Reducing the risk

A multi-hazard approach to progressive collapse mitigation

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The structural engineering profession is in the midst of a new architectural "renaissance," propelled by continued technological advances in the engineering and construction industry, and a desire by many to build defining iconic symbols. Today, modern tools allow designers the freedom to transcend simple building forms and consider more creative and innovative systems.

As engineers, our understanding of natural hazards and building behavior has evolved and improved. We are moving away from prescriptive designs to performance-based approaches. In executing our designs, we have new and powerful 3-D analysis, design, drawing, and coordination tools. While our finished projects may appear comprised of the same steel and concrete of old, our means and methods embrace all that technology has to offer.

It would seem that all is well, but sadly and with increasing frequency, our work has become a pawn in a battle of socio-political — not artistic — ideology. Buildings that have a high number of occupants or are of cultural or social significance can be viewed as high-impact soft targets to those who choose to make a statement through mayhem. Terrorism, whether domestic or internationally based, is now a real concern for the designers of many buildings. While architects are often credited for the design of even the most structurally complex buildings, engineers are the professionals questioned and held responsible if tragedy strikes.

Progressive collapse controversy

The attacks on military barracks and embassies abroad, along with the Murrah Federal Building in Oklahoma City, encouraged the U.S. government to begin addressing abnormal load requirements as part of its building design criteria. In comparison, the British addressed abnormal loading, and in particular progressive collapse, in its building code as early as 1970. This was a direct result of the Ronan Point collapse in 1968, in which a gas explosion in an 18th floor apartment led to a progressive collapse of floors and walls along the entire height of the building.

Today, structural engineers involved in General Services Administration (GSA) and Department of Defense (DoD) projects are required to consider progressive collapse mitigation in their design and analysis. In the aftermath of the World Trade Center (WTC) attacks, many owners of high-profile buildings requested similar design evaluations to mitigate potential progressive collapse. Furthermore, serious discussions are ongoing about whether to mandate progressive collapse mitigation requirements for a broader spectrum of building types by including provisions in the International Building Code.

ASCE 7-05 defines progressive collapse as "the spread of an initial local failure from element to element resulting eventually in the collapse

A resource on progressive collapse prevention

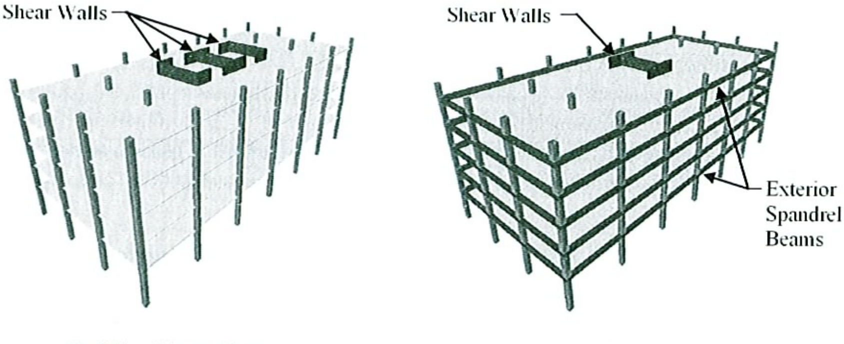
National building codes currently lack explicit consideration of progressive collapse mitigation. At the same time, the U.S. government has been developing approaches to address progressive collapse prevention in building design. Two major building owners, the General Services Administration (GSA) and the Department of Defense (DoD), require engineers to consider progressive collapse mitigation as a design criterion. The design guidance provided by these two organizations represents the most comprehensive information in the United States currently available on this topic.

However, few engineers are familiar with the GSA or DoD requirements for the mitigation of progressive collapse. This is attributable to the fact that, unlike wind and seismic design, progressive collapse mitigation lacks a nationally recognized design methodology. General guidance is provided in several documents, but no quantifiable or enforceable criteria exist.

The purpose of Prevention of Progressive Collapse in Multistory Concrete Buildings by Francis K. Humay, Steven M. Baldridge, and S.K. Ghosh is to help bridge this information gap. The text demonstrates the implementation of GSA and DoD methodologies for progressive collapse mitigation in reinforced concrete buildings. It is intended to help the practicing engineer understand the design process for different structural systems. Although the examples are specific to the GSA and DoD criteria, the fundamental principles are applicable to all structures.

Prevention of Progressive Collapse in Multistory Concrete Buildings is published by the Structures and Codes Institute and the International Code Council and is available at www.skghoshassociates.com.

Figure 1: Multi-hazard structural framing The first structure is built using a building frame system and the second structure is built using a dual system. With the dual system, resistance to lateral forces is provided by interior shear walls and moment frames acting together.



Building Frame System

Dual System

of an entire structure or a disproportionately large part of it." The onset of progressive collapse can be triggered by unintentional overload, misuse of the facility, or an abnormal loading (such as caused by an accidental explosion or an act of terrorism) not considered in the design. Progressive collapse increases the likelihood of human casualties and trapped survivors.

In discussions concerning collapses of the Murrah Federal Building and the WTC towers, there is general consensus that these were undeniably tragic acts of violence. From a technical standpoint, however, there are varying opinions amongst engineers on whether these events should be classified as progressive collapses and whether current progressive collapse design guidelines would have helped reduce the number of casualties.

In the case of the WTC towers, the triggering event included the loss of extensive areas of supporting columns and was certainly not a local failure. The eventual collapse was the result of strength reduction and subsequently increasing levels of stress around the areas of global damage induced by severe heat from burning jet fuel. Although elements of the building design have been thoroughly scrutinized, most engineers agree that it is not economically feasible to design a building that can withstand the impact, and ensuing fire, from a large commercial jetliner.

While the Murrah Building may seem to be a clearer example of progressive collapse, the initiating event, equivalent to the explosion of 4,000 pounds of TNT, caused the loss of three out of the five supporting columns on one face of the building. The loss of this many columns on one face of a building is not truly a local failure, and the blast pressure originating from a large truck bomb is certainly not a small initiating event.

Since all failures have a progressive nature to them, some engineers have rightly raised the question as to whether the focus should actually be on preventing disproportionate collapse. As to the Ronan Point disaster, the collapse was undoubtedly both progressive in nature and disproportionate to the initiating event. This cannot be said about collapses resulting from larger terrorist attacks.

The right thing to do

There can be no argument that part of the learning process for engineers should be to figure out how a building acts as the sum of its parts. The basic concept of continuous load path, even from a gravity standpoint, is becoming more challenging as complex architecture is often forcing structural engineers to deal with less rational and often poorly arranged structural layouts. Even with relatively simple building types, certain structural systems and layouts are less forgiving to abnormal loading than others.

Because the cost of incorporating extensive protective design into a structure can be significant, each project should be looked at individually.

For example, DoD buildings are designed for a range of protection that varies from a "very low level of protection" to a "high level of protection." The final level of protection is dependent on building usage and assessed threat, ensuring that resources are spent where they are most needed. While the debate over code-required progressive collapse mitigation will continue, there are many general design philosophies that structural engineers can use in their current practice to produce more robust structures efficiently.

The Best Practices for Reducing the Potential for Progressive Collapse in Buildings, published by the National Institute of Standards and Technology (NIST) in February 2007, provides a comprehensive resource on the topic. The following are excerpts from this publication:

To reduce the risk of progressive collapse in the event of loss of structural elements, the following structural traits should be incorporated in the design. Collectively they produce "robust" structures capable of limiting the spread of damage due to an initiating event.

Redundancy — The incorporation of redundant load paths in the vertical load-carrying system helps to ensure that alternate load paths are available in the event of local failure of structural elements.

Ties — The loss of a major structural element typically results in load redistributions and member deflections. The ability of a structure to re-distribute or transfer loads is based in large part on the interconnectivity between adjacent members. This is often called "tying a building together" by using an integrated system of ties in three directions along the principal lines of structural framing.

	Original Building (SF)	Pier-Spandrel Scheme (SF)	SMF Scheme (SF)	Shear Wall Scheme – Line F.5 (SF)
% of Total Floor Area Damaged	42%	4%	4%	31%
% of Damaged Area Due to Blast	10%	100%	100%	12%
% of Damaged Area Due to Progressive Collapse	90%	0%	0%	88%

Table 1: Estimated damage based on floor area To analyze how different structural systems might have reduced the extent of damage in the Murrah Federal building, the impact of incorporating a multi-hazard approach was evaluated. Results indicate that moment frame-type systems would have performed better than the original design.

Ductility — In a catastrophic event, members and their connections may have to maintain their strength through large deformations (deflections and rotations) and load redistributions associated with the loss of key structural elements. For steel structures, ductility is achieved by using steel with high toughness, maintaining overall and local structural stability, and creating connections between elements that exceed the strength and toughness of the base material. For reinforced concrete and reinforced masonry structures, ductility is achieved by providing sufficient confinement of reinforcing steel, providing continuity in reinforcement through adequate lap splices or mechanical couplers, maintaining overall structural stability, and creating connections between elements that exceed the strength and toughness of the base members.

Adequate shear strength — Structural elements in vulnerable locations, such as perimeter beams or slabs, should be designed to withstand shear load in excess of that associated with the ultimate bending moment in the event of loss of an element. Direct shear failure is a brittle mode of failure and should not be the controlling failure mechanism. Shear capacity should always exceed flexural capacity to encourage a ductile response. Typical two-way slabs without beams must be capable of providing post-failure resistance in the presence of punching shear failures and severe distress around the columns. Continuous top and bottom reinforcement properly anchored into the columns prevents "rip-out" after shear failure has occurred. This reduces the likelihood of progressive collapse as the slab-column connection is maintained by membrane action of the slab reinforcement.

Capacity for resisting load reversals — The primary structural elements (columns, girders, roof beams, and lateral-load-resisting systems) and secondary structural elements (floor beams and slabs) should be designed, using acceptable techniques, to resist reversals in load direction at vulnerable locations.

Cost-effective resistance

On projects where DoD or GSA progressive collapse design criteria must be met, the engineer should remember that even the government has limited budgets. Advanced planning is required prior to performing any detailed structural analysis. Selection of the most appropriate structural system is a complex process that should consider unique features of the project such as local construction practices, material price and availability, and other potential issues. The primary goal is developing an economical structural system that meets or exceeds project requirements.

A lack of experience in incorporating progressive collapse resistance in the design process can result in overly conservative and potentially cost-prohibitive structural designs. Assessing progressive collapse mitigation requirements separately from other design requirements is an undesirable approach. Most engineers will agree that it is inefficient to provide one lateral-force-resisting system to resist wind loads and another to resist seismic forces. For this same reason, it is cost-prohibitive to provide progressive collapse resistance without regard to these other hazards.

The solution is to take a "multi-hazard approach" to design. This involves integration of progressive collapse, seismic, and wind-load resistance into a single structural system. The primary goal is to provide, where possible, a lateral-load-resisting system that can perform "double duty," simultaneously addressing both lateral and progressive collapse requirements.

As an example, consider an identical office building framed with two different structural systems. The first structure is built using a building frame system. This system has an essentially complete space frame to support gravity loads and interior shear walls to resist lateral loads. In many cases, space frames in such buildings consist of slab-column frames without beams. Such framing is efficient in supporting gravity loads, but has little resistance to load reversals. Furthermore, a lack of ductile detailing, as is required in seismically detailed members, provides a system with very limited ability to redistribute loads and prevent progressive collapse.

The second structure is built using a dual system. Resistance to lateral forces is provided by interior shear walls and moment frames acting together (see Figure 1). Moment frames located on the perimeter of the building can be initially sized for progressive collapse resistance and then the overall system checked for lateral resistance. Economy is achieved by reducing the interior shear wall demands.

System selection can have significant impact on overall structural cost. Consider a case in which the example office building must be designed to remain stable after the loss of an exterior column. In the first structure, progressive collapse resistance is provided by either significantly modifying the structural slab or adding a secondary structural system. Designing the slab to bridge over a removed column requires providing more continuity in the slab reinforcement, adding additional reinforcing steel in the slab, and/or increasing the slab thickness. These changes, made on a global scale, can significantly reduce efficiency of the slab system. A second option is to provide exterior spandrel beams, designed to independently span over a removed column. In this scenario, efficiency of the slab system is maintained; however, a secondary structural system must be added. Any cost savings realized by not having to modify the slab is nullified by the cost of the extra spandrel beams.

On the other hand, in the second structure, progressive collapse mitigation requirements are incorporated during the design of the lateral-force-resisting system. One structural system is designed to resist all hazards, maximizing overall efficiency and likely reducing the cost of the structural system.

The impact of incorporating a multi-hazard approach has been evaluated in a FEMA-funded project intended to analyze how different structural systems might have reduced the extent of damage in the Murrah Federal building. The results, shown in Table 1, indicate that moment-frame-type systems, which would be able to provide both lateral and progressive collapse resistance, would have performed better than the original design.

Summary

Engineers should, as a matter of standard practice, consider load paths, layout, and details that minimize the potential for progressive collapse. Where projects require specific progressive collapse-resistant design, engineers need to be creative and incorporate the aforementioned principles cost effectively into the building design. One recommended strategy involves the "multi-hazard" integration of progressive collapse, seismic, and wind-load resistance into a single structural system. ▼

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