Progressive Collapse Basics

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A rational look at today's building codes, with an eye on blast-resistant design.

On May 16, 1968, Ivy Hodge, a tenant on the 18th floor of the 22-story Ronan Point apartment tower in Newham, east London, struck a match in her kitchen. The match set off a gas explosion that knocked out load-bearing precast concrete panels near the corner of the building. The loss of support at the 18th floor caused the floors above to collapse.

The impact of these collapsing floors set off a chain reaction of collapses all the way to the ground. The corner bay of the building collapsed from top to bottom. Mrs. Hodge survived but four others died.

While the failure of the Ronan Point structure was not one of the larger building disasters of recent years, the magnitude of the collapse was completely out of proportion to the triggering event. This type of sequential, domino-effect failure was labeled "progressive collapse." Since then, the engineering community and public regulatory agencies resolved to change the practice of building design to prevent the recurrence of such tragedies.

Progressive Collapse and Disproportionate Collapse

Progressive collapse can be defined as collapse of all or a large part of a structure precipitated by failure or damage of a relatively small part of it. The General Services Administration (GSA, 2003b) offers a specific description of the phenomenon: "Progressive collapse is a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse."

It has also been suggested that the degree of "progressivity" in a collapse be defined as the ratio of total collapsed area or volume to the area or volume damaged or destroyed directly by the triggering event. In the case of the Ronan Point collapse, this ratio was of the order of 20. By any definition, the Ronan Point disaster would qualify as a progressive collapse. It was also disproportionate: A corner of a 22-story building collapsed over its entire height as a result of a fairly modest explosion that did not take the life of a person within a few feet of it. The scale of the collapse clearly was disproportionate to the cause.

Murrah Federal Office Building

The Murrah Federal Office Building in Oklahoma City was destroyed by a bomb on April 19, 1995. The bomb, in a truck at the base of the building, destroyed or badly damaged three columns. Loss of support from these columns led to failure of a transfer girder. Failure of the transfer girder caused the collapse of columns supported by the girder and floor areas supported by those columns. The result was a general collapse.

The Murrah Building disaster was progressive collapse by all definitions of that term. Collapse of a large part of the building was precipitated by destruction of a small part of it (a few columns). The collapse also involved a clear sequence or progression of events: column destruction; transfer girder failure; collapse of structure above.

But was the Murrah Building collapse disproportional? The answer is not nearly as clear as in the case of the Ronan Point collapse. The Murrah collapse was large, but the cause of the collapse, the bomb, was very large too—large enough to cause damage over an area of several city blocks. Ultimately, we must judge the Murrah Building collapse "possibly

Ronan Point building after the May 1968 collapse.

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disproportional" only because we know now that with some fairly modest changes in the structural design, the damage from the bomb could have been reduced significantly.

World Trade Center 1 and 2

The twin towers of World Trade Center 1 and 2 collapsed on Sept. 11, 2001 following this sequence of events: A Boeing 767 jetliner crashed into each tower at high speed; the crash caused structural damage at and near the point of impact, and set off an intense fire within the building; the structure near the impact zone lost its ability to support the load above it as a result of some combination of impact damage and fire damage; the structure above collapsed, having lost its support; the weight and impact of the collapsing upper part of the tower caused a progression of failures extending downward all the way to the ground.

Clearly, this was a "progressive collapse" by any definition. But it cannot be labeled a "disproportionate collapse." It was a very large collapse caused by a very large impact and fire. And unlike the case with the Murrah Building, simple changes in the structural design that might have greatly reduced the scale of the collapse have not yet been identified.

Observations on "Progressive" and "Disproportionate" Collapse

Prevention of progressive collapse generally is an imperative in structural engineering today. But virtually all collapses could be regarded as "progressive" in one way or another, and a building's susceptibility to progressive collapse should be of particular concern only if the collapse is also disproportionate. The engineering imperative should be not the prevention of progressive collapse but the prevention of disproportionate collapse.

Codes and Standards

Since the progressive collapse of the Ronan Point apartment tower in 1968, many codes and standards have attempted to address this type of collapse. A sampling of current and recent provisions related to progressive collapse highlights alternative approaches and the direction in which these efforts are evolving.

ASCE 7-02: The American Society of Civil Engineers Minimum Design Loads for Buildings and Other Structures (ASCE, 2002) has a section on "general structural integrity" that reads:

"Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage. This shall be achieved through an arrangement of the structural elements that provides stability to the entire structural system by transferring loads from any locally damaged region to adjacent regions capable of resisting those loads without collapse. This shall be accomplished by providing sufficient continuity, redundancy, or energy-dissipating capacity (ductility), or a combination thereof, in the members of the structure."

The focus in the ASCE standard is on redundancy and alternate load paths over all other means of avoiding susceptibility to disproportionate collapse. But the degree of redundancy is not specified, and the requirements are entirely threat-independent.

ACI 318-02: The American Concrete Institute Building Code Requirements for Structural Concrete (ACI, 2002) include extensive "Requirements for structural integrity" in the chapter on reinforcing steel details. Though the Commentary states that it "is the intent of this section … to improve …redundancy" there is no explicit mention of redundancy or alternate load paths in the Code. The Code provisions include a general statement that "In the detailing of reinforcement and connections, members of a structure shall be effectively tied together to improve integrity of the overall structure" and many specific prescriptive requirements for continuity of reinforcing steel and interconnection of components. There are additional requirements for the tying together of precast structural components. None of the ACI provisions are threat-specific in any way.

GSA PBS Facilities Standards 2000: The 2000 edition of the GSA's Facilities Standards for the Public Buildings Service (GSA, 2000) included the following statement under the "Progressive Collapse" heading in the "Structural Considerations" section: "The structure must be able to sustain local damage without destabilizing the whole structure. The failure of a beam, slab, or column shall not result in failure of the structural system below, above, or in adjacent bays. In the case of column failure, damage in the beams and girders above the column shall be limited to large deflections. Collapse of floors or roofs must not be permitted."

This is an absolute and unequivocal requirement for one-member (beam, slab, or column) redundancy, unrelated to the degree of vulnerability of the member or the level of threat to the structure.

GSA PBS Facilities Standards 2003: The 2003 edition of the GSA's Facilities Standards for the Public Buildings Service (GSA, 2003a) retained the "Progressive Collapse" heading from the 2000 edition, but replaced all of the words reproduced above with the statement: "Refer to Chapter 8: Security Design."

The structural provisions in Chapter 8 apply only to buildings deemed at risk of blast attack. For such buildings, the chapter provides general performance guidelines and references to technical manuals for study of blast effects. This represents a complete change of approach from the 2000 version of the same document.

GSA Progressive Collapse Guidelines 2003: The GSA Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects (GSA, 2003b) begins with a process to determine if a building is exempt from progressive collapse considerations. Exemption is based on the type and size of the structure (for instance, any building more than 10 stories is nonexempt) and is unrelated to the level of threat. Typical non-exempt buildings in steel or concrete have to be shown by analysis to be able to tolerate removal of one column or one 30′ length of bearing wall without collapse. Considerable detail is provided regarding the features of the analysis and the acceptance criteria. In some ways, these guidelines appear to be a throwback to the GSA's PBS Facilities Standards of 2000, in that their central provision is a requirement for one-member redundancy, unrelated to the degree of vulnerability of the member or the level of threat to the structure.

Methods of Preventing Disproportionate Collapse

In general, there are three alternative approaches to designing structures to reduce susceptibility to disproportionate collapse:

- Redundancy or alternate load paths
- Local resistance
- Interconnection or continuity

Redundancy or Alternate Load Paths

In this approach, the structure is designed such that if any one component fails, alternate paths are available for the load in that component, preventing a general collapse from occurring. This approach has the benefit of simplicity and directness. In its most common application, design for redundancy requires that a building structure be able to tolerate loss of any one column without collapse. This is an objective, easily understood performance requirement.

The problem with the redundancy approach, as typically practiced, is that it does not account for differences in vulnerability. Clearly, one-column redundancy when each column is a W8x35 does not provide the same level of safety as when each column is a 2000 lb/ft built-up section. An explosion that could take out the 2000 lb/ft column would likely destroy several of the W8 columns, making one-column redundancy inadequate to prevent collapse in that case. And yet, codes and standards that mandate redundancy do not distinguish between the two situations; they treat every column as equally likely to be destroyed. In fact, since it is generally much easier to design for redundancy of a small and lightly loaded column, redundancy requirements might have the unfortunate consequence of encouraging designs with many small (and vulnerable) columns rather than fewer larger columns. For safety against deliberate attacks (as opposed to random accidents), this may be a step in the wrong direction.

Local Resistance

In this approach, critical components that are potential subjects for attack and that are susceptible to progressive/disproportionate collapse are provided with additional resistance. This requires some knowledge of the nature of potential attacks and is difficult to codify in a simple and objective way.

Interconnection or Continuity

This is, strictly speaking, not a third approach separate from redundancy and local resistance, but a means of improving them. Studies of recent building collapses show that failure could have been avoided or at least reduced in scale at little additional cost if structural components had been interconnected more effectively. This is the basis of the "structural integrity" requirements in the ACI 318 specification (ACI, 2002).

To illustrate the techniques for reducing susceptibility to disproportionate collapse, consider how redundancy, local resistance or interconnection might have been used to improve the performance of Ronan Point, the Murrah Building and WTC 1 and 2.

Case Outline: Ronan Point

Greater redundancy would have been difficult to build into the type of structure employed in the Ronan Point tower. Improved local resistance, in the form of greater strength of the precast concrete wall panels that blew out, precipitating the collapse, would not have helped; the panels would have blown out regardless of their strength.

Better interconnection of structural components is the key for this structure. Stronger and more positive connections between the wall panels and the floors, with less reliance on friction due to weight to hold everything together, is likely to have greatly reduced the scale of the collapse of the Ronan Point building.

Case Outline: Murrah Building

The columns at the front face of this reinforced concrete building were at 20′ centers on upper floors and 40′ centers at ground level, with a transfer girder to make the transition. A requirement for one-column redundancy almost certainly would have eliminated the transfer: The smaller columns 20′ apart would have extended down to the ground and the structure would have been designed to tolerate the loss of one of them. Would this have reduced the magnitude of the collapse on April 19, 1995? Probably not. The explosion would almost certainly have taken out several (at least five) of the small closely-spaced columns, easily overwhelming the one-column redundancy built into the design, leading to a collapse not significantly different from what actually occurred.

Improved local resistance, within plausible limits, would not have prevented destruction of the ground-floor column closest to the bomb. But improved ductility and shear capacity of the columns, possibly through reinforcing steel details used in earthquake-prone regions, and better interconnection and continuity throughout the building, could have prevented the loss of any of the other large ground-floor columns. They also could have limited the collapse to a 60′ to 80′ width of structure from the ground to the roof — a major disaster but much less than what actually happened. So the performance of the Murrah building would not have been improved by a requirement for redundancy in the design, but could have been improved by better interconnection and continuity throughout the structure and different reinforcing steel details in the columns.

Case Outline: WTC 1 and 2

The exterior frame of each WTC tower was already so highly redundant that greater redundancy would be hard to contemplate. The interior columns were not redundant, except for the limited redundancy created by the hat trusses. But the impact and fire damage were so pervasive that greater redundancy in the interior is not likely to have changed the outcome. Greater local resistance (in the strictly structural sense, fire protection could be a different issue) was not a practical proposition for these towers. Finally, notwithstanding early reports to the contrary, connection failures do not appear to have contributed significantly to the disaster, so improved interconnection would not have been useful.

The conclusion that none of the typical means of preventing disproportionate collapse would have been useful for the WTC towers reinforces the idea that the collapse of these buildings was not disproportionate.

Application of Codes and Standards to the Cases Considered

The use of current codes and standards would not consistently provide assurance against the types of collapse that occurred in the above buildings — not even against the clearly disproportionate collapse at Ronan Point or the "possibly disproportionate" collapse at the Murrah Building.

Would use of these codes and standards in their design have improved the performance of Ronan Point, Murrah and WTC?	Redundancy	Local Resistance	Interconnection	Threat-dependent analysis	Ronan Point	Murrah Building	WTC 1 & 2
ASCE 7-02	•				?	N	N
ACI 318-02			•		Y	?	N
GSA...PBS, 2000	•				?	N	N
GSA...PBS, 2003				•	N	Y	N
GSA PC Guidelines	•				N	N	N

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*This paper has been edited for space considerations. To learn more about progressive collapse, read the complete text online at **www.modernsteel.com** or in the 2004 NASCC Proceedings.*