ASSESSING THE BENEFITS AND COSTS OF EARTHQUAKE MITIGATION

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ABSTRACT

Surveys were conducted to gather information from experts on structural vulnerability and the benefits and costs of retrofitting a structure for an earthquake hazard. The results indicate that the views of structural engineers on the benefits of mitigation and contractors on the costs of mitigation are widely dispersed. Care must be taken when using these estimates in calculating economic losses from a significant earthquake event.

INTRODUCTION

Over the past decade, as the cost of natural disasters has skyrocketed in the United States, much emphasis has been placed on mitigating these hazards. From earthquakes to floods to hurricanes, agencies such as the Federal Emergency Management Agency (FEMA) and the Institute for Business and Home Safety (IBHS) have tried to increase public awareness of natural hazard risk and encourage those at risk to mitigate for the hazard. At the same time, advanced software tools have emerged to allow these agencies, as well as individual insurance companies, to more accurately assess their hazard risk exposures. Notable software packages include those by Applied Insurance Research, Inc. (AIR), EQECAT, and Risk Management Solutions, Inc. (RMS). Each firm's software package analyzes the economic effects from both earthquakes and hurricanes in the United States primarily for insurance and reinsurance companies. Additionally, in 1997, FEMA and the National Institute of Building Sciences (NIBS) released its own software estimating potential earthquake losses in the United States, called HAZUS [7], which stands for "Hazards U.S."

In the course of analyzing insurance company portfolio losses for the Managing Catastrophic Risks project based in the Wharton School of the University of Pennsylvania [6], I realized that there is considerable uncertainty involved in the earthquake loss estimation (ELE) process. Furthermore, when one considers mitigating a structure for earthquake risk, the assumed benefits and costs of the mitigation technique complicate the analysis. To date, limited published data exists on the vulnerability of structures for various levels of ground shaking, and quantitative benefit-cost studies on earthquake mitigation are minimal. Therefore, surveys were conducted to gather information from experts on structural vulnerability and the benefits and costs of retrofitting a structure for an earthquake hazard.

This paper presents quantitative and qualitative information gathered from experts on earthquake mitigation. Section I discusses the background on the current study into the uncertainty in earthquake loss estimation and the basis for the surveys. Section II describes the design of the survey,

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background on who was queried, and period of the study. Section III discusses comments from those responding, with an acknowledgment of possible errors and justification of the survey design. Section IV describes the relevant findings. Sections V and VI discuss the implications and conclusions, respectively.

I. BASIS FOR SURVEYS

The initial focus of the current study at the Wharton School was on the complementary role that insurance and structural mitigation could play in the reduction of residential losses during a natural disaster. The regions chosen for the study of managing earthquake risk were the cities of Oakland and Long Beach, California. The tax assessor's office supplied the inventory of the residences in these cities. The insurance coverage is defined in terms of a homeowner's policy with varying deductible and limit levels, and the software packages previously mentioned are being utilized for analysis.

While the private industry's software and the HAZUS software are intended for different audiences, each is based on the same general methodology to analyze catastrophic earthquake losses. This methodology includes four basic steps: define the hazard, define the inventory exposure characteristics, estimate the inventory damage potential, and calculate the loss. In each stage of the process, there is uncertainty: in the seismological data used to define the earthquake hazard, in the exposure data and vulnerability functions used for damage estimation, and in the costs and benefits used in determining losses.

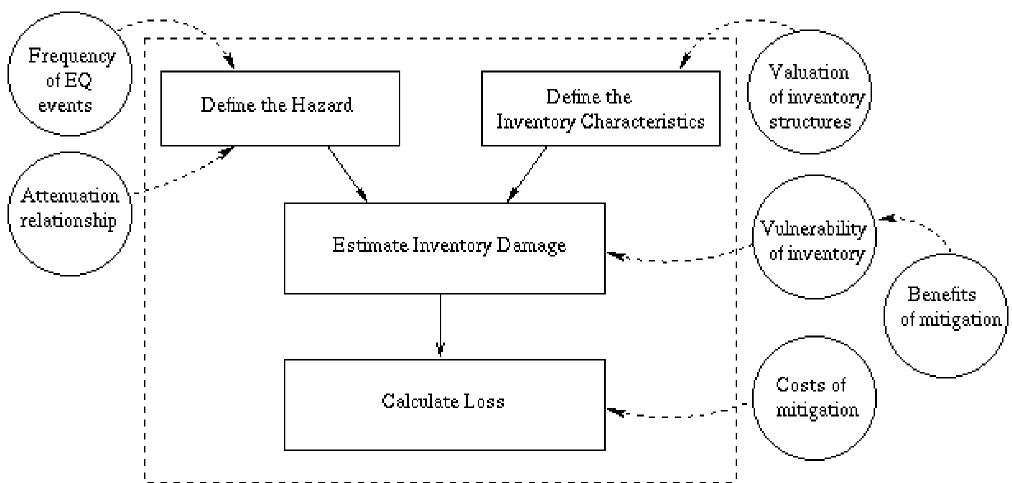

FIGURE I. Steps in earthquake loss estimation and scope of uncertainty study

A comprehensive sensitivity analysis on the uncertainty involved in the ELE process is being conducted. Those parameters being considered include the frequency of earthquake events on the fault sources in the surrounding area, the attenuation relationship assumed for earthquake site hazard, the replacement value and vulnerability of the structures in the inventory, and the costs and benefits of structural mitigation (Fig. I). The survey results presented in this paper are an attempt at understanding and reducing the uncertainty associated with structural vulnerability and the costs and benefits of earthquake mitigation.

Based on the residential characteristic of the two study regions, the structures chosen for study were pre-1940 wood-frame single family residences. These homes ordinarily have cripple walls, which are the walls between the top of the foundation and the first floor diaphragm (Fig. II).

The typical problems with homes built prior to World War II are twofold. First, there is a lack of connection between the wood frame and the foundation. Second, since the construction was completed before the predominant use of plywood, there is a lack of shear bracing at the cripple wall level. Therefore, the structural mitigation for pre-1940 homes in California requires bolting the structure to its foundation and bracing its cripple wall.

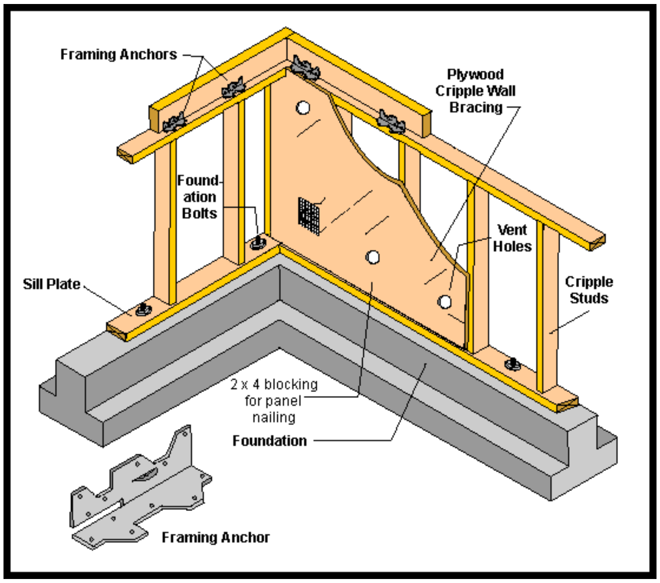

FIGURE II. Cripple wall configuration (courtesy of Ed Sylvis of Seismic Safety)

In this paper, three separate questions of validity are being addressed. (1) How valid are the initial vulnerability or damage curves utilized in an ELE analysis? Is the use of Modified Mercalli Intensity (MMI) appropriate for damage estimates? (2) How valid are the assumptions on the reduction in vulnerability after mitigation? How beneficial is "bracing the cripple wall and bolting the structure to its foundation" in reducing damage for various levels of ground shaking? (3) How valid are the estimates of the costs of mitigation? Since the costs are upfront and the benefits are seen over the life of the structure, an accurate assessment of the costs is important.

II. SURVEY DESIGN

The purpose of the survey is to determine, through expert opinion, the expected benefits and costs associated with "bracing the cripple wall and bolting the structure to its foundation" for pre-1940 wood frame residential structures in the cities of Oakland and Long Beach, California. Estimated ranges of benefits and costs are based on responses from structural engineers on the benefits of mitigation and contractors on the costs of mitigation. Five hundred surveys were sent to structural engineers in Northern California (NC) and Southern California (SC) (i.e. 250 to NC and 250 to SC). The mailing list was obtained from the Structural Engineers Association of California (SEAOC) roster, of which the author is a member. Nearly all of those queried were registered structural engineers in the state of California. Further, 160 surveys were sent to contractors in NC and SC (i.e. 80 to NC and 80 to SC). Mailing lists were obtained from the Association of Bay Area Government's (ABAG) website for the NC contractors and EQE's website for the SC contractors. All contractors had previously completed training sessions on retrofitting wood frame homes.

The mailings were done in the spring and summer months of 1998. All respondents were informed as to the purpose of the questionnaire and assured that their specific response information would be anonymous. Typically, each was given a month to reply, and reminders were sent to those who had not responded by the reply date. Both the structural engineers and the contractors were given the following building specifications: "Consider a 2,200 square-foot wood frame residential building in the city of Oakland, CA [or Long Beach, CA]. It is a pre-1940 two-story structure with a market value of $130,000. It has 24" unbraced cripple walls and it is inadequately bolted to its foundation."

Benefits from structural engineers

The structural engineers were asked to rank their experience in post-earthquake damage evaluation of residential structures on a scale of 0 (no experience) to 10 (extensive experience). Based on their expert knowledge, they were queried as to the expected mean damage factor (MDF) to this structure before mitigation and after mitigation for levels of MMI ranging from VI to XII (For clarification of MDF, see Section V). The mitigation technique was broken down into "bracing the cripple wall", "bolting the structure to its foundation", and "bracing and bolting." The engineers were asked for estimates of direct physical damage from ground shaking only. No collateral hazards such as ground failure, fault rupture, inundation, or fire following are considered.

Furthermore, they were asked to rank their confidence in their estimates of damage for the various levels of ground shaking, a "0" designating "not confident at all" and a "10" designating "very confident". Their belief in the determining factors in evaluation of damage was inquired, with a ranking of "0" implying "not important at all" and a "10" implying "very important". These factors include, but are not limited to, square footage of the structure, age of the structure, number of stories of the structure, value of the structure, height of the cripple wall, and inadequacy of the bolting to the foundation. Finally, their estimates on the percentage of structures in the model city which would have more than $1,000 worth of damage for MMI levels ranging from VI to XII was obtained.

Costs from contractors

Similar to the questionnaire sent to the structural engineers, the contractors were asked about their experience with retrofitting of wood frame residential construction (i.e. 0 designates no experience and 10 designates extensive experience). Based on this experience, they were asked cost estimates on "bracing the cripple wall", "bolting the structure to its foundation", and "bracing and bolting." Cost estimate ranges given were {$1,000-$3,000, $3,000-$5,000, $5,000-$7,000, $7,000-$9,000, or >$9,000}. Within these ranges, estimates of mean values were requested, as well estimates of the cost of material and labor in terms of a percentage of the mean value.

The contractors were inquired about their confidence in their cost estimate and the importance of several factors in determining the cost of the retrofit. Similar to the benefits survey, a "0" designated "not important at all" and a "10" designated "very important". The factors include, but are not limited to, square footage of the structure, age of the structure, number of stories of the structure, value of the structure, height of the cripple wall, and accessibility to the foundation.

III. COMMENTS AND JUSTIFICATION

Although a pilot test of both surveys was conducted, some errors in the data can still arise. For both groups of respondents, there were two issues they had with the survey: the limited information given on the characteristics of the structure and the separation of "bracing the cripple wall" and "bolting the structure to its foundation" as two separate retrofit techniques. One engineer stated that there was "too little information…How well is the building tied together? How strong is the shear resisting material? How much weight exists above the first floor – at the 2nd floor, at the roof? What kind of soil conditions exists under the building? How long does the severe shaking last?"

A contractor also noted that "this survey is too limited. There are more factors relevant to the cost of retrofitting: condition of existing concrete or brick foundation; level lot or hillside lot; width and length of building; presence of large openings in walls."

These respondents have a valid point. A limited amount of information was given. This is purposeful. Most of the software models estimating damage calculate this damage based on a few structural characteristics (i.e. construction type, occupancy class, number of stories, year built). I wanted to ascertain how experts differ in their views on damage and retrofit cost based on this limited information, and what additional information on the structure would be most useful in predicting a better estimate of the benefits and costs.

As for the partitioning of "bracing" and "bolting" as two separate techniques to mitigate for an earthquake hazard, engineers were quick to note that "doing just one or the other…makes no sense. Both should be done." "Bolting in absence of bracing can actually increase the hazard as the energy absorbed by sliding will not happen and the walls are more likely to overturn out-of-plane since the bolting pins them at the base." This notion was confirmed by comments from contractors, including: "It would be poor practice to apply shear panel without bolts; both must be done together."

Again, this is a valid point. Bolting and bracing *must* be done together to be effective. The purpose of the separation of the mitigation techniques was to get a better indication of whose responses to consider in the analysis (i.e. without having to rely solely on *their* opinion of *their* experience) and to get the respondents to really think about their answers. With this in mind, the survey results for bolting and bracing together will be presented in Section IV.

The structural engineers had two other broad comments on the design of the surveys: one relating to monetary values and one relating to the MMI scale. First, the use of $130,000 for market value of the structure seemed low. One engineer noted that: "value of such a property would be nearer to $300,000 than $130,000. Caution must be used if you are going on the basis of assessed value of structures (i.e. California Proposition 13, passed in the late 70's, caps the valuation increase at 2% per year unless a property is sold)." Most respondents realized that there is a distinction between market value and replacement value of a structure. The value of the structure used in the survey is based on an average of the structure replacement value in databases from the tax assessor's office in the cities of Oakland and Long Beach.

The use of the Modified Mercalli Intensity (MMI) scale to estimate mean damage was not, in general, well received by those responding to the survey. One engineer noted that "engineering seminars almost never refer to MMI, but to Richter or [peak] ground acceleration." Further, the use of MMI levels above X is questioned. "Most communities that have experienced earthquakes with the type of construction described have not been subjected to ground shaking over great areas of MMI's greater than VIII or IX." "Once you get above a X, then the superstructure will probably fail and you are back to having a lot of damage even though the cripple wall was braced and anchor bolts added." "MMI XI and XII relate to geological damage, so the bolting/bracing retrofit measures not applicable. This survey is only reliable for MMI up to X."

This is a well-founded point and one to keep in mind. MMI is not the *ideal* measure of ground motion to use and extreme values of ground shaking intensity (i.e. MMI XII or total damage) are not used in most probabilistic analyses. The choice was made to be consistent with previous work done in this area (i.e. ATC-13). On the other hand, it has been viewed by some as appropriate if characterizing damage on a regional level. One engineer summed it up nicely by commenting: "MDF or PML is…only appropriate for institutions that own many buildings or governments seeking to lessen impacts for whole cities or regions."

IV. FINDINGS

The results are divided into the information obtained from structural engineers on structural vulnerability and the benefits of mitigation and from contractors on the costs of mitigation. First, though, the relevant statistics on the background of those who completed a survey are presented (Table I). The return rate is based on the number of surveys sent out less the number that were returned undeliverable. Also, twenty-seven percent of the structural engineers and twenty-four percent of the contractors who responded declared their experience with damage assessment and retrofitting of residential wood frame construction as extensive (i.e. 10 on a scale of 0 to 10).

TABLE I. Survey respondents' statistics

	Benefits of mitigation			Costs of mitigation		
	NC	SC	Total	NC	SC	Total
Total number of responses	70	49	119	28	18	46
Return rate	29%	21%	25%	37%	28%	33%
Average range of age and years in practice	45-55 years old 20-25 years in practice			35-45 years old 15-20 years in practice		

<u>Benefits from structural engineers</u>

The majority of structural engineers responding to the survey either works for or owns a structural engineering consulting firm (82%). The results presented considered the differences between (1) all respondents, (2) those that anchored their "before mitigation" damage values to the default values given or below (i.e. ATC-13 standard construction MDF as given in Table IV), and (3) those that estimated damage at 100% for MMI XII before mitigation. The last two cases can be viewed loosely as a lower and upper bound on the structural vulnerability. Therefore, these three groups will be referred to as "lower", "average", and "upper" estimates.

All respondents' values were weighted according to their experience in post-earthquake damage evaluation and their confidence in their MDF values. The weights associated with each engineer's estimates are obtained using Eq. 1 where ε is the experience level of each expert *i* and ζ is the confidence of expert *i* at MMI level *m*. The corresponding estimates of mean damage, y_m, for each MMI level, with associated variance, s_m, and coefficient of variation, ν_m, are given in Eqs. (2a), (2b), and (2c), respectively.

$$w_{i,m} = \sum_i e_i z_{i,m} \tag{1}$$

$$\overline{y_m} = \frac{\sum_i w_{i,m} y_{i,m}}{\sum_i w_{i,m}} \qquad s_m^2 = \frac{\sum_i w_{i,m}\left(y_{i,m} - \overline{y_m}\right)^2}{\sum_i w_{i,m}} \qquad u_m = \frac{s_m}{\overline{y_m}} \qquad \text{(2a) (2b) (2c)}$$

Graphical results of the mean damage associated with various levels of ground shaking for the three groups of respondents are shown in Figure III. Those in the upper group tended to estimate mitigation as more effective than those in the lower group (i.e. percentage reduction is greater). Furthermore, the structural engineers responding ranked the given determining factors in the evaluation of damage as follows: (1) inadequacy of bolting to the foundation, (2) the height of the cripple wall, (3) number of stories of the structure, (4) age of the structure, (5) value of the structure, (6) square footage of the structure.

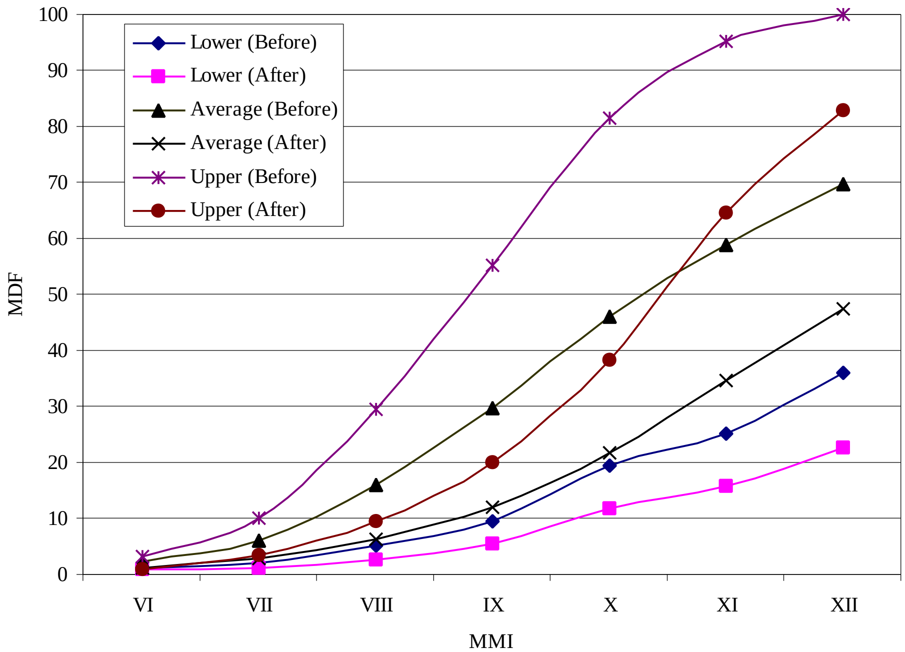

FIGURE III. Comparison of damage estimates

As for other information obtained from the structural engineers, the percentage of structures with damage exceeding $1,000 for levels of MMI indicate that there is a distinct change in distribution for the lower and upper groups of respondents (Table II). The upper group estimates a larger spread of damage over the range of shaking intensity, with more conservative estimates at the larger MMI levels. Further, three additional factors to consider in post-earthquake damage evaluation emerged from the surveys. They include: (1) the importance of the quality of construction, (2) the importance of the weight of the structure and shear capacity above ground level, and (3) the significance of nonstructural damage.

TABLE II. Percentage of structures with damage ≥ $1,000

MMI	Lower	Average	Upper
VI	14.25%	8.15%	6.50%
VII	20.49%	18.62%	17.70%
VIII	36.16%	34.73%	32.37%
IX	51.01%	53.38%	63.78%
X	59.60%	66.49%	79.82%
XI	68.21%	77.24%	89.61%
XII	75.24%	85.59%	93.49%

First and foremost, the quality of construction is critical. One engineer noted that "current quality is so bad that older homes – if they are bolted down and have cripple walls braced – will have less damage than new ones. Newer homes (i.e. many wall openings, discontinuous floors and roofs, cathedral ceilings, etc.) make structural design critical and most architects and builders will not pay for it. Current code requirements are not adequate for this, and the present code is not understood and ignored too often."

Additionally, another engineer noted that "in your questions, you have ignored the conditions above the cripple walls." "Though foundation rehabilitations are a cost effective method for hazard mitigation of single family dwellings, I feel that upgrading of stucco only shear walls to ½" minimum plywood shear walls would go a long way to improving the performance of pre-1940 houses." Also, one engineer remarked that he had "observed that the houses which had the original roofing replaced with a tile roof sustained much more damage than those which still had a light weight shingle roof. Houses which have heavier roofs installed should also be evaluated for lateral (seismic) forces."

Finally, the importance of nonstructural damage should not be underestimated. "The 1994 Northridge earthquake exposed a flaw in our philosophy concerning seismic resistant design of residential buildings. It is not enough to bolt down and brace the cripple walls of raised foundation houses. The damage to so-called nonstructural plaster and stucco walls often caused the repair of residences damaged by the Northridge earthquake to cost in excess of 35% of the pre-earthquake value of the residence. So although bolting down and bracing the cripple walls prevent total loss, it does not prevent severe economic hardship and loss of use of the residence after a moderate to severe earthquake."

Costs from contractors

The analysis of the data collected from the contractors considered (1) all respondents, (2) those with experience ≥ 8, and (3) those with extensive experience only. Analyzing the differences between these three conditions seemed most appropriate. All respondents' values were weighted according to their experience in residential earthquake retrofit and their confidence in their cost estimates, similar to weights used for an engineer's response to the benefits survey. The estimated means, standard deviations and coefficients of variation for the cost of material and the total cost for the three cases are presented in Table III. Those with more experience estimated a lower cost of material. Considering all respondents, the total cost ranged from $2,000 at the minimum to $10,000 at the maximum.

TABLE III. Cost estimates from contractors

	$\mu_{material}$	$\sigma_{material}$	$\nu_{material}$	μ_{total}	σ_{total}	ν_{total}
All Contractors	$1,148	$737	0.64	$4,975	$2,642	0.53
All with experience ≥ 8	$973	$579	0.59	$4,958	$2,750	0.55
All with experience = 10	$942	$351	0.37	$5,032	$2,509	0.50

The contractors ranked the given determining factors in the evaluation of the cost to retrofit a pre-1940 wood frame structure as follows: (1) accessibility to the foundation, (2) height of the cripple wall, (3) square footage of the structure, (4) number of stories, (5) age of the structure, and (6) value of the structure. A comparison of the importance of the determining factors as estimated by the structural engineers and the contractors is shown in Figure IV.

Although accessibility to the foundation is the "number one import factor", additional determining factors in the cost of structural mitigation were obtained from the contractors. These include the size of the company doing the work (i.e. a larger company has a bigger overhead cost), local codes, the structure's configuration, and the existing conditions of the foundation. One contractor declared: "Existing conditions are of extreme importance. Often foundations on older homes have significant settlement cracks, may have deteriorated concrete and/or the cripple walls and mudsills may be dryrotted or termite infested. Significant additional costs of repair can result. There are also many different foundation designs. Some dwellings have cripple walls going through the center of the crawl space in addition to the perimeter. Foundation/cripple wall design determines the type and cost of hardware and methods employed."

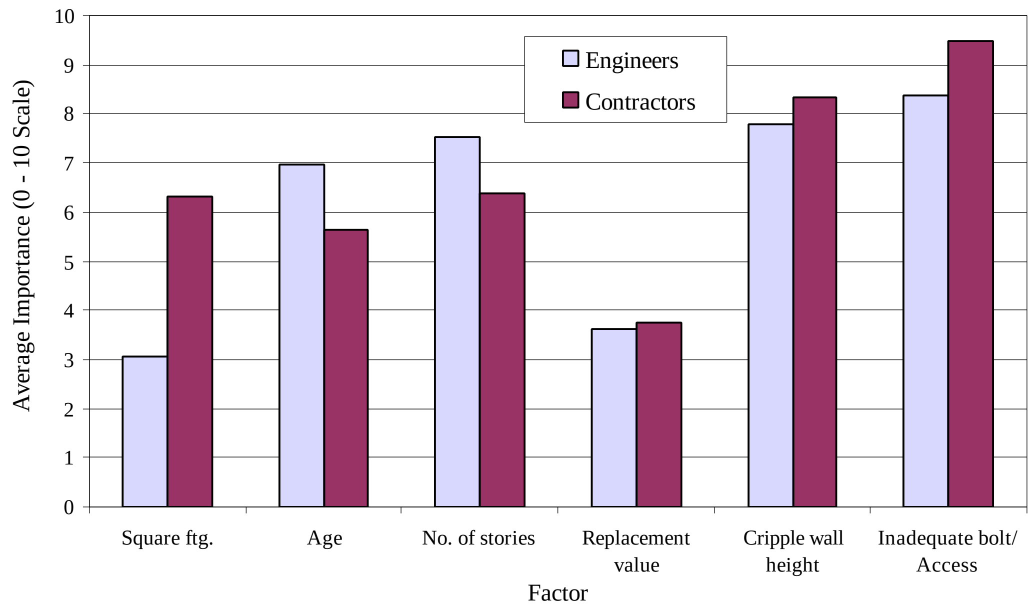

FIGURE IV. Comparison of determining factors

V. IMPLICATIONS

To assess the implication of these results, the three validity questions presented in Section I are reexamined in the context of previous research done on the vulnerability of these structures before and after mitigation and the costs associated with this mitigation technique.

Vulnerability before mitigation

Typically, the damage or vulnerability functions for a structure type is estimated through the use of historical loss data, engineering data, and expert opinion of structural engineers proficient in post-earthquake damage assessment. Focusing on the state of California, historical loss data includes damage estimates from recent earthquakes, such as the Loma Prieta earthquake in 1989 or the Northridge earthquake in 1994. Engineering data refers to experimental testing in laboratories on the strength of materials and construction methods. Expert opinion on damage estimates for structures in California include data compiled and published by the Applied Technology Council (ATC).

The primary source of damage information utilized by most software modelers is from ATC-13, *Earthquake Damage Evaluation Data for California* [1], published in 1985. In this document, FEMA and ATC worked with researchers to ascertain estimated damage evaluation data for 78 different types of structures. The data was compiled using the Delphi Technique and expert opinion. The thirteen members of the Project Engineering Panel (PEP), as well as 58 additional experts in earthquake engineering, were asked their opinion on the low, best, and high estimates of the damage factor to each of the facility classes for MMI levels VI through XII. A mean damage factor (MDF) was estimated, defined as the expected ratio of dollar loss to replacement value for the structure. Additionally, each expert evaluated his own level of experience and his own degree of certainty associated with each damage estimate for each facility class.

Since 1985, claims data primarily from the Loma Prieta and Northridge earthquakes provided an update to the fragility curves for wood frame housing, but only some of this data is published. Other events that provided information before 1989 include the San Fernando, California earthquake of February 9, 1971, the Coalinga, California earthquake of May 2, 1983, and the Whittier Narrows, California earthquake of October 1, 1987. Information about damage from these three earthquakes is included in [9].

According to ATC-13, the class of structures in this study is *facility class 1* (i.e. low-rise wood frame), and they are of *nonstandard construction* (i.e. pre-1940 construction). In these guidelines, pre-1940 wood frame residential construction in California is discussed and it is noted that "these structures normally are supported on cripple studs and generally do not have a perimeter foundation that extends up to the floor." The way in which design and construction quality is dealt within the study is to shift the probabilities of a given damage state intensity downward from standard construction to nonstandard construction. Comparison of ATC-13 values to the survey values (Table IV) indicate that the average estimates of damage for the lower MMI levels from the respondents are significantly lower than those estimated in the ATC-13 guidelines.

TABLE IV. Comparison of damage before mitigation

MMI	ATC-13 MDF		MDF survey results		
	Standard	Nonstandard	Lower	Average	Upper
VI	0.8	4.7	1.15	2.37	3.20
VII	1.5	9.2	2.08	6.14	10.07
VIII	4.7	19.8	5.26	15.93	29.31
IX	9.2	24.4	9.50	29.63	55.26
X	19.8	37.3	19.48	46.03	81.45
XI	24.4	--	25.20	58.86	95.16
XII	37.3	--	35.87	69.76	100.00

Vulnerability after mitigation

The reduction in damage to pre-1940 residential structures with this type of mitigation is not well documented. Although there exists a number of qualitative sources of information on the benefits of bolting residential structures to their foundations and bracing cripple walls of older residential construction, there is limited information on quantifying the benefits of such techniques. Two notable sources of information on quantifying the benefits of mitigation are the FEMA 227/228 report [4] and published data on experimental testing of retrofitted cripple walls after the Loma Prieta earthquake [8].

The FEMA 227/228 series, *A Benefit-Cost Model for the Seismic Rehabilitation of Buildings*, provides percentage reductions in mean damage to various classes of structures for levels of ground shaking ranging from MMI VI to XII. These new mean damage ratios for "after mitigation" effects assume that the earthquake retrofit technique used is a structural strengthening based primarily on life safety. As in ATC-13, these estimates were based on the engineering experience and judgment of those involved in compiling the report (i.e. expert opinion). The authors of FEMA 227/228 were quick to note that "effectiveness of retrofit will vary depending on the rehabilitation techniques used, on the standard, code, or safety level to which seismic rehabilitation is carried out, and on the design, construction, and condition of the building before rehabilitation." Comparisons of MDF using the FEMA guidelines and the survey results (Table V) show that the respondents believe this mitigation technique is very effective in reducing damage.

As for the experimental testing on cripple walls, the testing was done at the University of California, Irvine, in 1990. Test specimens included non-retrofitted panels and those retrofitted with diagonal bracing, Simpson strap ties, and plywood sheathing. Panels retrofitted with plywood showed a 90% increase in shear load capacity (in lb/ft). Although this testing indicates the increase in strength and stiffness of bracing a cripple wall, it does not include the increased benefit of bolting the structure to its foundation. Therefore, comparisons to the survey results presented are difficult.

TABLE V. Comparison of damage after mitigation

MMI	ATC-13		MDF Survey Results					
			Lower		Average		Upper	
	%	MDF	%	MDF	%	MDF	%	MDF
VI	50%	2.7	34.2%	0.76	52.1%	1.14	73.4%	0.85
VII	50%	6.0	45.3%	1.14	53.4%	2.86	66.1%	3.41
VIII	43%	14.3	50.6%	2.60	59.9%	6.39	67.6%	9.48
IX	35%	19.5	43.7%	5.35	59.7%	11.93	64.0%	19.91
X	28%	29.8	40.2%	11.65	52.8%	21.71	53.0%	38.32
XI	20%	--	37.8%	15.68	41.1%	34.68	32.2%	64.49
XII	20%	--	37.0%	22.60	32.1%	47.37	17.1%	82.90

Costs of mitigation

The costs associated with retrofitting an existing structure for earthquake effects can be much more than those associated with a new building. Additionally, these costs can be rather uncertain in nature. During a search on current reports estimating the costs associated with seismic rehabilitation of buildings, publications by FEMA [3], the California Seismic Safety Commission (CSSC) [2], and R. P. Gallagher Associates, Inc. [5] were uncovered (Table VI).

TABLE VI. Costs of earthquake mitigation

FEMA 156/157	CSSC	R. P. Gallagher Associates
$C = C_1\ C_2\ C_3\ C_L\ C_T$ C=(12.29)(.97)(1.43)(1.12)(1.34) C = $25.58 per square foot	Bolting foundation: $375 -$7500 Bracing cripple wall: $750-$3750 Total: $1,125 - $11,250	New cripple wall sheathing and foundation anchor bolts: $1,590 - $3,180

The FEMA 156/157 series, *Typical Costs for Seismic Rehabilitation of Buildings*, estimates costs based on 1993 data and the CSSC ranges are based on 1991 prices with the lower end price for material only and the upper end price for a professional doing the work. The Gallagher estimates are based on 1990 mitigation costs for San Francisco and Los Angeles areas. All three of these estimated costs are converted to 1998 dollars assuming a 6% inflation rate. Comparing these numbers to those obtained from the surveys, the results from the survey respondents match closely to those from the CSSC publication.

VI. CONCLUSIONS

The results from these surveys show a wide dispersion among experts on what the costs and benefits of mitigation might be. While the cost estimates obtained from the contractors varied considerably ($2000-$10,000), the cost for a homeowner to do the job himself is quite reasonable (i.e. $1,000). The results also show that the accessibility to the foundation and the existing conditions of the foundation are very important in the estimation of cost. The quality of construction and the shear capacity of a structure above ground level are important in the estimation of damage.

Furthermore, damage estimates with mitigation are, on average, less than those estimated using the ATC-13 and FEMA 227/228 guidelines. I hope that these results encourage debate over the ways in which expert opinion is used in estimating fragility curves for earthquake loss modeling (i.e.

statistical versus Bayesian methods). Additionally, I hope that there is a greater appreciation for the complexity involved in the earthquake loss estimation (ELE) process, particularly in the importance of construction quality.

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