Multi Hazard Approach to Progressive Collapse Mitigation

S. M. Baldridge¹ and F.K. Humay²

¹Baldridge & Associates Structural Engineering, Inc. 1164 Bishop Street Suite 605, Honolulu, HI 96813; PH (808) 534-1300; FAX (808) 534-1301; email: sb@baseengr.com
²Baldridge & Associates Structural Engineering, Inc. 1164 Bishop Street Suite 605, Honolulu, HI 96813; PH (808) 534-1300; FAX (808) 534-1301; email: fkh@baseengr.com

Abstract

In light of current world developments, engineers are increasingly being required to consider progressive collapse mitigation as a basic design criterion. Progressive collapse requirements, however, must typically be incorporated into a structure without substantial increases in the cost of the structural system. One method of achieving this goal efficiently is to utilize a multi hazard approach to structural system selection.

This paper illustrates how progressive collapse criteria can be economically incorporated into typical structural systems. Although three very different examples are presented, the overall design approach is basically the same.

Structural Steel Office Building – The use of some types of moment frames to resist lateral wind and seismic loads can also provide the additional ductility and redundancy required for progressive collapse resistance.

Reinforced Concrete Office Building – Analysis of an example existing building indicated that seismically designed reinforced concrete moment frames have an inherent capability of providing progressive collapse resistance.

Reinforced Concrete Apartment Building – One cost effective construction method for apartment building construction is the tunnel-form concept. Analysis methods indicate that with minor modifications these structures can be designed to withstand the loss of a supporting wall without experiencing progressive collapse.
**Introduction**

In light of current world developments, engineers are being required to increasingly consider progressive collapse mitigation as a basic design criterion. To remain economically viable, this additional design requirement must typically be incorporated without a substantial increase in the cost of the structural system. As with addressing natural hazards in the past, engineers are now faced with finding cost effective solutions that will make buildings more resilient to both natural and man-made hazards.

**Progressive Collapse**

Building performance has been a consideration throughout the centuries, dating as far back as The Code of Hammurabi (2200 B.C.).

“If a builder builds a house for a man and does not make its construction firm and the house collapses and causes the death of the owner of the house – that builder shall be put to death.”

In modern times, building codes have evolved to address lessons learned from both natural and man-made hazards. For example, the huge losses resulting from Hurricane Andrew prompted South Florida to enact more stringent design requirements. Similarly, the Northridge Earthquake spawned research and code changes related to welded connections in steel framed buildings.

The triggering event for consideration of progressive collapse in the design process was the failure of a portion of the 22-story Ronan Point apartment building on 16 May 1968 in Newham, England (see Figure 1).

![Figure 1. Progressive Collapse – Ronan Point](image-url)
The Ronan Point collapse was particularly eye opening for the engineering community. The initiating event, the striking of a match in an 18th floor apartment, triggered a gas explosion that displaced a load bearing precast concrete panel near the corner of the building. The loss of support led to a progressive collapse of floors and walls along the entire height of the building. The collapse at Ronan Point led to significant code changes in the United Kingdom, but only rather limited changes and discussion in U.S. codes.

While progressive collapse failures in completed buildings are few, the dramatic nature of such events continues to bring attention to the issue. The evolution of building codes and related design criteria is closely related to major historic events as illustrated by the timeline in Figure 2.

![Figure 2. Building Disasters and Code Changes](image)

The current edition of the ASCE 7 “Minimum Design Loads for Buildings and Structures” provides only general and unenforceable guidance related to the issue of progressive collapse:

“Except for specially designed protective systems, it is usually impractical for a structure to be designed to resist general collapse caused by gross misuse of a large part of the system or severe abnormal loads acting directly on a large portion of it. However, precautions can be taken in the design of structures to limit the effects of local collapse to prevent or minimize progressive collapse.”

The concept of general structural integrity is discussed as an indirect method of addressing progressive collapse. As with seismic and wind design, consideration of desirable levels of strength, ductility and continuity are fundamental principles in ensuring structural integrity.
In order to explicitly consider progressive collapse resistance through direct design however, the problem must first be defined in more detail. ASCE 7-02 provides a general definition of progressive collapse, but no specific criteria on how to incorporate this information into the design process. According to ASCE 7-02, progressive collapse is:

"The spread of an initial local failure from element to element resulting eventually, in the collapse of an entire structure or an disproportionately large part of it."

The problem with this definition is that it is open to interpretation. For instance, what constitutes a “local” failure or a “disproportionately large part” of a structure will vary from engineer to engineer. To illustrate this point, if one were to ask a group of engineers if the following building failures; Ronan Point, The Murrah Federal Building in Oklahoma City, and the World Trade Center towers were examples of “progressive collapse”, you would most likely receive a varied opinion. ASCE 7-02 acknowledges that it is not intended “for this standard to provide specific design criteria to minimize the risk of progressive collapse.”

With the terrorist attacks on the Murrah Federal Building, overseas military barracks and foreign embassies, the United States of America government agencies such as the General Services Administration (GSA) and the Department of Defense (DoD) have developed more specific criteria for both what is considered progressive collapse and what is considered an acceptable level of collapse (see Figure 3).

Figure 3. GSA – Maximum Allowable Collapse Areas
In both the GSA guidelines and DoD standards the triggering event or “local” failure is defined as the loss of “one” primary vertical or horizontal load bearing member. Progressive collapse is then further defined by maximum allowable collapse areas. If it is found that removal of a single member will result in damage beyond the limits of these areas, the collapse is considered disproportionate, and progressive collapse is likely. In this case, the design is considered non-compliant and requires redesign and re-analysis.

The area of collapse is determined analytically in a two, or preferably, three-dimensional model of the building. The analysis requires removing single members, one at a time, from the analytical model and evaluating the performance. To avoid an overly conservative design, factored load combinations are reduced to represent a more realistic representation of the actual loads that might be present in a structure. In addition, to account for material over-strength and strain hardening, material strength factors are increased.

**Multi Hazard Approach to Progressive Collapse**

As with the design of all conventional structures, analysis is only part of the process. Careful thought and planning is first required to develop a structural “program” that takes into account unique aspects of the project requirements, local construction practices, material price and availability, and a myriad of other considerations. The goal of the “program” is to develop an economical structural system that meets or exceeds the project requirements.

While there are no simple approaches that address every building type, general guidance can be provided. As indicated in Figure 4, the GSA illustrates two different redesign approaches to mitigate progressive collapse.

![Figure 4. GSA – Possible Approaches for Redesign](image)

Even when considering reduced load factors and increased material strengths, designing for progressive collapse can become overly conservative and cost prohibitive, especially if considered separately from the other design requirements. For the same reason that it would not be economical to provide one lateral system in a structure to resist wind loads and another to resist seismic forces, it can be cost prohibitive to consider progressive collapse outside of these other hazards.
A multi hazard approach requires selecting a structural system that has the ability to address progressive collapse, seismic and wind loads. This requires, where possible, the use of lateral load resisting systems that can do “double duty,” simultaneously addressing both lateral and progressive collapse requirements. A building utilizing interior shear walls to provide all of the structure’s lateral load resistance and ordinary moment frames, or flat slab system for gravity loads, for example, may have a very limited ability to redistribute loads and prevent progressive collapse.

In a multi hazard approach the goal is to fully incorporate the systems providing progressive collapse resistance into the overall lateral load resisting system. One example is a “dual system”, consisting of moment frames and shear walls acting together to resist the design lateral loads. Moment frames located on the perimeter of the building can first be designed for progressive collapse requirements and then the remainder of the system checked for lateral requirements. Economy will be achieved by reducing the interior shear wall requirements.

**Structural Steel Office Building**

The first example is a 7-story, roughly 30,000 square meter office building. This example can be representative of government buildings requiring progressive collapse mitigation (i.e., a GSA building) or a high profile private client, such as a financial institution, desiring a greater level of protection than specified in the model building codes. In either case, the goal is to provide a greater resistance to progressive collapse with minimal impact on the overall budget.

The initial design included a lateral load resisting system consisting primarily of concrete shear walls at the elevator and stair cores with a composite metal deck and concrete slab diaphragm. The concrete walls provide the required resistance to lateral wind and seismic loads while steel beams and columns provide the majority of the gravity framing for the building. In this type of framing scheme the typical connections of the steel members are “simple” or “non-moment” type connections.

![Figure 5. Initial Structural Framing Concept](image-url)
To satisfy the progressive collapse requirement the structural framing needs to provide sufficient redundancy and ductility to bridge over a removed column. While common and economical, the “simple” or “non-moment” type connection utilized in the initial concept does not provide these essential characteristics. An alternate structural framing concept that provides “moment” type connections around the perimeter of the building can, however, be designed to develop the required “alternate load path” around a removed column.

The use of “moment” type connections on the perimeter of the building will result in increased cost. If the overall framing concept is not reevaluated, there could be a significant increase in the overall cost of the building. This is where utilizing a multi hazard approach can provide an efficient system design. An alternate system that retains the original elevator and stair cores for the structure’s lateral resistance and “adds” moment frames to address progressive collapse is not only more expensive but ignores the lateral capability that the added moment frames can provide.

A multi hazard approach is an alternate structural steel scheme that evolves towards a global steel frame structure designed for the progressive collapse requirement and then checked of its ability to resist wind, earthquake and gravity loads. By optimizing the location and orientation of the steel moment frames, the steel scheme becomes a structure with enhanced redundancy, ductility and energy dissipation characteristics.

![Figure 6. Multi Hazard Moment Frame Structural Concept](image)

The original three-dimensional model of the structure (see Figure 5) was modified (see Figure 6) to remove the core walls and rely on perimeter moment frames for both the lateral and progressive collapse requirements. In moderate seismic zones the resulting design can be compared to other light conventional steel frame structures. This is particularly impressive, considering the stringent design requirements. This innovative solution was made possible by creatively exploring a multi hazard approach.
Reinforced Concrete Beam-Column Frame Office Building

The second example is a 13-story, roughly 11,000 square meter office building. In this particular case the example building is taken from the design manual entitled Design of Concrete Buildings for Earthquake and Wind Forces. In concept this can be an existing building that intends to lease space to a tenant requiring progressive collapse design such as the GSA or a high profile private client desiring a greater level of protection then specified in the model building codes. In either case the goal is to determine if the existing structure will need to be retrofitted to meet the progressive collapse design criteria.

Figure 7. Progressive Collapse Analysis of Existing Moment Frame

The existing construction includes a lateral load resisting system consisting primarily of concrete beam-column frame action. The beams and columns are configured and reinforced to provide the required resistance to lateral wind and seismic loads as well as the gravity framing for the building. In this type of cast-in-place framing scheme, the inherent continuity of the framing members increases the available moment resisting capacity under load reversals of the cast-in-place concrete members.
Figure 8 indicates the results from an analysis that follows the GSA guidelines for progressive collapse mitigation. The numbers in Figure 8 represent the Demand Capacity Ratio (DCR) for moment and shear. Where the DCR is < 2.0 the structure is considered a low potential for progressive collapse. The structural frame in this analysis has been proportioned and reinforced to meet 1991 Uniform Building Code – Zone 2B seismic requirements. In Case 1 the impact of a “missing column” along the long face of the building is considered. By removing this column the beam span in this area is doubled from roughly 8 meters to 16 meters. The seismically detailed frames do, however, have sufficient capacity to develop an alternate load path.

The multi hazard approach in this case was unintentional. A structure designed to an older building code with only moderate seismic requirements was found to meet GSA progressive collapse requirements. In general, seismically detailed reinforced concrete frames provide a structure with continuity, redundancy and ductility. Therefore moment frame type systems have an inherent ability to better resist progressive collapse.

An actual example of this concept is the Deutsche Bank Building located directly adjacent to the World Trade Center Towers. A major column on the perimeter of this building was “removed” by falling debris from the collapse of the adjacent tower. This building sustained substantial damage without progressive collapse. The performance was attributed to similar perimeter moment frames that were originally proportioned only to provide the building’s wind resisting system.
Reinforced Concrete Residential Building

The last example is a 5-story, roughly 5,500 square meter residential building. In concept, this can be a DoD building, such as housing for the military, requiring progressive collapse design. Even though the DoD has required these more stringent design requirements, they have not significantly increased project budgets.

One typical and cost effective construction method for residential building construction is the tunnel-form concept. Load bearing concrete walls are located at party walls separating units or living space within the units. These walls then support a reinforced concrete slab spanning between the walls as indicated in Figure 9.

![Figure 9. Structural Framing Concept](image)

For this example, the vertical load carrying elements are primarily walls. “Local” collapse was defined as the loss of any one wall within 3 meters from the exterior of the building. One approach was to design the individual floor slabs to be able to span over a “removed” wall. This approach would require the slab to span twice as far and carry the weight of the wall area above the “removed” portion of wall. With this type of approach the efficiency of the slab system would be lost.

An innovative alternate considered the load bearing walls as individual elements connected at the top (see Figure 10).

![Figure 10. Loss of Wall without Progressive Collapse](image)
The exterior or vulnerable portion of wall, as defined by the design criteria, is “removed” in the analysis. By connecting the walls at the top of the building an “alternate load path” could be provided at minimal additional cost. The “alternate path” is analogous to a “hanger” carrying the loads of the lower floors (see Figure 11). Analysis methods indicated that with minor modifications this structure could be constructed to reduce the potential of progressive collapse due to the loss of large areas of supporting wall.

![Figure 11. “Hanger” Concept of Alternate Load Path](image)

**Conclusion**

While there is not consensus in the engineering community about the need to extend specific progressive collapse requirements into the building codes, the general concepts related to progressive collapse mitigation are important to consider in the design of every building. The desirable properties included in mitigation techniques include:

*Redundancy – Continuity – Ductility*

Progressive collapse design requirements can add major cost to building construction if it is achieved without consideration of other design requirements. By taking a multi hazard approach progressive collapse mitigation can often be achieved with minimal additional construction costs.

While the progressive collapse mitigation discussed will result in more robust and resilient designs they will not be able to prevent damage or injury that occurs under abnormal loading (i.e. loss of several columns). Current progressive collapse design guidelines will not mitigate damage from large scale deliberate attacks.
References


