Performance-Based Seismic Design

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An explanation of specific performance criteria and how the process works.

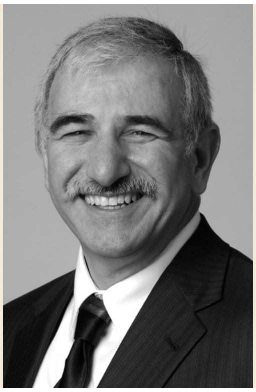
NEARLY ALL BUILDINGS AND STRUCTURES today are designed to conform to the prescriptive strength, detailing and deflection limitations specified in the applicable building code and its referenced industry standards including the AISC *Specification* (AISC 360), *Seismic Provisions* (AISC 341), and *Prequalified Connections* (AISC 358). These requirements are intended to provide structures an ability to meet certain performance objectives such as resisting likely loading without failure, and normal loading without occupant discomfort. But in most cases, the ability of the structure to actually provide this performance is never evaluated.

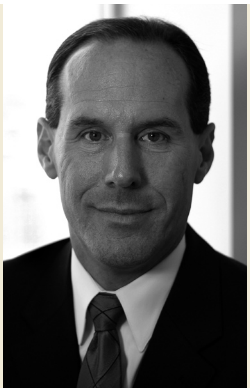
Performance-based design is an alternative approach, specifically permitted under Section 104 of the *International Building Code*, which permits building officials to approve any design or means of construction on the basis of satisfactory evidence that the completed construction will be capable of providing equivalent protection to the public as designs that conform to the code's prescriptive requirements. This article provides a brief overview of performance-based design's development history, recent advances in performance-based earthquake engineering and some recent applications of the technique to building design.

A Brief History

Performance-based approaches have been permitted by nearly every U.S. building code in the past 100 years, primarily because, 100 years ago, this was the only means available to allow new technological approaches entry into practice. The prescriptive requirements of early building codes were based on the observed performance of real buildings. When building officials and engineers noted that wood frame structures in dense urban areas lead to frequent conflagrations, the codes banned combustible construction in urban settings and required the use of noncombustible or protected construction. Similarly, in 1933, California engineers recognized that unreinforced masonry buildings had collapsed in nearly every earthquake over the past 100 years and wrote requirements into the building code prohibiting such construction where strong earthquakes could be anticipated, a requirement that remains in the code to this day. Performance-based design gave building officials the ability to approve designs that had not been tested by time and real events based on submittal of evidence that the design would perform adequately. This approach was used to introduce such innovations as reinforced concrete, welding, high-strength (Grade 50) steel and other technologies common in today's construction.

During the 1970s and 1980s, engineers in the Western U.S. began to adopt performance-based design approaches for seismic design, both for new buildings and existing structures. Initially, these efforts were driven by the observation that during the 1971 San Fernando earthquake, several hospitals and emergency response facilities did not perform well (see Figure 1), creating the demand that important buildings be designed, not only to protect life safety, but also to enable continued post-earthquake occupancy and function. This prompted engineers to adopt judgmentally enhanced versions of the code requirements for the design of important structures. Later, in the 1980s, following a series of California earthquakes that seemed to occur on an almost annual basis, building owners began to request that engineers evaluate their existing buildings and upgrade them to achieve various performance criteria ranging from protection of life safety, to post-earthquake functionality, to limiting probable repair costs to specified percentages of building replacement cost. This created a problem for engineers who had no tools, other than their professional judgment, to determine criteria for these designs.





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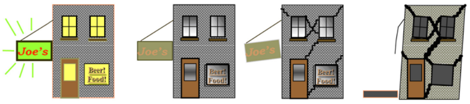
USGS

Fig. 1: Olive View Hospital following the 1971 San Fernando earthquake; where a stair tower and the psychiatric wing collapsed.

In the mid-1990s, the Federal Emergency Management Agency responded to this need by funding a joint association of the Applied Technology Council, the Building Seismic Safety Council and American Society of Civil Engineers to develop consensus guidelines for seismic rehabilitation of existing buildings. Initially published as the FEMA 273 report, the resulting effort underlies the present ASCE 31 *Seismic Evaluation* and ASCE 41 *Seismic Rehabilitation* standards. Both implement performance-based approaches to evaluation and design, and together, form the core technology underlying present-generation performance-based design procedures, both for seismic engineering and also force-protection design. The standards define a series of standard performance levels for structural and nonstructural components, illustrated in Figure 2. These range from Operational, a performance state in which after a design event, the building and its contents are undamaged, to Collapse Prevention, a state of extreme damage to structural and nonstructural systems, just short of collapse. Figure 3 illustrates the basic ASCE 41 design process.

The process begins with a group of stakeholders including the building owner, building official and engineer jointly selecting one or more project-specific performance objectives as the design basis. Each performance objective is a statement of the acceptable building performance given that the structure experiences a particular intensity of earthquake motion. Many building



Operational

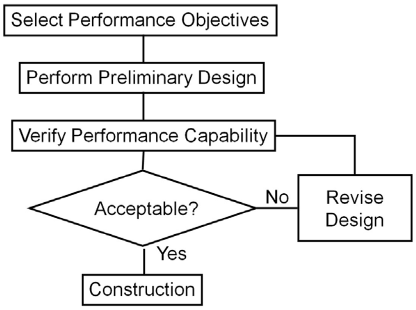
Immediate Occupancy

Life Safety

Collapse Prevention

Fig. 2: The ASCE 41 performance levels: Operational, Immediate Occupancy, Life Safety and Collapse Prevention.

Fig. 3: Performance-based design process.



officials have accepted a pair of standardized performance objectives, designated by ASCE 41 as the Basic Safety Objective, as being equivalent to the performance intended by the building code for Occupancy Category I and II structures.

The Basic Safety Objective consists of Collapse Prevention performance for Maximum Considered Earthquake shaking and Life Safety performance for Design Earthquake shaking, both as defined in the ASCE 7 standard. Despite this common acceptance, the original developers of the FEMA 273 report envisaged the Basic Safety Objective as being slightly inferior to the performance objectives inherent in the building code, but which represented a practical equivalent for use in upgrade of existing buildings.

Performance verification consists of the use of analysis to demonstrate that the building is capable of meeting the desired performance objectives. ASCE 41 includes four analysis types: (1) a linear static procedure, that is comparable to the equivalent lateral force method contained in the building code, (2) a linear dynamic procedure, that uses response spectrum analysis, (3) a nonlinear static (pushover) procedure, and (4) a nonlinear dynamic (response history) procedure. In the nonlinear procedures, analysis is used to predict peak inelastic deformations on ductile elements and peak forces on non-ductile elements. These are compared against acceptable values of deformation and strength that depend on the element type (e.g. brace, moment connection) and the material properties and detailing. For linear procedures, elastic demand-to-capacity ratios are computed as the ratio of strength demand to element capacity. These are taken as surrogates for ductility demand and compared against acceptable values, similar to, but more conservative than, those contained in the standard for use with nonlinear procedures.

In recent years, the ASCE 41 procedures have become an accepted method not only for seismic retrofit of existing buildings, but also for the seismic design of new buildings, including very tall structures. Recently, the Pacific Earthquake Engineering Research Center (PEER) developed performance-based seismic design criteria for tall buildings that significantly extend and improve the ASCE 41 procedures, but employ the same basic technologies and principals. The PEER methodology, which can be downloaded from **http://peer.berkeley.edu**, requires the use of response spectrum analysis and near-elastic performance for service-level earthquake shaking, having a 43-year return period, and nonlinear response history analysis for Maximum Considered earthquake shaking, with a performance goal of substantial margin against collapse.

The Next Generation

In 2001, FEMA funded the Applied Technology Council to begin development of next-generation performance-based seismic design criteria. The resulting FEMA P-58 document is scheduled for publication in early 2012. Rather than using standard performance levels to characterize performance, the P-58 methodology directly uses the probability of incurring casualties, repair costs and repair time as measures of performance.

Because the prediction of earthquake performance includes many uncertainties, associated with prediction of the actual intensity and character of ground motion, the number of people and contents present in the building at the time of the earthquake, the strength and construction quality of the building and the inaccuracy of our analytical techniques, the methodology expresses performance probabilistically in the form of performance curves. Illustrated in Figure 4, performance curves indicate the probability that a performance measure, such as repair cost, will exceed different amounts. The P-58 methodology will permit performance assessments for a single, user-defined shaking intensity, defined by a response spectrum; a user-defined earthquake scenario, characterized by a magnitude and distance from the site; or on a time-basis, considering all earthquakes that may occur, the probability of their occurrence, and the probable intensity of shaking given that they occur. The P-58 methodology will be provided with companion software that can perform the necessary probabilistic calculations, will produce the performance curves and also will indicate the sources of loss.

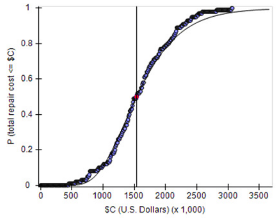


Fig. 4: Example performance curve, indicating the probability of incurring repair costs of varying amounts.

Examples of Recent Use

Two recent projects, the Mineta San Jose Airport Terminal B and Concourse and the Providence Everett Medical Center (PEMC) Acute Care Tower, used ASCE 41-based performance levels outlined previously in their design. Both buildings were initially designed, and the seismic elements sized, based on the prescriptive building code and AISC standard requirements. The San Jose Airport used a steel, special truss moment frame (STMF) as its primary seismic force-resisting system while the 12-story PEMC Acute Care Tower consists of steel buckling-restrained braced frames (BFBF).

The Mineta San Jose International Airport Terminal B and Concourse extends more than 2,100 ft in length and reaches 55 ft in height. The project encompasses more than 600,000 sq. ft and was constructed over a nearly eight-year time frame.

The STMF was analyzed to confirm that it was capable of providing Life Safety Performance for the Design Earthquake shaking. A non-linear static procedure was implemented in confirming the as-designed system was capable of delivering life-safe performance.

The PEMC Acute Care Tower project encompasses more than 700,000 sq. ft over its 12 stories. Design began the spring of 2006 and final occupancy is scheduled for June 2011. The U-shaped plan required careful placement of the BRBF. At the subterranean levels, the BRBF are transferred to concrete shear walls.

The BRBF was analyzed to confirm that it was capable of providing Immediate Occupancy Performance for Design Earthquake shaking. A non-linear response history procedure was implemented to reevaluate key member sizes, such as columns and foundation caissons, and to confirm the final system was capable of delivering immediate occupancy performance. The resulting analysis indicated that the prescriptive "essential facility" BRBF code design could be reduced by approximately 200 tons and still meet the intended immediate occupancy performance goal. MSC

*This article is the basis of a presentation the authors will make at NASCC: The Steel Conference, May 11-14 in Pittsburgh. Learn more about The Steel Conference at **www.aisc.org/nascc**.*