A PreStandard Prospectus:

Robustness and Collapse Resistance for Buildings

Prepared by the steering group of the SEI Progressive Collapse Standards and Guidance Committee

Introduction—Efficient and economical structures are designed to ever maturing guidelines, codes and standards that take advantage of the latest research related to material and system performance. The satisfactory performance of these structures within the constraints of societal norms of safety, reliability, cost and useful life is highly dependant and closely related to the defined loads and response mechanisms and the uncertainties associated with these loads and responses. Thus, when unanticipated loads, accidents, errors during design or construction or deliberate actions occur, optimized elements and systems may have little redundancy or additional capacity to resist these loads.

Due to a lack of clear and detailed guidance in current U.S. building codes, a new approach is needed to define a rational design methodology relative to these unanticipated events. This approach should be based on a risk assessment which considers the consequences of a likely combination of unanticipated events and actions. The Structural Engineering Institute (SEI) Progressive Collapse Standards and Guidance Committee has been chartered to address this need through the development of a design pre-standard and commentary. This pre-standard and commentary would support the extant design standards (ASCE7) and, by reference, the building codes. It is not anticipated that this pre-standard would be mandatory in whole or in part. The goal of the committee is to develop guidance that is comprehensive yet applicable to buildings and structures only as dictated by building officials through local statute or by building owners.

Pre-Standard Approach—The committee has determined that such a pre-standard 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.

Risk Determination

Structural measures that either add robustness or prevent collapse should be selected (or deemed unnecessary) through the application of a logical process that considers qualified or quantified acceptable risk based on the likelihood of a normally unanticipated event/action, the vulnerability of the structural system to damage or collapse, and the consequences of the resulting response. Assessing the likelihood of various actions could consider the presence of specific hazards, the proximity to other structures at higher risk or nearby hazards, the structure's likelihood of being targeted for deliberate attack and other factors. Assessing vulnerability of the structural systems would consider the inherent differences in the response of various types of structural systems. Considerations in determining the consequence of an action could include the occupancy, functional importance (hospital, public safety, emergency response, etc.), use or potential future use, and local determination of multi-use (schools or meeting facilities used as public safety assembly areas). The factors of likelihood of the event/action, vulnerability of the structure, and consequence would be combined to determine the recommended "acceptable risk" category or "bin" into which that structure or facility would fall. Each risk "bin" would have a recommended engineering approach associated with it.

Engineering Approaches

Robustness—The measure(s) to be employed at the lower levels of risk would be the incorporation of appropriate robustness in the structural elements and system. Robustness can be defined as "insensitivity to local failure," where insensitivity and local failure are to be quantified (prescribed) as design objectives. Defined in this way, robustness is a property of the structure, and is independent of possible causes of initial local failure[1]. Regardless of robustness design approach, verification of required increased robustness would be based on an *assumed extent of initial local failure and an assumed extent of collapse progression or extent of damage to the remaining structure.*

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 checks and 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 the flexural bridging over, across or around a notionally "lost" key element. Response limits for the bridging analysis could be made more restrictive for higher risk levels. 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 where bridging is not possible or practical.

Collapse Resistance—At higher levels of risk, collapse resistance would be incorporated into the design through the identification of specific initiating events including the severity and initial local damage resulting from those events. The structural design would then be performance based, where structural system redundancy and element capacities would be designed to resist these initiating events or resist the progression of damage or collapse. Collapse resistance can then be defined as the structure's insensitivity to the quantified accidental circumstances and initial damage. Regardless of collapse resistance design approach, verification of required increased resistance would thus be based on an *assumed set of accidental actions with initial damage severity and extent based on these accidental actions, a quantified extent of collapse progression, and a defined acceptable extent of damage to the remaining structure.*

Collapse resistance measures might include "bridging" techniques where true dynamic non-linear analysis and design techniques are employed to evaluate the flexural bridging over, across or around the identified extent of local failure. Response limits for the bridging analysis could be made

[1] Starossek, Uwe, "Progressive Collapse of Structures: Nomenclature and Procedures," Structural Engineering International, Volume 16, No. 2, May 2006, pp. 113-117.

more restrictive for higher risk levels or for special functional requirements. In lieu of bridging, key element loads could be determined based on the identified accidental actions and local hardening or specific local resistance could be incorporated to resist these loads. Finally, non-structural protective measures or event control might be used to mitigate some or all of the initiating events identified. Event control might include barriers to resist vehicle impact, perimeter barriers to increase standoff to reduce blast loads from deliberate attacks, or sacrificial elements to attenuate identified loads.

Because the extent of initial damage and the extent of collapse progression are defined in this performance based approach, consideration could be given to compartmentalization approaches. Compartmentalization occurs when the initial damage extent and the "volume" of allowable collapse are deliberately designed to be identical. Compartmentalization approaches may be desirable in some structures where element to element continuity may actually be detrimental; e.g., low rise large bay structures of limited number of bays in plan.

For all resistance approaches, verification of acceptable damage to the remaining structure outside of the collapse extent might be determined by an analysis that allows a comparison of residual inelastic capacity to initial capacity (or a similar metric). Also, in every case, post-event stability of the structural system should be verified.

Final Product—The goal of this 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. It is also anticipated that building owners and developers may independently invoke higher performance levels defined in the pre-standard to protect their facility investments. In that way, the protection provided as well as the cost incurred can be determined locally through a careful consideration of risk and the acceptance of a portion of that risk by the local population.