DEVELOPMENT AND APPLICATION OF

AN EMPIRICAL LOSS ANALYSIS FOR WOODFRAME

BUILDINGS SUBJECT TO SEISMIC EVENTS

by

Gregory O. Black

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Approved: ____
Rachel A. Davidson, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
Harry W. Shenton, Ph.D.
Chair of the Department of Civil and Environmental Engineering

Approved: ____
Michael J. Chajes, Ph.D.
Dean of the College of Engineering

Approved: ____
Debra Hess Norris, M.S.
Vice Provost for Graduate and Professional Education

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This thesis introduces a new seismic loss model for woodframe buildings and examines how it can be used to provide input for the development of seismic performance objectives for woodframe buildings in terms of economic loss, a measure that is more directly useful to building owners than qualitative performance levels such as “Life Safety.” The model employs a non-linear dynamic structural analysis program in order to determine the structural response of the woodframe buildings it analyzes. Next, it uses experimental and analytical fragility and repair cost data in order to translate the structural response into damage and damage into economic loss. The thesis demonstrates the use of the model using two-story, single-family homes as an example building category, although the model can actually be applied to any category of woodframe building. In this case, the model is applied to estimate losses as a function of ground motion intensity and building design. By incorporating actual ground motion recurrence data, the analysis is used to assess the interaction between hazard and loss for an example location. The results are discussed to illustrate how such an analysis can be used to help characterize estimated losses, define performance objectives, and guide design to meet those performance objectives. The results for the example case presented in this thesis reaffirm the importance of explicitly recognizing the large variability in losses and the contribution of non-structural and contents loss in performance-based design.

Chapter 1

INTRODUCTION

1.1 Motivation

Performance-based seismic design (PBSD) requires defining performance objectives for the design of a building. In the past, performance objectives have typically been defined in terms of a combination of performance expectations that should be met at a specified hazard level, sometimes with the probability it is satisfied. The development of these performance objectives usually depends on consideration for stakeholder values and what is reasonably achievable. They should reflect the dimensions and levels of performance that building owners and users deem important. At the same time, they should reflect levels of performance that can reasonably be met through engineering design within a reasonable cost range.

In this thesis, a new seismic loss model for woodframe buildings is developed and applied to an example building category to demonstrate how it can be used to inform the development of seismic performance objectives for woodframe buildings. The model follows the PEER approach to loss estimation with assembly-based vulnerability [1-3], comprehensively implementing it for woodframe buildings in particular. It employs the most up-to-date available seismic analysis procedures, and experimental and analytical fragility data for woodframe buildings, and may be used for any category of woodframe building. Following some background on the history of performance-based seismic design in general, and related to woodframe buildings specifically in Section 1.2, the loss model is described in Chapter 2. In Chapter 3, we apply the model to an example building category—two-story, single-family woodframe homes—and examine the results to illustrate how such an analysis can be used to help: (1) characterize the magnitude, causes, and variability of direct economic loss as a function of ground shaking intensity and building design; (2) define performance objectives in terms of economic loss, recognizing the inherent variability; and (3) guide building design using objectives specified in that way.

1.2 Background

Although performance objectives had been stated in various forms for many years, performance-based seismic design as a formal process was introduced in the 1990s with ATC 40 [4], SEAOC's Vision 2000 [5] and FEMA 283/284 [6-7] (which was later superseded by FEMA 356/357 [8-9] which eventually became ASCE Standard 41 [10], the first PBSD standard in the U.S.). This first generation of PBSD methods introduced some key concepts. It defined building performance in terms of a few discrete, qualitative levels, such as "Immediate Occupancy," "Life Safety," and "Collapse Prevention," that related to both structural and nonstructural component damage. Performance objectives were specified in terms of a performance level achieved at a particular earthquake hazard level (e.g., ground shaking with a 50% chance of exceedence in 50 years) [11]. They also provided approximate relationships between engineering demand parameters (EDPs, such as, inter-story drifts and member forces) and performance-oriented descriptions (e.g., life safety). The impetus and focus for these initial efforts was evaluation and upgrade of existing buildings. Holmes et al. [12] provides a detailed history of PBSD.

While these efforts served an important need, limitations were recognized. In particular, there were questions regarding the accuracy of the analytical procedures in predicting actual building response and the level of conservatism in acceptance criteria; and a need for methods that are more easily applied to the design of new buildings and that communicate performance to stakeholders in a more meaningful and effective way [11]. As a result, FEMA 283 [13], FEMA 349 [14], and most recently FEMA 445 [11], were created to initiate the development of a second generation of PBSD. The ATC 58 project was a follow on effort of those projects. One key change in ATC 58 is that the next generation PBSD uses new performance measures—direct economic loss, casualties, and downtime—that are more directly useful to building owners and users in making decisions [1]. Another important change is an explicit representation of uncertainty in the performance objectives and methods. Performance is described in terms of a cumulative distribution function of loss rather than a point estimate [1]. A third modification is assessment of performance based more on global response parameters, so that the response of individual components does not unnecessarily control the prediction of overall structural performance [11].

There has been relatively little research related to the performance of light-frame residential wood buildings subject to earthquake ground motions compared to steel or reinforced concrete buildings. Recognizing that they comprise 90% of all residential buildings in the U.S. [15], however, woodframe construction has begun to receive more attention recently. The CUREE-Caltech Woodframe project (http://www.curee.org/projects/woodframe) was a $6.9 million, Federal Emergency Management Agency (FEMA)-funded project aimed at improving building codes and standards so as to reduce earthquake risk associated with woodframe construction (with part of the study focused on financial loss estimation [3]). NEESWood, funded through the National Science Foundation Network for Earthquake Engineering Simulation (NEES), built on that effort with a focus on developing a PBSD framework for woodframe buildings. These and related efforts have led to many recent advances in the development of the concepts and tools needed to apply PBSD to woodframe buildings (e.g.,[15-22]). This study, part of the NEESWood project, makes use of those new tools and findings, and recasts performance objectives in terms of economic loss.

Chapter 2

SEISMIC LOSS MODEL FOR WOODFRAME BUILDINGS

This chapter of the thesis explains the loss model itself. It describes the various inputs that the model uses, explains the process by which it functions and details the final output.

2.1 Definitions

A *building category*, *B*, is defined to be a general class of woodframe buildings that are assumed to perform similarly. The focus of the example application in this thesis is average (less than 2500 ft^2), two-story, single-family woodframe homes. A single specified floor plan is used to represent all buildings in that category, but there are many variations in the structural design associated with that floor plan. Each *building variant*, B_v, has different structural details (e.g., nail schedules, wall sheathing thickness), but the same floor plan. (To capture the variability within a building category more completely, one could consider multiple floor plans as well.) Each building is considered to be a collection of different types of *assemblies* (e.g., partition walls, shear walls), which are grouped into performance groups, where a *performance group* is a collection of assemblies for which loss can be estimated together (i.e., they will experience the same structural response and have the same fragility curves and repair cost functions). For example, all gypsum wallboard interior partition walls along the same wall line on the first floor could be treated as a single performance group.

Each assembly is categorized as structural, nonstructural drift-sensitive (NSDS), or nonstructural acceleration-sensitive (NSAS). In this analysis, only those structural and NSDS assemblies considered most important for determining structural performance were modeled explicitly—shear walls, sill plates, partition walls, doors, and windows. Potential damage and loss associated with the remaining (not modeled) structural and NSDS assemblies were estimated based on those that were modeled; and the damage and loss associated with NSAS assemblies and contents were modeled in aggregate, considering all NSAS (and contents) assemblies on one floor as a performance group (see Section 2.2.2).

2.2 Model Overview

The goal of the loss model is to simulate a probability distribution of direct economic loss (not including loss associated with downtime or casualties) for a specified building variant B_v and ground motion intensity (or set of intensities). Ground motion intensity is defined in terms of spectral acceleration at the building's first period $S_{a(T1)}$ (although if desired, peak ground acceleration (*PGA*) or another parameter could be used instead). Figure 1 summarizes how the model works for a specified building variant B_v and $S_{a(T1)}$ value. There are two main modules—the structural analysis conducted with the Seismic Analysis Package for Woodframe structures (SAPWood) program [23], and the loss module programmed in Matlab [24]. Each module includes two databases (shown with the dotted outline in Figure 1) that can be used for any building category analyzed, and that are easily modified to incorporate new advances.

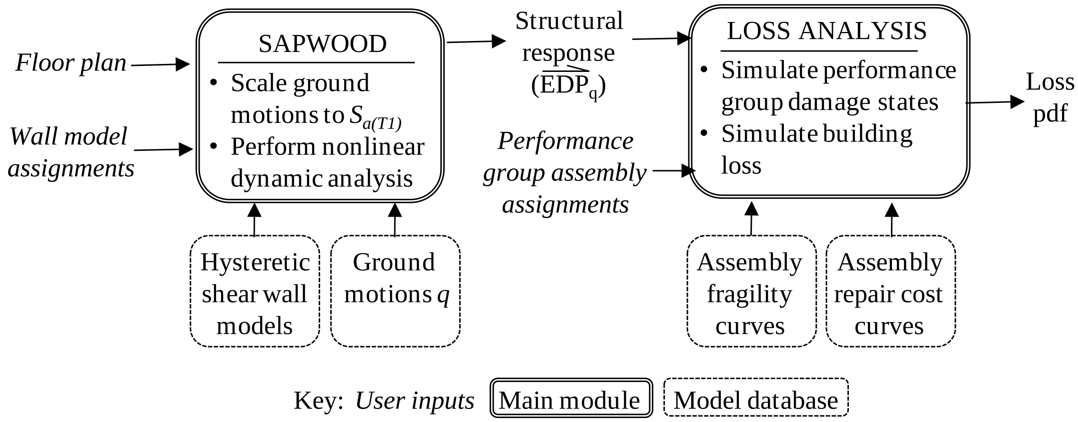

Figure 1. Schematic of new seismic loss simulation model for woodframe buildings, as applied for a specified building variant B_v and ground motion intensity $S_{a(T1)}$

For each wall in the building floor plan, the user assigns one of six configurations, and the associated assemblies are then included in the model at the wall location. The six wall configurations are: interior partition walls with gypsum wallboard (GWB) on both sides, shear walls with GWB on both sides, and exterior shear walls with or without GWB on the interior and with or without stucco on the exterior. (The damage and repair costs for each assembly at a particular wall location are modeled separately.) For each wall in the building, the user assigns a hysteretic shear wall model that represents its structural details (e.g., nail type and schedule).

Every earthquake ground motion *q* in the database is scaled to $S_{a(T1)}$, and for each scaled ground motion, SAPWood conducts a nonlinear dynamic analysis to estimate a vector of engineering demand parameters (EDPs). The vector of EDPs describes the structural response in terms of inter-story drifts, floor accelerations, and base shears. Keeping the EDPs together as a vector ensures the correlation among the responses of different performance groups is retained. The user must then define performance groups and assign a particular assembly type to each (see Table 1), which determines which fragility and repair cost curves apply to it. For each performance group, the loss model uses fragility curves to simulate the damage state from the EDP that represents its response. Based on performance group damage states and repair cost functions for each assembly, total direct economic loss for the building category is simulated. The modules in the analysis are described in more detail in Sections 2.2.1 and 2.2.2. Uncertainty is represented in the earthquake ground motions q, the estimation of performance group damage states from EDPs, and the estimation of loss from damage states. The model can be run for many different building variants and $S_{a(T1)}$ values to examine the relationships between loss, ground shaking intensity, and building design.

2.2.1 SAPWood Structural Analysis Module

The SAPWood structural analysis module relies on two databases: (1) a suite of possible ground motions, and (2) a collection of hysteretic models of shear walls. The analysis uses the 22 horizontal earthquake ground motion pairs used in ATC 63 [25] for the ground motion database. Each pair is applied both with the first record parallel to the *x*-axis of the building floor plan, and rotated 90° so the second record is parallel to the *x*-axis. In effect, therefore, there are 44 pairs of input ground motion for the analysis. The record set includes motions from sites at least 10 km from fault rupture. In each run, each ground motion pair is scaled so that the $S_{a(T1)}$ with 5% assumed damping becomes the desired $S_{a(T1)}$ value for that run.

Table 1. Assembly types, with fragility and repair cost data

		Fragility curve information				Repair cost information ($/unit)			
	Assembly Type	Damage State	Response Parameter[a]	x_m	β	Repair	Unit	x_m	β
Walls									
1	Partition walls with gypsum wallboard[b]	1: Cracking of paint over fasteners or joints	δ (%)	0.33	0.55	Cosmetic repair	64 ft^2	88	0.3
		2: Local and global buckling out of plane and crushing of gypsum wallboard	δ (%)	0.56	0.56	Replace gypsum wallboard	64 ft^2	184	0.3
2	Shear walls with seismic design and no exterior stucco[b]	1: Slight separation of sheathing or nails come loose	δ (%)	1.50	0.40	Renail wood sheathing	64 ft^2	132	0.3
		2: Permanent rotation of sheathing, tear out of nails or sheathing tear out	δ (%)	2.62	0.16	Replace wood sheathing	64 ft^2	264	0.3
		3: Fracture of studs, major sill plate cracking	δ (%)	3.69	0.17	Replace entire wall	64 ft^2	398	0.3
3	Shear walls with basic strength design and no exterior stucco[b]	1: Slight separation of sheathing or nails which come loose	δ (%)	1.00	0.40	Renail wood sheathing	64 ft^2	131	0.3
		2: Permanent rotation of sheathing, tear out of nails or sheathing	δ (%)	1.75	0.40	Replace wood sheathing	64 ft^2	254	0.3
		3: Fracture of studs, major sill plate cracking	δ (%)	2.50	0.40	Replace entire wall	64 ft^2	377	0.3
4	Shear walls with seismic design and exterior stucco[b]	1: Cracking of stucco	δ (%)	0.25	0.43	Repair stucco	64 ft^2	121	0.3
		2: Spalling of stucco, separation of stucco and sheathing from studs	δ (%)	0.52	0.28	Replace stucco & wall sheathing separated from wood studs	64 ft^2	385	0.3
		3: Fracture of studs, major sill plate cracking	δ (%)	2.52	0.12	Replace entire wall, incl. studs, top plate, & sill	64 ft^2	519	0.3
5	Shear walls with basic strength design and exterior stucco[b]	1: Cracking of stucco	δ (%)	0.17	0.50	Repair stucco	64 ft^{22}	121	0.3
		2: Spalling of stucco, separation of stucco and sheathing from studs	δ (%)	0.35	0.40	Replace stucco & wall sheathing separated from wood studs	64 ft^2	375	0.3
		3: Fracture of studs, major sill plate cracking	δ (%)	1.70	0.40	Replace entire wall, incl. studs, top plate, & sill	64 ft^2	498	0.3

Table 1 (cont'd). Assembly types, with fragility and repair cost data

		Fragility curve information				Repair cost information ($/unit)			
	Assembly Type	**Damage State**	**Response Parameter**[a]	x_m	β	**Repair**	**Unit**	x_m	β
Sill plates									
6	2x, no hold downs, 2.5"x2.5"x0.25" washers	1: Sill plate failure	V (kN)	3.81	0.12	Replace entire wall	64 ft^2	Varies	0.3
7	2x, no hold downs, standard round 1.5" dia. washers	1: Sill plate failure	V (kN)	3.13	0.40	Replace entire wall	64 ft^2	Varies	0.3
8	2x, no hold downs, 3"x3"x0.5" washers	1: Sill plate failure	V (kN)	3.58	0.40	Replace entire wall	64 ft^2	Varies	0.3
9	3x, no hold downs	1: Sill plate failure	V (kN)	5.22	0.40	Replace entire wall	64 ft^2	Varies	0.3
10	2x, with hold downs[c], std. round 1.5" dia. washers	1: Sill plate &/or hold down failure	V (kN)	12.41	0.40	Replace entire wall	64 ft^2	Varies	0.3
11	2x, with hold downs[c], 3"x3"x0.5" washers	1: Sill plate &/or hold down failure	V (kN)	11.65	0.26	Replace entire wall	64 ft^2	Varies	0.3
12	3x, with hold downs[c]	1: Sill plate &/or hold down failure	V (kN)	10.34	0.40	Replace entire wall	64 ft^2	Varies	0.3
Doors and windows									
13	Doors, sliding, patio, aluminum, standard, 6'0''x6'8'', with wood frame, insulated glass	1: Cracked	δ (%)	2.8	0.44	Replace	Each	190	0.2
14	Window, Al frame, sliding, standard glass, <25 ft^2	1: Cracked	δ (%)	3.0	0.4	Replace	Pane	120	0.3
15	Window, Al frame, fixed, standard glass, 80" x 80" pane	1: Cracked	δ (%)	3.0	0.3	Replace	Pane	120	0.3
16	Window, wood, double hung, standard glass, 3'x 4'	1: Cracked	δ (%)	3.0	0.29	Replace	Pane	178	0.2

Table 1 (cont'd). Assembly types, with fragility and repair cost data

		Fragility curve information				Repair cost information ($/unit)			
	Assembly Type	**Damage State**	**Response Parameter**[a]	x_m	β	**Repair**	**Unit**	x_m	β
Miscellaneous									
17	Paint on exterior stucco or concrete	1: Light cracking of stucco, light damage to GWB	N.A.	N.A.	N.A.	Paint	1 ft^2	0.81	0.2
18	Paint on interior concrete, drywall, or plaster	1: Light cracking of stucco, light damage to GWB	N.A.	N.A.	N.A.	Paint	1 ft^2	0.81	0.2
19	**Non-Structural Acceleration Sensitive** (For high code W1 (SFD <464 m^2), from HAZUS-MH Tables 5.13, 15.3, 15.5)	1: Slight	PDA (g)	0.3	0.73	N.A.	%R[d]	0.5	0
		2: Moderate	PDA (g)	0.6	0.68	N.A.	%R[d]	2.7	0
		3: Extensive	PDA (g)	1.2	0.68	N.A.	%R[d]	8.0	0
		4: Complete	PDA (g)	2.4	0.68	N.A.	%R[d]	26.6	0
20	**Contents** (For high code W1 (SFD <464 m^2), from HAZUS-MH Tables 5.13, 15.3, 15.5)	1: Slight	PDA (g)	0.3	0.73	N.A.	%R[d]	1	0
		2: Moderate	PDA (g)	0.6	0.68	N.A.	%R[d]	5	0
		3: Extensive	PDA (g)	1.2	0.68	N.A.	%R[d]	25	0
		4: Complete	PDA (g)	2.4	0.68	N.A.	%R[d]	50	0

[a] δ=inter-story drift; V= shear force per anchor bolt; PDA= peak diaphragm acceleration

[b] For wall piers with aspect ratios between 2:1 and 3.5:1, fragility x_m should be multiplied by $2b_s/h$

[c] For hold downs other than HTT22 Simpson Strong Tie, the fragility x_m should be multiplied by T/5260, where T is the allowable uplift load of the hold down considered. The fragility dispersion (β) should also be increased to 0.40.

[d] % replacement cost

The shear wall models were developed by first fitting a 10-parameter hysteretic model [26] for each of 9 connection types, as defined by nail type-sheathing thickness combinations (e.g., 8d common nails in 7/16 in. thick sheathing). Cyclic nail test data [27] was used to calibrate the hysteretic model parameters for five of the connection types; the model parameters for the remaining 4 combinations without nail test data were obtained by scaling the calibrated models based on the relative design values designated in the National Design Specification (NDS) code [28] for these connections. These hysteretic models of connections were then used in SAPWood's Nail Pattern analysis to develop similar 10-parameter hysteretic models for each of 108 shear walls, each representing a different combination of nail type (6d, 8d, or 10d, all common), sheathing thickness (7/16 in., 5/8 in., or 3/4 in.), nail spacing (2/12 in., 3/12 in., 4/12 in., or 6/12 in.), and shear wall length (2 ft., 4 ft., or 8 ft.). Note: x/y nail spacing refers to nails at x inches on center on the edges and y inches on center in the field. These hysteretic shear wall models are stored in the SAPWood shear wall parameter database to be used to represent individual shear walls in building models. For a description of the hysteretic model and the parameters that were used in this analysis, see Appendix A.

SAPWood V1.0 is used to analyze a building variant for each of the 44 ground motions q scaled to the specified $S_{a(T1)}$ value. The buildings are modeled as bi-axial structures, assuming 3 degrees of freedom at each story and rigid diaphragms. The output provided, for each B_v, earthquake ground motion q, and $S_{a(T1)}$ is a vector of EDPs that includes the following components: inter-story drift and base shear for each wall line w on each floor i (δ_{wi} and V_{wi}, respectively), and maximum inter-story drift and floor acceleration in the X and Y directions at each floor i (δ_{Xi}, δ_{Yi}, a_{Xi}, and a_{Yi}, respectively).

2.2.2 Loss Analysis Module

The loss analysis module uses two main inputs: the EDP vector from nonlinear time history analyses and the assembly type (Table 1) of each modeled performance group. Appendix B describes the configuration of the various input files used in the analysis. The loss module first simulates damage states from EDP values for each performance group, and then estimates economic loss from performance group damage states. The first step relies on a database of fragility curves (Table 1). For each performance group, they relate the appropriate EDP to the probability each damage state occurs. The fragility curves in this study are lognormal cumulative distribution functions: $F(x) = \Phi\left(\ln(x/x_m)/\beta\right)$, where $\Phi(s)$ represents the cumulative standard normal distribution evaluated at s, and x_m and β are the median and dispersion. The fragility curves for wall and sill plate assemblies were taken from ATC 58 [1]; those for doors and windows are from Porter et al. [3]; and those for NSAS assemblies and contents are from HAZUS-MH [29]. For each GWB assembly, the SAPWood analysis estimate of inter-story drift at the wall location is reduced before applying the fragility curves. The reduction factors, as seen in Table 2, are based on experimental results from the full-scale testing in Christovasilis et al.[27]. The drift of the wall line is multiplied by the reduction factor before being applied to the fragility function for any GWB panel. This reduction reflects the finding in Christovasilis et al. [27] that the connections are such that the GWB does not experience the full drift that shear walls in the same location experience. If the sill plate is damaged, the entire wall

Table 2. Drift reduction factors for partition walls

	Characteristics			
Partition Wall Type	**Top Floor**	**Connected to Structural Wall**	**Stucco**	**Drift Reduction Parameter**
1	Y	Y	N	0.15
2	Y	Y	Y	0.15
3	Y	N	N	0.50
4	Y	N	Y	0.60
5	N	Y	N	0.44
6	N	Y	Y	0.40
7	N	N	N	0.74
8	N	N	Y	0.76

is replaced and the damage states of the other assemblies in the wall do not matter (Table 1).

In estimating economic loss from damage, the model first determines if the building has collapsed. Collapse is assumed to occur when either the maximum inter-story drift for the building is at least δ=0.07, as in ATC 63 [25], or the modeled structural assembly losses exceed 95% of their total value. If the building has collapsed, the loss is the sum of the full value of the structural, NSDS, and NSAS assemblies, plus 50% of the value of the contents. The value of each assembly category is estimated as $V_i = k_{ij} V_T$ for i= structural, NSDS, NSAS, and contents and j=occupancy type (e.g., single-family house), where k_{ij} is the value of category i as a percentage of the total building value (without contents), V_T. The values of k_{ij} for the single-family building were taken from HAZUS-MH to be 0.234, 0.500, 0.266, and 0.500 for structural, NSDS, NSAS, and contents, respectively [29].

If the building does not collapse, the cost to repair each performance group is simulated assuming the lognormal distributions on repair cost with parameters listed in Table 1. The median unit repair cost estimates x_m for the shear wall, partition wall, and sill plate assemblies were estimated by extracting and modifying data from Porter et al. [3] as seen in Table 3. The dispersion β for unit repair cost estimates for the shear wall, partition wall, and sill plate assemblies were assumed to be 0.3, as in Porter et al. [3] for assemblies estimated by its authors. The assembly repair cost data for the doors, windows, and painting were taken directly from Porter et al. [3]. Developed by a professional cost estimator assuming the building is in Santa Monica, California in 2001, the Porter et al. cost data include labor costs, material requirements, and when applicable, debris removal and equipment rental [3]. Since not all structural and NSDS assemblies were modeled explicitly, the model assumes that the percentage loss (repair cost/value) for those that were not modeled explicitly was 25% (for structural) and 30% (for NSDS) of the percentage loss for the ones that were. This reflects an assumption that the assemblies modeled explicitly are the ones most likely to be damaged. Sensitivity analysis was conducted to examine the effect of these percentage levels and the effect of varying them 5% was minimal. The building under investigation is divided into rooms, each with its own associated paint area, including the ceiling. The model assumes that when a wall with paint on it is damaged, that wall will need to be repainted. If the damage state is the highest damage state (2 for drywall, 3 for shear wall), or if more than half of the room area needs to be painted, the entire room is painted. Paint costs account for a portion of the initial estimate of the NSDS value, but in disaggregating the causes of loss, the painting cost associated with wall damage repair is separated out. Repair costs for NSAS assemblies and contents are from HAZUS-MH and are deterministic [29].

Table 3. Estimates of ATC-58 [1] assembly unit repair costs and derivation from Porter et al. [3] report cost data sheets

	ATC-58 assembly damage state, necessary repairs	Unit repair cost* and how it was derived from CUREE report cost data sheets
1	DS1. Cracking of paint over fasteners or joints. Cosmetic repair. Replace tape along the seam of two adjacent panels, apply new joint compound, sand and repaint	$88 per 64 sf for one side, without painting From 1A, 2A, 6A, 8A (same for all). Assumes: Labor: $78 (2 hours @$36-$42/hr) Mat: $10
	DS2. Local and global buckling out-of-plane and crushing of gypsum wallboard. Entire panel replaced along with application of new tape and joint compound, sand, and repaint	$184 per 64 sf for one side, without painting From 1CB. Assumes: Labor: 0.25*$2.20/sf (demo) + $1.39/sf (drywall) + 0.25*$0.76/sf (debris removal) Mat: $0.39/sf Extra: add $22.50 (½ outlet or switch)
2	DS1. Slight separation of sheathing or nails come loose. Renail wood sheathing. Remove exterior siding, replace nails that came loose in wood sheathing and reapply siding.	$132 per 64 sf, without painting From 6BA. Assumes: Labor: $106 (2.5 hours $40-$45/hr) (stucco) + $11 (renailing, includes 10% increase b/c of seismic details) Mat: $15 (stucco)
	DS2. Permanent rotation of sheathing, tear out of nails or sheathing tear out. Replace wood sheathing. Remove siding and wood sheathing, then replace with new sheathing and reapply siding.	$264 per 64 sf, without painting or GWB 6BA minus $10 for renailing + debris removal, labor and materials for new sheathing from 8CE (assume it's 50% of total framing cost; 15/32 plywood). With 10% increase in framing labor and materials for seismic details. Assumes: Labor: $106 (2.5 hours $40-$45/hr) (stucco) + 0.5[$2.29(1.1)+$0.76+$0.02]/sf*64 Mat: $15 (stucco)+ 0.5[$0.96(1.1)+$0.13]/sf*64
	DS3. Fracture of studs, major sill plate cracking. Replace entire wall. Take out entire wall, including studs, top plate and sill, and install all new members.	$398 per 64 sf, without painting or GWB 8C minus painting, and minus drywall labor, materials, demo, and debris removal. Assume demo & debris removal for drywall are 25% of total. 15/32 plywood. With 10% increase in framing labor and materials for seismic details. Labor: [0.75*$2.10+$2.29(1.1)+0.75*$0.76+$0.02 (15/32 plywood)]/sf*64 Mat: [$0.96(1.1)+$0.13 (15/32 plywood)]/sf*64 Extra: add $22.50 (½ outlet or switch)

Table 3 (cont'd). **Estimates of ATC-58 [1] assembly unit repair costs and derivation from Porter et al. [3] report cost data sheets**

	ATC-58 assembly damage state, necessary repairs	Unit repair cost* and how it was derived from CUREE report cost data sheets
3	DS1. Slight separation of sheathing or nails come loose. Renail wood sheathing. Remove exterior siding, replace nails that came loose in wood sheathing and reapply siding.	$131 per 64 sf, without painting Assume damage state and unit repair cost is same as System #50 without 10% increase in renailing labor.
	DS2. Permanent rotation of sheathing, tear out of nails or sheathing tear out. Replace wood sheathing. Remove siding and wood sheathing, then replace with new sheathing and reapply siding.	$254 per 64 sf, without painting or GWB Assume damage state and unit repair cost is same as System #50 without 10% increase in framing labor and materials. 6BA minus $10 for renailing + debris removal, labor and materials for new sheathing from 8CE (assume it's 50% of total framing cost; 15/32 plywood). Assumes: Labor: $106 (2.5 hours $40-$45/hr) (stucco) + 0.5[$2.29+$0.76+$0.02]/sf*64 Mat: $15 (stucco)+ 0.5[$0.96+$0.13]/sf*64
	DS3. Fracture of studs, major sill plate cracking. Replace entire wall. Take out entire wall, including studs, top plate and sill, and install all new members.	$377 per 64 sf, without painting or GWB Assume damage state and unit repair cost is same as System #50 without 10% increase in framing labor and materials. 8C minus painting, and minus drywall labor, materials, demo, and debris removal. Assume demo & debris removal for drywall are 25% of total. 15/32 plywood. Labor: [0.75*$2.10+$2.29+0.75*$0.76+$0.02 (15/32 plywood)]/sf*64 Mat: [$0.96+$0.13 (15/32 plywood)]/sf*64 Extra: add $22.50 (½ outlet or switch)
4	DS1. Cracking of stucco. Repair stucco.	$121 per 64 sf, without painting 6A or 6B (same), without drywall or paint. Assume: Labor: 2.5 hr @ $40-$45/hr Mat: $15
	DS2. Spalling of stucco, separation of stucco and sheathing from studs. Replace stucco & wall sheathing that may have separated from wood studs.	$385 per 64 sf, without painting or GWB Same as System #50 (Assembly 2) DS2 repair cost, plus stucco labor (2.5 hr @ $40-$45/hr) and materials ($15) from 6B
	DS3. Fracture of studs, major sill plate cracking. Replace entire wall, including studs, top plate, & sill.	$519 per 64 sf, without painting or GWB Same as System #50 (Assembly 2) DS3 repair cost, plus stucco labor (2.5 hr @ $40-$45/hr) and materials ($15) from 6B

Table 3 (cont'd). Estimates of ATC-58 [1] assembly unit repair costs and derivation from Porter et al. [3] report cost data sheets

	ATC-58 assembly damage state, necessary repairs	Unit repair cost* and how it was derived from CUREE report cost data sheets
5	DS1. Cracking of stucco. Repair stucco.	$121 per 64 sf, without painting Assume damage state and unit repair cost is same as System #51.
	DS2. Spalling of stucco, separation of stucco and sheathing from studs. Replace stucco & wall sheathing that may have separated from wood studs.	$375 per 64 sf, without painting or GWB Assume damage state and unit repair cost is same as System #51 without 10% increase in framing labor and materials.
	DS3. Fracture of studs, major sill plate cracking. Replace entire wall, including studs, top plate, & sill.	$498 per 64 sf, without painting or GWB Assume damage state and unit repair cost is same as System #51 without 10% increase in framing labor and materials.
6-12	DS1. Failure of sill plate and/or holdowns. Replace entire wall.	Varies. Cost to replace whatever wall and partition assemblies are part of the associated wall (i.e., assume DS2 for Assembly 1, and DS3 for Assembly 2 to 5 are included)

* No unit costs include painting, or overhead and profit.

2.3 Validation

The model was run for the two-story, single-family home example building category as described in Chapter 3. The loss estimates for that analysis are quite reasonable when compared to observations from the 1994 Northridge earthquake. EQE/OES [30] reports, for example, that for single-family homes up to 232 m^2 (2500 ft^2) and built 1977-1993, 1%, 7%, and 15% of buildings were damaged at *PGA*=0.3g, 0.5g, and 0.7g, respectively. Given a building is damaged, the average damage levels (repair/replacement value) are approximately 5%, 6%, and 7% at *PGA*=0.3g, 0.5g, and 0.7g, respectively. Schierle [31] reports that for single-family homes built 1977-1993 that experienced 0.3g to 0.6g, about 5.6% were damaged; the average damage level is 8.5% according to repair cost estimates or 23% according to rapid screening estimates; and the average repair cost is about $25,500. Since available Northridge damage observations are related to ground motion in terms of *PGA*, a conversion of $S_{a(0.25s)}=2.6PGA$ was estimated by determining $S_{a(0.25s)}$ for 111 Northridge earthquake ground motion records from the Center for Engineering Strong Motion Data [32] and averaging the results. Using this conversion and the results for the base case building, the loss model estimates a median loss as a percentage of building value of less than 2%, 7%, and 12% at *PGA*=0.3g, 0.5g, and 0.7g, respectively. Overall, the loss model tends to estimate a slightly higher percentage of buildings damaged compared to the observations, but given that damage occurs, the estimated damage levels as percentage of building value are similar. It is likely that the observations are at least somewhat overestimated because the data in Schierle [31] omits green-tagged buildings which may include minor damage, and because below some lower threshold, a building may not be recorded as being damaged. At this time, the structural analysis does not consider the influence of nonstructural assemblies such as stucco or cladding, which can be nontrivial in woodframe buildings, so the model may overestimate the probability of collapse somewhat. Nevertheless, the loss values estimated by the model are reasonable and the estimated relative performance of building variants should be valid.

Chapter 3

EXAMPLE MODEL APPLICATION

3.1 Building Variants and Analysis Scope

Figure 2 shows the floor plan assumed to represent an average North American two-story, single-family woodframe home. The floor plan is the 2139 ft^2 benchmark building from Christovasilis et al. [27].

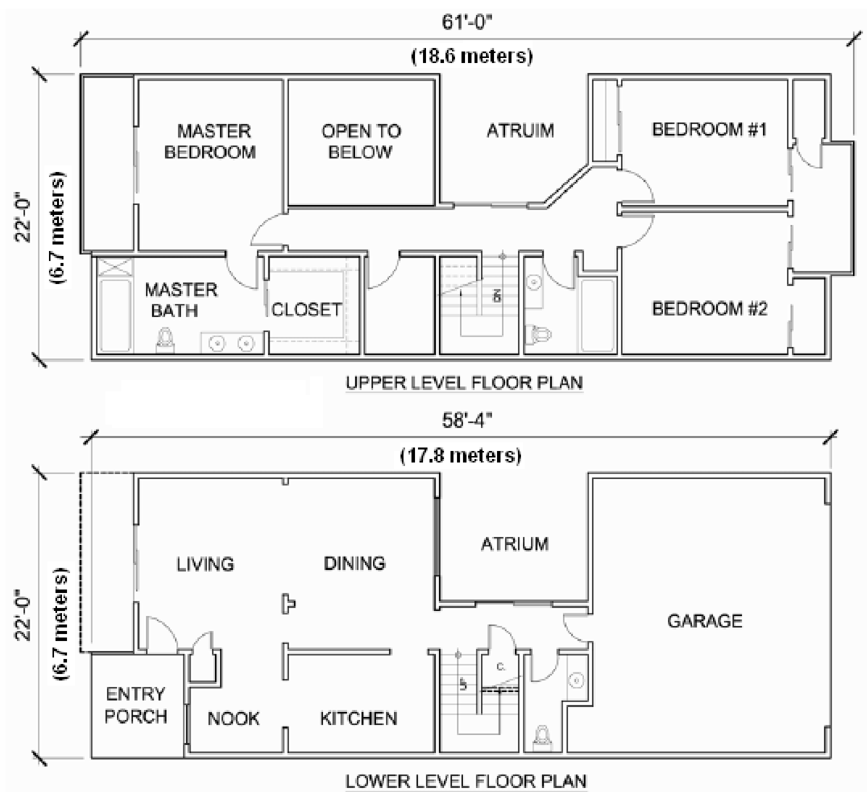

Figure 2. Building floor plan [27]

Table 4. Cost estimate breakdown via RS Means [33]

Item Description	Cost ($) / Unit	Unit	Quantity	Cost ($)
Base cost	79.76	ft^2	2139	170,598
Air conditioning	1.75	ft^2	2139	3743
Additional bathroom	4559	Each	1	4559
Additional 1/2 bathroom	2870	Each	1	2870
Open porch	48.37	ft^2	46.35	2242
Built-in two car garage	-3371	Each	1	-3371
Smoke Alarm	91	Each	1	91
Fixed Picture Windows, 3.5' X 4.0'	514	Each	9	4626
Fixed Picture Windows, 6.0' X 6.0'	1065	Each	1	1065
Vanity Bases, 2 door, 30" high, 21" deep, 30" wide	285	Each	2	550
Vanity Tops, 22" X 25"	267	Each	2	534
Vanity Bases, 2 door, 30" high, 21" deep, 48" wide, for master bath	430	Each	1	430
Vanity Tops, 22" X 49", for master bath	432	Each	1	432
		Subtotal ($)		188,269
		Location Factor		1.06
		Total ($)		***199,565***

Using RSMeans [33], as shown in Table 4, the total building value (excluding contents) V_T was estimated to be about $199,600. Using the procedure from ASCE 7 [34], the building's fundamental period was estimated to be T_1=0.25 seconds. All walls within a story are 8 ft. tall.

Nineteen building variants were defined for the analysis in this thesis, each representing a different combination of nail type, sheathing thickness, nail spacing, and sill plate/hold down assembly type. One could also vary the lengths and locations of shear walls within the specified floor plan. The force-based design for the building developed in Christovasilis et al. [27] was defined as the base case building configuration. Based on engineered construction according to the seismic provisions of the 1988 edition of the Uniform Building Code, it included 7/16 in. sheathing with 8d common nails at 6 in./12 in. spacing, shear walls of type 2 (Table 1), and sill plates of type 11 with HTT22 hold downs (Table 1). Sixteen additional building variants were defined by modifying that design to represent typical construction choices. Finally, two variants were defined to represent rough bounds on seismic vulnerability—a particularly resilient building with double shear walls throughout the building, and a particularly vulnerable building variant with no hold downs, small nails (8d common), large nail spacing (6 in./12 in.) and thin sheathing (7/16 in.). Table 5 displays the details of each of the 19 building variants. See Appendix B for examples of the input files used for one building variant.

The loss model was run for each of the 19 building variants. For each, 528 loss estimates were calculated (12 for each of the 44 ground motions) at each of 28 $S_{a(0.25s)}$ values (0.1g, 0.2g, …, 2.7g). By applying all 44 ground motions the same number of times for each $S_{a(0.25s)}$ value, we avoided introducing additional sampling variability that could confound comparison across ground motion intensities. The result is, for each building variant, a probability distribution of loss at each $S_{a(0.25s)}$ value, where the variability is due to the ground motions, fragility curves, and repair cost functions. In Sections 3.2 to 3.4, we illustrate how these results can be used for buildings of this type to help: (1) characterize estimated losses, (2) define performance objectives, and (3) guide design.

3.2 Characterizing Estimated Losses

The loss model can be used to provide an understanding of the magnitude of loss to be expected given different levels of ground shaking, the causes of that loss, and the variability in the estimates. Using the base case building as an example, Figure

Table 5. Building variant descriptions

	Primary Shear Wall Configuration				Sill Plate Type				
Variant Name	**Sheathing Thickness (in)**	**Nail Type**	**Nail Pattern**	**Associated Fragility***	**Anchor Washer Type**	**Hold Down**	**Allowable Uplift Load (lbs)**	**Sill Thickness**	**Associated Fragility***
Base Design	7/16	8d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
3/4 6d 6/12	3/4	6d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
3/4 8d 6/12	3/4	8d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
3/4 10d 6/12	3/4	10d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
5/8 6d 6/12	5/8	6d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
5/8 8d 6/12	5/8	8d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
5/8 10d 6/12	5/8	10d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
7/16 6d 6/12	7/16	6d	6/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
7/16 8d 4/12	7/16	8d	4/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
7/16 8d 3/12	7/16	8d	3/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11
7/16 8d 2/12	7/16	8d	2/12	2	3” x 3” x 0.5”	HTT22	5260	2X	11

Table 5 (cont'd). Building variant descriptions

	Primary Shear Wall Configuration				Sill Plate Type				
Variant Name	**Sheathing Thickness (in)**	**Nail Type**	**Nail Pattern**	**Associated Fragility***	**Anchor Washer Type**	**Hold Down**	**Allowable Uplift Load (lbs)**	**Sill Thickness**	**Associated Fragility***
7/16 10d 6/12	7/16	10d	6/12	2	3" x 3" x 0.5"	HTT22	5260	2X	11
7/16 10d 4/12	7/16	10d	4/12	2	3" x 3" x 0.5"	HTT22	5260	2X	11
7/16 8d 6/12, no hold downs	7/16	8d	6/12	3	2.5" x 2.5" x 0.25"	-	-	2X	6
7/16 8d 6/12, 10 sill 6500hd	7/16	8d	6/12	2	Standard round 1.5" dia.	-	6500	2X	10
7/16 10d 4/12, no hold downs	7/16	10d	4/12	3	2.5" x 2.5" x 0.25"	-	-	2X	6
7/16 10d 4/12, 10 sill 6500hd	7/16	10d	4/12	2	Standard round 1.5" dia.	-	6500	2X	10
Base design, double shear walls	7/16	8d	6/12	2	3" x 3" x 0.5"	HTT22	5260	2X	11
7/16 8d 6/12, 10 sill 6500hd, double shear walls	7/16	8d	6/12	2	Standard round 1.5" dia.	-	6500	2X	10

*See Table 1 for fragilities

3 shows the estimated loss as a percentage of building value (excluding contents) versus ground shaking intensity, with percentiles to illustrate the variability in those estimates. It suggests that, for the base case building, the median loss is less than 2%, or about $4000, when $S_{a(0.25s)}$ is less than 0.82g. As the spectral acceleration increases from that level, the median increases linearly to an estimated building loss of about 21% at $S_{a(0.25s)}$=2.5g. The figure also shows the substantial variability in estimated losses, which increases with $S_{a(0.25s)}$. For example, excluding contents, while the median loss at $S_{a(0.25s)}$=1.0g is 3.7% of the building value ($7,400), there is a 5% chance that it would be more than 15.4% ($30,600). In fact, the 80th and 95th percentile curves jump up to 100% at 1.8g and 2.6g, respectively, the ground shaking intensity levels at which the building is estimated to exceed 7% drift and therefore, to collapse. Including contents would, of course, increase the losses.

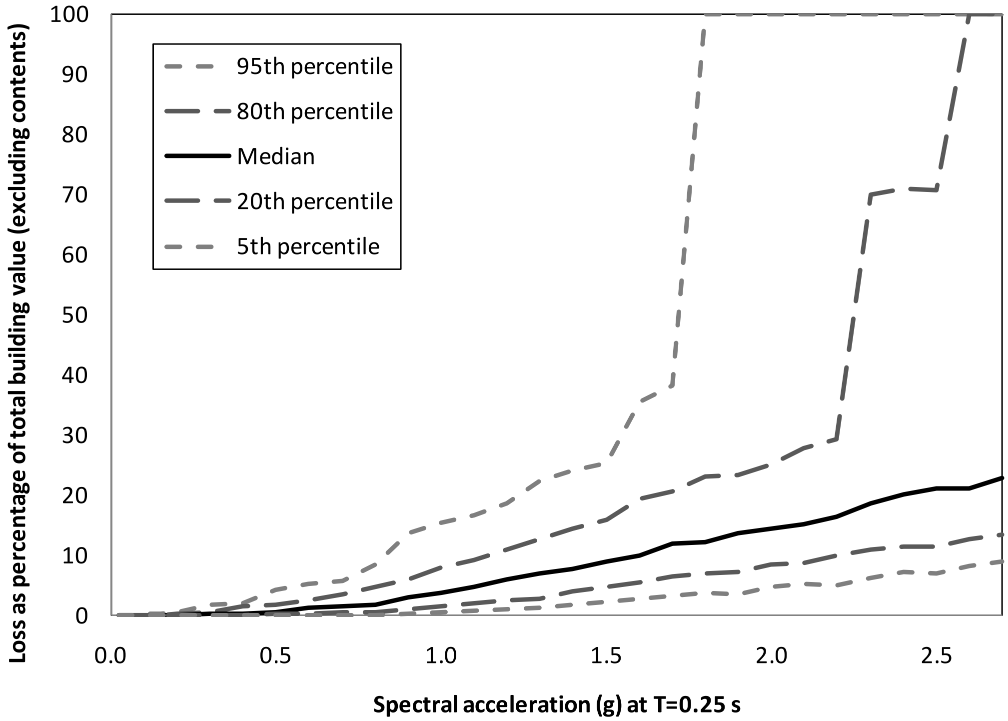

Figure 3. Loss (in percentage of building value, excluding contents) vs. spectral acceleration at T=0.25s, median with percentiles for the base case building

To see how the results vary with building variant, one can compare similar curves across building variants. Figure 4, for example, compares the median loss versus spectral acceleration curves across 8 selected building variants (for clarity, the additional building variants are not shown and variants are identified using their key parameter values in English units). It suggests similar shapes of loss curve across variants, although some of them do intersect. When considering building variants with extremely strong or weak configurations, there is a substantial range in magnitudes, especially as ground shaking increases, but there is a lot less among the more likely building variants. At $S_{a(0.25s)}$=1.5g, for example, the median loss ranges from 4.8% to

16.5%, but when building variants with double shear walls and no hold downs are removed, the range is only 7.9% to 10.6%. The variability across variants is larger if one compares higher percentile curves. At the 95th percentile, for example, even without the variants with double shear walls and no hold downs, the estimated loss ranges from 23.2% to 36.0%. The base case design is in the middle range of loss across variants. Comparing sets of variants in which only one parameter differs (e.g.,

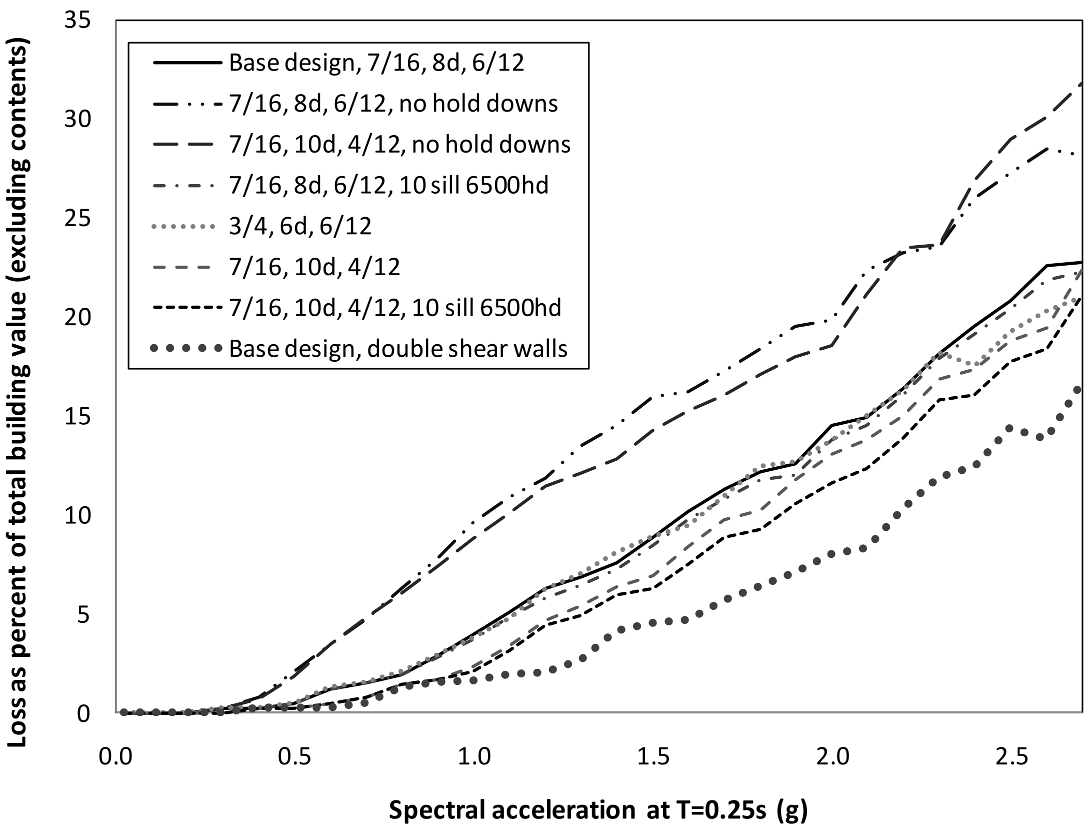

Figure 4. **Loss (in percentage of building value, excluding contents) vs. spectral acceleration at T=0.25s, median curve for 8 selected building variants (*10 sill 6500hd* refers to assembly type 10 in Table 1, with hold downs with an allowable uplift load of 28.91 kN (6500 lbs.))**

sheathing thickness) suggests the relative importance of the sheathing thickness, nail type, nail spacing, sill plate/hold down configuration, and number of shear walls. For the range of values considered in these 19 building variants, the sill plate/hold down configuration and number of shear walls (single or double) are the most influential in determining loss.

Because it is based on detailed modeling of individual building components, the loss model allows one to disaggregate loss to determine which assemblies contribute to the loss at each level of ground shaking intensity. Figure 5 shows the median loss estimate as a percentage of building value (excluding contents) versus ground shaking intensity for the base case building, with a curve for each of the major assembly categories—structural, nonstructural drift-sensitive (NSDS), nonstructural acceleration-sensitive (NSAS), contents, and painting. It suggests that as the ground shaking intensity increases, the NSAS and contents begin to see damage first at small intensity levels (about $S_{a(0.25s)}$=0.3g), and contribute most to the overall loss for all $S_{a(0.25s)}$ values. NSDS and painting losses (mostly due to partition wall damage) begin to be substantial at about 0.6g and increase steadily with $S_{a(T1)}$, with the increase for painting-related loss occurring less quickly than for NSDS. Structural damage begins to appear at about 1.0g and rises steadily with $S_{a(0.25s)}$ up to about 2.4% of the total building value at $S_{a(0.25s)}$=2.5g. Note that the NSAS and contents curves have discrete jumps when a higher damage state becomes likely (e.g., at 1.25g and 2.15g) because those assembly types are modeled in aggregate for each floor in the building, and there is no uncertainty in the repair cost given damage state (Table 1). This figure suggests that when the focus on performance shifts from structural performance to losses, nonstructural assemblies and contents become extremely important.

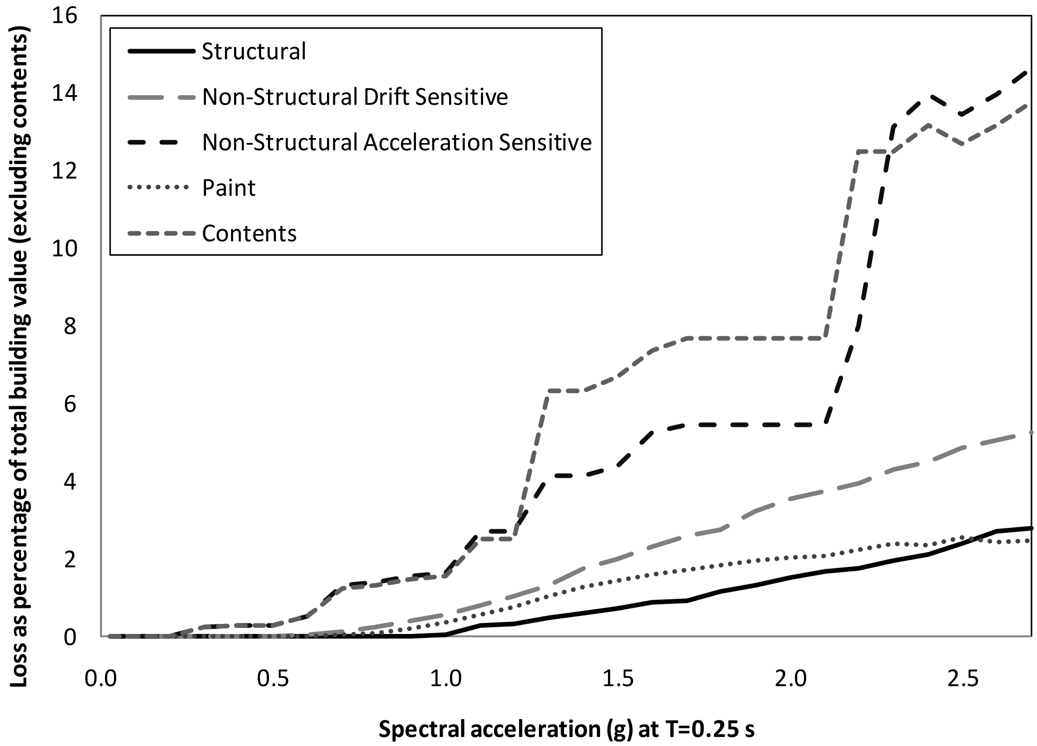

Figure 5. **Loss (in percentage of building value, excluding contents) vs. spectral acceleration at T=0.25s, median curve for each major assembly type, base case building**

As Figure 3 illustrates, the loss estimate for each building variant at a specified ground shaking intensity includes a great deal of variability. For the base case building, when $S_{a(0.25s)}$>0.5g, the coefficient of variation of percent loss is 0.75 to 1.3. This substantial variability highlights the importance that any performance objective includes not just a target loss, but also the probability that target is met. Variability in loss is introduced through the collections of building variants and ground motions, and the estimates of damage given EDPs (fragility curves) and repair costs given damage states. All four of these aspects of the model contribute greatly to the overall variability. Figure 4 suggests the importance of the building variant in determining the loss estimate. Figure 6a, which shows the maximum inter-story drift vs. ground motion intensity for the base case building, suggests the importance of ground motion, since all the variability in that graph is due to the choice of ground motion. Figure 6b, which shows the percentage loss vs. ground motion intensity for a single typical building variant and ground motion, suggests the extent to which fragility and repair cost curves introduce variability as well, since all the variability in that graph is due to the fragility and repair cost curves. (Note that while the trend in the curves in Figure 6b is that loss increases with spectral acceleration, the curves fluctuate as an effect of the dynamic analysis for a particular ground motion and sampling variability.)

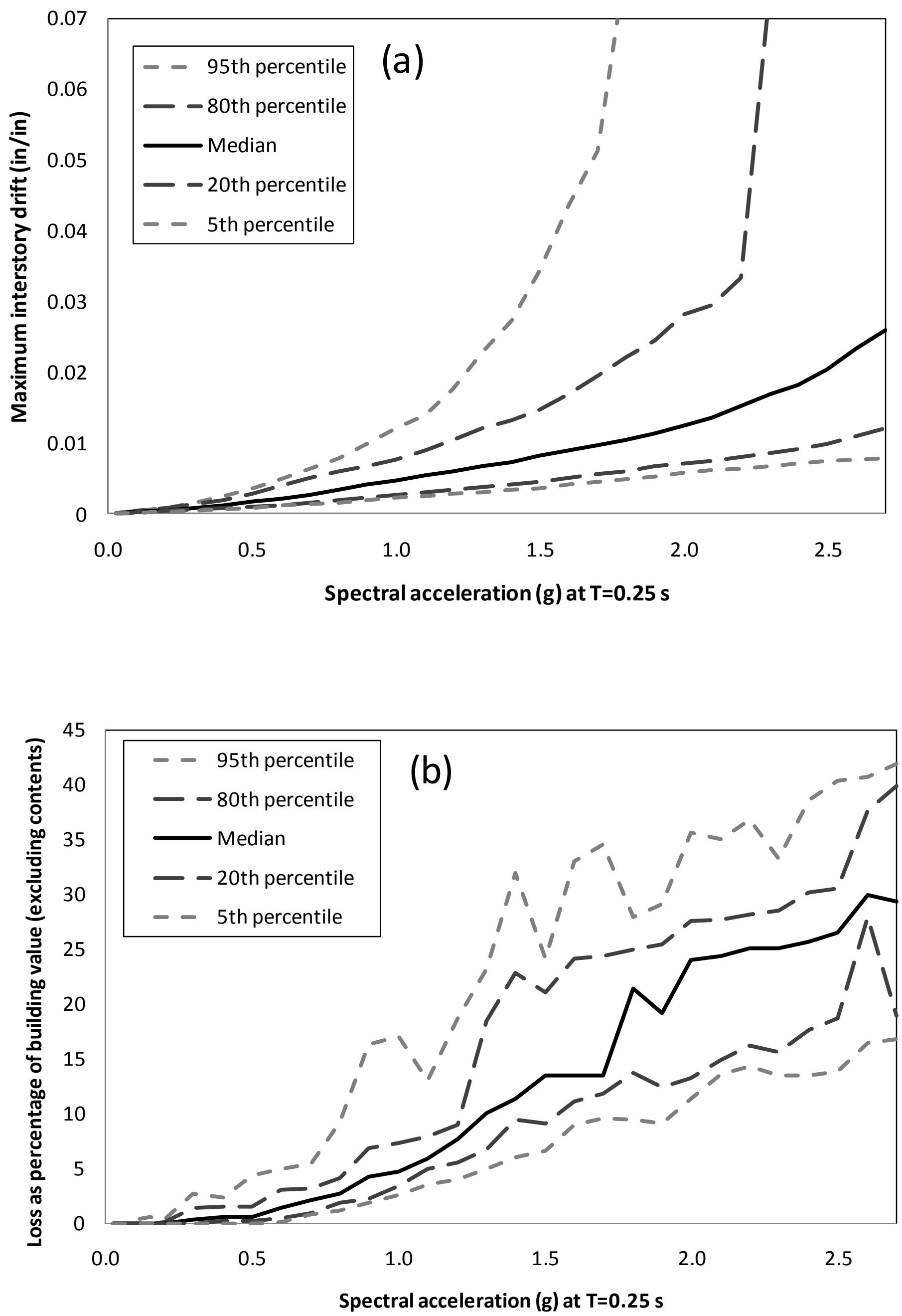

Figure 6. (a) Maximum inter-story drift vs. ground motion intensity for the base case building, and (b) loss (in percentage of building value, excluding contents) vs. ground motion intensity for a single typical ground motion for the base case building

3.3 Defining Performance Objectives

There are many ways to phrase performance objectives in terms of loss, each of which may be useful for different decision makers in different situations, and all of which can be applied using a loss analysis like this. Possible ways of expressing a performance objective include the following [1, 2, 35 and 36]. In these examples, we define loss as a percentage of total building value, but one could use loss in absolute dollars instead. Using the terminology of ATC 58 [1], the first two are intensity-based objectives; the last two are time-based.

1. **There is an *NE*% chance that the building will not experience loss greater than *L*% of the building value when subjected to a ground motion $S_{a(T1)}$**. Figures 3 and 4 could be used to help establish or apply a performance objective in the form. Specifying the objective in terms of $S_{a(T1)}$ is likely to be meaningful to a structural engineer, but less so to a building owner. It does not account for the likelihood that the building will experience the specified spectral acceleration.

2. **There is an *NE*% chance that the building will not experience loss greater than *L*% of the building value when subjected to a ground motion with a return period of RP_{GM} years**. This objective is the same as the first, but with the ground motion expressed in terms of the return period rather than spectral acceleration. This takes into account the likelihood that a building at a particular location will experience different ground shaking intensities. The relationship between $S_{a(T1)}$ and RP_{GM} will, of course, vary with location, however, so the objective applies to a building *at a particular location*. In this form, the uncertainty due to ground motion intensity and the uncertainty due to loss given ground

motion intensity are separated—the former in RM_{GM}; the latter in *NE*—which makes the format similar to the first generation of performance objectives, allows greater detail in specifying objectives, but may make it awkward for a building owner to specify.

3. **There is an *NE*% chance that the building will not experience loss greater than *L*% of the building value over a *t*-year period**. In this format, the uncertainty due to ground shaking intensity and the uncertainty due to loss given ground motion intensity are combined. Applying this objective requires convolving the Loss vs. $S_{a(T1)}$ from Figure 3 with the hazard curve at a particular location, so again, it applies to a building at a particular location. Figure 7 shows an example of loss model results that can be used to apply this objective, as discussed below.

4. **The RP_L-year return period of loss is not greater than *L*% of the building value**. By using the Possion relationship, $NE = P(\text{no events with loss} > L \text{ in } t \text{ years}) = exp(-t/RP_L)$, the third option can be rephrased in this way. This approach only requires specification of two parameters—RP_L and *L*, as opposed to three in the case of the third option—*NE*, *L*, and *t*, making it easier to summarize in a single figure. Figure 8 shows an example of loss model results that can be used to apply this objective, as discussed below. It may, however, be less intuitive for stakeholders to think about a loss return period than a chance of not exceeding a particular loss in a specified number of years. One could also integrate this curve over all loss values to obtain an expected annual loss, which would provide a scalar summary of performance.

The choice among these performance objective formats depends on the specific user and use of the information. Further, multiple performance objectives may be specified if desired. An appropriate set of performance objectives should depend both on stakeholder values and an understanding of what level of performance is reasonably possible. The loss model results can be used to provide some insight into the latter aspect of the performance objective development, i.e., estimating what levels of loss are achievable with what probability at different ground shaking intensities or in different time horizons.

We focus on the third and fourth performance objective formats for the rest of discussion. Using an example location in Hollywood, California at (34.087°, -118.333°) and hazard curves from the 2002 USGS National Seismic Hazard Maps [37], Figure 7 presents *P(no loss > L in t years)* vs. *L* for *t*=50 years (for clarity of the figure, not all variants are shown). As expected, the results show that as the loss value *L* increases or time horizon *t* decreases, the probability of not exceeding *L* in *t* years increases. The time horizon of 50 years was selected because it corresponds to a reasonable expected building lifespan, but one could make similar figures for any time horizon of interest. Figure 7 could be used to help establish performance objective guidelines for the two-story, single-family woodframe home building category. For example, suppose that based on building owner or other stakeholder input, the following performance objective was proposed: a 70% chance a building will not experience loss greater than 10% of the building value in 50 years (Point A on Figure 7). Figure 7 suggests that it may be quite easy to meet that performance objective and that it could reasonably be modified by increasing the nonexceedence probability *NE*, reducing the loss *L*, or increasing the time horizon *t*. Similarly, Figure 7 suggests that a performance objective specifying a 95% chance a building will not experience loss greater than 5% of the building value in 50 years (Point B) might be difficult to meet.

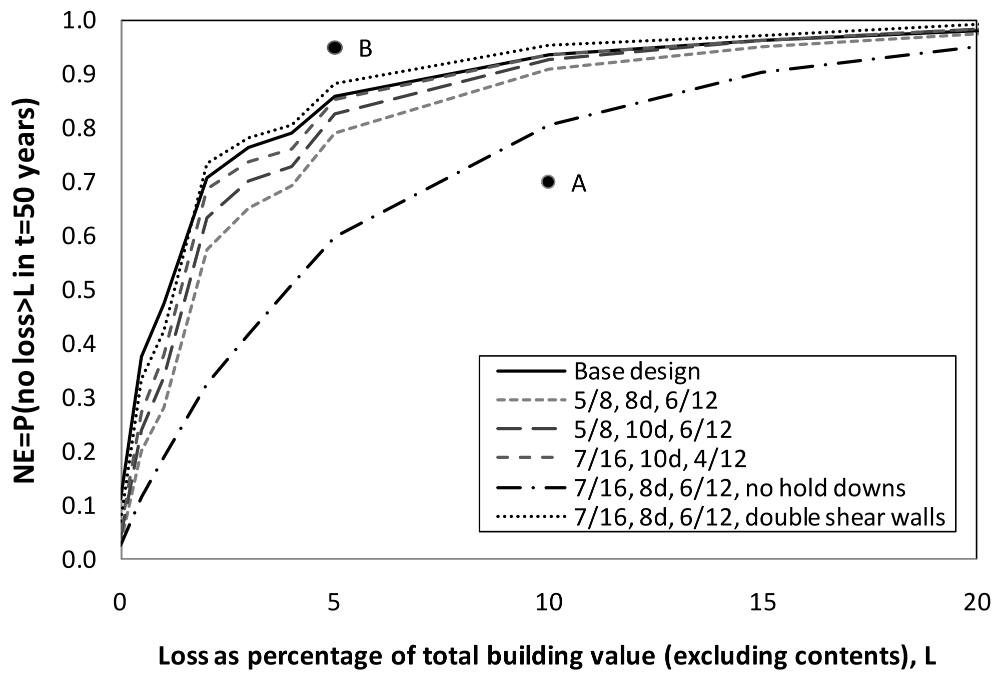

Figure 7. **Probability loss does not exceed loss L (in percentage of building value, excluding contents) in t=50 years vs. Loss L, for selected building variants**

These loss results can also provide guidance as to how many performance objectives should be specified. Too few may not guarantee the desired performance at different levels of ground shaking or in different time horizons, but since performance at different ground shaking intensities or time horizons are related, too many may be unnecessary if one will always govern. For example, if the two previously stated performance objectives were both specified (A and B), the latter would govern the design, thus making it unnecessary to include the former.

Figure 8 shows the loss results in a form that can be used to specify performance objectives using the 4th method, return period of loss, RP_L, vs. loss L. It shows that there is range of estimated loss across building variants. The return period of 5% loss, for example, is from 100 to 400 years depending on the building variant (i.e., the design). Examining the full set of building variants, we also note that the curves for different building variants sometimes intersect, indicating that the variant that best satisfies one performance objective for one loss level may not be the one that best satisfies a performance objective at another loss level. Of the variants represented,

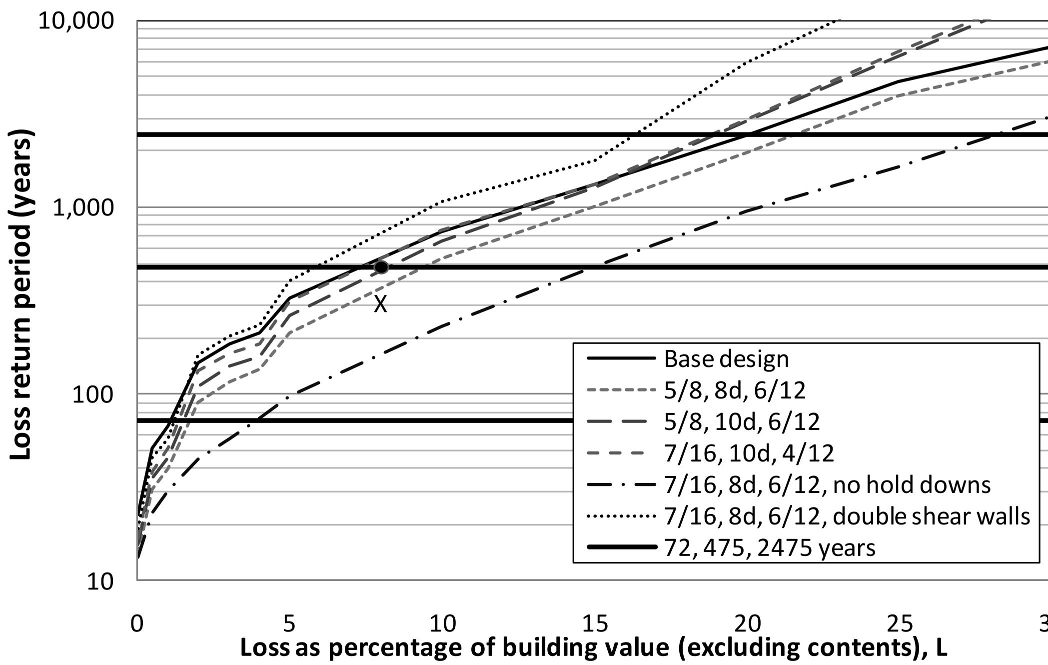

Figure 8. Loss return period (years) vs. loss (in percentage of building value, excluding contents), for selected building variants

the base case design, for example, has the best performance at the 72-year return period, but one of the worst at the 2475-year return period. Nevertheless, at any given loss value, the slopes of different building variant curves are typically approximately equal, so when curves do cross, the return period values are usually quite similar.

Before proposing new performance objective guidelines, it is informative to place previously proposed performance objectives in the context of this analysis. There are many ways to state the objectives that a particular design meets. For purpose of a simple comparison, we can see, for example, that the base case building, designed using a force-based design approach, meets the performance objectives in Table 2. For example, force-based design has implicitly met the performance objective that there is a 90% chance that loss will not exceed 6.8% of the building value ($13,600) in 50 years.

Table 6. Performance objectives implicitly met by force-based design (base case) building

Loss (% of building value), L	0.4	1.1	4.6	6.8	15.7	20.1
Nonexceedence probability, NE	0.5	0.5	0.9	0.9	0.98	0.98
Time horizon (years), t	30	50	30	50	30	50
Loss return period (years), RP_L	43	72	285	475	1485	2475

In previous efforts, performance expectations have typically been related to engineering demand parameters to facilitate design to meet them. FEMA 356/357, for example, relates performance objectives in terms of "Immediate Occupancy" and "Life Safety" to drifts, which can be quantified by structural engineers through analysis [8-9]. When defining performance expectations in terms of economic loss, as in this analysis, there is not an equivalent drift that can be used to guide design directly. Because of the uncertainty in the fragility and repair cost curves, there is not a one-to-one correspondence between achieving a performance objective of 50% non-exceedence of 1% maximum inter-story drift in 475 years, for example, and some similar objective in terms of loss.

Recognizing again that performance objective guidelines should be based on stakeholder input, based on the results of all building variants tested, a reasonable suggestion of performance objective guidelines for two-story, single-family woodframe homes in Los Angeles might be, for example (Figures 7 and 8): (1) 50% nonexceedence of 2% loss in 50 years (RP_L=72 years), (2) 90% nonexceedence of 8% loss in 50 years (RP_L=475 years), and (3) 98% nonexceedence of 20% loss in 50 years (RP_L=2475 years). For the building model in this analysis, these loss percentages correspond to approximately $4000, $16,000, and $40,000, respectively.

3.4 Guiding Design

Once a set of performance objectives is specified, a loss analysis of the type presented in this thesis could be used to help guide design of a building to meet them. For each building category (e.g., two-story, single-family woodframe homes), a database of loss return period vs. loss curves similar to the curves shown in Figure 8 could be developed and made available for a range of realistic building variants. As an example, assume three performance objectives are specified. For a particular building project then, one would first determine the loss return period associated with the first performance objective, RP_{L1}, and select all building variants that have an estimated loss less than the associated loss L_1 specified in the first performance objective at RP_{L1}. For example, if the objective had RP_{L1}=475 years and L_1=7.5%, then using Figure 8 would suggest that the three building variants above point X all meet the first performance objective, while the others do not. Using that group of building variants as the new set of candidate designs, one would then repeat the process for the second performance objective RP_{L2} to further reduce the possible set of candidate building variants. Finally, after repeating the process for the third performance objective, the remaining building variants would be those that satisfy all performance objectives and would be suitable designs. If no building variant satisfied all three, additional variants would have to be developed, perhaps adding shear walls, for example. This process would provide a reasonable starting point of a design (i.e., building variant) which could then be modified as desired. If one preferred the third performance objective type, the process could be applied similarly with curves as in Figure 7.

If a database of building variants were not available, the process could be conducted in an iterative manner. One would first develop loss return period vs. loss curves for an initial preliminary design, as in Figure 8. One would use those curves to determine if the initial design meets or exceeds all specified performance objectives. If not, one could identify which performance objective was not met, and by disaggregating the results as in Figure 5, or to an even more detailed assembly level, one could identify possible design modifications. The modified design would then be checked similarly, and the process would continue until a suitable design was identified.

3.5 Conclusions

Two key components of efforts to develop a second generation of performance-based seismic design are: (1) recasting the performance objectives in terms of economic loss, downtime, and casualties—measures that are more directly useful to building owners, users, and the public than qualitative performance levels;

and (2) representing uncertainty in performance more explicitly. This thesis introduces a new seismic loss model for woodframe buildings and demonstrates through an example application how it can be used to help achieve those two goals.

Specifically, a new seismic loss model for woodframe buildings is introduced and applied. The loss model brings together the state-of-the-art in seismic analysis and the best available experimental and analytical data on damage and loss estimation for woodframe buildings. In the example application for the two-story, single-family woodframe home building category, empirical relations are developed between loss, ground motion intensity, and building design. The results are discussed to illustrate how such a loss analysis can be used to help: (1) characterize the magnitude, causes, and variability of direct economic loss as a function of ground shaking intensity and building design; (2) define performance objectives in terms of economic loss, recognizing the inherent variability; and (3) guide building design using objectives specified in that way. The results reaffirm the importance of explicitly recognizing the large variability in losses and the contribution of non-structural and contents loss in performance-based design.

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Appendix A

SHEAR WALL HYSTERESIS PARAMETER DATABASE

Figure 9 shows the 10 parameters that make up the model [26] used by the SAPWood structural analysis software [28]. Table 7 lists the ten parameters for each of the 144 nail type, sheathing thickness, nail pattern and wall length combinations that were used in the database. These parameters were derived from cyclic test data from tests done in support of the "Benchmark" test at the University of Buffalo [27]. All of these numbers are for walls 8ft tall.

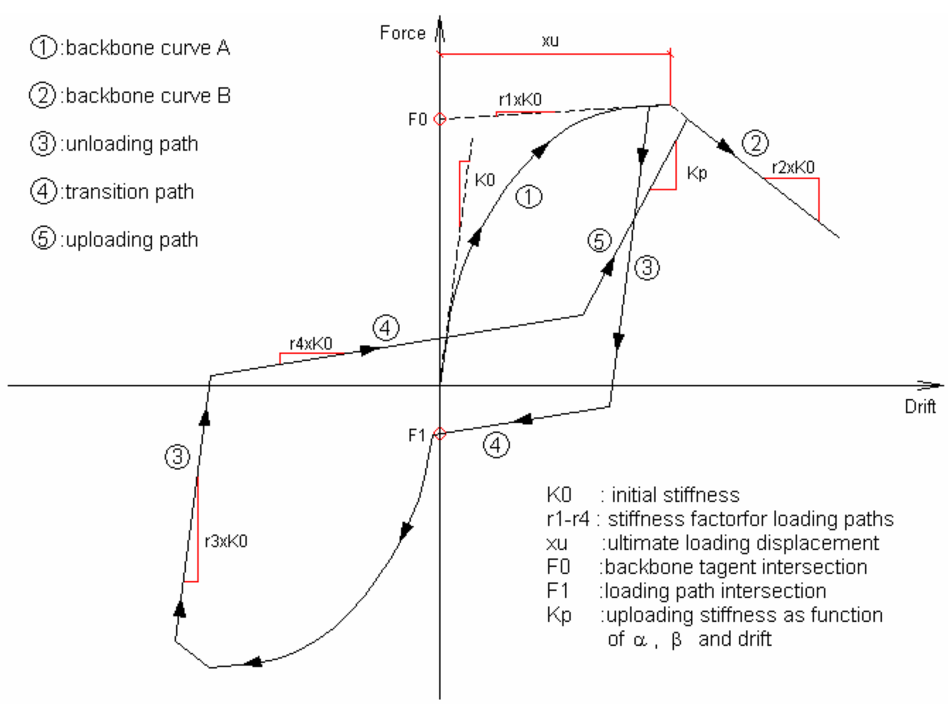

Figure 9. 10 parameter hysteresis model [26][28]

Table 7. Shear wall hysteresis parameters

Nail Type	Sheathing Thickness (in)	Nail Pattern	Wall length	K_0	F_0	F_1	R_1	R_2	R_3	R_4	Xu	Alpha	Beta
10d common	7/16	2/12	2ft	3.80E+03	3.73E+03	6.21E+02	3.60E-02	-9.50E-02	0.65	3.20E-02	3.720	0.75	1.28
			4ft	1.60E+04	8.66E+03	1.44E+03	3.30E-02	-9.00E-02	0.70	3.60E-02	1.990	0.75	1.26
			8ft	4.20E+04	1.85E+04	3.09E+03	1.50E-02	-7.50E-02	0.80	2.80E-02	1.600	0.75	1.29
		3/12	2ft	3.20E+03	2.67E+03	4.45E+02	2.00E-02	-7.50E-02	0.60	2.00E-02	3.200	0.75	1.31
			4ft	1.35E+04	5.80E+03	9.66E+02	3.10E-02	-7.00E-02	0.64	3.10E-02	1.780	0.75	1.28
			8ft	3.40E+04	1.29E+04	2.15E+03	1.00E-02	-6.50E-02	1.00	2.50E-02	1.460	0.75	1.30
		4/12	2ft	2.40E+03	2.11E+03	3.52E+02	1.00E-02	-8.00E-02	0.75	2.50E-02	3.160	0.75	1.31
			4ft	1.05E+04	4.77E+03	7.96E+02	1.60E-02	-7.00E-02	1.00	2.70E-02	1.600	0.75	1.28
			8ft	2.65E+04	9.89E+03	1.65E+03	1.00E-02	-6.50E-02	0.85	2.40E-02	1.450	0.75	1.30
		6/12	2ft	1.65E+03	1.41E+03	2.35E+02	1.00E-02	-7.00E-02	1.00	2.60E-02	2.920	0.75	1.33
			4ft	7.50E+03	3.40E+03	5.66E+02	1.50E-02	-8.00E-02	0.80	2.70E-02	1.580	0.75	1.30
			8ft	2.00E+04	6.79E+03	1.13E+03	1.00E-02	-5.50E-02	1.00	2.20E-02	1.420	0.75	1.32

Table 7 (cont). **Shear wall hysteresis parameters**

Nail Type	Sheathing Thickness (in)	Nail Pattern	Wall length	K_0	F_0	F_1	R_1	R_2	R_3	R_4	Xu	Alpha	Beta
10d common	5/8	2/12	2ft	3.15E+03	3.85E+03	7.09E+02	4.50E-02	-1.60E-01	0.70	3.20E-02	5.355	0.58	1.23
			4ft	1.40E+04	8.40E+03	1.63E+03	5.50E-02	-1.65E-01	0.65	3.20E-02	2.900	0.58	1.20
			8ft	3.90E+04	1.80E+04	3.36E+03	3.00E-02	-1.05E-01	0.75	2.70E-02	2.250	0.64	1.26
		3/12	2ft	2.70E+03	2.35E+03	5.22E+02	6.00E-02	-1.20E-01	0.70	2.80E-02	4.900	0.60	1.26
			4ft	1.15E+04	5.50E+03	1.20E+03	6.00E-02	-1.20E-01	0.65	2.50E-02	2.655	0.60	1.24
			8ft	2.70E+04	1.20E+04	2.37E+03	4.00E-02	-9.00E-02	0.82	2.80E-02	2.280	0.57	1.28
		4/12	2ft	2.10E+03	1.95E+03	3.88E+02	4.00E-02	-1.20E-01	1.00	2.60E-02	4.550	0.57	1.26
			4ft	9.00E+03	4.50E+03	9.14E+02	4.50E-02	-1.20E-01	0.75	2.00E-02	2.400	0.60	1.23
			8ft	2.10E+04	9.60E+03	1.82E+03	3.00E-02	-9.50E-02	0.85	2.80E-02	2.220	0.60	1.28
		6/12	2ft	1.70E+03	1.18E+03	2.41E+02	5.00E-02	-1.00E-01	0.75	2.20E-02	4.635	0.54	1.30
			4ft	6.40E+03	3.35E+03	6.28E+02	3.50E-02	-9.00E-02	0.80	2.60E-02	2.200	0.60	1.26
			8ft	1.60E+04	6.60E+03	1.24E+03	2.50E-02	-8.00E-02	0.80	2.30E-02	2.160	0.65	1.28
	3/4	2/12	2ft	3.45E+03	4.72E+03	7.86E+02	3.00E-02	-1.70E-01	0.65	3.00E-02	5.600	0.80	1.21
			4ft	1.50E+04	1.09E+04	1.81E+03	2.60E-02	-1.90E-01	0.60	2.80E-02	3.000	0.75	1.18
			8ft	4.20E+04	2.14E+04	3.57E+03	2.10E-02	-8.00E-02	0.70	2.00E-02	2.360	0.75	1.23
		3/12	2ft	2.90E+03	3.15E+03	5.24E+02	2.40E-02	-1.20E-01	0.64	2.50E-02	5.000	0.78	1.23
			4ft	1.20E+04	7.41E+03	1.24E+03	2.20E-02	-1.50E-01	0.64	2.50E-02	2.750	0.75	1.21
			8ft	2.90E+04	1.51E+04	2.52E+03	1.30E-02	-9.50E-02	0.75	2.20E-02	2.400	0.84	1.28
		4/12	2ft	2.50E+03	2.39E+03	3.99E+02	1.70E-02	-1.10E-01	0.65	2.20E-02	4.800	0.80	1.24
			4ft	1.00E+04	5.55E+03	9.25E+02	2.10E-02	-9.50E-02	0.65	2.00E-02	2.580	0.80	1.22
			8ft	2.40E+04	1.16E+04	1.93E+03	1.40E-02	-1.00E-01	0.70	2.00E-02	2.300	0.80	1.28
		6/12	2ft	1.65E+03	1.68E+03	2.80E+02	1.20E-02	-1.00E-01	0.75	2.20E-02	4.560	0.75	1.26
			4ft	7.50E+03	3.86E+03	6.44E+02	1.80E-02	-8.00E-02	0.70	2.40E-02	2.400	0.80	1.25
			8ft	1.50E+04	8.25E+03	1.37E+03	1.00E-02	-9.00E-02	0.85	2.20E-02	2.300	0.75	1.28

Table 7 (cont). Shear wall hysteresis parameters

Nail Type	Sheathing Thickness (in)	Nail Pattern	Wall length	K_0	F_0	F_1	R_1	R_2	R_3	R_4	Xu	Alpha	Beta
8d common	7/16	2/12	2ft	4.00E+03	3.48E+03	5.80E+02	2.50E-02	-6.50E-02	0.60	5.00E-02	3.600	0.75	1.22
			4ft	1.60E+04	8.02E+03	1.45E+03	3.00E-02	-8.00E-02	0.60	6.00E-02	1.978	0.73	1.20
			8ft	5.00E+04	1.50E+04	2.80E+03	3.00E-02	-5.50E-02	0.60	4.00E-02	1.838	0.75	1.28
		3/12	2ft	3.00E+03	2.45E+03	4.20E+02	1.70E-02	-8.00E-02	0.65	4.50E-02	3.500	0.70	1.26
			4ft	1.30E+04	5.60E+03	9.53E+02	2.00E-02	-6.50E-02	0.60	5.00E-02	1.838	0.70	1.24
			8ft	3.20E+04	1.15E+04	1.97E+03	2.00E-02	-6.00E-02	0.75	4.20E-02	1.400	0.73	1.28
		4/12	2ft	2.20E+03	1.94E+03	3.23E+02	1.00E-02	-8.00E-02	1.00	4.00E-02	3.200	0.75	1.28
			4ft	1.00E+04	4.30E+03	7.57E+02	3.00E-02	-6.50E-02	1.00	5.00E-02	1.600	0.70	1.28
			8ft	2.10E+04	9.00E+03	1.51E+03	2.00E-02	-7.00E-02	1.00	4.80E-02	1.450	0.70	1.28
		6/12	2ft	1.60E+03	1.31E+03	2.19E+02	1.00E-02	-8.00E-02	1.00	4.20E-02	2.800	0.75	1.30
			4ft	8.00E+03	2.75E+03	5.29E+02	4.00E-02	-6.00E-02	0.75	4.50E-02	1.600	0.65	1.28
			8ft	1.45E+04	6.11E+03	1.02E+03	2.50E-02	-6.50E-02	1.00	4.60E-02	1.480	0.75	1.28
	5/8	2/12	2ft	3.36E+03	3.34E+03	6.50E+02	3.00E-02	-1.85E-01	0.80	5.40E-02	5.364	0.71	1.23
			4ft	1.34E+04	7.70E+03	1.62E+03	3.00E-02	-1.66E-01	0.80	5.40E-02	2.947	0.71	1.23
			8ft	4.20E+04	1.44E+04	3.13E+03	2.00E-02	-1.44E-01	0.80	5.40E-02	2.739	0.71	1.23
		3/12	2ft	2.52E+03	2.35E+03	4.70E+02	3.00E-02	-1.11E-01	0.80	4.38E-02	5.215	0.71	1.23
			4ft	1.09E+04	5.38E+03	1.07E+03	3.00E-02	-9.94E-02	0.80	4.38E-02	2.739	0.71	1.23
			8ft	2.69E+04	1.10E+04	2.20E+03	2.00E-02	-8.64E-02	0.80	4.38E-02	2.086	0.71	1.23
		4/12	2ft	1.85E+03	1.86E+03	3.61E+02	2.00E-02	-1.11E-01	0.80	4.44E-02	4.768	0.71	1.23
			4ft	8.40E+03	4.13E+03	8.48E+02	2.00E-02	-9.94E-02	0.80	4.44E-02	2.384	0.71	1.23
			8ft	1.76E+04	8.64E+03	1.69E+03	2.00E-02	-8.64E-02	0.80	4.44E-02	2.161	0.71	1.23
		6/12	2ft	1.34E+03	1.26E+03	2.45E+02	2.00E-02	-1.11E-01	0.80	4.26E-02	4.172	0.71	1.23
			4ft	6.72E+03	2.64E+03	5.92E+02	2.00E-02	-9.94E-02	0.80	4.26E-02	2.384	0.71	1.23
			8ft	1.22E+04	5.87E+03	1.14E+03	2.00E-02	-8.64E-02	0.80	4.26E-02	2.205	0.71	1.23

Table 7 (cont). Shear wall hysteresis parameters

Nail Type	Sheathing Thickness (in)	Nail Pattern	Wall length	K_0	F_0	F_1	R_1	R_2	R_3	R_4	Xu	Alpha	Beta
8d common	3/4	2/12	2ft	3.64E+03	4.18E+03	6.96E+02	3.00E-02	-2.04E-01	0.80	4.91E-02	5.580	0.71	1.20
			4ft	1.46E+04	9.62E+03	1.74E+03	3.00E-02	-1.83E-01	0.80	4.91E-02	3.066	0.71	1.20
			8ft	4.55E+04	1.80E+04	3.36E+03	2.00E-02	-1.59E-01	0.80	4.91E-02	2.849	0.71	1.20
		3/12	2ft	2.73E+03	2.94E+03	5.04E+02	3.00E-02	-1.23E-01	0.80	3.99E-02	5.425	0.71	1.20
			4ft	1.18E+04	6.72E+03	1.14E+03	3.00E-02	-1.10E-01	0.80	3.99E-02	2.849	0.71	1.20
			8ft	2.91E+04	1.38E+04	2.36E+03	2.00E-02	-9.56E-02	0.80	3.99E-02	2.170	0.71	1.20
		4/12	2ft	2.00E+03	2.32E+03	3.87E+02	2.00E-02	-1.23E-01	0.80	4.04E-02	4.960	0.71	1.20
			4ft	9.10E+03	5.16E+03	9.08E+02	2.00E-02	-1.10E-01	0.80	4.04E-02	2.480	0.71	1.20
			8ft	1.91E+04	1.08E+04	1.81E+03	2.00E-02	-9.56E-02	0.80	4.04E-02	2.248	0.71	1.20
		6/12	2ft	1.46E+03	1.58E+03	2.63E+02	2.00E-02	-1.23E-01	0.80	3.88E-02	4.340	0.71	1.20
			4ft	7.28E+03	3.30E+03	6.35E+02	2.00E-02	-1.10E-01	0.80	3.88E-02	2.480	0.71	1.20
			8ft	1.32E+04	7.33E+03	1.22E+03	2.00E-02	-9.56E-02	0.80	3.88E-02	2.294	0.71	1.20
6d common	7/16	2/12	2ft	3.00E+03	3.17E+03	5.28E+02	3.40E-02	-6.50E-02	0.70	4.50E-02	4.000	0.65	1.31
			4ft	1.10E+04	7.90E+03	1.20E+03	5.00E-02	-1.00E-01	0.60	5.00E-02	2.000	0.70	1.39
			8ft	3.00E+04	1.53E+04	2.20E+03	2.00E-02	-5.50E-02	0.70	3.50E-02	1.800	0.70	1.40
		3/12	2ft	2.50E+03	2.11E+03	3.51E+02	3.00E-02	-6.00E-02	0.65	3.70E-02	3.500	0.69	1.28
			4ft	1.00E+04	5.28E+03	8.78E+02	1.00E-02	-7.00E-02	0.70	4.60E-02	2.140	0.70	1.28
			8ft	2.30E+04	1.08E+04	1.79E+03	1.00E-02	-5.00E-02	1.00	4.00E-02	1.900	0.75	1.33
		4/12	2ft	1.80E+03	1.71E+03	2.85E+02	2.00E-02	-6.50E-02	0.80	4.00E-02	3.390	0.69	1.32
			4ft	7.80E+03	4.17E+03	6.96E+02	1.00E-02	-4.00E-02	0.80	4.20E-02	1.900	0.70	1.32
			8ft	2.00E+04	8.21E+03	1.37E+03	1.00E-02	-5.00E-02	0.75	3.50E-02	1.600	0.75	1.32
		6/12	2ft	1.30E+03	1.16E+03	1.94E+02	1.00E-02	-8.00E-02	1.00	4.00E-02	3.710	0.70	1.33
			4ft	5.75E+03	2.85E+03	4.75E+02	1.00E-02	-4.00E-02	1.00	4.00E-02	1.800	0.75	1.30
			8ft	1.30E+04	5.64E+03	9.41E+02	1.00E-02	-4.00E-02	0.90	4.00E-02	1.600	0.75	1.33

Table 7 (cont). **Shear wall hysteresis parameters**

Nail Type	Sheathing Thickness (in)	Nail Pattern	Wall length	K_0	F_0	F_1	R_1	R_2	R_3	R_4	Xu	Alpha	Beta
6d common	5/8	2/12	2ft	2.52E+03	3.04E+03	5.91E+02	3.00E-02	-1.85E-01	0.80	4.50E-02	5.960	0.71	1.29
			4ft	9.24E+03	7.58E+03	1.34E+03	3.00E-02	-1.66E-01	0.80	4.50E-02	2.980	0.71	1.29
			8ft	2.52E+04	1.47E+04	2.46E+03	2.00E-02	-1.44E-01	0.80	4.50E-02	2.682	0.71	1.29
		3/12	2ft	2.10E+03	2.02E+03	3.93E+02	3.00E-02	-6.78E-02	0.80	4.14E-02	5.215	0.71	1.29
			4ft	8.40E+03	5.06E+03	9.84E+02	3.00E-02	-6.07E-02	0.80	4.14E-02	3.189	0.71	1.29
			8ft	1.93E+04	1.03E+04	2.01E+03	2.00E-02	-5.28E-02	0.80	4.14E-02	2.831	0.71	1.29
		4/12	2ft	1.51E+03	1.64E+03	3.19E+02	2.00E-02	-7.39E-02	0.80	4.00E-02	5.051	0.71	1.29
			4ft	6.55E+03	4.01E+03	7.79E+02	2.00E-02	-6.62E-02	0.80	4.00E-02	2.831	0.71	1.29
			8ft	1.68E+04	7.88E+03	1.53E+03	2.00E-02	-5.76E-02	0.80	4.00E-02	2.384	0.71	1.29
		6/12	2ft	1.09E+03	1.12E+03	2.17E+02	2.00E-02	-6.65E-02	0.80	3.80E-02	5.528	0.71	1.29
			4ft	4.83E+03	2.74E+03	5.32E+02	2.00E-02	-5.96E-02	0.80	3.80E-02	2.682	0.71	1.29
			8ft	1.09E+04	5.42E+03	1.05E+03	2.00E-02	-5.18E-02	0.80	3.80E-02	2.384	0.71	1.29
	3/4	2/12	2ft	2.73E+03	3.80E+03	6.33E+02	3.00E-02	-2.04E-01	0.80	4.10E-02	6.200	0.71	1.26
			4ft	1.00E+04	9.48E+03	1.44E+03	3.00E-02	-1.83E-01	0.80	4.10E-02	3.100	0.71	1.26
			8ft	2.73E+04	1.84E+04	2.64E+03	2.00E-02	-1.59E-01	0.80	4.10E-02	2.790	0.71	1.26
		3/12	2ft	2.28E+03	2.53E+03	4.21E+02	3.00E-02	-7.50E-02	0.80	3.77E-02	5.425	0.71	1.26
			4ft	9.10E+03	6.32E+03	1.05E+03	3.00E-02	-6.72E-02	0.80	3.77E-02	3.317	0.71	1.26
			8ft	2.09E+04	1.29E+04	2.15E+03	2.00E-02	-5.84E-02	0.80	3.77E-02	2.945	0.71	1.26
		4/12	2ft	1.64E+03	2.05E+03	3.42E+02	2.00E-02	-8.18E-02	0.80	3.64E-02	5.255	0.71	1.26
			4ft	7.10E+03	5.01E+03	8.35E+02	2.00E-02	-7.33E-02	0.80	3.64E-02	2.945	0.71	1.26
			8ft	1.82E+04	9.85E+03	1.64E+03	2.00E-02	-6.37E-02	0.80	3.64E-02	2.480	0.71	1.26
		6/12	2ft	1.18E+03	1.39E+03	2.32E+02	2.00E-02	-7.36E-02	0.80	3.46E-02	5.751	0.71	1.26
			4ft	5.23E+03	3.42E+03	5.70E+02	2.00E-02	-6.60E-02	0.80	3.46E-02	2.790	0.71	1.26
			8ft	1.18E+04	6.77E+03	1.13E+03	2.00E-02	-5.73E-02	0.80	3.46E-02	2.480	0.71	1.26

Appendix B

MATLAB LOSS MODEL INPUT FILES

Table 8 describes the configuration of the .bldinpt files used in the analysis. These files contain the building value and assembly configuration data used in the loss analysis. They are used by both the build analysis and SAPWoodoutputconverter functions.

Table 8(a) *.bldinpt file configuration

Row	Data	
1	Occupancy type	
2	S = Total number of stories	
3	BV = Set of building values (excluding contents) ($), {*Economy, Average, Custom, Luxury*}	
4	Area of each floor (in^2), $\{A_1,\ldots,A_S\}$	Height of each floor (in), $\{H_1,\ldots,H_S\}$
5	Number of separate wall groups in each floor, $\{W_1,\ldots,W_S\}$	
6	R_m = Number of rooms	
7	Paint area of each room (in^2), $\{PA_1,\ldots,PA_{Rm}\}$	
8	Line of wall group data, for $g_{1,1}$	
…	…	
$7 + W_1$	Line of wall group data, for $g_{1,W1}$	
$8 + W_1$	Line of wall group data, for $g_{2,1}$	
…		
$7 + W_1 + W_2$	Line of wall group data, for $g_{2,W2}$	
…	…	
8 + sum($W_{1\ldots S-1}$)	Line of wall group data for $g_{S,1}$	
…	…	
7 +sum($W_{1\ldots S}$)	Line of wall group data for $g_{S,WS}$	

$g_{s,w}$ = Wall group number w in story s, $w = 1,\ldots,W_s$, $s = 1,\ldots,S$

Table 8(b). *.bldinpt file, wall group data configuration

Column	Data
1	Wall fragility identifier, (1 = partition wall, 2,…, or 5 = shear wall)*
2	Sill plate fragility identifier, (6,…,12)*
3	Maximum allowable uplift load for hold down (lbs)
4	Drift reduction factor**
5	*nsds* = number of NSDS components, (aside from dry wall)
5 + *n*	NSDS fragility identifier* for component *n*
…	…
5 + *nsds*	NSDS fragility identifier* for component *nsds*
5 + *nsds* + 1	*wseg* = number of wall segments in this wall group
5 + *nsds* + 2	$length_1$ = length of wall segment 1
…	…
5 + *nsds* + 1 + *wseg*	$length_{wseg}$ = length of wall segment *wseg*
5 + *nsds* + *wseg* + 2	dw_1 = number of attached dry wall panels to wall segment 1
…	…
5 + *nsds* + 2**wseg* + 1	dw_{wseg} = number of attached dry wall panels to wall segment *wseg*
5 + *nsds* + 3**wseg* + 1	Paint data for wall segment 1
…	…
5 + *nsds* + 2**wseg* + 2	Paint data for wall segment *wseg*

*See Table 1 for fragility data
**See Table 2 for drift reduction factors

Table 8(c). *.bldinpt file, Paint data for a wall segment

Column	**Data**
1	$Rooms_{SP}$ = number of rooms associated with the sheathing panel (meaning not the attached dry wall) (≥ 0)
2	$room_{SP,1}$ = 1st room associated with sheathing panel
…	…
1 + $Rooms_{SP}$	$room_{SP,Roomssp}$ = last room associated with sheathing panel
1 + $Rooms_{SP}$ + 1	$Rooms_{DW1}$ = number of rooms associated with the 1st attached drywall panel
2 + $Rooms_{SP}$ + 1	$room_{1,1}$ = 1st room associated with 1st attached drywall panel
…	…
2 + $Rooms_{SP}$ + $Rooms_{DW1}$	$room_{1,RoomsDW1}$ = last room associated with 1st attached drywall panel
…	…
2 + $Rooms_{SP}$ + sum($Rooms_{DW1 \ldots dwwseg-1}$)	$Rooms_{DWdwwseg}$ = number of rooms associated with last attached drywall panel, dw_{wseg}
2 + $Rooms_{SP}$ + sum($Rooms_{DW1 \ldots dwwseg-1}$) + 1	$room_{dwwseg,1}$ = 1st room associated with last attached drywall panel
…	…
2 + $Rooms_{SP}$ + sum($Rooms_{DW1..dwwseg}$)	$Room_{dwwseg,\, RoomsDWdwwseg}$ = last room associated with last attached drywall panel

Table 9 contains describes the configuration of the .wallconfig files. These files dictate how the EDP data from SAPWood is interpreted for use in the MATLAB simulation. They are used by the SAPWoodoutputconverter function.

Table 9 (a). *.wallconfig file configuration

Row	Data
1	S = Total number of stories
2	Number of separate wall groups in each story, $\{W_1,\ldots,W_S\}$
3	Number of separate wall panels analyzed in SAPWood in each story, $\{WP_1,\ldots,WP_S\}$
4	Wall panel inputs for wall group 1 in story 1
…	…
$3 + W_1$	Wall panel inputs for wall group W_1 in story 1
…	…
$4 + \text{sum}(W_{1\ldots S-1})$	Wall panel inputs for wall group 1 in story S
…	…
$3 + \text{sum}(W_{1\ldots S})$	Wall panel inputs for wall group W_S in story S

Table 9(b). *.wallconfig file, wall panel inputs configuration

Column	Data
1	WPN = number of wall panels associated with this wall group
2	Indicates whether wall group is at a 45° angle to the primary axes, if = 1, it is not, if = 0 it is, consecutive panels are combined in output and $WPN = 2*WPN$
3	1^{st} panel associated with wall group
…	…
$2 + WPN$	Last panel associated with wall group

Table 10 describes the basic configuration of the .xy and .yx files which contain the EDP data output by SAPWood. Each file should have the results for 22 different ground motions. The .xy file has the results for the analysis when the x and y directions of the ground motion input match up with the x and y directions of the building model, respectively, while the .yx file has the results for the analysis when the y and x directions of the ground motion match up with the x and y directions of the building model, respectively.

Table 10. *.xy and *.yx file configurations

Row	**Data**
1	*SA* = Total number of ground motion intensity levels that this file has data for
2	Row vector of length *SA* containing all the ground motion intensity levels contained in this file
3 +…	EDP data as output by SAPWood 2.0's Multi-IDA analysis for a biaxial building model. Story data, wall data.

Table 11 and 12 contain data for an example *.bldinpt file and an example *.wallconfig file, respectively. This file is used as the base file for the loss analysis discussed in the thesis. Combine with Table 8 to interpret.

Table 11. Example *.bldinpt file

1																												
2																												
143146	199565	222701	280088																									
1035	1104	103	120																									
20	28																											
20																												
1144	219	165	306	147	492	346	578	167	559	280	333	233	290	404	520	1394	475	987	436									
2	11	5260	0.413	3	14	15	15	5	118.25	112.75	105.5	83.5	48	0	0	0	0	0	1	19	1	19	1	19	1	19	1	19
2	11	5260	0.413	1	14	1	47.5	1	1	5	1	18																

Table 11(cont'd). Example *.bldinpt file

2	11	5260	0.413	0	1	9.5	0	1	18																		
2	11	5260	0.413	1	13	1	107.5	0	1	18																	
2	11	5260	0.413	2	15	15	4	90.5	87	45	192	0	0	0	0	1	17	1	17	1	17	1	17				
2	11	5260	0.413	0	2	59.5	96.5	0	1	1	17	1	12	0													
2	11	5260	0.413	1	13	1	64.5	0	1	17																	
2	11	5260	0.413	0	2	129.5	103	0	1	1	17	1	2	0													
2	11	5260	0.413	0	1	70.5	0	1	20																		
1	0	0	0.735	0	5	118	112	102	82	45	0	0	0	0	0	1	1	2	1	2	2	3	4	1	4	1	5
1	0	0	0.735	0	1	44	0	1	5																		
1	0	0	0.735	0	1	104	0	1	7																		
1	0	0	0.735	0	4	87	84	45	192	0	0	0	0	1	7	1	6	1	1	1	1						
1	0	0	0.735	0	2	56	94	0	0	1	6	1	4														
1	0	0	0.735	0	1	56	0	1	3																		
1	0	0	0.735	0	2	129	97	0	0	1	1	1	1														
1	0	0	0.735	0	1	66	0	1	1																		
1	0	0	0.735	0	1	103	1	1	4	1	6																
1	0	0	0.735	0	1	87	1	1	2	1	3																
1	0	0	0.735	0	1	39	1	1	4	1	5																
2	11	5260	0.125	4	14	14	14	15	4	144	76.5	168	168	0	0	0	0	1	19	1	19	1	19	1	19		
2	11	5260	0.125	0	1	83.5	0	1	18																		
2	11	5260	0.125	0	1	42.5	0	1	18																		
2	11	5260	0.125	1	13	1	107.5	0	1	18																	

Table 11(cont'd). Example *.bldinpt file

2	11	5260	0.125	3	15	15	15	4	90.5	63	44.5	144	0	0	0	0	1	17	1	17	1	17	1	17
2	11	5260	0.125	0	1	131.5	0	1	17															
2	11	5260	0.125	1	15	1	44	0	1	17														
2	11	5260	0.125	0	1	77	0	1	17															
2	11	5260	0.125	0	1	100.75	0	1	17															
2	11	5260	0.125	0	3	44.5	61	44.5	0	0	0	1	20	1	20	1	20							
1	0	0	0.5	0	4	141	73	165	165	0	0	0	0	1	8	1	11	2	13	14	1	15		
1	0	0	0.5	0	1	83	0	1	15															
1	0	0	0.5	0	3	42	160	46	0	1	1	1	15	2	14	15	1	16	1	12	1	13		
1	0	0	0.5	0	1	104	0	1	16															
1	0	0	0.5	0	4	87	60	44	141	0	0	0	0	1	16	1	6	1	10	1	10			
1	0	0	0.5	0	2	131	83	0	1	1	6	1	13	1	12									
1	0	0	0.5	0	2	41	165	0	1	1	12	1	8	1	10									
1	0	0	0.5	0	1	38	0	1	12															
1	0	0	0.5	0	1	100	0	1	10															
1	0	0	0.5	0	3	44	58	44	0	0	0	1	9	1	9	1	8							
1	0	0	0.5	0	1	30	1	1	10	1	12													
1	0	0	0.5	0	1	33	1	1	8	1	9													
1	0	0	0.5	0	1	87	1	1	11	1	12													
1	0	0	0.5	0	1	83	1	1	13	1	14													
1	0	0	0.5	0	1	41	1	1	14	1	15													
1	0	0	0.5	0	1	147	1	1	6	1	16													
1	0	0	0.5	0	1	99	1	1	8	1	11													
1	0	0	0.5	2	13	13	1	70	1	1	9	1	10											

Table 12. Example *.wallconfig file

2											
20	28										
56	69										
10	1	1	2	3	4	5	39	40	41	42	43
2	1	6	44								
2	1	7	45								
2	1	8	46								
8	1	9	10	14	15	47	48	52	53		
4	1	11	18	49	56						
2	1	12	50								
2	1	13	17	51	55						
2	1	16	54								
5	1	19	20	21	22	23					
1	1	24									
1	1	25									
4	1	26	27	31	32						
2	1	28	35								
1	1	29									
2	1	30	34								
1	1	33									
1	1	36									
1	1	37									
1	1	38									
8	1	1	2	3	4	51	52	53	54		
2	1	5	55								
2	1	6	56								
2	1	7	57								
8	1	8	9	14	15	58	59	64	65		
2	1	10	60								
2	1	11	61								
2	0	12	19	62	69						
2	1	13	63								
6	1	16	17	18	66	67	68				

Table 12(cont'd). Example *.wallfig file

4	1	20	21	22	23
1	1	24			
3	1	25	42	43	
1	1	26			
4	1	27	28	33	34
2	1	29	45		
2	1	30	40		
1	0	31	38		
1	1	32			
3	1	35	36	37	
1	1	39			
1	1	41			
1	1	44			
1	1	46			
1	1	47			
1	1	48			
1	1	49			
1	1	50			