted as part of a controlled demolition was identified as a relatively inexpensive way to develop empirical data for a wide range of structural systems and materials. However, based on the experience of the controlled demolition industry, these pre-demolition tests are not likely to generate dramatic response data. Nevertheless, these measured response motions will provide a basis for validating the different analytical approaches for a wide range of existing structures and materials.

Although the breakout group agreed that analytical tools exist, they also cited the need for a consistent definition of the analytical methodology and the need for appropriate guidance to be provided to the general practicing engineer. The criteria should be for the protection of life safety (limiting the extent of collapse) and although seismic considerations are useful and may serve as a basis for specifying details and analytical approximations. It was also noted that seismic design methods are not a substitute for protective design methods and do not serve as an umbrella providing protection to all forms of abnormal loading conditions. In order to provide effective multi-hazard protection, the group noted the need for structural engineer to have more information regarding fire loads and blast effects. Research and testing will provide a greater level of confidence in developing design strategies, the identification of appropriate analytical approaches, the establishment of meaningful performance criteria and the effect of age on member properties (some engineers say the materials improve with age, while other engineers noted a degradation in member capacity). In the near term, the most effective approach would be to catalog prescriptive details for various structural systems and to develop additional details that will enhance the structural resistance to progressive collapse without adding much cost.

### **Participants in Structural Systems and Analytical Tools Breakout Session**

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### **3.2.3 Report of Existing Buildings Breakout Session, James Jirsa, University of Texas at Austin, and Larry Reaveley, University of Utah**

**Objective:** Develop an action plan for the cost-effective means of retrofitting buildings.

#### **Participants and Discussion**

A general discussion of the topics assigned to Breakout Group 3 led to defining some broad issues to be considered in subsequent discussions. It was agreed that a multi-hazard approach would avoid duplication of work related to studies of existing buildings for other loadings and hazards. The work done to develop FEMA 356 seismic rehabilitation of existing structures represents an approach applicable for handling progressive collapse using model buildings and different material types. The current “window of opportunity” to address issues related to progressive collapse of buildings should be utilized to advance knowledge regarding structural safety. There was also agreement that a multi-level assessment approach was likely to be the most feasible by establishing procedures that would exclude the need for detailed study of most typical structures but would identify weaknesses that needed further evaluation in special or complex systems. It was agreed that for progressive collapse, local effects would be critical for typical structures and that global effects of blast loadings would be less than those for wind or earthquake loadings. However, it is important to note that progressive collapse analyses are different than seismic analyses and are equally complex.

The topics suggested were divided into two groups for discussion:

- Tools to assess vulnerability to progressive collapse of different structural systems. Evaluation tools with different levels of sophistication.
- Systems approach to retrofit. Strengthening methods for columns, beams, floor slabs, walls, and connections.

Two discussion groups were formed:

- Reaveley (chair), Crawford, Hayes, Schalfly, Sunshine, Wyllie
- Jirsa (co-chair), Duthinh, Gould, Houghton, Miller, Swatzell

Each group was asked to consider the other following topics within the context of their discussions

- What are current best practices?
- Knowledge gaps.
- Required resources

#### **Assessment/Evaluation Tools**

Discussions in both groups were based around assessing/evaluating buildings for progressive collapse using a tiered approach. The first tier might consist of a general, qualitative assessment based on configuration of the global system and on details of the components of the system. The

second tier might be based on some simple analyses such as consideration of alternate paths (missing element) or other indirect analyses of conditions that could lead to progressive collapse. Third and fourth tier methods would involve sophisticated methods of analysis using FEA or other commercially available software and would be threat-specific.

Further discussion resulted in defining the first tier approach as an “Assessment for Structural Integrity-Progressive Collapse.” The main features of such an approach would include--

1. Identification of obvious deficiencies/problems using a “checklist” based on physical characteristics of the building (procedures developed in the UK may be helpful in establishing guidelines).
2. The intent would be to identify those characteristics that provide a “basic level of resistance to progressive collapse.”
3. Any first-tier approach should make use of graphics to illustrate critical features of the basic level of resistance to progressive collapse and should be based on model building types. While a first-tier approach may provide a means of quickly determining whether a building is vulnerable to progressive collapse, it is important to remember that the more approximate and general the procedure, the more likely that important factors could be missed in assessing a specific building.

Second, and higher, levels of evaluation/analysis should be directed for higher levels of performance or for quantitative (perhaps, indirect) evaluation of features of structures that do not meet the requirements identified in the checklist. Some features of higher level methods--

1. Clarification as to whether building meets the requirements for basic level of resistance to progressive collapse. (some questions in the checklist could be established to trigger higher tier analysis based on owner desires, socio-economic considerations, and possibly, level of threat).
2. Permit consideration of procedures to provide for higher levels of security or to consider issues (not included in checklist) that require analysis to assess level of level of resistance to progressive collapse, basic or higher.
3. Threat specific
4. Direct and indirect approaches.

A critical element of assessment/evaluation procedures is the development of acceptance criteria for many building types. The information needed will have to be obtained through physical tests on elements, subassemblies, entire structures subjected to the types of loads and deformations expected to trigger progressive collapse conditions.

### **Systems Approach/Strengthening Methods**

A “systems approach” was identified as one that involves a comprehensive assessment of a structure that may often triggered by issues other than progressive collapse. However, such assessments provide windows of opportunity for including progressive collapse as part of a multi-hazard study. The issues were discussed:

1. Structure, global and components (except foundation/geotechnical issues).
2. Mechanical/Electrical systems (considered to beyond scope of discussion).

3. Architectural issues— Configuration, egress, alternatives for venting, aesthetics, cladding (may affect behavior of structural elements), siting, setbacks, traffic or other barriers.
4. Fire Protection--Passive coatings, fire suppression, fuel loads (beyond scope of this workshop).

It was agreed that the use of case studies base on model building types and with cost data to illustrate the economic aspects of providing resistance to progressive collapse were essential to advancing the inclusion of progressive collapse evaluation into general usage by structural engineers and architects. When strengthening for improving the resistance to progressive collapse is undertaken, peer review of the procedures and techniques used is desirable.

Issues related to structural system rehabilitation for progressive collapse include:

1. Redundancy/dual systems, alternate load paths.
2. Loss of elements or subassemblies of the gravity load-carrying system.
3. Effect of debris or uplift due to pressures from blast or loss of other portions of structure.
4. Loss of stability bracing for columns.
5. Rehabilitation approach to provide functions critical to progressive collapse performance (strength, ductility, continuity).

A “tool-box” approach was discussed as a way to illustrate appropriate rehabilitation procedures to structural engineers. It would make use of model buildings and suggestions for basic rehabilitation techniques (including costs for case studies) for the various elements making up the gravity load-carrying system (columns, beams, braces, floor slabs, walls, connections/joints, in-fills, cladding, “non-structural” features) that can be used to provide a basic level of resistance to progressive collapse.

### **Proposed Program of Work**

The breakout group established a program or work with specific tasks and identified them short-term (12-18 months) or long-term research and development issues. The budgets indicated were added by the Chair and Co-Chair of the group after the discussion had concluded.

Task 1. Review of current state of practice for progressive collapse of existing building.

- Task 2. Tier 1 Assessment procedure for Structural Integrity/Progressive Collapse
- Checklist of qualifying attributes (true/false or complying/non-complying)
  - Based on at least three major groups of model buildings
  - Concrete frames
  - Steel frames
  - Precast panel or bearing wall buildings

(Estimated Cost of Tasks 1 and 2--short term, \$700k)

- Task 3. Causes of Progressive Collapse
- Definition of demand or hazard

(Estimated Cost of Short term, \$200k)

Task 4. Advanced Assessment Procedure for Structural Integrity/Progressive Collapse

- Development of acceptance criteria based on-
  - ✓ Local and/or global rehabilitation
  - ✓ Hazard or threat reduction
- Tier 2
  - ✓ Simple Analysis (to be used if qualifying attributes from checklist are identified)
  - ✓ Not threat specific
  - ✓ Use of new or adaptations of existing procedures (GSA, DOD, UK)
- Tier 3+
  - ✓ Higher level analyses
  - ✓ Defined threats

(Estimated Cost of Long-term, \$400k--Tier 2, \$200k--Tier 3)

Task 5. Techniques Manual

- Component modifications to meet tier 1 checklist (graphics coupled with descriptive text to facilitate understanding of continuity, torsional strength of girders, redundancy of load paths, ductility)
- Advanced techniques used with tier 2, 3 analysis

(Estimated Cost of Long-term, \$500k)

Task 6. Tests on Existing Buildings to develop understanding of behavior under progressive collapse conditions and to develop acceptance criteria for use in evaluation of existing buildings.

- Field tests on buildings scheduled for demolition
- Static tests—gravity loads only

(Estimated Cost of Long-term, \$500k/test)

General Task. Component-based laboratory tests to support items 2,4, and 5 (Different loading and deformation conditions than for seismic evaluation and rehabilitation)

(Estimated Cost of Long-term, \$2000k/yr for 5 years)

**Participants in Existing Buildings Breakout Session**

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Nathan Gould, ABS Consulting  
Jack Hayes, U.S. Army Research and Development Center  
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Douglas Sunshine, Defense Threat Reduction Agency  
Scott Swatell, Applied Research Associates  
Loring Wyllie, Degenkolb Engineers

## **APPENDICES**