# DECISION ANALYSIS FOR SEISMIC RETROFIT
# OF STRUCTURES

A Thesis

by

RYAN J. WILLIAMS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Civil Engineering

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Approved by:

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| Co-Chairs of Committee, | Paolo Gardoni |
| | Joseph M. Bracci |
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# ABSTRACT

Decision Analysis for Seismic Retrofit of Structures.

(August 2007)

Ryan J. Williams, B.S., The University of Mississippi

Co-Chairs of Advisory Committee: Dr. Paolo Gardoni
Dr. Joseph M. Bracci

A methodology is presented that can be used to make informed decisions on whether or not to retrofit structures for seismic events based on the expected economic benefit due to retrofitting. The seismic fragility of a given structure as well as the seismic hazard at a specific building location is incorporated into the decision-making process. The prescribed methodology is used to study two identical reinforced concrete buildings, one located in Memphis, Tennessee and one in San Francisco, California. The probabilities of failure and generalized reliability indices are calculated for the identical structures in both locations. A parametric analysis is performed to determine the effects that achievable loss reduction, investment return period, and retrofit cost have on the economic feasibility of seismic retrofitting in Memphis and San Francisco. A case study is conducted to find the impact of a modest retrofit strategy applied to the identical buildings in Memphis and San Francisco. The probabilities of failure and generalized reliability indices are calculated for the retrofitted building in both locations and compared to the corresponding values for the original buildings.

The results of the parametric analysis and case study are used to determine the effects of building location on retrofit feasibility. In Memphis, the annual probability of exceeding a specified performance level for a low-rise gravity-load designed building is approximately ten times less than if the same building is located in San Francisco. For most circumstances, a seismic retrofit of a gravity-load designed building in San Francisco is more economically feasible than if the same building is located in Memphis. Furthermore, retrofitting gravity-load designed buildings may not be financially viable in Mid-America unless the indirect value associated with such buildings is greater than the direct structural value.

# ACKNOWLEDGMENTS

I would like to express my overwhelming thanks and appreciation to Dr. Paolo Gardoni and Dr. Joseph M. Bracci for their guidance and support throughout the process of researching and writing this thesis. The road was at times winding, but I believe the end result of our efforts is a body of work of which we can all be proud.

I must also recognize Jong-Wha Bai, Dr. Sathish Ramamoorthy, and Dr. Mary Beth Hueste, as well as Dr. Gardoni and Dr. Bracci, for their previous work which allowed this research to be possible. I am also grateful to Dr. Walter Peacock for generously serving as an advisor on my thesis committee.

I thank all of my professors at Ole Miss and The Sally McDonnell Barksdale Honors College, and especially Dr. Ahmed Al-Ostaz, for preparing me extremely well for the rigors of graduate education. I also express my gratitude to the Zachry Department of Civil Engineering for providing me the opportunity and financial assistance to pursue my graduate degree at Texas A&M. In particular, I thank Dr. Terry L. Kohutek for recommending me to be his teaching assistant for three great semesters. I also thank the civil engineering graduate office staff for always working so hard to answer my questions and making sure that I never missed an administrative deadline.

Finally, and most importantly, I want to thank my family and my incredible girlfriend, Stephanie, for their unending support of me during my entire graduate career. We have lived through trying events during the past two years, but I know because of each other’s love and support and our faith in the Lord, we have persevered and will enjoy many blessed and joyful days in the future.

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# CHAPTER I

# INTRODUCTION

Investors, city planners, and owners of buildings in geographic regions subject to seismic hazards are faced with the decision of whether or not to retrofit existing structures in order to lower their potential losses due to seismic events. This decision becomes more problematic in low-risk, high-consequence seismic areas such as those located in the New Madrid Fault Zone (NMFZ). Building owners in Mid-America need adequate methods to make informed decisions regarding whether or not seismic retrofitting is advantageous and/or appropriate for their buildings.

Because a variety of factors can affect the consequences of a decision, addressing as many relevant factors as possible in the decision-making process will likely lead to the most satisfying results (Hall and Wiggins 2000). For decisions regarding the effects of seismic events on buildings, these consequences include mortality as well as direct and indirect economic losses (Ellingwood and Wen 2005). The challenge lies in incorporating these factors and their consequences, given a particular course of action, into a measurable quantity that can be used to define success or failure. Addressing this challenge is crucial as any decision is ultimately judged on the consequences of its outcome.

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This thesis follows the style and format of *Journal of Structural Engineering*.

## 1.1 BACKGROUND

Currently, state and local authorities in parts of the central United States that are at risk from earthquakes in the NMFZ are considering adopting the International Building Code (IBC 2006) which would increase the earthquake provisions for new buildings to levels similar to those in high-seismic application zones of California. Seismic design provisions of the IBC are based on the maximum considered earthquake (MCE) for a particular location. For the majority of the United States, including the Mid-America region, the MCE is defined as an earthquake with a return period of 2500 years or a 2% probability of exceedance in 50 years (ASCE/SEI 2005). This is not the case in portions of California where, because seismic sources are better known, MCE is defined as the largest earthquake that can be delivered by the known seismic sources in the region (Frankel et al. 2002). As a result, the values of spectral acceleration used for the design of buildings in Mid-America would approach those used in coastal California. For example, the MCE spectral response accelerations used for design at short periods in Memphis, TN would be 1.21g compared to 1.50g in San Francisco, CA (IBC 2006). However, in contrast to the design basis used in the IBC, FEMA estimates that buildings in the NMFZ are 5 to 10 times less likely to be damaged during their lives than are buildings in California (Stein et al. 2003).

According to Stein et al. (2003), some provisions in the IBC were proposed with almost no consideration of their costs and associated benefits. Estimates suggest that due to the adoption of the IBC, building costs could increase significantly, perhaps by 10% or more, depending on building type (Stein et al. 2003). While new construction would be required to meet increased seismic provisions if the IBC is adopted in Mid-America, owners of existing buildings may also be prompted to retrofit their buildings to meet the new provisions. In this case, decision analysis can be used to determine a proper course of action in a rational way.

However, an individual's judgment regarding which risk is acceptable is affected by personal biases that may lead to decisions based on a false understanding of the actual risk. That is to say, as noted by May (2004), images of earthquakes are often more important in shaping the sense of risk than are their actual probability of occurrence. Furthermore, people tend to have trouble addressing uncertainties associated with small samples, such as interpretation of recurrence intervals for earthquakes. Individuals might be expected to think of long recurrence intervals of earthquakes as deterministic statements that will not occur for a long time rather than as probabilistic statements about the events (May 2004).

Due to the aforementioned concerns regarding the decreased likelihood of building damage from seismic activity in the NMFZ compared to that in California as well as human bias in the decision-making process, a quantitative measure of the economic costs and benefits of seismic retrofitting that considers the probability of occurrence of seismic events is necessary to make a rational decision.

## 1.2 OBJECTIVES

Four major objectives are identified to understand the feasibility of seismically retrofitting existing structures. The first objective is to investigate how building location affects the annual probability of attaining or exceeding specified performance levels. The second objective is to develop a framework to determine the economic feasibility of seismic retrofitting. The third objective is to study the effects that achievable loss reduction, investment return period, and retrofitting cost have on the economic feasibility of seismic retrofitting. The final objective is to determine the impact of a modest retrofit strategy applied to identical example buildings in Memphis, TN and San Francisco, CA.

To effectively address the outlined objectives, this thesis is divided into four major sections. Each section focuses on one of the stated objectives. The sections follow the order of the objectives as listed above.

# CHAPTER II

# ANNUAL PROBABILITY OF FAILURE OF EXAMPLE BUILDINGS

To investigate how building location affects the annual probability of attaining or exceeding selected performance levels, two identical example buildings, one located in Memphis, TN and one in San Francisco, CA, are considered. The selection of Memphis and San Francisco for this study is relevant because the provisions in the latest version of the IBC, if adopted, would increase the earthquake design levels for new buildings in Memphis similar to those for buildings in high-seismic application zones of California. In this chapter, the formulation for the probability of failure and generalized reliability index of a structure due to seismic events is presented. Design details of the example buildings are outlined and the parameters necessary to compute the probabilities of failure of the buildings, including the building fragility and seismic hazard at the building locations, are defined.

## 2.1 FORMULATION OF PROBABILITY OF FAILURE

The probability of failure of a structure due to seismic events can be computed using the total probability rule as

$$P_f = \int_{S_a} F\left(S_a\right) f\left(S_a\right) dS_a \tag{2.1}$$

where $S_a$ is spectral acceleration, $F(S_a)$ is the seismic fragility of the structure defined as the conditional probability of attaining or exceeding a specified performance level for a given $S_a$, and $f(S_a)$ is the annual probability density of $S_a$ at the site of the building. The corresponding generalized reliability index (Ditlevsen 1979) can be expressed in terms of $P_f$ as

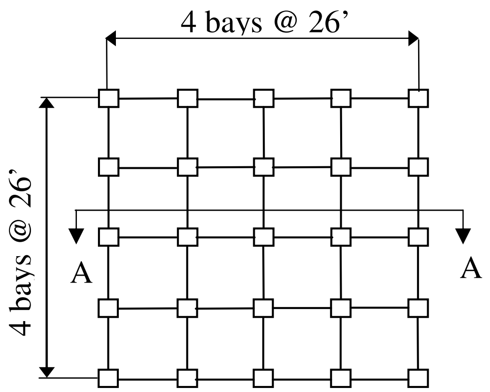
$$\beta = \Phi^{-1}\left(1 - P_f\right) \tag{2.2}$$

where $\Phi^{-1}(\cdot)$ represents the inverse standard normal cumulative distribution function.

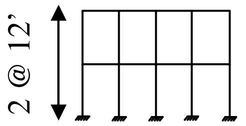
## 2.2 DESIGN DETAILS OF EXAMPLE BUILDINGS

Two identical two-story reinforced concrete (RC) frame buildings designed primarily for gravity loads are used in this study (Ramamoorthy et al. 2006). The example buildings are prone to "soft-story" failure mechanisms and intended to be representative of low-rise construction typically found in Mid-America.

All components of the example buildings, including slabs, beams, and columns, were designed and detailed only for gravity-load effects according to ACI-318 (ACI 2005) non-seismic design provisions. The gravity loads consist of the structural self weight of each building, 20 psf superimposed dead loads for electrical, mechanical, plumbing, and floor and ceiling fixtures, 250 lb/ft for exterior cladding, and 50 psf for live loads for a typical office building. Each example building has a fundamental natural period of 0.58 sec. as determined by eigenvalue analysis (Ramamoorthy et al. 2006). Figs. 2.1 and 2.2 show the resulting building plan and section details.



(a) Plan View



(b) Elevation View (Section A-A)

**Fig. 2.1** Plan and elevation views of example buildings (Ramamoorthy et al. 2006) (Not to scale)

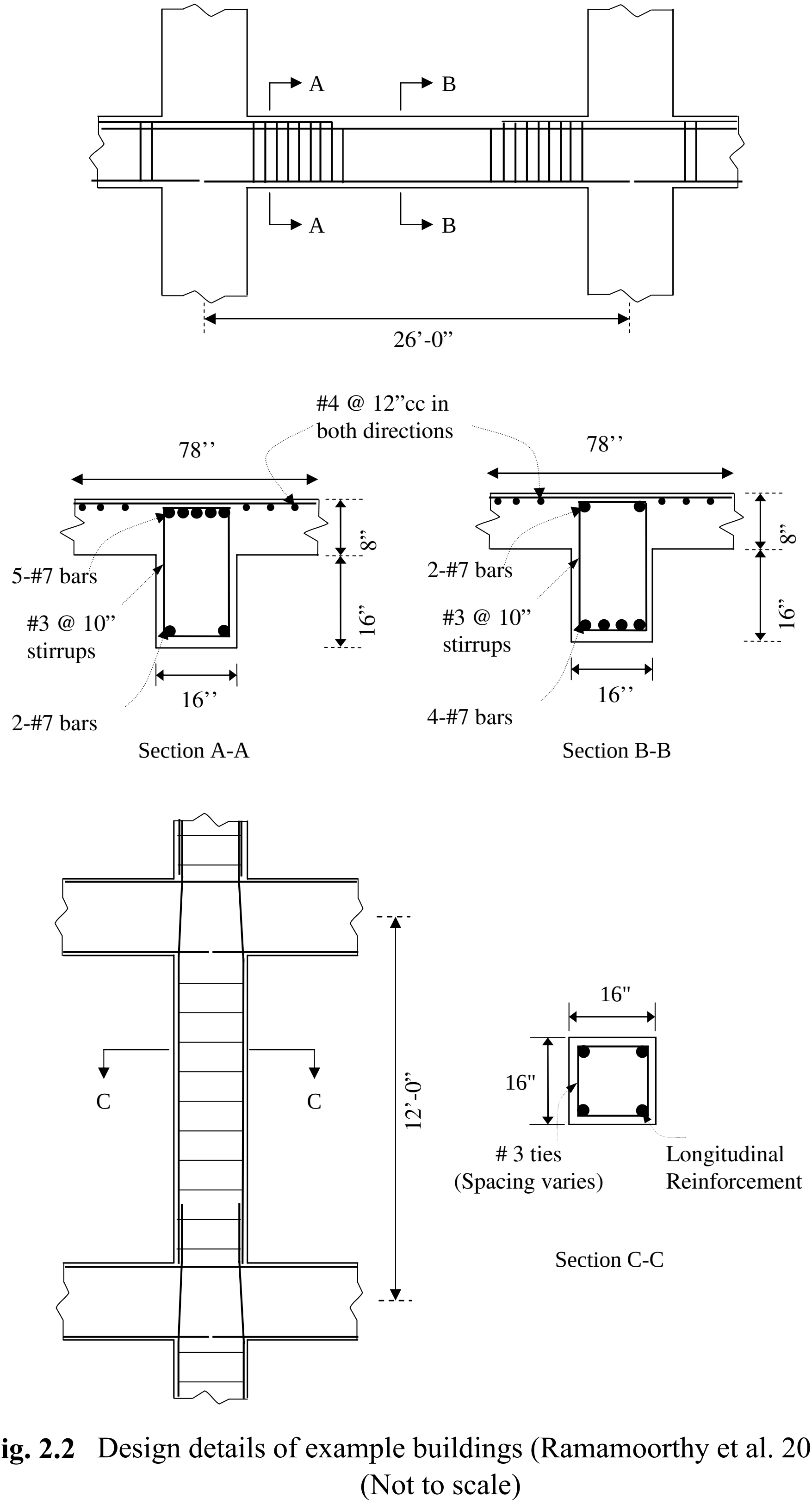


**Fig. 2.2** Design details of example buildings (Ramamoorthy et al. 2006) (Not to scale)

## 2.3 FRAGILITIES OF EXAMPLE BUILDINGS

Fragility estimates, $F(S_a)$, developed by Ramamoorthy *et al.* (2006) for the two-story RC example buildings are used in this study. These estimates were constructed using predicted drift demands developed using a Bayesian methodology and structural drift capacity values for three qualitative performance levels described in FEMA-356 (FEMA 2000) guidelines: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). For RC structures, the IO, LS, and CP performance levels are defined by deterministic inter-story drift limits of 0.5%, 1%, and 2% of the story height (FEMA 2000). Fig. 2.3 shows the fragility curves for the identical example buildings.

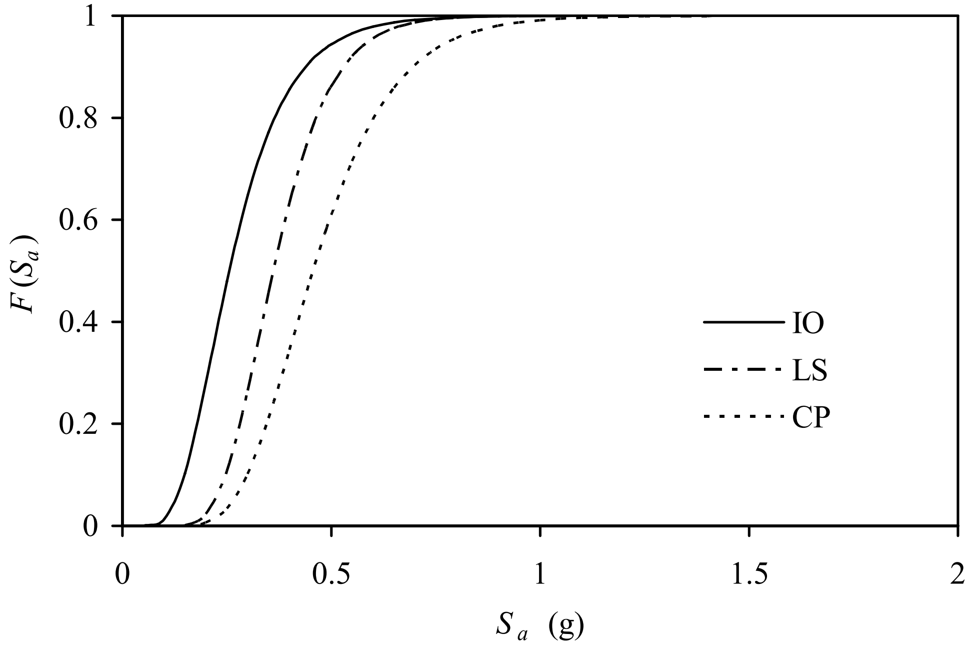


**Fig. 2.3** Fragility curves for identical example 2-story RC buildings designed primarily for gravity loads

## 2.4 SEISMIC HAZARD AT MEMPHIS, TN AND SAN FRANCISCO, CA

The probability of future seismic activity at a specific location can be quantified using the seismic hazard function, $G(S_a)$. $G(S_a)$ is defined as the expected annual frequency of a site experiencing ground motion intensity equal to $S_a$ or greater. Assuming the arrival of earthquakes is a Poisson process (Frankel et al. 2002), $f(S_a)$ can be expressed in terms of $G(S_a)$ as

$$f\left(S_a\right) = \exp\left(-G\left(S_a\right)\right)\left(-\frac{dG\left(S_a\right)}{dS_a}\right). \tag{2.3}$$

Annualized seismic hazard exceedance curves containing discrete values of $G(S_a)$ for locations throughout the United States are available from the United States Geological Survey (USGS). These curves are produced using available information about past earthquakes, deformation of the earth's crust, seismic attenuation relationships, and geologic site conditions (Frankel et al. 2002). Values of $G(S_a)$ from the USGS seismic hazard exceedance curves for Memphis, TN and San Francisco, CA are used for this study. Fig. 2.4 shows a comparison of USGS (Frankel et al. 2002) seismic hazard curves at Memphis and San Francisco for one-second spectral accelerations. The figure clearly shows that the annual probability of occurrence of an earthquake in San Francisco is significantly larger than in Memphis.

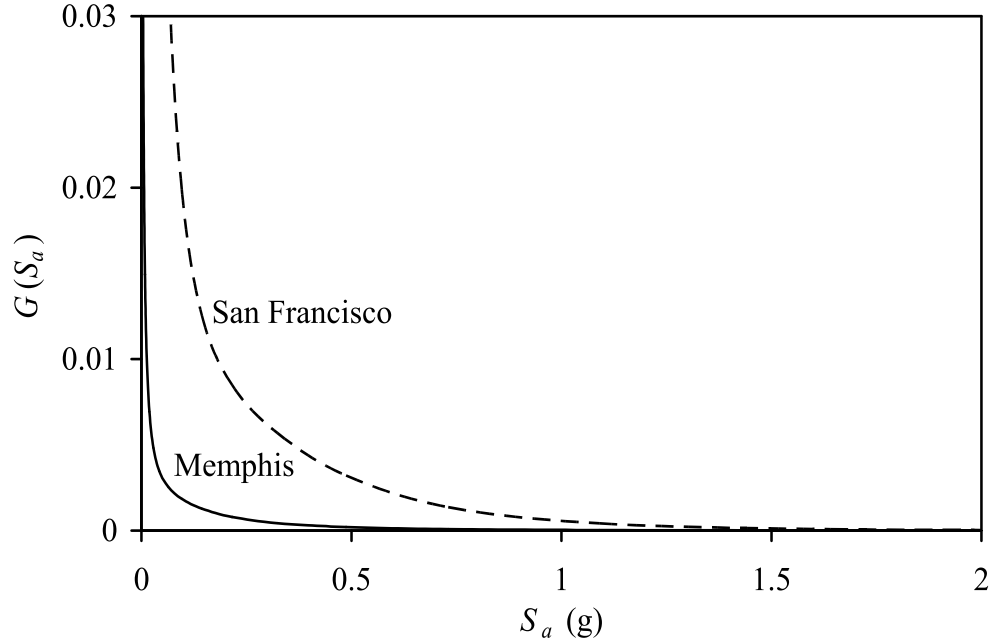


**Fig. 2.4** Comparison of USGS (2002) seismic hazard curves at Memphis, TN and San Francisco, CA for one-second spectral accelerations

## 2.5 RESULTS

Table 2.1 shows the values of $P_f$ and $\beta$ for the example buildings for each FEMA-356 performance level. A key observation from these results is that, for each performance level, $P_f$ in San Francisco is approximately 10 times greater than in Memphis. It is also important to note that the values of $\beta$ for the example RC building in Memphis are within a commonly accepted range (TRB 2005). This suggests that seismically retrofitting the example building in Memphis may be unnecessary unless some financial benefit can be gained as a result.

**Table 2.1** Probabilities of failure and generalized reliability indices for identical example 2-story RC buildings in Memphis, TN and San Francisco, CA

| | | Memphis | San Francisco |
|---|---|---|---|
| Failure Probability $P_f$ | IO | 0.0059 | 0.0644 |
| | LS | 0.0047 | 0.0469 |
| | CP | 0.0038 | 0.0351 |
| Reliability Index $\beta$ | IO | 2.52 | 1.52 |
| | LS | 2.60 | 1.68 |
| | CP | 2.67 | 1.81 |

# CHAPTER III

# FRAMEWORK FOR ECONOMIC BENEFIT AND ESTIMATED ANNUAL LOSS

In order to determine the economic feasibility of a seismic retrofit, the costs and benefits of such a retrofit must be considered. A framework is outlined in this chapter to compute the expected economic benefit resulting from a retrofit based on $F(S_a)$ and $G(S_a)$.

## 3.1 FORMULATION OF ESTIMATED ANNUAL LOSS

In order to evaluate the economic benefit of a seismic retrofit, a method is needed to determine the expected value of estimated annual loss, *EAL*, due to seismic events that can be easily repeated for numerous cases without having to modify individual parameters based on particular characteristics of a specific building. Numerous accepted methods exist to determine *EAL*. However, different methods require different input data. While several methods were considered, based on the available information for this study, the method of integration of seismic vulnerability and hazard (Porter et al. 2004) appears most practical.

Applying the method of integration of seismic vulnerability and hazard, *EAL* can be defined as

$$EAL = V \int_{S_a=0}^{\infty} y\left(S_a\right) v\left(S_a\right) dS_a \tag{3.1}$$

where $V$ denotes the replacement value of a building, the random variable $y(S_a)$ is the total damage factor defined as the repair cost of a building for a given $S_a$ as a fraction of $V$, and $v(S_a)$ is the average annual frequency of experiencing $S_a$, which can be determined from $G(S_a)$. A point estimate of the expected *EAL* can be computed considering mean values of $y(S_a)$. As such, Eq. (3.1) can be rewritten as

$$E\hat{A}L = V \int_{S_a=0}^{\infty} \hat{y}\left(S_a\right) v\left(S_a\right) dS_a \tag{3.2}$$

where $E\hat{A}L$ and $\hat{y}(S_a)$ indicate point estimates of the expected *EAL* and mean $y(S_a)$, respectively. While the use of mean values of $y(S_a)$ is appropriate when estimating the expected *EAL*, it should be noted that this approach does not fully capture collapse of the building.

Because only discrete values of $G(S_a)$ are available from the USGS, Porter et al. (2004) proposed a discrete formulation for Eq. (3.2) as follows:

$$E\hat{A}L = V \sum_{i=1}^{n} \left( \hat{y}_{i-1} G_{i-1} \left(1 - \exp\left(m_i \Delta S_a\right)\right) - \frac{\Delta \hat{y}_i}{\Delta S_a} G_{i-1} \left( \exp\left(m_i \Delta S_a\right) \left( \Delta S_a - \frac{1}{m_i} \right) + \frac{1}{m_i} \right) \right) \tag{3.3}$$

where $m$ is the slope of the natural log of $G(S_a)$ and can be expressed as

$$m_i = \frac{\ln\left(\frac{G_i}{G_{i-1}}\right)}{\Delta S_a}. \tag{3.4}$$

In accordance with the methodology proposed by Porter *et al.* (2004), $E\hat{A}L$ is calculated from Eq. (3.3) using 20 discrete values of $S_a$ equally spaced and ranging from 0.1g to

2.0g. The available hazard exceedance values of $G(S_a)$ are interpolated in the log-frequency domain to calculate the hazard at the fundamental period of the building.

## 3.2 TOTAL DAMAGE FACTORS FOR EXAMPLE BUILDINGS

For this study, $\hat{y}(S_a)$ is computed using the loss estimation framework proposed by Bai et al. (2007). Applying this framework, four damage states are assumed to be bounded by $F(S_a)$ for each FEMA-356 performance level. The probability of being in each damage state $k$ for a given $S_a$ is calculated and is then used to compute $\hat{y}(S_a)$ using the following expression:

$$\hat{y}\left(S_a\right) = \sum_{k=1}^{4}\left(\mu_k \times P_{k|S_a}\right) \tag{3.5}$$

where $\mu_k$ is the mean percentage of damage associated with damage state $k$, and $P_{k|S_a}$ is the probability of being in each damage state for a given value of $S_a$. Fig. 3.1 shows calculated values of $\hat{y}(S_a)$ for the example buildings. Because the example buildings in Memphis and San Francisco are identical, the values of $\hat{y}(S_a)$ at both locations are the same.

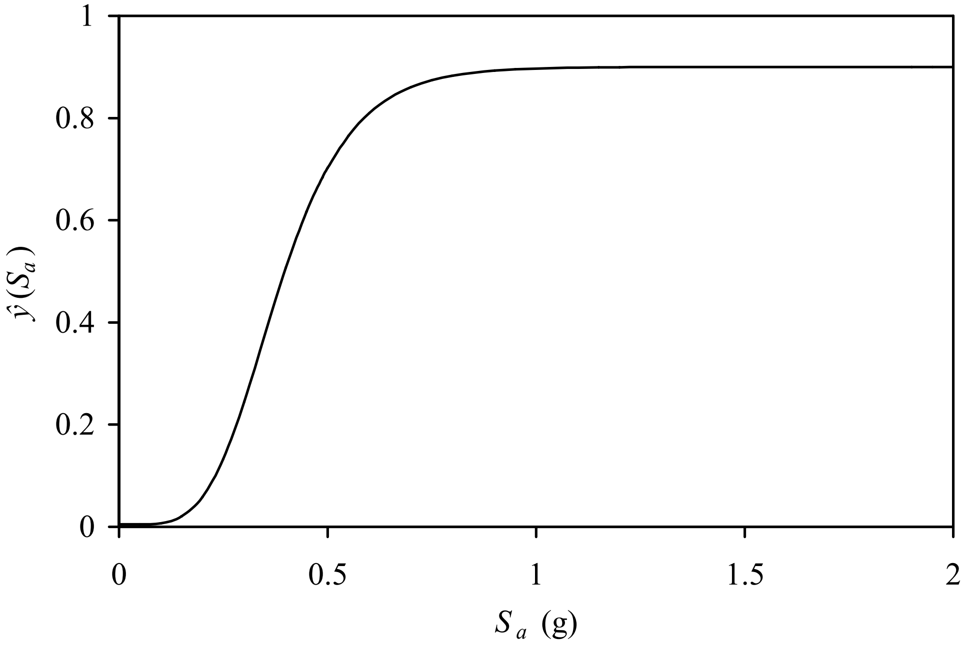


**Fig. 3.1** Total damage factors for identical example 2-story RC buildings designed primarily for gravity loads

## 3.3 DETERMINATION OF ECONOMIC BENEFIT

The expected *EAL* due to seismic events can be used to determine the economic benefit of a retrofitting strategy. This approach was used by Porter et al. (2006) to define the expected value of economic benefit, $B$, of a seismic retrofit in terms of present value as

$$B = \left( E\hat{A}L - E\hat{A}L_r \right) \left( \frac{1 - e^{-\rho T}}{\rho} \right) \tag{3.6}$$

where $\rho$ is the real discount rate and $T$ is the investment return period in years. The subscript $r$ indicates the value of $E\hat{A}L$ following a seismic retrofit. For a seismic retrofit to be financially viable, $B$ must be greater than the retrofit costs (Porter et al. 2006).

## 3.4 RESULTS

From Eq. (3.3), values of $E\hat{A}L$ for the example buildings in Memphis and San Francisco are 0.41% and 4.09% of $V$, respectively. Therefore, $E\hat{A}L$ for the building in San Francisco is roughly ten times greater than for the building in Memphis. Because $E\hat{A}L$ is already so small for the example building in Memphis, it may be difficult for any retrofit to produce a meaningfully reduction. Accordingly, the results also suggest that a greater need may exist to retrofit the example building in San Francisco rather than the one in Memphis in order to reduce $E\hat{A}L$. A tabulated summary of the calculation of $E\hat{A}L$ for both example buildings is included in the appendix of this thesis.

# CHAPTER IV

# PARAMETRIC ANALYSIS OF FEASIBILITY OF SEISMIC RETROFIT

A seismic retrofit of a building is a viable option if some economic benefit can be gained as a result of the retrofit. A parametric analysis is conducted to study the feasibility of seismically retrofitting an example building in Memphis compared to the feasibility of retrofitting an identical building in San Francisco.

## 4.1 FRAMEWORK FOR PARAMETRIC ANALYSIS

Retrofit feasibility is studied in Memphis and San Francisco considering the investment return period, the reduction in $E\hat{A}L$, and the retrofit cost. For this analysis, the retrofit feasibility is framed in terms of the maximum allowable cost of a seismic retrofit, which is equivalent to $B$. If a retrofit procedure will be more expensive than its maximum allowable cost based on the desired return period and reduction in $E\hat{A}L$, the retrofit is not economically feasible. Similarly, as the expense of a seismic retrofit compared to its maximum allowable cost decreases, the economical feasibility of the retrofit increases. For all calculations in this study, the maximum allowable retrofit cost is computed as a fraction of $V$, and a value of 0.03 or 3% is used for $\rho$.

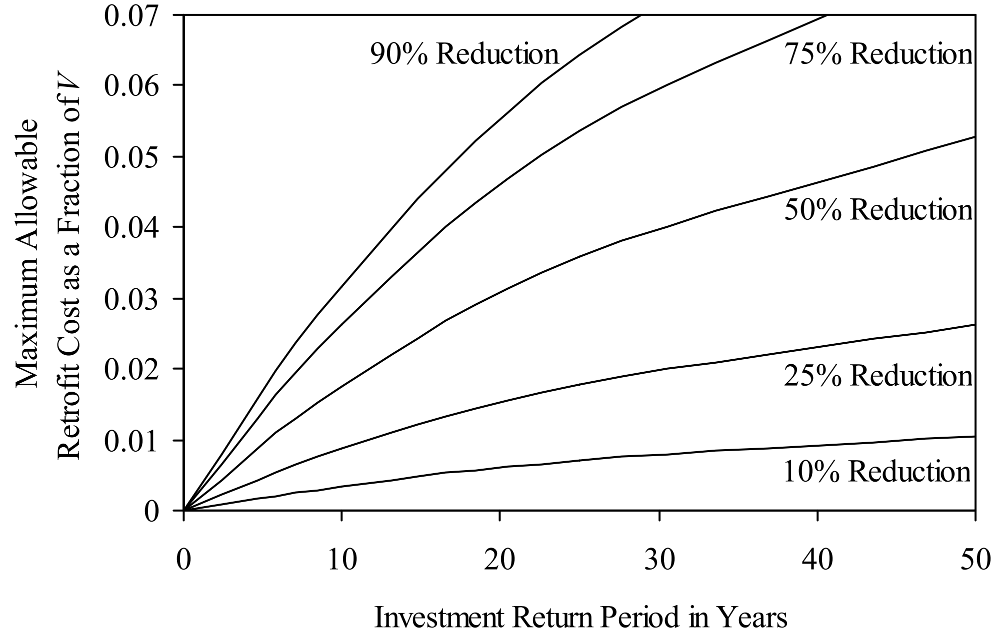
To easily display the results of the parametric analysis, feasibility graphs are constructed. The data in the feasibility graphs are represented in the form of "break-even" curves; for the particular seismic retrofit represented by each point along these curves, the retrofit cost is equal to $B$. Each feasibility graph is constructed by keeping one of the three parameters constant and varying the other two parameters. Using this method, three sets of feasibility graphs are created with each set containing one graph for the example building in Memphis and one for the building in San Francisco. It is important to note that while each set of feasibility graphs has a specific purpose and use, the same data is used in each set. Therefore, each set of graphs contains the same information, but each set represents that information in different ways. The numerical data used to create each set of feasibility graphs is tabulated in the appendix of this thesis.

Fig. 4.1 shows the first set of feasibility graphs that can be used to determine the maximum allowable retrofit cost for a desired investment return period when the reduction in $E\hat{A}L$ due to a retrofit is known. To use these graphs, select the desired investment return period from the horizontal axis. Next, select the curve that most accurately corresponds to the likely reduction in $E\hat{A}L$ resulting from a particular seismic retrofit. Finally, the corresponding maximum allowable retrofit cost in order to break even can be determined from the vertical axis.

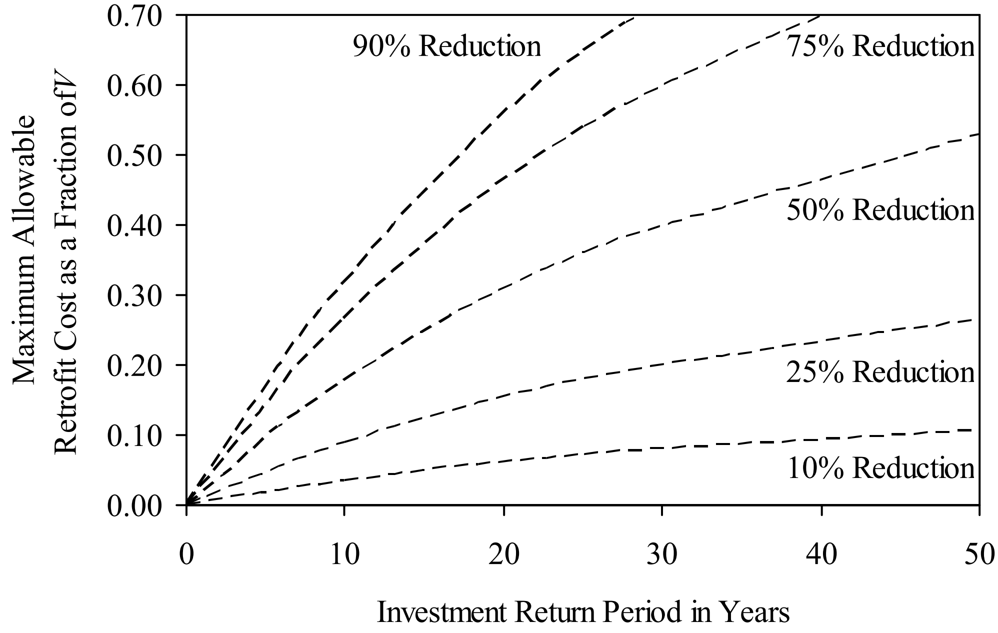
Fig. 4.2 shows the second set of feasibility graphs that can be used to determine the required reduction in $E\hat{A}L$ for a seismic retrofit to be economically viable for a desired cost and return period. To use these charts, select the desired retrofit budget from the horizontal axis. Next, select the line that corresponds to the desired investment return period for retrofit costs. Finally, the minimum required reduction in $E\hat{A}L$ in order to break even is determined from the vertical axis.

Fig. 4.3 shows the third set of feasibility graphs that can be used to determine the cost for different return periods when the reduction in $E\hat{A}L$ due to a retrofit is known. First, select the reduction in $E\hat{A}L$ from the horizontal axis. Next, select the contour line that most accurately corresponds to the desired seismic retrofit budget as a fraction of $V$. Finally, determine the corresponding return period from the vertical axis for the selected retrofit cost and $E\hat{A}L$ reduction. This value is the time required to recover the cost of the retrofit.

From a business perspective, a seismic retrofit is a viable option in most situations if a positive economic benefit exists for a five-year planning period (Porter et al. 2004). However, different circumstances may allow for longer return times. For comparison purposes, planning periods of up to 50 years are considered in this analysis. If the reduction in $E\hat{A}L$ due to indirect losses as a result of retrofitting is known, the graphs can be used to consider both structural and non-structural losses in the decision-making process. It is possible that in certain situations, a particular retrofit procedure could greatly reduce or nearly eliminate indirect losses as the result of seismic activity. In such cases, extremely large reductions in total $E\hat{A}L$ due to a retrofit are possible and are therefore considered in the feasibility graphs.

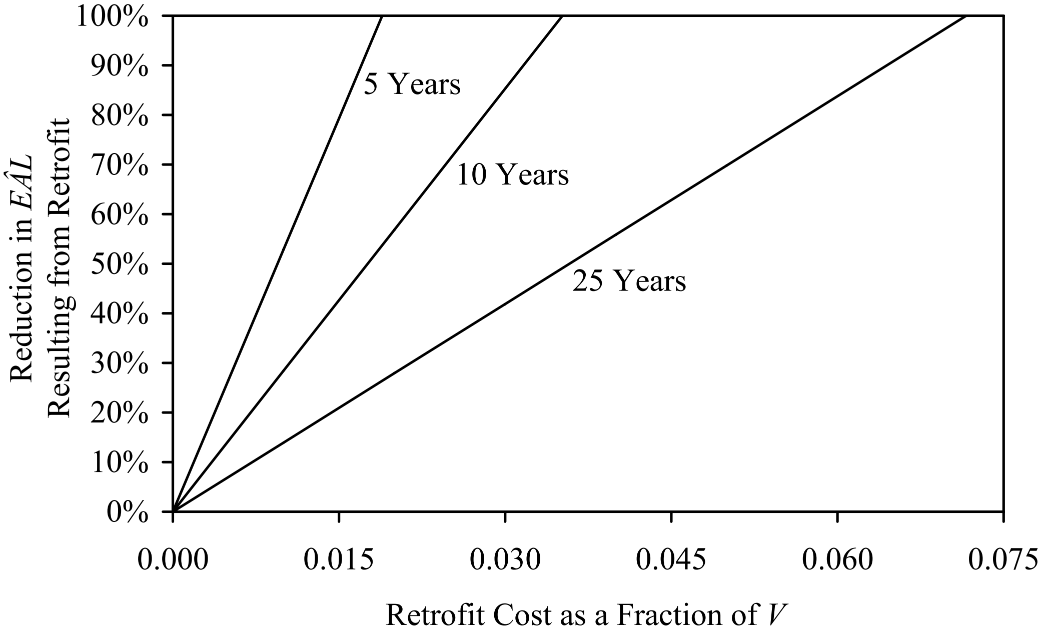


(a) Memphis, TN

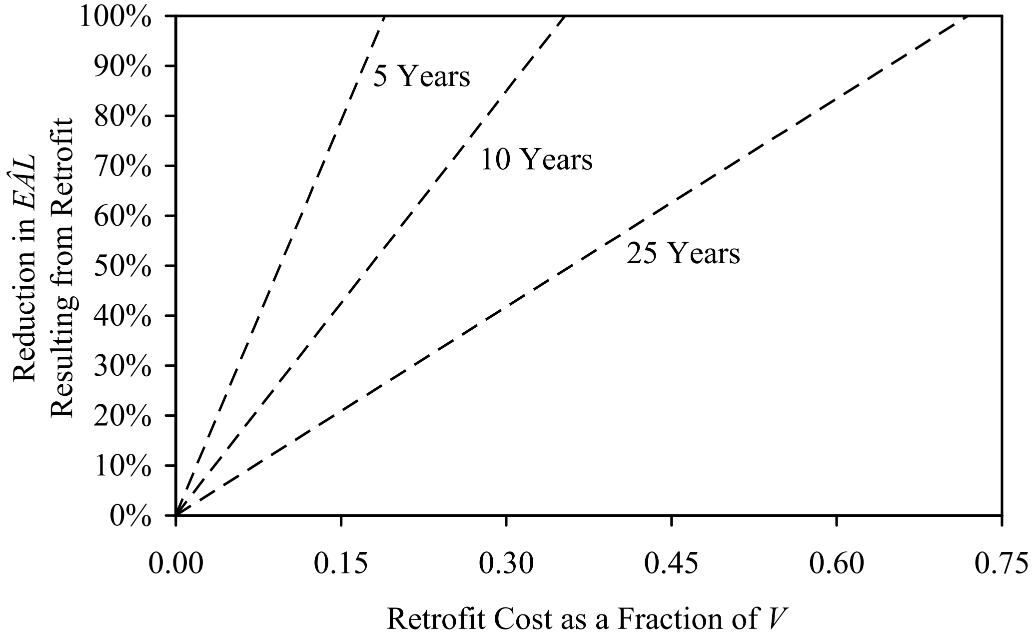


(b) San Francisco, CA

**Fig. 4.1** Feasibility of seismic retrofit for example buildings in Memphis, TN and San Francisco, CA for given reductions in $E\hat{A}L$

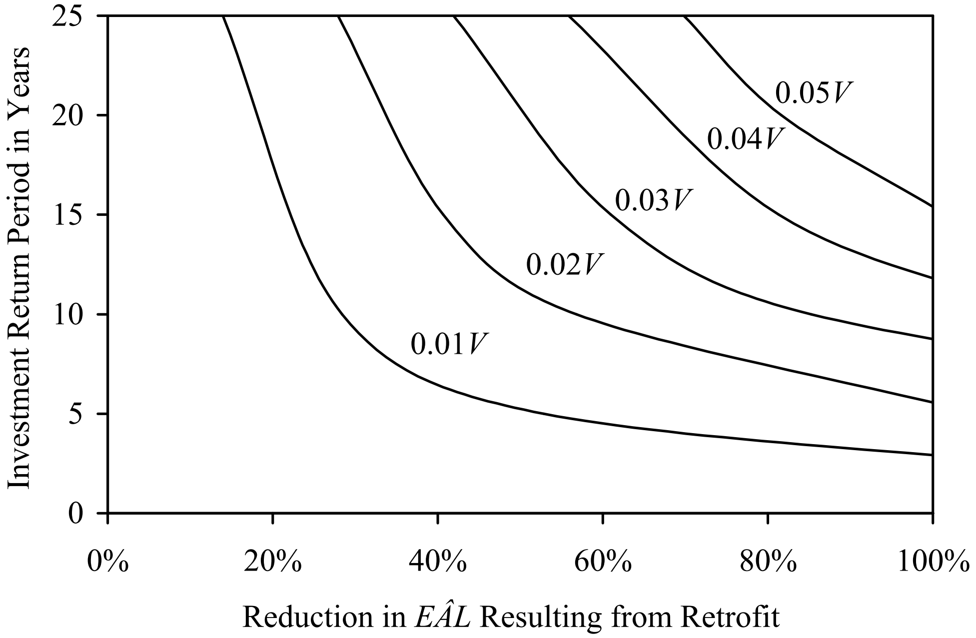


(a) Memphis, TN

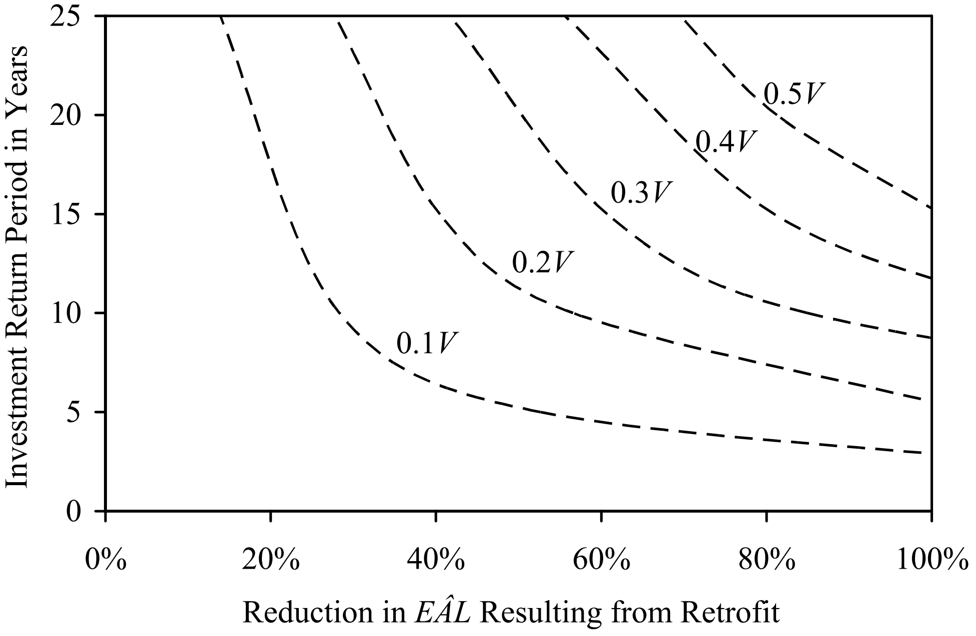


(b) San Francisco, CA

**Fig. 4.2** Feasibility of seismic retrofit for example buildings in Memphis, TN and San Francisco, CA for desired investment return periods



(a) Memphis, TN



(b) San Francisco, CA

**Fig. 4.3** Feasibility of seismic retrofit for example buildings in Memphis, TN and San Francisco, CA for varying retrofit costs

## 4.2 RESULTS

The results of the parametric analysis indicate that, for most situations, a seismic retrofit of the example building in San Francisco is more economically feasible than a retrofit of the building in Memphis. For instance, consider a retrofit that reduces $E\hat{A}L$ for a building by 50% and has a planning period of 10 years. Such a retrofit in Memphis is only viable at a cost of less than 1.78% of $V$, which is an extremely small budget considering that for such a retrofit in San Francisco, up to 17.7% of $V$ can feasibly be spent. As a rule of thumb, the budget for a retrofit that reduces $E\hat{A}L$ by any given percentage is 10 times greater in San Francisco than in Memphis

A reasonable cost for a retrofit that reduces $E\hat{A}L$ up to 50% would be 5% to 10% of the replacement cost of the building (Porter et al. 2006). That cost comfortably fits into the allowable budget for a retrofit in San Francisco for investment return periods of 5 to 10 years. However, for such a retrofit to be viable in Memphis, an extremely extended and likely unreasonable investment return period would have to be used for planning purposes, or the amount of indirect cost saved or recovered due to a retrofit would have to account for an overwhelming majority of the cost of the retrofit. Consequently, it is unlikely that, for most buildings in the Memphis area, retrofitting will reduce $E\hat{A}L$ enough to garner any substantial economic benefit for a reasonable return period of 5 to 10 years.

# CHAPTER V

# IMPACT OF RETROFIT: A CASE STUDY

Stakeholders need to consider the improvements in the reliability provided by a retrofitting strategy in addition to its expected economic benefit to determine if a retrofit is feasible. A case study is performed for the example buildings in Memphis and San Francisco based on a modest retrofit strategy as suggested by Ramamoorthy et al. (2006). Estimates of $P_f$ and $\beta$ as well as $E\hat{A}L$ for the retrofitted example buildings are calculated and compared to the corresponding values for the original buildings.

## 5.1 OVERVIEW OF RETROFIT STRATEGY

For the case study, retrofitted column-to-beam strength ratios of 1.8 are used to deter the "soft-story" failure mechanism (Bracci et al. 1992, 1995). $F(S_a)$ for the example buildings based on this retrofit strategy has been calculated by Ramamoorthy et al. (2006) and is used to determine $P_f$, $\beta$, and $E\hat{A}L$ for the retrofitted structures. Values of $F(S_a)$ and $\hat{y}(S_a)$ for the retrofitted buildings are plotted in Fig. 5.1 and 5.2, respectively. As shown by Dooley and Bracci (2001), column-to-beam strength ratio at beam-column joints is a key variable in controlling seismic damage to RC frame structures. Consequently, column jacketing is an efficient technique used to accomplish column strengthening by enlarging existing column sections with new concrete and additional reinforcement (Bracci et al. 1992, 1995). Using this retrofit strategy, capacity limits for the buildings are increased to approximately the same limits of seismically designed structures. This type of retrofit is a likely choice for a low-rise RC frame building similar to the example buildings used in this study.

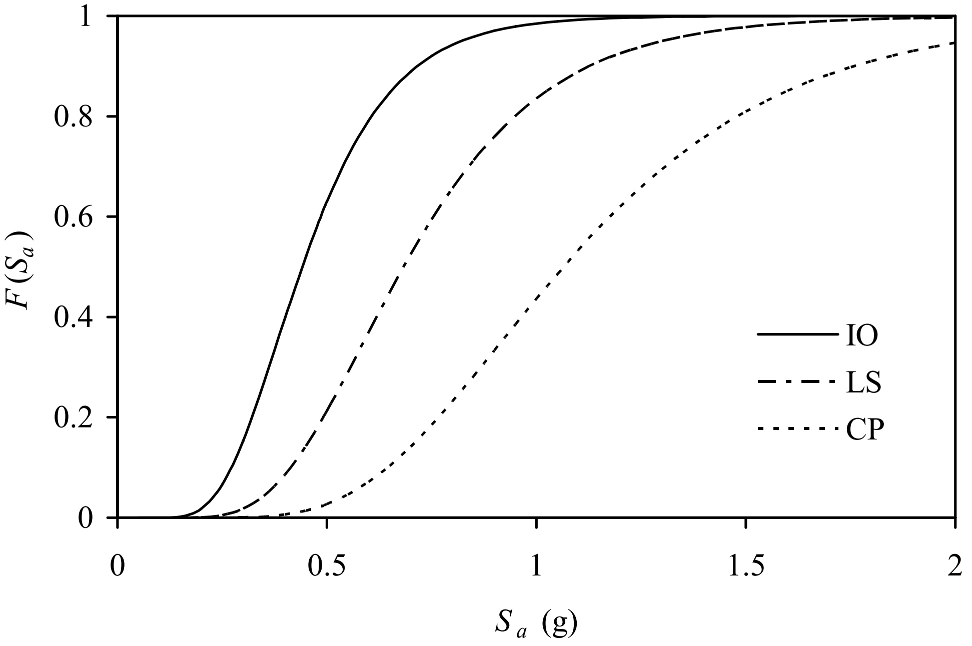


**Fig. 5.1** Fragility curves for retrofitted example 2-story RC buildings

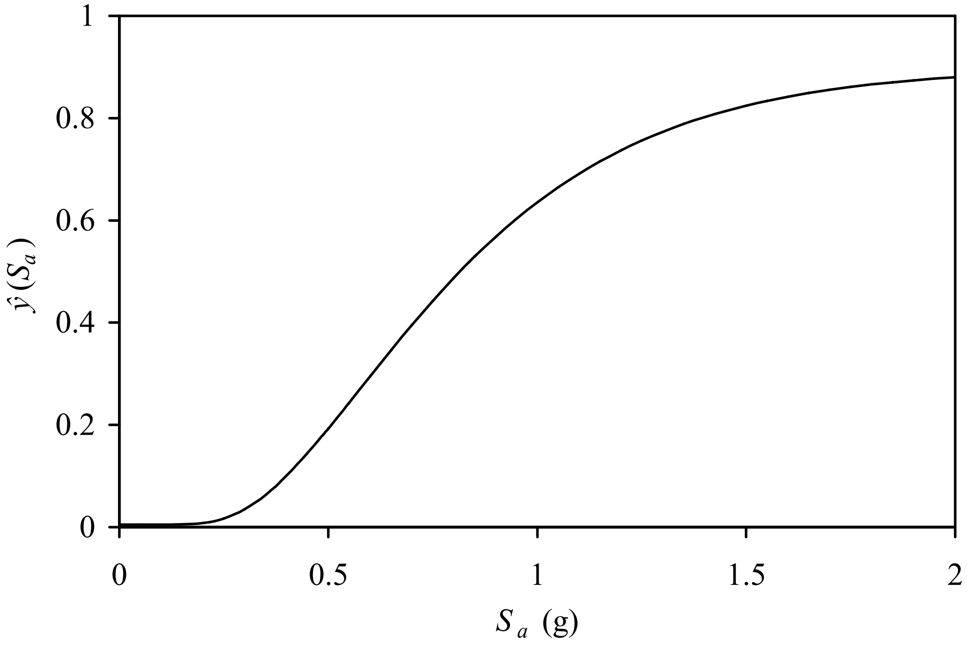


**Fig. 5.2** Total damage factors for retrofitted example 2-story RC buildings

## 5.2 RESULTS AND DISTRIBUTION OF EAL FOR EXAMPLE BUILDINGS

The annual probabilities of failure and generalized reliability indices are calculated for the retrofitted example buildings in Memphis and San Francisco. Table 5.1 shows $P_f$ and $\beta$ for the retrofitted buildings compared to the corresponding values for the original buildings. The results indicate that the reliability of the original un-retrofitted building in Memphis is higher than that of the retrofitted building in San Francisco.

The reduction in $E\hat{A}L$ for the example buildings due to retrofit is also determined using the loss estimation framework described earlier. For the example buildings, the column-strengthening retrofit strategy reduces $E\hat{A}L$ in Memphis by 51% and in San Francisco by 60%. Fig. 5.3 shows a comparison of the maximum allowable retrofit costs for the example buildings in Memphis and San Francisco based on the reductions in $E\hat{A}L$ due to retrofit. For $T$ equal to five years, the maximum allowable retrofit cost is nearly 12 times greater for the example building in San Francisco than for the building in Memphis. Therefore, the prescribed retrofit can be accomplished in San Francisco with a much larger budget and potentially a greater financial benefit than in Memphis.

Fig. 5.4 shows simulated probability density functions, $f(EAL)$, for the original and retrofitted example buildings in Memphis and San Francisco. Applying engineering judgment, the probability densities of $EAL$ are modeled as beta distributions based on random simulations of $EAL$. An important observation from Fig. 5.4 is that the distributions of $EAL$ for retrofitted example buildings are skewed towards higher values of $EAL$ whereas the distributions of $EAL$ for the original example buildings are more symmetrical. This is particularly significant because $B$ for the retrofit procedure examined in this study is determined using expected values of $EAL$. Because the $EAL$ for the retrofitted buildings is more likely to be higher than the expected value rather than lower, it is also more likely that the actual reduction in $EAL$ due to a retrofit procedure will be lower than the expected reduction in $EAL$ rather than higher. Although the expected value of $EAL$ is what generally interests insurance professionals and city planners, building owners and investors will likely also consider that tails of the distribution when making a decision regarding seismic retrofitting.

**Table 5.1** Comparison of probabilities of failure and generalized reliability indices for original and retrofitted example RC buildings in Memphis, TN and San Francisco, CA

| | | Memphis | | San Francisco | |
|---|---|---|---|---|---|
| | | Original | Retrofit | Original | Retrofit |
| Failure Probability $P_f$ | IO | 0.0059 | 0.0039 | 0.0644 | 0.0372 |
| | LS | 0.0047 | 0.0024 | 0.0469 | 0.0192 |
| | CP | 0.0038 | 0.0013 | 0.0351 | 0.0077 |
| Reliability Index $\beta$ | IO | 2.52 | 2.66 | 1.52 | 1.78 |
| | LS | 2.60 | 2.82 | 1.68 | 2.07 |
| | CP | 2.67 | 3.02 | 1.81 | 2.42 |

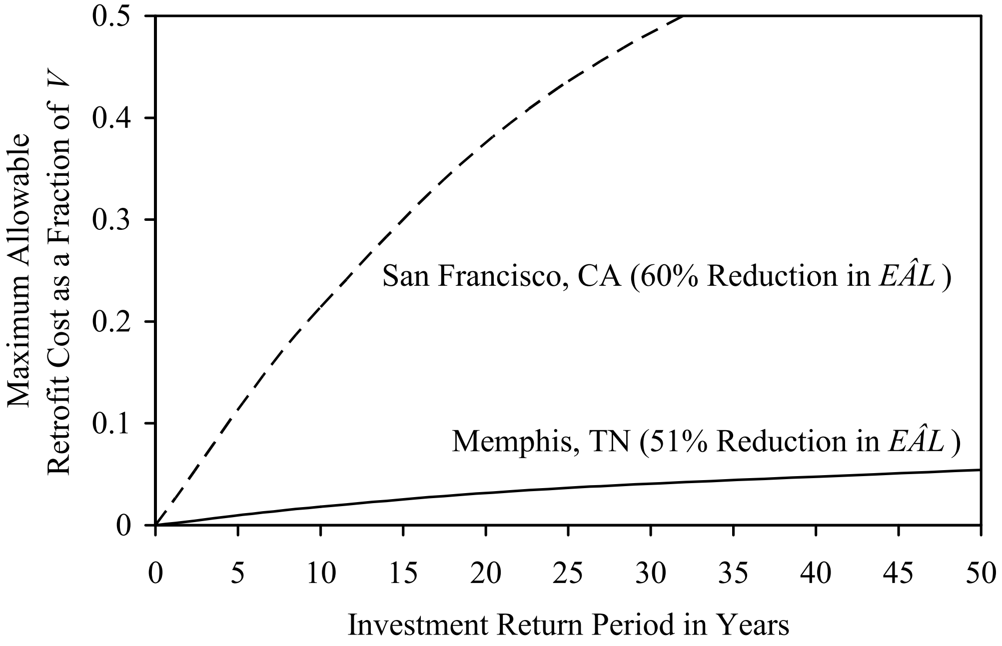
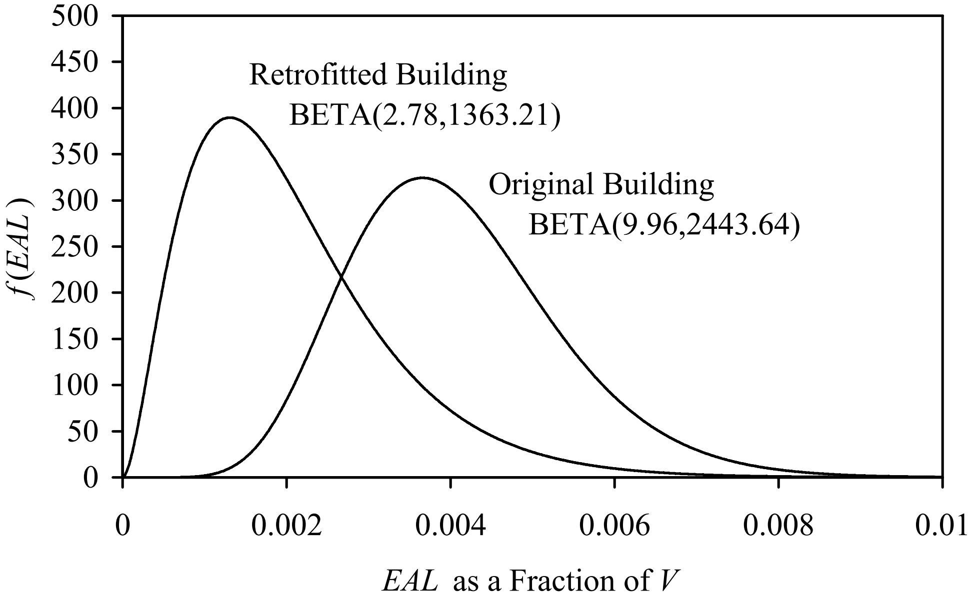
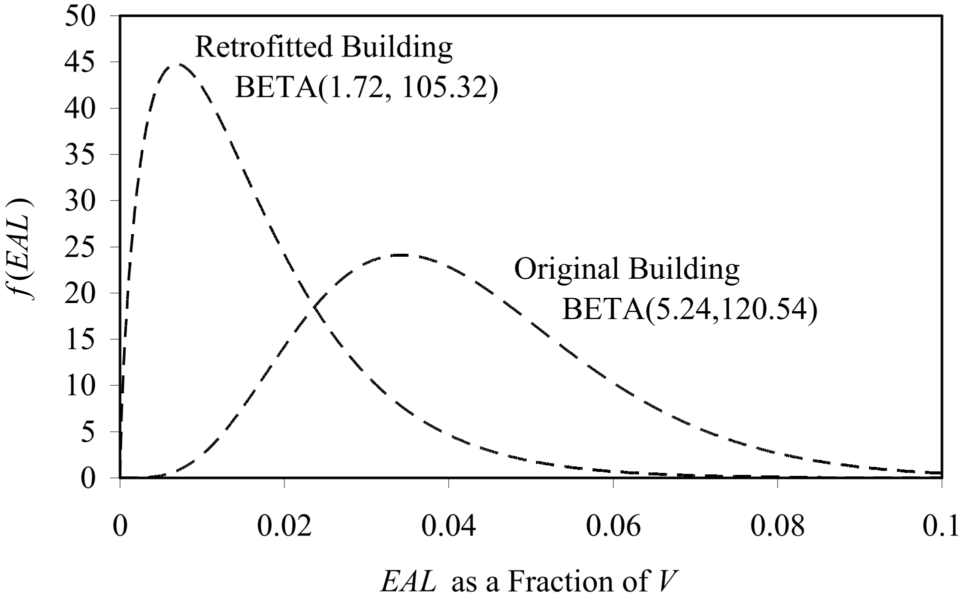


**Fig. 5.3** Feasibility of modest retrofit strategy for example buildings in Memphis, TN and San Francisco, CA for varying retrofit costs



(a) Memphis, TN



(b) San Francisco, CA

**Fig. 5.4** Probability density function of *EAL* for original and retrofitted example buildings in Memphis, TN and San Francisco, CA

# CHAPTER VI

# CONCLUSIONS

The economic benefit of a given retrofit procedure can be determined using the framework detailed in this study. A parametric analysis is conducted to determine how certain parameters affect the feasibility of a seismic retrofit. A case study is performed for the example buildings in Memphis and San Francisco using a modest retrofit procedure. The results of the parametric analysis and case study advocate that, for most situations, a seismic retrofit of an existing building is more financially viable in San Francisco than in Memphis.

Important contributions identified in this study are listed below:

1. The annual probability of exceeding a specified performance level for a gravity-load designed building in San Francisco is about ten times greater than if the same building is located in Memphis.
2. Using 2% earthquake intensity for the design basis of structures will not create uniform reliability (or probability of failure) on an annual basis throughout the United States. It will only ensure that buildings throughout the United States will not collapse under the 2% MCE.
3. The retrofit of gravity-load designed buildings may not be financially viable in Mid-America unless the indirect value (i.e. higher-importance use, expensive contents, human lives, etc.) is significantly greater than the direct

structural value. This may be the case for facilities such as emergency headquarters, hospitals, etc.

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# APPENDIX

**Table A.1** Calculation of $E\hat{A}L$ for 2-story RC building in Memphis, TN designed primarily for gravity loads

| $i$ | $S_a$ | $\Delta S_a$ | $G(S_a)$ | $\hat{y}(S_a)$ | $\Delta\hat{y}$ | $m$ | $v(S_a)$ | $E\hat{A}L_i$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.1 | | 0.002855 | 0.006866 | | | | |
| 1 | 0.2 | 0.1 | 0.001614 | 0.058486 | 0.051621 | -5.70 | 0.009205 | 0.000330 |
| 2 | 0.3 | 0.1 | 0.001052 | 0.245017 | 0.186530 | -4.28 | 0.004504 | 0.000998 |
| 3 | 0.4 | 0.1 | 0.000738 | 0.506943 | 0.261926 | -3.54 | 0.002611 | 0.001209 |
| 4 | 0.5 | 0.1 | 0.000502 | 0.702478 | 0.195535 | -3.85 | 0.001936 | 0.000651 |
| 5 | 0.6 | 0.1 | 0.000391 | 0.809481 | 0.107004 | -2.51 | 0.000982 | 0.000417 |
| 6 | 0.7 | 0.1 | 0.000279 | 0.860293 | 0.050812 | -3.37 | 0.000939 | 0.000177 |
| 7 | 0.8 | 0.1 | 0.000217 | 0.882907 | 0.022614 | -2.52 | 0.000546 | 0.000093 |
| 8 | 0.9 | 0.1 | 0.000176 | 0.892682 | 0.009775 | -2.09 | 0.000368 | 0.000053 |
| 9 | 1.0 | 0.1 | 0.000135 | 0.896860 | 0.004178 | -2.65 | 0.000357 | 0.000041 |
| 10 | 1.1 | 0.1 | 0.000097 | 0.898643 | 0.001783 | -3.31 | 0.000321 | 0.000035 |
| 11 | 1.2 | 0.1 | 0.000085 | 0.899407 | 0.000765 | -1.34 | 0.000114 | 0.000012 |
| 12 | 1.3 | 0.1 | 0.000073 | 0.899738 | 0.000331 | -1.55 | 0.000113 | 0.000011 |
| 13 | 1.4 | 0.1 | 0.000060 | 0.899883 | 0.000145 | -1.84 | 0.000111 | 0.000011 |
| 14 | 1.5 | 0.1 | 0.000048 | 0.899947 | 0.000064 | -2.25 | 0.000109 | 0.000011 |
| 15 | 1.6 | 0.1 | 0.000036 | 0.899975 | 0.000029 | -2.91 | 0.000105 | 0.000011 |
| 16 | 1.7 | 0.1 | 0.000029 | 0.899988 | 0.000013 | -2.02 | 0.000059 | 0.000006 |
| 17 | 1.8 | 0.1 | 0.000027 | 0.899995 | 0.000006 | -1.02 | 0.000027 | 0.000003 |
| 18 | 1.9 | 0.1 | 0.000024 | 0.899997 | 0.000003 | -1.14 | 0.000027 | 0.000003 |
| 19 | 2.0 | 0.1 | 0.000021 | 0.899999 | 0.000001 | -1.29 | 0.000027 | 0.000003 |

Total $E\hat{A}L$ = 0.00407 $V$

**Table A.2** Calculation of $E\hat{A}L$ for 2-story RC building in San Francisco, CA designed primarily for gravity loads

| $i$ | $S_a$ | $\Delta S_a$ | $G(S_a)$ | $\hat{y}(S_a)$ | $\Delta \hat{y}$ | $m$ | $v(S_a)$ | $E\hat{A}L_i$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.1 |  | 0.049098 | 0.006866 |  |  |  |  |
| 1 | 0.2 | 0.1 | 0.022781 | 0.058486 | 0.051621 | -7.68 | 0.174933 | 0.003837 |
| 2 | 0.3 | 0.1 | 0.013261 | 0.245017 | 0.186530 | -5.41 | 0.071754 | 0.010508 |
| 3 | 0.4 | 0.1 | 0.008614 | 0.506943 | 0.261926 | -4.31 | 0.037161 | 0.012164 |
| 4 | 0.5 | 0.1 | 0.005318 | 0.702478 | 0.195535 | -4.82 | 0.025649 | 0.006280 |
| 5 | 0.6 | 0.1 | 0.003917 | 0.809481 | 0.107004 | -3.06 | 0.011975 | 0.003798 |
| 6 | 0.7 | 0.1 | 0.002517 | 0.860293 | 0.050812 | -4.42 | 0.011136 | 0.001745 |
| 7 | 0.8 | 0.1 | 0.001800 | 0.882907 | 0.022614 | -3.35 | 0.006034 | 0.000867 |
| 8 | 0.9 | 0.1 | 0.001376 | 0.892682 | 0.009775 | -2.69 | 0.003695 | 0.000476 |
| 9 | 1.0 | 0.1 | 0.000952 | 0.896860 | 0.004178 | -3.68 | 0.003506 | 0.000401 |
| 10 | 1.1 | 0.1 | 0.000562 | 0.898643 | 0.001783 | -5.27 | 0.002963 | 0.000354 |
| 11 | 1.2 | 0.1 | 0.000475 | 0.899407 | 0.000765 | -1.68 | 0.000800 | 0.000083 |
| 12 | 1.3 | 0.1 | 0.000388 | 0.899738 | 0.000331 | -2.03 | 0.000786 | 0.000080 |
| 13 | 1.4 | 0.1 | 0.000301 | 0.899883 | 0.000145 | -2.54 | 0.000765 | 0.000079 |
| 14 | 1.5 | 0.1 | 0.000214 | 0.899947 | 0.000064 | -3.42 | 0.000731 | 0.000078 |
| 15 | 1.6 | 0.1 | 0.000126 | 0.899975 | 0.000029 | -5.24 | 0.000663 | 0.000078 |
| 16 | 1.7 | 0.1 | 0.000085 | 0.899988 | 0.000013 | -3.94 | 0.000336 | 0.000037 |
| 17 | 1.8 | 0.1 | 0.000075 | 0.899995 | 0.000006 | -1.32 | 0.000099 | 0.000010 |
| 18 | 1.9 | 0.1 | 0.000064 | 0.899997 | 0.000003 | -1.53 | 0.000098 | 0.000010 |
| 19 | 2.0 | 0.1 | 0.000054 | 0.899999 | 0.000001 | -1.80 | 0.000096 | 0.000010 |

Total $E\hat{A}L$ = 0.04089 $V$

**Table A.3** Required $E\hat{A}L$ reduction for increasing retrofit costs and return periods for 2-story RC building in Memphis, TN

| $E\hat{A}L_r$ as a fraction of $V$ | 0.00192 | 0 |
|---|---|---|
| $E\hat{A}L$ as a fraction of $V$ | 0.00407 | 0.00407 |
| $\rho$ | 3% | 3% |
| $T$ in years | 5 | 5 |
| $B$ as a fraction of $V$ | 0.010 | 0.0189 |

| $E\hat{A}L_r$ as a fraction of $V$ | 0.00292 | 0.00176 | 0.00060 | 0 |
|---|---|---|---|---|
| $E\hat{A}L$ as a fraction of $V$ | 0.00407 | 0.00407 | 0.00407 | 0.00407 |
| $\rho$ | 3% | 3% | 3% | 3% |
| $T$ in years | 10 | 10 | 10 | 10 |
| $B$ as a fraction of $V$ | 0.01 | 0.02 | 0.03 | 0.0352 |

| $E\hat{A}L_r$ as a fraction of $V$ | 0.00350 | 0.00294 | 0.00237 | 0.00180 | 0.00123 | 0 |
|---|---|---|---|---|---|---|
| $E\hat{A}L$ as a fraction of $V$ | 0.00407 | 0.00407 | 0.00407 | 0.00407 | 0.00407 | 0.00407 |
| $\rho$ | 3% | 3% | 3% | 3% | 3% | 3% |
| $T$ in years | 25 | 25 | 25 | 25 | 25 | 25 |
| $B$ as a fraction of $V$ | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.0716 |

**Table A.4** Required $E\hat{A}L$ reduction for increasing retrofit costs and return periods for 2-story RC building in San Francisco, CA

| $E\hat{A}L_r$ as a fraction of $V$ | 0.01935 | 0 |
|---|---|---|
| $E\hat{A}L$ as a fraction of $V$ | 0.04089 | 0.04089 |
| $\rho$ | 3% | 3% |
| $T$ in years | 5 | 5 |
| $B$ as a fraction of $V$ | 0.10 | 0.1899 |

| $E\hat{A}L_r$ as a fraction of $V$ | 0.02932 | 0.01774 | 0.00617 | 0 |
|---|---|---|---|---|
| $E\hat{A}L$ as a fraction of $V$ | 0.04089 | 0.04089 | 0.04089 | 0.04089 |
| $\rho$ | 3% | 3% | 3% | 3% |
| $T$ in years | 10 | 10 | 10 | 10 |
| $B$ as a fraction of $V$ | 0.10 | 0.20 | 0.30 | 0.3533 |

| $E\hat{A}L_r$ as a fraction of $V$ | 0.03521 | 0.02952 | 0.02384 | 0.01815 | 0.01246 | 0 |
|---|---|---|---|---|---|---|
| $E\hat{A}L$ as a fraction of $V$ | 0.04089 | 0.04089 | 0.04089 | 0.04089 | 0.04089 | 0.04089 |
| $\rho$ | 3% | 3% | 3% | 3% | 3% | 3% |
| $T$ in years | 25 | 25 | 25 | 25 | 25 | 25 |
| $B$ as a fraction of $V$ | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.7192 |

**Table A.5** Maximum allowable retrofit costs for increasing $E\hat{A}L_r$ and return periods for 2-story RC building in Memphis, TN

| $B$ as a fraction of $V$ | 0.003519 | 0.008797 | 0.017593 | 0.026390 | 0.031668 |
|---|---|---|---|---|---|
| $E\hat{A}L$ reduction due to retrofit | 10% | 25% | 50% | 75% | 90% |
| $E\hat{A}L_r$ as a fraction of $V$ | 0.003666 | 0.003055 | 0.002036 | 0.001018 | 0.000407 |
| $E\hat{A}L$ as a fraction of $V$ | 0.004073 | 0.004073 | 0.004073 | 0.004073 | 0.004073 |
| $T$ in years | 10 | 10 | 10 | 10 | 10 |

| $B$ as a fraction of $V$ | 0.007163 | 0.017908 | 0.035816 | 0.053724 | 0.064468 |
|---|---|---|---|---|---|
| $E\hat{A}L$ reduction due to retrofit | 10% | 25% | 50% | 75% | 90% |
| $E\hat{A}L_r$ as a fraction of $V$ | 0.003666 | 0.003055 | 0.002036 | 0.001018 | 0.000407 |
| $E\hat{A}L$ as a fraction of $V$ | 0.004073 | 0.004073 | 0.004073 | 0.004073 | 0.004073 |
| $T$ in years | 25 | 25 | 25 | 25 | 25 |

| $B$ as a fraction of $V$ | 0.010547 | 0.026367 | 0.052734 | 0.079101 | 0.094921 |
|---|---|---|---|---|---|
| $E\hat{A}L$ reduction due to retrofit | 10% | 25% | 50% | 75% | 90% |
| $E\hat{A}L_r$ as a fraction of $V$ | 0.003666 | 0.003055 | 0.002036 | 0.001018 | 0.000407 |
| $E\hat{A}L$ as a fraction of $V$ | 0.004073 | 0.004073 | 0.004073 | 0.004073 | 0.004073 |
| $T$ in years | 50 | 50 | 50 | 50 | 50 |

| $\rho$ | 3% | 3% | 3% | 3% | 3% |
|---|---|---|---|---|---|

**Table A.6** Maximum allowable retrofit costs for increasing $E\hat{A}L_r$ and return periods for 2-story RC building in San Francisco, CA

| | | | | | |
|---|---|---|---|---|---|
| $B$ as a fraction of $V$ | 0.035329 | 0.088322 | 0.176643 | 0.264964 | 0.317957 |
| $E\hat{A}L$ reduction due to retrofit | 10% | 25% | 50% | 75% | 90% |
| $E\hat{A}L_r$ as a fraction of $V$ | 0.036803 | 0.030669 | 0.020446 | 0.010223 | 0.004089 |
| $E\hat{A}L$ as a fraction of $V$ | 0.040892 | 0.040892 | 0.040892 | 0.040892 | 0.040892 |
| $T$ in years | 10 | 10 | 10 | 10 | 10 |
| $B$ as a fraction of $V$ | 0.071921 | 0.179802 | 0.359604 | 0.539406 | 0.647287 |
| $E\hat{A}L$ reduction due to retrofit | 10% | 25% | 50% | 75% | 90% |
| $E\hat{A}L_r$ as a fraction of $V$ | 0.036803 | 0.030669 | 0.020446 | 0.010223 | 0.004089 |
| $E\hat{A}L$ as a fraction of $V$ | 0.040892 | 0.040892 | 0.040892 | 0.040892 | 0.040892 |
| $T$ in years | 25 | 25 | 25 | 25 | 25 |
| $B$ as a fraction of $V$ | 0.105894 | 0.264734 | 0.529469 | 0.794203 | 0.953043 |
| $E\hat{A}L$ reduction due to retrofit | 10% | 25% | 50% | 75% | 90% |
| $E\hat{A}L_r$ as a fraction of $V$ | 0.036803 | 0.030669 | 0.020446 | 0.010223 | 0.004089 |
| $E\hat{A}L$ as a fraction of $V$ | 0.040892 | 0.040892 | 0.040892 | 0.040892 | 0.040892 |
| $T$ in years | 50 | 50 | 50 | 50 | 50 |
| $\rho$ | 3% | 3% | 3% | 3% | 3% |

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