

Structural Systems for Progressive Collapse Prevention

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ABSTRACT

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.

PROGRESSIVE COLLAPSE IN THE UNITED STATES

The Ronan Point disaster in 1968 exposed a significant gap in understanding of progressive collapse in the international structural engineering design community. In the United Kingdom, building regulations were revised to explicitly account for accidental loading, and those provisions are presented in David Moore's paper at this workshop. The United States experience has evolved more slowly into building codes that express concepts of limiting disproportionate collapse, but offer little guidance on how to achieve these goals. Similarly in education and professional registration exams, the U.S. has lagged behind the UK practical training for the design of buildings for accidental loading.

The Oklahoma City Federal Building bombing did bring about change in the way federal buildings are designed, and this methodology is discussed below. Advances in seismic analysis and design in the US have many applications in the resistance to progressive collapse. A workshop on this topic was held on September 10, 2001. (Carino and Lew 2001) On September 11, 2001 the World Trade Center disaster made progressive collapse a structural behavior understood by nearly everyone in the world that watched television that day. This disaster has also generated a debate in our engineering profession, as well as the political environment, on how to address these issues in commercial buildings and other non-governmental buildings. Several examples of these building types are discussed below.

PROGRESSIVE COLLAPSE FOR FEDERAL GOVERNMENT BUILDINGS

Design professionals engaged in the design of new federal buildings or modernization of existing federal buildings are normally required to comply with the “GSA Progressive Collapse Analysis and Design Guidelines”. This document provides a threat independent methodology for reducing the risk of progressive collapse. An overview of the guideline’s general approach is as follows:

- First determine if the structure is exempt from the guideline requirements. Exemptions can be granted in some circumstances, such as if the structure is classified for only incidental human occupancy, or if it meets the appropriate defended standoff distance and exhibits acceptable levels of redundancy.
- Once it has been established that building is non-exempt, the progressive collapse analysis and design process can be implemented. Note that use of the guidelines should be limited to low-rise to medium-rise buildings and those that do not contain atypical structural configurations.
- The procedure involves performing a series of linear-elastic static analyses of the structure for an instantaneous loss of various local primary vertical support elements. The number of cases analyzed should cover the worst case scenarios for all sides of the building’s perimeter including corners. Interior bays are required to be analyzed if the building has underground parking or uncontrolled access to the ground floor. The instantaneous loss of vertical elements can consist of the loss of either columns or sections of walls for one floor above grade while assuming the horizontal structural elements at the 2nd floor remain intact.
- The guideline also stresses the inclusion of the following structural characteristics when designing the structural systems.
 1. Redundancy and alternate load paths
 2. Ductile structural elements and details
 3. Designing for load reversal
 4. Shear capacities which preclude shear failure prior to flexural failure

The analysis procedure requires the use of a specific loading criterion, $2.0 \times (DL + 0.25 \times LL)$, which is then compared to the ultimate un-factored structural capacity. This criterion does not differentiate between materials and structural systems that have large differences in energy absorption and ductility. It should be noted that use of a dynamic load factor 2.0 is suitable for non-ductile material such as un-reinforced masonry, but may be considered conservative for reinforced concrete properly detailed for ductility. The Guideline also recommends the use of strength increase factors for different structural materials when design properties can be accurately predicted. The GSA Guidelines were utilized for the design of three projects listed below.

New Suburban Office Building for Federal Government Agency

This structure consisted of a cast-in-place concrete flat slab system with continuous spandrel beams and rigid moment frames. The spandrel beams were upturned and down-turned from the floor line, and served as both potential transfer elements for progressive collapse and as the

façade. The spandrel beams (up to 7' deep) acted as the sill and head of the building's strip windows, and no other façade elements were required. This provided a simple solution to meeting the progressive collapse design requirements but had a significant impact on the cost of the structure. The large depth and robust reinforcement of the spandrel beams added approximately 30% to the cost of the structure. However, the significant reduction in the cost of the façade and elimination of additional façade trades offset the increased structural cost. Use of surface parking and controlled access to the building eliminated the progressive collapse requirements for the interior of the building.

New Urban Office Building with Primary Federal Government Tenant

A waiver was provided for the exterior threat on this building, leaving only the requirement for progressive collapse design for the interior columns in the basement parking levels. The parking levels were designed as mild reinforced conventional flat slabs while the 12 stories above grade utilized a long-span post-tensioned system. It was determined that the risk of progressive collapse could be mitigated by sufficiently hardening the garage levels to withstand the design threat as an alternative to designing for the instantaneous removal of columns. The columns were designed to be jacketed with steel plates and the slabs were designed to resist uplift blast pressures. This approach only added approximately 10% to the total structural cost, but required approval for the deviations from the GSA Guidelines.

Existing Urban Historic Government Building

Investigation of this 1920s steel-framed building with a concrete joist terra cotta tile infill floor system, revealed that the potential for progressive collapse was high. The concrete-encased steel spandrel beams varied in size and ran parallel to the concrete floor joists. Their primary function was to support the brick and stone façade, and their connection to the steel columns was minimal. It was determined that loss of a first floor column would likely result in the failure of that column's adjacent bays for the full height the six-story building. The most cost effective and least intrusive retrofit was determined to be the introduction of a new continuous steel 36" deep wide flange transfer girder placed behind the roof parapet and connected to the existing steel columns. This new transfer girder would allow for the suspension of the compromised column below and would span approximately 30' between the adjacent intact columns. The cost of this remedial work has not yet been determined.

PROGRESSIVE COLLAPSE FOR COMMERCIAL BUILDINGS

Design professionals engaged in the design of new high-rise buildings are being asked to address physical security issues. Among these issues is that of progressive collapse. ASCE 7-98 requires that buildings be designed to sustain local damage with the structural system as a whole remaining stable and undamaged or not being damaged to an extent disproportionate to the original local damage. ASCE 7-98 does not provide prescriptive design requirements or acceptable levels of performance. The New York City Building Code does provide some

additional criteria for designers along the lines of ASCE 7-98 that is consistent with the GSA criteria. The Chicago Building Code has a similar philosophy for general structural integrity, but on specific requirements on how to achieve resistance to disproportionate collapse is not included. The code is currently being amended, and the inclusion of provisions for progressive collapse prevention is being considered.

The NYC Building Code requires that unless all members of a structure are connected by joints capable of transferring 100% of their working capacity in tension, shear, or compression (as appropriate) without reliance on friction due to gravity loads, the members must provide adequate protection against progressive collapse under abnormal load. Either the Alternate Path Method or the Specific Local Resistance Method can be used to determine the resistance of the structure to progressive collapse. However, the Specific Local Resistance Method is not to be used unless the Alternate Path Method is not feasible.

Alternate Path Method

The Alternate Path Method requires that proof be provided by analysis and/or physical simulation that the building structure can resist the loss of a critical element under the following load combinations: $2.0D + 0.25L$, and $1.0D + 0.25L + 0.2W$. A critical element is defined as a single wall panel (or nominal length thereof), two adjacent wall panels (or nominal lengths thereof) forming a corner, one beam or girder and its tributary floor area, one column, or any other structural element judged to be vital to the stability of the structure.

Specific Local Resistance Method

The Specific Local Resistance Method requires that any single element essential to the stability of the structure, together with its connections, shall not fail after being subjected to a uniform static pressure of 720 psf (36 kN/m²) in the most critical direction. This load shall be applied directly to the face of the element and to the face of all space dividers supported by or attached to the element within the particular story.

Many high-rise steel-framed buildings have utilized the specific local resistance method rather than the alternate path method because of the cost associated with providing an alternate load path for the large gravity load columns at the base of the tower. However, developers in New York City are currently willing to explore possibly better solutions available by providing the alternate load paths at additional project cost. Some of these alternate load paths are provided by:

- the use of transfer trusses at upper or intermediate floors allowing columns to hang
- stronger connections and beams of floor framing to allow for catenary action
- moment connections to allow floor framing to cantilever out to the perimeter in the event that the perimeter columns are lost
- perimeter frames with sufficient capacity to span two bays

Finally, there are yet some instances where an alternate load path is not feasible, especially for existing structures. In these instances, we find that the building owners are actively hardening these structures for threats far in excess of the mandated 720 psf (36 kN/m²) minimum.

REFERENCES

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