Blast and Progressive Collapse Resistance

A Journal Review

*In December of 2003, the American Institute of Steel Construction and the Steel Institute of New York jointly sponsored the Steel Building Symposium: Blast and Progressive Collapse Resistance, which featured eleven speakers on current capabilities and future needs. This article summarizes the papers presented by three of those eleven speakers. The full proceeding, including all eleven papers, is available at **www.aisc.org/blast**.*

Progressive Collapse Basics

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This paper presents the basics of progressive collapse, which is the collapse of all or a large part of a structure precipitated by damage or failure of a relatively small part of it. The phenomenon is of particular concern since progressive collapse is often (though not always) disproportionate, i.e., the collapse is out of proportion to the event that triggers it. Thus, in structures susceptible to progressive collapse, small events can have catastrophic consequences. The following major points are addressed in the paper:

•The progressive and disproportionate collapse of the Ronan Point apartment tower in England in 1968 established the prevention of progressive collapse as one of the unchallenged imperatives in structural engineering.

•Ronan Point, the Murrah Federal Building, and WTC Towers 1 and 2 are examined as cases of progressive collapse.

•By any definition, the Ronan Point disaster would qualify as a progressive collapse. In addition to being progressive, the Ronan Point collapse was *disproportionate*. A corner of a 22-story building collapsed over its entire height as a result of a fairly modest explosion, an explosion that did not take the life of a person within a few feet of it. The scale of the collapse was clearly disproportionate to the cause.

•The Murrah Federal Building disaster clearly was a progressive collapse. 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. The Murrah collapse was large. But the cause of the collapse – the bomb – was very large too. Thus, the author judges the Murrah Building collapse as "possibly disproportional", knowing that with some fairly modest changes in the structural design (as discussed in the full paper), the damage from the bomb might have been significantly reduced.

•Each of the twin towers of World Trade Center 1 and 2 collapsed on 11 September 2001 following this sequence of events: a Boeing 767 jetliner crashed into the tower at high speed; the crash caused structural damage at and near the point of impact and also 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". 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.

•The author examines the approaches taken by code-writing bodies and governmental user agencies in ASCE 7, ACI 318, and three GSA standards, which generally provide design guidelines and criteria that would reduce or eliminate the susceptibility of buildings to this form of failure. These efforts tend to focus on improving redundancy and alternate load paths, to ensure that loss of any single component would not lead to a general collapse. Redundancy is only one of the ways of reducing susceptibility to disproportionate collapse. Improved local resistance for critical components and improved continuity and interconnection throughout the structure (which can improve both redundancy and local resistance) can be more effective than increased redundancy in many instances. Through an appropriate combination of improved redundancy, local resistance and interconnection, it should be possible to greatly reduce the susceptibility of buildings to disproportionate collapse.

Learning from Structures Subjected to Loads Extremely Beyond Design

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This paper examines buildings that have been subjected to loads greatly in excess of their design criteria and have not collapsed, including lessons learned from several of these buildings. It also establishes that the concept of risk is an important factor about which structural engineers need to communicate clearly with the building owner, architect, and building officials, not only for what loadings may have been considered, but perhaps more importantly for those not considered in a project design. The following major points are addressed in the paper:

•Building designers cannot design for every extremely remote hazard that their project may be subjected to in its life. The objectives of design commonly include hazards from gravity, wind, earthquake and fire. For each of these, the hazard is defined, the performance objective identified and the conformance strategy established.

•When they are to be considered, extreme loadings such as the effect of a blast, have to be treated the same way, though clearly, many extreme loadings present hazards are beyond the realm of cost effective resistance, and in many cases beyond the ability to overcome the physics of the hazard.

•One of the most common strategies to resist progressive collapse is to use a notional removal of one exterior element at a time and creating alternate load paths. This does not relate to any specific hazard and therefore does not create a performance objective for a "real" threat. It is simply meant to increase the redundancy of the structure. Many structures that have not been designed for this criterion actually have shown some capacity to lose a column without global collapse. Designers should consider the possibility of negative impacts of excessive horizontal ties under more extreme loading when using the notional removal technique.

•Ronan Point is the most famous case of "pure" progressive collapse. There were five deaths. There was extensive vertical propagation of the collapse, but almost no horizontal propagation. If the building had been well tied together and the initiating event was larger, would the entire structure have collapsed?

"…risk is an important factor (which must be communicated)…"

•Murrah Federal Building had complete vertical and some horizontal propagation of the collapse. The blast was the equivalent of 4,000 lbs. of TNT.

•600 California in San Francisco had a crane accident, which demonstrated tremendous ductility of concrete filled steel pipes.

•WTC Towers 1 and 2 had highly redundant steel exterior moment frames that were able to bridge about 140 feet of missing columns before this damage, plus the ensuing intense fires, ultimately brought down both buildings.

•Bankers Trust in New York City survived debris from collapse of WTC 2 which removed an exterior column over a partial height of the building. The redundancy of the structure above provided the necessary bridge to transfer loads from the missing column.

•World Financial Center 3 (American Express) in New York City survived with sections of the corner column destroyed. The corner bay was supported by the cantilevered structure above and stiffening provided by the exterior wall system.

•WTC 3 (Marriott Hotel) in New York City was crushed by debris from both WTC 1 and WTC 2. WTC 2 hit it first and, even though hundreds of tons of debris partially collapsed the southern part of the building, the collapse did not propagate to the north. The floor connections were not strong enough to allow the propagation.

•Based on observations of these buildings, the concept of structural compartments seems to have merit. Within each compartment, strong horizontal ties could be used to prevent vertical propagation of a collapse from a relatively small overload. In the event of a massive overload, the collapse would propagate horizontally until it hit an extra strong bulkhead wall (or one with weak connections) to arrest the collapse. This dual level protection concept is similar to the way that a submarine design deals with military hazards.

Design of Steel Structures for Blast-Related Progressive Collapse Resistance

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This paper establishes that structural steel framing has excellent ability to arrest collapse in the event of extreme damage to one or more vertical load carrying elements. A common strategy is to employ moment-resisting framing to re-distribute loads away from failed elements to alternative load paths through

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the flexural action of the framing. Other solutions can be obtained by relying on the development of catenary behavior in the framing elements, though such an approach requires members and connections capable of resisting large tensile demands simultaneously applied with large inelastic flexural deformations. Additional research on such moment connections is needed, as is refinement of current simplified analysis methods. The following major points are addressed in the paper:

•Three examples of the effectiveness of moment-resisting steel frames in arresting collapse and preventing progressive collapse as a result of extreme localized damage can be observed in the performance of buildings at New York's World Trade Center following the terrorist attacks of September 11, 2001. The closely spaced columns and deep girders of the moment-resisting steel frame that formed the exterior wall of the structure was capable of bridging around the massive local damage caused by impact of the aircraft, and arrest the global collapse of the structure for nearly 2 hours.

"…to employ moment-resisting framing to re-distribute loads away from failed elements…"

•The more conventional moment-resisting steel frame of the Deutsche Bank Building allowed that structure to arrest partial collapse induced by falling debris from the south tower of the World Trade Center, despite the fact that an entire column was removed from the structure over a height of 10+ stories.

•A series of one-bay moment-resisting steel frames placed around the perimeter of the WTC-6 building arrested collapse and limited collapse to areas not protected by moment-resisting framing, after the north wall of the North Tower fell across the top of the building.

•Simplified guidelines for the design of such systems have been developed for the U.S. General Services Administration (ARA, 2003) and are available to designers engaged in the design or review of federal facilities. The design model utilized in these simple procedures is conceptually incorrect, but probably provides adequate design solutions.

•The assumption that load redistribution occurs through flexural behavior alone is very conservative and results in the design of members that are much larger than actually required to resist progressive collapse. *Diagram 1* illustrates an alternative load resisting mechanism for redistribution of load that relies on catenary behavior of the steel framing and compressive arching of the concrete floor slab. In the top illustration in this figure, the frame is supporting loads prior to column removal. In the middle illustration the central column has been removed beneath the floor and the frame is redistributing loads to the outer columns through flexure, as the floor locally falls downward. If the girders are not sufficiently strong to resist the strength demands resulting from the instantaneous removal of the central support column in an elastic manner, which is what is inherently assumed by the federal guidelines, plastic hinges will form at the two ends of the beams and in the mid-span region, near the removed column. Neglecting loading along the beam span, the two-span beam will have a strength equivalent to $8M_p/L$, where M_p is the plastic moment capacity of the beam and L is the distance between the outer columns, to resist the load imposed on the beam by the now discontinuous central column and to slow the downward movement of the floor system. If this strength is not sufficient, the beam will deflect enough to mobilize catenary tensile action, which if sufficient, will eventually arrest the collapse. This mode of behavior, which is not explicitly considered in the federal guidelines but is relied upon, where the beam has formed plastic hinges at the beam-column joints and is now resisting loads from the interior column through catenary tensile behavior of the beam, balanced at the columns by compressive action in the slab. In fact, if the beam were compact and laterally supported, the federal guidelines would permit the beam to arrest the collapse of a central column load with a magnitude as high as $12M_p/L$. Clearly, in such a case, even though neglected by the federal guidelines, either catenary tensile behavior will be mobilized or the structure will fail to arrest collapse.

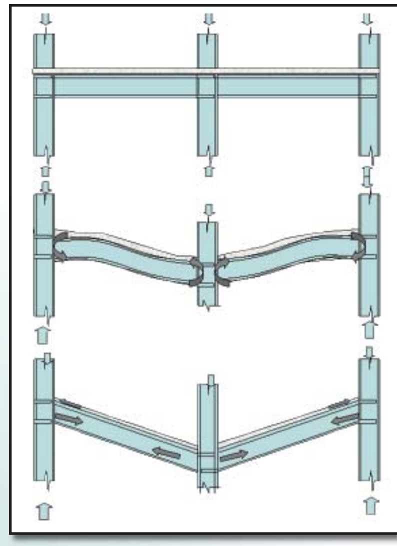

Diagram 1

•As an illustration of the potential efficiency of the catenary mechanism, in a recent study it was determined that in a structure with 30 foot bay spacing, ASTM A992, W36 horizontal framing could safely support the weight of nearly 20 stories of structure above in the event of column removal, although deflection would be significant. There are several potential implications of this finding. First, it is not necessary to provide moment resisting framing at each level of a structure in order to provide progressive collapse resistance. Second, it is not necessary to have substantial flexural capacity in the horizontal framing, either in the beam section itself or in the connection, in order to provide this collapse resistance. Third, it may not be necessary to provide full moment resistance in the horizontal framing, and conventional steel framing may be able to provide progressive collapse resistance as long as connections with sufficient tensile capacity to develop catenary behavior are provided.

•When properly configured and constructed, using materials with appropriate toughness, steel connections can provide outstanding ductility and toughness. A program of research and development similar to that conducted after the 1994 earthquake is underway to determine the types of connection technologies that can be effective in resisting progressive collapse, so that less conservative but more reliable approaches to blast resistant design can be adopted by the design community.▪