EARTHQUAKE ENGINEERING IN AN AGGRESSIVE LEGAL CLIMATE

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Abstract

Throughout the 20th Century, the goal of earthquake engineers in seismically active regions of developed countries has been the advancement and refinement of building code provisions that promote the design and construction of buildings that are sufficiently earthquake resistant to minimize the odds of collapse and ensuing loss of life. To this end, the profession has been largely successful, though our most modern designs remain untested. In addition, there remains an enormous inventory of buildings designed and constructed to lower standards. The earthquake engineering community has more recently set their sights on retrofit of the more vulnerable of these existing buildings with the intent of reducing the hazard of collapse. The earthquake engineering profession recognizes that due to the myriad uncertainties in our work, collapse prevention is a goal, but not a guarantee. The profession is also quite comfortable with the expectation that many code compliant buildings will be badly damaged (economically) in major earthquakes. Unfortunately, neither the general public nor the legal profession share that understanding. Rather, there is widespread belief that a building "properly" designed to code, should perform as well during earthquakes as it does for all other environmental conditions. The unfortunate result of this asymmetry in understanding and expectations is that litigation over the performance of recently constructed or recently retrofitted buildings (i.e. within the preceding decade) will be a prominent feature of post-earthquake recovery. Those who have been most dedicated to improving the seismic safety of our communities will likely find themselves defending their work before a lay jury. This paper is illustrated with several prominent legal cases where owners, engineers, and contractors have had their decisions and work examined in the adversarial and non-technical legal environment. The paper concludes with thoughts regarding how those trained to deal with technical risks can better appreciate potential legal risks.

Keywords: performance; legal risk; litigation; standard of care; retrofit

1. Introduction

The code of Hammurabi, specifically Laws 229-232 [1], is the earliest recorded performance-based building code, specifying both the expected performance level (i.e. buildings should not collapse) as well as penalties for the builder if the performance standard is not met. While not explicitly stated, it may be presumed that the laws were not intended to include earthquake-induced collapse, which throughout most of recorded history has been viewed as an unpredictable act-of-God beyond the control of mortals. Long ago, builders figured out how to build buildings to resist the force of gravity. It is only recently that we have come to understand the nature of earthquakes and build buildings to resist their effects. As a result of the fine work of dedicated researchers, talented structural engineers, and conscientious builders, modern structures are economically constructed, yet collapse in major earthquakes is rare. For this accomplishment, one might expect a grateful public that would forgive the rare earthquake-induced collapse. Unfortunately, in the United States, public expectations of building performance in earthquakes have outpaced the development of aseismic technology.

Herein we discuss the disconnects between structural engineers working hard to improve seismic safety, public expectations regarding the performance of our work-product, the evolving legal climate in the United States and the implications for what might happen in the legal arena following the next major California earthquake.

2. Evolution of Seismic Design

Over the past century, seismic design has evolved from simple, deterministic, static lateral forces imposed on an elastic structure to progressively more detailed probabilistic-based building code requirements that incorporate numerous variables including dynamic and inelastic response, site conditions, building importance, materials and details of construction, etc. Most recently we have seen the rise of Performance-Based Earthquake Engineering (PBEE), wherein the desired performance levels are identified and the designer configures a structural system to satisfy those performance objectives. In the process, the designer is aided by powerful analytical tools that quantify the building response to a selection of hypothesized ground motions.

Throughout this evolution, the design process has become more rigorous and more precise. Implicit assumptions have been replaced with explicit analysis based on research and test data. Simple hand calculations have been replaced by progressively more powerful analysis and design software that allows much greater insight into structural behavior. The record of the improved performance of modern structures in major earthquakes indicates that our seismic designs are also becoming more “accurate” with respect to our ability to predict behavior of the actual prototype in a real earthquake. More accurate, but certainly not perfect. While we are better at focusing on the most important design parameters, there remain numerous uncertainties in the process, ranging from our abilities to predict important characteristics of ground motions that may occur once every 2500 years to our ability to accurately predict the overall behavior of thousands of structural and non-structural components fabricated and assembled by constructors focused on budgets and deadlines. Unlike most other “products” on the market, with respect to earthquakes, every building structure is an untested prototype. An actual earthquake is the only test most buildings will ever experience. It is only during that testing that the weaknesses in our codes, our designs and our design philosophy are exposed.

We deal with this uncertainty by means of what I will generically categorize as factors of safety. We systematically and purposefully underestimate the capacity of structures while systematically overestimating the demands generated by hypothetical earthquakes that we believe are likely to occur during the life of the structure. These over- and underestimation factors are calibrated to allow for “reasonable” designs that are economically feasible to build yet reasonably safe. The tradeoff is a small, but non-zero probability of collapse in a major earthquake for a properly designed and constructed building. A non-zero probability of failure for a code compliant building is not a concept that resonates with the lay public.

3. Performance "Predictions"

Beginning in 1959, the Seismology Committee of the Structural Engineers Association of California (SEAOC) has published *Recommended Lateral Force Requirements and Commentary* [2] (generally referred to as the SEAOC Blue Book), the recommendations of which have guided seismic design in the U.S. for half a century. The performance predictions contemplated by the SEAOC Seismology Committee were as follows:[1]

> *The SEAOC Recommendations are intended to provide criteria to fulfill life safety concepts. … More specifically with regard to earthquakes, structures designed in conformance with the provisions and principles set forth therein should, in general, be able to:*
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> 1. *Resist minor earthquakes without damage;*
> 2. *Resist moderate earthquake without structural damage, but with some nonstructural damage;*
> 3. *Resist major earthquakes, of the intensity of severity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage.*

These descriptions of performance expectations are suitably vague and qualitative, reflecting the numerous assumptions and uncertainties in all the factors that contribute to building performance.

Performance-based earthquake engineering, which considers a range of hazard levels, material damage and inelasticity, and large (non-linear) displacements to quantify the building response in a probabilistic sense was first codified in ASCE 7-05 [3]. The methodology has become much more precise, but there remain numerous assumptions and significant uncertainties underlying the predictions. Seasoned engineers understand this; younger engineers are inclined to be seduced by the precision of their numerical analyses and are deluded into the belief that their precise results reflect an accurate prediction of seismic behavior. But it is essential to understand the limitations of performance predictions. Performance predictions are helpful for validating the intended behavior, for establishing code compliance, and for informing the selection of alternative designs (e.g. financial benefit of designing for damage control). It is important that clients understand that performance predictions are statistically driven estimates, not guarantees of a certain deterministic performance. Often design contracts specify explicit performance targets, such as a sewage treatment plant that can process a specified volume of sewage per day or a power plant that will generate a certain amount of energy. In such cases, delivering the specified performance is a contract requirement. Deterministic predictions of seismic performance are not currently possible and limitations on the interpretation and use of such data should be explicit in that regard.

4. Existing Building Retrofit

Prediction of the performance of existing buildings and their retrofits adds another layer of uncertainty, including details of concealed construction, physical properties of archaic materials, and the structural effects of deterioration, both visible and concealed. Relative performance predictions are extremely helpful for assessing the cost/benefit tradeoffs of alternative retrofits. Absolute performance predictions, no matter how precise, cannot be considered reliable and should not be represented as such.

The tension between providing a public safety benefit and exposing oneself to litigation is perhaps nowhere more salient that in the case of a voluntary, partial seismic retrofit to address a specific seismic vulnerability. The clearest example of this is a building with a weak/soft story. The greatest benefit to the building owner/occupants (and society in general) is to strengthen/brace that story. While the overall seismic

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[1] Quoted text is from the Commentary to the Fourth Edition SEAOC Blue Book. While varying slightly between editions, the language remained largely unchanged from 1973 to 1999.

performance and safety of the building are improved, lesser, but not insignificant, vulnerabilities remain. What are the limits of the design engineer's liability for portions of the structure that weren't addressed as part of the partial retrofit?

5. Perceptions

Engineers and the lay public have very different perceptions of both seismic safety and the role of engineers in the design and construction process. That difference is perhaps most succinctly summarized in a humorous but brutally honest assessment of the profession:

> *Structural Engineering is the Art of molding materials we do not wholly understand into shapes we cannot precisely analyze, so as to withstand forces we cannot really assess, in such a way that the community at large has no reason to suspect the extent of our ignorance.*
> (attributed to E.H. Brown) [4]

Far from appreciating engineers as artists or suspecting engineers of ignorance, the lay public views engineers as technicians who punch numbers into computer programs that design the structure. Good engineers and good engineering are invisible … until something goes wrong. At that point the search begins for someone to blame. No longer is earthquake damage attributed to an act of God; nowadays earthquake damage has to be the fault of some mortal. And the knee-jerk public reaction is often to assume that the engineer was negligent or contractor was incompetent.

Recognizing the infrequency of major earthquakes, from the structural engineering perspective, the interests of society are best served if we design buildings that are economical to construct and unlikely to collapse in a major earthquake. In reality, most buildings will never experience a major earthquake over the course of their service life. Thus, from a strict economic perspective seismic design should focus on collapse prevention and not property damage. Before the fact, there is probably alignment between build owners and engineers – few owners want to pay extra for seismic safety. In part, this may stem from the fundamental perception by the lay public that safety is a binary concept – a building is either safe or unsafe. That a building properly designed and constructed according to the current building code will be not only safe, but perhaps even "earthquake proof" with respect to both collapse and damage.

From the perspective of engineers, zero deaths from building collapse in a major earthquake would be considered a great success. While initially the public would be pleased with a low number of causalities, the financial reality for many faced with high price tags for repair of damaged buildings would cause them to look for a responsible party to compensate them for their loss. The lay public understands that the extent of damage to a car increases with the speed of a collision and are most happy if they can walk away from an accident even if the automobile is beyond repair. Similar perceptions do not hold for multimillion-dollar buildings in a major earthquake.

6. Litigation Climate

The United States is generally regarded as the world's most litigious country. When things go wrong, litigation ensues and the search for those responsible begins. In the case of building failures, all who touched the project will typically be sued and their work on the project scrutinized. Their work-product will be scrutinized for errors and their professional judgements will be second guessed. Ultimately, the work of engineers will be judged not by their professional peers but by a lay jury that has little understanding or appreciation of the incredible challenges of seismic design and vastly different perceptions of the roles, responsibilities, and knowledge of engineers. In litigation, engineers are generally viewed as having superior knowledge and responsibility to ensure, i.e. force, the owner and contractor to build perfect buildings.

Demonstrating that one's work met the standard of care is crucial to defending an engineer's work and work-product. In this regard, explicit reliance on building codes and other published standards. But it is also essential the engineers keep abreast of developing changes in practice that have yet to be codified in published standards, such as the publications of local and regional engineering societies. For cutting edge designs, reliance on academic tests and studies is essential.

7. Case Studies

Two case studies illustrate the vagaries of the litigation process and the differing perceptions of the engineering profession and the lay public.

7.1 Royal Palm Resort

The Royal Palm Resort was a recently constructed 12-story hotel on the island of Guam that sustained partial collapse in 1993 during a Magnitude 7.8 earthquake at an epicentral distance of 60km. The EERI reconnaissance team inspected the damaged structure and correctly concluded that the cause of collapse was brittle failure of captive columns in the second story of one wing of the building, as shown in Fig. 1 [5, 6]. The building was eventually demolished and protracted, costly litigation ensued. Detailed inspection of the structure and review of project documents revealed significant structural and architectural design errors. The structural system consisted of a reinforced concrete moment frame. The drawings specified a gap between the frame and non-structural concrete masonry unit walls. Rather than respecting the specified gaps, the architect directed that the gaps be filled with mortar, greatly restricting the flexibility of the structure, especially that portion above the second story. In the open second story, non-structural elements consisting of a planter and fin-wall restrained flexure of the perimeter columns (as shown in Fig. 2), forcing shear failure in the lightly reinforced mid-height portion of the columns, leading to loss of gravity capacity and partial collapse.

The litigation was effectively between the owner and the general contractor. The architect and engineer had worked under contract to the owner and were not party to the litigation. The owner argued that the collapse was the result of a construction defect, specifically inadequate hoop reinforcing in the beam column joints, even though the structural engineer of record had explicitly approved the as-built joint reinforcing. The contractor argued that it had constructed the building in accordance with the contract documents and directives from the architect and engineer. Following many months of trial and many more months of deliberation, the jury found in favor of the owner, a finding that flies in the face of any objective analysis of the facts.

7.2 Northridge Moment Frames

In the early 1990’s, specially detailed welded steel moment frames were considered a state-of-the-art lateral force resisting system, and the Building Code explicitly prescribed the design methodology and details. However, during the 1994 Northridge California Earthquake, beam column connections fractured in approximately 100 welded steel moment frame structures in the greater Los Angeles area. Many of the failures occurred in new buildings that had been constructed in the decade immediately preceding the earthquake. Following development of the framing system and the connection detail in the 1960s, welded steel moment frames had become the preferred structural system for multi-story office buildings and were generally believed to be among the most desirable framing systems for use in a seismic area. The system and joint detail were utilized by virtually every engineering office in California. In the early 1990s, Michael Engelhardt reported test results that showed brittle failure of the connections rather than the expected highly ductile behavior [7, 8]. His warnings were generally dismissed. The system had an outstanding reputation and was in widespread use – how could it be fundamentally flawed? Following the discovery of numerous brittle failures, FEMA sponsored an in-depth study, from which emerged better understanding of the joint behavior and development of new joint configurations designed to ensure reliable ductility.

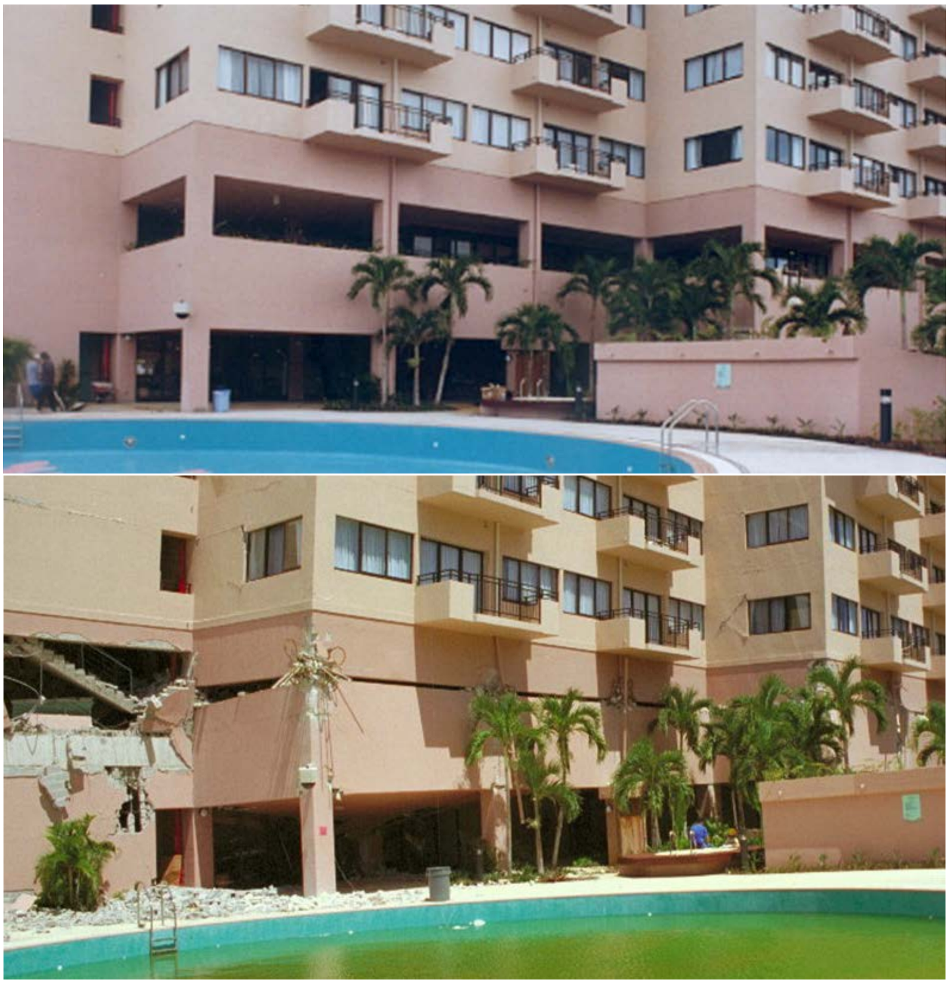

Fig. 1 – Royal Palm Resort, before (top) and after (bottom).

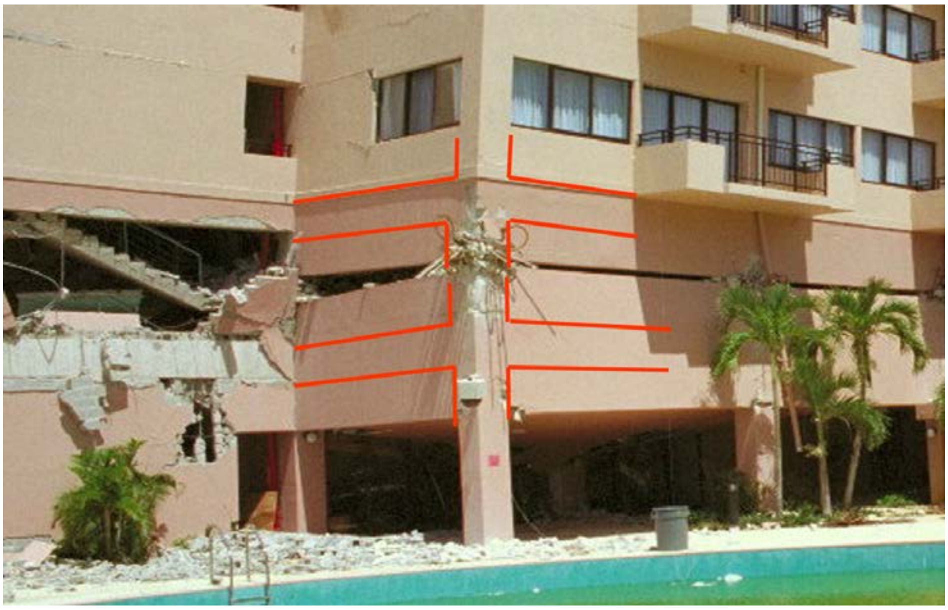

Fig. 2 – Royal Palm Resort – beam, column, and non-structural elements outlined.

Although none of these buildings collapsed (consistent with SEAOC performance expectation #3 discussed earlier), owners refused to believe that their expensive new buildings, designed by top engineers to the latest codes and constructed by reputable contractors, could have suffered serious structural damage requiring millions of dollars to repair. Given the great expense of inspecting and repairing damaged joints, litigation against designers, fabricators, and the welding material supplier ensued. Engineers, in particular, were sued for professional negligence, notwithstanding that their designs typically met the letter of the prescriptive requirements of the Building Code and were nominally identical across all design offices. If one defines professional negligence as the failure to do what other reasonable engineers would do in the same situation, it is logically inconsistent to argue that all of these engineers failed to meet the standard of care. That did not prevent litigation against the engineers. In fact, subsequent research identified several factors leading to the brittle failures including initial testing done on small specimens, low ductility weld deposits, weld procedures and workmanship, and the strain concentrations and constraint inherent in the geometry. As such, there was no shortage of defendants.

8. Acknowledgements

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9. Conclusions

In the course of their design work, structural engineers need to be mindful of public perceptions regarding expected seismic performance of buildings. At a later date, their work may be scrutinized and judged not by their peers but by a lay jury unschooled in the science and art of earthquake engineering based on their perceptions of how a building should perform and the engineer's role in influencing the building's behavior. Demonstrating that one's work met the standard of care is crucial to defending an engineer's work and work-product. In this regard, explicit reliance on published standards, ranging from building codes to the publications of local engineering societies,.5 is desirable. For cutting edge designs, reliance on academic tests and studies is essential. But it is also essential the engineers keep abreast of developing changes in practice that have yet to be codified in published standards.

Limitations on the interpretation and use of performance "predictions" must be explicit. Performance predictions are helpful for establishing code compliance and for aiding in the choice between alternative designs (i.e. financial benefit of designing for damage control). It is important that clients understand that performance predictions are statistical estimates, not a guarantee of a certain deterministic performance.

Of course, the best defense is a vigorous offense – a robust design that is tolerant of construction imperfections with explicit fuses that will allow the building to "fail" (or yield) gracefully yet be repairable following a major earthquake.

The ultimate question is how can structural engineers continue to contribute to improving the resilience of our cities by improving the performance of both new and existing structures without exposing themselves to ruinous litigation following a major earthquake?

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