

Evaluating Premium Incentives for the California Earthquake Authority

MAIN REPORT

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March 2006

ABSTRACT

This study evaluates the California Earthquake Authority's premium incentive program, which offers homeowners of pre-1979 dwellings a reduction in their annual earthquake insurance premium if their home has foundation bolts, structural sheathing on its cripple walls, and the water heater is secured to the building frame. By legislation, the premium discount must be at least 5%. The study contains an engineering evaluation of the reduction in the CEA's risk associated with such retrofits, quantifying risk reduction by the ratio of the expected annualized loss (*EAL*) for a retrofitted home, compared with an average home. The ratio is calculated for each of 1,647 California ZIP Codes.

The *EAL* values are calculated for these two cases—retrofitted and average—using EQECAT's proprietary risk-estimation software USQUAKE, which accounts for known faults and fault zones, seismicity, site soils, building vulnerability (damage as a function of shaking intensity), and insurance. (The 2005 update of this document reflects EQECAT's latest hazard model and its vector-based vulnerability functions.) EQECAT's building vulnerability relationships are based on empirical evidence: actual claims experience from the Northridge earthquake. However, these data reflect only average conditions, i.e., there is no information about foundation type or retrofit conditions.

To distinguish between retrofitted and average conditions, this study creates detailed models of several particular houses, called index buildings (Figure 1), using engineering theory. The theory allows one to create seismic vulnerability functions for each particular house accounting for: design (configuration, materials, construction details, and retrofit); ground motions that could affect it; its response to those motions; the damageability of its components; costs to repair damaged components; and important uncertainties in each aspect. The method used to create the theoretical seismic vulnerability functions is well documented, having been published in several peer-reviewed reports and journal articles. Its principal advantages over alternative engineering approaches are that it (1) avoids the heavy reliance on expert opinion common to other approaches; (2) rigorously accounts for major sources of uncertainty; and (3) uses a type of structural analysis (nonlinear time-history structural analysis) that avoids major assumptions common to other techniques.

The resulting theoretical functions are used with EQECAT's empirical ones to create theoretically-adjusted empirical seismic vulnerability functions for retrofitted houses. The new functions are then used in USQUAKE to calculate *EAL* for retrofitted homes on a ZIP-Code basis. The ratio of this *EAL* to the one calculated using the unadjusted (average) vulnerability function is then mapped by ZIP Code (see Figure 2) and tabulated in a database.

The analysis suggests that *EAL* is reduced on average by 33%, with houses in half of California ZIP Codes experiencing average reduction in *EAL* of 17% to 50%. The index buildings, which have three different foundation types, have dramatically different seismic vulnerability and hence *EAL*, suggesting that foundation type might be a useful rating factor for the CEA. Finally, the study suggests that the seismic retrofit considered here is cost-effective for many homeowners. Ignoring insurance, by bracing unbraced cripple walls, the homeowner in the average ZIP Code can reduce his or her average annual earthquake repair cost by an estimated \$2.75 per \$1,000 replacement cost, as shown in Figure 3. This is equivalent to average repair-cost savings of \$550 per year for a house costing \$200,000 to build. These savings can equate with a present value of benefits in excess of \$3,000 for reasonable planning period and discount rate. This can be compared with up-front retrofit costs on the order of \$2,500.

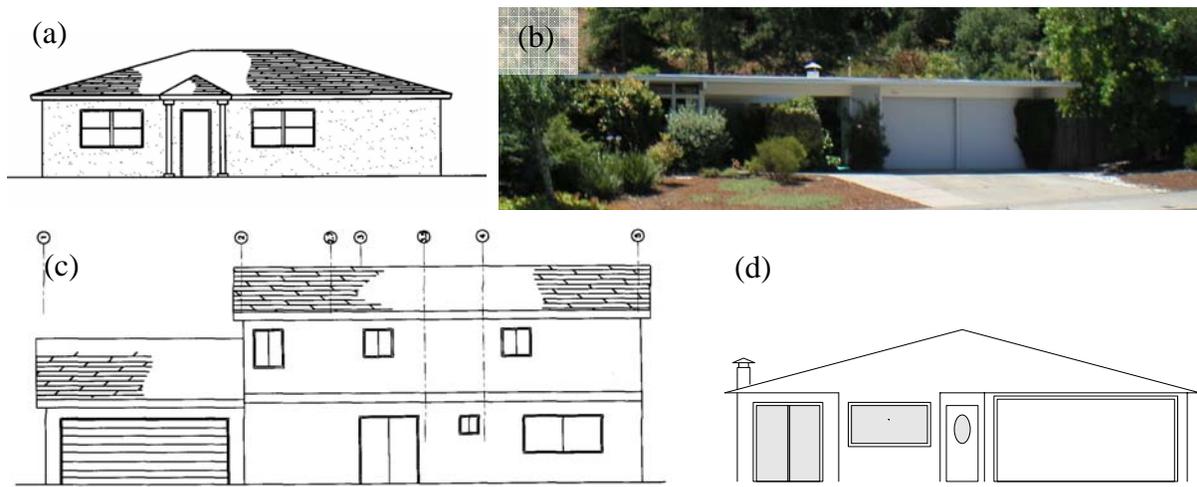


Figure 1. Index buildings (IB) used here (a) IB1 and 2; (b) IB3; (c) IB4 and 6; (d) IB6

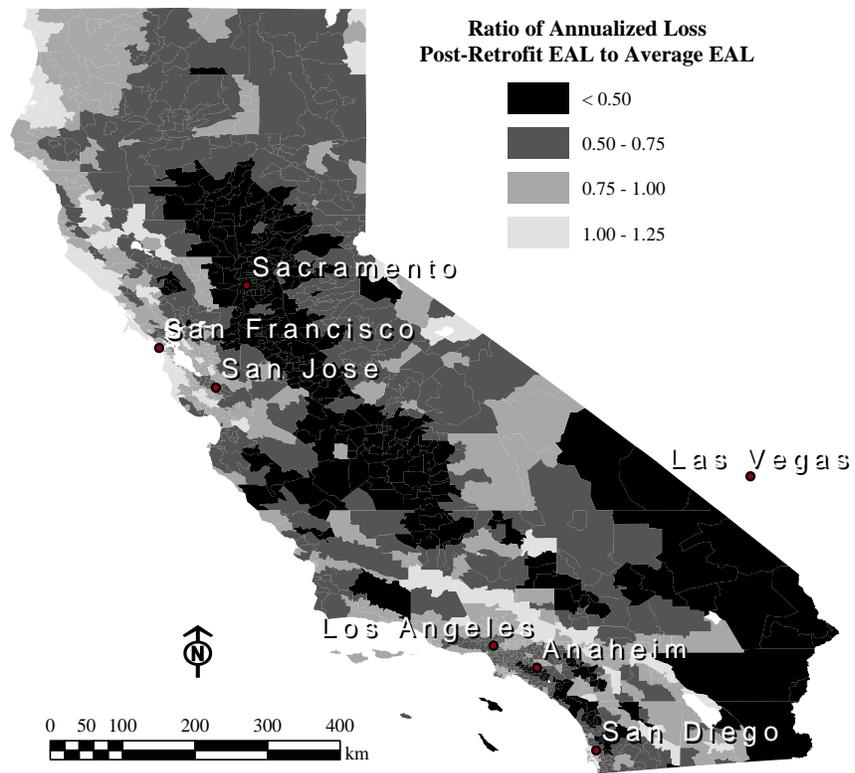


Figure 2. Ratio of post-retrofit *EAL* to average *EAL*, by ZIP Code

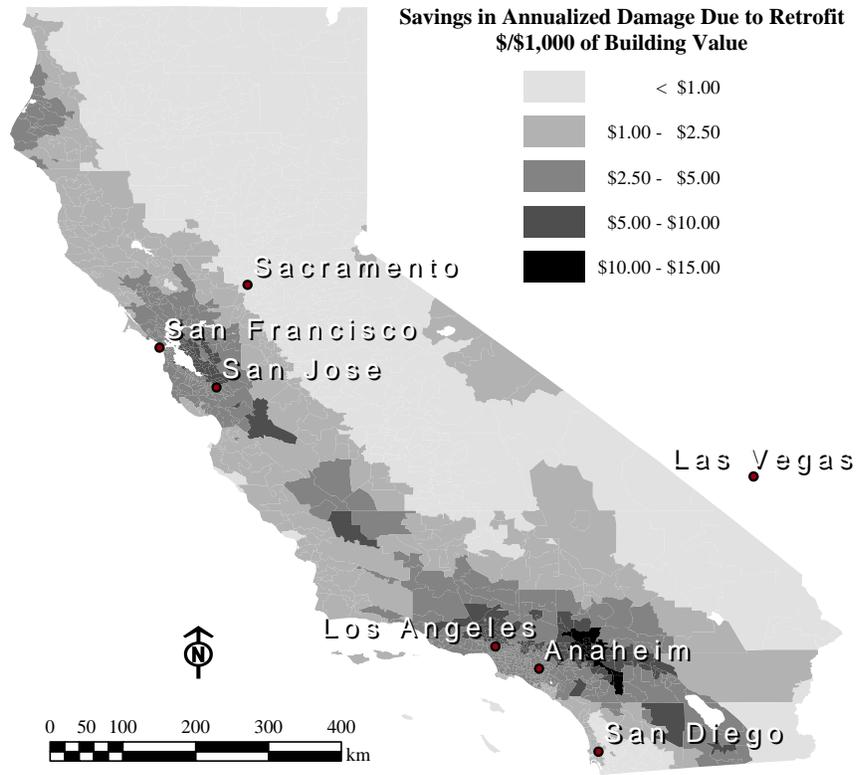


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1 INTRODUCTION

1.1 OBJECTIVE: QUANTIFY REDUCTION IN RISK FROM SEISMIC RETROFIT

This is a study for the California Earthquake Authority (CEA). The CEA was established by the State of California in 1996 as a privately financed, publicly managed entity to provide insurance to California homeowners against earthquake loss. The CEA has become the United States' largest residential earthquake insurer. In addition to providing earthquake insurance, the CEA promotes seismic risk reduction by supporting the State Assistance for Earthquake Retrofits (SAFER) program, and of more immediate interest to this study, by providing premium incentives to policyholders who voluntarily retrofit their homes. This study examines how much the CEA's risk is reduced when policyholders retrofit their homes. This report is written primarily for the non-technical reader. Others are referred frequently to publications that document the methodology employed here.

The CEA's premium-discount program. The California Insurance Code (California Legislative Council, ND)¹ section 10089.40 requires the CEA to provide a premium discount of 5%, if "the dwelling, at a minimum, meets the following requirements: the dwelling was built prior to 1979, is tied to the foundation, has cripple walls braced with plywood or its equivalent, and the water heater is secured to the building frame.... The board may approve a premium discount or credit above 5 percent, as long as the discount or credit is determined actuarially sound by the authority." (Similar discounts are provided for mobile homes, but these are not treated here.) The question asked here is,

1. CEA risk reduction. *By how much is the CEA's estimated risk reduced when the owner of a pre-1979 house informs the CEA that the house meets the retrofit-incentive requirements, i.e., has foundation bolts, braced cripple walls, and water heater strapped to the frame?* (This is not the same as asking how much the proper premium discount should be. Premiums are based on more than risk, such as administrative costs.)

In the process of answering that question, this study produces data that inform two other questions:

2. Policyholder risk reduction. Because the policyholder pays for all earthquake repair costs below the deductible, the policyholder's risk is not proportional to the CEA's risk. Consequently, the policyholder's benefit from retrofit is not proportional to the CEA's benefit. A second question then is: *How much does the policyholder benefit from seismic retrofit?*
3. CEA rating factors for dwelling characteristics. The CEA's homeowner premiums are based on location, dwelling type, insured value, deductible, and personal-property and loss-of-use coverage amount. The five dwelling types are: framed construction (i.e., woodframe construction), 1991 or later; framed construction, 1979-1990; framed construction, 1978 or earlier; mobile home; and all other construction. This rating system is approved by the California Department of Insurance. However, other features affect seismic risk, such as foundation type for framed construction. The third question is, *How*

¹ Chapter 6 provides references for all important sources. Many have associated Web addresses.

much does foundation type affect the CEA's risk? (Not the same question as whether the CEA should include foundation type as a rating factor, which is not addressed here.)

1.2 SCOPE: EAL REDUCTION BY ZIP CODE FOR PRE-1979 FRAME DWELLINGS

Every house is unique. Even apparently identical tract houses built next door to each other can behave very differently in the same earthquake, because of differences in number and quality of structural connections, material properties, and other characteristics. The evidence for this fact appears in laboratory tests of apparently identical specimens of the same wall that nonetheless exhibit strength and deformability differences of 15% to 30%. See for example Pardo et al. (2000). Therefore any study of the benefit of seismic retrofit using a small number of buildings can only provide approximate results.

Six single family frame dwelling designs, 400 samples of each, 1600 ZIP Codes. This study is limited to six particular sample building designs, called *index buildings*, each modeled 400 times (considering their variability in structural and other characteristics), with the probabilistic loss to each calculated for each of approximately 1600 ZIP Codes in California. One of the index buildings is real; the others are hypothetical, but all are realistic and intended to be representative of woodframe, pre-1979 single family woodframe dwellings in the CEA's portfolio. The study does not address mobile homes, condominiums, or other dwelling types. The index buildings were selected in collaboration with the CEA and a committee of independent experts.

Seismic risk quantified via coverage-A expected annualized loss. The seismic risk calculations estimate a quantity called expected annualized loss, or *EAL*, on a per-\$1000 of coverage-A limit. This is the constant annual amount of money per \$1000 of value that an insurer would pay, equivalent to the uncertain losses that in reality occur with irregular frequency and severity. Other measures of insurance loss, such as probable maximum loss, are not examined. *EAL* is calculated for coverage A (primary structure) only; this study does not address content loss, additional living expenses, or possible building-code upgrade requirements.

Result: two weighted-average EAL figures per ZIP Code. Losses for each index building are combined to produce two weighted-average *EAL* figures for each ZIP Code. The first is the "average" case, considering unretrofitted houses, retrofitted houses, and cases where the retrofit incentive does not apply, i.e., houses with slab-on-grade foundations. The second case is just the post-retrofit houses. Weighting factors are calculated based on the distribution of the CEA's portfolio by era of construction and foundation type, as of the 4th quarter of 2004. (The weighting factors are not varied by ZIP Code to reflect a different distribution of the CEA's portfolio in each ZIP Code.) The final result is a ratio of post-retrofit *EAL* to average *EAL*, by ZIP Code, per \$1000.

No actuarial advice. No advice is offered as to how the CEA's administrative and other costs should be considered along with these *EAL* figures, nor how the combined costs should be used to determine the proper premium discount.

1.3 METHODOLOGY: COMBINED THEORETICAL AND EMPIRICAL MODEL

Risk is a combination of hazard and vulnerability. The calculation of earthquake risk requires two pieces of information: knowledge of how frequently and how strongly the earth shakes in any given location (called the seismic hazard), and knowledge of how heavily damaged a building is when subjected to some level of shaking (called the seismic vulnerability). The US Geological Survey has produced ever-more-advanced models of seismic hazard, considering the locations of earthquake faults at the frequency with which they produce earthquakes of various magnitudes. Figure 1-1 illustrates a portion of the USGS' latest hazard model. It shows how strongly the ground will shake on average once every 475 years in the Western United States. (More precisely, it shows a measure of 475-year shaking intensity called 5% damped spectral acceleration at 1-second period. For simplicity's sake, this measure is not defined here.) This is only a fragment of the overall hazard model. The complete picture includes estimates of how strongly the ground will shake at this and many other rates of occurrence. The USGS hazard model has been incorporated into computer software such as EQECAT's computer model of seismic risk, called USQUAKE (described in EQECAT, 1999, although the current version of the software is used here).

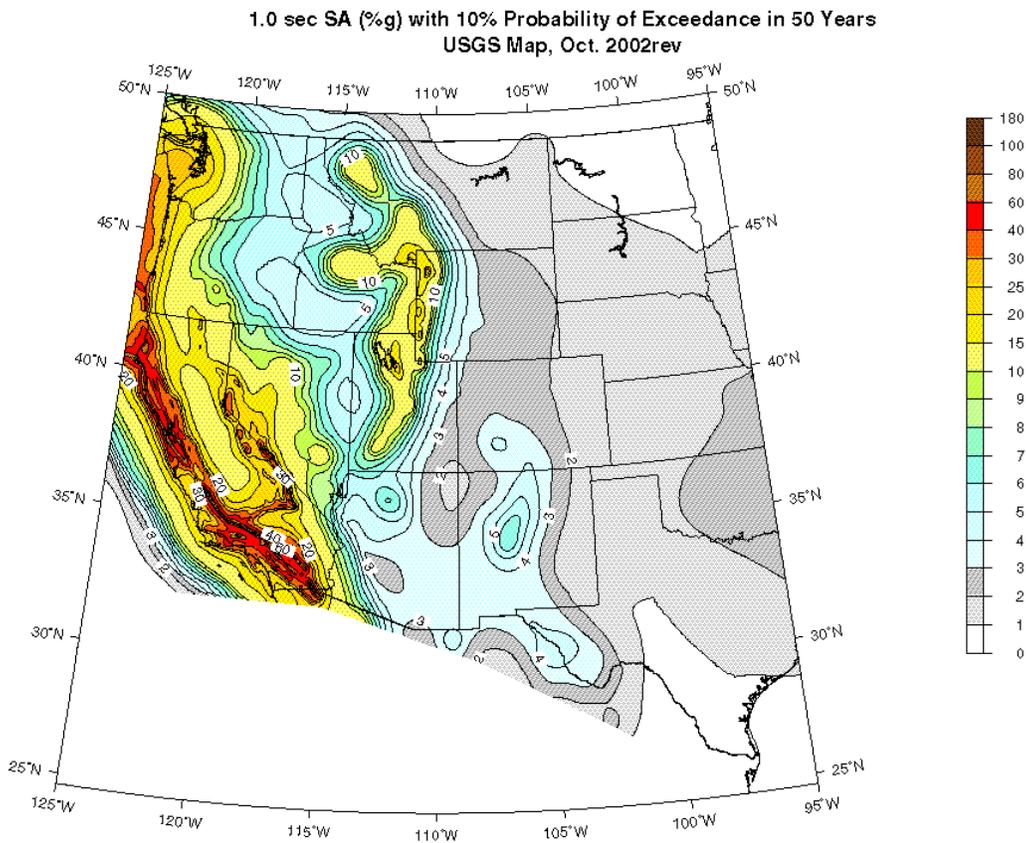


Figure 1-1. A portion of the latest USGS hazard model for California (USGS, 2002).

Empirical loss data provide real-world evidence of risk. Historic earthquake data exist that describe large numbers of houses that were shaken by recent earthquakes, how strongly they were shaken, and the resulting insurance losses they suffered. EQECAT has incorporated such empirical data into USQUAKE and has used them to estimate the seismic vulnerability of houses in CEA's insurance portfolio. USQUAKE also performs the integral calculus that combines hazard and vulnerability to calculate the CEA's seismic risk. The CEA's actuaries used these estimates of seismic risk to establish the CEA's insurance premiums.

Empirical vulnerability data are inadequate to estimate risk reduction. The principal challenge to answering the questions faced here comes from the vulnerability (rather than the hazard) model. The problem is that empirical vulnerability data do not distinguish between pre-1979 houses with and without foundation bracing, foundation bolts, and water-heater restraint. In fact, nobody has collected data in enough detail about real houses and their actual earthquake losses to say how much the CEA's risk drops if the owner of such a house retrofits it. Thus, empirical approaches, which rely on such whole-building real-world historical data, won't work. (The interested reader is referred to Porter, 2002, for further information on this topic.)

Theoretical models can estimate earthquake risk reduction. The present study takes an alternative approach. To distinguish between the vulnerability of a retrofitted house and one that hasn't been retrofitted, theoretical (computer) models of the six index buildings mentioned are created. These computer models rely on state-of-the-art but well-accepted engineering principles, peer-reviewed laboratory studies, and standard construction-cost-estimation techniques to estimate theoretical reduction in vulnerability. The methodology used to create these theoretical models is called assembly-based vulnerability (ABV), a recently developed approach that has been published in peer-reviewed engineering reports and journals and tested on a variety of different types of structures, including woodframe dwellings. The interested reader is referred to Porter et al. (2001, 2002a) for details.

Theoretical models can overlook important real-world effects. An important problem is that an insurer's risk is based on more than theoretical considerations. When a loss occurs and an insurance adjuster pays a claim, he or she might accidentally pay for pre-existing damage or might fail to observe real but concealed damage that was caused by the earthquake. Furthermore, insurance adjustments are often rounded up for convenience. These are real-world processes that theoretical models have difficulty capturing, but that nonetheless affect the insurer's risk. Furthermore a theoretical model, though built up from well-established principles and laboratory tests, can fail to capture important details correctly. A theoretical model can include hidden systematic errors and consistently under- or over-estimate damage and the consequent risk relative to real-world experience. As noted above, it is the real-world loss that counts, so any systematic errors must either be shown to be small or must be avoided or minimized before the results of a theoretical model can be considered actuarially sound.

Combining the strengths of empirical and theoretical approaches. One can perform validation studies to test the accuracy of the theoretical models against empirical data, but because empirical data lack detail comparable to the theoretical model, the tests can only check order-of-magnitude agreement (e.g., see Porter et al. 2002a, pp. 83-90). This study pursues the approach of avoiding or minimizing any systematic error through a combination

of empirical and theoretical approaches. In particular, the theoretical approach is used here to calculate the reduction in damage that comes from retrofitting, thus overcoming the problem of inadequately detailed empirical information. This theoretical reduction in damage is then applied to empirical models of how real-world houses perform in earthquakes. The result is an adjusted empirical model of the damageability of retrofitted houses.

Independent expertise to judge scientific and actuarial validity. An expert panel of engineers, an architect and insurance experts were contracted to review this document and judge the soundness of its assumptions, methodology and conclusions. The experts are:

- Ms. Shawna Ackerman. She is a Fellow of the Casualty Actuarial Society and a member of the American Academy of Actuaries. She has over ten years of experience in the insurance industry with a focus in catastrophe ratemaking and related issues.
- Dr. Janet Burger represents the CEA and has provided oversight of the project.
- Dr. John Hall is a Professor of Civil Engineering and Applied Mechanics at the California Institute of Technology. Dr. Hall is an expert in structural engineering and recently served as Principal Investigator of the CUREE-Caltech Woodframe Project, an extensive effort by a consortium of earthquake research institutions to explore and understand the seismic behavior of woodframe buildings.
- Mr. Robert Reitherman is an architect and the Executive Director of the Consortium of Universities for Research in Earthquake Engineering. He administered the CUREE-Caltech Woodframe Project.
- Mr. James Russell is a Civil Engineer and building-code consultant. He recently served on the CUREE-Caltech Woodframe Project, helping to draft a number of recommended changes to the building code to reflect the research results.

1.4 ORGANIZATION OF THE REPORT

This report is presented in six chapters. This chapter has introduced the problem to be addressed, the scope of the study, and the methodology employed. Chapter 2 briefly reviews available engineering studies of the problems addressed here. Chapter 3 summarizes the index buildings used in the theoretical vulnerability model. Chapter 4 details the analytical methodology. Results, conclusions, and recommendations are presented in Chapter 5. Chapter 6 presents bibliographic references to documents discussed here. Four appendices present supporting information. Appendix A presents design documents of the index buildings. Appendix B details structural modeling assumptions. Construction cost estimates are presented in Appendix C. EQECAT's USQUAKE model is summarized in Appendix D.

1.5 ACKNOWLEDGMENTS

The author thanks the California Earthquake Authority for sponsoring this interesting research. The project team included Mr. Andrew Cowell of EQECAT (Oakland), who calculated losses using EQECAT's earthquake model and wrote Appendix D; Mr. David L. McCormick of Simpson, Gumpertz, and Heger (San Francisco), who provided the structural design and design documents for several of the index buildings shown in Appendix A; and Mr. Tom Boyd of Ray Young Associates (Palm Desert, CA) who provided construction and

repair-cost estimates shown in Appendix C. Thanks also to the advisory panel: Ackerman, Burger, Hall, Reitherman, and Russell. Dr. Charles Scawthorn (C. Scawthorn Associates, Oakland, CA) helped to initiate the project, and Prof. Goetz Schierle of the University of Southern California generously provided the floorplan to the 1970s house and advice regarding the 1950s house. The author gratefully acknowledges the contributions of all these individuals.

2 THEORETICAL BASIS FOR THE PRESENT STUDY

2.1 INTRODUCTION TO THE LITERATURE REVIEW

A substantial body of literature is relevant to the calculation of the benefits of seismic retrofit. The present chapter attempts to do two things: to summarize some of scientific literature on these topics that is used or referred to in the present study, and to provide the lay reader with an overview of the technical concepts used here. The material summarized here reflects well-established knowledge presented in peer-reviewed scientific and engineering journals and other publications. Relevant topics include:

- *Seismic hazard.* This is the quantification of how frequently and with what severity earthquakes cause shaking at a given site. Ground failure and inundation (e.g., tsunamis and dam failure) are also considered seismic hazards, but they are not addressed here.
- *Seismic vulnerability.* This is the quantification of the economic, human, or other loss that occurs at a given location, conditioned on a given level of seismic excitation (i.e., shaking, ground failure, or inundation). Under this topic are three relevant sub-topics: structural analysis, the mechanical characteristics of woodframe building components, and construction cost estimation.
- *Seismic risk.* This is the study of how seismic hazard and seismic vulnerability are combined to calculate how frequently and with what severity earthquakes cause economic, human, and other losses.
- *Seismic risk mitigation.* This is the study of how changes to a site, to a fixed facility, or to the human and other processes that occur in the facility can reduce seismic risk.
- *Performance-based earthquake engineering.* This is an analytical framework for evaluating seismic hazard, structural response, damage, and loss. It is in development by large portions of the academic and professional earthquake engineering community.

2.2 SEISMIC HAZARD

The U.S. Geological Survey continuously works to quantify the likelihood and severity of fault rupture and consequent ground motion for all parts of the United States. Of particular interest for the present study are seismicity parameters hazard maps produced for the National Earthquake Hazard Reduction Program (NEHRP), e.g., Building Seismic Safety Council (1998), Frankel et al. (1996, 1997), and Peterson et al. (1996). These models, recently updated, are incorporated in a computer model employed by EQECAT for loss estimation.

There are several ways to depict seismic hazard; Figure 2-1 shows two important examples. Figure 2-1(a) depicts the shaking intensity that is estimated to have a 10% probability of being exceeded in the next 50 years (US Geological Survey, 2002). For example, consider the location of the CEA's Sacramento, California, headquarters. The map shows that this site has a 10% probability of experiencing at least 14% of gravity in horizontal acceleration in the next 50 years. How likely are other levels of shaking for this Sacramento location? Figure 2-1(b) shows the average frequency with which other levels of shaking are expected to be exceeded (data from Frankel and Leyendecker, 2001). For example, consider the point on the curve whose x-value is 0.10g: it is estimated that this

Sacramento site will experience this level of shaking on average 0.005 times per year. (For the technical reader, the intensity measure depicted here is the 5%-damped elastic spectral acceleration response at 1-second period, on a site with NEHRP site classification at the B-C boundary.) The interested reader is referred for more information to <http://geohazards.cr.usgs.gov/eq/>.

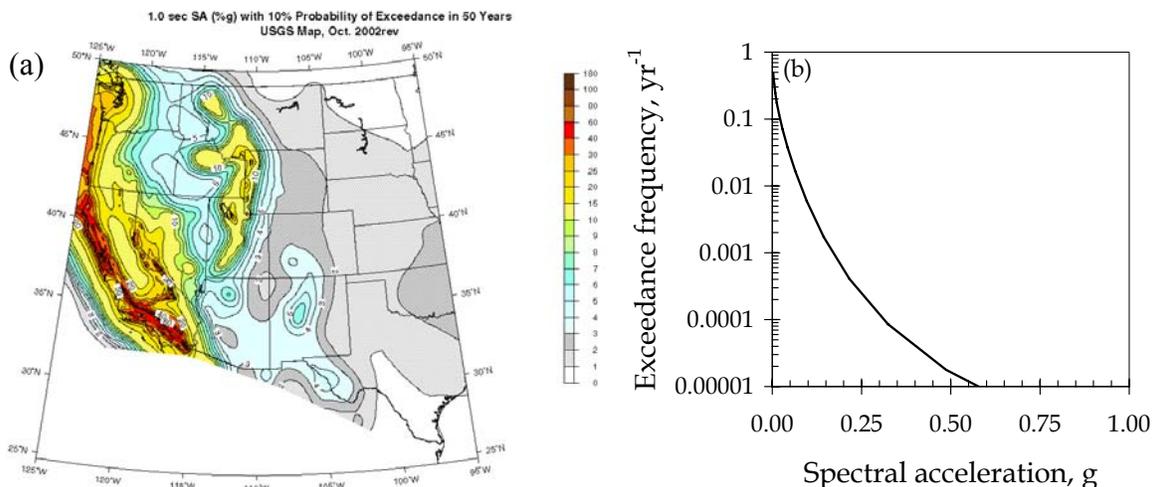


Figure 2-1. Two depictions of seismic hazard

2.3 SEISMIC VULNERABILITY FUNCTIONS

What is a seismic vulnerability function? The mathematical relationship between ground motion and loss (economic loss, casualties, or loss-of-use duration) is referred to as a seismic vulnerability function. These functions can be plotted on a graph in which the horizontal axis measures shaking intensity; the vertical axis, loss. There are three general approaches to develop relationships between ground motion and repair cost: empirical, expert opinion, and theoretical. Each has its pros and cons, summarized in Table 2-1.

Figure 2-2 contains examples of seismic vulnerability functions developed using each method. Figure 2-2(a) depicts empirical loss data compiled by Steinbrugge and Algermissen (1990) using summarized and partially analyzed information on the 1933 Long Beach earthquake, 1971 San Fernando earthquake, 1983 Coalinga earthquake, and 1987 Whittier Narrows earthquake. In this figure, the horizontal axis measures modified Mercalli intensity (MMI); the vertical, mean repair cost as a fraction of market value of the house. (These values are difficult to relate to repair cost as a fraction of building replacement cost, mostly because the relative value of the land is unknown.) Figure 2-2(b) depicts the opinion of six experts on the mean damage factor (repair cost as a function of replacement cost) for woodframe buildings, as a function of MMI (ATC-13, Applied Technology Council, 1985). Figure 2-2(c) shows the results of computer simulation of damage to a real 7-story hotel building in Van Nuys, California (Beck et al., 2002).

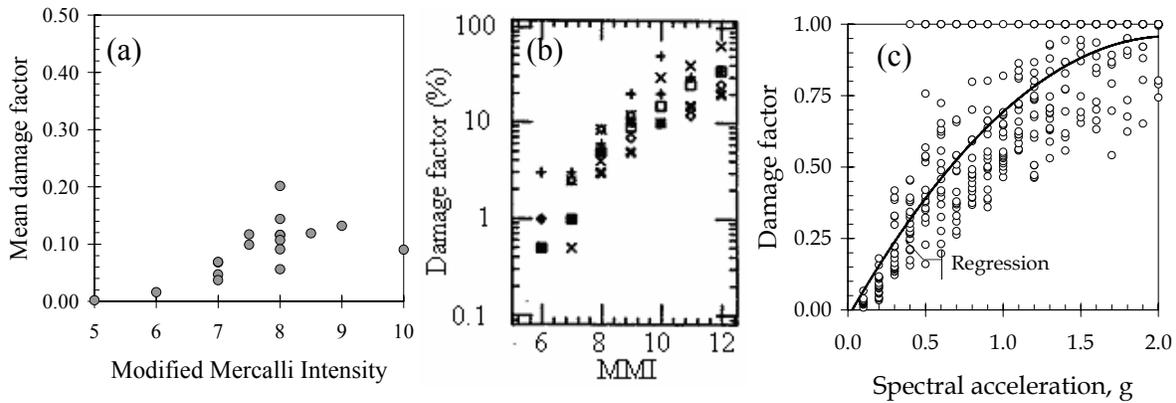


Figure 2-2. Seismic vulnerability functions: (a) empirical, (b) expert opinion, and (c) theoretical

Empirically derived vulnerability functions. The empirical approach relies on gathering data on the location, value, physical characteristics, shaking severity, and loss for a large unbiased set of facilities exposed to earthquake shaking. These data are grouped by structure type and then regression analysis is used to estimate the relationship between loss and shaking for each type. Because it relies on actual earthquake experience, the empirical approach, when successful, is strongly defensible. The challenges are poor data quality, inadequate quantity, disproportionate sampling from damaged facilities, old data that do not reflect current construction characteristics, data from non-representative geographic regions, lack of data from large earthquakes, and lack of detail, particularly to distinguish between buildings with and without some risk-mitigation measure. Important examples of studies that use the empirical approach are listed in the table. We found in Porter et al. (2002a) that none of these studies provides the necessary detail to distinguish the effects of mitigation studied here.

Table 2-1. Methods of creating seismic vulnerability functions

Method	Advantages	Disadvantages	Examples
Empirical	Strongly defensible	Detail, regional, time differences ignored. Provides little information on new measures.	Martel (1964), U.S. Coast and Geodetic Survey (1969), EQECAT (1999)
Expert opinion	Versatile	Difficult to judge new measures; difficult to verify.	Freeman (1932), Applied Technology Council (1985)
Theoretical	Versatile Verifiable Continual improvement Building-specific	Difficult to use for macroscopic loss estimation. Assessing new assemblies is laborious.	Czarnecki (1973), Scawthorn et al. (1981), Kustu et al. (1982), Porter (2000), Porter et al. (2002a)

An important source of empirical seismic vulnerability functions is the analysis EQECAT performed to create its proprietary earthquake loss model, USQUAKE¹. As part of the development process, EQECAT compiled insurance loss data from the 1994 Northridge earthquake. The data give information at the level of individual insurance policies. The data include street address (which can be converted to a latitude and longitude), policy limits and deductibles, structure type and era of construction, and claims paid. Using the latitude and longitude together with a computer map of shaking intensity in the earthquake, EQECAT estimated the shaking to which each policy was subjected. It then calculated a damage factor (repair cost as a fraction of replacement cost, which is based on policy limit) for each claim. These data can be plotted on a graph where the x -axis is shaking intensity—parameterized through a measure called spectral acceleration, denoted by $S_a(1 \text{ sec}, 5\%)$ —and the y -axis is damage factor. A smooth curve is fit to the data to create an empirical seismic vulnerability function. EQECAT created several such seismic vulnerability functions, each covering up to 20 years of construction (e.g., 1940 to 1959). The principal difficulty of using these seismic vulnerability functions for the present application is that they do not distinguish between houses with different foundation types or retrofit conditions. Summary information is available at <http://www.eqecat.com/usqhelp.htm>.

Zeng (1997) reviewed EQECAT's USQUAKE model on behalf of the Arkwright Mutual Insurance Company. He evaluated the model's components by comparing its results with publicly available hazard information and Arkwright's own insurance loss experience. He finds that, "Most components of the model are quite accurate and without bias.... In general, USQUAKE is a very well conceived and thoroughly researched natural disaster modeling environment.... Our independent experiments as well as the advice of seismologists and engineers lead us to conclude that the system is an excellent tool for managing the risk of seismic disasters in the commercial property insurance."

Expert opinion. The expert-opinion approach overcomes many of the difficulties of creating empirical seismic vulnerability functions, as experts can be asked to guess or judge the vulnerability of any type of facility, as long as they feel familiar enough with that facility type to offer a judgment. If they feel they lack adequate experience, experts typically refuse to offer judgment. An early application of expert opinion to earthquake vulnerability is found in Freeman (1932), who offers his judgment regarding future insurance losses by structure type and soil conditions. More recently, the authors of ATC-13 (Applied Technology Council, 1985) gathered the judgments of 58 earthquake engineering academics and practitioners, who estimated loss for 40 categories of California buildings as a function of shaking intensity. Typically between four and nine experts provide opinions on a given type of model structure type. The more-recent HAZUS software (NIBS and FEMA, 1999), employs scientific measures of intensity and uses engineering methods to estimate vulnerability, but relies (to a lesser degree) on expert opinion. Furthermore, HAZUS does not distinguish between woodframe houses with and without the retrofit measure that is the subject of the present study.

Theoretical vulnerability functions. The need for theoretical seismic vulnerability functions has been recognized at least since the early 1970s. Czarnecki (1973) appears to be the first to formulate and illustrate a methodology to relate repair costs to shaking intensity using purely theoretical means. His methodology called for a structural analysis to assess the member forces that an earthquake ground motion would produce in a building, followed by a

¹ Full disclosure: the author was employed by EQE International, EQECAT's parent company, from 1990 through 1997. He was involved in developing aspects of the predecessor to USQUAKE, but not ones that are relevant to the present study.

loss analysis that related repair costs to member structural response. Czarnecki made a number of simplifying assumptions about the loss analysis stage. In the early 1980s, Scawthorn (1981), Kustu et al. (1982), and others advanced the theoretical approach, adding empirical information to the loss-analysis stage, and explicitly treating uncertainty in component damage.

In developing assembly-based vulnerability (ABV), the present author added treatment of several other sources of uncertainty, e.g., ground motion, mass, damping, and force-deformation behavior (Porter and Kiremidjian, 2001; Porter et al., 2002a), along with greater detail regarding the components of which a facility is constructed, and standardization to facilitate use of standard construction cost-estimation principles and resources. The authors of Porter et al. (2002a), believe we were the first to apply a rigorous probabilistic vulnerability analysis to woodframe buildings.

The interested reader is referred to Porter et al. (2002a) for a detailed explanation of the ABV methodology, but for present purposes it is important to note only that the methodology has five analytical stages: facility definition, hazard analysis, structural analysis, damage analysis, and loss analysis, as illustrated in Figure 2-3.

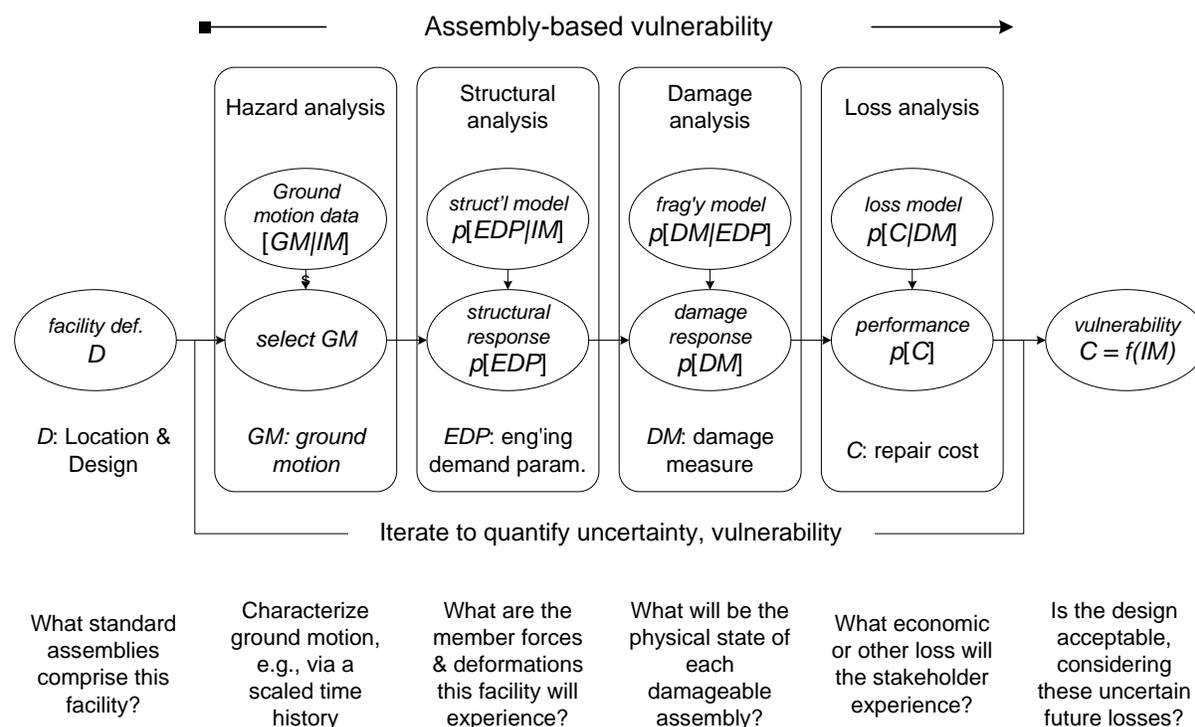


Figure 2-3. Summary of assembly-based vulnerability method

2.4 SELECTION OF GROUND MOTIONS

In the present context, the ABV hazard analysis amounts merely to a selection of sample ground motions (accelerograms) to apply to the facility. There are several possible sources. Somerville et al. (1997) offer a suite of 50 pairs of accelerograms for use in California. Most are from earthquakes recorded in California; most are actual recordings (some are simulated). Somerville et al. (1997) scaled the recordings (multiplied each acceleration in the record by a constant factor) for use in a large FEMA-sponsored project dealing with steel-moment-frame

buildings. The author has returned them to their original values, and then re-scaled them by as much as $\pm 50\%$ for use in the ABV structural analyses. More recently, PEER (2000) has compiled a suite of 1557 accelerograms from 143 earthquakes worldwide. The present study uses the former set.

2.5 STRUCTURAL ANALYSIS

Analysis of shearwall components using CASHEW. Structural analysis is the process of calculating the forces and deformations in a structure when it is subjected to some external loading or excitation such as an earthquake. It is usually performed by computer. Two relevant sources are used here. As part of the CUREE-Caltech Woodframe Project, Folz and Filiatrault (2001) developed the CASHEW finite-element software (Cyclic Analysis of SHEarWalls) for modeling the nonlinear force-deformation behavior of woodframe shearwalls. (“Nonlinear force-deformation behavior” means that deformation does not increase in direct proportion to force. A real wall tends to become more flexible at higher levels of force, so a model that captures this behavior is expected to produce more accurate estimates of seismic performance than linear models.)

One can use the software to simplify a shearwall from a very complicated system involving hundreds or more of finite elements (framing elements, panels, and connectors such as nails) to a single nonlinear spring. The simpler spring has approximately the same force-deformation behavior, in terms of the force applied at the top and bottom edge of the panel, and the corresponding displacement of the top edge of the shearwall relative to the bottom. The resulting simpler spring can then be used in another structural analysis program to model an entire building.

Analysis of whole buildings using Ruaumoko. Second, this study uses the Ruaumoko structural-analysis package developed by Carr (2001) in New Zealand to calculate the forces and deformations of whole buildings subjected to earthquake motion. (Ruaumoko is the Maori god of earthquakes.) The Ruaumoko software offers a variety of advantages over more familiar programs, chief amongst them being that it allows one to account for strength and stiffness degradation of the building elements, along with other nonlinearities.

Pancake model. Isoda et al. (2001) offer the example of a “pancake-model” analysis of woodframe buildings using CASHEW and Ruaumoko. In that study for the CUREE-Caltech Woodframe Project, the authors created a structural model of woodframe buildings by modeling the building as a collection of flat deformable plates (“pancakes”) occupying the same plane. Each pancake is a floor or roof. The building’s shearwalls are represented by zero-height mathematical springs whose stiffness and strength properties are determined using CASHEW to model the behavior of the real shearwalls. Figure 2-4 illustrates a pancake model.

2.6 DAMAGE ANALYSIS

Damage analysis as used here is the process of estimating the physical damage to the assemblies of a facility, given the forces or deformations to which those assemblies are subjected. A variety of laboratory tests provide insight onto the mechanical properties and damageability of the types of assemblies examined here.

2.6.1 Various shearwall types

Pardoen et al. (2000) report on a series of racking tests of a variety of woodframe wall specimens that were performed at the University of California, Irvine. The testing regimen includes 35 groups of three identical specimens each. Each specimen is an 8-ft x 8-ft (2.44m x 2.44m) wall subjected to the test protocol recommended by Shepherd (1996) for the Structural Engineers Association of Southern California (SEAOSC). Two of the 35 groups are relevant here. The mean and standard deviation of several of their strength and stiffness characteristics were used in modeling the index buildings. See Appendix B of this study for technical details.

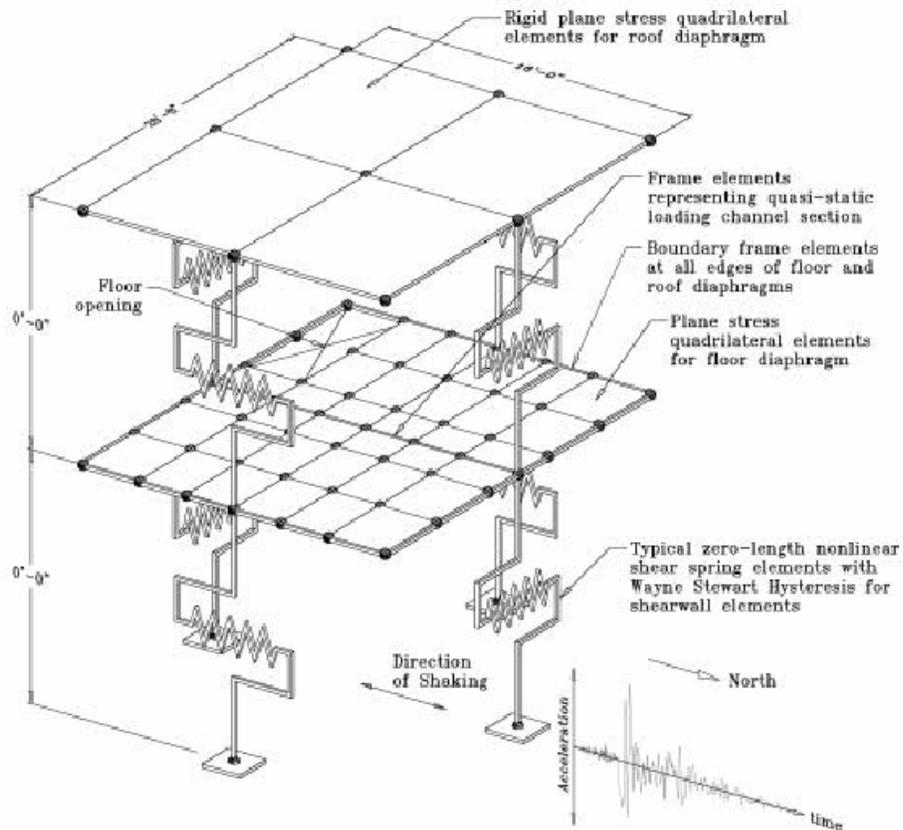


Figure 2-4. Pancake model of a building (Isoda et al. 2001)

2.6.2 Stucco exterior walls

Several of the buildings examined in the present study are sheathed with a 7/8-in-thick stucco exterior finish. Stucco on woodframe construction is a relatively rigid material that acts as a structural element, that is, it contributes substantially to the lateral strength and stiffness of a woodframe house during an earthquake. In a study such as the present one, where structural analyses are performed as part of the loss-estimation process, it is therefore necessary to include the stucco in the mathematical model of the force and deformation behavior of the house, and therefore to understand its mechanical characteristics, i.e., how it deforms when subjected to lateral forces, and how it becomes damaged when subjected to those forces.

Three recent studies provide useful laboratory data on the mechanical characteristics of stucco-wall test specimens. Pardoen et al. (2000) is discussed above. Chai et al. (2002) report on lateral tests of 2-ft and 4-ft level and stepped cripple walls, structurally sheathed with 15/32-in oriented strandboard (OSB, similar to plywood). Tests were performed with and without stucco exterior finish on the opposite face of the studs from the OSB. Recently, Arnold et al. (2003) completed an investigation (performed with major funding from the CEA) of the force-deformation-damage behavior of woodframe shearwalls with 7/8-in stucco exterior finish and 1/2-in gypsum wallboard interior finish. The three sets of tests provide laboratory evidence of strength and stiffness characteristics relevant for creating computer models of the stucco-sheathed walls in the index buildings studied here.

2.6.3 Shearwalls sheathed with T1-11 siding

Texture 1-11 siding (referred to as T1-11) is a plywood product made in sheets 4 ft wide and 8, 9, or 10 ft long. They have distinguishing features: 3/8-in wide vertical grooves that provide the textured appearance simulating board siding, and shiplap joints at the vertical edges, which can cause strength problems. As SEAOC (2003 draft) notes about T1-11 siding, “At the edges where two adjacent panels adjoin, each panel must be nailed to the wall stud with a separate row of nails.... A common, improper construction practice [provides] only one row of nails through both sheets (at the overlap). This creates a weakness as the plywood thickness.... Such practice led to failures in the 1984 Morgan Hill (California) Earthquake.” No laboratory test data on the force-deformation behavior of woodframe shearwalls sheathed with T1-11 siding were available, but one can estimate the force-deformation behavior of a shearwall analytically, using the CASHEW software discussed above (Folz and Filiatrault, 2001).

2.6.4 Gypsum wallboard interior finish

The research by Pardoen et al. (2000), discussed above, includes six tests of woodframe walls with gypsum wallboard on both sides of the wall. The authors provide force-deformation records of all six tests, along with summary information about strength, stiffness, and degradation. McMullin and Merrick (2001) present results of 17 tests of gypsum wallboard partition. They test specimens with various door and window openings, fastener types, and fastener spacing. Of the 17, three have nailed connections. The interesting novelty of these tests is that the authors provide the drift (lateral displacement) associated with each of eight damage states for each test, and record three construction contractors’ estimates of the repairs required and their costs as functions of drift.

In Porter et al. (2002a), we combined the results of the Pardoen et al. (2000) and McMullin and Merrick (2001) tests to define damage states and develop fragility functions for gypsum wallboard partitions. Repair costs were provided by a professional cost estimator, the same involved in the present study. The interested reader is referred for details to Porter et al. (2002a), Appendix E. The present study also considers the results of tests by Arnold et al. (2003), in research performed with major funding from the CEA. These tests are consistent with those of McMullin and Merrick (2001) and with Pardoen et al. (2002) in terms of drift levels associated with finish damage at fasteners, cracking at joints, and collapse.

2.6.5 Windows

A modest amount of empirical testing has been performed on the seismic resistance of windows. Pantelides et al. (1994), Behr et al. (1995), and Behr and Worrell (1998) report on laboratory tests of curtain-wall glazing subject to racking as in earthquake. More relevant for present purposes is a study by Sucuoglu and Vallabhan (1997), who present an analytical approach to estimating the drift capacity of window glass. They examine two failure modes: cracking because of in-plane deformation and because of out-of-plane vibration. They report that observations from past earthquakes indicate that in-plane deformation is the primary cause of glass breakage. In a model proposed by the authors, glass accommodates drift two ways: closing of the gap between the frame and the edge of the glass, and in-plane diagonal shortening of the glass resulting from out-of-plane buckling. They provide a theoretical equation for the drift ratio capacity that was used in Porter (2000), Porter et al. (2002a), and Beck et al. (2002) to create fragility functions for windows. In those studies, it is found that window breakage is a minimal contributor to economic seismic risk in several common building types, including woodframe dwellings.

2.7 MODELING COLLAPSE

What value of peak transient drift results in collapse? Chai et al. (2001) show that collapse does not occur when maximum strength is reached, but that a cripple wall resists some lateral force at drift ratios twice that reached at the maximum lateral force. In tests of 2-ft. stucco- and wood-sheathed cripple walls subjected to cyclic loading, lateral resistance drops to 80% of its maximum value at approximately 1.4 in., but the walls still resist some lateral force at drifts of 2 to 3 in. In the present model, the collapse of a short, stucco-sheathed cripple wall, with or without plywood, is associated with a drift of 2.5 in \pm 0.5 in. (mean and standard deviation, respectively). Here, if the house is modeled as having collapsed because of excessive drift, an overall repair cost is applied, rather than summing individual costs, as in Porter et al. (2002a).

2.8 LOSS ANALYSIS

In the present context, loss analysis amounts to calculating the repair cost to repair each damaged assembly and where necessary to repaint rooms or other lines of sight where damage occurred. The total cost is calculated as the cost to repair a single damaged assembly of a certain type (referred to here as a unit cost), times the number of those damaged assemblies, summed over the various types of damageable assemblies. To this sum is added a factor to account for the contractor's overhead and profit. The unit costs and overhead and profit factors are provided by professional construction cost estimators. In quantifying unit costs, the estimator typically considers the quantity and costs of material, labor, equipment, and supplies required to perform the work. These values are commonly tabulated in manuals such as RS Means Co. (2003).

2.9 UNCERTAINTIES

Risk is a relationship between the *severity* of some undesirable outcome and the *frequency* of its occurrence. Here, severity is measured in terms of earthquake claim amount (repair cost in excess of the deductible); frequency is measured in number of earthquake events per year causing that level of loss. For present purposes, one can simplify the risk measure via the expected annualized loss, denoted by *EAL*, that is, the average amount of

money paid per year. Some integral calculus is required to explain how *EAL* is calculated from hazard and seismic vulnerability. The math is omitted here, but the interested reader is referred, for example, to Chapter 6 of Porter et al. (2002a). It is important to consider some of the sources of uncertainty in *EAL* for a particular facility. Important sources of uncertainty that are considered in the present study are listed in Table 2-2. Some uncertainties are not accounted for here. For example, only one repair method is associated with each type of physical damage, although there might be alternatives.

Table 2-2. Sources of uncertainty in *EAL* considered here

Source of uncertainty	Sample references
The intensity of ground motion that will occur during some planning period	Frankel and Leyendecker (2001)
The acceleration time histories affecting the site (moment-to-moment shaking)	Somerville et al. (1997), PEER Center (2000)
Site soil characteristics	Wills et al. (2000)
Structural characteristics of the facility	Ellingwood et al. (1980), McVerry (1979), Camelo et al. (2001)
Damageability of facility components	Pardoen et al. (2000), Chai et al. (2002)
Repair costs for damaged assemblies	RS Means Co., Inc. (2003)
Contractor's overhead and profit	RS Means Co., Inc. (2003)

2.10 CALCULATION OF BENEFITS FROM SEISMIC RETROFIT

The economic benefits of seismically retrofitting woodframe dwellings derive primarily from reduction in future losses (Equation (2-1)) and from change in market value. There are other benefits: reduced risk of death and injury, reduced likelihood of being rendered homeless and the associated additional living expenses, peace of mind, and possibly others. Only the first is considered here. The author is aware of only one prior study that estimates the reduced economic risk for woodframe dwellings: Porter et al. (2002a), which uses the same methodology employed here. In that study, we created theoretical seismic vulnerability functions for 19 woodframe dwellings (index buildings) and calculated *EAL* (zero deductible) for a sample site. The present study considers sites across California, but the process is essentially the same.

$$\text{Annual benefit} = (EAL \text{ without retrofit}) - (EAL \text{ with retrofit}) \quad (2-1)$$

3 INDEX BUILDINGS

3.1 CRITERIA FOR SELECTING INDEX BUILDINGS

This chapter summarizes the buildings examined for the present study. The author and the CEA selected six house designs for analysis. The selection was based on observations of the CEA’s portfolio as of the 4th quarter of 2004. See Figure 3-1 for the statistics considered. Figure 3-1(a) shows that houses built between 1940 and 1979 constitute 87% of pre-1979 homeowner policies; this age range was therefore selected as the subject of the present investigation. Figure 3-1(b) shows the distribution of policies by number of stories. It shows that the bulk of these policies are for single-story construction (70%), with 20% being two-story houses. Four of the six houses (67%) were therefore selected as single story, and two as two-story construction. Figure 3-1(c) depicts the distribution of square footage by era of construction. The index buildings were selected to match approximately these averages. Figure 3-1(d) shows that the information on most policies shows a foundation type that is either unknown or does not fit either “slab” or “raised” descriptions. The author does not know how to ascribe a particular foundation type to these “other” or “unknown” records for present purposes, nor does the CEA, so they are ignored here.

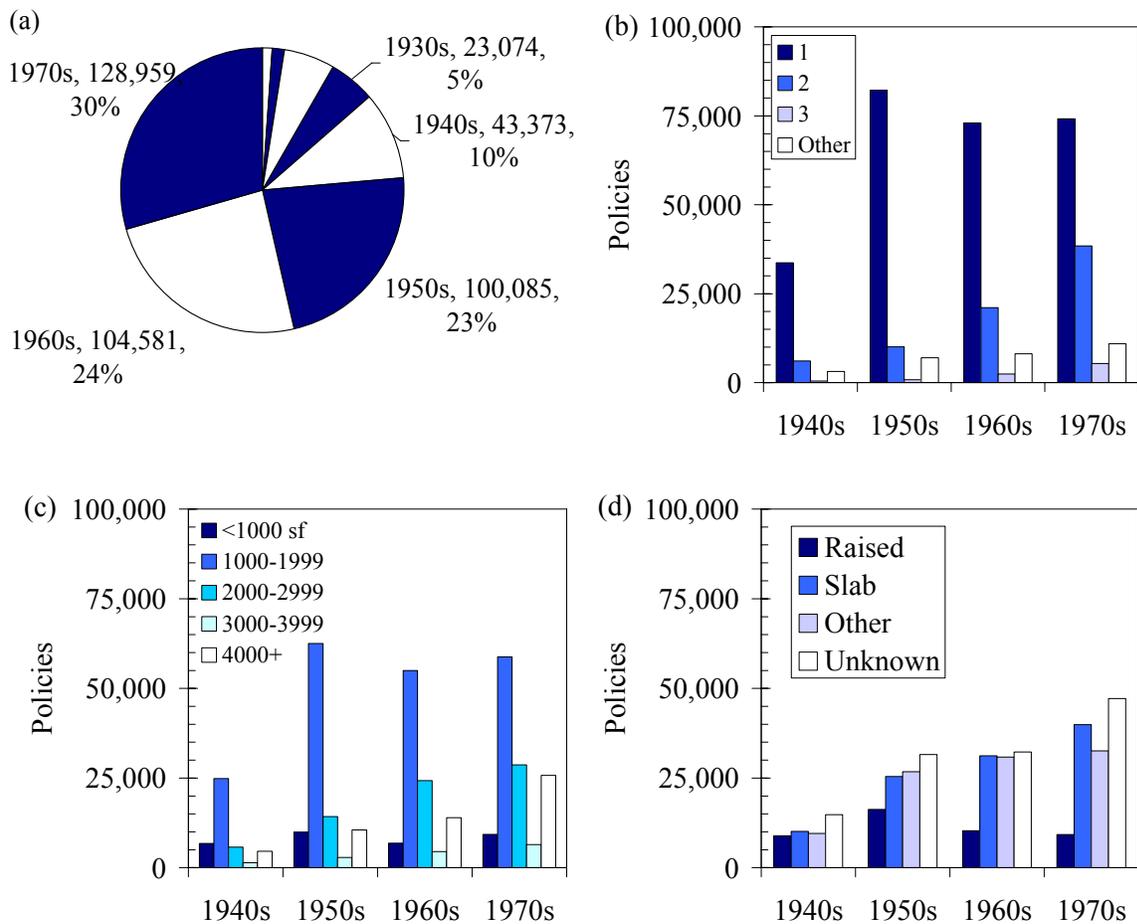


Figure 3-1. Portfolio statistics as of 2004, 4th quarter: (a) era of construction; (b) number of stories by year built; (c) square footage by year built; and (d) foundation type by year built.

3.2 SELECTED INDEX BUILDINGS

3.2.1 Index buildings 1 and 2

The following six buildings (referred to here as index buildings) are studied. Details are provided in Appendix A. The first (index building 1, or IB1) is a single-story, 1200-sf house with raised foundation, rectangular floor plan of 30 ft by 40 ft, stucco exterior walls, no structural sheathing (no plywood underneath), gypsum wallboard interior finish, bolted foundation, unbraced cripple walls, and water heater not secured to the frame. The cost estimator estimates the replacement cost at \$128,000 in 2002, or approximately \$137,000 in 2005. This is construction cost, not market value, which would include land value. Figure 3-2 shows elevations and a floor plan for this house. The same design is used for index building 2, except that the cripple walls have structural sheathing and the water heater is secured to the frame, at an estimated replacement cost for the entire building of \$129,000, or approximately \$138,000 in 2005. (The cost to retrofit index building 1 would be larger than the difference in two replacements costs, because of the difficulty of access and other issues.) This is a hypothetical building, with a design that is typical of the 1940s or 1950s.

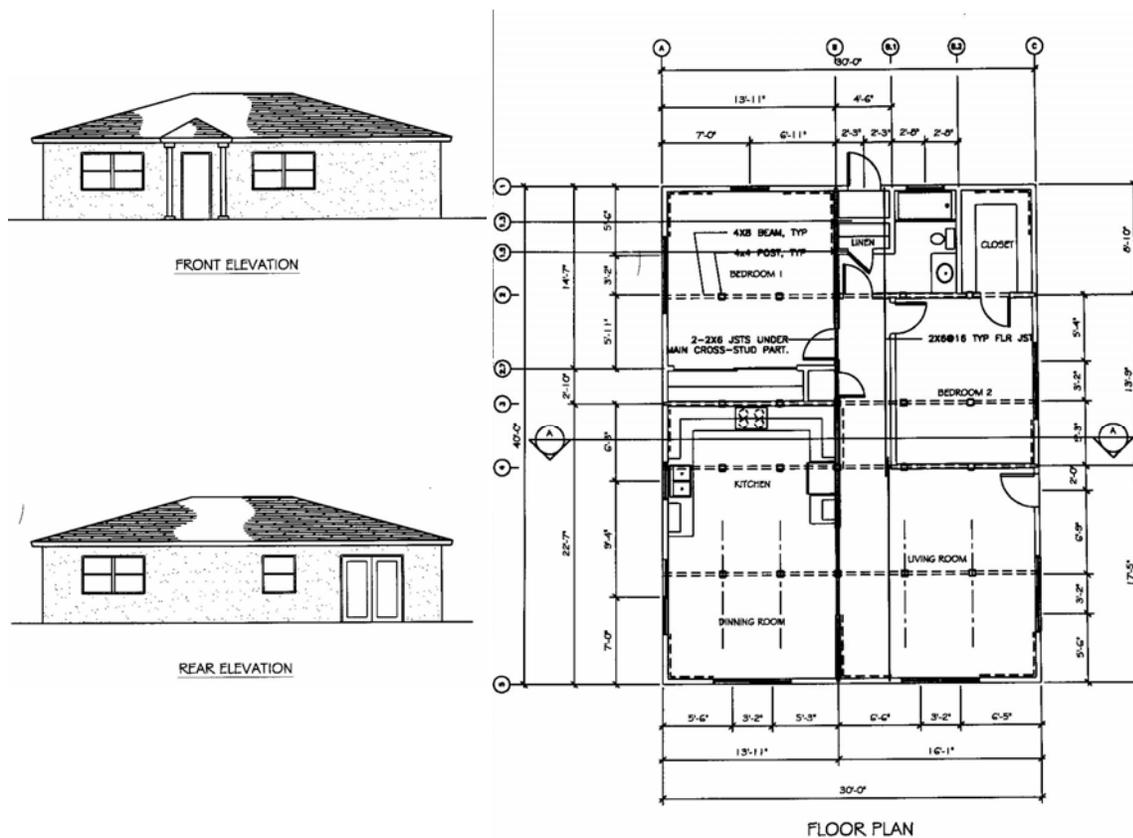


Figure 3-2. Index buildings 1 and 2

3.2.2 Index building 3

Index building 3 (IB3) is a real, single-story, Eichler-style, 1600-sf house with slab foundation, irregular, C-shaped floor plan, overall dimensions 54 ft by 52 ft, painted plywood exterior walls, and interior walls finished on some walls with gypsum wallboard and on others with Philippine Mahogany (also known as luan paneling). The frame is bolted to the foundation and the water heater is strapped to the frame. The cost estimator involved in the

present project estimates the replacement cost of this house at \$182,000 in 2002, or approximately \$193,000 in 2005. Figure 3-3 shows photo of the front elevations and a floor plan for this house. This building was built in 1956.

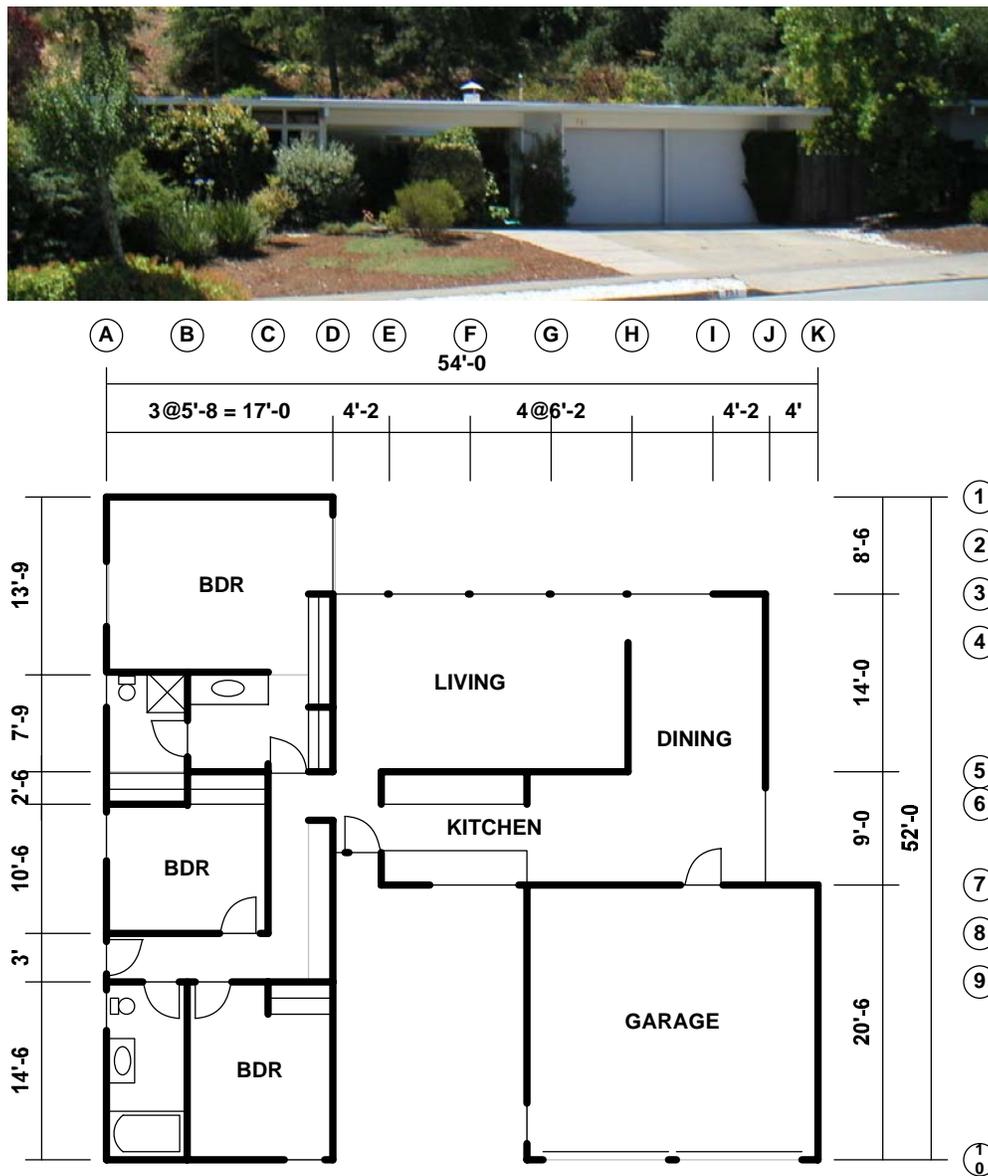
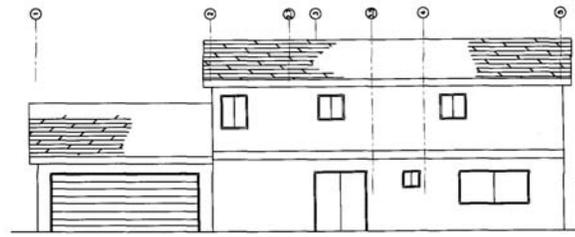


Figure 3-3. Index building 3

3.2.3 Index buildings 4 and 5

Index building 4 (IB4) is a hypothetical, two-story, 2400-sf house with raised foundation with unbraced cripple walls, but bolted to its foundation. The water heater is strapped to the wall. The house has T-shaped floor plan, almost rectangular, with overall dimensions 36 ft by 60 ft, with an upper story of 26 ft by 40 ft. Exterior walls are stucco without structural sheathing and interior walls finished with gypsum wallboard. The cost estimator involved in the present project estimates the replacement cost of this house at \$242,000 in 2002, or \$257,000 in 2005. Detailed drawings are provided in an appendix. Figure 3-4 shows elevations and floor plans for this house. This is building is designed to be consistent with construction in the 1960s. Index building 5 is the same house but with retrofitted cripple

walls, i.e., with structural sheathing added to the cripple walls. The replacement cost for index building 5 would be \$245,000 in 2002, or \$260,000 in 2005.



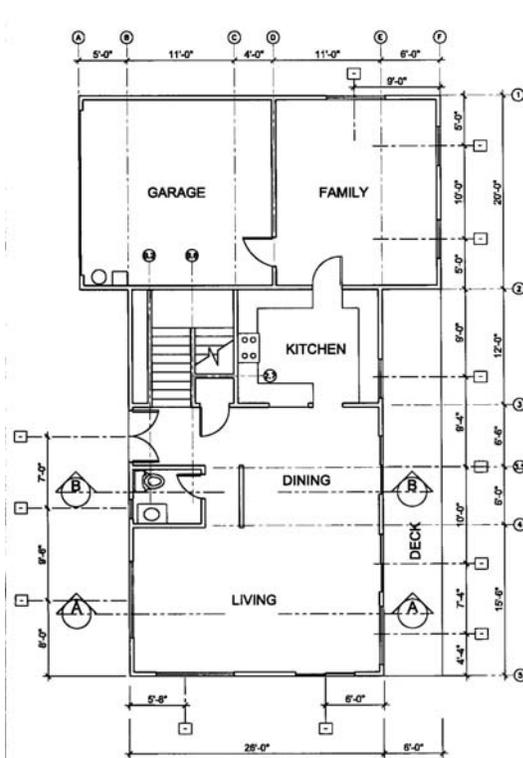
WEST ELEVATION

1/4" = 1'-0"



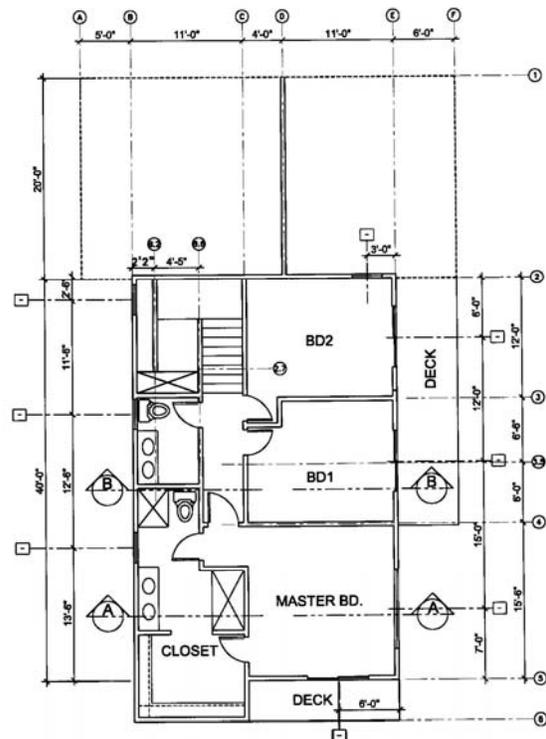
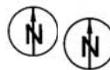
EAST ELEVATION

1/4" = 1'-0"



FIRST FLOOR PLAN

1/4" = 1'-0"



SECOND FLOOR PLAN

1/4" = 1'-0"

Figure 3-4. Index buildings 4 and 5

3.2.4 Index building 6

Index building 6 is a single-story, 1900-sf house with slab on grade foundation. The water heater is strapped to the wall and the frame is bolted to the foundation. The house has an almost rectangular plan, with overall dimensions 44 ft by 56 ft. Exterior walls are T1-11 siding. Interior walls are finished with gypsum wallboard. The cost estimator involved in the present project estimates the replacement cost of this house at \$189,000 in 2002, or \$202,000 in 2005. Detailed drawings are provided in an appendix. Figure 3-5 shows elevations and floor plans for this house. This is a hypothetical building with construction that would be characteristic of homes of the 1970s.

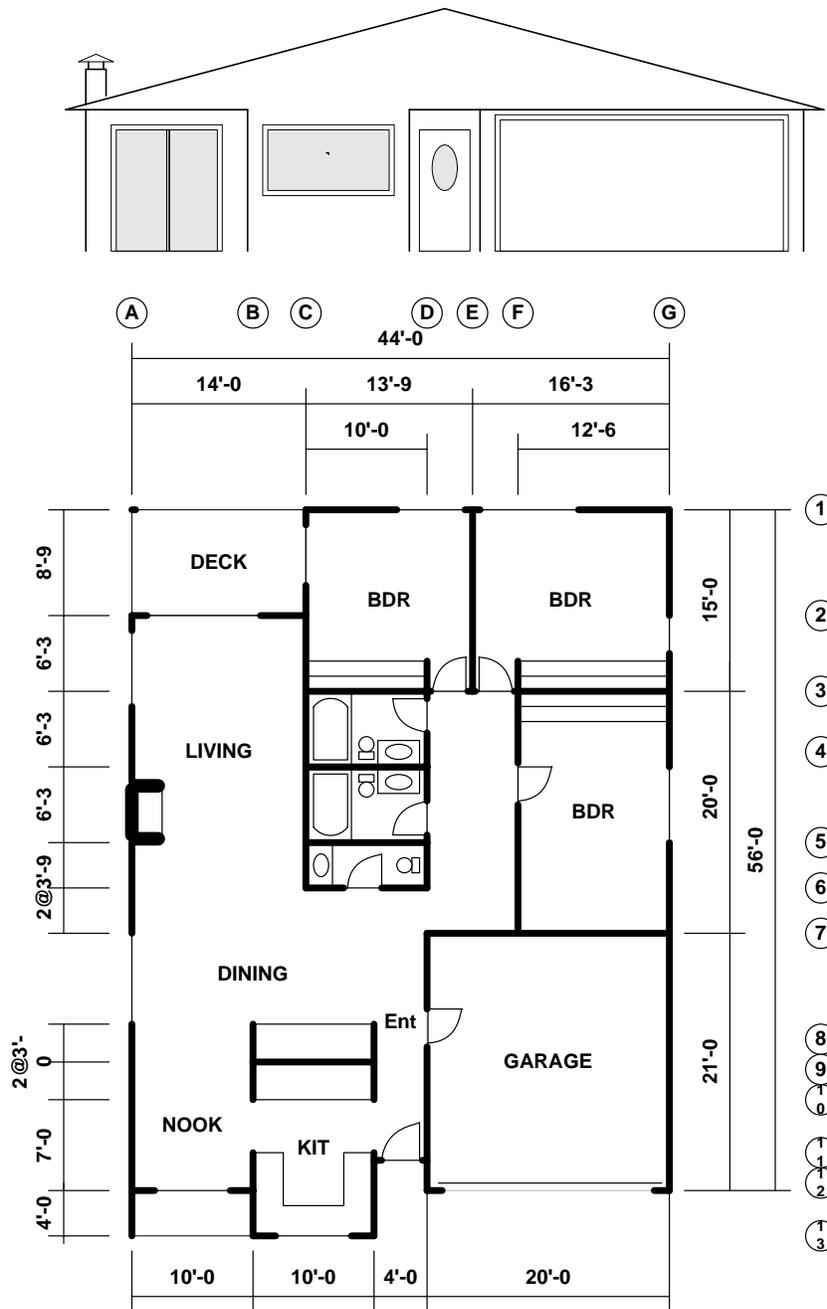


Figure 3-5. Index building 6

Notes on inflation and location. Construction costs have increased since the original version of this report was created. In general, construction costs have increased on average by approximately 6%, according to published cost factors. Furthermore, the construction costs noted above were calculated for a particular location, in Santa Monica, CA. Costs elsewhere in California can be somewhat less or substantially greater. In San Francisco, local construction costs are estimated to be on average 14% higher; in San Bernardino, 6% lower.

4 METHODOLOGY

4.1 OVERVIEW

The author calculated probabilistic relationships between repair cost and shaking intensity (the relationships are called seismic vulnerability functions) for each of the index buildings summarized in Chapter 3 using the assembly-based vulnerability (ABV) method summarized in Chapter 2, and described in detail in Porter and Kiremidjian (2001) and Porter et al. (2002a). The ABV methodology has been published in peer-reviewed journals and technical reports, and was summarized briefly in Chapter 2, so it will not be detailed here. The present chapter discusses only new aspects of the methodology introduced in this study for the California Earthquake Authority. It necessarily includes some calculus and mathematics of probability.

There are two novelties. One is that it represents the first study to quantify the reduction in insurance loss resulting from seismic retrofit of woodframe dwellings on a wide-scale basis, using a theoretical loss-reduction factor applied to empirical seismic vulnerability functions. (Porter et al. 2002a offers an example calculation of the reduction in annualized repair cost for the retrofit or redesign of several different houses, but at a single site. Porter et al. 2006 presents reduction in annualized repair costs for a variety of houses throughout California, but does not consider either insurance recovery or combining empirical with theoretical seismic vulnerability functions.)

The second novelty is the use of a vector-valued intensity measure. In the first edition of this study and in past studies using ABV, intensity was measured using damped elastic spectral acceleration a single period and mean viscous damping ratio. The particular period and mean damping ratio varied by building and by study, but the point is that repair cost was depicted as a function of a single number, and could be plotted on an x - y chart where the horizontal (x) axis measured intensity and the vertical (y) axis measured repair cost or damage factor. Here, because of developments in EQECAT's loss-estimation algorithm, the damage factor is calculated as a function of two intensity measures, and could be plotted on an x - y - z chart where the x - and y -axes measure two different aspects of intensity and the damage factor is measured by the z -axis. The mean damage factor on such a chart would look like a curved surface in space, rather than a curved line on a flat piece of paper.

4.2 CALCULATION OF THEORETICAL LOSS-REDUCTION FACTOR

General formulation. This section deals with the calculation of a loss reduction factor, denoted here by r , that represents the basis for a theoretically justifiable premium incentive for performing seismic retrofit. The factor r is expressed as a fraction of pre-incentive risk premium. The following discussion considers only pre-1979 woodframe, CEA-insured single-family dwellings, and considers only the main building. (The CEA policy also provides coverage for components that are in addition to the assemblies considered in this study, such as walkways and patios, contents, and additional living expenses. The ultimate premium incentive will necessarily have to consider these additional items.) For illustration purposes, let us imagine that for purposes of loss estimation, all such dwellings can be

adequately categorized using three structure types; the math shown here is readily generalizable to more structure types. Let

s = shaking intensity, measured, e.g., in terms of S_a , etc. Can be a scalar value (a single number) such as $S_a(1 \text{ sec}, 5\%)$ or peak horizontal ground acceleration or a vector value (groups of two or more numbers). Scalar intensity measures are common; the use of vector intensity measures is new.

B = structure type, where B can take on any of three values, $\{b_1, b_2, b_3\}$

b_1 = pre-retrofit (raised foundation, unbraced cripple walls, bolted sill plates, strapped water heater)

b_2 = post-retrofit (same as b_1 but with braced cripple walls)

b_3 = not retrofittable (e.g., slab on grade)

Note that “raised foundation” refers here to a structural system where the first floor is raised off of the ground, supported on a wooden frame that in turn rests on concrete footings. The notation $p[]$ means the probability that the term in brackets is true. Thus, the notation $p[B = b_2]$ means the probability that the structure type is b_2 . For shorthand, let us denote the probability that the structure type is i by

$p_i = p[B = b_i]$, which can be determined from the CEA’s portfolio information

It is common to measure earthquake loss in terms of a damage factor, defined here as the uncertain repair cost as a fraction of replacement cost (new). (Later we deal with repair cost in excess of the deductible.) Damage factor is often expressed as a function of shaking intensity, with a different function for each of one or more structure types. These functions are referred to as seismic vulnerability functions. Let

$Y(s|b_i)$ = uncertain theoretical damage factor at intensity s , given structure type b_i (from ABV)

$f_{Yi(s)}(y)$ = the probability density function of $Y(s|b_i)$, from ABV analysis

$y(s|b_i)$ = expected (mean) value of $Y(s|b_i)$, calculated by

$$y(s|b_i) = \int_{y=0}^{\infty} y \cdot f_{Yi(s)}(y) dy \quad (4-1)$$

$Y(s)$ = uncertain theoretical damage factor at intensity s , unknown structure type

$$Y(s) = \sum_{i=1}^3 Y(s|b_i) p_i \quad (4-2)$$

$y(s)$ = expected (mean) value of $Y(s)$, calculated by

$$y(s) = \sum_{i=1}^3 y(s|b_i) p_i \quad (4-3)$$

d = deductible as a fraction of replacement value

m = limit of liability as a fraction of replacement value ($m \approx 1.0$)

$Z(s|b_i)$ = uncertain loss factor (claim as a fraction of replacement value) given structure type b_i :

$$Z(s | b_i) = \begin{cases} 0 & Y(s | b_i) < d \\ Y(s | b_i) - d & (Y(s | b_i) - d) < m \\ m & (Y(s | b_i) - d) \geq m \end{cases} \quad (4-4)$$

$f_{Zi(s)}(z)$ = probability density function of $Z(s|b_i)$, calculated using $f_{Yi(s)}(y)$ and Equation (4-4).

$z(s|b_i)$ = expected value of $Z(s|b_i)$, calculated from

$$z(s | b_i) = \int_{z=0}^{\infty} z \cdot f_{Zi(s)}(z) dy \quad (4-5)$$

$Z(s)$ = uncertain loss factor at intensity s given unknown structure type

$$Z(s) = \begin{cases} 0 & Y(s) < d \\ Y(s) - d & (Y(s) - d) < m \\ m & (Y(s) - d) \geq m \end{cases} \quad (4-6)$$

$z(s)$ = expected value of $Z(s)$, calculated from

$$z(s) = \sum_{i=1}^3 z(s | b_i) p_i \quad (4-7)$$

$G(s)$ = annual frequency of shaking intensity reaching or exceeding s , e.g., from Frankel and Leyendecker (2001), or from EQECAT's hazard model in USQUAKE.

$G'(s)$ = $dG(s)/ds$, i.e., the first derivative of $G(s)$ with respect to s

$eal(b_i)$ = expected annualized loss given structure type b_i as a fraction of replacement value, given by

$$eal(b_i) = \int_{s=0}^{\infty} z(s | b_i) |G'(s)| ds \quad (4-8)$$

$eal(B)$ = expected annualized loss for unknown structure type B

$$eal(B) = \int_{s=0}^{\infty} z(s) |G'(s)| ds \quad (4-9)$$

USQUAKE for EAL calculation. Equations (4-8) and (4-9) are calculated using EQECAT's loss-estimation software USQUAKE. The software contains all the required data on fault locations, seismicity, local soil characteristics, seismic attenuation, seismic vulnerability, and deductibles. No aspects of the software are novel for this study, other than the new seismic vulnerability functions discussed here, so the assumptions, databases, and methodology of USQUAKE are not detailed here. The interested reader is referred to Appendix D of the present study, EQECAT (1999) and Zeng (1997) for further information.

Denominator of loss-reduction factor. The CEA assigns premiums based on $eal(B)$ and on other considerations such as administrative costs and the desire to smooth rates over geographic areas. This is important: we have *not* assumed that the pre-incentive premium is based on $eal(b_i)$. The pre-incentive premium reflects neither the details of foundation type (which is not a rating factor) nor the presence or absence of seismic retrofit, which make the

difference between the structure types b_1 , b_2 , etc. used here. Rather, the premium incentive should be based (in part) on the reduction in EAL relative to the average structure type, B . That is, the premium incentive should be based in part on

$$r = \frac{eal(b_2)}{eal(B)} \quad (4-10)$$

where both numerator and denominator vary by geographic location (here, ZIP Code). Note that $eal(b_2)$ is the post-retrofit annualized loss as a fraction of replacement cost, and that $eal(B)$ is the average annualized loss as a fraction of replacement cost. Thus one can refer to r as the *post-to-average* reduction factor. It is a theoretical value, and will most likely be only one issue in the calculation of an appropriate premium incentive. Other relevant issues include:

- Geographic aggregation—i.e., using the same premium incentive for many or perhaps all ZIP Codes.
- Content losses and additional living expenses, both of which are beyond the scope of the present project.
- Taxes, administrative costs, and other nonstructural issues

Observe that r is *not* calculated as the ratio of post-retrofit loss to pre-retrofit loss, referred to here the post-to-pre loss-reduction factor and denoted by

$$r_2 = \frac{eal(b_2)}{eal(b_1)} \quad (4-11)$$

Why should the CEA's premium incentive be based on r rather than r_2 ? Because the CEA wishes to provide an incentive that adjusts premium—which as discussed above is based on $eal(B)$, not on $eal(b_1)$ —to acknowledge the performance of a seismically retrofitted house, whose structure type is b_2 . Consider: let $\pi(B)$ denote the premium for a given insured and let us define a load factor L such that

$$\pi(B) = L \cdot eal(B) \quad (4-12)$$

where L accounts for risk load, overhead and profit, and the desire to smooth rates over geographic areas. Let the after-incentive premium for a retrofitted house be denoted as $\pi(b_2)$. If the CEA applies the same risk load L , then $\pi(b_2)$ is given by

$$\begin{aligned} \pi(b_2) &= L \cdot eal(b_2) \\ &= L \cdot \frac{eal(b_2)}{eal(B)} \cdot eal(B) \\ &= L \cdot r \cdot eal(B) \end{aligned} \quad (4-13)$$

To summarize: if the CEA wishes to apply the same risk load L to a retrofitted house (type b_2) as it does to all houses (B), then it will charge premium $\pi(b_2)$ and r must be calculated as in (4-10), i.e., as the post-to-average loss-reduction factor r , not as the post-to-pre-retrofit loss reduction factor r_2 , per Equation (4-11).

4.3 THEORETICAL SEISMIC VULNERABILITY WITH VECTOR INTENSITY

In ABV, one performs a number of simulations of loss, accounting for a variety of uncertainties in the analyses of seismic hazard, structural response, damage and loss. One aspect of that simulation is that the structural analyses use ground-motion time-histories in the calculation of structural member forces and deformation.

Each ground-motion time-history can be measured a variety of ways. EQECAT's loss model, USQUAKE, measures intensity in terms of a two-component vector of 5%-damped elastic spectral acceleration response, one component at 0.3-second period, the other at 1.0-second period. (To be precise, each of the two components is itself the geometric mean of pairs of 5%-damped elastic spectral acceleration with the same period, measured in two perpendicular and randomly oriented directions.) The components are denoted here as $S_a(0.3 \text{ sec}, 5\%)$ and $S_a(1.0 \text{ sec}, 5\%)$.

ABV simulations of loss can be plotted in terms of an 3-dimensional scatter diagram, with the x- and y-axes being $S_a(0.3 \text{ sec}, 5\%)$ and $S_a(1.0 \text{ sec}, 5\%)$, respectively, and the z-axis measuring mean damage factor. A smooth 3-dimensional surface can then be fit to the data. In practice, any (x, y) pair can be represented by a single distance s from the origin (i.e., the "diagonal distance" from (0,0) to (x,y)). A smooth 2-dimensional curve is then fit to the (s, z) data, and the mean damage factor can then be evaluated for any (x, y) pair, producing a 3-dimensional seismic vulnerability function.

4.4 COMBINATION OF THEORETICAL AND EMPIRICAL VULNERABILITY

4.4.1 Difficulty using empirical seismic vulnerability to calculate loss-reduction factor

Why use adjusted empirical seismic vulnerability functions? It is probably inappropriate to base premium incentives solely on theoretical seismic vulnerability functions, at least at present. The reason is that actual claims adjusters may overlook earthquake-induced damage, may pay for pre-existing damage (not earthquake-induced), and may round claims payments up for simplicity and to prevent argument. Theoretical seismic vulnerability functions do not reflect these effects, but empirical seismic vulnerability functions based on actual claims experience do. EQECAT has compiled such empirical seismic vulnerability functions.

The problem is that historical claims data do not distinguish between b_1 , b_2 , and b_3 —that is, no loss database of which the author is aware (including EQECAT's) shows whether houses that experienced earthquakes in the past were retrofitted or not, and to what extent. Hence, empirical seismic vulnerability functions can be used to calculate $eal^*(B)$, but not $eal^*(b_2)$, where the asterix (*) denotes the effects of claims-adjustment practices. Thus empirical claims data cannot be used to calculate r by Equation (4-10).

Potential changes because of claims-adjustment practices. Note that with sponsorship from the CEA, Osteraas (Consortium of Universities for Research in Earthquake Engineering, 2002) has proposed claims-adjustment practices for CEA to mitigate the potential for overlooking earthquake-induced damage and also for paying for pre-existing damage (not earthquake-induced). If these practices were applied in future earthquakes, then actual losses might more closely approach theoretical values.

4.4.2 Adjusting empirical seismic vulnerability functions based on theoretical ones

Let r^* denote a loss-reduction factor that accounts for the claims-adjustment practices discussed above (again, we note these practices by the asterix). It can be approximated as follows. Let

$Y^*(s)$ = uncertain empirical damage factor at intensity s , with unknown structure type, such as from EQECAT data

$Y^*(s|b_i)$ = uncertain theoretical damage factor at intensity s , given structure type b_i . Past claims data do not provide the necessary building data to calculate this value directly, but it can be approximated using the theoretical seismic vulnerability functions $y(s|b_i)$ and $y(s)$ by

$$Y^*(s|b_i) \approx Y^*(s) \frac{y(s|b_i)}{y(s)} \quad (4-14)$$

$Z^*(s|b_i)$ = uncertain loss factor (claim as a fraction of replacement value) at intensity s given structure type b_i and accounting for past claims-adjustment practice, from

$$Z^*(s|b_i) = \begin{cases} 0 & Y^*(s|b_i) < d \\ Y^*(s|b_i) - d & (Y^*(s|b_i) - d) < m \\ m & (Y^*(s|b_i) - d) \geq m \end{cases} \quad (4-15)$$

$z^*(s|b_i)$ = expected value of $Z^*(s|b_i)$, from

$$z^*(s|b_i) = \int_{z=0}^{\infty} z \cdot f_{Z^*(s|b_i)}(z) dz \quad (4-16)$$

$Z^*(s)$ = uncertain loss factor at intensity s and unknown structure type, accounting for past claims-adjustment practice, from

$$Z^*(s) = \begin{cases} 0 & Y^*(s) < d \\ Y^*(s) - d & (Y^*(s) - d) < m \\ m & (Y^*(s) - d) \geq m \end{cases} \quad (4-17)$$

$z^*(s)$ = expected value of $Z^*(s)$, from

$$z^*(s) = \int_{z=0}^{\infty} z \cdot f_{Z^*(s)}(z) dz \quad (4-18)$$

$eal^*(b_i)$ = expected annualized loss given structure type b_i as a fraction of replacement value, accounting for past claims-adjustment practice, given by

$$eal^*(b_i) = \int_{s=0}^{\infty} z^*(s|b_i) |G'(s)| ds \quad (4-19)$$

$eal^*(B)$ = expected annualized loss given unknown structure type, as a fraction of replacement value, given by

$$eal^*(B) = \int_{s=0}^{\infty} z^*(s) |G'(s)| ds \quad (4-20)$$

Then a loss-reduction factor that accounts for past claims-adjustment practice can be calculated as

$$r^* = \frac{eal^*(b_2)}{eal^*(B)} \quad (4-21)$$

As noted above, current empirical claims data lack the necessary building detail to calculate $Y^*(s|b_i)$ directly, so one cannot calculate $eal^*(b_2)$ based solely on empirical claims data. As shown here, however, one can combine theoretical and empirical seismic vulnerability functions to calculate a loss-reduction factor r^* that accounts for past claims-adjustment practice and the theoretical benefit of seismic retrofit.

Of course, if future claims-adjustment practices differ substantially from past practices by mitigating the claims-adjustment errors discussed above, then it might be preferable to base premium incentives on r of Equation (4-10), rather than on r^* of Equation (4-21).

4.5 SOME ADDITIONAL DECISION-MAKING INFORMATION CEA COULD PROVIDE

This study produces information that can be used to provide additional information that a homeowner could use in deciding whether to perform a seismic retrofit. It is an assumption of the CEA's premium-incentive program that a policyholder with a structure-type b_1 house would make a retrofit decision considering the premium savings reflected by r . But the insured might also find other information relevant to the retrofit decision. For example, the policyholder (and other owners of b_1 houses), might care about the reduction in repair cost (not loss) associated with changing his or her house from b_1 to b_2 . The policyholder might care about two or three measures of reductions in repair cost:

1. The average annualized reduction in repair cost (denoted here by D_3).
2. The reduction in repair cost given some scenario earthquake (denoted here by D_4)
3. The chance (denoted by p_5) that the repair cost will exceed some intolerable amount such as the homeowner's equity (denoted by D_5).

Capital letters are used here to indicate that the units of D_3 , D_4 and D_5 are dollars, not some fractional change. Of these measures, the present study addresses only D_3 , although the intermediate results could be used to quantify the other measures of performance as well. Consider the new reduction factor r_3 :

$$r_3 = \frac{ead(b_1) - ead(b_2)}{V} \quad (4-22)$$

where V refers to replacement cost of the house and $ead(b_i)$ refers to the expected annualized damage for a house of structure type b_i . The value of $ead(b_i)$ is given by

$$ead(b_i) = \int_{s=0}^{\infty} y(s | b_i) |G'(s)| ds \quad (4-23)$$

The benefit retrofitting a house can then be calculated as follows:

$$D_3 = \left(\frac{r_3 (1 - e^{-\rho t})}{\rho} \right) V \quad (4-24)$$

where of the D_3 is the present value of benefit, r_3 is the tabulated value of annualized benefit for the homeowner's ZIP Code, V is the replacement cost of the homeowner's dwelling, ρ is the discount rate (e.g., mortgage interest rate less inflation) and t is the planning period (e.g., an average duration of homeownership such as 7 years). If the cost of retrofit is less than D_3 , then the retrofit is estimated to be cost-effective. This calculation neglects any increase in the resale value of the house because of retrofit; any such increase would add to the benefit of the retrofit. This calculation could be modified to reflect premium incentives and insurance recovery.

The term in parentheses in Equation (4-24) could be tabulated or mapped by ZIP Code for various values of ρ and t , to allow a homeowner to estimate the benefit of retrofitting his or her home. For the present study, only the value of r_3 is tabulated by ZIP Code, but the additional calculation of the term in parentheses in Equation (4-24) is straightforward, given r_3 .

Before disseminating such additional data, serious thought must be given to how, where, when, and to whom this information be provided. The CEA should consider who are the people either most likely to choose to retrofit, or who would get the most benefit from retrofit, or who would be most harmed by earthquake.

5 RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SEISMIC VULNERABILITY FUNCTIONS

Number of analyses performed. For each of the six buildings, 20 samples of the structural model were created. The samples vary in mass, damping, and force-deformation behavior to reflect uncertainty in these characteristics. Each sample of each index building was subjected to 20 (x, y) pairs of ground motions of intensity varying from 0.1g to 2.0g of damped elastic spectral acceleration, according to the constraints noted in Chapter 4, for a subtotal of 400 nonlinear time-history structural analyses per each of six index buildings. For each analysis and each damageable structural or nonstructural component, damage was simulated once according to the fragilities discussed in Chapter 4, and costs were simulated once for each damage simulation. Thus, a total of 2400 structural, damage, and loss analyses were performed to model the index buildings' forces and deformations, detailed damage state, and repair costs, as a function of ground motion intensity.

Theoretical seismic vulnerability functions. In the following discussion, $S_a(T)$ refers to 5%-damped spectral acceleration response at T -second period, and is typically shown in units of gravities, abbreviated by the symbol "g." (One gravity is approximately equal to 32.2 feet per second per second).

In the ground motions used to analyze the index buildings, $S_a(1.0)$ is on average approximately 0.6 times $S_a(0.3)$, so $S_a(1.0)/0.6$ is on average equal to $S_a(0.3)$. One can take advantage of this to define an intensity measure \hat{S}_a that combines $S_a(0.3)$ and $S_a(1.0)$ and takes on a value comparable with $S_a(0.3)$. The combined intensity measure is given by

$$\hat{S}_a = \sqrt{\frac{1}{2} \left((S_a(0.3))^2 + \left(\frac{S_a(1.0)}{0.6} \right)^2 \right)} \quad (5-1)$$

This definition allows one conveniently to fit idealized curves to the probability that the cripple wall will collapse (denoted here by P_C) and to the damage factor (repair cost divided by replacement cost) given that the cripple wall does not collapse (denoted here by y_{NC}). Then the mean damage factor for a particular index building is given by the equation:

$$y(\hat{S}_a) = P_C(\hat{S}_a) \cdot y_C + (1 - P_C(\hat{S}_a)) \cdot y_{NC}(\hat{S}_a) \quad (5-2)$$

Where

$y(\hat{S}_a)$ = mean damage factor at shaking intensity \hat{S}_a

$P_C(\hat{S}_a)$ = probability of cripple-wall collapse, given shaking intensity \hat{S}_a

y_C = mean damage factor given that the cripple-wall collapses

$y_{NC}(\hat{S}_a)$ = mean damage factor at shaking intensity \hat{S}_a , given no cripple-wall collapse

The first part of Equation (5-2) gives the contribution to the damage factor from cases where the cripple wall collapses, weighted by the probability that the cripple wall will collapse. The second part gives the contribution to the damage factor given that the cripple wall does not collapse, weighted by the probability that the cripple wall will not collapse.

The resulting 3-dimensional seismic vulnerability functions are shown in Figure 5-1(a) through (f). The vertical (z) axis of the figure shows the mean damage factor. The x - and y -

axes measure the shaking intensity used by USQUAKE. The x -axis measures $S_a(0.3)$. The y -axis measures $S_a(1.0)$. The vertical axis is shown on a logarithmic scale to provide greater resolution at lower intensities.

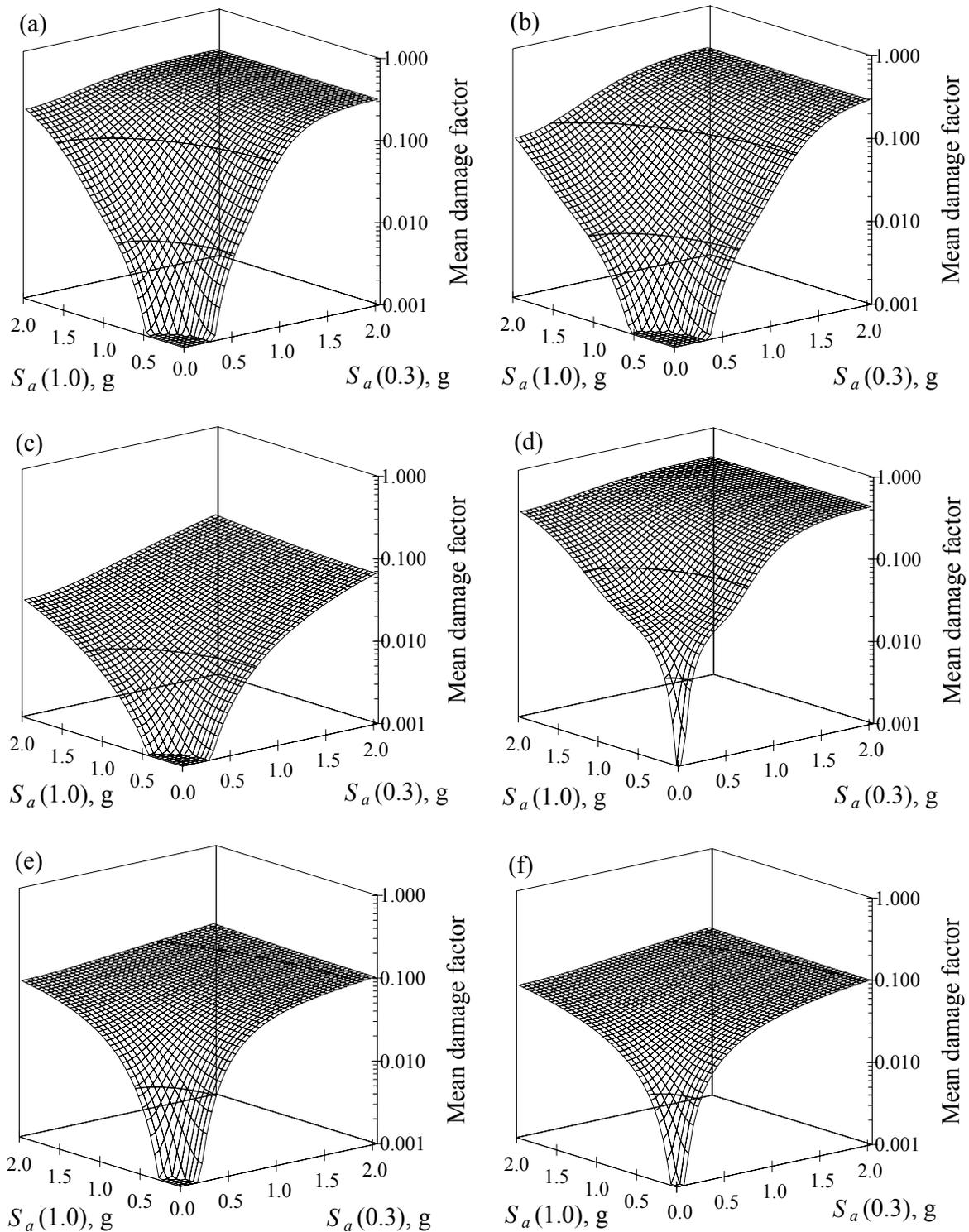


Figure 5-1. Theoretical seismic vulnerability functions for study index buildings (a) IB1, (b) IB2, (c) IB3, (d) IB4, (e) IB5, and (f) IB6

Reading the seismic vulnerability functions. The reader should understand that damaging shaking starts at about 0.05g on either x - or y -axis. The surfaces show mean repair cost as a fraction of replacement cost. For example, a point on a curve with (x, y, z) coordinates of (1.15, 0.7, 0.22) means that, given shaking with $S_a(0.3) = 1.15g$ and $S_a(1.0) = 0.7g$, one would expect repairs to cost 22% of the replacement cost of the house, on average. For a house that would cost \$200,000 to replace (building only, not land), that would equate with \$44,000 on average of repair costs. Only a portion of each surface is realistic or relevant, for two reasons. The first is that $S_a(0.3)$ and $S_a(1.0)$ are correlated: $S_a(1.0)$ is typically on the order of 0.6 times $S_a(0.3)$, and is rarely less than 0.2 times $S_a(0.3)$ or greater than 1.5 times $S_a(0.3)$. Thus, a point on the vulnerability function surface at $S_a(0.3) = 0.7g$, $S_a(1.0) = 0.1g$ has a z -value, but an earthquake with spectral accelerations in these proportions would rarely if ever occur. The second reason is that shaking with $S_a(1.0 \text{ sec}, 5\%) \geq 1.0g$ or $S_a(0.3 \text{ sec}, 5\%) \geq 1.5g$ is rare.

For reference, index building 1 (IB1) is the rectangular single-story stucco-sided house with raised, unbraced but bolted foundation, deemed typical of 1940s construction. IB2 is the same house with seismic retrofit. IB3 is the U-shaped single-story Eichler-style house built in 1956 with slab-on-grade, bolted foundation. IB4 (the poorest-performing house) is the 2-story, stucco-sided house with raised, bolted, unbraced foundation, characteristic of 1960s construction. IB5 is the same house with seismic retrofit. IB6 is the single-story, nearly rectangular house with slab-on-grade, bolted foundation and T1-11 siding, deemed characteristic of 1970s construction.

Because of the definition of \hat{S}_a , it is possible to depict the vulnerability functions of Figure 5-1 in the form shown in Table 5-1.

Table 5-1. Theoretical mean damage factors

\hat{S}_a, g	IB1	IB2	IB3	IB4	IB5	IB6
0.1	0.000	0.000	0.000	0.006	0.000	0.002
0.2	0.000	0.000	0.000	0.016	0.001	0.006
0.3	0.000	0.000	0.001	0.026	0.004	0.012
0.4	0.002	0.001	0.002	0.034	0.009	0.018
0.5	0.005	0.002	0.003	0.041	0.016	0.024
0.6	0.010	0.005	0.005	0.050	0.024	0.030
0.7	0.016	0.008	0.006	0.064	0.032	0.036
0.8	0.025	0.011	0.009	0.086	0.040	0.042
0.9	0.040	0.016	0.011	0.116	0.048	0.047
1.0	0.062	0.022	0.014	0.153	0.055	0.052
1.1	0.091	0.030	0.016	0.193	0.061	0.057
1.2	0.125	0.043	0.019	0.234	0.066	0.062
1.3	0.160	0.060	0.023	0.273	0.071	0.066
1.4	0.195	0.082	0.026	0.307	0.076	0.070
1.5	0.225	0.108	0.030	0.338	0.080	0.074
1.6	0.251	0.136	0.033	0.363	0.083	0.078
1.7	0.271	0.165	0.037	0.384	0.086	0.082
1.8	0.287	0.193	0.041	0.400	0.089	0.085
1.9	0.299	0.219	0.046	0.413	0.092	0.088
2.0	0.308	0.242	0.050	0.424	0.095	0.091

Comparison. Comparing the seismic vulnerability functions, it is noteworthy that the poorest-performing house is IB4, and that the retrofit (IB5) provides significant improvement, reducing damage by roughly 50% to 80% between 0.3g and 2.0g. The next poorest-performing house is IB1. Its retrofit (IB2) reduces damage by up to 70%.

Also note that IB6 performs fairly poorly, exceeding IB1 at some intensity levels. As will be shown shortly, this poor performance is attributable to relatively high line-of-site costs: IB6 has large open rooms with gypsum wallboard finish, where any damage requires the entire room to be repainted. IB3 (the U-shaped Eichler), IB4 (the 2-story house), and IB5 (IB4 with retrofit) also have large open rooms, but IB3's large room has mostly wood paneling, which does not require repainting. IB4 and IB5 have stucco siding, which although brittle is very stiff in comparison to IB6's T1-11 wood shearwall. The stucco reduces the deformations that cause damage to the wallboard interior finish and hence reduces the interior repainting cost.

Technical notes. Some brief notes for the technical reader: Latin Hypercube sampling was used to ensure that the structural models sampled the tails of the distributions of these structural uncertainties (mass, damping, and force-deformation behavior). The definitions and distributions of these characteristics and their parameters are taken from Porter et al. (2002b), with the exception that the mean viscous damping is taken as 10% of critical as opposed to 5%, per Porter et al. (2002a), which in turn refers to Camelo et al. (2001). Note that repair costs are *calculated* using structural analyses that assume mean viscous damping is 10% of critical. However, vulnerability is *reported* in terms of the 5%-damping spectral acceleration response values for the same ground motions, because that is what is required by USQUAKE.

A test was performed to assure using the intensity measure \hat{S}_a does not introduce a bias in the 3-D vulnerability functions. Let \hat{s} denote the unit vector $(0.86i + 0.51j)$; it points through the center of the cloud of pairs $(S_a(0.3)i + S_a(1.0)j)$ formed by the ground motions used in the structural analyses. Let S denote the vector $(S_a(0.3)i + S_a(1.0)j)$ for any ground motion used in a single simulation of damage factor. Let t denote the angular distance in the $(S_a(0.3), S_a(1.0))$ plane counter-clockwise from \hat{s} to S . Let Y denote the damage factor from an individual simulation. Let e denote the relative error in the mean damage factor for a single simulation, i.e., $(Y - y(\hat{S}_a))/y(\hat{S}_a)$. One can now compare the relative error in the damage factor, e , with the angular deviation of the ground motion intensity from the vector through the center of the cloud of ground motion intensities, t . One calculates the correlation coefficient $\rho_{t,e}$, and takes as the null hypothesis that $\rho = 0$, i.e., that no trend exists between t and e . It is found that one cannot reject the null hypothesis at the 5% significance level.

5.2 ADJUSTMENT OF EMPIRICAL VULNERABILITY FUNCTIONS

Portfolio statistics. The theoretical seismic vulnerability functions presented above are used to adjust EQECAT's empirical seismic vulnerability functions contained in USQUAKE. Statistics for creating weighting factors come from the CEA's portfolio information. The following information was provided by the CEA for its portfolio as of February 2005. Table 5-2 shows number of homeowner policies by era of construction and foundation type, as reported by the CEA. As used here, slab foundation means the first floor is constructed of a concrete slab resting on the ground. Raised foundation means that the first floor is on a

wood-frame system above the ground. Note that “other” and “unknown” foundation-type information cannot be used here, as discussed in Chapter 4.

Table 5-2. Homeowner policies by era of construction and foundation type

	1940s	1950s	1960s	1970s
Slab	10,125	25,430	31,207	39,902
Raised	8,895	16,279	10,284	9,258
Other ⁽¹⁾	9,549	26,785	30,823	32,605
Unknown ⁽²⁾	14,804	31,591	32,267	47,194

(1) Foundations other than slab or raised foundation type, e.g., post and pier

(2) Unusable data: either not reported or reported with odd coding

Retrofit discount statistics. Table 5-3 shows the number of these policies with a claimed retrofit discount. Note that the CEA only started tracking discount in 1999. There may be some policies receiving the discount since before 1999 that are not reported here, but the CEA thinks there are few of these. Note also that carriers have allowed the discount in many unexpected cases: it is not supposed to be applied to slab-on-grade foundation types. The only statistics that matter for present purposes in Table 5-3 are contained in the first row: number of houses with raised foundation where a retrofit discount has been claimed.

Table 5-3. Homeowner policies with claimed retrofit discount

	1940s	1950s	1960s	1970s
Slab	898	2,579	3,324	3,355
Raised	4,095	7,256	4,697	3,346
Other	1,843	4,348	3,927	3,245
Unknown	3,426	8,578	6,430	4,998

Accuracy of retrofit-discount statistics. The author and the CEA attempted to assess the accuracy of the retrofit claims. Possibly some policyholders are entitled to the discount but have not claimed it (to which one can refer as false-negatives); some might be receiving the discount who do not technically qualify (false positives). We intended to use a database in the CEA’s possession that shows detailed engineering evaluations of several thousand homes, comparing claimed discount with the engineer’s observations. For confidentiality reasons, the CEA could not release the database. It undertook to perform the comparison in-house, but was unsuccessful because of difficulties uniquely identifying houses in the inspection database with houses in the policy database. We agreed therefore to proceed as if the data in Table 5-3 were completely accurate.

The resulting distribution of policies by era of construction and relevant foundation type is shown in Table 5-4. Based on their judgment, EQECAT engineers believe that the ratio of braced to unbraced raised foundations may be unrealistically low, particularly for 1970s-era construction, i.e., there may be many false negatives. This could be checked using the engineering inspection database described above, but again, the author does not have access to this information.

Table 5-4. Homeowner policies by foundation type, bracing, and era

	1940s	1950s	1960s	1970s	Total	Fraction
Slab	10,125	25,430	31,207	39,902	106,664	70.5%
Raised, unbraced	4,800	9,023	5,587	5,912	25,322	16.7%
Raised, braced	4,095	7,256	4,697	3,346	19,394	12.8%

Theoretically adjusted empirical seismic vulnerability functions. The weighting factors p_i of Equation (4-2) are presented in Table 5-5, in the columns labeled “%.” The average theoretical seismic vulnerability function is calculated by weighting the damage factors shown in Table 5-1 using the weights shown in Table 5-5 under the heading “% of avg.” The post-retrofit seismic vulnerability function is calculated by weighting the damage factors shown in Table 5-1 using the weights shown in Table 5-5 under the heading “% of retrofit.” The resulting average and post-retrofit theoretical seismic vulnerability functions are shown in Table 5-6; the table also shows the ratio of the latter to the former. This ratio is applied to the empirical seismic vulnerability functions created by EQECAT to create theoretically-adjusted empirical seismic vulnerability functions.

EQECAT used these theoretically adjusted empirical seismic vulnerability functions in USQUAKE to calculate expected annualized losses (*EAL*) for average and post-retrofitted conditions, for each California ZIP Code. The ratio of the post-retrofit *EAL* to the average *EAL* is the final result for selecting the retrofit premium incentive.

Table 5-5. Weighting factors

Era	Foundation	Policies	Applied to	% of avg	% of retrofit
1940-1959	Raised, unbraced	13,823	IB1	9%	0%
1940-1959	Raised, braced	11,351	IB2	8%	59%
1940-1959	Slab	35,555	IB3	23%	0%
1960-1979	Raised, unbraced	11,499	IB4	8%	0%
1960-1979	Raised, braced	8,043	IB5	5%	41%
1960-1979	Slab	71,109	IB6	47%	0%
Total		151,380		100%	100%

Table 5-6. Adjustment factor for empirical seismic vulnerability functions*

\hat{S}_a, g	$y(\hat{S}_a)$	$y_r(\hat{S}_a)$	$\frac{y_r(\hat{S}_a)}{y(\hat{S}_a)}$
0.1	0.001	0.000	0.009
0.2	0.004	0.000	0.082
0.3	0.008	0.002	0.211
0.4	0.012	0.004	0.354
0.5	0.017	0.008	0.484
0.6	0.022	0.013	0.587
0.7	0.027	0.018	0.658
0.8	0.034	0.023	0.695
0.9	0.041	0.029	0.708
1.0	0.050	0.035	0.713
1.1	0.059	0.043	0.725
1.2	0.070	0.053	0.756
1.3	0.080	0.065	0.808
1.4	0.090	0.079	0.878
1.5	0.100	0.096	0.958
1.6	0.110	0.114	1.042
1.7	0.118	0.133	1.123
1.8	0.126	0.150	1.196
1.9	0.132	0.166	1.258
2.0	0.138	0.181	1.309

* Values shown to 3 decimal places but calculated to more

Implications of Table 5-6. The table deserves some discussion. First, although results are shown to three decimal places, this is done merely to avoid accumulating rounding error, not to imply accuracy to three decimal places. More importantly, observe that at high shaking intensity, the retrofitted building has higher vulnerability than the weighted average, i.e., the adjustment factor exceeds 1.0. This is reasonable. To retrofit a poorer-than-average building does not guarantee that it will become better than average, just that it will become better than it was before. The “average” includes some houses with slab-on-grade foundations, which can perform much better than houses with raised foundations, even if retrofitted. It is possible therefore that the retrofitted house can have expected annualized loss (before or after applying the deductible) greater than that of the average house.

The fact that the adjustment factor in Table 5-6 exceeds 1.0 at higher shaking intensities has another implication: it is generally at higher intensities that damage exceeds the deductible. Thus the risk to the insurer is dominated by higher intensities, where Table 5-6 shows the benefit of retrofit is lower. One can expect generally less reduction in expected annualized insurance loss than in ground-up loss, before insurance. In some cases, it may be that the ratio of post-retrofit *EAL* to average *EAL* exceeds 1.0, even where the ground-up loss (pre-insurance) is reduced by retrofit, because the intensities that dominate in the one case are different from those that dominate in the other.

How can one justify a premium incentive on the post-to-average *EAL* ratio, when the ratio is greater than 1.0, and yet there is clearly a reduction in the CEA’s risk? To be more concrete, consider two neighbors whose homes have the same replacement cost and the same insurance premium. Anne owns IB1 and Bill owns IB3. Suppose Anne changes her house to an IB2 by seismic retrofit, but her house still has an *EAL* higher than the average. Should

Anne receive a premium incentive? If she does, she will pay less premium than Bill, who is not eligible for the incentive, even though his house poses less risk to the CEA. This is probably a common actuarial problem of risk-spreading and simplicity versus fairness. One solution might be to charge different rates for IB1, IB2, and IB3, i.e., to include foundation type as a rating factor. The author offers no recommendation on that point other than to suggest that the CEA consider it.

Three important notes. The adjusted EQECAT seismic vulnerability functions are not presented here, for confidentiality reasons. To show the adjusted seismic vulnerability functions would be to reveal publicly EQECAT's proprietary, empirical seismic vulnerability functions. Nor does this report provide any information about how the theoretical seismic vulnerability functions $\gamma(s)$ compare with EQECAT's empirical ones, for the same reason. Second, the adjustment was applied to EQECAT's mean seismic vulnerability functions. No adjustment was made to EQECAT's coefficients of variation of repair cost given S_a . The reason for this decision is that it is desirable to rely as much as possible on empirical information already used by the CEA in its rate filings and other decisions, and to limit the influence of the theoretical seismic vulnerability functions solely to issues where the empirical data are inadequate.

Finally, at low levels of intensity ($S_a(1 \text{ sec}, 5\%) \leq 0.13g$ in the case of IB2, 0.085 in the case of IB5), some of the ABV-produced damage-factor values are zero or near zero, that is, all of the samples for a particular value of S_a produced zero or near-zero repair cost. In principle, some damage is always *possible* when earthquake shaking occurs, but it would take more simulations than were performed here to observe a nonzero repair cost. Nonetheless, these essentially zero values mean that the adjusted empirical seismic vulnerability functions for post-retrofit conditions are questionable: they would be calculated as zero, even though in principle they should be nonzero. Instead of using zero values, EQECAT applied the lowest nonzero ratio for all lower values of S_a , as shown in Table 5-6.

5.3 RETROFIT BENEFIT

EAL reduction. As discussed above, the adjusted seismic vulnerability functions were employed in EQECAT's USQUAKE model, which calculates expected annualized loss, accounting for seismicity, seismic attenuation, site soils. The results presented here are for 15% deductible and coverage A (main structure). Figure 5-2 shows the ratio of post-to-average *EAL* for each of 1,647 ZIP Codes in California, as calculated by EQECAT using the post-retrofit and average seismic vulnerability functions. The figure shows that the fractional affect on *EAL* from seismic retrofit varies between an increase of 24% and a decrease of 87% (i.e., the ratio varies between 1.24 and 0.13), with half of ZIP Codes showing a reduction of 17% to 50%, and the average ZIP Code showing a reduction of 33%. The same information is presented in tabular form in an electronic database delivered with this report. As noted on page 5-7, it is not surprising that in some locations, the ratio exceeds 1.0.

Lower hazard and higher relative reduction in EAL. It is interesting that there is a trend to greater relative (percent) reduction in *EAL* farther from major faults and on firmer soil, i.e., in lower-hazard areas. Two reasons combine to cause this effect. First is the fact that farther from the major faults and on firmer soil, earthquakes produce weaker shaking. Second is that the ratio of post-retrofit repair cost to average repair costs is lower at the lower shaking intensities. The *relative* reduction in repair cost is greater at lower levels of shaking, although the *absolute* dollar-amount reduction may be small. Thus, close to major faults and on softer soil, there is some relative reduction in repair cost and hence in *EAL* because of retrofit. Far

from major faults and on firmer soil, there is more relative reduction in repair cost and hence in *EAL* because of retrofit *and* because of weaker shaking. Again, the absolute dollar-amount reduction may still be small. In both cases the retrofit reduces *EAL*, but in the lower-hazard regions, the *relative* reduction is greater.

Fractional reduction in ground-up loss. The central purpose of the present study was to produce Figure 5-2 and the database it maps. Of some interest however is the ratio of zero-deductible *EAL* (average annual total repair cost, sometimes referred to as annualized damage) before and after seismic retrofit. This ratio is shown in Figure 5-3. It shows much more dramatic difference, from 46% to 93%, between unretrofitted and retrofitted homes. Retrofit in half of California ZIP Codes is estimated to reduce ground-up loss by 65% to 75%.

Absolute reduction in ground-up loss. Another figure, not central to the present study, is also of interest. Figure 5-4 shows the difference in expected annualized repair cost between the pre-retrofit and post-retrofit cases, in dollars per \$1,000 replacement cost of the main structure. It shows that in the high-hazard regions of California, the repair-cost savings resulting from seismically retrofitting a house with unbraced cripple walls can exceed \$5.00 per year per \$1,000 replacement cost in 10% of California ZIP Codes. The average reduction is approximately \$2.75 per year per \$1,000. The implication is that, for a house with \$200,000 replacement cost, the average annual reduction in repair cost is estimated to exceed \$500 per year. This makes a \$3,000 seismic retrofit of a raised foundation with unbraced cripple walls cost-effective for the typical homeownership tenure, even ignoring the possibility that the cost of the retrofit would be recovered by increased home value at resale.

The reader should not infer that premium incentives should be based on the ratio shown in Figure 5-3, for two reasons. First, these ratios refer to total repair costs, not after-deductible losses; it is the latter that are important when setting premium incentives, not the former. Second, these figures reflect changes from pre-retrofit to post-retrofit, not from average to post-retrofit. This point was discussed in detail in Chapter 4, but in summary, because premiums are based on the average case, not the pre-retrofit case, the premium incentive (a reduction from average premium) should be based on the change from the average to the post-retrofit case, not from the pre-retrofit to the post-retrofit case.

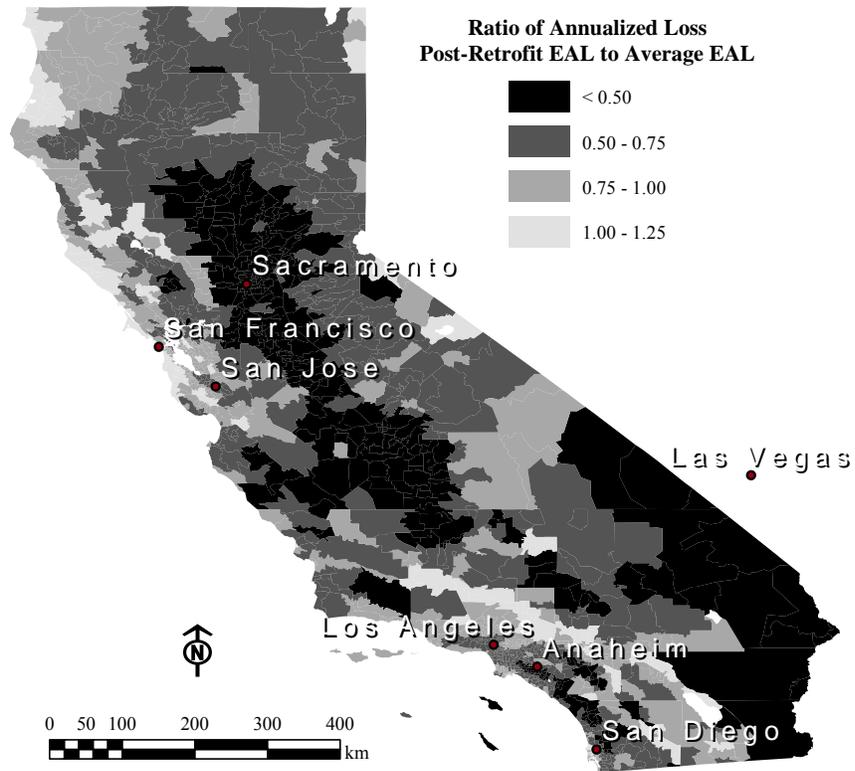


Figure 5-2. Ratio of post-retrofit *EAL* to average *EAL*, by ZIP Code.

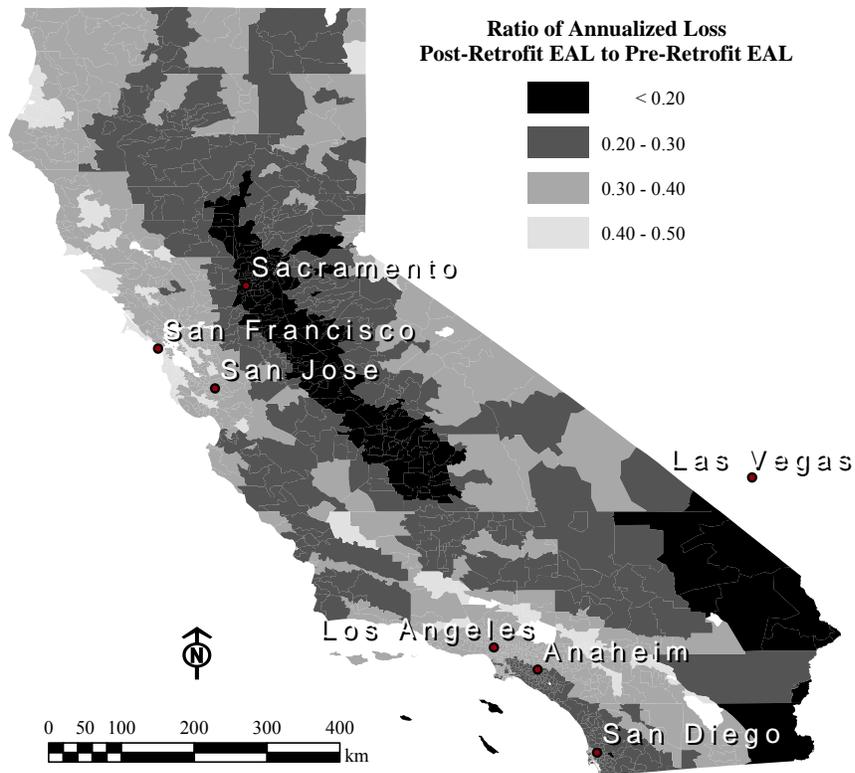


Figure 5-3. Ratio of post-retrofit *EAL* to pre-retrofit *EAL*, by ZIP Code

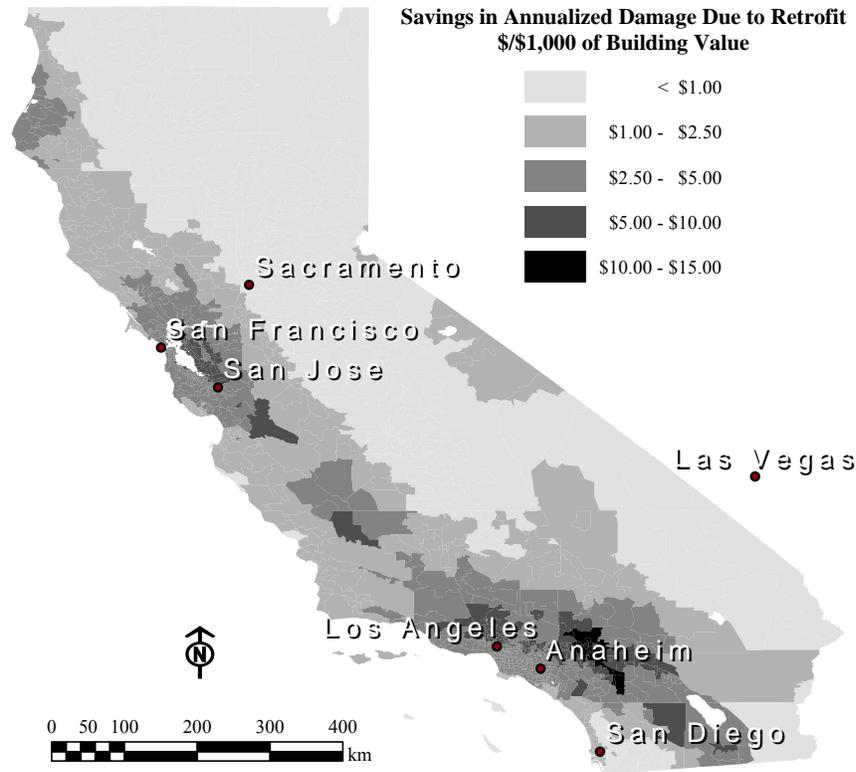


Figure 5-4. Reduction in ground-up *EAL* per \$1000 replacement cost, by ZIP Code

5.4 TOP CONTRIBUTORS TO DAMAGE

Repainting costs are important. The ABV methodology produces some intermediate results that may be of use. Figure 5-5 shows the parts of each house that contribute to the overall repair cost, as a function of shaking intensity. There are six diagrams in the figure, corresponding to the six index buildings. Each diagram shows shaking intensity on the horizontal axis (here, measured in terms of $S_a(T_1, 10\%)$, where T_1 is the small-amplitude fundamental period for that index building). On the vertical axis is average percent contribution to the total repair cost. Each region of the diagram corresponds to a cost category: stucco exterior wall finish, wood shearwalls, gypsum wallboard interior finish, etc. The figures do not show the overall total (for that, see Figure 5-1), nor do they reflect collapses. Stucco sheathing on cripple walls is included under “stucco” in the figures.

It is noteworthy that repainting dominates repair costs at lower levels of shaking. The reason is that even with minor damage to a painted wall, such as gypsum wallboard with a few nail heads tearing through the paper or popping the paint, insureds typically pay to have the entire room repainted to achieve a reasonable uniform appearance, because it is so difficult to match paint exactly. Reasonable-uniform-appearance costs might be an important opportunity for loss control through better paint-matching techniques.

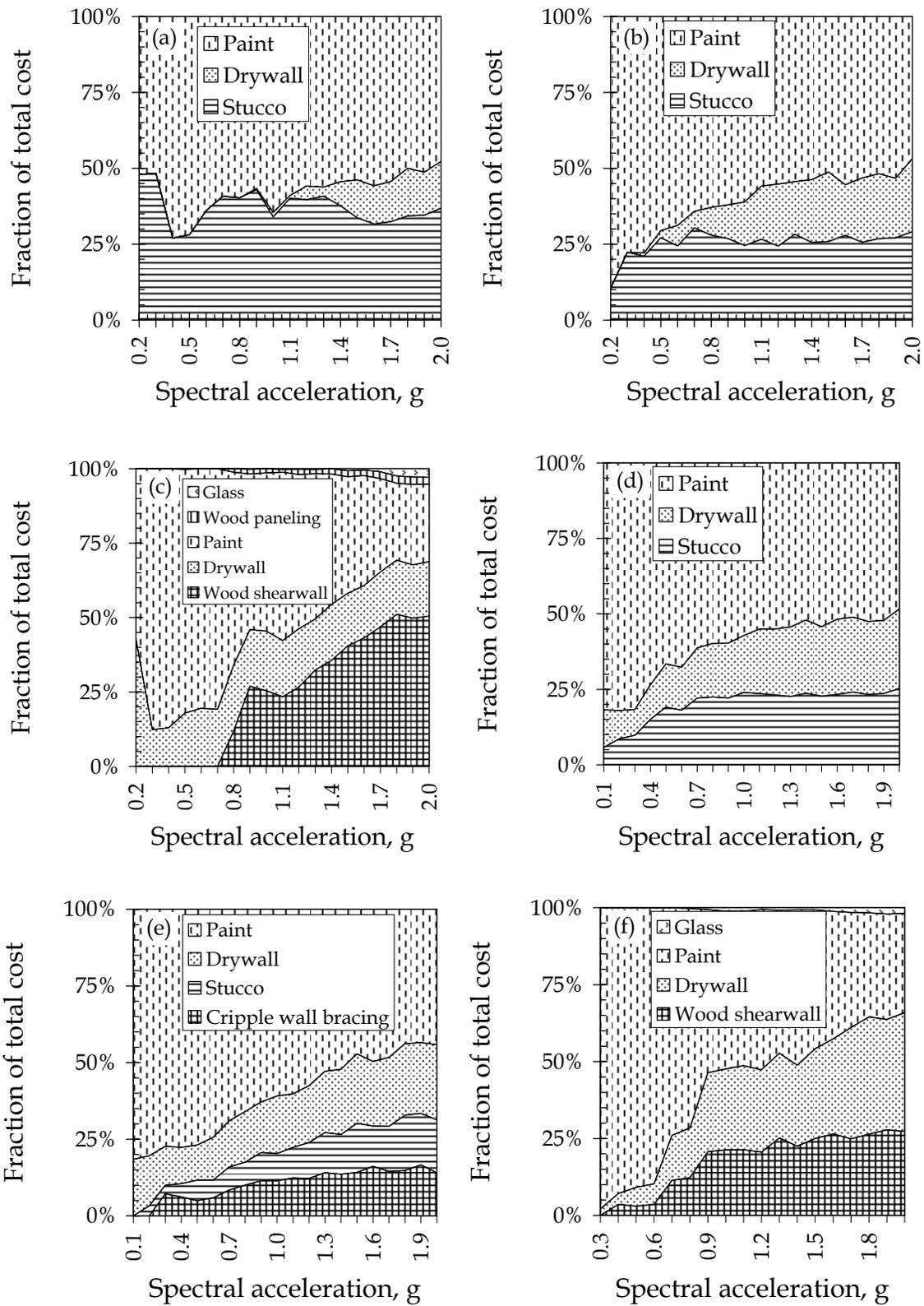


Figure 5-5. Source of repair costs for index buildings (a) IB1, (b) IB2, (c) IB3, (d) IB4, (e) IB5, and (f) IB6

5.5 CONCLUSIONS

Conclusions. This study combines engineering theory and historical loss information to create seismic vulnerability functions for woodframe buildings with three types of foundation: slab on grade, unbraced stucco-sheathed cripple walls, and braced stucco-sheathed cripple walls. Theoretical vulnerability models have been used to adjust empirical seismic vulnerability functions. The theoretically adjusted empirical models reflect post-retrofit conditions for which purely empirical information does not exist.

The resulting seismic vulnerability functions are combined with a well-established model of seismic hazard in California to calculate the benefit of adding structural sheathing to unbraced cripple walls at locations throughout California. The loss-reduction information presented here provides an apples-to-apples comparison of post-retrofitted expected annualized loss (*EAL*) to the CEA with the *EAL* calculated using the same empirical vulnerability information that the CEA has used in past rate filings (although with updated seismic hazard information).

Retrofit is estimated to reduce the CEA's *EAL* by approximately 33%, although the figure varies from an increase of 24% to a decrease of 87%, depending on location. Benefits are also calculated from the perspective of the homeowner, ignoring insurance recovery. It is found that the average annual benefit is approximately \$2.75 per \$1,000 replacement cost of the house, and can exceed \$5.00 per \$1,000 in many locations. These figures equate with annual savings of approximately \$550 to \$1000 per year for a \$200,000 house, for a present value in excess of \$3,000, implying that the benefit of this seismic retrofit exceeds its cost.

The author believes this is the first study to offer such findings based on rigorous engineering analysis. Both sets of data—insurer and homeowner benefit—are provided on a ZIP-Code basis for all of California.

Limitations. Three important limitations to the present study should be acknowledged. First, the empirical seismic vulnerability functions in the EQECAT model were taken as-is; this study does not address their accuracy or applicability to future earthquakes. If new claims-adjustment practices change future claims substantially, then the empirical seismic vulnerability functions might become less accurate. Second, only a few index buildings were studied here to create the factors used to adjust the empirical seismic vulnerability functions for post-retrofit conditions. The possible effect of studying additional index buildings is unknown; no opinion is offered about the magnitude of potential change in the calculated benefits. Finally, the author offers no opinion regarding how the loss-reduction information presented here should be used to select premium incentives. Administrative and other issues beyond the present scope must necessarily be considered in this decision.

5.6 RECOMMENDATIONS

1. The expected-annualized-loss (*EAL*) reductions presented here can be used for evaluating premium incentives. Figure 5-2 illustrates how these savings vary throughout the state. A database is provided with this study tabulating the same information.
2. Consider using Figure 5-4 to help communicate to homeowners the value of seismic retrofit, even regardless of premium incentives and insurance payments. It suggests that in half of California ZIP Codes, a homeowner might expect to save in excess of \$500 per year in annualized repair costs for a house with \$200,000 replacement cost. In 10% of California ZIP Codes, the saving is estimated to be in excess of \$1,000 per year on a

\$200,000 house. This information, appropriately qualified and explained, could be disseminated by the CEA for the benefit of the public (e.g., via the CEA website).

3. Consider using foundation type as a rating factor. In Section 5.2, it was noted that a retrofitted house can still have higher-than-average *EAL*, raising the problem of offering a premium incentive that allows people to pay less premium for worse-than-average homes than do homeowners with better-than-average homes, because the former are eligible for the incentive program and the latter are not. This problem could be alleviated by basing the premium, in part, on foundation type. That there can be a marked difference in performance associated with foundation type is supported by ATC-50 (2001), which identifies several common foundation conditions that contribute substantially to dwelling loss. The most important condition noted in ATC-50 is unbraced cripple walls. The ATC authors also note as important conditions: raised foundation, especially with post-and-pier construction; slope in excess of 3:1; lack of foundation bolts; heavy roofing; masonry veneer; more than 3 stories; and various soft-story conditions.
4. Consider line-of-sight costs for loss control. It can be costly to repaint entire rooms when repairs are required only to a small portion of the walls. Perhaps approaches similar to those used in auto repair, where new paint is carefully blended into the surrounding color near the repair, could be developed for application to houses.

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