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MAKING PERFORMANCE-BASED ENGINEERING USEFUL

Chris D. POLAND[1]

SUMMARY

Achieving specific seismic performance expectations is the core purpose of the developing practice of performance-based earthquake engineering. Over the past ten years, a variety of styles and definitions of expected performance levels have been developed though they are generally not understood by the building owners and communities they are intended to serve. A full range of consistent seismic performance levels should be included in the seismic design provisions for new and existing structures and they should be stated in terms that relate to the needs of the users. Owners need to know what to expect from their seismic designs, even in the face of the uncertainty that accompanies their definition. They must be given the opportunity to select higher or lower performance levels, if desired, and be able to consider the economic advantages if they wish. As a bonus, written, transparent seismic provisions will actually reduce the engineer's liability if the performance expectations are not met.

Structural engineers need to continue to assist in the process of defining public policy related to acceptable safety and include it in the codes and guidelines they write. They should work within their communities to define acceptable levels of safety, and translate those needs into specific prescriptive provisions and analysis procedures that are needed for validation. The provisions must be consensus-based, economically-sound, and reflect the best estimates of demand and capacity that are available. They should be transparent, clear, simple, consistent, rooted in reality, and updated as often as new techniques are developed.

Unfortunately, such an open process has not been generally embraced thus far and is perpetuating the myth that modern earthquake engineering will eliminate damage.

INTRODUCTION

Structural engineers, working with building officials and other earthquake professionals, have always been the authors of the seismic design provisions that are used worldwide. The various provisions that they have developed are prescriptive, tailored to their observations from damaging earthquakes, and based on their collective understanding about what is cost effective and acceptable. In the process, they apply conservatism to cover for uncertainty.

The goal of earthquake engineering has been in a constant state of evolution for at least the past hundred years. It appears that the earliest attempts were to eliminate damage and neutralize the concerns raised by developers, bankers, and insurance companies. After the 1906 San Francisco, 1925 Santa Barbara, and the 1933 Long Beach earthquakes, mandatory building codes emerged as a tool for eliminating the

[1] Structural Engineer and CEO, Degenkolb Engineers, San Francisco, CA, USA.

damaging effect of earthquakes. With the 1952 Kern County earthquake came a more rational goal of protecting lives in earthquakes and keeping damage to repairable levels in all but the largest earthquakes. This life-safety goal remains the underlying principle of earthquake engineering today, though it has taken on a very broad definition.

The 1971 San Fernando earthquake produced a call for stronger, more resilient buildings that would experience less damage, for the design of "essential buildings" that would remain functional, and for the development of techniques for dealing with the massive inventory of old buildings that were constructed without sufficient seismic resilience. The seismic provisions of the building codes for new buildings and the rehabilitation guidelines for existing buildings that have since developed have included, in a prescriptive manner, building type-specific provisions that are intended to yield different levels of performance in major earthquakes for buildings of different uses. The requirements include specific provisions for design, construction, and quality assurance. In essence, performance-based engineering has been embedded into the seismic provisions, often without significant declaration.

The current seismic design provisions are used in various locations because of mandatory requirements. They are also used worldwide on a voluntary basis to achieve an acceptable level of safety that is sought by building owners.

California's Seismic Standards for New Buildings

In California, the seismic design and evaluation provisions have grown over the past thirty years to include a variety of performance levels that better match specific needs of the state's communities. The Northridge earthquake experience suggests that these embedded seismic provisions are generally not disclosed and building owners are generally unaware of the level of damage that will happen. The overall reaction from Northridge was a call for better performance and the challenge has been how to accomplish an improvement in a transparent manner.

The current California Administrative Code provides a good example of the variation in the provisions that cover the seismic design of new buildings in California. It includes special standards for hospitals and other essential buildings that should be "*…reasonably capable of providing services to the public after a disaster….*" Different design and construction standards are required for K-12 schools with the goal that these school buildings "*resist earthquake forces …without collapse, but may experience some repairable architectural or structural damage.….*" For all other buildings, the code requirements are less stringent in terms of design and quality assurance with the expectation that the construction will "*safeguard against major structural failure and loss of life, not to limit damage or maintain function.*"

The current provisions in the California Code are based on the nationally-developed BSSC guidelines (BSSC 1996) that are written to apply to all parts of the United States. They are a derivative of provisions originally written for California and, unfortunately, they are not universally applied outside of California. There are a variety of reasons for this lack of acceptance. The high added construction cost related to seismic design is cited most often, even though cost studies always show that the added cost is nominal, in the range of two to four percent. There is also a general sense that the hazard is not as large and the need for higher levels of performance as prominent.

It is interesting to observe that only communities that have experienced the effects of damaging earthquakes seem to be willing to accept the scientific evidence that major earthquakes are likely and need to be considered in design. While other communities might be convinced to adopt less stringent requirements, the seismic standards for new buildings cannot be easily unbundled to meet the perceived need of communities outside of California that may choose lower minimum performance levels. This problem is clearly at the heart of the lack of receptivity to the new IBC 2000 and 2003 Codes.

Seismic Guidelines and Standards for Existing Buildings

Specific provisions for the evaluation and rehabilitation of existing buildings began to be developed in the 1980's. These provisions grew out of the recognition that the requirements for new buildings could not be easily met by strengthening existing construction, and the growing body of earthquake experience that showed it was not often necessarily. At first, these provisions focused on identifying the buildings that were "unsafe" because of "fatal flaws", i.e., life threatening deficiencies based on observations after major earthquakes. Using prescriptive techniques individually tailored to fifteen building types, ATC 14 (ATC 1986) defined minimum standards for buildings that would, by definition, protect the lives of the occupants and allow them to safely exit buildings after the shaking stopped. Ironically enough, these minimum provisions were much less stringent than those set for new buildings even though they shared a common performance expectation. While this difference made perfect sense to the engineers drafting the seismic provisions, others, including building owners, rarely understood.

The provisions for existing buildings have since yielded a suite of guidelines and standards for rehabilitating buildings that allow for the consideration and selection of specific performance expectations. SEAOC's Vision 2000 defined a framework for performance-based engineering that focused on defining performance objectives in terms of a variety of hazard levels combined with a range of performance levels. The basic assumption was that building owners would define their performance expectations as the goals for rehabilitation projects. What began as a set of special provisions for improving the behavior of existing construction to a life-safety level has grown to allow a range of performance expectations from "collapse prevention" to "fully functional" with many user-tailored steps in between. The current versions of these provisions include ASCE 31 (ASEC 2003) that focuses on the evaluation of buildings and FEMA 356 (FEMA 2000) that covers their rehabilitation.

Building owners have responded to the opportunity to define performance expectations in a variety of ways to their own individual buildings. Some find the Vision 2000 style of defining performance objectives helpful and usable. As a group, they tend to be owners of large inventories of buildings, have earthquake engineers on staff that understand the opportunities, and direct the decision makers through the process of defining performance levels, hazard levels, and suitable performance objectives. They tend to be veterans of damaging earthquakes and understand the value of achieving predictable performance, or better for a suite of possible earthquakes.

A second group of owners, also most often veterans of earthquake damage, rely on a general understanding of the performance options and select performance expectations in terms of the impact that the expected damage will have on their overall operations. While they often consider saving lives as one consideration, they also often consider the cost of repairs and the length of time that will be needed to repair the building to the point that it can be returned to service. Some of these owners are concerned with optimizing the cost/benefit ratio of the rehabilitation efforts, others are interested in minimizing the cost of repairs, while others focus entirely on minimizing the "downtime." These owners tend to retain earthquake engineers that they trust who translate their performance expectations into design criteria and carry out the needed analysis and design, and direct the resultant construction.

The majority of building owners that are faced with seismic rehabilitation projects are working to comply with mandatory code requirements or requirements imposed by their lenders. They have little to no interest in defining seismic performance expectations, and focus only on minimizing the cost and impact of seismic rehabilitation as much as possible. They usually have not personally experienced the effects of earthquake damage and often do not believe that they ever will. Ironically enough, the structural engineers they rely on often do not understand the significance of the earthquake potential and downplay the need for rehabilitation.

Damaging earthquakes affect more that just the building owners and occupants that suffer loss. Earthquakes often can have a serious impact on a community's economic viability. Appropriately established design requirements for new and existing buildings can provide an appropriate level of protection for a community, both in terms of its people and also in terms of its economic viability. The community benefit, however, depends on the building owners' actions. Without specific code provisions, most owners will not choose to do anything about improving the seismic performance of their buildings.

EERI, in their report "Securing Society against Catastrophic Earthquake Losses", estimates that the total annual average financial loss from earthquakes is expected to exceed $10 billion, with the loss from a single major event well in excess of $100 billion. They also suggest that the expected loss is increasing because of the lack of proper seismic design requirements and land use planning in areas that face seismic risk. Mandatory requirements are needed in each community that is at risk if the growing seismic risk that the United States faces is to be arrested and brought to an acceptable level.

Barriers Within Performance-based Engineering

Performance-based engineering (PBE) was formalized in the United States after the Northridge Earthquake in an effort to reduce the financial losses to an acceptable level. After the Northridge earthquake, engineers were proud that the vast majority of their designs achieved the life-safety target they had set. Unfortunately, the public was enraged that the total cost was over $40 billion dollars. PBE has succeeded in stimulating the development of a vocabulary for establishing performance expectations. It has been successful in encouraging an open dialogue about seismic risk and performance, but it has not triggered a significant change in the willingness to incorporate seismic design in new or existing buildings located in seismic areas. At the root of the problem appears to be a general lack of understanding and/or acceptance of the defined earthquake hazard nationwide, minimum performance expectations that are too high, and unnecessarily conservative and restrictive evaluation and design guidelines.

Seismic Hazard Assessment and Earthquake Engineering are both developing fields that rely mostly on observations from moderate and larger earthquake and computer simulations. After over thirty years of earth science research, the USGS has produced seismic hazard maps for the United States. These scientifically defendable maps have been available and have been regularly updated since 1997. They have been incorporated into the various seismic provisions that are available and used mostly on a voluntary basis. Unfortunately, many communities outside of California continue to ignore the seismic hazard they are facing.

Research in the earth science field has traditionally been disconnected from earthquake engineering research that predicts building behavior. As a result, the commonly-used seismic provisions are not directly tied to the recorded ground motions, only to design values that are derived from ground motion estimates. This has created a gap in understanding that has increased the cost of seismic design unnecessarily and also may explain the lack of responsiveness to the new hazard definitions. This gap in understanding also stands as a barrier to advances in seismic evaluation and design using actual records.

Observations from earthquakes for over a hundred years have shown that the greatest life-safety risk to people in earthquakes comes from complete building collapse. A close look at the evaluation and design provisions reveals that many of the requirements are aimed at eliminating damage, not just preventing collapse. While these are proper goals for some communities, they may not suit others. A fresh, interdisciplinary look at the options for minimum levels of seismic design and evaluation are needed to provide communities with useable tools to manage their seismic risks. The cost of seismic protection would be much lower if the minimum goals related to life-safety permitted serious damage to the point of near collapse. More mandatory mitigation programs might appear if only buildings that could completely collapse were targeted for rehabilitation; those that are often referred to as exceptionally high risk (EHR).

Dedicated and thoughtful researchers and professionals write the seismic provisions that are used worldwide today. They are generally written in a collaborative environment that combines the personal work and experiences of all of the participants. Most often, because of a lack of data from actual earthquakes, the provisions and acceptance criteria are based on testing and computer simulation. Non-linear time history analysis is currently treated as the benchmark for reality. While this appears to be convenient, it is not particularly accurate.

Seismic monitoring programs have been in place throughout the United States for over seventy years. Significant data sets of records have been obtained from a variety of large earthquakes since 1971. The most significant sets came from Loma Prieta, Northridge, and Taiwan. In each case, it was not uncommon to observe undamaged structures at or near strong motion records that appeared to be at or above design levels. The Templeton Hospital record from the recent 2003 San Simeon earthquake is a good example. A similar conclusion can be drawn from the thousands of buildings that would fail an ASCE 31 evaluation, though survived a "design level" earthquake with essentially no significant damage.

The effectiveness and usefulness of PBE is hampered by uncertainty and lack of concensus on what can be predicted. This problem is covered with conservatism that results in more buildings being slated for rehabilitation than needed and at a higher cost. High cost, added to the low perceived benefits, yields the growing earthquake risk that the United States faces today. The answer is not in developing advanced analysis techniques that require thousands of man-hours to implement. Such a tool may be useful for research and calibration, but it has no place in common building design. The United States hosts some $17 trillion dollars worth of buildings and constructs another $500 billion dollars worth each year. 75% of these are residential construction and the vast majority are designed using simplified, prescriptive techniques. It is highly unlikely that this trend will change.

MAKING PERFORMANCE-BASED ENGINEERING USEFUL

The development of performance-based engineering over the past ten years has provided a consistent set of tools for discussing performance expectations in an orderly manner. These have been useful to a few building owners when confidently applied by their earthquake engineers. Their availability, however, has not triggered a level of seismic mitigation activities that will protect communities and prevent significant losses from occurring in the next major earthquake. It appears that there are at least five key actions that need to be taken to make performance-based engineering useable:

- Recognition that there are no wrong answers when it comes to performance expectations and acceptable levels of safety. Seismic provisions for new and existing buildings need to be transparent in their declaration of a wide variety of performance expectations.

Earthquake scientists and engineers need to remain the primary developers of seismic provisions, but the goal, the level of acceptable safety, must be developed by the community at large. This action is especially important as it relates to the development and enforcement of seismic provisions for new buildings. Traditional minimum levels of seismic safety that are embedded in the seismic provisions are blocking the initiation of seismic mitigation programs in areas outside of the high seismic regions. To do this, the seismic design provisions must be transparent in terms of expected performance and hazard level. Minimum levels of safety should be established as a community initiative given all possible options, and selecting options above the minimum should be a fully transparent process.

- Performance expectations need to be declared in terms that building owners find clear and usable, not those that are familiar to the earthquake engineers. This discipline will also yield a higher level of consistency between engineers.

Earthquake engineers think about seismic evaluation and design in terms of lateral forces, special details of construction, specific analysis techniques, and strong ground motion parameters. Owners, users, regulators, and other interested parties think of performance in terms of safety, cost of repair, and downtime. The disconnect between the traditional engineering procedures and the information needed by owners causes inconsistency, breeds confusion, and often blocks appropriate mitigation from occurring. Carefully-defined performance states, defined in terms of safety, repair cost, and downtime, are needed to bring clarity to the process. These must be supported by specific and reliable engineering procedures that will assure the expectations are met. Conservatism should be used to accommodate the uncertainty that is inherent in the process.

- Simple, prescriptive requirements are needed for use in the daily seismic evaluation and design process.

Owners think about safety, cost of repairs and downtime needed for repairs deterministically, not probabilistically. Design professionals need prescriptive requirements that they can quickly incorporate into the dozens of other project requirements that are not related to seismic performance. The prescriptive requirements should be developed using proper applications of probability, reliability, benefit/cost considerations, and advanced analysis techniques. To be useful, performance expectations need to be distilled into transparent options that can be incorporated in the vast majority of projects using prescriptive requirements. The transparency of the process should also allow for a consistent, project-specific application of the advanced processes when a more refined solution is needed.

- Seismic provisions for new and existing buildings need to be drawn into a single set of seismic provisions that are fully compatible and consistent.

Building owners and users, whether homeowners, corporate facility managers, governmental agencies or others, often judge the suitability of requirements based on their consistency and universal acceptance. The current practice of maintaining seismic provisions for new buildings, apart from those for existing buildings, is understandable and unacceptable. The separation is rooted in the fact that it costs very little to design and build a new building to a suitable level of seismic resistance. Existing buildings, on the other hand, require significant investment to achieve an acceptable state of safety. This all makes good sense to the engineers, but not to the public. A common set of provisions, that extends over a wide range of performance expectations, is needed to simplify and clarify the issues and bring the expected performance into clear view. There is no reason why a community should not be able to allow a new building to perform at the minimum level permissible for existing buildings as long as they understand the details of the performance expectation.

- The analysis and design tools must be advanced and calibrated to the reality of the actual performance of structures in earthquakes, not to the most sophisticated analysis available.

The present practice of calibrating analysis methods to non-linear dynamic procedures is an effective tool, but one that is adding a significant amount of conservatism to the process. Seismic monitoring, the long-term effort to record earthquake motions, is growing both in capability and extent. The records that will be retrieved will yield new information about the actual performance of buildings in earthquakes and provide fundamental information needed to calibrate the computer simulations that form the backbone of the seismic provisions. The popular analysis methods and models need to be expanded as they are calibrated based on recorded motion and observed damage. New procedures are needed that are integrally tied to the earth science hazard characterization and tuned to accurately predict performance. Once available, they should be able to determine when design level earthquakes have occurred and buildings can be considered proof tested. All buildings that experience strong shaking remain the best instruments for recording the effects of the earthquake. Procedures need to be established and exercised after every event to capture the performance so that it can be used to calibrate the analysis procedures. The cost of seismic design can be significantly reduced once this calibration is advanced, a trait that will make seismic mitigation more attractive.

- Put liability concerns in proper perspective.

Many earthquake engineers have been reluctant to fully embrace performance-based engineering or to make it a part of the seismic provisions out of their concern about uncontrolled liability. They fear that specifically defining performance expectations would leave them vulnerable to legal action post-earthquake when the expectations are not met. Admittedly, there is a good possibility that some buildings will not perform as expected, even when they are properly designed and constructed. When this occurs in an environment where there are no specific seismic provisions, the potential for misunderstanding, legal action, and diverse expert opinion is high. When it occurs in the context of specific, defined performance expectations that are accompanied by specific provisions that should be used, the issue becomes simply one of whether the designer followed the state of the practice as defined by the written seismic provisions. The presence of consensus-based performance-based engineering provisions actually reduces the potential for liability claims against the engineer.

BENEFITS

Low probability, high consequence events, such as earthquakes, rarely capture the attention of the public until they occur. At that point, interest is high, and there is an opportunity to communicate the need for proper planning, design, evaluation, and mitigation. The public's willingness to prepare for the next event depends on the clarity and consistency of the message that is presented by the expert community. Performance-based engineering has taken significant steps in the last ten years to prepare the way for clarity. The enhancements that will be added to PBE in the next decade will determine if significant mitigation steps begin and start the process of arresting the growth of seismic risk and reducing it to an acceptable level of safety. The addition of transparency, clarity, simplicity, consistency, and reality to the process should lead to a clear community-based statement of expectations that will in turn lead to expanded mitigation activities. These, in turn, will lead to better urban planning, appropriate design, less post-earthquake trauma and cost, and fewer missed expectations.

As a bonus, the availability of usable performance-based earthquake engineering provisions will reduce the design engineer's liability in the event that the expectations are not met.

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