Performance-Based Earthquake Design

Lessons Learned from a Building Code Option

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Performance-Based Earthquake Design (PBD) has become a standardized process in Structural and Earthquake Engineering with the publication of the American Society of Civil Engineers Standard ASCE 41-13, *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE 41). It represents a shift from the prescriptive code provisions of the past that are silent about what they achieve, to a design tool that meets the varying needs of the public by targeting specific performance objectives.

Figure 1. Damage to the Northridge Meadows Apartments.

The need for a new approach was formally recognized after the 1989 Loma Prieta Earthquake and became a nationally funded effort after the 1994 Northridge Earthquake (Northridge). Those moderate earthquakes proved that the then current design standards saved lives. However, the public declared on multiple fronts that the extent of damage was unexpected and too expensive to repair, and therefore unacceptable. Thanks to the tireless work of the Applied Technology Council (ATC) and their hundreds of volunteer experts and millions of dollars of funding from the Federal Emergency Management Agency (FEMA), ASCE 41 stands today as a significant PBD tool that can be used by Structural Engineers to achieve acceptable performance and improve the resilience of communities.

Moving the profession from the prescriptive, non-committal, seismic design rules of the 1960s to PBD was, and continues to be, very controversial and contentious. Some believed that the simplicity of the existing codes was enough to guide the expert judgment of the designers. Others argued that there was too much uncertainty in the entire PBD process to declare the anticipated performance. Unspoken was a need to hide under the building code's mandate to protect the public. Still, others believed that while designing to various performance levels was possible; the potential liability was too high. Many feared to be sued out of business after the next major earthquake if expectations were not met. Fortunately, the earthquake design profession is protected by consensus-based codes and standards, including ASCE-41, that define the "state of the practice" the courts use to judge liability.

While structural engineers recognized that their design provisions had achieved life-safety, there were a handful of specific examples of performance that got everyone's attention. Excessive damage to multi-story wood frame buildings and the collapse of the three-story Northridge Meadows Apartments (*Figure 1*) demanded new analysis techniques, design procedures, and detailed provisions. The damage to the apartments not only illustrated the collapse potential of code permitted soft-first story construction, but also the deficiencies in the design of shear walls and diaphragms. While concrete buildings designed after the 1971 San Fernando Earthquake generally performed well, there was excessive damage and even collapse for newly designed parking garages with precast elements (*Figure 2*). Precast elements, while tied together for the then-code-level forces, did not perform as well as the cast-in-place concrete structures where the interconnection is continuous and not the weak link. New code provisions were needed to assure that the precast elements were adequately designed and interconnected. Within a year of the Northridge earthquake, over 100 steel moment resisting frame buildings were found to have a significant number of weld fractures in the beam-column connections that compromised their strength and ability to resist future earthquakes. A multi-year research and testing program followed, completely changing analysis, design, and detailing procedures. Damage to existing non-ductile concrete buildings as shown in *Figure 3* demanded that attention be given to older, non-conforming buildings. *Vision 2000*, *Performance-Based Seismic Engineering of Buildings* (Structural Engineers Association of California, 1995), cataloged these lessons. ASCE 41 has incorporated the evaluation of these and many other deficiencies in its four styles of evaluation and material specific acceptance criteria. The earthquake occurred just months before the needed seismic retrofit of this building was scheduled to begin.

The *Vision 2000* committee was organized in 1992 and, after Northridge, received a grant from the California Office of Emergency services to formally develop PBD recommendations. By 1995, the team of 20 academic and design professionals published a conceptual framework and interim recommendations in their report, *Vision 2000*. They knew it was feasible to design and construct buildings that would not experience damage in the most severe earthquakes, but believed it was unnecessary and uneconomical. It was judged to be more prudent to design to varying levels of performance depending on the occupancy of the building, its importance to community response and recovery, and the economic viability of investing in reducing future losses. The committee formalized the process and vocabulary used today to define earthquake design levels, performance levels, and performance objectives Their design framework begins with

Figure 2. Collapse of the precast concrete parking garage at Northridge Fashion Center.

Figure 3. Damage to this non-ductile concrete frame building.

site selection followed by a three-stage design process (Tiers 1 to 3), design review, and quality assurance during construction. The *Vision 2000* report stands as the foundation for ASCE 41.

Vision 2000 also looked closely at the performance of buildings in and around strong motion recording stations as a means of testing the consistency and accuracy of the analysis and design provisions used in the past. The structural and non-structural performance of almost 200 building were surveyed and cataloged using a comprehensive data gathering form that included 10 levels of damage (10 being fully functional and 1 being collapse) that matched the *Vision 2000* performance descriptions. While the sample size is not statistically balanced and focuses on damaged buildings, the results were judged acceptable enough to draw general conclusions. Of the most significant conclusions related to structural performance was the observation that buildings designed to modern codes had little impact on the average performance of the structural system. Also, for non-structural performance, no correlation was observed between the damage recorded and the ages of the building or their design to modern standards; *Vision 2000* is filled with additional information. Refined analysis and design techniques were needed for PBD's goal of producing predictable performance. ASCE 41 provides 2 force-based and 2 displacement analysis procedures that better predict the expected damaged to a wide variety of structural systems and material types. A new generation of non-structural evaluation procedures are also provided.

The 1971 San Fernando Earthquake demonstrated that the provisions being used for the design of new buildings did not yield the desired results. The earthquake also generated hundreds of strong motion records that cataloged the variation in strong shaking across the region. The ground motion records showed that the shaking was much larger than expected and demonstrated the need for a new process for defining the design ground motions based on the relationship between the strong motion records and the observed damage. By 1980, such a process had been developed and has since formed the basis of the *International Building Code* (IBC) in use today.

The 1971 earthquake also signaled the need to do something about the seismic resilience of the existing building stock. With the updated design process for new buildings in place, FEMA began to focus on design standards for the evaluation and rehabilitation of existing buildings. A landmark workshop held in Tempe, Arizona, produced an action plan that would eventually result in ASCE 41. It began as a conceptual framework followed by a development guide that resolved the major controversial issues (ATC 28), a published guideline (ATC 33/FEMA 273), a pre-standard suitable for the America National Standards Institute (ANSI) balloting process (FEMA 356) and, finally, published as an ANSI approved standard in 2006 as ASCE 41-06. It was immediately recognized as an acceptable PBD tool by the State of California for use in the SB 1953 Hospital Retrofit Program and by the IBC a few years later.

In parallel with the development work that led to ASCE 41-06, FEMA sponsored the transition of FEMA 178, *Handbook for the Seismic Evaluation of Existing Buildings*, from a guideline to the pre-standard FEMA 310, *Handbook for the Seismic Evaluation of Buildings – A Pre-standard*. ASCE subsequently balloted the pre-standard and published ASCE 31, *Seismic Evaluation of Existing Buildings.* ASCE 31 and 41 then became widely used standards for the evaluation and rehabilitation of existing buildings. As they gained acceptance and popularity, engineers also used ASCE 41-06 as a PBD tool for the design of new buildings under the alternate design procedures clause in the IBC. Because ASCE 31, ASCE 41, and ASCE 7 were developed under different programs and did not share a common origin, they were not universally compatible. In the worst cases, a building found to meet the life safety standards of ASCE 31 when evaluated did not meet the same performance objective specified in ASCE 41.

Further, the characterization of seismic hazards in ASCE 41 did not match the characterization in ASCE 7, the basis for the IBC. These inconsistencies became barriers to the use of ASCE 41-style PBD but were eventually reconciled. ASCE 41 now stands as a consistent PBD tool that is accepted by the IBC as suitable for new building design.

Following the lessons learned in the San Fernando and Northridge earthquakes, *Vision 2000* saw that a single set of design provisions that would be used for both new building design and existing building rehabilitation was important. Unfortunately, since they were developed under different programs, only ASCE 41 became a PBD standard. The controversy continues as to whether ASCE 7 and the IBC should fully embrace and incorporate the PBD process as outlined in ASCE 41. Fortunately, engineers can and should choose to use ASCE 41's PBD on all their projects, either as a design tool or validation tool after the design is complete, because of the defined performance expectations. Either way, it is critical to the resilience of buildings and communities that structural engineers determine and declare the performance that is expected during design level and extreme level earthquakes, so their clients can invest wisely and their communities can plan accordingly.▪

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