Implications of Seismic Design Values for Economic Losses

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ABSTRACT: In the U.S., seismic design values are determined mostly through a risk-targeting process, which combines information about the expected collapse fragility of code-designed structures with seismic hazard at a site. However, this target only applies where the risk-targeted ground motions govern the design. In other areas, primarily close to active faults, seismic design values are reduced to values calculated from deterministic seismic hazard analysis, increasing seismic risk for near-fault sites by an unknown quantity. This study investigates the implications of designing buildings using deterministic and probabilistic design values in terms of earthquake-induced economic consequences. This investigation is carried out using a performance-based seismic risk assessment of modern code-designed buildings with various structural systems, following the FEMA P-58 framework. Specifically, structural responses and losses associated with code-designed systems (i.e., reinforced concrete, steel, wood light frame, and precast tilt-up buildings) considering different design values (i.e., risk-targeted, deterministic, and uniform-hazard) are assessed. This study finds that, while risk-targeted design maps specify a uniform collapse risk, they do not provide uniform risk of economic losses to modern buildings across the U.S. and are instead dependent on building type and site properties. Also, for the sites in this study governed by deterministic capping, design values in the current code may be up to 30% lower than design values derived from risk-targeted design maps, resulting in up to 40% higher expected seismic losses.

1. BACKGROUND

In the U.S., buildings are designed for two-thirds of the forces from a maximum considered earthquake (MCE), which may be based on probabilistically or deterministically derived ground motions, depending on the site. Seismic design values governed by a MCE first appeared in the U.S. as part of the 1997 National Earthquake Hazards Reduction Program (NEHRP) provisions (BSSC, 1997), and were adopted as part of the 2000 International Building Code (IBC, 2000). The introduction of the MCE was coincident with the introduction of probabilistic seismic design values into the U.S. codes, mostly replacing the previously controlling deterministic approach. These provisions defined the design spectra as the larger of the uniform-hazard 2% in 50-year motions, or a deterministic value calculated as 1.5 times the largest median ground motion from nearby faults not less than 1.5g and 0.6g for the short and one-second periods, respectively.

More recently, the 2009 NEHRP provisions (BSSC, 2009) modified the probabilistic ground motions to be based on a risk target of 1% chance of collapse in 50 years. This risk target was achieved by combining the probabilistic ground motion hazard curve at a site with the expected structural collapse fragility (Luco et al., 2007). Comparison to the deterministic values was retained, but the deterministic values were set at the 84th percentile of spectral response of the maximum magnitude earthquake on the controlling fault (Kircher et al., 2010). The update to risk-targeted ground motions was intended to achieve a more uniform level of collapse prevention. The 2009 NEHRP provisions were adopted as part of the 2012 IBC (IBC, 2012), and risk-targeted MCE (denoted MCE_R) design values were sustained through the 2015 NEHRP provision (BSSC, 2015) that were adopted as part of ASCE 7-16 (ASCE, 2016).

The risk-targeted values govern the built environment for most of the country. However, high seismic regions near active faults tend to be controlled by their deterministic counterparts, effectively "capping" the risk-targeted values. As a result, buildings in near-fault regions that cover much of California are designed for smaller levels of shaking than implied by the risk-targeting calculations and may incur higher risks. Deterministic capping remains part of the NEHRP provisions as it allows for risk-targeted values to be used in most of the country, but produces "less drastic changes to ground motion values for coastal California" (BSSC, 1997, Commentary, page 292).

Seismic design maps that are mostly probabilistic, but incorporate deterministically-capped regions, have governed the built environment in the U.S. for nearly the last 20 years. New design at sites controlled by deterministic values have smaller design values and perhaps less expensive construction costs, but the risk to the 11-12 million people living or working in these capped regions is increased by an unquantified amount. A recent study by Luco et al. (2017) showed that, where design is governed by deterministic values, collapse risk may be up to nine times higher than for buildings designed using risk-targeted values. While collapse risk is paramount, it represents a low probability of occurrence. The work presented in this paper extends these findings to investigate the effect that deterministic capping and other design value decisions have on expected economic losses.

2. METHODOLOGY

To quantify a building's seismic losses. and compare the implications of various seismic design maps, this study utilizes the Seismic Performance Prediction Program (SP3) Risk Model (HB-Risk, 2018). The *SP3 RiskModel* is a web-based software application that uses the FEMA P-58 methodology (FEMA, 2012). FEMA P-58 is a probabilistic framework for quantifying seismic risk of buildings in terms of economic losses, repair times, and casualties. The method combines structural properties and occupancy characteristics, along with component level fragilities based on experimental data, to develop a model of the building. The structural response of the building is assessed at various intensities of shaking, accounting for uncertainties in response at each level. The building model is analyzed using Monte Carlo simulation to calculate consequences for each building component for every realization of structural response and shaking intensity. Component level consequences are tracked for repair costs, repair time and casualties and are aggregated into building level consequences. Through the Monte Carlo simulations, uncertainties in structural response, component fragilities, repair costs, and other consequences are explicitly tracked and used to develop probability distributions for each of the risk metrics.

This study utilizes default algorithms in the *SP3 RiskModel* to produce 15 building typologies at 34 sites across the U.S., resulting in a set of 510 unique P-58 building models that represent various building types and occupancies common in modern US construction: reinforced concrete (RC) moment frames, RC shear walls, steel moment frames, precast tilt-up, and wood light frame buildings. Ten of the 34 sites have design values controlled by deterministic capping in ASCE 7-16 (ASCE, 2016). The sites used in this study are shown in Figure 1.

Each building typology is designed using each of three seismic design maps at each site:

- Current NEHRP 2015 (BSSC, 2015) and ASCE 7-16 (ASCE, 2016) provisions, which combine risk-targeted sites with deterministic capping, referred to as "ASCE 7-16."
- Risk-targeted map, as defined in NEHRP 2009 (BSSC, 2009), without deterministic capping, referred to as "risk-targeted."
- Uniform-hazard map, as defined in NEHRP 1997 (BSSC, 1997), without deterministic capping, referred to as "uniform-hazard."

Design values for each of the buildings are obtained from the USGS design maps web services (USGS, 2019).

Each building model is assessed using the FEMA P-58 method, and predictions in terms of expected building repair costs are compared between seismic design maps. Indirect economic losses such as lost business from downtime are not quantified.

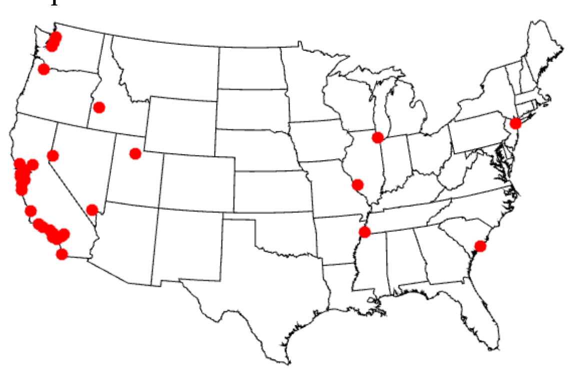

Figure 1 - U.S. sites used in this study.

3. RESULTS

3.1. Overview

First, to understand the different design values drawn from the three design maps used in this study, we investigate the distributions of the ratio of the spectral design values from one map to the next. Figure 2 shows the distribution of 0.2 second period spectral accelerations, S_s, ratios, comparing current ASCE 7-16 maps to a risk-targeted map. Sites outside of deterministic zones have the same design values from both design maps, but sites in our study in deterministic zones have ASCE 7-16 seismic design values that are as much as 30% lower than their risk-targeted counterparts. If you look at this ratio for all of California, as in Figure 3, design values for deterministic zones can be as much as 50% less that their risk-targeted counterparts.

Figure 4 shows the distribution of S_s ratios when comparing the risk-targeted map with the uniform-hazard map. Seismic design values from the risk-targeted map sites used in this study are lower than their uniform-hazard counterparts and fall within the range of variation specified in Luco et al. (2007), which showed the ratio between risk-targeted and uniform-hazard maps tended to be between 0.7 and 0.9 for the central and eastern U.S. and 0.9 to 1.15 for the western U.S. Similar distributions can be shown for the 1-second period spectral values, S_1.

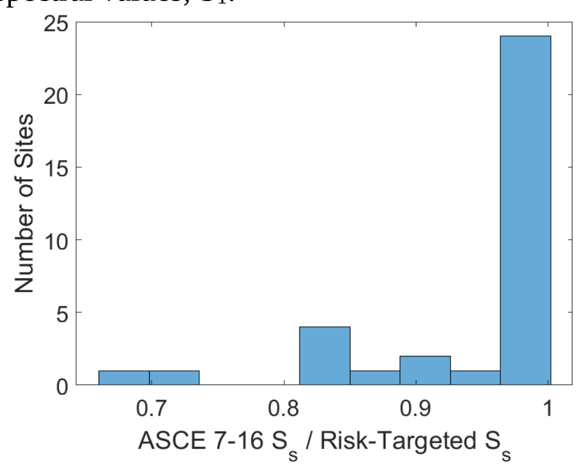

Figure 2 - Distribution of the ratio of the short period accelerations, S_s, from the ASCE 7-16 design maps to the risk-targeted design map, for all 34 sites used in this study.

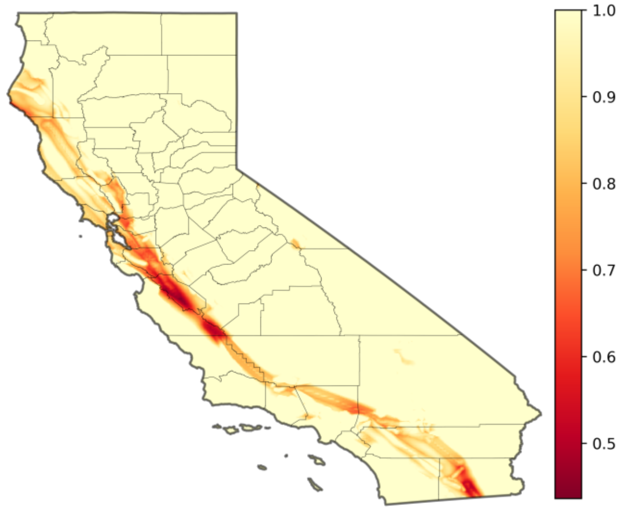

Figure 3 - Distribution of the ratio of the short period accelerations, S_s, from the ASCE 7-16 design map to the risk-targeted design map across California.

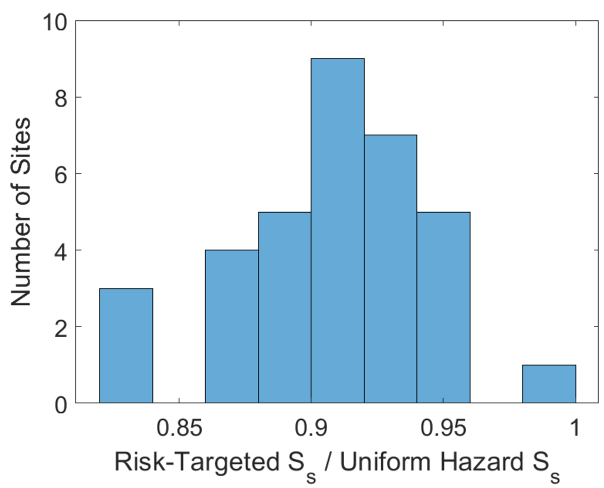

Figure 4 - Distribution of the ratio of the short period accelerations, S_s, from the risk-targeted design map to the uniform-hazard design map for all 34 sites used is this study.

To quantify variations in expected loss from one seismic design map to the next across all levels of hazard, Figure 5 and Figure 7 show the ratio of expected annualized loss (*EAL*) from different design maps, as a function of the design value. *EAL* represents the lifetime losses in an annuity and is calculated by integrating the expected losses for a particular shaking intensity (i.e., hazard level) with the probability of exceedance for that hazard level from the seismic hazard curve. In the figure, the site S_s is normalized by 1.5 because design values governed by deterministic capping values are never less than 1.5g at short periods; so $S_s/1.5$ shows where deterministic caps might start to kick in.

Figure 5 compares the ratio of EAL based on an ASCE 7-16 (ASCE, 2016) design map to those based on a risk-targeted design map. When design ground motions are based on deterministic caps, *EAL* can increase by up to 40%. The smaller the deterministic design values are, compared with their risk-targeted counterparts, the larger the difference in predicted loss can become (Figure 6).

Figure 7 shows the ratio of *EAL* when using a risk-targeted design map, to those calculated from the uniform-hazard design map. On average, losses based on a risk-targeted map tend to be similar to losses from a uniform-hazard map across most sites, with risk targeted losses trending slightly higher than uniform-hazard losses, due to larger design values from the uniform-hazard maps at the sites used in this study.

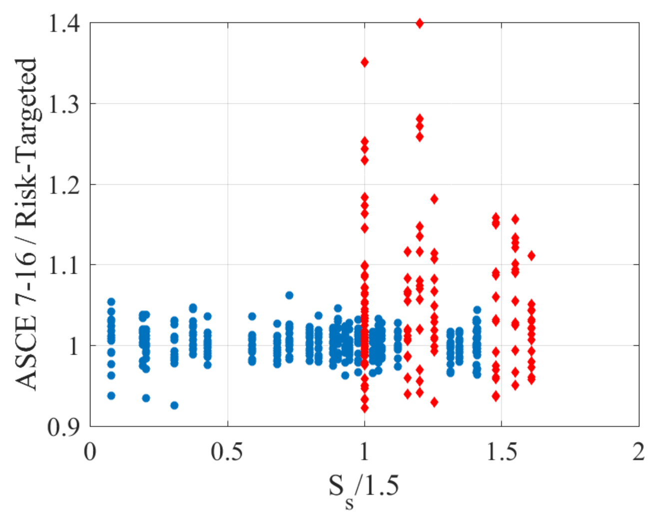

Figure 5 - Ratio of EAL from ASCE 7-16 (ASCE, 2016) seismic design maps to the EAL from a risk-targeted seismic design map vs. the short period spectral acceleration normalized by the minimum deterministic value. Sites where design is governed by deterministic caps in ASCE 7-16 are shown in red.

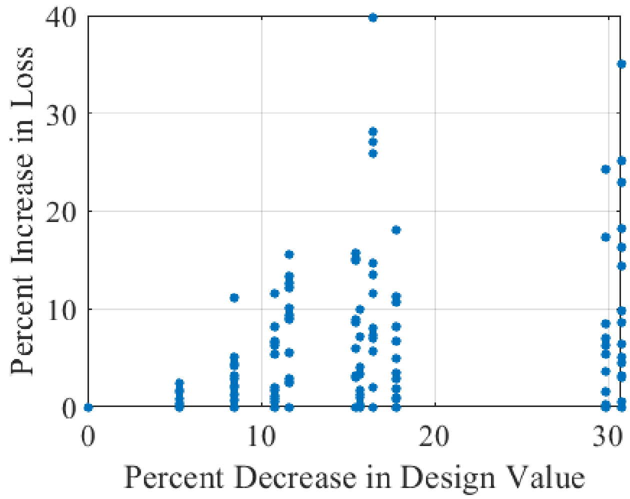

Figure 6 - Relative change in EAL vs. the relative change in design value when going from risk-targeted design maps to ASCE 7-16 design maps.

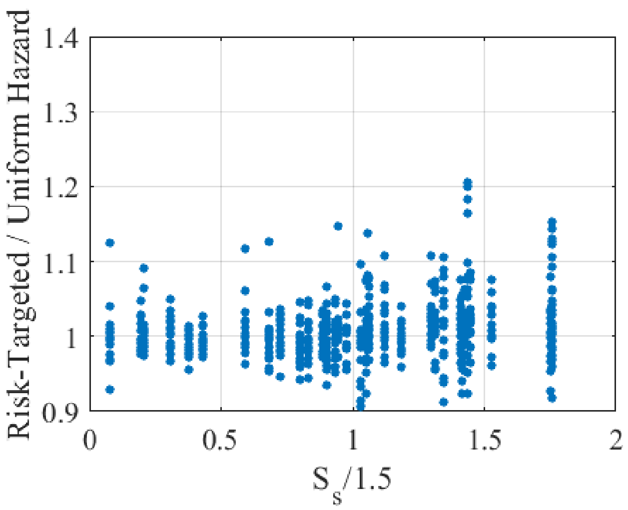

Figure 7 - Ratio of EAL from risk-targeted seismic design maps to the EAL from the uniform-hazard design map vs. the short period spectral acceleration normalized by the minimum deterministic value.

3.2. Trends with Hazard

The results shown above examine *EAL*, which combine the assessment of losses at different shaking levels. Separating out these results, we find that variations in expected loss with seismic design map are highly dependent on the ground motion level at which the risk assessment is performed.

Figure 8 shows the ratio of expected losses to the building replacement value, for each of the seismic design maps. The expected loss at the 72-year return period level of shaking shows little to no difference between the three design maps (Figure 8a). However, the losses at the 475-year level of shaking (Figure 8b), which is similar to the level of shaking targeted for modern design, show that current ASCE 7-16 (ASCE, 2016) design maps have a higher loss in high seismic areas, as compared with risk-targeted maps. Therefore, changes in the design value make less difference for smaller earthquakes and lower seismically active areas, where very small losses are expected, as compared with design level events in seismically active areas.

When performing risk assessment for real estate transactions, a probable maximum loss (PML) study is often used to quantify expected losses at a 475-year return period (ASTM, 2016). Most PML reports expect that, for new design, buildings should have less than 20% loss. Figure 8b compares expected losses at the 475-year earthquake with the 20% PML criteria, as a litmus test for expected losses in modern buildings. While only 6 of the building models designed using the risk-targeted maps exceed this 20% criteria, there are 17 building models that exceed the 20% criteria when designed using the current ASCE 7-16 (ASCE, 2016) maps, due to the deterministic capping at high seismic sites.

By investigating a single hazard level, such as the 475-year return period in Figure 8, this study also shows that expected losses have a clear trend with site seismicity (PGA on the x-axis), where losses increase as the expected shaking levels increase across various sites. This trend holds regardless of the design map used to design the buildings. Therefore, while the risk-targeted design maps are calibrated to a uniform risk of collapse across the country, they are not expected to provide a uniform risk in terms of direct economic losses.

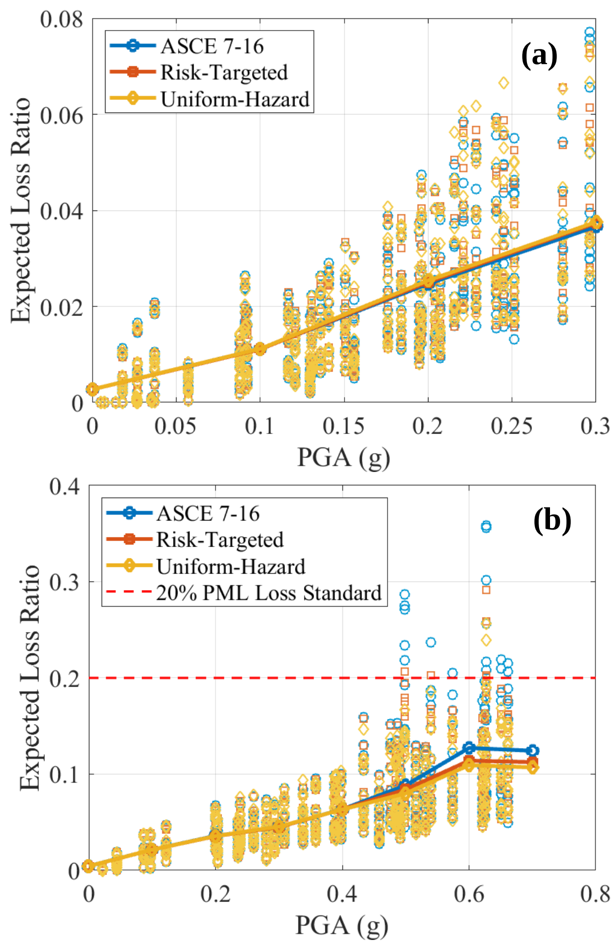

Figure 8 - Expected loss ratio (i.e., expected repair costs normalized by the replacement value of the building) of the three seismic design maps assessed at two hazard levels: (a) 72-year return period, (b) 475-year return period.

3.3. Trends with Building Type

This study also finds that sensitivities in loss to seismic design maps depend on the building type. For example, RC and steel moment frames respond differently to changes in seismic design values than wood light frame buildings. As shown in Figure 9, RC moment frames designed in high seismic areas using the ASCE 7-16 (ASCE, 2016) design maps experience a significant increase in loss as compared with the risk-targeted design maps (up to 40%). However, there are seemingly negligible increases in seismic loss for wood light frame buildings (only up to about a 7% increase).

This variation in sensitivity to design maps is due to the inherent vulnerability differences in various building types. To illustrate this point, Figure 10 provides a comparison of a wood light frame building and a RC moment frame office at a site in San Jose, CA. Each building is redesigned according to the design values from each of the three seismic design maps at that site. The RC moment frame shows larger expected annual loss ratios using the ASCE 7-16 (ASCE, 2016) maps as compared with the risk-targeted maps, whereas the wood light frame building shows no change in loss using the various design maps. Modern wood light frame structures tend to be both stiff and lightweight, with relatively large overstrength from modern construction and design practices, especially the high concentration of walls and finishes. As long as they have no severe irregularities, modern wood frame structures are very seismically resilient at moderate to large levels of shaking, because they are already overdesigned relative to the design level. RC moment frames, on the other hand, are typically used for larger construction projects and are more likely to be designed closer to the minimum strength requirement, making them more sensitive to changes in design value.

Our results show that RC moment frames, steel moment frames, and precast tilt-up structures are the most sensitive to changes in design values and have the largest relative risk increase for buildings designed in deterministically capped regions. RC shear walls and wood light frame buildings show little change from one seismic design map to the next.

A trend with building height can also be observed. For most building types, low- to mid-rise structures tend to be more sensitive to changes in design value than high-rise buildings (12+ stories). Damage in high-rise structures tends to localize in only a few stories, reducing the cost to repair the building relative to the total value of the structure, and essentially capping the losses until collapse is reached. Damage in low- to mid-rise structures is more likely to be spread across all floors. This vulnerability to losses makes them more sensitive to changes in design values.

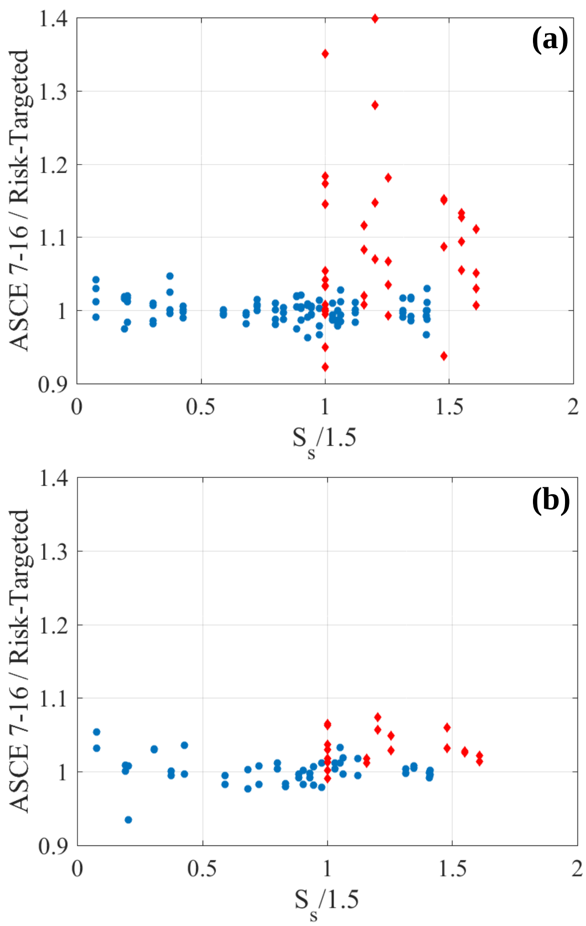

Figure 9 - EAL for (a) RC moment frames and (b) wood light frame buildings from ASCE 7-16 (ASCE, 2016) seismic design maps, normalized by the EAL of a risk-targeted seismic design map. Sites where design is governed by deterministic caps in ASCE 7-16 are shown by red diamonds.

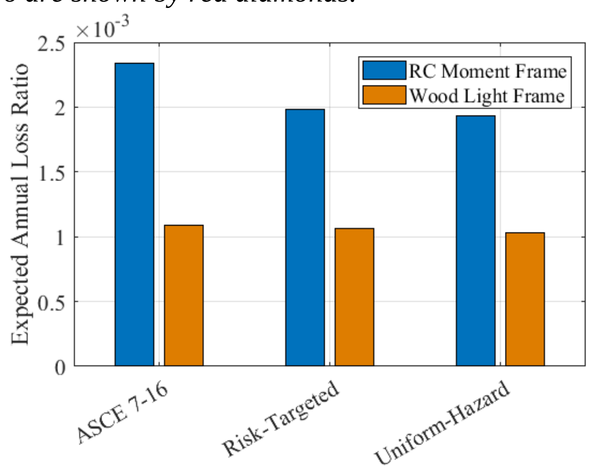

Figure 10 - Comparison of EAL ratio (EAL normalized by the replacement value of the building) among seismic design maps for wood light frame and RC moment frame buildings in San Jose, CA.

4. DISCUSSION

This study examines the variation in expected seismic loss in buildings across the U.S. when designed using three different seismic design maps. Seismic design values from these maps may differ by as much as 30% for the sites used as part of this study.

Seismic losses are quantified using FEMA P-58 for various types of buildings representative of modern U.S. construction at 34 sites across the U.S. The *SP3 RiskModel* is used to generate assumptions and calculate design parameters needed to realistically compare buildings at a large number of sites.

Comparison of results for the three seismic design maps show:

- Expected economic losses, such as expected annual repair costs, may be as much as 40% larger for buildings designed based on deterministic values in high hazard areas, as compared with designs using risk-targeted values at the same location.
- Difference in loss between seismic design maps heavily depends upon the level of shaking being assessed. Small to moderate adjustments in the design values, which tend to be around a 475-year event, resulted in little difference in expected loss between the design maps at low levels of shaking. However, assessments performed at moderate to large levels of shaking exhibited significant differences between design maps.
- Difference in loss between seismic design maps depends on a building type's sensitivity to loss. For example, regular wood light frame buildings of modern construction observed little change from one design map to the next, whereas low-rise moment frame buildings demonstrated a significant change.

This study quantifies the increased loss associated with designing buildings using smaller seismic loads controlled by deterministic ground motions in near-fault locations, which occur in many highly populated areas, such as the San Francisco Bay Area of California. However, more work is needed to evaluate whether and how U.S.

design maps should change. Many other factors have historically been part of this discussion and should be taken into consideration. In particular, larger design forces in high seismic zones may increase the cost of construction in those regions. Also, there is a significant amount of uncertainty in quantifying the design maps, due to a lack of empirical evidence. This uncertainty in ground motion mapping may make it difficult to justify updates to the current design maps, as updates to the code must represent a significant enough change in knowledge or design values to overcome that uncertainty.

For various reasons, deterministic ground motions have remained in modern seismic design maps for the past 20 years. Nevertheless, quantification of the increased risk is important for promoting risk-informed decision making. In a similar vein, recent efforts from the National Institute of Building Science (NIBS) Project 17 and work by Luco et al. (2017) have proposed new seismic design maps that explicitly define variations in collapse risk across the U.S. While these proposals were not accepted into ASCE 7-16 (ASCE, 2016) as part of the most recent code cycle, further discussion and education on the implications of seismic design policy is continuing to develop and move forward (Luco et al., 2018).

5. AKNOWLEDGEMENTS

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