SEI Pre-Standard and Commentary on Disproportionate Collapse: Part II—Prescriptive Approaches to Provide Robustness

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Summary

At lower levels of risk, prescribed levels of appropriate robustness could be incorporated into the structural elements and system, even in the absence of specified threat or probability of occurrence. As a minimum, robustness can be added to an element or system through the prescription of integrity requirements such as element to element connectivity, balanced minimum requirements for multiple response mechanisms, and enhanced stability requirements. At higher risk levels, robustness requirements might include so-called “tying” requirements, “bridging” techniques, prescriptive key element hardening, or, for certain form factor buildings, compartmentalization.

Keywords: progressive collapse, disproportionate collapse, tie forces, alternate paths, extraordinary loads, robustness.

1. Introduction

The Structural Engineering Institute (SEI) Progressive Collapse Standards and Guidance Committee has determined that a design pre-standard and commentary for disproportionate collapse mitigation will have two components: 1) a risk determination approach that leads the developer, owner, or building official to a determination of the prescriptive or performance based structural measures to be employed, and 2) engineering approaches for the inclusion of these structural measures. The engineering approaches would be selected or “triggered” based on risk and would have two parts; a) a robustness standard that is a function of risk and offers prescriptive measures to be employed and b) a comprehensive performance-based approach that is also a function of risk, but that bases design measures employed on pre-determined and identified actions or combinations of actions.

2. Robustness in structural systems

As a minimum, robustness can be added to an element or system through the prescription of integrity requirements such as element to element connectivity, balanced minimum requirements for multiple response mechanisms (elimination of premature shear or other non-ductile failures), and enhanced stability requirements (assumption of increased unsupported lengths, etc.) At higher risk levels, robustness requirements might include so-called “tying” requirements, where minimal lateral and vertical capacity is assured such that notional catenary or “cable” action could be achieved should a primary gravity element be compromised in some way. In lieu of tying, optional “bridging” techniques might be employed, where static linear “quasi-” or “pseudo-nonlinear procedures are employed to evaluate flexural bridging. Finally, in lieu of bridging, prescriptive key element loads could be assigned as a function of building type or material to allow local hardening or the provision of specific local resistance.

3. Integrity, redundancy, hardening, protection and limitation of damage

3.1 Tying to achieve integrity

In a prescriptive approach, robustness can be achieved "through the provision of minimum levels of strength, continuity and ductility". The approach recommended in Eurocodes and the updated US

https://doi.org/10.2749/222137908796294063

DoD criteria, is to require "Tie Forces", which are minimum tensile force capacities with a specified magnitude, location, and orientation, carried by the structural members and connections and distributed throughout the building. The goal of Tie Forces is to keep the structure together in the event of an abnormal loading that damages a portion of the structure.

3.2 Improvements in alternate load path procedures

Linear static procedures in current guidance require the use of a load increase factor (LIF) to account for both dynamic and non-linear effects. In nonlinear static procedures, a dynamic increase factor (DIF) is required to account for the inertial effects. For linear and nonlinear static analysis methods, both the existing UFC 4-023-03 and the GSA Guidelines use a load multiplier of 2.0 applied directly to the progressive collapse load combination.

To rectify this inaccuracy and conservatism, a series of reinforced concrete and steel building models were developed and analyzed with SAP 2000. The ASCE 7 extreme event load case was used for all analyses. Results of the analyses resulted in equations for LIFs and DIFs in concrete and steel structural systems as follows (where m is the ASCE41-06 material non-linearity factor for static linear analysis):

Concrete Structures:

$$\text{LIF} = 1.2\ m + 0.80 \tag{1}$$

$$\text{DIF} = 1.04+(0.45/((\text{allow plastic rot/member yield})+0.48)) \tag{2}$$

Steel Structures:

$$\text{LIF} = 0.9\ m + 1.1 \tag{3}$$

$$\text{DIF} = 1.08+(0.76/((\text{allow plastic rot/member yield})+0.83)) \tag{4}$$

A review of 10 steel connection tests, conducted to determine the response of steel columns, base plates, and beam-column connections to blast loading, was conducted to evaluate connection performance. Performance parameters evaluated for each connection in the various tests included:

- Rotational Capacity
- Internal Energy
- Stiffness

The analyses concluded that significant increases in allowable rotations used in current acceptance criteria could be recommended. Additionally, recommendations regarding modeling stiffness to be used in analysis were made.

3.3 Enhanced local resistance, protection and compartmentalization

Alternatives to tying and bridging include local hardening of the structure. One approach has been developed to enhance the performance of perimeter columns and walls for the first and second story of framed structures, such that perimeter column and wall flexural performance is increased above that "expected" for the gravity/lateral based structural system. While not detailed here, alternatives to enhanced robustness through tying or bridging, or through enhanced resistance, also would include protection of the building through linear or spaced impact prevention (barriers), and traffic and parking restrictions. Compartmentalization would also be permitted in certain structural systems such as long low-rise construction; i.e., integrity would be intentionally compromised to halt a progression of failure.

4. Final SEI product

The goal of the SEI effort is to produce a consensus document; one that has been fully "vetted" by the academic, design professional, constructor and materials communities. While the intention is to have the pre-standard included in building codes by reference, it will be up to local municipalities and governments to determine its mandatory application through statute.