Not Safe Enough: The Case for Resilient Seismic Design

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Abstract

When discussing future earthquakes, engineers often focus on existing buildings, not new ones. But today's new buildings become tomorrow's existing stock and are worth examining. The International Building Code aims for new buildings to be life safe, not earthquake-proof (resilient in the phrase de jour), with a maximum 1% collapse probability in 50 years and a maximum 10% collapse probability at shaking in the risk-targeted maximum considered earthquake (MCE_R). A large but not-exceedingly-rare earthquake (a Big One) can cause shaking to approach or exceed MCE_R across thousands of square kilometers. For every collapse, 60 buildings are red- or yellow-tagged. I illustrate using a hypothetical M 7.0 Hayward Fault earthquake, a reasonable sample of the Big One. With an entirely code-compliant building stock, the Big One could displace more people than vacancies can accommodate, producing outmigration like New Orleans after Hurricane Katrina. Making buildings 50% stronger can achieve a 95% shelter-in-place objective for about 1% additional cost. A survey finds that people in earthquake country expect resilient new buildings (habitable or functional after the Big One), and would willingly pay the extra cost. It can be shown that the First Fundamental Canon of the ASCE Code of Ethics requires civil engineers to elicit the public's preferences for the seismic performance of new buildings and to reflect them in design standards. The implications are that life-safety seismic design does not meet the public's expectations for a resilient building stock, that the public would be willing to pay for a resilient building stock, and that it is unethical for civil engineers to continue to provide only life-safety in minimum design standards. Exactly how civil engineers might best provide for resilient design is an open question, but cities need not wait for the civil engineering community to catch up to public expectations; they can adopt a simple modification to the International Building Code to produce a resilient building stock.

Introduction: U.S. Seismic Design Evolved by Back-calibration, Aims for Life-safety

Do seismic design guidelines in the United States encode the right performance objectives? Has anyone ever deliberately selected those objectives? Who should have a say in selecting them and what bases for selection should be considered valid?

The 1927 edition of the Uniform Building Code (UBC) [1] contains the earliest seismic design guidelines in the United States. It aimed to provide "adequate additional strength" for buildings or other structures to resist earthquake loads in the Western U.S., though its authors do not state what objectives they believed it adequately met. An appendix recommends a design base shear of 10% of building weight (the recommendation later became mandatory), but no explanation of how the authors selected that value. Perhaps it seemed to be an achievable, better-than-nothing value. Olson [2] suggests the 1925 Santa Barbara earthquake led to the inclusion of earthquake provisions in the UBC; perhaps 10% seemed reasonable to resist future earthquakes similar to the 1925 earthquake.

Seismic design provisions expanded in subsequent editions of the UBC and its successor the International Building Code (IBC) [3], which together predominate seismic design in the Western U.S. where most U.S. earthquake risk exists as measured by annualized economic loss. Sometimes changes from edition to edition react to damage, such as in the collapse of unreinforced masonry school buildings in the 1933 Long Beach earthquake (Olson [2] describes the process) or the failure of nonductile reinforced concrete moment frames in the 1971 San Fernando earthquake. Other changes followed research such as the incorporation of strength design or load and resistance factor design (LRFD) into concrete and steel design manuals ([4] and [5]). Rarely however have authors of new U.S. design guidelines assessed overall performance targets, and apparently never have they deliberately chosen a level of acceptable risk other than by back-calibrating to risk implicit in prior codes.

A few authors between 1927 and 1980 address the question of appropriate seismic performance, often in the form of a dichotomy between elastic design for earthquake loads and a fairly status-quo approach that accepts damage. For example, concerning whether it was practical to design water tanks and other structures to remain elastic under earthquake loading, Housner [6] wrote, “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 [7] wrote, “It is not economical to design every structure to resist the strongest possible earthquake without damage,” and therefore codes “permit yielding and structural damage in the event of very strong shaking.” The authors of ATC-3-06 [8] unsuccessfully sought figures on the probable costs to keep buildings 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. These works implicitly assume that engineers are the proper judges of what is economical, most desirable, and best for the public. Many authors implicitly or explicitly express a false dichotomy: either design for zero earthquake risk, which is uneconomical, or accept whatever risk was currently implicit in contemporary seismic design.

Ellingwood and his coauthors of NBS 577 [9] may be the first to quantify seismic risk in new engineered buildings in general. In establishing the load and resistance factors for ANSI A-58, the precursor to ASCE 7, they calculated that previous allowable-stress-design (ASD) guidelines impose about 4% probability of life-threatening damage given design-level shaking. They then set the load and resistance factors to ensure that future design was consistent with the level of risk prior implicit in ASD. But they expressed reservations, stating that “[R]eliability with respect to wind or earthquake loads appears to be relatively low when compared to that for gravity loads.... [T]he profession may well feel challenged ... to explain why lower safety levels are appropriate for wind and earthquake vis-a-vis gravity loads... [but] this report was not the appropriate forum for what should be a profession-wide debate.” They called for a profession-wide debate on the subject, a debate that never took place.

Almost 30 years later, as the emergence of new structural systems demanded design parameters to ensure consistent risk, the authors of FEMA P-695 (the so-called R-factor project initially named ATC-63 [10]) recommended design to control collapse probability at maximum-considered-earthquake (MCE) shaking, as opposed to the probability of life-threatening damage to individual beams, columns, braces, walls, and connections. The collapse probability would be consistent with that of recent design, even though recent design using LRFD controlled the probability of collapse of individual members and connections. The FEMA P-695 authors addressed appropriate safety in a section entitled Acceptable Probability of Collapse. In that section, they suggest that “the probability of collapse due to MCE ground motions … be limited to 10%…. A limit of twice that value, or 20%, is suggested … for evaluating the acceptability of potential ‘outliers’….” The 10% figure was not deliberately chosen, but back-calibrated to the collapse risk implicit in a number of code-compliant modern designs.

Perhaps FEMA P-695 [10] merely describes how code-compliant buildings perform rather than expressing of its authors’ belief that a 10% collapse probability is acceptable. But the section has the word “Acceptable” in the title and “suggested” in the text. The text states 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.” The use of the words acceptable, reasonable, and suggested clearly show that the authors recommend 10% as an acceptable value, based solely on the fact that it had been acceptable in prior LRFD codes, which themselves had been back-calibrated to ASD, in which nobody had ever calculated or expressed the quantitative objectives that the code adequately met. A collapse probability of 10% was safe enough, but safe enough according to whom? The FEMA P-695 authors seemed to say that 10% was safe enough according to prior writers of design guidelines and building codes, presumably including Ellingwood et al., who themselves back-calibrated to authors of ASD-based guidelines and codes, who never calculated risk at all.

Contemporaneous with FEMA P-695, Luco et al. [11] offer risk-targeted design procedures that were immediately taken up by ASCE 7-10 [12] and adopted by reference in the 2012 edition of the International Building Code. Risk-targeted design here means to provide for a uniform upper bound collapse probability during the building’s design life. Luco et al. found that previous design achieved approximately 1% collapse probability in 50 years and incorporated that figure into the calculation of risk-targeted maximum-considered earthquake shaking, MCE_R. Again, risk for new buildings was back-calibrated to match risk implicit in previous codes, but using a new performance metric. Luco in personal communication relates that no debate took place over whether 1% per 50 years was the proper design goal.

The most recent edition of the NEHRP Seismic Provisions [13] describes the present performance goal qualitatively, saying that the Provisions aim to “provide reasonable assurance of seismic performance that will avoid serious injury and life loss due to structure collapse, failure of nonstructural components or systems, and release of hazardous materials; preserve means of egress; avoid loss of function in critical facilities; and reduce structural and nonstructural repair costs where practicable.” And indeed modern U.S. codes achieve a high degree of life safety compared with other threats to human life as shown in Table 1. Statistics in the table are mostly drawn from the U.S. Centers for Disease Control [14], with the exception of earthquake risk. The figure for new buildings in earthquakes assumes:

- An average 0.6% collapse probability in 50 years, as opposed to Luco's 1% upper bound. See [15].
- An average of 25% of building area collapses when a building experiences collapse, derived from a survey of photographs of 73 collapsed California buildings in earthquakes of the last 50 years. See [16].
- That 10% of occupants in the collapsed area are killed, a typical value in Hazus-MH [17]. And
- That the typical engineered building is fully occupied about 25% of the time (40 of 168 hours per week).

The last row, California earthquake fatalities in the last 50 years, draws on USGS [18], which shows 206 deaths in California earthquakes during a 50-year period when the population rose from about 11 million to about 38 million.

Table 1 – Leading threats to life safety in the U.S.

Peril	Deaths per 100,000 pop/yr	Where, when
Heart disease	194	US, 2010
All accidents	39	US, 2010
Occupational fatality, roofers	32	US, 2011
Auto accidents	11	US, 2009
Firearms	10	US, 2010
New building (earthquake)	0.1	40 hr/week occupancy
CA earthquakes last 50 yr	0.02	California, 1965-2014

The Big One in a U.S. Metropolis could Impair 1 in 4 Engineered Buildings

Examining the consequences of the life-safety seismic performance objective for new engineered buildings

Despite 90 years of code development, including at least 35 years during which engineers have been capable of estimating the risk posed by earthquakes to engineered buildings, U.S. engineers have never deliberately set seismic design objectives, preferring or being compelled when opportunity arose to back-calibrate to performance that was implicit in prior codes. Let us examine the consequences of current seismic design objectives through the lens of the number of impaired buildings in a large but not exceedingly rare metropolitan earthquake, the Big One of popular conception.

To focus entirely on the outcomes of code objectives, let us imagine a building stock that is entirely transformed into new, code-compliant engineered buildings that meet current objectives, behaving exactly how the authors of FEMA P-695 expect the average engineered building to perform, i.e., with an average of 6% collapse probability given MCE_R shaking (again, a 6% expected value as opposed to a 10% upper limit; [15]). As an additional experiment, let us examine a hypothetical resilient building stock with a simple enhancement: all new buildings are designed with an ASCE 7-10 earthquake importance factor of 1.5, i.e., 50% stronger than life-safety minimum. One can imagine alternatives, such as limiting drift, but I_e = 1.5 is a simple option, easily encoded in a local code-adoption ordinance and easily treated here, so let us examine it.

Code assumption of the collapse fragility of new buildings

Let us model collapse probability exactly as did Luco et al. [11], who like many researchers before them, assume collapse probability of new buildings is reasonably approximated by a lognormal cumulative distribution function (CDF). The lognormal CDF is a two-parameter function, with the parameters sometimes expressed as the median of the uncertain value (here, the uncertain value is the shaking that causes collapse, which one can call the collapse capacity) and the standard deviation of the natural logarithm of the uncertain value, denoted here by β. Luco et al. take β = 0.8. Let us measure the collapse capacity in terms of 5% damped elastic spectral acceleration response at some index period of vibration such as 0.2 sec, normalized by ASCE 7-10's S_{MS}, the soil-adjusted MCE_R 0.2-sec spectral acceleration response. Let us refer to the normalized shaking measure as *DDR*, the demand-to-design ratio. One can establish the median collapse capacity in terms of *DDR* with Luco et al.'s value of β and the fact that the CDF must pass through (1.0, 0.06). With these constraints, one can show that the median collapse capacity of a code-compliant building is 3.47. Thus, collapse probability for a new building designed to code minimum as a function of *DDR* is given by Eq. (1). For a building that is designed with an ASCE 7-10 earthquake importance factor I_e = 1.5, the median collapse capacity would be 1.5 time greater, as in Eq. (2).

$$P_c^{(1.0)} = \Phi\left(\frac{\ln\left(DDR/3.47\right)}{0.8}\right) \tag{1}$$

$$P_c^{(1.5)} = \Phi\left(\frac{\ln\left(DDR/5.20\right)}{0.8}\right) \tag{2}$$

where Φ denotes the standard normal cumulative distribution function evaluated at the term in parentheses. ASCE 7-10 in essence uses this equation along with site-specific seismic hazard to establish the maps of risk-targeted maximum considered earthquake shaking, MCE_R. With some adjustments near large faults, the mapped values are established to ensure that the integral of the product of P_c and annual exceedance frequency, converted from an annual rate of Poisson arrivals to 50-year occurrence probability, equals 1%. The adjustments generally raise risk above the target 1%/50-yr value near large faults. Here as in FEMA P-695, "collapse includes both partial and global instability of the seismic-force-resisting system, but does not include local failure of components not governed by global seismic performance factors, such as localized out-of-plane failure of wall anchorage and potential life-threatening failure of nonstructural systems."

Red- and yellow tagging of buildings as a multiple of collapsed buildings

Although ASCE 7-10 cares about and controls collapse probability, let us assume that the public also cares about whether their homes or businesses will be red-tagged (rendered unsafe to enter or occupy according to ATC-20 [19]) or yellow-tagged (restricted use, generally either restricted to use for a limited period of time to remove belongings, or limited to use of only a portion of the building, again according to ATC-20). FEMA P-58 [20] offers an approximate methodology to estimate red-tag probability but not yellow-tagging, and as far as I know no study comparable to FEMA P-695 or NIST GCR 12-917-20 [21] has been undertaken to characterizes the probability of red- or yellow-tagging for new buildings. Absent a theoretical model of red- and yellow-tagging, let us rely on empirical evidence from California earthquakes (Table 2, Table 3), and estimate red- and yellow tagging as a multiple of collapses: 13 red tags per collapse and 3.8 yellow per red, or 63 impaired buildings per collapse. (The ratio, incidentally, holds up for the 2014 South Napa earthquake, which produced 57 impaired buildings per collapse.)

Obviously the ratio of 63:1 applies better to existing California buildings of all kinds (prescriptive design as well as engineered) rather than to new buildings, but let us assume that the lesser degrees of damage in existing buildings are in the same proportion to collapse as in new buildings, and that the supposedly greater seismic resistance of new buildings is adequately accounted for by the lower collapse fragility of Eq. (1) or (2).

Table 2 – Red tagging as a multiple of collapses

Earthquake	Red	Collapse	Ref
1989, SF Marina District	110	7	NIST [22], Harris et al. [23]
1989, Santa Cruz City	100	40	SEAONC [24], Fradkin [25]
1994	2,157	133	EQE & OES [26]
Total	2,367	180	

Table 3 – Yellow tagging as a multiple of red tags

Earthquake	Yellow	Red	Ref
1989 Loma Prieta Bay Area	3,330	1,114	SEAONC [24]
1994 Northridge	9,445	2,290	EQE and OES [26]
Total	12,775	3,404	

Impairment rate would be estimated by Eq. (3), where C is the ratio of impaired to collapsed buildings (here, 63) and P_c is taken from Eq. (1) or (2), depending on whether one wishes to examine a code-minimum building stock or our hypothetical resilient building stock.

$$\begin{aligned} P_i &= C \cdot P_c \\ &\leq 1.0 \end{aligned} \quad (3)$$

Tags undercount damage

Either scenario—code-minimum or resilient buildings—probably significantly undercounts the number of buildings with costly damage. Comerio [27] observed that in 1994 Northridge earthquake, moderate damage to single-family homes was under-counted. Compared with 58,000 housing units that were yellow or red-tagged (housing units, not buildings, the former generally being more numerous because of multi-unit buildings), 195,000 homeowners made insurance claims averaging $30,000 to $40,000 in 1994 USD, ($45,000 to $60,000 in 2015 USD), which in a present-day environment of 10% insurance penetration would pose a substantial, perhaps insurmountable, challenge for most US homeowners to pay. At the time, Comerio relates, "About 40 percent of homeowners began repairs within one year.... For the remainder, it took two to three years to resolve the insurance claim.... [R]epairs were likely to be delayed until the insurance funding was available." But let us set aside the costly damage and only consider impairment as collapsed, red-, or yellow-tagged buildings in a hypothetical large urban earthquake: a M_w 7.0 Hayward fault rupture in the San Francisco Bay area.

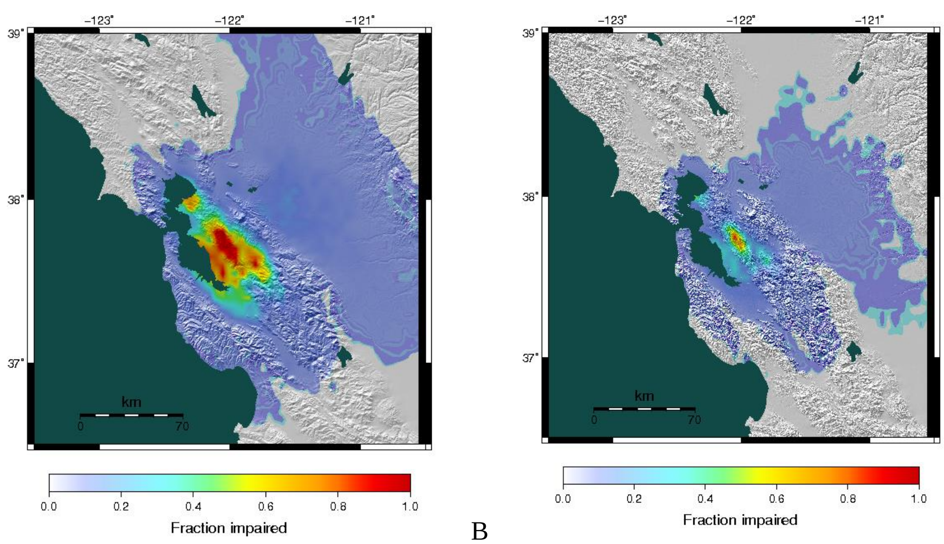
Outcomes of a M_w 7.0 earthquake on the Hayward fault in the San Francisco Bay area

The Hayward Fault in the San Francisco Bay area is one of the most urbanized large active faults in the U.S., so let us examine an earthquake there as a sample urban Big One. Aagaard et al. [28,29] used physics-based modeling to estimate shaking in each of a suite of 39 hypothetical earthquakes involving the Hayward Fault. Of the 39, only six scenarios include broadband (short-period) motions at frequencies of 0.1 sec to 1.0 sec. Since most buildings are sensitive to spectral acceleration in this period range, it seems useful to select from among these six. Of them, only three rupture both the Hayward South and Hayward North segments, which seem more worth planning for than the three Hayward-South-only, M_w 6.8 scenarios. The three remaining M_w 7.0 simulations differ by hypocenter: north (beneath San Pablo Bay), central (beneath Oakland), and south (beneath Fremont). The north-to-south rupture (San Pablo Bay hypocenter) produces the most adverse motion for the heavily developed and economically important Silicon Valley. The south-to-north rupture (Fremont hypocenter) would not strongly test Silicon Valley. Bilateral rupture initiating beneath Oakland represents a reasonable compromise. The M_w 7.0 scenario has a mean recurrence interval of approximately 200 years under the latest California earthquake rupture forecast (Field et al. [30]). There are many possible large Bay Area earthquakes, but this one seems to be a reasonable example of an urban Big One.

The interested reader is referred to Aagaard et al. [28, 29] for the relevant maps of shaking. Fig. 1 shows Eq. (3) evaluated for an entirely modern code-compliant building stock (A) or a resilient building stock (B). The code-compliant stock suffers an average 60% impairment over an area of 3,300 km^2, in an urban area with a population density of 411 people per square km. Impairment to a resilient building stock is much lower. More to the point, one can overlay the impairment map on Bay Area building stock as estimated by Hazus-MH. (Hazus-MH's estimated inventory uses the population census and business data, among other quantities, as its basis.) Doing so produces the estimates of impairment shown in Table 4. Undamaged vacancies in the San Francisco Bay area could not accommodate the 24% of the population displaced by building damage to the code-compliant stock, but could, perhaps with difficulty, largely accommodate the 6% displaced from the hypothetical resilient stock. To emphasize: life-safety seismic design, when it completely replaces older buildings, would protect lives but lead to a substantial outmigration in this particular urban earthquake.

Table 4 – Estimated impairment of code-compliant or resilient buildings in M 7.0 Hayward Fault earthquake

Condition	Buildings affected	
	I_e = 1.0	I_e = 1.5
Collapsed	8,000	2,000
Red tagged	102,000	27,000
Yellow tags	390,000	100,000
Total impaired buildings	500,000	130,000
Displaced people	1,500,000	390,000
Displaced businesses	150,000	39,000
% of 2,050,000 buildings in 9 San Francisco Bay area counties	**24%**	**6%**



A B

Fig. 1 – Building impairment in M 7.0 Hayward Fault earthquake: (A) life safe (I_e = 1.0) and (B) resilient (I_e = 1.5) buildings

Resilient Design Costs about 1% More

There are several reasons to believe resilient design, as imagined here, would be affordable. Informal discussion between the author and four California engineers suggests that designing to I_e = 1.5 would increase construction costs on the order of 1–3 percent (D Bonneville, oral commun., Jan 2015; E Reis, oral commun., Apr 2014; J Harris, oral commun., Aug 2015; R Mayes, oral commun., Jan 2015). A fifth source is given by NIST GCR 14-917-26 [31], whose authors found that to redesign six particular buildings in Memphis, TN to comply with the 2012 International Building Code rather than the 1999 Southern Building Code, their strength would increase on average by 60%, and their construction cost would increase between 0.0 and 1.0%.

A sixth source of support can be found in Olshansky and others [32], who estimated a similar marginal cost to increase from no seismic design to code minimum. It is further supported by the estimated cost to achieve an immediate occupancy performance level rather than life safety for one of the index buildings of the CUREE-Caltech Woodframe Project (Porter and others [33]). In California, the marginal construction cost increase of 1–3% would translate to a much smaller marginal development cost increase, since land can constitute more than half the value of a building, and land value is unaffected by I_e.

An eighth argument can be seen in the fact that we build stronger buildings all the time and never notice: build five architecturally identical buildings in (A) Sacramento California, (B) San Diego California, (C) eastern San Francisco, and (D) western San Francisco, and you will find that they have S_{MS} motions of 0.8g, 1.2g, 1.5g, and 2.3g, respectively. Pluck the life-safe building at (D) out of the ground and place it 10 km east at (C) and it will satisfy design for I_e = 1.5, our hypothetical resilient-design paradigm. Place it 800 km south at (B) and it would nearly satisfy I_e = 2.0, or a mere 140 km northeast at (A) to satisfy I_e = 3.0. If it were unaffordable to build buildings 50% stronger than life-safety, there would be no new construction in San Francisco, and all new development would take place 140 km away in Sacramento.

The reader still might not believe such low marginal costs are realistic. How can such a strength increase not produce a similar cost increase? Consult a square-foot cost manual such as RSMeans [34] and you will find that approximately 67% of construction cost of a new office building is spent on the architectural, mechanical, electrical, and plumbing elements (Fig. 2) approximately 17% on overhead and profit, and of the remaining 16% structural cost, approximately half is spent on labor. Most of the final 8% (mostly structural material) is spent on the gravity-resisting system: the foundation, floor slabs, and gravity-resisting columns and beams. Of the very small remaining portion that is spent on materials for the earthquake load resisting system (perhaps as much as 2%), consider that strength does not increase linearly with quantity of material, but can increase with the square or a higher power of material. For example, a W44x230 wide-flange steel shape is about 63% stronger than a W30x191 shape but weighs (and therefore costs) only about 20% more. In that particular case, strength increases with cost to the power of 2.6 (i.e., $1.20^{2.6} = 1.63$). More-extreme cases can be cited.

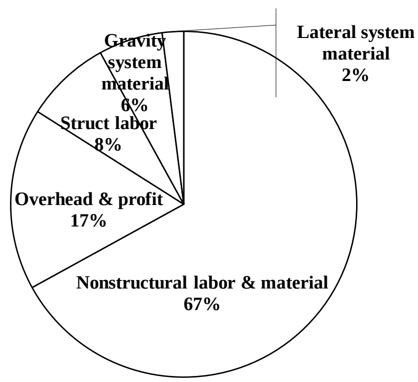


Fig. 2 – Why 50% stronger buildings cost ~1% more

The Public Prefers and Would Pay for Resilience, Deserves a Say in Code Objectives

Would the public care about such a hypothetical resilient stock, and would they be willing to pay for it? The first-ever rigorous public-opinion survey of 804 adults in California and the Central US (the Memphis and St Louis metropolitan statistical areas) found that most prefer that new buildings be habitable or functional after a Big One, not merely life safe (Fig. 3A). More than half expressed a willingness to pay the additional $3 per square foot (also expressed in terms of increased mortgage payments) required to achieve their preferred performance (Fig. 3B). Asked how strongly they cared about the issue, 82% responded that it was either important or very important (Fig. 3C). Responses were similar regardless of income, education, or geographic location. See [38] for details.

The survey is supported by other evidence. The City of Moore Oklahoma adopted mandatory requirements that make buildings 125% stronger than its previous code required to better resist tornadoes [35]. The City of San Francisco, encouraged by a committee of owners and tenants who participated in the Community Action Plan for Seismic Safety (CAPSS), adopted mandatory retrofit of older woodframe apartment buildings with costs shared by owners and tenants [36]. This example deals with retrofit rather than new design, but it supports the notion that people will pay for better seismic performance than code minimum.

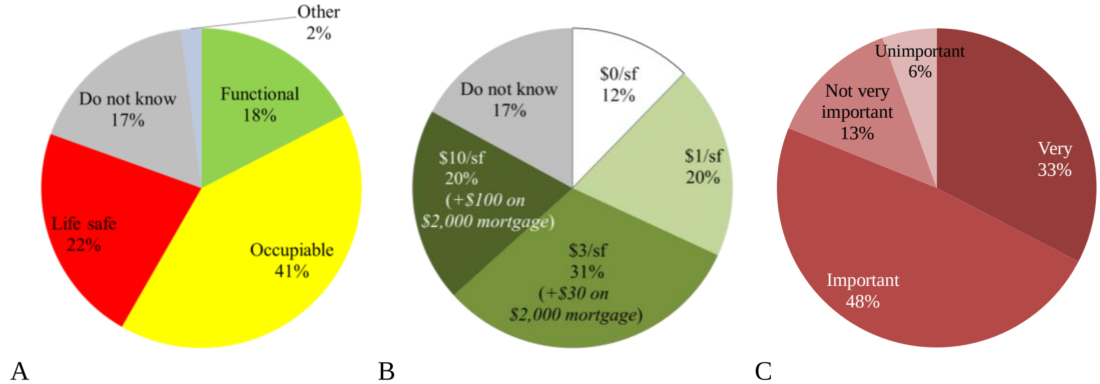


Fig. 3 – A large survey shows (A) the public prefers a resilient building stock, (B) is willing to pay for it, and (C) finds the issue important or very important

Another example: the board of directors of the Building Owners and Managers Association of Greater Los Angeles (BOMAGLA) expressed support of strict mandatory seismic design requirements in the form of across-the-board increases that would affect all equally. It is noteworthy that BOMAGLA objected to voluntary ordinances because they place the volunteer at a competitive disadvantage, which is part of the reason why offering developers the option to build above code does not absolve civil engineers of the duty to reflect the public's preferences in seismic design guidelines.

Some engineers may dismiss the survey results on the basis that civil engineers and building professionals are best qualified to judge the proper balance between the health, safety, and welfare of the public. That is a difficult case to make since civil engineers have never actually done so, despite very public urging by Ellingwood et al. [9] when they developed LRFD. As pointed out earlier, we have only ever back-calibrated tolerable risk to previous codes in which risk was not quantified. Arguments about who is best qualified to judge are moot when the supposedly best qualified group declines to do so.

There are stronger reasons to take the survey seriously. In a scholarly examination of the American Society of Civil Engineers' Code of Ethics [37], Davis, a philosophy professor and a leading thinker on engineering ethics, found [38] that the ASCE Code of Ethics "requires civil engineers to make a reasonable effort to elicit and reflect the preferences of the public, whose lives and livelihoods are at stake, when setting seismic performance objectives." (I was a co-author of that work.) Davis and I sent the work (that is, [38]) to several leading ethicists for their impressions: R. Hollander of the National Academy of Engineering, J. Heckert of Arizona State University, M. Loui of Purdue University, and M. Martin of Chapman University. They all agreed that such a requirement is implicit in the code of ethics, one saying "Emphatically yes."

So engineers must make a reasonable effort to elicit the public's preferences and then reflect those preferences when setting design guidelines. By our own code of ethics, civil engineers are obliged to consider and reflect this survey and other valid inquiries into public preferences when setting seismic performance objectives.

Some might argue that engineers are members of the public and therefore *do* represent the public. Is that true? Who is "the public?" The ASCE Code of Ethics distinguishes among five groups: (1) the public, (2) civil engineers' clients, (3) civil engineers' employers, (4) the civil engineering profession, and (5) the individual civil engineer. Is the public anyone except someone in groups 2 through 5? The answer matters because the interests of the five groups diverge in important ways. (If they did not diverge, we would not need or have a code of ethics and we would not be instructed to hold the interests of the public paramount, meaning above the interests of the other groups.) Davis [39] considers four reasonable alternatives for the definition of the public, and concludes that "The public comprises those people who are relatively innocent, helpless, or passive in the face of decisions that we make as engineers." Davis says, "On this interpretation, 'public' would refer to those persons whose lack of information, technical knowledge, or time for deliberation renders them more or less vulnerable to the powers an engineer wields on behalf of his client or employer." Thus, the engineer members of ASCE 7 (who *do* have the information, technical knowledge, and time for deliberation) do not represent the public. Their opinions do not satisfy the requirement to elicit and reflect the preferences of the public when setting seismic performance objectives.

Some might say that the public already has a say in the development of seismic design guidelines, since membership in ASCE 7 "is completely open to members and non-members of ASCE. To ensure balanced representation, the committees must be comprised of between 20 and 40 percent of three primary interest groups: producers, consumers, and general interest." [40] But "complete openness" and representation by the public are not the same: the current committee roster for ASCE 7-16 (http://goo.gl/XSYH46) shows 118 members, of whom 106 (90%) are licensed professional engineers or structural engineers, and most of the rest are engineering professors or representatives of building trades. The committee has essentially no public representation. The vast discrepancy between ASCE 7's earthquake life-safety objective and the public's preferences for resilience as expressed in the survey reinforce the notion that ASCE 7 does not reflect the public's preferences.

I have offered a new survey showing that the public seems to prefer a resilient building stock and argued that civil engineers have an ethical obligation to reflect these preferences in seismic design guidelines. I supported the argument several ways, with reference to: (1) City of Moore; (2) CAPSS; (3) BOMAGLA; (4) Ellingwood et al.; (5) Luco et al., (6 and 7) two works on engineering ethics by Davis; and (8) ASCE 7's domination by P.E.s and S.E.s. Some readers may still doubt the value of eliciting and reflecting public preferences. To those readers, I quote an extensive literature review on the value of public participation in costly risk-management decisions. Citing [41-45], Bonstrom et al. [46] argue:

> **Experts and the general public bring different and unique perspectives to the risk decision-making process. Given the uncertainty and variability of risk-reduction decisions, even the most fundamental analytical methods include a high degree of subjectivity…. Participation is essential in public issues, particularly when there are conflicting objectives and a significant degree of uncertainty. Direct representation of public preference in risk reduction decision-making can complement views of experts, and develop support for a decision maker's final choices…. Furthermore, if public opinion is omitted from the decision-making process, it is likely that environmental decisions will be postponed…. [T]he quality of a project design and stakeholder support for the project will be reduced if effective participation has not occurred…. [A]ctive public involvement may be one of the few ways to start resolving issues of mistrust. For these and many other reasons, … it is imperative to incorporate the perspectives and knowledge of the spectrum of interested and affected parties from the earliest phases of the effort to understand the risks. As a result, public participation in the development of local plans is increasingly a requirement by federal, state, and local laws.**

Conclusions

Life-safety seismic design can lead to unacceptably widespread building impairment in a large but not-exceedingly-rare earthquake, a Big One. This conclusion requires only the same collapse fragility model underpinning the risk-targeted seismic design maps in the current International Building Code, evidence of 15,000 collapsed, red-tagged, and yellow-tagged buildings in two California earthquakes, and a state-of-the-art physics-based ground-motion model of a large urban earthquake. I have shown at least five different ways that it is practical to build a more resilient building stock, one that avoids massive displacement and allows most people to shelter in place after a Big One.

I have shown through a rigorous public survey that the public expects and is willing to pay for resilient building stock, and supported the survey nine different ways, including an examination of the American Society of Civil Engineers' Code of Ethics that shows the public is entitled to have a say in setting seismic design requirements. I also showed that offering developers the option to build above code does not satisfy civil engineers' ethical obligations to provide the resilient building stock the public expects.

Even if the civil engineering profession and the ASCE 7 committee as the profession's representatives choose not to enact code changes to produce a resilient building stock, cities need not wait to address the gap between the code and the public's preferences. They can do so by requiring new ordinary buildings to be designed 50% stronger than life-safety minimum. I do not assert that adopting $I_e = 1.5$ is the only way or the best way to improve the resilience of future U.S. buildings, but it is simple, easily understood, and easily encoded in a local ordinance to adopt the current edition of the International Building Code, along the following lines:

> **In recognition that a more resilient city can be built at a small marginal cost (on the order of 1%), and that the public expects and is willing to pay for resilient buildings, the [most recent] edition of the International Building Code is adopted with the exception that, where it refers to ASCE 7-10, all values of I_e in ASCE 7-10 Table 1.5-2 shall be taken as 1.5.**

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