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Safe Enough? A Building Code to Protect Our Cities as Well as Our Lives

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Seminal works of earthquake engineering hold that greater seismic resistance of the building stock is impractical; that the public is unwilling to pay for it; that the public has no proper role in setting code philosophy; and that current seismic provisions encode the proper performance goals. Recent projects undermine these conventionalities. In light of performance expectations for new buildings, the code seems almost to guarantee that a future large but not-very-rare earthquake will damage enough buildings to displace millions of people and hundreds of thousands of businesses from a major metropolitan area, producing a catastrophe more severe than Hurricane Katrina. A discussion with the public should take place in which we reconsider how to measure risk and how to balance risk and construction cost in code objectives.

INTRODUCTION

US building codes aim to protect life safety and limit property damage. The explicit intent of the 2009 International Building Code for example is to "establish minimum requirements to safeguard the public health, safety, and general welfare...." and includes "safety to life and property" among its goals (ICC 2009). The NEHRP Provisions (BSSC 2009) aim "to avoid structural collapse in very rare, extreme ground shaking," and "to provide reasonable control of damage to structural and nonstructural systems that could lead to injury and economic or functionality losses for more moderate and frequent ground shaking." Note well the inclusion of protecting the general welfare and avoiding property loss along with protecting life safety. Building codes have historically recognized that it is impossible to achieve perfect safety and property loss avoidance from overloading by dead and live loads, wind, earthquakes, etc. FEMA P-695 (ATC 2009) and NEHRP Consultants

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Joint Venture (2012) estimate that the Provisions result in at least partial collapse of as much as 10% of code-compliant buildings in risk-targeted maximum considered earthquake motion, MCE_R. Luco et al. (2007) explain how MCE_R is generally established so that, considering all possible levels of shaking, achieving an upper bound 10% collapse probability in MCE_R shaking produces an overall 1% chance of collapse in 50 years due to any level of ground shaking, with exceptions close to faults. Here, "MCE_R shaking" means, for example, 0.2-sec, 5%-damped spectral acceleration response equal to ASCE 7's (2010) S_{MS}, or 1.0-sec, 5%-damped spectral acceleration response equal to ASCE 7's S_{M1}.

For earthquake loads in particular, authors of modern codes have assumed it is impractical or uneconomical to achieve seismic resistance much greater than what is implicit in prior codes. (Here, seismic resistance refers generally to the capacity of buildings to resist damage or loss of functionality in earthquakes.) This means that the authors believe that the public would be unwilling to pay for safer buildings, perhaps buildings that would be functional after very strong shaking. ASCE 7 (ASCE 2010) and by adoption the International Building Code (ICC 2012a) measure acceptability on a per-building basis, which implies that per-building risk or per-person risk is the best measure of risk.

Let us first review these assumptions more closely, then consider recent projects that call them into question. Writing about whether it was practical to design water tanks and other structures to remain elastic under earthquake loading, Housner (1956) wrote that "it would be quite costly to design for lateral forces of this magnitude, and it would probably be considered desirable to make a less strong structure and accept permanent deformations in the event of a severe earthquake." Housner and Jennings (1982) wrote that "It is not economical to design every structure to resist the strongest possible earthquake without damage," and that therefore codes "permit yielding and structural damage in the event of very strong shaking." The authors of ATC-3-06 (1978) tried but were unable to provide figures on the probable costs to make buildings remain functional after a rare earthquake. Still, they codified the assumption that it is economically infeasible to do so and prefaced the document with a philosophy of allowing structural damage in major earthquakes.

To say that it is uneconomical to provide greater seismic resistance is roughly equivalent to saying that people would be unwilling to pay for it ("economical" being a subjective judgment, not necessarily measured in terms of, say, benefit-cost ratio). Is that true? In these sources and in others that underlie current code requirements for new buildings there is no examination of the public's willingness to pay. Owners and tenants have generally not been asked to express their preferences and are typically absent from the committees that establish codes. ("The code" is used here as shorthand for earthquake design provisions for new buildings in ASCE 7 and the IBC.) The authors of SP 577 (Ellingwood et al. 1980) expressed the notion that the A58 standards committee (precursor to ASCE 7) represented "those substantially concerned with its [the standard's] scope and provisions." Though committee members included "a broad-spectrum group of professionals from the research community, building code groups, industry, professional organizations and trade associations," it did not include representatives of owners or tenants.

The authors of a FEMA-sponsored workshop on communicating earthquake risk interviewed a small group of primarily commercial real-estate interests about their preferred measures of seismic performance (ATC 2002). The authors expressed the belief that "this workshop represents one of the first significant attempts to obtain input on issues of acceptable levels of seismic risk used as a basis for design, from other than the technical community..." although they acknowledged that "several important stakeholder groups, notably residential and institutional building owners, and retailers were not represented at all." The point is that the public is generally not consulted about their preferences for the seismic performance of the buildings they rely on. It would be easier, perhaps necessary, for engineers to support judgments about what is economical if the public were asked what they would be willing to pay for greater seismic resistance.

One could argue that engineers' clients could opt to build above code. But most new commercial buildings are short-term investments for owners who are subject to competitive pressure and would disadvantage themselves by opting for above-code design. One could also argue that construction industry representatives have been involved in code development for generations, and they strongly influence any proposed code change. But the construction industry is not the public. It is a commercial sector with its own interests that may diverge from those of the public. For example, one might compare the construction industry with the auto industry, which has resisted mandatory seatbelts, airbags, and greater fuel efficiency.

One could argue that code objectives have been presented to the public with little or no pushback. If so, the implications of the performance of the building stock in large earthquakes remain unclear to the public. In the opinion of a USGS scientist who deals regularly with local governments, city councils and mayors “absolutely do not know” how a code-compliant building stock designed to meet the life-safety objective will perform in the aggregate, and are unsatisfied when they do learn of it (L. Jones, pers. comm., 19 Nov 2013).

Conversely, one could argue that FEMA P-695 was merely a description of how code-compliant buildings perform, rather than expressing the authors’ belief that 10% collapse probability is acceptable. But in the section entitled Acceptable Probability of Collapse, the authors state that “The fundamental premise of the performance evaluation process is that an acceptably low, yet reasonable, probability of collapse can be established as a criterion for assessing the collapse performance of a proposed system. In this Methodology, it is suggested that the probability of collapse due to Maximum Considered Earthquake (MCE) ground motions be limited to 10%.” Judging by an April 2014 draft of the NEHRP Provisions, the next edition of that document may reject the implication that a 10% failure rate would be considered acceptable. But if 10% were unacceptable, why would a design that meets that objective satisfy the provisions? What does “acceptable” mean if it is not synonymous with satisfying the provisions’ requirements?

GREATER SEISMIC RESISTANCE CAN BE COST EFFECTIVE

Let us consider a few projects that suggest that greater seismic resistance might not be so costly or impractical. As part of the CUREE-Caltech Woodframe project, the present author and colleagues (Porter et al. 2002, 2006) employed 2nd generation performance-based earthquake engineering (recently standardized in FEMA P-58 [ATC 2012]) and found that seismic retrofit of several of the project’s so-called index buildings could be cost-effective, in the sense that the retrofit cost is exceeded by the expected present value of the future reduction in earthquake-related repair costs, across much of California. In some cases and locations the benefit-cost ratio (BCR) reached 8:1. The BCRs only included reduced future building repair costs; they would have been higher including casualties, living expenses, and other costs of dislocation. Another project, a cost-benefit study performed for the US Congress of FEMA-funded seismic risk mitigation (Multihazard Mitigation Council 2005), showed that a broad portfolio of retrofit projects can be cost effective. The overall portfolio exhibited a BCR of 1.4, which included a variety of benefits, including the acceptable cost per statistical casualty avoided. These were all retrofits, for which the BCR is generally lower than similar enhancements to new design (the "ounce of prevention" principle).

More to the point for new seismic design, Reitherman and Cobeen (2003), who created the CUREE-Caltech Woodframe Project's index buildings, also presented variants with above-code performance. One building was designed to remain immediately occupiable (IO) after design-level shaking and had a marginal cost of 3% over that of the conventional variant ($229,000 versus $221,000 in 2002 USD). See Porter et al. (2002) and Isoda et al. (2001) for details about index-building variants. Another example comes from the use of buckling-restrained braced (BRB) frames. The Broad Center for the Biological Sciences on the campus of the California Institute of Technology in Pasadena, a 120,000 sf, $47 million science building, was the second new US building to include BRB frames in its lateral force resisting system. According to an Arup engineer involved in the design (Zekioglu, pers. comm. 2014), the braces allow the building to meet something near the immediate occupancy performance level at design-level shaking, and added approximately 2% to the construction cost over conventional alternatives. He estimated that the facades, clad in travertine and stainless steel, added 10% to the construction cost, which suggests that the marginal cost for a remarkable seismic enhancement can be modest compared with acceptable costs for premium finishes. While it may be too costly to make every structural system achieve IO performance at design-level shaking, it does appear to be practical for some systems.

THE PUBLIC IS SOMETIMES WILLING TO PAY FOR SEISMIC RESISTANCE

As part of the San Francisco Community Action Plan for Seismic Safety (CAPSS), a public advisory committee was formed comprising self-selected volunteers representing neighborhood groups, landlords, tenants, affordable housing advocates, and others. One of their roles was to consider the risk to high-occupancy woodframe residential dwellings with soft-story conditions. When CAPSS engineers (including the present author) provided the committee with risk estimates in terms that they had requested—number of red, yellow, and green tags—along with costs to reduce the risk, the committee strongly recommended a mandatory retrofit program (ATC 2010). (A red tag is a placard placed on a building with the authority of the local jurisdiction that informs people that the building has been inspected, found to be seriously damaged, and is unsafe to enter or occupy. Entry is unlawful. A yellow tag restricts the entry, occupancy and use of a building, sometimes to parts of the building and sometimes to brief occupancy to remove possessions. A green tag indicates the building has been inspected, and lawful occupancy is permitted. See ATC [2005].)

The CAPSS landlords and tenants agreed to share the burden of paying for evaluation and mitigation. The committee recommended the strongest retrofit, not the least-expensive one. The recommendation evolved into a mandatory retrofit ordinance enacted into law in 2013 (City and County of San Francisco 2013). The CAPSS soft-story program was about remediating the worst existing buildings in a city, not about design of new buildings, but it shows that under some circumstances, the public is willing to pay more for a more earthquake-resistant building stock. Those circumstances may relate as much to the process by which the decision is made as to the wealth of the community making the investment.

IMPLIED PERFORMANCE OF ENGINEERED BUILDINGS

What if we continue to design buildings to a life-safety objective, that is, to have a 10% maximum collapse probability in MCE_R shaking, and not to be usable? Let us focus on engineered buildings, as opposed to conventional construction, and on buildings designed to meet a current code, say the 2012 IBC. To decouple the present discussion of the code from the separate issue of existing buildings, let us consider what happens when a large earthquake—the Big One—occurs after most of the older buildings have been replaced. Let us consider the Big One to be something like the Mw 7.8 ShakeOut scenario or an Mw 7.9 repeat of the 1906 San Francisco earthquake. These are not very rare events, at least compared with MCE_R shaking. Under the Uniform California Earthquake Rupture Forecast version 3 (Field et al. 2013), there is a 5% chance each year that California will experience an earthquake of at least Mw 7.8. An earthquake like the ShakeOut on the southern San Andreas Fault has a mean recurrence interval on the order of 150 years. It has been 300 years since the last one. What will happen in such an event? Rather than relying on computer models of building vulnerability, let us assume that the outcome is exactly what ASCE 7-10 aims for, namely an upper bound of 10% collapse rate in MCE_R shaking.

In the ShakeOut or a repeat of the 1906 earthquake, some areas will be shaken very strongly, with shaking in some areas close to the fault reaching or exceeding MCE_R. Other areas father from the fault will experience lower shaking. (The likelihood of a particular fault rupture is not the same as the likelihood of shaking at a particular location in that earthquake. A rupture with a 200-year mean recurrence interval can produce shaking in some places with much rarer occurrence rate, in part because of variability in ground motion. A 200-year earthquake can produce 2500-year shaking in small areas.)

In places with MCE_R shaking, FEMA P-695 envisions that "the probability of collapse due to Maximum Considered Earthquake (MCE) ground motions [is] limited to 10%." The authors of NEHRP Consultants Joint Venture (2012) estimated that this goal was achieved by current code requirements: they plotted collapse probability of 179 buildings given MCE_R shaking as a function of design period; the result is copied to Figure 1. Lead author Kircher (pers. comm. 8 May 2014) believes that collapse probabilities in buildings with period T ≤ 0.5 sec are overestimated. Assuming that one should completely ignore those buildings and omit the three circled data points, the average collapse probability of the remaining data points in Figure 1 is approximately 6%. Let us assume for the moment that this is how the new building stock performs: in areas shaken at MCE_R, 6% of buildings collapse.

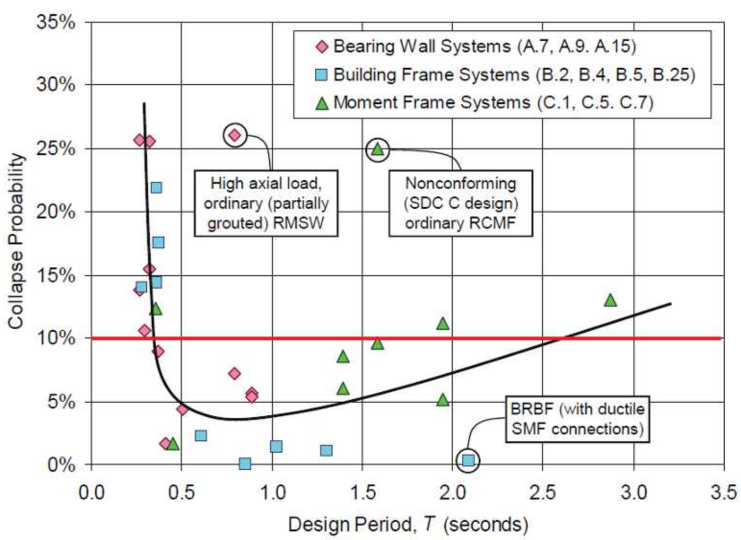


Figure 1. Collapse probability in MCE_R shaking in 179 buildings examined in FEMA P-695 and NIST GCR 10-917-8 (NEHRP Consultants Joint Venture 2012).

Many other buildings would probably be otherwise impaired. What is the broader impairment rate, by which is meant here the fraction of buildings that collapse, are red-tagged, or are yellow-tagged? The authors of FEMA P-695 do not address red- or yellow-tagging. The present author is unaware of studies of new, code-compliant buildings that do so. One could use HAZUS-MH (e.g., Kircher et al. 2006) or other analytical methodology (as in the CAPSS Soft Story project, Porter 2009). Both efforts were validated by hindcasting losses in past earthquakes. Kircher et al. (2006) hindcasted number of damaged buildings, casualties, and property repair costs within a factor of 3. In the case of CAPSS, the present author hindcasted tag colors in the Marina District in 1989 Loma Prieta earthquake within a factor of 1.6. But both required the exercise of judgment, and a reader could doubt their application to new buildings and could claim that the model parameters can be tweaked to achieve any desired results. As another option, one could assume that ratios of yellow tags to red and red tags to collapse that were observed in past earthquakes would also apply in a future one. Balanced against this shortcoming (the assumption just mentioned) is the advantage that this approach avoids recourse to models and offers simplicity and transparency. Let us use history to estimate red and yellow tags. Table 1 lists evidence of the ratio of red tags to collapses, where both are known (an admittedly limited dataset). It suggests approximately 13 red tags per collapse. Table 2 suggests 3.8 yellow tags per red. Let r denote the ratio of impaired buildings to collapsed buildings. With 13 red tags per collapse and 3.8 yellow tags per red, r = 63 impaired buildings for each collapsed building (1 + 13 + 13·3.8 = 63.4), which includes the collapsed building. The data in Table 1 and Table 2 do not reflect a code-compliant stock, and they do not account for the fact that the ratios might actually vary with shaking intensity. But using this empirical evidence seems preferable to relying entirely on HAZUS-MH or another model.

Table 1. Ratio of red tags to collapses

Earthquake	Red	Collapse	Reference
1989 Loma Prieta SF Marina Dist	110	7	NIST (1990), Harris et al. (1990)
1989 Loma Prieta Santa Cruz City[1]	100	40	SEAONC (1990), Fradkin (1999)
1994 Northridge[2]	2157	133	EQE and OES (1995)
Total	2367	180	Ratio = 13:1

[1] 100 is an estimate: 300 county wide, factored by number of structures in city vs county, and reduced by number of collapses to avoid double-counting

[2] 133 is taken from the ATC-20 form data in an unpublished database described by EQE and OES (1995); red tags reduced by number of collapses to avoid double-counting

Table 2. Ratio of yellow tags to red tags

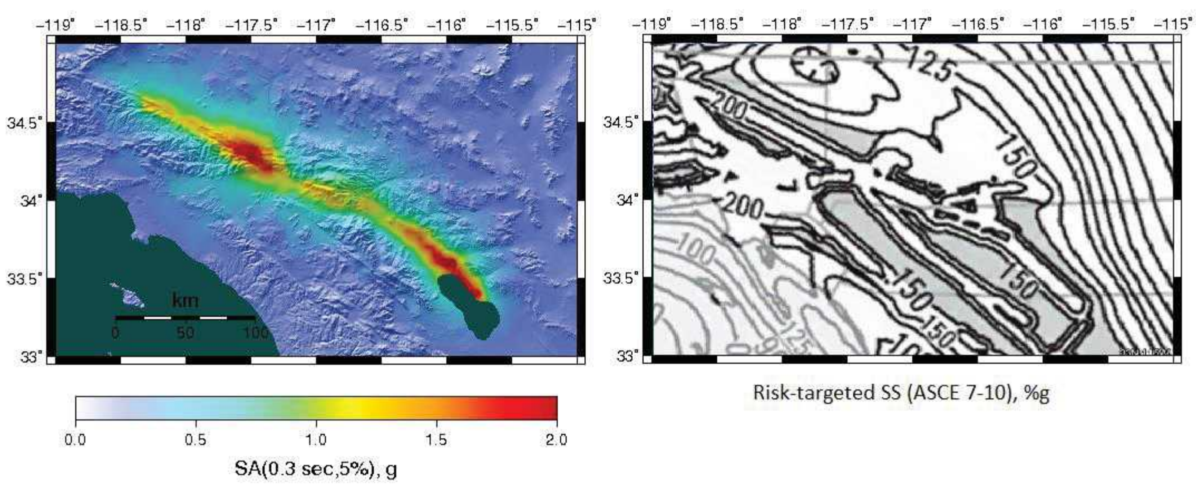
Earthquake	Yellow	Red	Reference
1989 Loma Prieta Bay Area	3330	1114	SEAONC (1990)
1994 Northridge	9445	2290	EQE and OES (1995)
Total	12775	3404	Ratio = 3.8:1

Table 3 summarizes implications for engineered buildings in MCE_R shaking. The table reflects the code's explicit objective, reduced to provide a best estimate rather than an upper limit, plus the assumption that ratios of red and yellow tags to collapses in new buildings would be the same as has been observed in existing buildings in two California earthquakes.

Table 3**.** Performance of new buildings in a small area with MCE_R shaking

Condition	Ratio	Fraction of stock
Collapse	6% of stock	6%
Red & not collapsed	13 red tags per collapse	78%
Yellow	3.8 yellow tags per red tag	Most of the rest
Total		Virtually all

The Big One produces MCE_R shaking over a small fraction of the strongly shaken area, so any given location experiences MCE_R shaking very rarely, on the order of once in 2500 years. Weaker shaking is more common and perhaps therefore of greater interest. What happens to buildings shaken at ½ MCE_R? Collapse capacity is commonly modeled as lognormally distributed in terms of spectral acceleration response. Let x denote shaking (e.g., in terms of 0.2-sec, 5% spectral acceleration response), let x_{MCE} denote MCE_R shaking in the same terms, and let DDR denote the demand-to-design ratio, x/x_{MCE}. Let β denote the logarithmic standard deviation of collapse capacity. Luco et al. (2007) considered a range of β values between 0.6 and 1.0 and settled on 0.8.



(a) (b)

Figure 2. (a) ShakeOut Sa(0.3 sec, 5%) compared with (b) S_S from ASCE 7-10. Shaking exceeds 0.5 · MCE_R shaking over roughly 10,000 km^2.

One can now express collapse probability P_c as a function of DDR, as in Equation (1). Equating MCE_R shaking (DDR = 1) with 6% collapse probability, we can evaluate the median collapse capacity as a multiple of x_{MCE} by rearranging Equation (1) as in Equation (2). One can use Equation (1) with θ = 3.47 and β = 0.8 to evaluate collapse probability at lower levels of *DDR* and Equation (3) to estimate impairment rate, denoted by P_i.

$$P_c\left(DDR\right) = \Phi\left(\frac{\ln\left(DDR/\theta\right)}{\beta}\right) \tag{1}$$

$$\begin{aligned} \theta &= \exp\left(-\Phi^{-1}\left(P_c\left(DDR=1\right)\right)\cdot\beta\right) \\ &= \exp\left(-\Phi^{-1}\left(0.06\right)\cdot 0.8\right) \\ &= 3.47 \end{aligned} \tag{2}$$

$$\begin{aligned} P_i\left(DDR\right) &= r\cdot P_c\left(DDR\right) \\ &\leq 1 \end{aligned} \tag{3}$$

With these parameter values, at *DDR* = 0.5 the collapse probability is approximately 0.8% and the impairment rate is approximately 49%, as shown in Figure 3b. One can map *DDR* and the impairment rate in an earthquake with known shaking. Figure 4a shows *DDR* for the ShakeOut scenario. For reference, in the mapped area, approximately 120 km^2 has *DDR* ≥ 1.0, 820 km^2 has *DDR* ≥ 0.75, 4,400 km^2 has *DDR* ≥ 0.5, and 8,000 km^2 has *DDR* ≥ 0.4. For reference, the City of Los Angeles covers 1,215 km^2, so an area roughly 4 times the area of the City of Los Angeles experiences at least half MCE_R shaking in this hypothetical earthquake. The foregoing analysis uses the Allen and Wald (2007) Vs30 model as reported by OpenSHA's Site Data Viewer/Plotter (http://opensha.org/apps-SiteData) to estimate NEHRP site class at 0.02-degree gridpoints across the map, and ASCE 7 (2010) Table 11.4-1 to estimate the site coefficient F_a and thus the MCE_R shaking S_{MS} at each gridpoint.

Applying the *DDR* values shown in Figure 4a to the collapse fragility function shown in Figure 3a produces the map of impairment rate shown in Figure 4b. In the 8,000 km^2 area of Figure 4b with *DDR* ≥ 0.4, an area 7 times the City of Los Angeles, has an average collapse probability of 1.3% and an average impairment rate of 60%. (The upper bound in Equation (3) forces the area-average ratio of impairment to collapse below *r*.) If we assume that buildings built to conventional design requirements (e.g., ICC 2012b) perform the same as engineered buildings, then a modern building stock in an area 7 times that of Los Angeles would have 60% of its buildings impaired in a ShakeOut earthquake, an event whose mean recurrence interval has been estimated to be 150 years. Much of this area is relatively lightly developed in 2014, but population growth may change that in the next several decades. The population density in the greater Los Angeles area was approximately 203 per km^2 in 2011, so 8,000 km^2 is home to approximately 1.6 million Californians (http://en.wikipedia.org/wiki/Greater_Los_Angeles_Area).

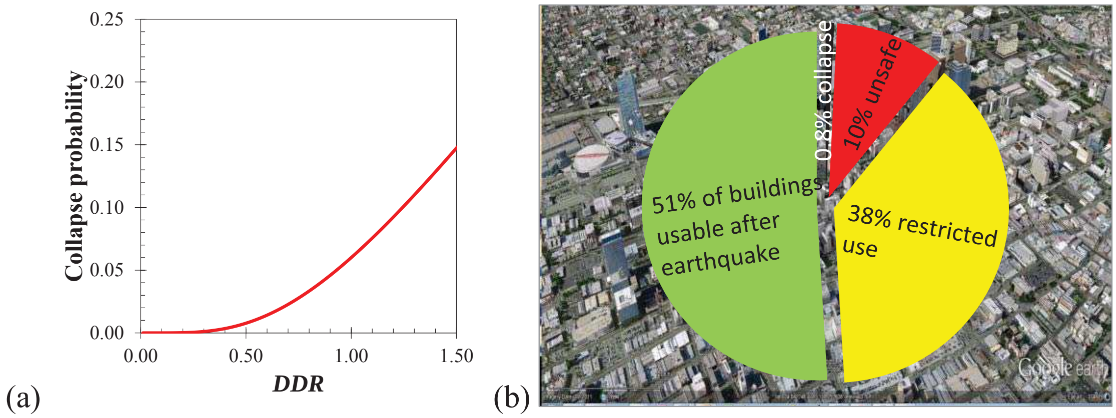


Figure 3. (a) Collapse probability as a function of demand-to-design ratio. (b) Approximately half of the building stock is impaired at shaking of *DDR* = 0.5, i.e., at ½ MCE_R.

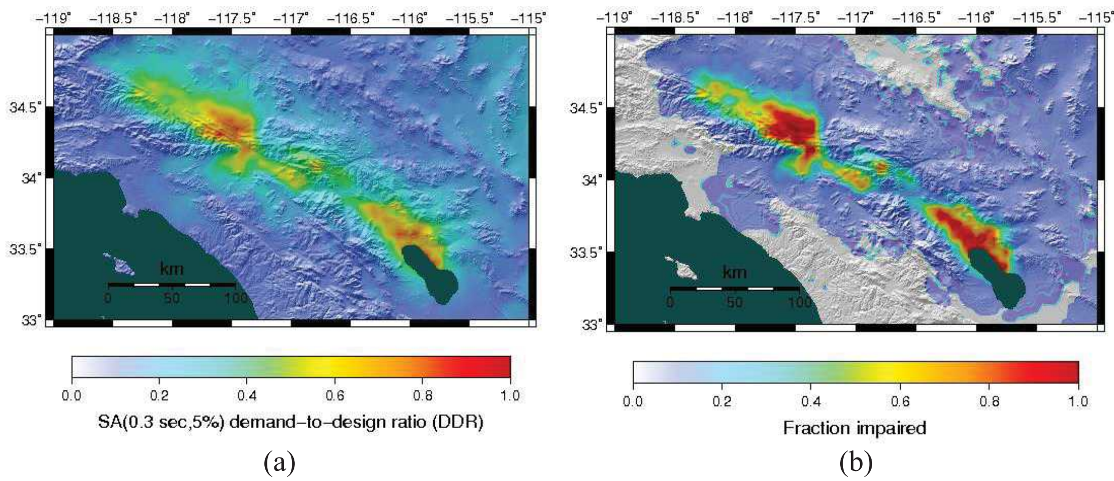
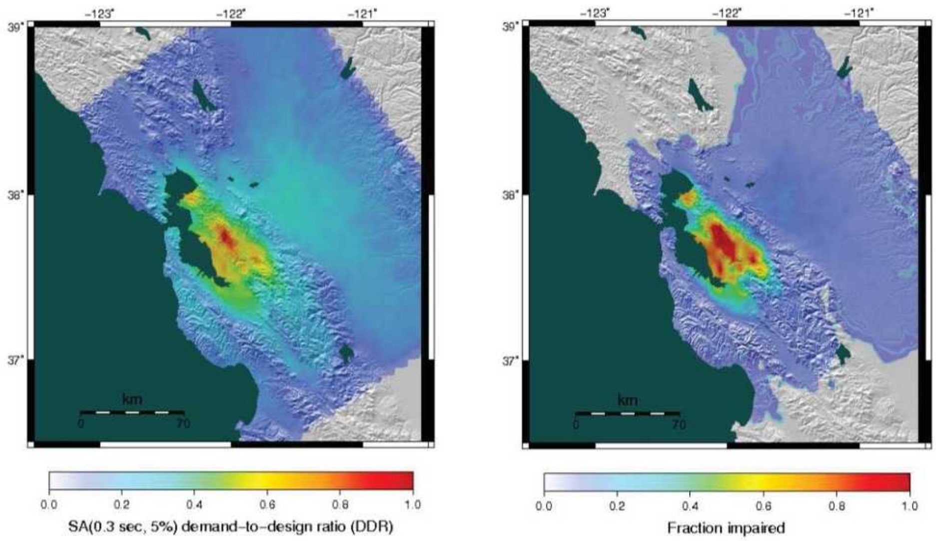


Figure 4. (a) Demand-to-design ratio *DDR* in the ShakeOut and (b) fraction impaired.

Nor is ShakeOut an outlier. Aagaard et al. (2010) estimated broadband shaking from 39 hypothetical earthquakes in the San Francisco Bay Area, including an Mw 7.05 earthquake on the Hayward Fault that ruptures the southern and northern segments and nucleates under Oakland. The mean recurrence interval for a Hayward Fault earthquake of this magnitude is approximately 200 years, according to Field et al. 2013. Figure 5 maps *DDR* and impairment for a modern building stock in this earthquake. It causes shaking at least 0.4 MCE_R across 3,300 km^2 of the San Francisco Bay Area, where approximately 1.4 million people live. (Population density 411 per km^2 according to http://en.wikipedia.org/wiki/San_Francisco_Bay_Area. *DDR* ≥ 0.75 in 260 km^2 and *DDR* ≥ 1.0 in 20 km^2.)



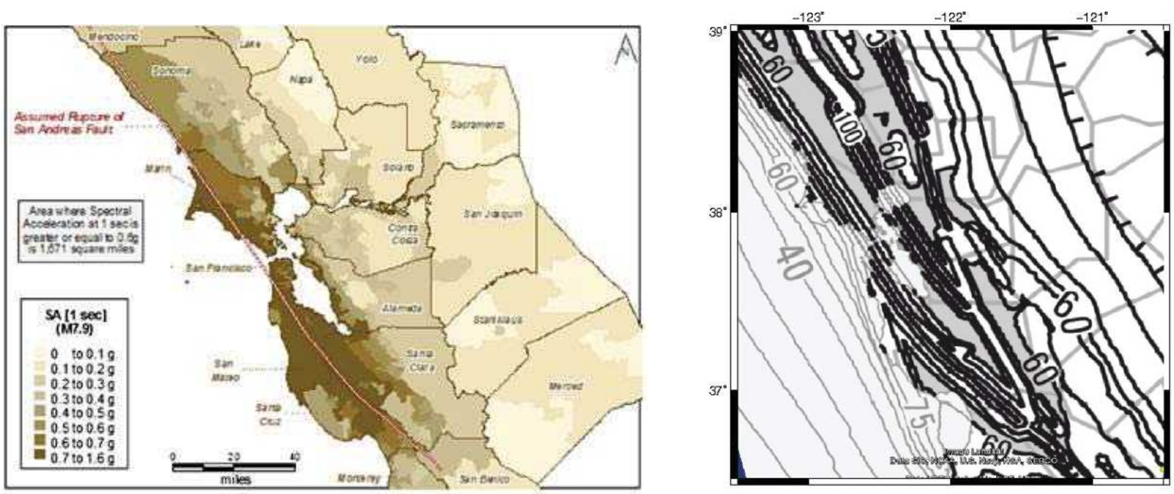
(a) (b)

Figure 5. (a) Demand-to-design ratio for M 7.0 Hayward Fault scenario and (b) fraction of lowrise buildings impaired (collapsed, red- or yellow-tagged) under this scenario.

These conclusions do not depend on the physics-based modeling of ShakeOut or Aagaard et al. (2010). Kircher et al. (2006) examined a repeat of the 1906 San Francisco earthquake using more-conventional modeling, and estimated shaking in the range of 0.5 to 1.0 times MCE over an area comparable to that of the ShakeOut (Figure 6). Under UCERF3, the mean recurrence interval for an earthquake of Mw ≥ 7.8 on the San Andreas Fault near San Francisco is on the order of 200 years. These Big Ones are *not* extremely rare events. One like them is more likely than not to occur by the time most of the building stock complies with current code objectives.

Where will people live and work after any of these events? Most buildings with red and yellow tags are eventually returned to functionality, but the process can take months or more. Comerio (2006) writes of experience after the 1994 Northridge earthquake that "Initial inspections ... listed 7,000 single-family homes, 2,000 mobile homes, and 49,000 multifamily units red- and yellow-tagged. Three years after the event, when insurance claims were tallied, it became clear that moderate damage to single-family homes was under-counted in the post-event inspections, as more than 195,000 homeowners made insurance claims, for an average of $30,000 to $40,000.... About 40 percent of homeowners began repairs within one year.... For the remainder, it took two to three years to resolve the insurance claim, and repairs were likely to be delayed until the insurance funding was available. The time needed for repairs of large apartment and condominium buildings was often longer." SEAONC (1990) provides some insight into how long yellow-tagged buildings remained unusable after Loma Prieta: “The majority of areas used yellow tags to qualitatively describe the amount of damage with the expectation that a report by a structural engineer, after a detailed analysis and/or some remedial repairs, would restore the structure to a green-tag status.” Consistent with Comerio’s (2006) observations from Northridge, in most cases either action to address a yellow tag would have taken weeks, months, or more.

In 2012, Los Angeles residential vacancy rates were 2-5%, 11% for commercial, and 5% for industrial. Vacant space will be impaired the same as the occupied buildings. There will be insufficient space to accommodate the displaced population. Even if some yellow-tagged space were usable and many of the temporarily displaced population were able to remain in the metropolitan area, perhaps in shelters or commuting from great distance, then something on the order of 25-50% of households and businesses in 8,000 km^2 area would have to move away, out of the metropolitan area. The SPUR Shelter-in-Place Task Force (2012) cites seven natural disasters since 1989 with significant outmigration (people moving away) that the authors link to disaster-induced loss of housing.



(a) (b)

Figure 6. Comparison of (a) Sa(1.0 sec, 5%) in a repeat of the 1906 San Francisco earthquake (Kircher et al. 2006), compared with (b) risk-targeted S_1 in %g.

The outmigration of 25% to 50% of the population represents a catastrophic change to a region’s economy and character and a profound shock to the populace. It will seriously affect the state and national economy as well. All of this follows solely from current code objectives, well vetted models of shaking and collapse fragility, and recent experience with the ratio of red tags to collapses and yellow tags to red tags among the general building stock. Such catastrophes are the logical consequences of the performance allowed in new buildings.

One could argue that some classes of existing older buildings are the real problem, if by "the real problem" we mean the near-term threat to life safety and the economy. But today's new buildings are tomorrow's existing buildings. As shown here, if the future building stock performs only as well as the code intends and no better, the code will produce catastrophes that society probably does not know it is getting. Perhaps the next Big One will occur before much of the building stock is replaced and older buildings will predominate in the damage. But the *next* Big One will not be the *last* Big One. Big Ones will occur after the building stock meets current requirements. The current code will drive the outcomes of the next-plus-one Big One, which should be important to code writers and communities that adopt the code. If the consequences estimated here are plausible and intolerable, then the current code is also the real problem. There can be more than one real problem.

Society can probably afford greater seismic resistance. The public is sometimes willing to pay the increased construction costs, even for seismic retrofit. Remember the examples showing that stronger design requirements can be practical. In light of the implications of our current design philosophy for our cities, perhaps it is time to review what we want from the seismic provisions of our building codes.

A SOCIETAL CONVERSATION

Code provisions for seismic safety have generally evolved by back-calibrating new requirements to match the safety provided by older ones. In drafting SP 577, Ellingwood et al. (1980) wrote that "The new probability-based load criterion should lead to designs which are essentially the same [level of safety]… as those obtained using current acceptable practice." The 2009 International Building Code (IBC) aims to be "consistent with the expected performance expressed in the Commentary of the 2003 NEHRP Provisions, namely that 'if a structure experiences a level of ground motion 1.5 times the design level [i.e., if it experiences the 2500-year ground motion level], the structure should have a likelihood of collapse… [of] 10%.'" The 2012 IBC employs new risk-targeted ground-motion maps that aim to ensure an upper limit of 1% collapse probability in 50 years, considering all levels of shaking that could happen and their various likelihoods. However, the adjustment factor (called the risk coefficient) relative to 2%/50-year shaking is on average 0.9 (for S_1) and has a standard deviation of 0.06. The new map is similar to the old one and slightly lower on an average geographic basis. The point is that each update involved calibration, not reconsideration.

Prior authors have questioned the adequacy of seismic design criteria. Ellingwood et al. (1980) were concerned that seismic and wind reliability in SP 577 was “relatively low when compared to that for gravity loads,” and called for “a profession-wide debate” over whether wind and seismic loads ought to have similar reliability as that inherent in gravity loads. Overload from gravity is different from earthquake in the way that automobile accidents are different from nuclear accidents: the former affect a few people at once; the latter, millions, so lower seismic reliability is even more of a problem when one considers societal impacts.

In discussions in 2008 over setting the goal for new design to be 10% collapse probability in 2500-year shaking, one discussant reported that “there was literally no debate” over whether the goal was reasonable or the right measure. In discussions in BSSC Project ‘07 (reassessment of seismic design procedures), there “may have been a little discussion” about measuring societal impacts, but no formal deliberation of the topic (Luco, pers. comm. 2012).

The SPUR Shelter in Place Task Force (2012) called for greater seismic resilience of the building stock, with a target that 95% of San Francisco’s housing units be in buildings that are strong enough for occupants to shelter in place after a M7.2 earthquake on the San Andreas Fault. Suppose conversations about seismic performance objectives took place in communities throughout the US, and some communities expressed a desire for a code that both protects life safety and prevents urban catastrophes. Such a code could uniformly increase per-building design requirements to provide post-earthquake operability for most buildings, which would have the indirect consequence of creating a catastrophe-resistant building stock for urban and rural communities. Recently, the City of Moore OK (2014) adopted code revisions to require above-code-minimum wind design, equivalent to a wind importance factor of 1.5, which demonstrates that some communities are willing to consider above-code-minimum design, at least when the modifications to the design requirements are simple and uniformly and fairly applied.

To determine what is equitable and what the public prefers will require a discussion beyond the engineering community, like the CAPSS Public Advisory Committee but on a larger scale and involving geographically diverse communities. How should the discussion be framed? Bonstrom et al. (2012) examined a variety of successful risk-mitigation efforts for how their leaders dealt with public risk perception (how the public thinks about risk), public values (what they care about), risk communication (how engineers talk with the public about risk), public involvement in risk-mitigation decisions, and policymaker's political constraints. They showed that successful efforts to bridge the gap between engineers and the public are commonly structured to express probabilities over a long time period, employ lessons from historical catastrophes, present risk in terms of particular scenario outcomes, educate the public on the specific issue at hand, incorporate public values into alternatives and solutions, and increase the importance and credibility of public influence in decision making. They warned that there is a conflict between long-term optimal policy and short-term political accountability, which can hamper policymaker support for hazard mitigation. They suggested that public education can counteract this effect, influencing political accountability for long-term planning and promoting action by elected officials. Recent news about Los Angeles' concrete buildings supports this argument (Lin et al. 2013 and Lin 2013). Policymakers and stakeholders widely accept that the public should be involved early and often in decisions involving environmental risks (National Research Council 1996).

Such a discussion would also require more exhaustive study of the costs and benefits of a resilient building stock, where benefits are measured in terms of public values. Such a study would require designing a variety of buildings for current code compliance and again for better performance. The difference in construction cost and the seismic fragility or vulnerability of each would be estimated and a hypothetical building stock created and analyzed for both futures: one with current code objectives and one assuming a catastrophe-resistant building stock. The consequences could be presented to the public, perhaps through larger or geographically diverse versions of the CAPSS Public Advisory Committee, which could then express its preferences and make recommendations to code-writing authorities and local jurisdictions that adopt or modify model building codes.

The public may express its preferences in fluid and imperfect ways. It may often express those preferences without fully grasping the issues. But engineers do not necessarily do a better job determining what is best for the public, nor do the imperfections in public decision-making justify the profession in declining to elicit those preferences. As the CAPSS Public Advisory Committee and the examples cited by Bonstrom et al. (2012) show, the public is capable of expressing its preferences sufficiently to direct policy about seismic safety.

CONCLUSIONS

US seismic design philosophy since 1980 reflects a life-safety performance objective with a lower reliability index for earthquakes than for gravity loads, despite that earthquakes cause large numbers of buildings to experience extreme loading simultaneously, unlike gravity loads. Furthermore, even though buildings are designed for very rare shaking, new buildings can collapse at lower levels of excitation, so if buildings just achieve the code's performance objective, a not-very-rare earthquake like the Big Ones discussed here could realistically impair half of a fully modern building stock in an area on the order of 10,000 km^2, occupied by more than a million people. Local vacancies will not accommodate the displaced population. People will move away, as much of New Orleans' population did after Hurricane Katrina in 2005. These figures follow from explicitly stated seismic performance objectives, ground-motion maps that were produced and vetted by dozens of leading seismologists, and historically observed ratios among collapses, red tags, and yellow tags. This is not a once-in-2,500-year outcome. These are Big Ones whose mean recurrence intervals are on the order of 200 years, and there are many possible Big Ones. The catastrophe discussed here could happen during the career of most readers of this paper.

These estimates might be overly pessimistic. Maybe engineered buildings will perform much better than the FEMA P-695 authors calculated. Maybe conventional construction will perform much better than engineered buildings. But at issue here are the societal implications of seismic code provisions that aim for life safety rather than operability, not how society might fortunately escape the catastrophe that seems baked into the code.

But the code and its objectives are not immutable. Civil engineers could revisit the seismic performance objectives they assume when developing design standards and set them deliberately, rather than back-calibrating to prior codes or expecting the ICC to undertake that policy discussion. With the advent of 2nd generation performance-based earthquake engineering as exemplified by FEMA P-58 (ATC 2012) and using modern earthquake scenarios like ShakeOut, we can estimate earthquake risk in terms of dollars, deaths, and downtime. We can evaluate the costs of producing a catastrophe-resistant building stock rather than assuming that it is uneconomical to do so. We can compare the cost of stronger buildings and the benefits in terms of reduced future losses. The author does not presume to know what such studies would eventually show, but the point is that they can be performed. As CAPSS showed, the public can express its preferences for balancing risk and cost. The engineering and building professions do not need to make those decisions in isolation.

Institutional constraints within ICC and ASCE may prevent adoption of a catastrophe-resistant building code unless an actual catastrophe occurs and public reaction compels a change. An alternative would be to create catastrophe-resistant design standards and a substantial educational program to inform city councils and the general public about an option to adopt stricter design requirements. Civil engineers could reinterpret their trusteeship of the public's safety, health, and welfare as requiring an effort to involve the public in deciding what its interests are, how to measure its risk, and what it is willing to pay for a seismically resilient society. That dialog can be part of a review of what we want our building codes to provide, how to achieve those ends, how cost-effectively to enhance society's safety, and how to avoid catastrophe.

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