Resources Review – Working Document

A Report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project

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ABSTRACT

This report is a working document developed during a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project." The overall objective of the PEER–CEA Project is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measures and documents the seismic performance of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies.

This report is an early product that focuses on reviewing relevant literature, data, and other resources that informed the PEER–CEA Project during its initial phase in 2017. The report is organized into sections that cover eight high-priority areas of knowledge, methods, and data sources that were foundational to the Project. Under each topic heading are several key research questions. Each topic section contains a table that identifies references that are relevant to the questions. Each of the listed references is annotated with a short description of how the resource is relevant to the project. Additional resources identified or drawn upon since October 2017 are cited as appropriate in other Project Reports posted at the project website [*https://www.peer.berkeley.edu/cw-woodframe*].

ACKNOWLEDGMENTS

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CONTENTS

LIST OF TABLES

1 INTRODUCTION

This report is a working document developed during a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

The overall objective of the PEER–CEA Project is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measures and documents seismic performance of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Three primary tasks support the earthquake loss-modeling effort. They are: (1) the development of ground motions and loading protocols that accurately represent the diversity of seismic hazard in California; (2) the execution of a suite of quasi-static cyclic experiments to measure and document the performance of cripple wall and sill anchorage deficiencies to develop and populate loss models; and (3) nonlinear response history analysis on cripple wall-supported buildings and their components.

This report is a product of Working Group 1 and focuses on reviewing relevant literature, data, and other resources that informed the PEER–CEA Project during its initial phase in 2017. The body of the report is organized into eight sections; each covers a high-priority area of knowledge, methods, and data sources that were foundational to the Project. Under each topic heading are several key research questions. Each topic section contains a table that identifies references that are relevant to the questions. When a reference is relevant to multiple topics, the resource may be mentioned in more than one section. Each of the listed references is annotated with a short description of how the resource is relevant to the project.

Additional resources identified or drawn upon in the project after October 2017 are cited as appropriate in other Project Reports posted at the project website [*https://www.peer.berkeley.edu/cw-woodframe*].

2 Index Buildings and Loss Functions for Wood-Frame Houses

2.1 ISSUES OR QUESTIONS

1. What are the common characteristics (variants) of wood-frame houses in California that should be considered for Index Buildings used to develop damage functions?
2. Do these characteristics meet the following three conditions: (1) prevalence in California construction; (2) have a large impact on seismic performance; and (3) affect the performance under seismic excitation if the house is retrofitted with the CEA's Earthquake Brace and Bolt (EBB) program?
3. How do these characteristics vary with the age of construction?
4. What are the common descriptive parameters used in damage functions for wood-frame houses?

2.2 RELEVANCE OF REFERENCES

Table 2.1 Relevance of references for Index Buildings and loss functions for wood-frame buildings.

Citation	Relevant questions			
	2.1	2.2	2.3	2.4
AIR Worlwide (2017)	✔	✔	✔	✔
Anderson and Heyer (1955)	✔	✔	✔	
APA (2016)		✔		
ATC (2009)				
Chai et al. (2002)		✔		✔
FEMA (2012)		✔		✔
FEMA (2015)	✔		✔	
HUD (1994)	✔	✔	✔	
ICC (2015)	✔			
Kang and Mahin (2014)	✔		✔	
Rabinovici (2017)	✔		✔	
Reitherman and Cobeen(2003)	✔		✔	
RMS (2015)				✔
Stewart et al. (1994)		✔		
Storsund et al. (2010)		✔		
U.S. Census Bureau (2017)	✔			
Welch and Filiatrault (2017)		✔		
Yancey et al. (1998)		✔		

2.3 REFERENCES AND ANNOTATIONS

AIR Worldwide (2017). "Location Building Detail Fields," Touchstone software, *http://www.air-worldwide.com/Documentation/Validation/3.0/Exposure_Data/Location_Building_Detail_Fields.htm.*

> This document lists all secondary modifiers–equivalent to Index Building variants–used by the loss modeler, AIR. This information is key to understanding how the loss models distinguish performance between retrofitted and unretrofitted buildings.

Anderson L.O., Heyer O.C. (1955). Wood-frame house construction, *Agricultural Handbook No. 73*, Forest Products Laboratory, U.S. Forest Service, Washington, D.C.

> This pamphlet provides information on typical archaic housing construction practices, which is important to identifying typical building characteristics, configurations, and building methods.

APA (2016). *Engineered Wood Construction Guide, Form E30*, Tacoma, WA.

This pamphlet provides information on typical housing construction practices and detailing requirements.

ATC 52-3 (2009). *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Earthquake Safety for Soft-Story Buildings*, Applied Technology Council, *http://sfgov.org/esip/sites/default/files/FileCenter/Documents/9756-atc523.pdf.*

This document provides information on construction detailing practices and requirements for retrofitting soft, weak, and open front multi-family housing in San Francisco.

Chai Y.H., Hutchinson T.C., Vukazich S.M. (2002). Seismic behavior of level and stepped cripple walls, *CUREE Publication No. W-17*, Division of Civil and Environmental Engineering, University of California, Davis, CA.

This CUREE report evaluated the capacity of 2-ft- and 4-ft-tall cripple walls (12 in. in length) under existing and retrofitted designs, both in level and stepped configurations. Stucco was the only exterior finish considered. Retrofitted bracing considerations were either two-thirds bracing or full bracing. Monotonic, normal, and near-fault loading histories were considered based off CUREE quasi-static lateral displacement history recommendations [Krawinkler et. al. 2001]. It was recommended that additional research be performed to consider more exterior finishes, larger cripple walls, and different boundary conditions of the finishes.

FEMA P-807 (2012). *Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings With Weak First Stories*, *FEMA P-807*, Federal Emergency Management Agency, Washington, D.C., *https://www.fema.gov/media-library-data/20130726-1916-25045-2624/femap_807.pdf*

This document provides information on construction detailing practices and requirements for retrofitting soft, weak, and open front multi-family housing developed through a FEMA-funded project.

FEMA (2015). *HAZUS MR-2 – Technical and User's Manuals*, Federal Emergency Management Agency, Washington, D.C.

HAZUS is a FEMA-funded project that establishes the current state-of-the-practice for many public sector agencies to estimate risk and damage potential to large inventories of buildings subject to earthquake, hurricane, and flood events. The manuals provide information on fragility characteristics of houses in terms of shear capacity and a methodology for estimating damage given ground motion input.

HUD (1994). *Assessment of Damage to Residential Buildings Caused by the Northridge Earthquake*, U.S. Department of Housing and Urban Development, Washington, D.C., *http://www.aresconsulting.biz/publications/northridge%20earthquake.pdf*

This report provides empirical data collected from inspections of housing stock in southern California following the 1994 Northridge earthquake. Information includes data on housing construction practices, configurations, ages, etc., and summarizes the amount of damage suffered by different types of buildings based on these characteristics.

ICC (2015). *International Residential Code,* International Code Council, Washington, D.C.

This building code provides information on prescriptive construction detailing practices and requirements for one- and two-family dwellings; e.g., it includes tables of fastener requirements for various types of wall sheathing materials.

Kang G.S., Mahin SA. (2014). PEER preliminary notes and observations on the August 24, 2014, South Napa earthquake. *PEER Report No. 2014/13*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

This reconnaissance report from the Pacific Earthquake Engineering Research Center followed the 2014 South Napa earthquake. The aim of the report was to examine both the strong-motion record of the earthquake and damage (structural and non-structural) of buildings within Napa. For single-family dwellings, it was found that in instances where major damage was present, there was a partial or total collapse of the house's cripple wall or the house had slid off its foundation. It was found that houses constructed pre-1970s suffered the most extreme damage.

Rabinovici S. (2017). *California Earthquake Authority South Napa Home Impact Study,* California Earthquake Authority. Available at: *https://www.earthquakeauthority.com/About-CEA/Research-Outreach/Our-Research/CEA-Napa-Fina-lReport-Exec-Summ.*

This report summarizes methods and data from a household survey (633 participants) and 34 interviews conducted following the 2014 South Napa earthquake for the CEA. The aim of the study was to catalogue the effects of the earthquake on single-family dwellings and homeowners. Important data from the survey included housing date of construction, presence/height of cripple walls, exterior finishes, presence of slope, and foundation type, as well as about 30 measures of damage and total financial and recovery implications of the event for households. In addition, the survey entailed questions pertaining to the commonality, cost, and extent of retrofits.

Reitherman R., Cobeen, K. (2003). Design documentation of CUREE Woodframe Project Index Buildings, *CUREE Publication No. W-29*, Consortium of Universities for Earthquake Engineering Research, Richmond, CA.

The CUREE-Caltech Woodframe Project developed four representative Index Buildings that were used as the basis for both analytical and loss estimation studies. Detailed plans, details, and descriptions of construction were developed and are documented in this report. An available CD provides CAD drawings.

RMS (2015). Secondary Modifiers, Risk Link software. Risk Management Solutions, Inc., *http://srmcsociety.org/wp-content/uploads/2016/03/SRMC-CAT-Modeling-Presentation-March-2015.pptx.*

This document lists all secondary modifiers—equivalent to Index Building variants—used by the loss modeler, RMS. This information is key to understanding how the loss models distinguish performance between retrofitted and unretrofitted buildings.

Stewart J.P., Bray J., Seed R.B., Sitar N. (1994). Preliminary report on the geotechnical aspects of the January 24,1994 Northridge earthquake*, Report No. UCB/EERC-94/08*, Earthquake Engineering Research Center, University of California, Berkeley, CA.

This report documents the available geotechnical data from the Northridge, California, earthquake of January 17, 1994. Aspects of the earthquake discussed in the report include damage patterns found within residential structures. While the body of the work focuses on the geotechnical aspects, there is attention given towards foundation failures in single-family wood-frame dwellings, including the common occurrence of these structures sliding off their foundations.

Storesund R., Dengler L., Dengler S., Mahin S., Collins B.D., Hanshaw M., Turner F., Welsh K. (2010). *M 6.5 Offshore Northern California Earthquake Reconnaissance Report*.

A report from the Geotechnical Extreme Events Reconnaissance Association (GEER) following the 2010 Offshore Northern California earthquake. The report discovered that single-family dwellings if damaged, were knocked off their foundations (resulting from collapse of the house's cripple wall). Damage was seen in houses ranging from old Victorians (late-19th century to early-20th century) up until 1970s-vintage houses. Although there is not a lot of depth in the report about the extent of damage to these homes, the mode of failure and the era of houses that were damaged and worth noting.

United States Census Bureau (2017). *Housing Statistics, Census of Population and Housing*, U.S. Department of Commerce, Washington, D.C.

This report provides demographic information on basic housing characteristics, including age, size, and height, which was helpful in quantifying the population of building types.

Welch D., Filiatrault A. (2017). *ATC-110: Summary of Simplified Superstructure Strength Estimates, One Story Cases.* Progress Draft. California Earthquake Authority, Applied Technology Council, Redwood City, CA.

This report provides information on housing styles and important information for identifying typical building characteristics, in addition to defining the fragility characteristics of houses in terms of shear capacity.

Yancey C.W., Cheok G.S., Sadek F., Mohraz B. (1998). *A Summary of the Structural Performance of Single-Family Wood-Framed Housing, NISTIR 6624.* Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.

This 1998 report presented a review of the structural performance of single-family, wood-frame houses subjected to selected earthquakes and hurricanes. The report found that instances where major damage occurred within the homes was primarily due to poor construction practices and noncompliance with building codes. In

addition, the report found that cripple wall failures were also a primary mode of failure during earthquakes. The report examined studies done on full-scale houses, shear walls, and inter-component connections. It should be noted that a good body of work (specifically the CUREE Reports) had been published since this report was initially published.

2.4 ADDITIONAL REFERENCES MENTIONED

Krawinkler, H., Parisi, F., Ibarra, L., Ayoub, A., Medina, R. (2001). Development of a testing protocol for wood frame structures, *CUREE Publication No. W-02*, Consortium of Universities for Research in Earthquake Engineering, Richmond, CA.

3 Behavior and Damage of Cripple Walls and Sill Anchorages

3.1 ISSUES OR QUESTIONS

1. What is the behavior, modes of failure, and damage to cripple walls and sill anchorages?
5. What test datasets are available to calibrate analysis and damage models of existing and/or retrofitted cripple walls?
6. What test datasets are available to calibrate analysis and damage models of existing and/or retrofitted sill anchorages?
7. What is known from analytical studies regarding the vulnerability of cripple walls and the effectiveness of retrofit measures?
8. How has deterioration due to age affected the strength characteristics of cripple walls and sill anchorages?
9. Under what conditions does retrofit of cripple walls notably increase damage to the occupied stories? What type of damage may occur?

3.2 RELEVANCE OF REFERENCES

Table 3.1 Relevance of references for behavior and damage of cripple walls and sill anchorages.

Citation	Relevant questions					
	3.1	3.2	3.3	3.4	3.5	3.6
ATC-110 (2017) (In progress work)				✔		✔
Arnold et al. (2003a)	✔	✔				✔
Arnold et al. (2003b)	✔	✔				✔
Chai and Hutchinson (2002)	✔	✔				
Dean and Shenton (2005)	✔					
Fennel et al. (2009)	✔		✔			
Ficcadenti et al. (2004)	✔		✔			
Filiatrault et al.(2002)	✔					
Gatto and Uang (2003)	✔		✔			
Kent et al. (2005)					✔	
Mahaney and Kehoe (2002)	✔		✔			
Ni and Karacabeyli (2007)	✔	✔				
Osteraas et. al. (2007, update 2010)	✔					
Pardoen et. al. (2003)	✔	✔				
Porter et al. (2002)				✔		
Rabinovici (2017)	✔					
Shepherd and Delos-Santos (1991)	✔			✔		
White et al. (2009)	✔	✔	✔			

3.3 REFERENCES AND ANNOTATIONS

Arnold A.E., Uang C.M, Filiatrault A. (2003a). Cyclic behavior and repair of stucco and gypsum woodframe walls: Phase I, *CUREE Publication No. EDA-03*. Department of Structural Engineering, University of California, San Diego, CA.

> This testing program focused on exploring exterior and interior finish capacities for typical 1970s shear walls. This first phase introduced a boundary condition that mimicked a two-story configuration while still only being the height of a single story. Cripple walls were not considered within the testing program, but the boundary conditions (wrapping of stucco around corners and a rigid stucco connection at the top) are useful for accurately representing the added capacity seen with continuous stucco running from the cripple wall to the first floor. The walls studied were 16 ft long × 8 ft high.

Arnold A.E., Uang C.M, Filiatrault A. (2003b). Cyclic behavior and repair of stucco and gypsum woodframe walls: Phase II. *CUREE Publication No. EDA-07*. Department of Structural Engineering, University of California, San Diego. CA.

> The second part of this testing program analyzed exterior and interior finishes for typical 1970s shear walls. The difference is that only one-story configurations were tested. Like the first phase of the experiment, a pseudo-static cyclic loading condition was used. Follow-up research was recommended to replicate stucco construction styles characteristic of pre-1970s construction because these early era single-family dwellings are more susceptible to damage during an earthquake than post-1970 homes. The walls studied were 16 ft long × 8 ft high.

Chai Y.-H., Hutchinson T.C., Vukazich S.M. (2002). Seismic behavior of level and stepped cripple walls, *CUREE Publication No. W-17*, Division of Civil and Environmental Engineering, University of California, Davis, CA.

> This CUREE report evaluated the capacity of 2-ft- and 4-ft-tall cripple walls (12 ft in length) under existing and retrofitted designs, both in level and stepped configurations. Stucco was the only exterior finish considered. Retrofitted bracing considerations were either two-thirds bracing or full bracing. Monotonic, normal, and near-fault loading histories were considered based off CUREE quasi-static lateral displacement history recommendations [Krawinkler et. al. 2001]. It was recommended that additional research be performed to consider more exterior finishes, larger cripple walls, and different boundary conditions of the finishes.

Dean P.K., Shenton H.W. (2005). Experimental investigation of the effect of vertical load of the capacity of wood shear walls, ASCE, *J. Struct. Eng*., 131(7), doi.org/10.1061/(ASCE)0733-9445(2005)131:7(1104)

> Presented in this paper are the results of 10 shear-wall tests, where specimens (with and without hold-downs) were subjected to three half-cycles of lateral loading, four with no vertical load, and six with varying vertical load. The tests analyzed the performances of the shear walls in terms of ultimate load, stiffness, and ductility, and demonstrated that the presence of a vertical load increased the lateral capacity and stiffness of the walls. Also, current code allowable shear forces were conservative when a vertical load was present, providing the wall with additional reserve capacity.

Fennel W.A, Moore K., Mochizuki G. (2009). *Structural Engineers Association of Northern California 2008-2009 Special Projects Initiative Report on Laboratory Testing of Anchor Bolts Connecting Wood Sill Plates to Concrete with Minimum Edge Distance*, Structural Engineers Association of Northern California, San Francisco, CA.

> This reports on a testing program for wood sill plate to concrete connections to determine capacity and failure modes. The testing was conducted in response to significant reductions in wood sill plate anchor bolt capacity introduced by ACI 318 Appendix D. As a result of testing, it was recommended that wood sill anchor bolt capacity for design be assigned using the higher values associated with

National Design Specification for Wood (NDS) based on wood portion of the connection, rather than the smaller capacity assigned by ACI-318. Test specimens included only foundation sill plates and no wall above. This is of interest as one available source of test data for wood connections to concrete foundations. Additional testing of anchorage was recommended as a part of this project, in part so that the effect of the cripple wall on the anchorage can be determined.

Ficcadenti S, Freund E., Pardoen G., Kazanjy R. (2004). Cyclic response of shear transfer connections between shearwalls and diaphragms in woodframe construction, *CUREE Publication No. W-28*, Consortium of Universities for Earthquake Engineering Research, Richmond, CA.

This reports on a testing program for shear transfer connections between the top of wood light-frame shear walls and floor framing systems above. The testing evaluated both conventional construction connections—to represent a common pre-retrofit condition in residential construction—and a series of configurations by adding proprietary clip angles and other connection types representative of retrofit conditions. This report is one available source of information on performance of load path connections at the top of cripple walls. Additional testing of shear transfer connections was recommended as a part of this project, primarily to evaluate the behavior of the wide range of connector and detail types commonly found at the top of shear walls.

Filiatrault A., Fischer D., Folz B., Uang C.-M. (2002). Seismic testing of two-story woodframe house: influence of wall finish materials, ASCE, *J. Struct. Eng.*, 128(10), doi.org/10.1061/(ASCE)0733-9445(2002)128:10(1337).

The article reports on a shake table test conducted on a full-scale two-story wood-frame house—a typical structural system found in North American housing stock—that incorporated several characteristics of modern residential constructions in California. The main purpose of this test was to evaluate the effects of wall finish materials, both interior (gypsum wallboard) and exterior (stucco), on the seismic response of the structure. Final results showed an increase of lateral stiffness, providing a valid motivation to consider wall finish materials as potential structural components of lateral load-resisting systems.

Gatto K., Uang C.-M. (2003). Effect of loading protocol on the cyclic response of woodframe shearwalls, ASCE, *J. Struct. Eng.*, 129(10), doi.org/10.1061/(ASCE)0733-9445(2003)129:10(1384).

The study focused on 2.4 m × 2.4 m wood-frame shear walls tested using different loading protocols that demonstrated how they influence the response of each specimen. Protocols with large number of cycles and equal amplitude cycles produced fatigue fractures in the nails, which caused a reduced ultimate strength and deformation capacity due to the large energy demand.

This study provided direct comparison of the performance effects of varying loading protocols, justifying the use of the CUREE Ordinary Protocol for the majority of the CUREE-Caltech Project component testing.

Kent S.M., et al. (2005). Effects of decay on the cyclic properties of nailed connections, ASCE, *J. Mat. Civil Eng*., 17(5): 579–585., doi:10.1061/(asce)0899-1561(2005)17:5(579).

> Abstract: “The effect of wood decay on the fully reversed cyclic performance of nailed oriented strand board OSB sheathing to Douglas-fir framing member connections was investigated. The connection geometry evaluated in this study was representative of lateral force resisting systems of light-framed wood structures, including shear walls and horizontal diaphragms. Maximum loads, slip at maximum loads, yield loads, initial stiffnesses, and cumulative energy dissipation of nailed connections exposed to increasing intervals to the brown rot fungus, Postia placenta, were characterized using fully reversed cyclic loading. After the destructive connection tests, portions of the sheathing and framing member from the samples were further evaluated for specific gravity. The OSB sheathing specific gravity was the best descriptive variable for the mechanical properties measured in this study. Cumulative energy dissipation was the connection property most affected by decay damage.”

Mahaney J., Kehoe B. (2002). Anchorage of woodframe buildings: laboratory testing report, *CUREE Publication No. W-1*4, Consortium of Universities for Earthquake Engineering, Richmond, CA.

> This report describes a testing program for anchorage of woodframe shear walls to concrete foundations. The testing was undertaken in response to observed splitting of wood foundation sill plates in the 1994 Northridge, California, earthquake. The tests used walls that were strengthened in order to move the failure into the wall anchorage. Walls were tested with a wide range of conditions, including with and without nuts, with cut washers, and with steel plate washers. The testing resulted in recommendations for use of steel plate washers in new construction and retrofits. This report serves as one source of information on performance of anchor bolt connections at the bottom of cripple walls.

Ni C., Karacabeyli E. (2007). Performances of shear wall with diagonal or transverse lumber sheathing, ASCE, *J. Struct. Eng.*, ASCE, 113(12), doi.org/10.1061/(ASCE)0733-9445(2007)133:12(1832).

> The article presents the results of 16 full-scale tests carried out on shear walls with diagonal and horizontal lumber sheathing. It compares the in-plane shear strength and investigates the effects of hold-downs the vertical load and width of sheathing on the in-plane shear wall capacity. Finally, the tests examine whether the shear resistance is cumulative, using lumber sheathing on one side and gypsum wallboard panels on the other side.

CUREE (2007, updated 2010). General guidelines for the assessment and repair of earthquake damage in residential woodframe buildings, *CUREE Publication No. EDA-02*, Consortium of Universities for Earthquake Engineering, Richmond, CA.

> This report provides guidance for insurance claims adjusters, contractors, and homeowners to assess earthquake damage within homes and on the property. In addition to assessment, it presents guidelines for repair of such damage. The report

covers both structural and geotechnical components within single-family dwellings.

This document—widely used by insurance adjustors—associates observable damage with a range of repair methods and describes differences in observed damage level that may lead to more expensive, invasive repairs being required.

Pardoen G.C., Waltman A., Kazanjy R.P., Freund E., Hamilton C.H. (2003). Testing and analysis of one-story and two-story shear walls under cyclic loading, *CUREE Publication No. 25*, Division of Civil and Environmental Engineering, University of California, Irvine.

This experimental program was geared towards the capacity of one and two-story shear walls. Although cripple walls were not considered in this program, various exterior finishes and boundary conditions were considered, which are helpful in guiding a cripple wall testing program. Walls were 16 ft in length and 8 ft in height for the one-story configuration and 17 ft in height for the two-story configuration.

Porter K.A., Beck J.L., Seligson H.A., Scawthorn C.R., Tobin T.L., Young R., Boyd T. (2002). Improving loss estimation of woodframe buildings, *CUREE Publication No. W-18*, Consortium of Universities for Research in Earthquake Engineering, Richmond, CA.

This report presents a theoretical and empirical methodology for creating probabilistic relationships between seismic shaking severity and physical damage and loss for buildings in general, and for woodframe buildings in particular. The methodology, called assembly-based vulnerability (ABV), is illustrated for 19 specific woodframe buildings of varying ages, sizes, configuration, quality of construction, and retrofit and design conditions. The study employs variations on four basic floor plans, called index buildings. These include a small house, a larger house, a townhouse, and an apartment building. The resulting seismic vulnerability functions give the probability distribution of repair cost as a function of instrumental ground-motion severity. Along with prediction of damage, detail estimates were made of cost of repair and cost of retrofit. The study identified damage thresholds of interest and the influence of quality of construction. The performance improvements of various types of retrofit were also identified.

Rabinovici S. (2017). *California Earthquake Authority South Napa Home Impact Study,* California Earthquake Authority. Available at: *https://www.earthquakeauthority.com/About-CEA/Research-Outreach/Our-Research/CEA-Napa-Fina-lReport-Exec-Summ.*

This report summarizes a household survey (633 participants) and 34 interviews conducted following the 2014 South Napa Earthquake for CEA. The aim of this study was to determine the effects of the earthquake on single-family dwellings and homeowners. Important data from the survey included housing date of construction, presence/height of cripple wall, exterior finishes, presence of slope, and foundation type, as well as about 30 measures of damage and total financial and recovery implications of the event for the household. In addition, the survey entailed questions pertaining to the commonality, cost, and extent of retrofits.

Shepherd R., Delos-Santos E.O. (1991). An experimental investigation of retrofitted cripple walls, *Bull. Seismol. Soc. Am*., 81(5): 2111–2126.

This paper reports on an experimental program that investigated the capacity of 2-ft- and 4-ft-tall cripple walls (16 ft in length) under existing and retrofitted designs. No finishes were considered in this program. The loading protocol was cyclic load controlled.

White K. B. D., Miller T. H., Gupta R. (2009). Seismic performance testing of partially and fully anchored wood-frame shear walls*, Wood Fiber Sci.*, 41(4): 396–413.

The paper presents the performances of fully and partially anchored walls under monotonic, cyclic and earthquake loads. Each wall is sheathed with two OSB panels and two gypsum wallboard panels. The fully anchored specimens have hold-downs at the ends, while partially anchored walls have two anchor bolts on the sill plate. Their performances are evaluated in terms of capacity, energy dissipation and failure modes, referring to the code measures.

3.4 ADDITIONAL REFERENCES MENTIONED

Krawinkler, H., Parisi, F., Ibarra, L., Ayoub, A., Medina, R. (2001). Development of a testing protocol for wood frame structures, *CUREE Publication No. W-02*, Consortium of Universities for Research in Earthquake Engineering, Richmond, CA.

4 Behavior and Damage of Existing Wood-Frame Houses

4.1 ISSUES OR QUESTIONS

1. What is the behavior, modes of failure, and damage to existing wood-frame houses from past earthquakes?
2. What surveys and/or studies have been performed to evaluate damage of existing wood-frame houses from past earthquakes?
3. What are the important features of house configurations and construction that have been observed to affect earthquake damage?
4. What correlations can be made between specific eras of houses and damage to houses?

4.2 RELEVANCE OF REFERENCES

Table 4.1 Relevance of references for behavior and damage of existing wood-frame houses.

Citation	Relevant questions			
	4.1	4.2	4.3	4.4
Buchanan et al. (2011)	✔	✔	✔	
Christovasilis et al. (2009)			✔	✔
FEMA (2012a)	✔	✔	✔	✔
FEMA (2012b)	✔	✔	✔	✔
FEMA (2015)		✔	✔	
Fischer et al. (2001)			✔	✔
Kang and Mahin (2014)	✔			✔
Mosalam et al. (2008)			✔	✔
Rabinovici (2017)	✔	✔		
Reitherman and Sabol (1995)	✔		✔	
Schierle (2001)	✔	✔		
Stewart et al. (1994)	✔	✔		✔
Storesund et al. (2010)	✔			✔
Vukazich et al. (2006)	✔		✔	
Yancey et al. (1998)	✔		✔	

4.3 REFERENCES AND ANNOTATIONS

Buchanan, A., Carradine D., Beattie G., Morris H. (2011) Performance of houses during the Christchurch earthquake of 22 February 2011, *Bull. NZ Soc. Earth. Eng.*, 44(4): 342–357.

This article presents an overview of observed damage of single and multi-family housing following the 2011 Christchurch, New Zealand, earthquake. A majority of the housing in Christchurch is light-frame wood housing. The general observation was that although residential housing performed very well in terms of life safety, thousands of buildings were damaged to varying degrees (e.g., slight to severe). The largest structural deficiencies revolved around the lack of clear load path from the floor diaphragms (e.g., the weight) to the foundation below the house. This included strength irregularities due to large openings, weak or poorly fastened sheathing materials, and a lack of anchorage of the superstructure framing to the foundation, the latter being the number one topic recommended for review for future code and standard development. For completeness, numerous houses were destroyed or badly damaged due to geotechnical phenomena including lateral spreading (e.g., liquefaction) and rockfall from nearby cliffs.

Damage to individual components and sub-assemblies included: (i) facade or veneer damage (poor anchorage conditions); (ii) damage to interior gypsum wallboard; (iii) damage to interior and exterior lath and plaster walls; and (iv) damage to concrete and clay tile roofs. Interestingly, the article reports that interior lath and plaster walls were typically exhibiting a larger level of damage compared to gypsum wallboard; with the description of increased damage including a much larger wall area containing cracks when compared to the gypsum wallboard that had cracks concentrated at panel joints and near door or window openings. The damage to tile roofs was mostly attributed to the lack of anchorage of individual tiles, yet the article states that the large vertical accelerations during the event added to the fragility of the roofs.

Christovasilis I., Filiatrault A., Wanitkorkul A. (2009). Seismic testing of a full-scale two-story light-frame wood building: NEESWood benchmark test, *Technical Report MCEER-09-0005*, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY.

This reports on shake table testing of a two-story 1980s-era wood light-frame townhouse with an attached garage (configuration per *CUREE Publication No. W-29* and used in loss estimation studies per *CUREE Publication No. W-18*). Tests were conducted at a range of ground motion levels and for a series of configurations including bare structure, exterior finishes added, interior and exterior finishes added. Detailed reports are provided of the location and nature of damage.

FEMA (2012a). *Simplified Seismic Assessment Guidelines for Detached, Single-Family Wood-Frame Dwellings, FEMA P-50*, Federal Emergency Management Agency, Washington, D.C.

This presents a method for assessment of the seismic hazard and vulnerability of wood-frame dwellings. The methodology is based largely on vulnerabilities observed in past earthquakes. Included in Appendix C is a discussion of observed past performance that helps to guide the assessment process. This is one source of collected information on seismic vulnerabilities experienced to date.

FEMA (2012b). *Seismic Retrofit Guidelines for Detached, Single-Family, wood-Frame Dwellings, FEMA P-50-1*, Federal Emergency Management Agency, Washington, D.C.

A companion document to FEMA P-50, this provides additional background on seismicity and portions of dwellings affected by earthquake loading, as well as providing guidance for retrofit.

FEMA (2015). *Performance of Buildings and Nonstructural Components in the 2014 South Napa Earthquake, FEMA P-1024*, Prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

This report documents the damage to various building types and nonstructural components following the 2014 South Napa event. Single-family residential houses were reported to be largely undamaged, yet homes with known structural deficiencies such as unbraced cripple walls and chimneys were shown to be heavily damaged in many cases. The report notes that failure occurred in both shorter and taller cripple walls but also noted the success of retrofits made to shorter cripple walls. Also noted is the lack of guidelines or prescriptive measures to provide seismic retrofit for taller cripple walls. Unbraced cripple walls were found to have completely collapsed or incurred large residual deformation. Observations of cripple wall failures were commonly found for homes with wood siding and predominantly of pre-1930s construction.

Fischer D, Filiatrault A, Folz B., Uang C.M, Seible F. (2001). Shake table tests of a two-story woodframe house, *CUREE Publication No. W-06*, Consortium of Universities for Earthquake Engineering, Richmond, CA.

This reports on shake table testing of a two-story 1980s-era wood light-frame single-family dwelling. Tests were conducted at a range of ground-motion levels, and for a series of configurations including bare structure, exterior finishes added, interior and exterior finishes added. Detailed reports are provided of the location and nature of damage.

Kang G.S., Mahin S.A. (2014). *PEER* Preliminary notes and observations on the August 24, 2014, South Napa earthquake, *PEER Report No. 2014/13*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

This reconnaissance report from the Pacific Earthquake Engineering Research Center followed the 2014 South Napa earthquake. The aim of the report was to examine both the strong-motion record of the earthquake and damage (structural and non-structural) of buildings within Napa. For single-family dwellings, it was found that in instances where major damage was present, there was a partial or total collapse of the house's cripple wall or the house had slid off its foundation. It was found that houses constructed pre-1970s suffered the most extreme damage.

Mosalam K., Hashemi A., Elkhoraibi T., Takhirov S. (2008). Seismic evaluation of wood house over garage, *Proceedings, 14th World Conference on Earthquake Engineering*, Beijing, China.

This reports on shake table testing of a two-story 1940s-era wood light-frame single-family dwelling typical of a San Francisco house over garage configuration. Tests were conducted to determine that global seismic response at a range of ground-motion levels for a series of configurations including bare structure, exterior finishes added, and interior and exterior finishes added. Information is also provided of location and nature of damage.

Rabinovici S. (2017). *California Earthquake Authority South Napa Home Impact Study,* California Earthquake Authority. Available at: *https://www.earthquakeauthority.com/About-CEA/Research-Outreach/Our-Research/CEA-Napa-Fina-lReport-Exec-Summ.*

This report summarizes methods and data from a household survey (633 participants) and 34 interviews conducted following the 2014 South Napa earthquake for the CEA. The aim of the study was to catalogue the effects of the earthquake on single-family dwellings and homeowners. Important data from the survey included housing date of construction, presence/height of cripple walls, exterior finishes, presence of slope, and foundation type, as well as about 30 measures of damage and total financial and recovery implications of the event for households. In addition, the survey entailed questions pertaining to the commonality, cost, and extent of retrofits.

Reitherman R., Sabol T. (1995). Nonstructural damage, in: Northridge Earthquake of January 17, 1994 Reconnaissance Report, J. Hall (ed.), *Earthq. Spectra*, 11(C), Earthquake Engineering Research Institute, Oakland, CA.

This report documents the reconnaissance efforts undertaken to understand damage to nonstructural components following the 1994 Northridge, California earthquake. Relating to wood-frame housing, the report highlights that unsecured roof tiles and unbraced masonry chimneys are two details that pose a significant source of damageability and threats to life safety. The report notes that some clay tile roofs had been mortared yet without additional tile anchorage. Some of these cases withstood the ground shaking yet were badly cracked and in need of repair, and were highly susceptible to posing a life safety threat under a subsequent aftershock.

Schierle G.G. (2001). Woodframe project case studies, *CUREE Publication No. W-04*, University of Southern California, Los Angeles, CA.

This CUREE report investigated damage caused to a number of wood light-frame building types, including single-family dwellings following the 1994 Northridge, California, earthquake. Common failures within single-family dwellings were found to be contained within the cripple walls. These failures were either houses sliding off foundations (insufficient anchorage), cripple walls buckling causing collapse (inadequate cripple wall strength), or overturning of the house off its foundation.

Stewart J.P., Bray J., Seed R.B., Sitar N. (1994). Preliminary report on the geotechnical aspects of the January 24,1994 Northridge earthquake, *Report No. UCB/EERC-94/08*, Earthquake Engineering Research Center, University of California, Berkeley, CA.

This report documents the available geotechnical data from the Northridge, California, earthquake of January 17, 1994. Aspects of the earthquake discussed in the report include damage patterns found within residential structures. While the body of the work focuses on the geotechnical aspects, there is attention given towards foundation failures in single-family wood-frame dwellings, including the common occurrence of these structures sliding off their foundations.

Storesund R., Dengler L., Dengler S., Mahin S., Collins B.D., Hanshaw M., Turner F., Welsh K. (2010). *M 6.5 Offshore Northern California Earthquake Reconnaissance Report*.

A report from the Geotechnical Extreme Events Reconnaissance Association (GEER) following the 2010 Offshore Northern California earthquake. The report discovered that single-family dwellings if damaged, were knocked off their foundations (resulting from collapse of the house's cripple wall). Damage was seen in houses ranging from old Victorians (late-19th century to early-20th century) up until 1970s-vintage houses. Although there is not a lot of depth in the report about the extent of damage to these homes, the mode of failure and the era of houses that were damaged and worth noting.

Vukazich S.M., Selvaduray G., Tran J. (2006). Conducting a soft first-story multifamily dwelling survey: An example using Santa Clara County, California, *Earthq. Spectra,* 22(4): 1063–1079.

This article presents the results of a large survey focusing on larger multi-family dwellings with known soft-story conditions (e.g., tuck-under parking). The article states that the four most common details of woodframe housing that leads to poor seismic performance are: (i) tuck-under parking structures; (ii) unbraced cripple wall dwellings; (iii) woodframe housing with stucco and gypsum comprising the lateral force resisting sheathing materials; and (iv) hillside home construction.

Yancey C.W., Cheok G.S., Sadek F., Mohraz B. (1998). *A Summary of the Structural Performance of Single-Family Wood-Framed Housing, NISTIR 6624.* Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.

This 1998 report presented a review of the structural performance of single-family, wood-frame houses subjected to selected earthquakes and hurricanes. The report found that instances where major damage occurred within the homes was primarily due to poor construction practices and noncompliance with building codes. In addition, the report found that cripple wall failures were also a primary mode of failure during earthquakes. The report examined studies done on full-scale houses, shear walls, and inter-component connections. It should be noted that a good body of work (specifically the CUREE Reports) had been published since this report was initially published.

5 Analytical Models for Wood-Frame Structures

5.1 ISSUES OR QUESTIONS

1. What are the common model types to analyze the nonlinear response of wood-frame houses?
2. What are the currently available software analysis programs that have capabilities and been applied to simulate the nonlinear and damage response of wood-frame houses?
3. What studies have been done to calibrate and validate the reliability of nonlinear analysis models for wood-frame houses?
4. What are the major gaps in knowledge and test data for analyzing the nonlinear response of wood-frame houses?
5. How significant is soil-foundation-structure interaction in the nonlinear response analyses of wood-frame houses?
6. How has or should unmodeled energy dissipation (e.g., viscous damping) be incorporated in the nonlinear dynamic response analysis of wood-frame houses?
7. How have or should modeling uncertainties be incorporated into demand parameters determined using nonlinear dynamic analysis?
8. What studies are available to incorporate material aging and deterioration in nonlinear analysis of wood-frame houses?

5.2 RELEVANCE OF REFERENCES

Table 5.1 Relevance of references for analytical models for wood-frame structures.

Citation	Relevant questions							
	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8
Bahmani and van de Lindt (2016)			✔	✔				
Bajwa et al (2009)								✔
Carll and Highley (1999)								✔
Ceccotti and Karacabeyli (2002)		✔	✔	✔				
Christovasilis and Filiatrault (2011)		✔	✔	✔		✔		
Collins et al (2005)			✔					
Filiatrault et al. (2003)		✔	✔			✔		
Folz and Filiatrault (2004a)	✔	✔						
Folz and Filiatrault (2004b)	✔	✔	✔			✔		
Goda and Atkinson (2010)	✔	✔						
Isoda et al. (2001)			✔			✔		✔
Jelle (2012)								✔
Kircher et al. (2016)					✔	✔		
Kirkham et al (2014)	✔	✔						
Lim et al. (2017)	✔	✔						
Osteraas et al (2008)		✔		✔				
Pang and Shirazi (2012)						✔	✔	
Pang and Shirazi (2013)	✔	✔	✔					
Weston and Zhang (2017)	✔		✔					
Wilcox (1978)								✔
Yin and Li (2010)						✔	✔	
van de Lindt et al. (2010)		✔	✔	✔		✔		

5.3 REFERENCES AND ANNOTATIONS

Bahmani P., van de Lindt J.W. (2016). Experimental and numerical assessment of woodframe sheathing layer combinations for use in strength-based and performance-based design, ASCE, *J. Struct. Eng.*, 142(4): E4014001.

The article illustrates the results of eighteen different cyclic tests on 8 ft × 8 ft wall specimens with various combinations of sheathing materials. The sheathing materials included: stucco, horizontal wood sheathing or siding, diagonal wood sheathing, gypsum wallboard and wood structural panel. Some of the combinations proved to be useful since recent tests using archaic materials is scarce (e.g., stucco + diagonal sheathing + gypsum wallboard). Conversely, the study explicitly mentions that plaster on wood lath and plywood panel siding (presumably T1-11) were not considered; an indication of the knowledge gap and need for test data on these materials.

The two objectives of the study beyond testing were as follows: (i) develop numerical models to represent the different sheathing materials; and (ii) investigate sheathing combination rules previously proposed within *FEMA-P-807* [FEMA 2012]. The numerical models of single wall specimens were developed using the CUREE/SAWS hysteretic model [Folz and Filiatrault 2001] and the evolutionary parameter hysteretic model [Pang et al. 2007]. The study did not indicate the acceptance criteria used for fitting the hysteretic parameters and simply showed side by side comparisons. The *FEMA P-807* rules (intended for design) produced more conservative responses in terms of displacement exceedance than equivalent parameters calibrated to combined tests. Conversely, the use of 100% superposition of individual materials produced slightly larger peak forces and therefore less conservative displacement estimates.

Bajwa S.G., Bajwa D., Anthony A. (2009). Effect of laboratory aging on the physical and mechanical properties of wood-polymer composites, *J. Thermoplast. Compos.,* 22(2): 227–243, doi:10.1177/0892705708091857.

“Mechanical properties tested included MOE and MOR under flexure, compressive strength, screw withdrawal force, hardness, and CLTE.”

Carll C.G, Highley T.L. (1999). Decay of wood and wood-based products above ground in buildings, *J. Testing Eval.,* 27(2):150–158, doi:10.1520/jte12054j.

This review paper of previous research described the deterioration of wood products in more detail, i.e., the effect on mechanical properties). Other papers discussed within: Tsongas G. (1994). Crawl space moisture conditions in new and existing northwest homes, *ASHRAE Technical Data Bulletin*, 10(3); American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA (not available online through Stanford); and Wilcox W. (1978). Review of literature on the effects of early stages of decay on wood strength, *Wood Fiber Sci*., 9(4): 252–257.

Ceccotti A., Karacabeyli E. (2002). Validation of seismic design parameters for woodframe shearwall systems, *Can. J. Civil Eng*., 29: 484–498.

This paper verified hysteresis models of wood-frame shear walls—designed according to the Canadian code—with shake table tests of multi-storey wood buildings. The effect of flexible diaphragms on the ultimate PGA of a symmetric building was also studied. The paper offers much detail on how various elements of structures were modeled and assumptions made.

Christovasilis I.P., Filiatrault A. (2011). Numerical and experimental investigation of the seismic response of light-frame wood structures, *Technical Report MCEER-11-0001*, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, The State University of New York, Buffalo, NY.

This research report describes the development of numerical models to capture the experimental response of wood shear walls with various aspect ratios, anchorage conditions, and sheathing. The experimental results demonstrated the contributions to global drift response in terms of the following: shear-wall racking, sill plate slippage, and stud uplift, which motivated the development of a numerical model capable of capturing wall response including the effects of uplift and anchorage deformation as well as framing to framing interaction. The detailed numerical models were compared with the more widely adopted "pure shear" models and found that the more explicit modeling gave better results when considering high aspect ratio walls and lower gravity loads (i.e., conditions where uplift and overturning are expected to be significant). The pure shear model performed reasonably with fully sheathed (i.e., low aspect ratio) walls and also first-story walls when considering a two-story configuration. Two-dimensional dynamic analysis was conducted, and 1% Rayleigh damping was assumed. The report provides a detailed description of the modeling efforts and how properties of various connections (e.g., nails, hold-downs and anchor bolts) were obtained.

Collins M., Kasal B., Paevere P., Foliente G.C. (2005). Three-dimensional model of light frame wood buildings. II: experimental investigation and validation of analytical model, ASCE, *J. Struct. Eng.,* 131(4): 684–692., doi:10.1061/(asce)0733-9445(2005)131:4(684).

These researchers validated their model through experimental testing but the model did not include interior finishes, which significantly affects performance.

Filiatrault A., Isoda H., Folz B. (2003). Hysteretic damping of wood framed structures, *Eng. Struct.*, 25: 461–471.

This study provides a model calibration and validation of a 2D planar ("pancake") model using RUAUMOKO. The tested structure was a two-story full-scale house including structural and non-structural finish materials [Fischer et al. 2001; Filiatrault et al. 2002]. The calibration of the model used individual material calibration performed by Isoda et al. [2001]. When modelling all materials (e.g., OSB, stucco, and gypsum) and assuming 0.1% Rayleigh damping, the results for a large intensity ground motion matched the experimental results very well in terms of peak roof displacement and phasing of cycles.

Folz B., Filiatrault A. (2004a). Seismic analysis of woodframe structures i: model formulation, ASCE, *J. Struct. Eng.*, 130(9): 1353–1360.

This article explains the development of the SAWS software program. The modeling approach utilized modeling reduction of a 3D structure to a 2D planar ("pancake") model with only three degrees-of-freedom (DOFs) per floor. Diaphragms were assumed rigid and interaction of intersecting shear walls was not accounted for. Nonlinear properties of wall elements were concentrated in a single

DOF spring exhibiting the CUREE hysteretic model (a.k.a, SAWS model). This software and modeling approach is extremely relevant to the current state-of-the-art given the large number of recent studies that have used it to analyze wood-frame houses.

Folz B., Filiatrault A. (2004b). Blind predictions of the seismic response of a woodframe house: An international benchmark study, *Earth. Spectra*, 20(3): 825–851.

This article reports on the results of a blind prediction study involving five teams representing six different countries. The main objective was to estimate the response of a two-story house that was tested via shake table [Filiatrault et al. 2002] and allow for various modeling approaches to be submitted. The various modeling approaches used by the teams ranged from excellent agreement to marginal. The study mentions that the benchmark test leads to the conclusion that nonlinear time history analysis of wood houses is not something readily possible by the general engineering community. This includes aspects of efficiency and availability as well as limitation of commercially available software programs. The models assuming lower viscous damping ratios had better agreement with displacement response from experiments; with one exception being the use of 5% damping and under-predicted shear-wall capacity leading to (deceptively) accurate global response estimates. A subsequent study was performed by the authors (not the original participants) where the viscous damping assumed in an equivalent SAWS model of the building was varied from 0% to 5% of critical. When comparing peak roof displacements, 0% damping provided the closest match for the lower intensity motion and 1% provided the closest match for the strongest near-fault ground motion considered. Full details of the study can be found in Folz et al. [2001].

Goda K., Atkinson G.M. (2010). Seismic performance of wood-frame houses in south-western British Columbia, *Earthq. Eng. Struct. Dyn.,* 40(8): 903–924., doi:10.1002/eqe.1068.

This paper includes information on existing models for analyzing the nonlinear response of wood-frame houses. Goda and Atkinson adapted existing SAWS models and calibrated them to extensive experimental test results. Four types of shear wall assemblies, including two that “reflect the practice in California as specified in the 1997 Uniform Building Code” were tested experimentally (quasi-statically and dynamically) and analytically. The hysteretic behavior of shear wall elements was represented by a nonlinear spring that was characterized based on the CASHEW model.

Isoda H., Folz B, Filiatrault A. (2001). Seismic modeling of index wood-frame buildings, *Report SSRP-2001/12*, Department of Structural Engineering, University of California, San Diego, La Jolla, CA.

This research report considered four different index buildings. Each building archetype considered three level of construction quality: poor, typical, and superior. The definitions of construction quality were a combination of installation practice and possible deterioration of materials due to aging and exposure. Estimates were made on the “percent reduction” of strength and stiffness of individual materials, elements, or sub-structures when compared to available high-quality laboratory test data. [NOTE: Details of the differences in construction quality and corresponding reductions cite only a personal communication with Keith Porter in 2001]. Notably, the study assumes 1% damping in the numerical models.

The study provides hysteretic parameters calibrated to experimental test data for exterior and interior finish materials as well as cripple walls. The study does not provide acceptance criteria or a procedure for the fitting of the hysteretic parameters. The parameters are for the Wayne-Stewart hysteretic model [Stewart 1987], which serves as a basis for the CUREE/SAWS hysteretic model [Folz and Filiatrault 2001].

Jelle B.P. (2012). Accelerated climate ageing of building materials, components and structures in the laboratory, *J. Mat. Sci.,* 47(18): 6475–6496, doi:10.1007/s10853-012-6349-7.

This is another review paper that discusses previous research of the deterioration of wood products in more useful detail.

Kircher C.A., Pang W., Ziaei E., Filiatrault A., Schiff S.D. (2016). Solutions to the short-period building performance paradox: A focus on light-frame wood buildings, *Proceedings, Structural Engineers Association of California Convention*, Maui, HI.

This conference paper represents the only document currently published about the ATC-116 project. Focusing on light-frame housing, the important findings of the paper include the most recent considerations for soil-structure interaction (SSI) and imperfect connectivity (e.g., uplift, framing detachment). The study suggests that explicit modeling of SSI is not warranted for light-frame wood buildings, with nonlinear response history results showing negligible differences when SSI is included. Further, the study looked at the effects of imperfect connectivity and describes the current results as "tentative" due to uncertainties in modeling capabilities and available experimental data. In terms of collapse performance, the study found that including imperfect connectivity reduced collapse probabilities; which was likely due to the increased displacement capacity provided by hold downs and flexibility included in framing (e.g., sill plates with anchor bolts). [NOTE: The effect of including imperfect connectivity on improperly detailed connections such as no hold downs or missing anchor bolts is not reported].

Kirkham W.J., Gupta R., Miller R.H. (2014). State of the art: seismic behavior of wood-frame residential structures. ASCE, *J. Struct. Eng.,* 140(4), doi:10.1061/(asce)st.1943-541x.0000861.

This review paper represents the most recent literature review of the seismic behavior of wood-frame houses published to date. The review covers topics including: joint or connection testing, shear wall testing, diaphragm testing, finite-element modeling, full-scale specimen testing, seismic damage surveys, and damage estimation methods. The research is summarized within large tables with brief summaries of the scope and/or specimens considered.

Knowledge gaps and future directions addressed by the article include the need to better understand the effects of brittle finish materials (e.g., stucco and gypsum) on the seismic behavior of wood-frame houses. Further, the use and development of finite-element methods to simulate seismic response is acknowledged, yet the lack of consensus with the modeling methods and elements to be implemented is noted as an important challenge to overcome before moving forward (e.g., moving to ubiquitous performance-based design and assessment approaches). The study notes that research comparing the various methods available would greatly benefit the practitioner moving forward (e.g., synthesis and dissemination of current level of knowledge).

Kirkham et al include summary tables of conventional wood shear wall testing and analysis, with details of the testing setup; horizontal wood diaphragm testing and analysis, with details of the testing setup; finite-element and analytic models of wood-frame houses, including the software used (SAWS, CASHEW, SAPWood, Lightframe, OpenSEES, NailPattern, and Abaqus); and wood-frame dwelling testing.

Lim H., Lam F., Foschi R.O., Li M. (2017). Modeling load-displacement hysteresis relationship of a single-shear nail connection, ASCE, *J. Eng. Mech.,* 143(6), doi:10.1061/(ASCE)EM.1943-7889.0001204.

This article explains the development of the RHYST program for analysis of wood-frame assemblies at the component level (i.e., connector-framing interaction). The basis of the predecessor, HYST, is explained, and recent developments to enhance the ability to predict the connector (nail) interaction with the sheathing material are explained as part of the new program, RHYST. The program provides insight into more explicit modeling of individual connections. The RHYST program and governing physical and mathematical relationships could be used if connector level analysis is sought to justify experimental results or provide additional information for materials that may not be adequately backed by experimental data.

Osteraas J.D., Gupta A., Griffith M., McDonald B. (2008). Woodframe seismic response analysis—Benchmarking with buildings damaged during the Northridge earthquakes, ASCE, *Proceedings, Structures Congress,* British Columbia, Canada.

"This paper presents the results of a series of analyses utilizing the new software (SAWS and SAPWood) and laboratory test data (COLA, CUREE-CalTech, CUREE-EDA) to hind cast the performance of two real woodframe buildings with documented damage due to the Northridge earthquake."

Pang W., Shirazi S.M.H. (2013). Corotational model for cyclic analysis of light-frame wood shear walls and diaphragms, ASCE, *J. Struct. Eng.*, 139(8): 1303–1317.

This article explains the development and application of the "M-CASHEW" software, which is a Matlab program that allows various complexities of light-frame walls and diaphragms to be incorporated on a detailed (e.g., every connector and nail modeled) level while maintaining computational efficiency through nodal condensation. The software is a large improvement, in terms of capability, over its predecessor "CASHEW" [Folz and Filiatrault 2001], which is limited to pinned rigid studs with deformations occurring only in the sheathing panels (elastic shear deformation) and the sheathing to framing connections (e.g., nails).

The most useful aspect of the article is that it thoroughly explains how the inclusion of numerous local phenomena can be achieved, including: bending in framing elements, accounting for bearing contact, accounting for uplift of individual framing elements (e.g., nail withdrawal) and hold down anchors. The different phenomena are described mathematically, and example hysteretic models are provided. [NOTE: All capabilities of M-CASHEW are possible within the larger (and more recent) Timber3D program [Pang et al. 2012].

Pang W., Shirazi S.M.H. (2012). Stochastic response of light-frame wood buildings under earthquake loading, *Proceedings of the World Conference on Timber Engineering*, Auckland, New Zealand.

This study complements the findings of Yin and Li [2010] on modeling the uncertainties for light-frame wood buildings. Uncertainties are limited to the hysteretic parameters used to model shear wall connections (e.g., nails), yet correlations between parameters are included using Cholesky decomposition. Further, the study addresses the idea that all hysteretic properties cannot realistically be assumed normally or log-normally distributed (e.g., variations in reloading stiffness factors is described by a Beta distribution). [NOTE: the work by Yin and Li [2010] found the reloading stiffness factor to be the most influential using a tornado diagram; this is likely due to improper considerations of the bounds and distribution of this parameter. The considerations of this study may be important for future work on assessing uncertainties within a more encompassing framework and using various available methods (e.g., Liel et al. [2009]). Finally, this study assumed 2% Rayleigh damping in the first and second modes.

van de Lindt J.W., Pei S., Liu H., Filiatrault A. (2010). Three-dimensional seismic response of a full-scale light-frame wood building: numerical study, ASCE, *J. Struct. Eng.*, 136(1): 56–65.

This article reports on a numerical investigation conducted to replicate the response of a two-story residential building tested dynamically via shake table [Filiatrault et al. 2009; Christovasilis et al. 2009]. The building construction was phased to incrementally include finish materials (i.e., structural wood only, gypsum interior added, stucco exterior, etc.). Analysis was performed using the SAPWood program [Pei and van de Lindt 2007; 2009] and included vertical stiffness considerations via lumped springs distributed to include: framing (e.g., studs), hold-downs, anchor bolts, and framing connectors (e.g., stud nail withdrawal). The hysteretic model selected was the EPHM model [Pang et al. 2007]. Wood structural panel parameters were calibrated at the connector level using Nail Pattern within SAPWood. Finish materials were reported to be estimated from 8 ft × 8 ft test data [NOTE: no reference to specific tests]. The numerical models assumed 1% Rayleigh damping (proportional to initial stiffness).

The numerical investigation provided very good results in terms of replicating the displacements found from shake table testing, at least within the phases prior to including exterior stucco. The numerical models were found to moderately overestimate the response when including exterior stucco. The authors suggest that the simplified study to estimate stucco parameters and neglecting diaphragm flexibility could be the main sources of discrepancy. [NOTE: This highlights the knowledge gap in terms of properly considering stucco finish on a full-scale building. Another source of discrepancy could also be that the stucco provided much more connectivity to the structure that could limit the uplift and vertical stiffness effects in the actual structure. This effect was most likely not considered in the numerical model since the vertical stiffness was not modified for the inclusion of stucco.]

Weston J., Zhang W. (2017). Finite element modeling of nailed connections in low-rise residential home structures, ASCE, Proceedings, *Structures Congress*, Denver, CO.

This paper discusses the implementation of equivalent parameterized beam connection (EPBC) models in place of equivalent nonlinear spring connection (ENSC) models within structural models, in both linear and nonlinear response regimes for one dimensional and multi-dimensional loading. The principal advantage seems to be that: "When modeling sheathing to framing connections for the interior sections of a panel, use of a single EPBC reduces the number of elements required to represent the translational behavior by a factor of 3 compared to ENSCs." The paper also discusses limitations of the EPBC models; while they match ENSC models for one-dimensional axial and transverse loading, under combined loading: "EPBCs couple the axial and transverse effects through the computation of element stress leading to a more conservative solution compared with ENSCs."

Wilcox W. (1978). Review of literature on the effects of early stages of decay on wood strength," *Wood Fiber Sci.*, 9(4): 252–257.

This article is a literature review on how early stages of decay influence wood strength in impact and static bending, tension, compression, and shear. Decay due to both white- and brown-rot fungi was considered. Takeaways include: "Clearly, wood loses most of its ability to withstand shock loads, absorb energy, and support loads in a bending mode at such early stages of decay that they are difficult to detect in all cases and may be overlooked in routine diagnostic procedures. If the decay is detectable, the wood should be suspected of lacking almost all strength in all of the properties listed above."

Yin Y.-J., Yue L. (2010). Seismic collapse risk of light-frame wood construction considering aleatoric and epistemic uncertainties, *Struct. Safety*, 32(4): 250–261.

This study aimed to quantify uncertainties in the response of light-frame wood buildings in a more modern context; with the term "modern" signifying useable quantities in advanced performance assessment. The study addresses uncertainty in collapse performance in terms of record-to-record and modeling uncertainty. Modeling uncertainty is limited to the parameters used to define the hysteretic properties of wood shear walls, with this uncertainty labeled as "resistance uncertainty." Since modeling variables such as damping and mass were not considered, the effect of varying additional epistemic uncertainty factors was considered. The study does not include correlation between hysteretic properties and assumes truncated normal distributions of parameters based on assumed coefficients of variation and physical limits (e.g., the post-peak slope cannot be positive). This study assumed 1% elastic damping in the numerical models.

This paper treated the epistemic and aleatoric uncertainties in both the seismic demand and seismic capacity. The aleatoric uncertainties in seismic demand were confined to record-to-record uncertainty and spectral shape. The aleatoric uncertainties in seismic capacity exist in the damping, stiffness, mass, and energy dissipation characteristics of the structure. Uncertainties were incorporated in the dynamic analysis using a Monte Carlo simulation with Latin Hypercube Sampling. For each ground motion, 40 NDAs were run. Each of the ten hysteresis parameters of the structure are independently sampled* 100 times. In total, for each NDA run, 1000 realizations of a single wood shear wall are created.

Conclusions state that it is necessary to include uncertainties: "Considering a moderate modeling uncertainty (i.e., bm = 0.4 in this paper), the dispersion due to both resistance and modeling uncertainties was found to be approximately 0.44, which led to an increase of annual collapse probability ranging between 25% and 168% depending on the site." Though logically they should be correlated, according to the author there is a lack of literature on how to do so.

5.4 ADDITIONAL REFERENCES MENTIONED

Christovasilis I., Filiatrault A., Wanitkorkul A. (2009). Seismic testing of a full-scale two-story light-frame wood building: NEESWood benchmark test, *Technical Report MCEER-09-0005*, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY.

FEMA (2012). *Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Stories, FEMA P-807*, Prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

Filiatrault A., Fischer D., Folz B., Uang C.-M. (2002). Seismic testing of two-story woodframe house: influence of wall finish materials, *J. Struct. Eng.,* ASCE, 128(10): 1337–1345.

Filiatrault, A., Christovasilis, I.P., Wanitkorkul, A., van de Lindt J.W. (2010). Experimental seismic response of a full-scale light-frame wood building, ASCE, *J. Struct. Eng.*, 136(3): 246–254.

Fischer D., Filiatrault A., Folz B., Uang C.-M. (2001). Shake table tests of a two-story woodframe house," *CUREE Publication No. W-06*, University of California, San Diego, La Jolla, CA.

Folz B., Filiatrault A. (2001). Cyclic analysis of wood shear walls, ASCE, *J. Struct. Eng*., 127(4): 433–441.

Folz B., Filiatrault A., Uang C.-M., Seible F. (2001). Blind predictions of the seismic response of a two-story woodframe house: An international benchmark, *Report No. UCSD/SSRP – 2001/15*, Structural Systems Research Project, University of California, San Diego, La Jolla, CA.

Liel A.B., Haselton C.B., Deierlein G.G., Baker J.W. (2009). Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings, *Struct. Safety*, 31: 197–211.

Pang W., Ziaei E., Filiatrault A. (2012) A 3D model for collapse analysis of soft-story light-frame wood buildings, *Proceedings, 2012 World Conference on Timber Engineering*, Auckland, NZ.

Pang W., Rosowsky D.V., Pei S., van de Lindt J.W. (2007). Evolutionary parameter hysteretic model for wood shear walls, ASCE, *J. Struct. Eng., ASCE*, 133(8): 1118–1129.

Pei S., van de Lindt J.W. (2007). *User's Manual for SAPWood for Windows, Version 1.0*, *http://www.engr.colostate.edu/NEESWood/*. [NOTE: Link is no longer active].

Pei S., van de Lindt J.W. (2009). Coupled shear-bending formulation for seismic analysis of stacked wood shear wall systems, *Earthq. Eng. Struct. Dyn.*, 38: 1631–1647.

Stewart W.G. (1987). *The Seismic Design of Plywood Sheathed Shear Walls*, Ph.D. dissertation, Department of Civil Engineering, University of Canterbury, Christchurch, NZ.

6 Damage and Loss Assessment of Wood-Frame Houses

6.1 ISSUES OR QUESTIONS

1. What methods are available to develop damage and loss functions of wood-frame houses?
2. What data are available to calibrate and validate component damage and loss (consequence) functions for wood-frame houses?
3. What data or studies have been done to validate the overall damage (loss) functions for wood-frame houses?
4. What are the implications of cripple wall damage and failure on observed losses?
5. How should large deformations, up to complete failure, of the cripple wall be incorporated in loss analysis? (i.e., at what point the cripple wall damage and resulting house damage is beyond repair)
6. How should large deformations, up to complete failure, of the sill plate anchorage be incorporated in loss analysis? (i.e., at what point the anchorage damage and resulting house damage is beyond repair)
7. How significant is damage to acceleration sensitive components in the overall damage (loss) functions for wood-frame houses?

6.2 RELEVANCE OF REFERENCES

Table 6.1 Relevance of references for damage and loss assessment of wood-frame houses.

Citation	Relevant questions						
	6.1	6.2	6.3	6.4	6.5	6.6	6.7
Black et al. (2010)	✔		✔			✔	
Certus (2005)	✔	✔	✔				
FEMA (2010)	✔						✔
FEMA (2012)	✔						
Graf and Seligson (2011)			✔				
Levenson (1992)							✔
Pei and van de Lindt (2009)	✔						
Porter and Cobeen (2009)			✔		✔		
Porter et al. (2002)			✔	✔	✔		✔
Reis et al. (2001)			✔				

6.3 REFERENCES AND ANNOTATIONS

Black G., Davidson R.A., Pei S., van de Lindt J. (2010). Empirical loss analysis to support definition of seismic performance objectives for woodframe buildings, *Struct. Safety*, 32: 209–219.

This article explains the implementation of a building-specific loss estimation framework (pre-*FEMA P-58*), i.e., loss estimation, definition of performance objectives, and how designs can be updated to meet the specified performance objectives. The study relies heavily on the fragility and consequence functions developed by Porter et al. (2002) within the CUREE project. Interestingly, the study includes a few additions to the loss model to extend the assemblies and damage states within the structure (two-story single-family dwelling). Acceleration sensitive nonstructural components and contents were considered using fragility curves provided in HAZUS. Further, demands on shear bolts anchoring sill plates were monitored and attributed a fragility based on the testing conduction by Christovasilis et al. [2009]. Also based on the testing by Christovasilis et al. [2009], the study assumed large reduction factors on the drift affecting interior partition walls (i.e., drifts from analysis were reduced before input into the loss model). These factors reportedly ranged from 0.15 to 0.76. There is no substantial evidence for these factors other than the observed contribution of total "diaphragm-to-diaphragm" drift within Christovasilis et al. [2009] not being 100% transferred to the shear walls at all points of the diaphragm.

The study compares generalized loss trends from reconnaissance reports (e.g., Schierle [2003]) to the numerical results, demonstrating that although the current loss model would likely estimate a larger number of damaged buildings than observed in reality, the loss ratios are reasonable; one possible reason for these results was that nonstructural finishes were not included in the model used for analysis (noting these materials are considered for loss estimation). This loss study represents more complete effort to implement building-specific loss estimation for woodframe buildings, yet it also highlights the need for more information in order to continue forward; particularly with the acquisition of acceleration-sensitive nonstructural component fragilities and fragilities of archaic materials.

Certus (2005). *CEA-Loss Modeling Study*, Report of the Scientific Modeling Workgroup, Engineering Component, Certus Consulting, Ltd.

This report investigates the seismic losses produced by the empirical software EQECAT (largely based on 1994 Northridge earthquake data) to four different analytical approaches. The analytical approaches include HAZUS, HAZUS ATC-55 (presumably AEBM precursor), FEMA/NIBS, and the CUREE loss model; note, it is uncertain whether the full report and findings of Porter et al. [2002] were incorporated at the time of the comparison. The different loss models were used to calculate Equivalent Annual Damage (EAD) estimates considering 10,000,000 realizations (location, soil type, construction era, return period, building type, etc.).

The general conclusion was that the CUREE loss model drastically underestimated the EQECAT results, while the HAZUS models also provided lower loss estimates, yet to a much lesser extent. The FEMA/NIBS model was found to overestimate EQECAT results in general. Important for the current project relates to the results of the CUREE model; a model that uses assembly-based vulnerability similar to *FEMA P-58* and SP3-type loss modeling. The authors of the report suggest that the lack of construction quality across construction eras may be a key factor for the large underestimation of losses. They use the example of the two-story models assuming plywood shear walls with exterior stucco and slab-on-grade foundation not reflecting the behavior of most buildings of that class (i.e., two-story homes). An additional source of discrepancy could very well be the number of damageable assemblies considered within the CUREE model and could further be rooted in the response parameters (e.g., drift) associated with the onset of damage. The study highlights the importance of low yet non-negligible damage levels that may occur during lower intensity events (i.e., events with larger annual occurrence probabilities) when conducting annualized loss assessment.

FEMA (2012). *Seismic Performance Assessment of Buildings: Volume 1, Methodology, FEMA P-58-1*, Federal Emergency Management Agency, Washington, D.C.

The guideline information contained within *FEMA P-58-1* illustrates the entire process of single building seismic performance estimation in line with modern capabilities of such assessments. The document transitions through each of the four basic steps of performance assessment (e.g., Site Hazard, Structural Response, Damage Assessment, Estimation of Losses, and Consequences). Most pertinent to the current review is the provision of pre-existing fragility information with the *P-*

58 fragility database (also the basis within the SP3 software) and an instructional appendix to indicate how damage fragilities may be developed from test data, post-event observation or expert judgment. Further, the guideline provides a number of normative quantities in order to estimate the inventory of structural and nonstructural components within a building of a specific occupancy. Notably, *FEMA P-58* only provides normative quantities for multi-unit residential buildings. The document mentions that these values can be used for single-family dwellings with slight modification without guidance on how to make such modifications.

FEMA (2010). *Hazus-MH MR5, Advanced Engineering Building Module (AEBM)*, Federal Emergency Management Agency, Washington, D.C.

The document is the user's guide to implementing the AEBM process within the HAZUS framework. Information on applying the HAZUS-MH procedure using "building-specific" capacity curves (e.g., pushover curves) is outlined and the use of existing damage functions for structural classes within HAZUS can be utilized to refine loss curves (e.g., expected loss vs. spectral acceleration). Modifications in fragility parameters due to the increase in structural strength or design considerations (i.e., seismic upgrade of retrofit) are approximately accounted for, and the implementation process is illustrated via example.

The damage functions within HAZUS include a consideration for the damage of acceleration-sensitive nonstructural components. For single-family dwellings, the HAZUS damage functions attribute 2.7% of building replacement cost for moderate acceleration demands up to 26.6% of replacement cost for complete damage of these components. According to these damage functions, acceleration-sensitive nonstructural components can be significant in the overall losses expected for a single-family dwelling.

Graf W.P., Seligson H.A. (2011). Earthquake damage to wood-framed buildings in the ShakeOut Scenario, *Earthq. Spectra*, 27(2): 351–373.

This article provides a summary of the ShakeOut scenario analysis for estimating the likely losses for residential woodframe buildings subjected to a M7.8 earthquake on the San Andreas fault. The study provides comprehensive reviews of past performance of woodframe construction in California, as well as the transitions in construction practices over the past century. Using the HAZUS software, lost estimates were conducted for Southern California for both residential and commercial woodframe structures. A comparison figure displays the loss functions (loss vs. *Sa*[0.3 sec]) for three assumed code compliance/construction quality levels with an equivalent curve developed by Wesson et al. [2004]. The article also discusses measures to retrofit or upgrade existing woodframe buildings and mentions the need to strap down gravity posts/columns that support floors within crawl space areas (i.e., cripple wall areas).

Levenson L.M. (1992). "Residential water heater damage and fires following the Loma Prieta and Big Bear Lake earthquakes, *Earthq. Spectra*, 8(4): 595–603.

This article illustrates the results of telephone surveys (299 participants) conducted following the 1989 Loma Prieta and 1992 Big Bear Lake earthquakes, focusing on the economic and safety aspects of residential hot water heaters (e.g., repair costs and fire ignition). The main finding of the study was that the occurrence of water heater damage and subsequent repair costs was found to be lower than what was anticipated. It was concluded that the use of more involved bracing techniques (e.g., rigid conduit bracing versus simple plumber's tape strapping) was not cost-effective for typical electric and gas water heaters when based on repair costs alone. Notably, the repair costs associated with solar water heaters was found to be much more substantial; a more extensive bracing system was deemed likely as cost-effective for these systems. Conversely, more reliable bracing of natural gas-powered water heaters was warranted when considering the possibility of preventing fire ignition, which occurred in several cases following the 1992 Big Bear Lake event. Evidence from the survey suggests that failure of gas-powered water heaters may be the largest potential cause for residential fires following an earthquake.

The main application to the current scope is that economic aspects of water heater damage is not likely to drive direct loss estimates considering repair costs alone. However, the damage of these acceleration-sensitive nonstructural components could be a significant source of indirect loss following an earthquake.

Pei S., van de Lindt J.W. (2009). Methodology for earthquake-induced loss estimation: An application to woodframe buildings," *Struct. Safety*, 31: 31–42.

This article illustrates the development of a seismic loss estimation methodology applied to woodframe houses. The novel aspect of the approach lies in using Bayesian models to include both subjective information based on judgment as well as information supported by experimental testing. This type of model and general framework will be a useful starting point when considering aspects of the building-specific loss estimation process for cripple wall dwellings and aspects with high levels of uncertainty and opinion-based standings on how they should be treated. This can include the treatment of collapse and residual displacements within the assessment of cripple wall dwellings.

Porter K.A., Beck J.L., Seligson H.A., Scawthorn C.R., Tobin L.T., Young R., Boyd T. (2002). Improving loss estimation of woodframe buildings, *CUREE Publication No. W-18*, Consortium of Universities for Research in Earthquake Engineering, Richmond, CA.

This report summarizes the development and implementation of a building-specific loss model (i.e., based on assembly-based vulnerability and in-line with the current *FEMA P-58* framework). The report provides the full background of the loss model (e.g., fragility functions, repair cost distributions, and justification) used to analyze various-sized woodframe structures. The capabilities of the loss model are limited to structures with varying grades of structural sheathing, exterior stucco, and interior gypsum. The study also provides appendices for the costing information used to estimate both repair costs and replacement costs of structures.

Porter K., Cobeen K. (2009). Loss estimates for large soft-story woodframe buildings in San Francisco, *Proceedings, ATC & SEI 2009 Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, American Society of Civil Engineers, San Francisco, CA.

> This article illustrates the findings of a loss assessment study on larger (i.e. multi-family, multi-story, and multi-unit) woodframe buildings exhibiting known soft-story conditions (e.g., tuck-under garages) in the city of San Francisco. The loss assessment was conducted using the HAZUS-MH AEBM approach with custom modifications by the authors. Building capacity curves assumed different strengths based on interior finish materials (e.g., plaster on wood lath or gypsum wallboard). Contribution of horizontal sheathing was included but provided negligible contribution to peak strength due to low stiffness and low strength. The study produced a set of displacement limits corresponding to various levels of damage following a review of available literature on older finish materials (e.g. horizontal siding, lath, and plaster). These damage thresholds, initially defined in terms of peak transient drift displacement, were assumed to be representative of spectral displacement demands for soft-story buildings. This is an important consideration since cripple wall dwellings failing at cripple wall level would exhibit similar behavior; with the effective height of the structure being the top of the first story with the remaining superstructure above behaving as (essentially) a rigid body. The implications of this on cripple wall dwelling needs to be assessed; with an emphasis on determining the proper procedure for performing capacity spectrum analyses such as those according to HAZUS-MH AEBM.
>
> The study included retrofit measures including the addition of oriented strand board (OSB) in the weaker lower story. Interestingly, the retrofit measures taken were not expected to shift damage to the upper stories in the buildings with lath and plaster interior, yet the OSB retrofits in some cases were shown to exceed the upper-story shear capacity of building with gypsum interiors. This response has been corroborated by the ATC-110 project for cripple wall dwellings. Another important consideration within the study was assuming that a residual displacement of 2 in. (or greater) would confidently return a red tag (ATC 20) upon post-event inspection. This value is for full height walls, so the equivalency for cripple walls will need to be determined, yet this is an interesting starting point. The study conducted was compared with reconnaissance data from the 1989 Loma Prieta earthquake in the Marina District of San Francisco [Harris and Egan 1992] and shows that the results using the adopted HAZUS model provided reasonable agreement with the loss values reported.

Reis E., Comartin C., King S. (2001). *HAZUS-99 SR1 Validation Study*. Federal Emergency Management Agency, Washington, D.C.

> This report provides a calibration between available loss documentation for the Whittier, Loma Prieta, Northridge, and Seattle earthquakes with loss estimates produced by HAZUS for the same earthquakes as hypothetical scenarios.

6.4 ADDITIONAL REFERENCES MENTIONED

Christovasilis I., Filiatrault A., Wanitkorkul A. (2009). Seismic testing of a full-scale two-story light-frame wood building: NEESWood benchmark test, *Technical Report MCEER-09-0005*, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY.

Harris S.K., Egan J.K. (1992). Effects of ground conditions on the damage to four-story apartment buildings, T.D. O'Rourke (ed.), The Loma Prieta, California earthquake of October 17, 1989 – Marina District, *Professional Paper 1551-F*, U.S. Geological Survey, Reston, VA, pp. 181–194.

Schierle G. (2003). Northridge earthquake field investigations: statistical analysis of woodframe buildings, *CUREE Publication No. W-09*, Consortium of Universities for Research in Earthquake Engineering, Richmond, CA.

Wesson R.L., Perkins D.M., Leyendecker E.V., Roth Jr. R.J., Petersen M.D. (2004). Losses to single-family housing from ground motions in the 1994 Northridge, California, earthquake, *Earthq. Spectra*, 20(3): 1021–1045.

7 Characterizing Ground Motions for Assessment of Wood-Frame Houses

7.1 ISSUES OR QUESTIONS

1. What ground-motion intensity parameters have or should be used to characterize ground motions (e.g., spectral acceleration, spectral shape, duration, near-fault pulses, etc.) for nonlinear analysis and loss assessment of wood-frame structures?
2. Of currently available methods, what techniques are best suited to characterize and combine different ground motion characteristics (e.g., spectral acceleration, spectral shape, duration, near-fault pulses, etc.) in nonlinear dynamic analysis?
3. What is the range of expected ground motions in regions of California with significant populations of wood-frame houses?
4. How significantly do site response characteristics affect the ground-motion shaking in the range expected to affect wood-frame houses? How should these site characteristics (mean and dispersion) be incorporated in the input ground motions?

7.2 RELEVANCE OF REFERENCES

Table 7.1 Relevance of references for characterizing ground motions for assessment of wood-frame houses.

Citation	Relevant questions			
	7.1	7.2	7.3	7.4
Abrahamson et. al. (2014)	✔			✔
ASCE 7-10 (2010)	✔	✔	✔	✔
Ancheta et al. (2014)	✔		✔	
Arias (1970)	✔			
Baker (2011)	✔	✔		
Boore et al (2014)	✔			✔
Bozorgnia and Campbell (2004)	✔	✔		✔
Campbell and Bozorgnia (2014)	✔			✔
Chiou and Youngs (2014)	✔			✔
Field et al (2013)			✔	
Hancock et al. (2006)	✔	✔		
Haselton et al (2009)	✔	✔		
Idriss (2014)	✔			✔
Kramer (1996)	✔	✔		✔
Krawinkler et al (2003)	✔	✔		
Mahin and Bertero (1981)	✔	✔		
McGuire (2004)	✔	✔		✔
USGS (2014)			✔	

7.3 REFERENCES AND ANNOTATIONS

Abrahamson N.A., Silva W.J., Kamai R. (2014). Summary of the ASK14 ground motion relation for active crustal regions, *Earthq. Spectra,* 30(3): 1025–1055.

This reference is one of five NGA-West2 ground-motion models (GMMs) chosen by the USGS for developing the U.S. National Seismic Hazard Maps in western United States. The PEER-CEA Project used this model along with the other NGA-West2 models (except that by Idriss, due to its restriction on the range of V_{s30} values) to develop to carry out PSHA at ten selected sites in California.

Ancheta T.D., Darragh R.B., Stewart J.P., Seyhan E., Silva W.J., Chiou B.S.-J., Wooddell K.E., Graves R.W., Kottke A.R., Boore D.M., Kishida T., Donahue J.L., (2013). PEER NGA-West 2 database, *PEER Report No. 2013/03*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

This document elaborates on the data and metadata of the NGA-West2 database. The data, attributes, and characteristics of the database have already been

implemented on the PEER online ground-motion site. The PEER–CEA Project used this database to select candidate ground motions to be scaled around the target spectra.

Arias A. (1970). A measure of earthquake intensity, in: *Seismic Design for Nuclear Power Plants*, R. J. Hansen (ed.), Cambridge, Massachusetts, pp. 438–483.

This classic paper defined the so-called Arias Intensity (AI) to be used for various definitions of ground-motion duration. Once the computer models were calibrated against experimental data and runs were carried out for the selected motions, the PEER–CEA Project examined the possible effects of duration on seismic response.

ASCE 7-10 (2010). *Minimum Design Loads for Buildings and Other Structures*, *ASCE/SEI 7-10,* American Society of Civil Engineers, Reston, VA.

This document includes definitions and requirements of design spectra, MCE, MCE_R and ground motions to be used for analysis and design, with the fundamental input data for ground motions obtained from the US National Seismic Hazard Maps. Although the PEER–CEA Project will reference this document, the ground motion hazard and ground motion time series to be used for simulation response of wood-frame structures at the selected sites were computed specifically for this Project.

Baker J.W. (2011). The conditional mean spectrum: a tool for ground motion selection, ASCE, *J. Struct. Eng.,* 137(3): 322–331.

This paper summarizes the concept of the conditional mean spectrum (CMS), developed for the need for a more realistic target spectrum compared to the uniform hazard spectrum (UHS). The PEER–CEA Project began with the UHS at different sites and at different return periods. Since the period of retrofitted cripple-wall structure can be different than that for the existing structure, a single CMS may not work for both existing and retrofitted systems, a review of the CMS and its benefit to the PEER–CEA Project was considered.

Boore D.M., Stewart J.P., Seyhan E., Atkinson G.M. (2014). NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. *Earthq. Spectra,* 30(3): 1057–1085.

This reference is one of five NGA-West2 ground-motion models (GMMs) chosen by the USGS for developing the US National Seismic Hazard Maps in western United States. The PEER-CEA Project used this model along with the other NGA-West2 models (except that by Idriss, due to its restriction on the range of V_{s30} values) to develop to carry out PSHA at ten selected sites in California.

Bozorgnia Y., Campbell K.W. (2004). Engineering characterization of ground motion, in: *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*, Y. Bozorgnia and V.V. Bertero (eds.), CRC Press, Boca Raton, FL.

This reference provides fundamental information on ground-motion issues for engineering applications, including basic information on the ground motion models, various intensity measures, duration of ground motions, etc.

Campbell K.W., Bozorgnia Y. (2014). NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. *Earthq. Spectra,* 30(3):1087–1115.

This reference is one of five NGA-West2 ground-motion models (GMMs) chosen by the USGS for developing the U.S. National Seismic Hazard Maps in western United States. The PEER-CEA Project used this model along with the other NGA-West2 models (except that by Idriss, due to its restriction on the range of V_{s30} values) to develop to carry out PSHA at ten selected sites in California.

Chiou B.S.-J., Youngs R.R. (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, *Earthq. Spectra,* 30(3):1117–1153.

This reference is one of five NGA-West2 ground-motion models (GMMs) chosen by the USGS for developing the U.S. National Seismic Hazard Maps in western United States. The PEER-CEA Project used this model along with the other NGA-West2 models (except that by Idriss, due to its restriction on the range of V_{s30} values) to develop to carry out PSHA at ten selected sites in California.

Field E.H., Biasi G.P., Bird P., Dawson T.E., Felzer K.R., Jackson D.D., Johnson K.M., Jordan T.H., Madden C., Michael A.J., Milner K.R., Page M.T., Parsons T., Powers P.M., Shaw B.E., Thatcher W.R., Weldon R.J. II, Zeng Y. (2013). *Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model*, U.S. Geological Survey, *USGS Open-File Report 2013–1165 CGS Special Report 228*, Reston, VA.

This report provides information on the process and assumptions used in developing UCERF3, the latest seismic-source characterization model used by the USGS to develop the U.S. National Seismic Hazard Maps for the State of California. It also more complicated than its previous version, UCER2, for PSHA applications. The PEER–CEA Project used UCERF3 along with NGA-West2 GMMs to carry out PSHA at several selected sites in California.

Hancock J., Watson-Lamprey J., Abrahamson N., Bommer J., Markatis A., McCoy E., Mendis R. (2006). An improved method of matching response spectra of recorded earthquake ground motion using wavelets, *J. Eartha. Eng.*, 10(Special Issue 1): 67–89.

This paper summarizes an improved method for generating ground motions with response spectra matching a target spectrum. After the initial workshop with ground-motion experts, the PEER–CEA Project decided to scale the selected seed ground motions such that their mean spectrum follows the target spectrum.

Haselton C.B., Baker J.W., Bozorgnia Y., Goulet C.A., Kalkan E, Luco N., Shantz T., Shome N., Stewart J.P., Tothong P., Watson-Lamprey J., Zareian F. (2009). Evaluation of ground motion selection and modification methods: predicting median interstory drift response of buildings, *PEER Report No. 2009/01*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

This report summarizes a variety of methods to scale and modify a set of seed ground motions. It is a useful report as it covers a wide range of methods. After the initial workshop with ground-motion experts, the PEER–CEA Project decided to scale the selected seed ground motions such that their mean spectrum follows the target spectrum.

Idriss I.M. (2014). An NGA-West2 empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes, *Earthq. Spectra*, 30(3): 1155–1177.

This reference is one of the NGA-West2 ground-motion models (GMMs). The model was one of the five GMMs chosen by the USGS for developing the US National Seismic Hazard Maps for the western United States. This model was not used for the PEER–CEA Project because the range of V_{s30} values for the PSHA runs at selected sites were restricted.

Kramer S.L. (1996). *Geotechnical Earthquake Engineering*, Pearson Education, U.K.

This reference provides fundamental information on ground-motion issues for engineering applications, including basic information on the ground-motion models, various intensity measures, duration of ground motions, etc. The ground-motion parts of the book are relatively old; however, the fundamental topics are very well-written and provide very good background.

Krawinkler H., Medina R., Alavi B. (2003). Seismic drift and ductility demands and their dependence on ground motions, Eng. Struct., 25(5): 637–653.

This reference provides fundamental information on effects of near-fault motions, especially pulses, on structural response. For the PEER–CEA project, the effects of long-period directivity pulses will be tested were of special relevance since for the periods of the structures studied are short with respect to pulse periods.

Mahin S.A., Bertero V.V. (1981). An evaluation of inelastic seismic design spectra, ASCE, J. Struct. Div., 107(ST7): 1777–1795.

This classic paper presented information on inelastic spectra and the impacts of near-fault long-period pulses on inelastic response. For the PEER–CEA project, the effects of long-period directivity pulses were of special relevance since for the periods of the structures studied are short with respect to pulse periods.

McGuire R. (2004). *Seismic Hazard and Risk Analysis*, Earthquake Engineering Research Institute, Oakland, CA.

This monograph provides fundamentals of probabilistic seismic hazard analysis (PSHA). It is a useful document to understand the assumptions and formulation of PSHA.

USGS National Seismic Hazard Maps (2014).

This website provides very useful links to various data and reports on the US National Seismic Hazard Maps, including the State of California, *https://earthquake.usgs.gov/hazards/hazmaps/.*

8 Loading Protocols for Testing of Wood-Frame House Components

8.1 ISSUES OR QUESTIONS

1. What are the common loading protocols for wood-frame component testing?
2. What is the sensitivity of wood-frame component behavior to various available loading protocols?
3. What are the major shortcomings of available loading protocols for assessing the behavior of cripple walls?
4. What is the suggested/recommended approach for developing loading protocols tailored for cripple wall testing?

8.2 RELEVANCE OF REFERENCES

Table 8.1 Relevance of references for loading protocols for testing of wood-frame house components.

Citation	Relevant questions			
	8.1	8.2	8.3	8.4
Chai et al. (2002)		✔	✔	
FEMA 461 (2007)	✔			
Gatto and Uang (2002)		✔		
Krawinkler et al. (2001)	✔		✔	
Krawinkler et al. (2000)				✔

8.3 REFERENCES AND ANNOTATIONS

Chai Y.-H., Hutchinson T.C., Vukazich S.M. (2002). Seismic behavior of level and stepped cripple walls, *CUREE Publication No. W-17*, Division of Civil and Environmental Engineering, University of California, Davis, CA.

This document summarizes research that evaluated the capacity of 2-ft- and 4-ft-tall cripple walls under existing and retrofitted designs both in level and stepped configurations. CUREE quasi-static loading histories were utilized. It was found out that strength and deformation capacity of cripple walls were slightly sensitive to the utilized loading protocol. In general, the strength capacity of cripple walls was 10% larger under the near-fault loading protocol; a higher deformation capacity with near-fault loading protocol was observed.

Loading histories used in this study were developed based on SDOF systems that mostly represent shear walls in woodframe buildings. Behavior of cripple walls, however, are different (i.e., they are stiffer with highly pinching behavior and heavy cyclic deterioration) and require re-evaluation of the suggested loading histories.

FEMA (2002). *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components, FEMA-461*, Federal Emergency Management Agency, Washington, D.C.

FEMA-461 presents loading protocols for testing general structural and nonstructural elements in buildings aiming at development of component fragility curves. Among the offered loading protocols, the one with deformation-controlled loading sequence is relevant. This loading protocol was developed based on the response of building structures, whose number of stories varied from 3- to 9-stories tall and experienced ductility demands up to m = 5. The protocol was developed using ordinary ground motions with no near-fault effects. The analysis results are post-processed into representative deformation-controlled loading histories that represent cumulative damage. The suggested loading history starts with a reference deformation that should be safely smaller than the amplitude at which the lowest damage state is first observed (~0.0015 drift ratio).

Gatto K., Uang C.-M. (2002). Cyclic response of woodframe shearwalls: loading protocol and rate of loading effects, *CUREE Publication No. W-13*, Department of Structural Engineering, University of California, San Diego. CA.

The study focusses quantifying the sensitivity of the response of 2.4 m × 2.4 m wood-frame shear walls to various loading protocols. It was shown that the performance of woodframe shear walls is highly dependent on the loading sequence; protocols with large number of equal size cycles were the most demanding. This research shows that shear wall components demonstrate different behavior under near-fault and dynamic loading histories compared to the ordinary loading protocol.

Krawinkler H., Parisi F., Ibarra L., Ayoub A., Medina R. (2001). Development of a testing protocol for wood frame structures. *CUREE Publication No. W-02*, Department of Civil and Environmental Engineering, Stanford University. Stanford, CA

This document summarizes research that developed two quasi-static loading protocols for experimentation on components of woodframe structures, namely, *ordinary* and *near fault*. The suggested loading protocols were based on results of nonlinear response history analyses of representative SDOF systems whose hysteretic behavior mimics woodframe shear wall behavior, subject to two sets of ground motion, each of which represented seismic hazard with 475 and 2475 return periods. The analysis results were post-processed into representative deformation-controlled loading histories that represent cumulative damage in woodframe components in ordinary and pulse-like ground motions.

The suggested loading histories rely on a reference deformation based on previous experience or execution of a monotonic test. The latter method is preferred; however, it necessitates two experiments for a single-component test; i.e., one monotonic test to identify the reference displacement followed by a quasi-static test to assess component behavior.

Krawinkler H., Gupta A., Medina R., Luco N. (2000). Loading histories for seismic performance testing of SMRF components and assemblies, Report No. SAC/BD-00/10, SAC Joint Venture, , Sacramento, CA.

This document shows the procedure used to develop loading histories for connection testing for the Phase II of the SAC Steel Project. Two loading histories are suggested denoted as *basic* and *near fault*. The significance of the suggested histories is that they are not dependent on a reference deformation whose determination require a monotonic test.

9 Communicating Risks and Incentivizing Risk Mitigation

9.1 ISSUES OR QUESTIONS

1. What data are available to quantify the cost of cripple wall and/or sill plate retrofit?
2. What data, methods, and information are available to demonstrate the cost-benefit of cripple wall and/or sill plate retrofit?
3. What concepts, stories (qualitative information), and data are available to quantify the benefits of cripple wall and/or sill plate retrofit?
4. What are effective ways to communicate risks, retrofitting concepts, and opportunities to California homeowners toward encouraging change in behavior?
5. What are some existing products and programs aimed at communicating about earthquake risks and retrofits to homeowners that this project can learn from and potentially reference?

9.2 RELEVANCE OF REFERENCES

Table 9.1 Reference relevance for communicating risks and incentivizing risk mitigation.

Citation	Relevant questions				
	9.1	9.2	9.3	9.4	9.5
Athavale et al. (2011)				✔	
Boase et al. (2017)				✔	
CSSC (1999)					✔
CSSC (2005)					✔
FEMA (2005)	✔	✔			
Greenberg et. al. (2012)				✔	
Humboldt State University (2017)					✔
Johnson et. al. (2016)				✔	
Knoblauch et al. (2017)				✔	
Lindell and Perry (2012)				✔	
Lindell et al. (2000)				✔	
Lindell et al. (2009)				✔	
MacKenzie (2014)				✔	
Nakayachi et. al. (2017)				✔	
Porter (2006)	✔	✔			
Porter et. al. (2004)	✔	✔			
Porter et. al. (2006a)		✔			
Porter et. al. (2006b)		✔			
Rabinovici (2017)			✔		
Rose et al. (2007)	✔				
Smerecnik et. al. (2010)				✔	
Stone et. al. (2017)				✔	
USGS (2005)					✔
Visschers et al. (2009)				✔	
Whitney and Lindell (2004)				✔	
Williams et. al. (2009)		✔			
Wood et. Al/ (2012)				✔	
Yoshikawa and Goda 2014		✔			
Yong et. al. (2017)				✔	

9.3 REFERENCES AND ANNOTATIONS

Athavale M., Avila S.M. (2011). An analysis of the demand for earthquake insurance, *Risk Manage. Insur. Rev.*, 14(2): 233–246, doi: 10.1111/j.1540-6296.2011.01205.x

This article summarizes research issues in the field of earthquake insurance and uses a study of New Madrid Fault Zone homeowners to explore the demand elasticity for such insurance. In this Missouri population, the demand for earthquake insurance was found to be relatively income inelastic and almost perfectly price inelastic. In other words, changes in income and policy prices are not likely to make more homeowners buy insurance.

Low insurance rates have implications for the homeowner and community in terms of the “cost” of not retrofitting. Low demand for catastrophic insurance increases the possibility of a systemic impact in the financial services sector. Stakeholders in this project will want to hear about the best evidence available on the types and magnitudes of these potential effects.

Boase N., White M., Gaze W., Redshaw C. (2017). Evaluating the mental models approach to developing a risk communication: A scoping review of the evidence, *Risk Anal*., 37(11): 2132–2149.

The mental models approach to risk communication (MMARC) was developed during the 1990s as a method for identifying and creating and testing risk communication materials to address gaps in understanding of a risk among experts and laypeople. MMARC differs from traditional risk communication in that both “expert” and “lay” perspectives are studied and involved in the risk communication process and design. Dialogue between these groups helps ensure the communication approach takes into account the audience’s knowledge and concerns, in theory more effectively communicating appropriate information. This scoping review identified twelve scientific evaluations of MMARC-based communications that support its claims of effectiveness. This study has implications for potential design of the stakeholder engagement processes used in the final stages of this project, which could include some mental model exercises.

CSSC (1999). Earthquake mitigation success stories. Can buildings be made earthquake-safe? *Report 99-05*, California Seismic Safety Commission, Sacramento, CA.

This case study-based report addresses the question of the capacity of retrofits to reduce earthquake risk and improve outcomes in a format accessible to the sophisticated public and local officials.

CSSC (2005). *Homeowner’s Guide to Earthquake Safety*, California Seismic Safety Commission Sacramento, CA.

This publicly available 50-page brochure is a collection of information for California homeowners about what earthquake risks they may face and what they can do about them. Diagrams, photos, lists, and example forms are included. State law requires real estate agents to provide a buyer with a copy of this document during a home purchase transaction.

FEMA (2005). *Earthquake Safety Guide for Homeowners FEMA 530,* Federal Emergency Management Agency, Washington, D.C.

This document is another potential model and resource for the project for how to describe earthquake risks homeowners may face and what they can do about them.

Greenberg M., Haas C., Cox Jr. A., Lowrie K., McComas K., North W. (2012). Ten most important accomplishments in risk analysis, 1980–2010. *Risk Anal.,* 32(5): 771–781.

While the field has advanced significantly since the 1980s and 1990s, there unfortunately can be no generic "how to" advice as to how to best communicate risks. This review highlights many of the complicating, contextual factors with which this project must contend, including: that there are always multiple audiences involved, each requiring somewhat unique communication efforts; that the effectiveness of communications is strongly influenced by affect and trust; and that the media and other social processes sometimes amplify risk perceptions (especially when locked into feedback loops with concerned citizens and activists) and other times attenuate attention and concern.

Grossi P. (1999). Assessing the benefits and costs of earthquake mitigation, *Report 99-24*, Wharton Financial Institutions Center, University of Pennsylvania, Philadelphia PA, 12 pgs.

This white paper demonstrates a theory for modeling the cost-benefit of earthquake mitigation. Its uniquely economic-focused approach could provide a good comparison for possible improvements to other models.

Johnson V.A., Ronan K.R., Johnston D.M., Peace R. (2016). Improving the impact and implementation of disaster education: programs for children through theory-based evaluation, *Risk Anal.,* 36(11): 2120–2135.

Although this article addresses development and evaluation of children educational programs specifically, it offers both rationale and recommendations for how to construct theory-driven preparedness programs and evaluate their effectiveness. When programs are developed with a clear theory about how the program will achieve its objectives, critical (and potentially faulty) assumptions can be detected and addressed. One example analyzed was a New Zealand family emergency plan curriculum, where creation of an explicit program theory showed that increased advertising to produce greater awareness of a curriculum or resource (even if very effective at that goal) may not lead to greater use of the resource if deterrent factors exist that would likely remain unaffected by an increase in advertising, such as discomfort with the subject matter. Identification and targeting of facilitating factors that could ease teachers' use of the resource, such as funding or supportive engagement from local civil defense staff, may be more effective but could require different resources than advertising.

Humboldt State University (2017). *Living on Shaky Ground: How to Survive Earthquakes and Tsunamis in Northern California*, Geology Dept., *http://www2.humboldt.edu/shakyground/.*

This website models online messaging and visual communication formats for residential preparedness and mitigation.

Knoblauch T.A.K., Stauffacher M., Trutnevyte E. (2017). Communicating low-probability high-consequence risk, uncertainty and expert confidence: Induced seismicity of deep geothermal energy and shale gas, *Risk Anal*., 38(4) 694–709.

> This article addressed the seeming trade-off between aiming for transparency by disclosing uncertainty and limited expert confidence, thereby decreasing clarity and increasing concern in the view of the public. These findings reinforce the need to clarify audience intentions in the final general audience report.

Lindell M.K., Arlikatti S., Prater C.S. (2009). Why people do what they do to protect against earthquake risk? Perceptions of hazard adjustment attributes. *Risk Anal.*, 29(8): 1072–1088.

> This research found that residents in hazardous areas differentiated among 16 potential hazard adjustment actions with respect to three noneconomic attributes (knowledge and skill, time and effort, and social cooperation). In other words, education programs designed to increase households' knowledge and skill about how to undertake specific mitigation actions could increase the probability of households actually undertaking these actions. However, cost was also an important differentiating attribute.

Lindell M.K., Perry R.W. (2000). Household adjustment to earthquake hazard: A review of research, *Enviro. Behav.*, 32: 590–630.

> The authors propose and test whether adjustments to earthquake hazards can be categorized into hazard-related and resource-related attributes, both of which differentiate among which hazard adjustments people do. Hazard-related attributes, such as efficacy in protecting people and property and usefulness for other purposes, have been found to be significantly correlated with adoption intention and actual adjustment. Resource-related attributes (cost, knowledge and skill requirements, time requirements, effort requirements, and required cooperation with others) generally have the predicted negative correlations with both adoption intention and actual adjustment, but these have been small and nonsignificant in studies conducted to date.

Lindell M.K., Perry R.W (2012). The Protective Action Decision Model: Theoretical modifications and additional evidence, *Risk Anal.,* 32(4): 616–632.

> This article summarizes the development and current state of the Protective Action Decision Model, to date the best developed and tested approach for understanding why people do what they do to protect themselves (or not) from personal risks. The PADM postulates a transition of a person from (1) threat awareness/perception (triggered by social, observed or experiential cues), to (2) conducting a low-cost search for appropriate solutions (that will not unnecessarily disrupt usual routines), to (3) a decision to act or not based on their assessment.
>
> The model posits nine factors that might explain mitigation incentive adoption expectations: four psychological (risk perception, perceived hazard knowledge, worry, and hazard intrusiveness—the frequency with which the hazard comes up), an experiential factor (hazard experience), two exposure factors (hazard proximity

and past tenure), and five demographic factors (gender, ethnicity, age, education, and income). Research to date shows household action-taking and expectations of participation in hazard mitigation incentive programs to be positively correlated with the psychological factors, hazard experience, female, Caucasian, age, educational attainment, and household income.

Another valuable contribution of this article was to articulate and characterize different stakeholders as authorities (federal, state, and local government), evaluators (scientists, medical professionals, universities), watchdogs (news media, citizens', and environmental groups), industry/employers, and households. The interrelationships among stakeholders can be defined by their power over influencing the risk system.

MacKenzie C.A. (2014). Summarizing risk using risk measures and risk indices, *Risk Anal.,* 34(12): 2143–2162**.**

This article addresses appropriate steps and concerns in the creation of information scales to summarize risks such as indices, colors, or categories. The most important goals for a communication situation should determine the type and structure of how the risk information is portrayed. A numerical measure is most appropriate when the goal is to assess how a mitigating action impacts the risk. In this case, the risk is first measured under the assumption of no mitigation strategy and then assessed assuming the mitigation strategy was enacted. The difference between the two measures describes the benefit of the mitigation strategy.

A numerical risk index can best achieve the objectives of comparing between different risks, determining the most serious risk, and understanding how a risk changes over time. In order to emphasize low-probability events without ignoring more likely scenarios, a multiple number measure can be used, such as presenting different quantiles, to give a fairly accurate picture of the probability distribution. A categorical scale can be most useful when the primary goal is to communicate risk to a large group of people and recommend actions if the risk falls into a certain category. Simple and clear messages can be most effective, especially in moments of crises, and a categorical scale that uses colors or words may be the clearest communication tool. These principles, in conjunction with clarity as to the goals of the final reports, can help guide choice of appropriate graphical techniques.

Nakayachi K., Johnson B.B., Koketsu K. (2017). Effects of acknowledging uncertainty about earthquake risk estimates on San Francisco Bay Area residents' beliefs, attitudes, and intentions, *Risk Anal.,* 38(4): 666–679.

This study used a condition-manipulation experiment in a survey of 750 Bay Area residents to test whether explicit expert acknowledgment of uncertainty in earthquake risk estimates enhanced trust or caused other reactions. The uncertainty acknowledgment increased belief that these specific experts were more honest and open, but did not change judged risk, preparedness intentions, or mitigation policy support. Overall, both qualitative expressions of uncertainty and quantitative probabilities had limited effects on public reaction. These results imply that both theoretical arguments for positive effects, and practitioners' potential concerns for negative effects of uncertainty expression may be less important in practicality than theorized.

Rose A, Porter K., Dash N., Bouabid J., Huyck C., Whitehead J.C., Shaw W.D., Eguchi R.T., Taylor, C., McLane T.R., Tobin, L.T., Ganderton P.T., Godschalk D., Kiremidjian A.S., Tierney K., Taylor-West C. (2007). Benefit-cost analysis of FEMA hazard mitigation grants, *Nat. Haz. Rev.*, 8(4): 97–111.

The authors analyze the costs and benefits of mitigation for flood, earthquake, and wind hazards in a statistical sample of FEMA-funded projects. A benefit-cost methodology is introduced that involves HAZUS MH. This is one of the most-cited studies in the field because it demonstrated that the value of investing in mitigation far exceeded the cost in most cases and on average by a ratio of 4:1. The average earthquake mitigation benefit-cost ratio was 1.5:1.

Smerecnik C.M.R., Mesters I., Kessels L.T.E., Ruiter R.A.C., De Vries N.K., De Vries H. (2010). Understanding the positive effects of graphical risk information on comprehension: measuring attention directed to written, tabular, and graphical risk information, *Risk Anal.*, 30(9): 1387–1398.

Textual risk information (written description) is relatively difficult to understand for the average recipient. Findings from this study of *cognitive workload* (how much energy is being devoted to comprehension, as measured by mean pupil size and peak pupil dilation) and *attention* directed to the risk information (as measured by viewing time, number of eye fixations, and eye fixation durations) suggest that graphical risk information improves comprehension of risk information because it attracts and holds attention for a longer period of time than textual risk information. Graphs do this in two ways: first, they tend to attract and hold attention, and second, they help recipients extract information with relatively less cognitive effort, and finally result in better comprehension. These findings speak to the importance of incorporating a variety of non-verbal communication techniques in the design of the lay audience final report.

Stone E.R.., Bruine de Bruin W., Wilkins A.M., Boker E.M., MacDonald-Gibson J. (2017). Designing graphs to communicate risks: understanding how the choice of graphical format influences decision making, *Risk Anal.,* 37(4): 612–628.

Results of this experimental study that compared two different formats for graphical risk information showed that approaches to accomplish one risk communication goal (for example promoting mitigation action-taking) may do so at the expense of another goal (increasing understanding). The experiment tested the same risk information (likelihoods of injury under different scenarios) conveyed in one of two different graphical displays: one as raw probability numbers in a bar graph (foreground only information) and one in the form of a stacked bar graph representing the number harmed relative to the total number at risk (both foreground and background information). The foreground-only graphical display invoked higher perceived likelihood and experienced fear, which produced greater worry, which in turn increased risk aversion. Thus, foreground-only graphical displays may be a better choice for improving public safety. However, the foreground-only graphical display also decreased accurate understanding of the risk magnitude. This suggests that interventions designed to increase risk aversion and persuade people to act may come at the cost of disempowering them from making well-informed decisions for themselves.

This study has implications for design of the graphics in the lay audience final report. Furthermore, it emphasizes how important it is to clarify the intent of that report—is it primarily to enhance understanding or to persuade? The answer will guide choice of appropriate graphical techniques.

USGS (2005). *Putting Down Roots in Earthquake Country: Your Handbook for the San Francisco Bay Region*. Reston, VA, US Geological Survey, with major funding from the California Earthquake Authority, https://pubs.usgs.gov/gip/2005/15/.

Developed and regularly revised by a large consortium of organizations, this guide gives extensive advice to homeowners on how to understand and reduce their earthquake risk. The primary recommendations, or 7-Steps, focus on personal preparedness, rather than home mitigation, but the messaging and delivery mode can serve as a baseline for development of communications materials for this project.

Visschers V.H.M., Meertens R.M., Passchier W.W.F., De Vries N.N.K. (2009). Probability information in risk communication: A review of the research literature, *Risk Anal.*; 29: 267–287.

The commonality of low *numeracy*, or comprehension of number and math concepts, in the American populace is well established. The authors of this review find that risk information presented in graphs promotes more accurate understanding than numerical information alone. The best type of graph depends on the context and communicator’s primary goals. For instance, bar graphs are particularly suitable for conveying trends over time and in comparing various risks. This study has implications for the design of the lay audience final report.

Whitney D.J., Lindell M.K., Nguyen H-H. (2004). "Earthquake beliefs and adoption of seismic hazard adjustments, *Risk Anal.*, 24(1): 81–102.

This study investigated the prevalence of both accurate and erroneous earthquake-related beliefs among a sample of Southern Californians and how inaccurate beliefs were best dispelled. The data revealed a significant degree of agreement with earthquake myths, a generally low level of correlation between earthquake beliefs and the level of hazard adjustments, and a significant effect of hazard information on the endorsement of accurate earthquake beliefs and increases in hazard adjustment. Compared with the “Earthquake Facts (Only)” format, an “Earthquake Myths versus Facts” format was slightly more useful for dispelling erroneous beliefs. This suggests that “myth-busting” could be a useful tactic in communicating some of the results of this study.

Williams R.J., Gardoni P., Bracci J.M. (2009). Decision analysis for seismic retrofit of structures. *Struct. Safety*, 31: 188–196.

This paper presents a methodology to assess the economic benefits and potential worth in the form of expected benefits of retrofitting using a comparative case study of two identical hypothetical reinforced concrete buildings, one located in Memphis, Tennessee, and one in San Francisco, California.

Wood M.M., Mileti D.S., Keno M., Kelley M.M., Rotrease R., Bourque, L.B. (2012). Communicating actionable risk for terrorism and other hazards, *Risk Anal.*, 32(4), doi: 10.1111/j.1539-6924.2011.01645.x

Using a national probability sample of 3300 households, researchers at the UCLA School of Public Health collected data about the experience of Americans regarding preparedness, mitigation, and perceptions related to terrorism-based natural disasters. This particular article draws on the results of the overall study to support a revised approach to risk communication that they term “communicating actionable risk.” New preparedness behaviors, they argue, arise from both information observed (watching what others are doing) and information received (recommendations regarding what to do). Individuals then initiate search and milling behavior in their social environment, whereby the appropriateness of taking the precautionary behavior is then either supported (confirmed) or not. Failure to find support for the behavior recommendation during the social milling process can lead new information to be ignored or discounted, implying that the social environment is pivotal to either enhancing or counteracting the effects of the information originally communicated.

This line of research holds many direct implications for how best to communicate the results of this study to general audiences when working to motivate preparedness action-taking. First, it would be wise to emphasize the practical aspects of hazard detection and investing in cripple wall and sill anchorages as well as the specific benefits. Second, the overall strategy for design and dissemination of final report should involve people who have already retrofitted their structures, and who are uniquely positioned to be effective communicators of the benefits of retrofitting. Finally, communication efforts should be undertaken in the context of conducting an overall campaign or strategy to increase the density of information and cues to which the target audiences are exposed.

Yong A.G., Lemyre L., Pinsent C., Krewski D. (2017). Risk perception and disaster preparedness in immigrants and Canadian-born adults: analysis of a national survey on similarities and differences, *Risk Anal.*, 37(12): 2321–2333, doi: 10.1111/risa.12797.

This study explored important questions about natural hazard risk perceptions and preparedness behaviors among immigrants compared to the Canadian-born general population. Previous research had found indications that immigrants may have distinct risk perceptions about natural hazards that might warrant different messaging approaches. The results indicate more similarities than differences and

suggest that natural disaster risk communications do not need to be radically altered for immigrant groups as a whole, other than by culturally competent translation.

Yoshikawa H., Goda K. (2014). Financial seismic risk analysis of building portfolios, *Nat. Hazards Rev*., 15(2): 112–120, doi: 10.1061/(ASCE)NH.1527-6996.0000129.

A case study for a group of wood-frame houses in Canada is presented to illuminate methods and issues in current risk-quantification approaches. Potential pitfalls in using simple risk metrics for decision analysis on seismic risk-transfer and risk-mitigation strategies are discussed. The results indicate that the use of tail value at risk may be appropriate as it provides more consistent risk-comparison results by reflecting the expected risk of rare events.

9.4 ADDITIONAL REFERENCES MENTIONED

USGS list of additional “Readiness” Guides for individuals:

https://earthquake.usgs.gov/learn/topics/topics.php?topicID=25.