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THOUGHTS ON THE FUTURE DEVELOPMENT OF U.S. SEISMIC CODES

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Abstract

U.S. seismic codes have undergone significant change over the past three decades. A substantial portion of the changes relate to three topics:

1. ground motion prediction and risk-targeted vs. uniform hazard ground motion characterization;

2. establishment of design parameters and detailing requirements for new and hybrid seismic force resisting systems (SFRS); and

3. enhancement of requirements for the protection of non-building structures such as oil refineries, and nonstructural components such as building cladding and egress systems.

Other changes, e.g., to implement nonlinear time history procedures or to revise requirements for assessing building irregularities, have largely been driven by changes in design practice.

More recently, many organizations engaged in the code development process in the U.S. have begun to refocus attention on infrastructure resilience. In terms of seismic design, resilience is generally characterized as the ability of the built environment (and the society that inhabits it) to recover in a reasonably short time frame (as measured from time of event to time of re-occupancy) from significant damaging events. This shift in emphasis is tied to a growing interest in performance-based code provisions to replace the current (largely) prescriptive requirements. While the emphasis on resilience and performance-based standards is laudatory, is it reasonable to expect the current design environment to produce predictable outcomes at the desired level of granularity? In short, are the goals being set for performance-based codes simply aspirational, or are they based in reality?

In this context, the paper will examine several aspects of current seismic code development including:

a. The “new” vs. “existing” structure paradigm and whether it truly serves our purposes.

b. Material-centric seismic code development and what this means for under-served issues related to resilience.

c. The impact of shifting funding sources in the privately-operated U.S. code development environment.

d. The separation of structural vs. nonstructural building elements in code provisions and the confusion that often arises around these terms.

e. The increasingly difficult case to be made for civil/structural engineering as a career choice and the impact that this could have on seismic code development.

The paper will attempt to distill and summarize views developed over a career spanning four decades that may be useful for codes and standards professionals engaged in seismic code development worldwide.

Keywords: seismic codes; resilience; performance-based design

1. What is a seismic code?

It is worth asking why earthquakes are addressed uniquely from other structural loading conditions. The design of structures involves consideration of a number of possible environmental factors, the most consistent being gravity. Wind, snow, and rain may also be decisive for structural integrity, depending on the siting of the structure and its use. Catastrophic environmental conditions such as wave impact (tsunami), tornadic air pressure changes, fire effects, and, more recently, collision of aircraft or other airborne missiles may be relevant as well. Designing for earthquake effects, however, has long occupied a unique position in the structural world. Why is this?

1. Earthquakes are unique in their destructive power – the history of modern structures is also the history of earthquakes. While most western engineers have some familiarity with the Lisbon earthquake of 1531, which is associated with approximately 30,000 deaths, the Shaanxi earthquake of 1556 is considered by USGS to be the deadliest earthquake in recorded history (830,000+ fatalities) (Wikipedia, 2019). These events were preceded by dozens of similarly catastrophic ground motion events as recorded in ancient records.

2. Mitigating earthquake damage need not be prohibitively expensive – relatively simple changes in construction practice have done much to reduce the effects of earthquakes on society. Top-down enforcement and provision of financial assistance has enhanced the ability of 1st world countries to mitigate seismic hazard, although there are important exceptions to this relationship.

3. For structural engineers, earthquakes represent a grand challenge, and the development of structural systems to effectively address strong ground motion has long been a magnet for the attention of the academic community. Originally, this interest was driven by private money directed at reducing insurable losses; more recently, it is fueled by government grants.

4. The uncertain nature of earthquake causation poses a unique challenge to code writers. Events of catastrophic consequence that may occur 1) a thousand years from now or 2) tomorrow, may or may not be worth addressing in public law from a return on investment standpoint. An analogous case is presented by the threat of large asteroid impact (Kaplan, 2019). On the other hand, pro-rating seismic design requirements (and the cost of seismic protection) on the basis of return period may not be sensible. If a low probability translates to relaxed seismic protection, then any effort and expenditure may simply be overwhelmed by the actual (unlikely) event should it occur.

For these reasons and others, seismic design of structures has traditionally been addressed in separate provisions, distinct from the statistical basis, safety considerations, and system requirements associated with other loading cases.

So, what is a seismic code? I submit the following definition:

> A seismic code is the imperfect distillation of observation, experience, and research regarding the response of structures to strong ground motion coupled with an *intuition* regarding the willingness of society (as represented by the building community) to shoulder additional costs associated with better seismic performance.[1]

The second part of this definition is important and refers to a process that is often disregarded. Producing a commercial structure that will survive a severe earthquake with minimal or no damage or disruption to function is certainly achievable. A builder with deep pockets having this objective will have no trouble finding a structural engineer to develop such a design. Codes, however, have historically not been targeted to the purpose of regulating this process, except perhaps in cases where an unscrupulous or mis-guided engineer might

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[1] Early in my career, I became familiar with a self-deprecating definition of our profession, posted in large typeface on the wall of the office where I worked: “Structural engineering is the art of molding materials we don’t understand into shapes we cannot analyze so as to withstand forces we cannot really assess, in such a manner that the public does not suspect.” I offer my definition in the same spirit of honesty and humility.

attempt to implement an inherently unsafe “earthquake-proof” structural system. Historically, codes provide “minimum standards” to ensure “safety”.

The 1927 Uniform Building Code contained an appendix on earthquake design as follows (Structural Engineers Association of California, 1975):

> *The following provisions are suggested for inclusion in the Code of cities located within an area subject to earthquake shocks. The design of buildings for earthquake shocks is a moot question but the following provisions will provide adequate additional strength when applied in the design of buildings or structures.*

The use of the phrase “moot question” is simply intended to note that the design of structures for earthquakes remained, in 1927, a bit of a mystery. Nevertheless, the authors of that document felt compelled to characterize their provisions as providing “adequate strength”. This phrase is retained in many codes today, although the notion of “adequate” is never defined.

The general purpose of building codes (and here I am referring to documents that are adopted as public law by a jurisdiction) is to regulate construction across the entire economic spectrum, including commercial, residential, institutional and industrial facilities. The general understanding is that application of a building code to a given construction type should result in a “safe” structure, but what is *safe*? In the Eurocode, the definition of safe is explicitly associated with a target reliability over a defined structure life. See, e.g., (Holický, 2011). In U.S. codes, the definitions of *safe* and *adequate* tend to be fungible. In the context of earthquake design, it is numerically defined only insofar as the triple integral (Moehle, 2004) used to develop hazard maps can be relied upon to yield an accurate estimate of collapse probability. In any case, specific application of the concept of *safe* in a seismic code takes many forms, from hard limits on building height to restrictions on analysis methods. In each instance, a unique combination of viewpoints held by the contributing authors results in a fixed outcome, often associated with little more citable evidence than “it feels right”.

2. How did we get here?

The history of U.S. seismic provision development begins with the (Great) San Francisco Earthquake and Fire of 1906. That singular event, which laid waste to 80% of a thriving metropolis and likely resulted in 3000+ fatalities (far fewer were reported), initiated a period of intense interest in the response of structures to strong ground motion, as evidenced by contributions to the *Transactions* of the American Society of Civil Engineers (see e.g., American Society of Civil Engineers, 1907). Nascent concepts of ductility, detailing, load path and system integrity were featured in many of the views expressed by Charles Derleth and others. In terms of regulations for the re-building of the city, the 1906 earthquake resulted in a prescriptive requirement that all structures be designed to resist a 30 pound per square foot (1436 N/m^2) pressure applied uniformly over any one face. This was deemed “adequate” for a structure with “a proper system of bracing” (Structural Engineers Association of California, 1975).

Damaging earthquakes in Santa Barbara, California in 1925 and in Long Beach, California in 1933 resulted in an increase in public funding for earthquake research and the implementation of public law (Field Act of 1933) to provide superior protection for public schools. The rationale was simple – students were required by state law to attend school; therefore the state had a unique responsibility to ensure their safety while attending school. This logic bypasses the cost-benefit relationship that might be used for justifying less seismically-resistant commercial construction. The Riley Act, also passed in 1933, replaced the 30 psf requirement with a minimum lateral force, applied uniformly over the structure height, of 2% of the total vertical design load (Structural Engineers Association of California, 1975). The concept of relating lateral forces to building mass found wide acceptance in the scientific community, although the coefficient of 2% underwent significant modification over the ensuing decades (a process that continues to this day).

In 1957, the Structural Engineers Association of California undertook the momentous task of creating a seismic code for the nation. The resulting document, first published in 1959 and later to be referred to simply as “the Blue Book”, provided the essential structure for modern lateral force provisions: lateral forces are related to the building lateral force resisting system and its detailing. “Bad” systems with fragile detailing and a high degree of instability when subjected to ground motion were assigned more severe design coefficients compared to “good” systems with ductility and redundancy. Engineering judgment was used to decide what level of protection was “adequate” and “reasonable” given construction costs at that time. The term “life safety” was eventually adopted to establish the fundamental objective of public law as it pertained to earthquake resistance (as opposed to damage control).

This concept (relating demand to system type and detailing) has undergone significant modification in the ensuing 60 years, but it remains the bedrock of U.S. seismic design as embodied in Table 12.2-1 of ASCE 7 (American Society of Civil Engineers, 2016). While the relationship between system performance (as embodied in the factor “R”) and lateral force has been formally quantified in FEMA P-695 (Federal Emergency Management Agency, 2009), the benchmark values (8 = high ductility, 3 = low…) may still be traced back to the original Blue Book formulation. In this sense, the original “imperfect distillation” from the 1957 SEAOC effort, and to a degree, the *intuition* of those authors regarding what is “adequate”, are preserved.

3. The case for more than life safety

In 1995, SEAOC issued *Vision 2000: Performance Based Seismic Engineering of Buildings* (Structural Engineers Association of California, 1995). The antecedents for distinct levels of seismic performance associated with lateral force assumptions, detailing, and system requirements were developed in the context of developing earthquake-resistant construction for high value manufacturing facilities in Silicone Valley. In such cases, the cost of seismic protection was deemed insignificant relative to the cost associated with loss of the facilities for any significant length of time.

Whereas the collective judgment of the Blue Book authors in 1959 centered around minimum requirements to protect building occupants, the authors of *Vision 2000* were motivated by property protection and, in specific cases, time to recovery. In the parlance of those engaged in seismic code development in the early 2000s, the multiple levels of performance were characterized as “death, dollars, and downtime”. Logically, these performance objectives were associated with specific event scenarios having defined probabilities of occurrence (or, more correctly, of exceedence). That is, an objective of “minimum downtime” might be associated with a level of ground shaking that could be expected to occur with relative frequency, whereas the objective “minimize injuries and fatalities” might be associated with a larger event of greater severity.

Performance based seismic design is defined in paragraph 1.3.1.3 and associated target reliability tables in ASCE 7-16 (American Society of Civil Engineers, 2016). The metric for establishing the acceptability of a performance based seismic design is to “provide a reliability that is generally consistent with the target reliabilities stipulated in this section.” The manner in which this is to be proven is undefined, other than that it should include analysis, testing, and peer review.

4. Reality check

What, in fact, can we say about our ability to provide these levels of reliability? In fact, the sophistication of structural analysis has improved considerably in the past decade. For some types of structural systems (e.g., steel moment frames, buckling restrained braced frames) the accuracy of the structural response prediction is quite good. In these cases, targeting a specific probability of failure for a given ground motion scenario is a plausible option. For other structural systems (shear walls, composite systems), the ability of current modeling techniques to capture the relevant response characteristics necessary for an accurate prediction of p_f is less clear.

It is widely recognized that nonstructural elements (e.g., cladding, partitions, electrical and mechanical systems) represent the greatest source of potential financial loss for structures subject to earthquakes (Federal Emergency Management Agency, 2011). The ATC-120 project (National Institute of Science and Technology,

2017) established probable goals for the performance of nonstructural components that attempted to address the "death, dollars, and downtime" paradigm. Outpacing code provisions, numerous systems for the assessment of structures for their resilience under various earthquake scenarios have been placed in the public domain (Structural Engineers Association of Northern California, 2015). How accurate will these predictions prove to be? Earthquake forensics - one of the hallmarks of seismic code development pioneered by Henry Degenkolb – may or may not provide the answer. Unraveling the cause and effect in earthquake failures is often difficult, particularly when it comes to nonstructural damage, and application of performance-based design techniques to nonstructural components and systems is, with rare exception, impractical given the complexity of these systems and the lack of experience data (Task Committee on Performance-Based Design, 2018).

5. Structural impediments

There are, I believe, several "built-in" aspects of seismic code design that present a challenge to present and future code writers. To advance the cause of creating codes that improve the built environment, these structural impediments will need to be addressed.

5.1 Lack of a clear demarcation between "new" and "existing" structures

Most building regulations apply to "new" buildings, that is, buildings in planning (not yet constructed). Seismic codes are generally written on the assumption that the most recent knowledge regarding seismic hazard, structural response, and performance expectations apply. More recently, reference standards such as ASCE 41 (American Society of Civil Engineers, 2017) have been produced to address the seismic hazard associated with "existing" structures. One feature of these standards is that they provide for relaxed metrics in recognition of the difficulties associated with seismic rehabilitation, and the desire to encourage remediation of deficient structures. It is unclear, however, at what point in time a structure becomes an "existing" structure.

A new building is awarded an occupancy permit by the authority having jurisdiction (AHJ) upon satisfaction of all relevant code requirements. Presumably, once the building is occupied, it becomes an "existing building", but application of seismic code provisions written for "existing" structures to a newly occupied building would be absurd on its face. Nevertheless, the existence of provisions for "new" and "existing" buildings side by side in public law demands that the code writing community clarify these boundaries and in so doing admit to the internal judgments regarding "what society can afford". Perhaps in this way the artificial distinction between "new" and "existing" will give way to a broader definition based on the public good.

5.2 Material-centric code development

Reference structural standard development is currently driven by the four primary structural materials: steel, concrete, wood, and masonry. The institutes associated with these materials, through their revenue sources (e.g., sales of standards and support materials, membership dues, convention fees) provide much of the funding for standard-writing activities. It goes without saying that most buildings are constructed with more than one material. Furthermore, the interests of material-based institutes, i.e., promotion of one material (e.g., concrete) over other competing materials, hardly serves as a good basis for a better built environment, efficient use of natural resources, and balanced code development.

Table 12.2-1 in ASCE 7 (American Society of Civil Engineers, 2016) lists the requirements for "conforming" seismic force resisting systems (SFRS). The rules for adding new SFRS are given in *12.2.1.1 Alternative*

Structural Systems and, for commercial structures, require demonstration of a maximum probability of collapse of 10% for MCE_R ground motions. The generally accepted vehicle for providing such proof is FEMA P-695, together with subassembly testing. The costs associated with this procedure are not insubstantial. In fact, not surprisingly, the majority of new systems added to ASCE 7 since the implementation of P-695 have been sponsored by one of the big four material interests.

5.3 Funding sources

The dominant U.S. model code is developed by a private non-profit, the International Code Council (ICC). The ICC is comprised principally of municipal building officials and other AHJs throughout the U.S. The model code in turn incorporates, by reference, the structural reference standards. This system has developed organically over several decades and is unique among 1st world economies. Absence of government oversight and intervention has some advantages over state-administered code development processes, but it is also subject to pressure and is in many cases less than transparent.

5.4 Lack of clarity regarding the importance of “structural” and “nonstructural” systems

As mentioned earlier, recognition of the importance of building components not part of the structural frame for financial losses associated with earthquakes has grown significantly over the past decade. The label “nonstructural” as applied to building cladding, piping, ductwork, partitions, equipment, stairways, etc. belies the structural challenge associated with protection of these building elements.

A sensible response would be to place the protection of nonstructural elements essential for life safety on a par with the goal of collapse prevention. Doing so might force the realization that, for many critical facilities, the only practical solution is some form of seismic isolation.

5.5. The structural engineering professional

The judgment required to produce sensible seismic codes requires a cadre of independent structural engineers of diverse background and experience with the time and energy to devote to the process. It is my own observation, developed over many years, that the structural engineering professional is an endangered species. Inadequate fees and substandard pay scales put civil engineering (the core curriculum for structural engineers) at the bottom of the ladder for incoming college aspirants with a technical/engineering bent. Despite efforts by engineering associations, enrollment in engineering programs as a percentage of the total number of qualified applicants is flat or declining in the U.S. and Europe (Roy, 2019; Becker, 2010). Many structural engineers switch careers mid-stream – often this is a reaction to low pay and long hours. Those that stay in the field are in no position to donate significant non-billable time to code development.

Reversing this trend will require concerted efforts on the part of government and the structural engineering community.

6. Some positive signs

In spite of the headwinds facing seismic code developers in the future, there are some encouraging trends to pay attention to in the near term.

6.1 Input/output

The use of numerical methods was in its infancy when I was an engineer in training (I started with punch cards). My cell phone contains more memory and processing speed (by several orders of magnitude) than the main frame computers we used in those days. Finite element analysis, once a costly technique applied only to highly indeterminant systems and resulting in piles of indecipherable "output", is now available on most engineering desktops. Much of what once was considered essential in a structural engineer's education (Hardy-Cross, virtual work, etc.) has fallen by the wayside. Some consider this to be a deplorable trend. I have an opposing view – that the advances in numerical analysis permit structural engineers to approach once insoluble problems with a greater degree of confidence, provided the use of these techniques is tempered with an appropriate degree of experience, caution, and humility.

6.2 Data fluidity

Most engineers work with electronic editions of their codes, a format of limited value for reading (I still prefer paper) but that is compact, transportable, and permits searches and some degree of cross-linking. Despite this, codes and reference standards are still issued with errata (published separately) and supplements. The American Concrete Institute has announced their intention to implement "living documents" – codes that can be amended and updated instantaneously. Such developments will enable further integration of code provisions in design software and permit significantly enhanced access to explanatory material, much the way that Wikipedia® has democratized access to general knowledge.

6.3 Diversity

When I entered the profession as a young engineer, the number of women in our local professional organization could be counted on one hand. This has changed considerably – today women make up a large percentage of structural engineers at all levels of the design community in my city. This has been matched by a corresponding increase in representation of all ethnic groups and nationalities in the structural engineering community. The benefits of this shift are very apparent. The "intuition" that is part of my definition of a seismic code is informed not just by engineering experience, but experience on many other levels of life. What is "appropriate" shifts with the shifting norms of society – having a broad representation of that society at the code-writing table can only improve the end result.

7. Conclusion - and a way forward

Seismic code development is as much an art as it is a science. The collective judgment of professional engineers must be tempered by both the science and a reading of the societal "tea leaves". This is unlikely to change anytime soon, but greater transparency and a re-engagement of practicing professionals is needed to keep the process honest.

Much is made in the current political climate of small government; that is, less involvement of government in business and in the affairs of its citizens. Arguments for this position are often rooted in a belief in the overwhelming benefits of unfettered market forces. Taken collectively, U.S. building codes and in particular, seismic codes represent a case where strict reliance on free enterprise and self-regulation has not been an unqualified success. Any vision for a code development process which is more open, more transparent, and more reflective of the underlying aspirations of society for a safer and more sustainable built environment will require an increased role for government oversight. This is not to say that developers and other financial and material interests should not participate, only that that their participation should be mediated and balanced against broader societal interests through an agency that provides for a level playing field.

What would this look like in practice? Establishment of a department or agency responsible for code development within the federal government would be a good place to start. Such an agency would have as its brief the funding and oversight of code writing activities as well as the facilitation of the necessary participation of industry, academia, and the professional community in those activities. Specifically, in the realm of seismic protection, the principle role of the agency would be to set the tone, in terms of cost/benefit, for all discussions surrounding the short-, mid-, and long-term objectives of a seismic protection strategy, and to place those discussions in the broader context of the opportunity costs of seismic protection (guns vs. butter).

Clearly, increased governmental regulation of U.S. seismic code development has potential downsides, but if U.S.-based structural engineers are to be an effective voice in future decisions about the use of natural resources for creating a stable and functional built environment, government will need to play an enhanced role, not only to thwart the natural inclination of private enterprise to skew the playing field for financial advantage, but to maintain credibility and the public's faith in the seismic code development process.

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