Preliminary Results of a Cost-Benefit Assessment of Replacing Seismically Vulnerable Non-Ductile Reinforced Concrete Frame Structures

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ABSTRACT

This study uses cost-benefit assessment to evaluate the cost-effectiveness of replacing existing seismically deficient reinforced concrete frames to improve their seismic safety. This assessment is based on a set of typical older California reinforced concrete frame structures, whose seismic performance, measured in terms of the risk of earthquake-induced collapse, fatalities and repair costs have been evaluated in previous studies (Liel et al. 2009, Liel and Deierlein 2008). The cost-benefit assessment accounts for the costs of replacement and the benefits of these actions, including improved seismic safety and reduced earthquake damage and repairs. While the assessments show that replacing these vulnerable structures can significantly reduce the life safety and repair cost risks, the cost-benefit rates (assuming a value of life saved of $2 million) are generally greater than one, suggesting that the costs outweigh the benefits. The breakeven point in the cost-benefit analyses (for building replacement) occurs at a cost per life saved of approximately $5 million. Alternatively, if building retrofit could achieve comparable life safety to a new building, it would be cost effective (assuming a value per life saved of $2 million) for retrofit costs less than $98 per square foot of building (on average).

INTRODUCTION

Non-ductile reinforced concrete (RC) frame structures, like those constructed in California prior to approximately 1975, are potentially vulnerable to earthquake-induced collapse, posing a threat to the life safety of building occupants. Recent research has shown that these older RC frame structures are approximately 30 to 40 times more susceptible to seismic collapse than modern RC frame structures designed according to today's building codes (Liel et al. 2009). When they do not collapse, non-ductile RC frame structures are more likely than their modern counterparts to experience earthquake damage, requiring expensive repairs (Liel and Deierlein 2008). These seismic deficiencies in older RC frame structures could be mitigated by retrofitting or replacing vulnerable structures. In this study, cost-benefit analysis is used to assess the cost-effectiveness of replacing seismically deficient non-ductile RC frame structures. The assessment accounts for the costs of replacement and the benefits that result, including improved seismic safety and reduced earthquake damage and repairs. Results of cost-benefit assessment can be used to develop cost-effective and equitable recommendations for mitigating seismic risk from non-ductile RC frame buildings.

OVERVIEW OF COST-BENEFIT ASSESSMENT

In this study, cost-benefit assessment is used to evaluate the tradeoffs involved in replacing seismically-deficient non-ductile RC frame structures, comparing the costs of replacement with the benefits of improved seismic performance. Benefits are measured in terms of reduced economic losses and fatalities in future earthquakes. The estimates of economic losses and fatalities used to compute benefits (described in more detail below) take advantage of recent advances in performance-based earthquake engineering methods, which produce robust probabilistic predictions of seismic performance. The outcome of the cost-benefit assessment is the cost-benefit ratio (CBR), a ratio of the costs of replacing the older RC frame structure to the benefits obtained from the higher level of seismic performance. A cost-benefit ratio less than 1 indicates that the benefits of mitigation exceed the costs. All costs and benefits reported in this study are expected values.

In order to compare costs and benefits, the benefits of replacing non-ductile RC frame buildings are quantified in economic (dollar) terms. To account for the benefit of saving lives, a value per life is assigned, which can be interpreted as the amount society is willing pay to save one life. Assigning dollar values to lives is controversial because it treats human life as a commodity. However, our society has limited resources to invest in public safety, such that evaluation of the economic efficiencies of various policies and regulations is needed to prioritize spending. Willingness to pay to prevent loss of life varies significantly depending on the type of risk and aspects of risk perception, but engineering cost-benefit assessments typically value human life between $2 and $5 million (Pate-Cornell 1994; Porter et al. 2006). More recently, the September 11th Victim Compensation Fund awarded an average of $2 million dollars per victim to relatives of the deceased in the 9/11 terrorist attacks (Feinberg et al. 2004). For the purposes of this study, human life is valued at $2 million dollars. For simplicity, this valuation is assumed to be constant for all people, and is not dependent on a victim's remaining life span, future earnings or other factors.

Benefits of replacing vulnerable structures are lives saved and losses avoided in *future* earthquakes. For comparison with costs of replacement, the *present value* of benefits is computed using a discount rate to account for the time value of money. In this context, discounting implies that losses in the distant future are less financially damaging than losses tomorrow, because we could invest money in the meantime, earning interest before the losses are incurred. Here, the present value of benefits is computed with a discount rate of 3%. The proposed value of 3% is based on historical values of inflation and interest rates on corporate bonds in the U.S. (Nuti and Vanzi 2003). Values between 2 and 7% are frequently used for public safety projects (Rackwitz 2004); larger discount rates decrease the present value of future losses, reducing the computed cost-effectiveness of replacing vulnerable non-ductile RC frame structures. The same discount rate is applied to benefits associated with human life and economic losses to ensure that individuals exposed to the same level or risk at different times have the same protection (Pate-Cornell 1985; Pate-Cornell 1984).

Cost-benefit assessment provides a value tool for systematically examining the advantages (benefits) and disadvantages (costs) of replacing non-ductile RC frame structures, which can help to prioritize seismic safety decisions and to enumerate the costs associated with protecting human life. The use of cost-benefit assessment presumes that the seismic safety risks examined fall within the range in which economic analysis is appropriate. It is considered appropriate here because significant constraints on resources exist, forcing prioritization of mitigation strategies (Pate-Cornell 2002; Pate-Cornell 1994). California's Multi-Hazard Mitigation Plan explicitly encourages "cost-effective mitigation" (California Office of Emergency Services 2004). Even so, it is important to recognize that cost-effectiveness – as computed here – is only one of many factors that affect policy making for seismic safety and risk reduction. Other factors such as risk aversion, particularly to the potentially catastrophic nature of earthquake collapse in a large urban area, alter spending priorities.

SEISMIC PERFORMANCE OF NON-DUCTILE RC FRAME STRUCTURES

This study focuses on seismic hazard mitigation of non-ductile RC frame structures of the type constructed before ductile detailing and capacity design requirements were introduced into California's building code seismic provisions in the mid-1970s. To evaluate the seismic performance of California's older RC frame structures, a set of typical structures was designed according to the 1967 Uniform Building Code (ICBO 1967) for a high seismic site in California by Liel and Deierlein (2008). This set of buildings ranges in height from 2 to 12 stories and includes both space (S) and perimeter (P) frame lateral resisting systems. As such, the set is expected to represent the average range of performance in California's older RC moment frame buildings (excluding buildings with infill walls and those with major strength or stiffness irregularities). Interested readers are referred to Liel et al. (2008; 2009) for details of building design.

To assess the risk of earthquake-induced collapse, damage and economic losses, and fatalities, the seismic response of structures was simulated in OpenSees. Collapse performance assessments use incremental dynamic analysis of nonlinear simulations models to predict the likelihood of earthquake-induced collapse. Economic losses, representing the costs of repairing earthquake damage in the structure, were computed using a loss-estimation toolbox developed by Mitrani-Reiser (2007; Ramirez et al. 2009). This toolbox uses drifts and acceleration demands from dynamic analysis to determine damage states for each nonstructural and structural component and the associated costs of repairing these components. Liel and Deierlein (2008) also estimated earthquake-induced fatalities in RC frames utilizing data on collapse rates, collapsed volume of the structure and building occupancy. Estimates of collapse risk, economic losses, and fatalities are probabilistic and account for uncertainties in ground motion intensity and frequency, structural modeling and fatality estimation.

Key metrics of seismic performance for non-ductile RC frame structures are summarized in Table 1. Collapse performance is given in terms of the mean annual frequency of collapse, a measure of the collapse rate (collapses per year), which depends on the structure's collapse resistance and the seismic hazard at a representative Los Angeles site. The expected annual loss expresses the amount an owner can expect to spend repairing earthquake damage, annualized over the life time of the structure (Liel and Deierlein 2008, Ramirez et al. 2009). This value has been normalized by the total replacement cost of each structure. The fatality predictions are reported as expected annual number of fatalities and represent an annualized seismic fatality rate (deaths per year). The buildings are assumed to be located a typical California high seismic site south of downtown Los Angeles, for which probabilistic seismic hazard analysis has been carried out by Goulet et al. (2007).

Table 1. Metrics for earthquake-induced collapse, economic losses and fatalities in non-ductile RC frame structures.

Building	*Mean Annual Frequency of Collapse (x 10^{-4})*	*Expected Annual Losses (% of Replacement Cost)*	*Expected Annual Number of Fatalities (x 10^{-3})*
2S[1]	109	5.2%	41
2P	47	3.2%	24
4S	107	2.3%	62
4P	100	2.3%	97
8S	64	1.8%	77
8P	135	2.1%	141
12S	50	1.6%	76
12P	119	1.6%	192

[1] Notation: 2S is a two-story non-ductile RC space frame, designed according to the 1967 Uniform Building Code.

REPLACEMENT OF NON-DUCTILE RC FRAME STRUCTURES

Replacement Structures and Costs

One option for mitigating the seismic hazard posed by non-ductile RC frame structures in California is to replace these structures with modern RC frame buildings that comply fully with current building code requirements. Code-conforming special moment frames have demonstrated superior seismic performance compared to older RC frames due to more stringent seismic design and detailing requirements. For the purposes of this assessment, it is assumed that the 2, 4, 8 and 12-story non-ductile (1967) RC frame structures would be replaced with modern (2003) special moment frames with the same number of stories as the original structure. The seismic performance of the replacement modern structures is based on a set of typical RC frame structures designed by Haselton et al. (2009) according to current building standards (ACI 2002; ASCE 2002; ICC 2003). The structures are designed for the high seismic Los Angeles site of interest with a maximum considered earthquake of $S_{M1} = 0.90$g.

The costs of replacing the non-ductile structures with modern RC frame office buildings are estimated using RS Means Construction Costs (Waier 2005). Estimated replacement costs (in 2006 dollars) range between approximately $140 and $170 per square foot, depending on the height of the building and whether it has a space or perimeter frame lateral resisting system (Ramirez et al. 2009). These estimates account for construction costs in Los Angeles associated with all significant structural and nonstructural components, including HVAC systems, partitions and interior finishes, exterior enclosures, services, and basements (for 8 and 12-story buildings). The replacement costs include a 25% contractor fee, but not additional fees related to permitting, administration, management and financing that may increase construction costs by 50 to 100% (Reis 2008). It is therefore expected that these cost estimates provide a lower bound on the true cost of replacement.

Seismic Performance of Modern RC Frame Structures

Seismic performance metrics for modern RC frame buildings, the assumed replacements to the non-ductile frame buildings, are summarized in Table 2 in terms of the same metrics as Table 1. Collapse performance assessments for these structures were conducted by Haselton et al. (2009), and the loss and fatality assessments are reported by Ramirez et al. (2009) and Liel and Deierlein (2008). Compared to older RC frames (for which performance metrics are reported in Table 1), the modern replacement structures are less likely to be damaged in future earthquakes, reducing economic losses incurred by the owner, and less likely to collapse, reducing occupant life safety risks. Expected annual losses are on average 1.0% for the modern RC frames, compared to 2.2% for the non-ductile RC frames; and fatality rates are approximately one-twentieth of those in older RC frames.

Table 2. Metrics of earthquake-induced collapse, economic losses and fatalities in modern replacement RC frame structures.

Building	*Mean Annual Frequency of Collapse (x 10^{-4})*	*Expected Annual Losses (% of Replacement Cost)*	*Expected Annual Number of Fatalities (x 10^{-3})*
2S	1.0	1.0%	0.4
2P	3.4	0.96%	1.7
4S	1.7	1.1%	1.3
4P	3.6	1.2%	2.7
8S	2.4	1.3%	3.1
8P	6.3	1.0%	8.3
12S	4.7	1.1%	9.4
12P	5.2	0.77%	9.9

COST-BENEFIT ASSESSMENT OF REPLACEMENT

The costs and benefits of replacing non-ductile RC frame structures in high seismic areas of California are compared in Table 3. The benefits are the improvements in seismic performance achieved when the vulnerable structure is replaced. The calculations assume that structures have a remaining usable lifespan of 50 years[1] and human life is valued at $2 million. As shown in Table 3, replacing a non-ductile RC frame structure is predicted to save an owner between 2.7 and 6.5 million dollars due to reduced seismic repair costs (economic losses avoided).

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[1] The longer the time horizon considered, the greater the benefits to replacement, though the present value of future benefits saturates at approximately 50 years due to the compounding effects of investments.

Likewise, between 2 and 9 fatalities are avoided over the lifetime of the structure. The total benefit of replacement ranges between 4.8 and 15.6 million dollars, depending on the structure, with approximately 40% to 60% of the computed benefits reported in Table 3 result from improved safety (reduced fatalities). The 2-story space frame structure has the best cost-benefit ratio (CBR = 0.7). The 12-story space frame is the least cost-effective candidate for replacement, with a cost-benefit ratio of 3.8.

There is significant variability in the results of the cost-benefit assessment for different structures. Of the case study structures considered, only the replacement of the 2-story space frame structure has a cost-benefit ratio less than 1. The non-ductile 2-story structure has particularly high predicted economic losses, such that, if replaced with a new building, there are significant savings from reducing earthquake-induced damage (5.2% EAL is reduced to 1.0% EAL, equal to $6.5 million over 50 years). For the other structures, the cost of replacement exceeds the computed benefits.

The cost-benefit assessment can also be expressed in terms of how much we would be willing to spend to obtain the benefits associated with replacement, which corresponds to the maximum value of the improvements. For the structures considered the improvements are valued from $44 to $200 per square foot. Assuming retrofit could provide performance comparable to a new building, this value suggests the maximum one could afford to spend on retrofit.

Table 3. Comparison of benefits and costs of replacing non-ductile RC frame structures.

Building	*Benefits over 50 years* *Losses Avoided ($, millions)*[1]	*Lives Saved*[2]	*Total Benefits of Replacement ($, millions)*	*Cost of Replacement ($, millions)*	*Cost-Benefit Ratio*
2S	6.5	2.0	8.6	6.1	0.7
2P	3.7	1.1	4.8	6.5	1.4
4S	3.9	3.1	7.0	12.5	1.8
4P	3.5	4.7	8.3	12.0	1.4
8S	2.7	3.7	6.5	19.9	3.1
8P	5.3	6.6	12.1	19.4	1.6
12S	4.2	3.3	7.6	29.1	3.8
12P	6.2	9.1	15.6	28.1	1.8

[1] Present value

[2] The lives saved column shows the estimated total number of lives saved (over 50 years) if the non-ductile RC frame structure is replaced. Note that the total benefits equal the sum of the benefits due to losses avoided and the benefits due to lives saved. The benefits due to losses avoided have been discounted over 50 years in Table 3. The dollar value of benefits due to lives saved are also discounted before they are used to compute the total and are therefore less than the $2 million times the number of lives saved (as shown in Table 3).

A cost-benefit ratio greater than 1 implies that the cost per life saved exceeds the $2 million value assigned in the assessment. If human life is valued more highly, the computed benefits of replacing these structures increases and the cost-benefit ratio decreases. As illustrated in Figure 1, we must be willing to spend between $4 and $6 million per life saved in order to achieve a neutral cost-benefit assessment (CBR = 1) for replacing the non-ductile perimeter frame structures. Replacement of the space frame structures is more variable, costing between \$1 million to \$10 million per life saved.

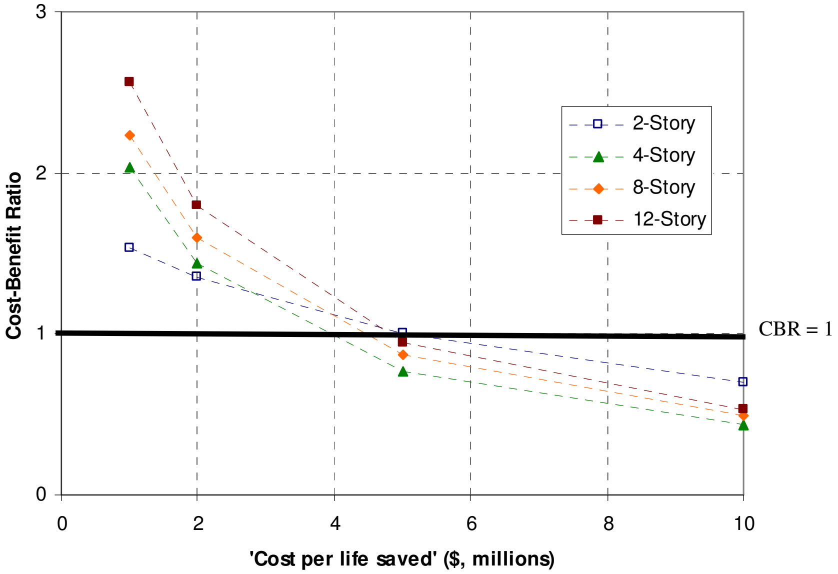

Figure 1. Effect of value of human life on cost-benefit assessment of replacing non-ductile RC perimeter frame structures of different heights.

EFFECT OF DESIGN AND CONSTRUCTION VARIABILITY

The results presented above reflect typical design characteristics of RC frame structures constructed between 1950 and 1975 in California. In reality, of the non-ductile RC frame structures existing in California today, these structures probably represent a subset of structures with average or above average seismic performance, since they are regular structures, meet all governing code requirements and are assumed to be constructed to high quality standards. Real buildings may have irregularities in plan or elevation due to architectural constraints or infill walls, construction deficiencies, or age-related deterioration that, if accounted for, may lead to higher predictions of seismic-related losses and fatalities.

This variation in the design and construction of older RC frame structures will impact the outcome of cost-benefit assessment. To examine the effects of design variability it is assumed that the typical perimeter frame structures already considered result in average (μ) cost-benefit assessment, and that variation in design features in the existing building stock leads to a coefficient of variation of 0.50 in the computed cost-benefit ratio. While the effect of variation in design and construction on cost-benefit assessments is difficult to quantify, the assumed coefficient of variation is based on previous studies of the effect of uncertainties in design, construction, and modeling on collapse (FEMA 2009; Haselton and Deierlein 2007; Liel et al. 2009b). The average plus or minus one standard deviation represent worse-case (ie., μ - σ) and better-case designs (ie., $\mu + \sigma$).

The cost-effectiveness of replacing non-ductile RC frame structures differs dramatically depending on whether the structure of interest is a 'worse', 'average' or 'better' building, as illustrated in Figure 2. Replacement of the 'worse'-case building costs only $1.5 million per life-saved (to achieve CBR = 1). The average structures require expending closer to $5 million dollars per life saved. This evidence points to the importance of targeting mitigation efforts toward the most deficient non-ductile RC moment frames, as these buildings are the more cost-effective candidates for replacement.

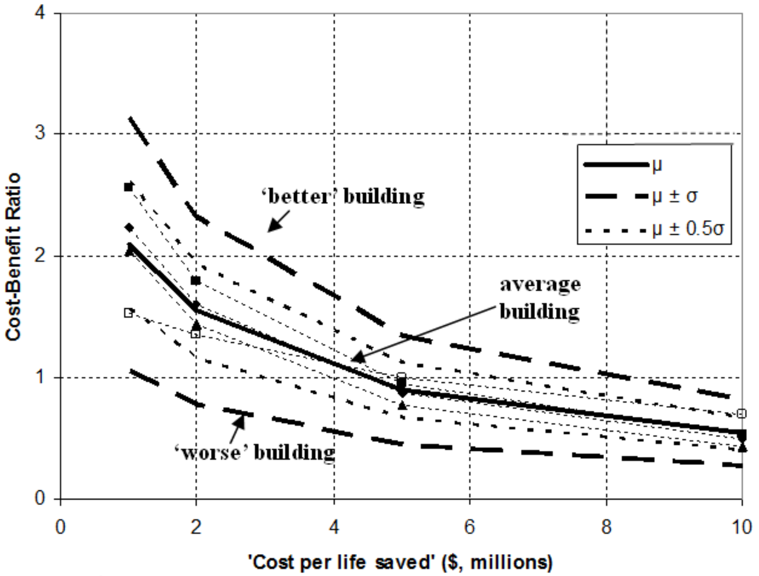

Figure 2. Effect of design variability on cost-benefit assessment of replacing non-ductile RC frame structures.

Identifying the most vulnerable of California's non-ductile RC frame structures remains a challenge (Anagnos et al. 2008). Some of the poorest performing structures can be identified on the basis of a study of design variation of regular structures, as described here. Other structures, such as T- and L-shaped structures, are vulnerable due to configuration issues in plan and elevation. The worst performing non-ductile RC frame structures may also be the result of human error in design and construction. These buildings will be difficult to locate without a building-specific examination of design drawings and as-built conditions. Other non-ductile RC frame structures are particularly vulnerable because of their location. The assessments conducted here assume that the structures are located at a typical high seismic site with stiff soil and rock (Goulet et al. 2007). Structures close to faults or on soft soils are also likely to be more susceptible to damage and collapse, and hence more cost-effective candidates for replacement.

OTHER BENEFITS: REDUCTION IN BUILDING DOWNTIME

Benefits associated with replacing non-ductile RC frame structures in Table 3 does not account building downtime, i.e. the losses associated with building closure and business interruption while inspections are made and repairs are being planned and carried out (Comerio 2006). If a seismically-vulnerable building is replaced as suggested in this study, downtime in future earthquakes will decrease, reducing the losses due to business closure and interruption. This reduction in downtime may contribute significantly to the benefits of replacement. To quantify the possible impact of downtime losses, data from a detailed study of downtime by Mitrani-Reiser (2007) for a 4-story RC frame structure is used. Mitrani-Reiser found that downtime-losses increase an owner's expected annual economic losses by approximately 30%. If downtime losses for both older and replacement structures are approximated based on Mitrani-Reiser's study, the computed cost-benefit ratios in Table 3 would decrease by approximately 15% on average. The true cost of downtime and building closure may be even more substantial for non-ductile RC frame structures. As improved information becomes available, modified assumptions can be incorporated into the cost-benefit model to examine their impact on the results.

The cost-benefit assessment also neglects the indirect economic impacts and the broader benefit to public well-being resulting from protecting buildings and infrastructure, making our communities, cities and economic systems more seismically resilient.

CONCLUSIONS

This study investigates the effectiveness of mitigating seismic collapse risks of non-ductile RC frame structures by replacing vulnerable structures, evaluated through cost-benefit assessment. The benefits of replacing potentially vulnerable structures are quantified in terms of improved seismic performance, as measured by reduced earthquake-related repair costs and improved occupant safety. Costs of replacement are estimated using a standard database. Seismic-induced economic losses (repair costs) and fatalities are obtained from dynamic analysis of nonlinear simulation models in the context of performance-based earthquake engineering. These detailed assessments of building-specific seismic performance have only recently become possible with advancements in performance-based earthquake engineering methods, nonlinear modeling and simulation, and development of component fragility functions for loss and damage.

Replacing non-ductile RC frame structures with modern code-conforming structures reduces the risk associated with loss of life in these structures and reduces the costs incurred by owners in repairing future earthquake damage. The total benefit of these reductions in seismic losses is 4.8 to 15.6 million dollars (or \$40 to \$200 dollars per square foot of building area). Although the reduction in costs of repairing seismic damage is significant if the buildings are replaced, justifying these investments economically requires some willingness to pay to save lives. The cost per life saved by building replacement typically costs between \$4 to \$5 million per life saved. These results reflect the cost of construction and the expected frequency of earthquakes in California. The most cost-effective candidates for retrofit or replacement are the worst non-ductile RC frame structures, such as those with configuration irregularities or deficiencies in design and construction. A study of cost-effectiveness of retrofit solutions for non-ductile RC frame structures is ongoing (Liel and Deierlein 2008).

Performance-based earthquake engineering assessment of replacing non-ductile RC frame structures contributes quantifiable metrics of risks, costs and benefits to discussions aimed at improving seismic safety in California. Crucially, cost-benefit assessment quantifies both the effectiveness of replacing non-ductile RC frame structures in reducing seismic risk and the significant costs associated with reducing that risk. That the worst older structures are shown to be the most cost-effective candidates for mitigation, points to the importance of developing policies aimed at prioritizing and identifying particularly vulnerable structures. For the purpose of developing policies for mitigating seismic risk, computed costs and benefits can be interpreted differently and do not necessarily recommend a particular course of action. The contribution of cost-benefit assessment is to quantify the magnitude and distribution of costs associate with seismic hazard mitigation for decision-making purposes given limitations on public resources.

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