Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

LONG TERM SEISMIC LOSS EVALUATION FOR WOODFRAME STRUCTURES: A PERFORMANCE-BASED PROCEDURE

S. Pei[1] and J.W. van de Lindt[2]

ABSTRACT

Light frame wood construction is the most widely used residential construction style today in North America. The merits of this type of structure lie in the speed of construction, availability of the material, and the affordability. Although the value of a single woodframe structure is relatively low compared to steel and concrete structures, woodframe structures, as a whole, still have the potential to cause significant financial losses during seismic events. As seismic design codes evolve towards a performance-based format, it is necessary to include long-term economic loss as one of the performance criteria for structures. This paper focuses on the evaluation of earthquake-related economic losses to woodframe structures in a specified region during a given period of time, i.e. the design life of a woodframe structure. A generalized framework to evaluate the long-term loss distribution based on both seismic hazard uncertainty and structural variation is developed. This procedure is capable of seamlessly incorporating information from numerical simulations, field investigations, and engineering expertise into a Bayesian framework in order to obtain a comprehensive representation for the loss distribution. A new nonlinear hysteretic numerical model for woodframe structures based on a large cyclic test database from the U.S. and Canada was used in the numerical analysis to improve the accuracy of the structural responses. The procedure is then applied to numerical examples and sensitivity analysis for the structural optimization to regional loss expectations. This procedure shows further potential applications within the broader context of a performance-based seismic design (PBSD) framework.

Introduction

Historically, earthquake engineering for structural systems provides life safety and makes no real implication as to expected levels of damage. Thus, life cycle costs are not considered with current strength-based design codes such as Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD). These objectives, once considered adequate in the past, had been rendered incomplete by the growing demands for additional structural and non-structural performance expectations by the end users, i.e. the building owners and occupants. An emerging and improving paradigm known as performance-based seismic design (PBSD) allows an engineer to consider far more than simply strength as the basis for a design. In PBSD, life safety is included and required but extensive effort is made to

---

[1] Doctoral student. Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523-1372. email: slpei@lamar.colostate.edu.

[2] ((**Corresponding Author)** Associate Professor, Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523-1372. e-mail: jwv@engr.colostate.edu.

minimize financial losses over the life of a structure. For woodframe structures, PBSD is in its early stages with costing still being developed. This paper presents a Bayesian procedure to estimate lifetime costs within the framework of PBSD, essentially minimizing lifetime losses from earthquakes for a structure. The resulting configuration serves as the optimal design for a woodframe structure.

A cost based optimization concept has been considered by researchers in seismic design since the early 1970's (Liu et al., 1972). There are existing methods developed to assess economic losses for a structure for a given earthquake (Porter, 2000). However, it makes more practical sense to estimate the potential earthquake induced loss as a stochastic quantity over the design life of a structure because of the inherent uncertainty of earthquakes. A handful of researchers have looked into the lifecycle cost of structures in recent years. Liu et al. (2004) proposed optimizing a seismic design procedure for steel moment frames towards lifecycle cost minimization. Similar research on reinforced concrete structures can be found in Ang et al. (2001).

Lifecycle loss based design for woodframe structures is further complicated due to the fact that the structural response is highly nonlinear and nonstructural component damage contributes a significant amount to the repair costs. In the CUREE Caltech woodframe research project (1999), studies on the damage-cost relationships for several typical woodframe building components were conducted (see Porter, 2000).

Modeling Lifetime Loss

Potential life time loss due to earthquakes is the cumulative economic loss induced by each earthquake during the life time of a structure. If we assume the uncertainty in the occurrence of an earthquake and earthquake intensity to be independent, a hierarchical model for life time loss given the length of its lifetime (*T*) can be established as,

$$C_t = \sum_{k=1}^{Ne} C_a(k) \tag{1}$$

$$Ne \sim Poisson(\lambda T) \tag{2}$$

$$C_a(k) \sim f_C(C_a \mid I_k) \tag{3}$$

$$I_k \sim f_I(I) \tag{4}$$

where C_t is the lifetime loss; *Ne* is the number of earthquakes during lifetime *T*, following a Poisson distribution with rate parameter λ; $C_a(k)$ represents the assembly loss (the cost of repair the whole structure after one earthquake event) of the building due to the k^{th} earthquake, conditional on the earthquake intensity *I*; and I_k is the intensity level for the k^{th} earthquake as a realization of a location-specific intensity distribution f_I.

To obtain a reliable estimation of life time loss, accurate models for the relationship between earthquake intensity, occurrence, and assembly loss-intensity must be used. From a Bayesian point of view, the model for such unknown random events can be constructed initially using subjective belief and then updated with available data. The most obvious benefit obtained from using a Bayesian model instead of a traditional regression model is a seamless interface to incorporate additional data (from tests or additional research investigations) as well as even subjective engineering expert opinion (if desired). Thus the accuracy of this framework can, in turn, be improved upon as more information becomes available.

In a Bayesian model, the parameters for a predictive distribution are taken as random variables themselves following posterior distributions which start from the prior distribution and then are updated with available data. Three quantities associated with lifetime loss, namely the number of earthquakes during a lifetime (*Ne*), assembly cost (C_a), and earthquake intensity (*I*), are modeled with this method.

The procedure used to perform the simulation can be illustrated in Fig.1. A database of earthquake records associated with occurrence time and intensity (constructed from historical records in the location of interest) is needed for the simulation. Then following the left branch of the flowchart, a series of intensity levels will be selected to simulate data needed for the cost-intensity relationship formulation (Eq. 3). A group of earthquake records randomly drawn from the database are then scaled to one intensity level in the series to yield structural responses using a nonlinear structural model (which will be discussed later). Component damage fragilities, which model the relationship between structural and non-structural component responses and loss, are used to convert the responses into a data pool of losses. After every intensity level is simulated, a generalized linear (or higher order) model can be constructed based on all the loss data in order to represent the loss-intensity relationship for the model building. With this model (Eq.3) ready, one can conduct simulations based on the hierarchical structure of the lifetime loss model following the right branch of the flowchart. Note in the flowchart there are entries for additional data at different levels. These various data sets can be incorporated into the simulation results through the Bayesian interface when necessary.

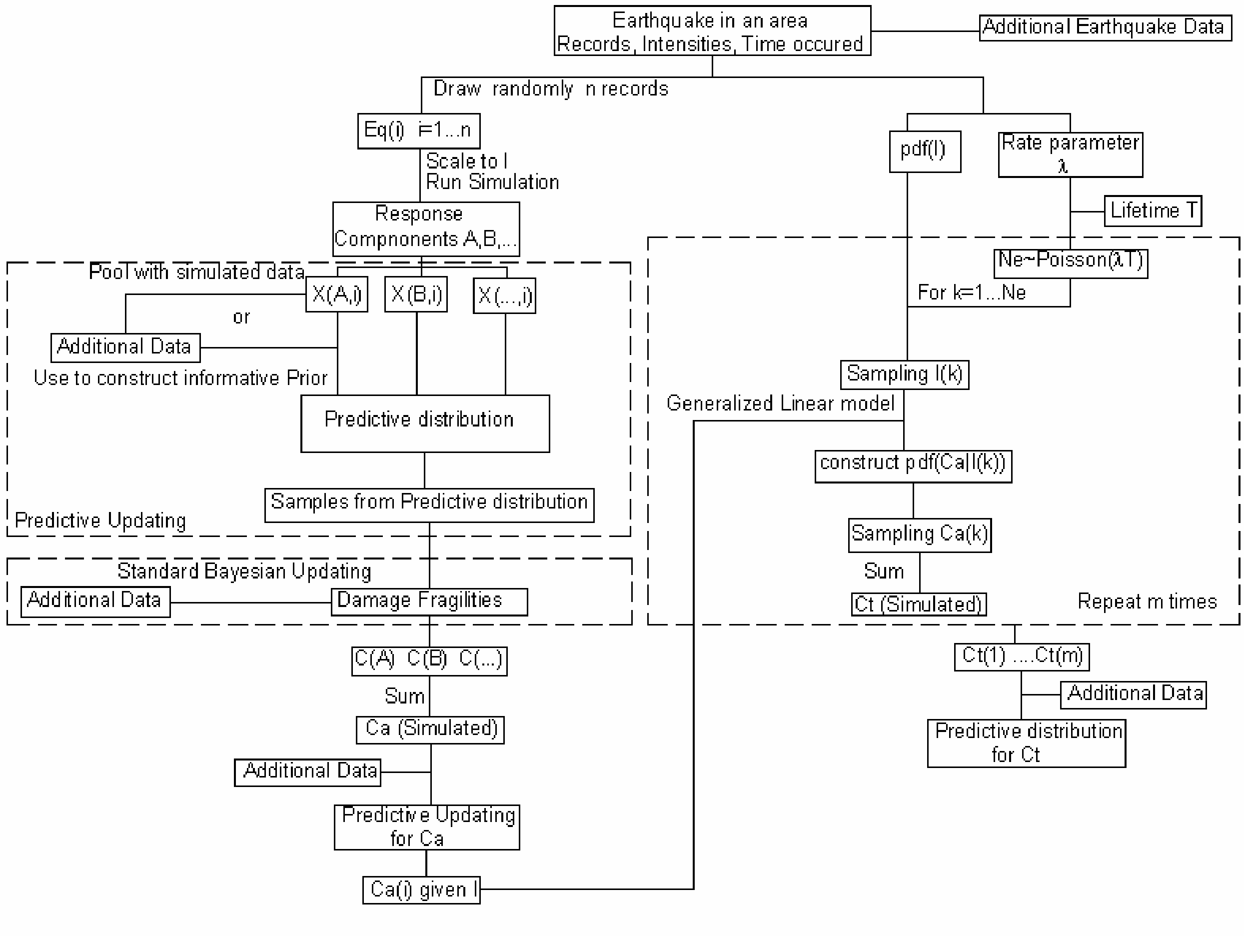

Figure 1. Flowchart for potential lifetime loss.

In order to estimate loss of the entire building, one may estimate the losses contributed through individual components inside the building. However, the time domain structural analysis only yields structural responses such as inter-story drifts. Component damage fragility serves as the link between structural response of a particular component to the cost involved to repair or replace this component. This concept has been developed and used in earlier studies (Porter, 2000).

A generalized damage level measure is used for all components. It includes four damage levels, namely Non-detectible (I), Repairable (II), Degrading repairable (III), and Demolish-replace (IV). Each damage level is connected with structural response (inter-story drift in this case) on one side and repair cost/loss on the other. The connections are represented by a Bayesian predictive distribution conditional on the damage level. It provides the upgrade option for the damage fragility when extra data (e.g. component or assembly test data) becomes available. The cost measure in the damage fragility is normalized by the new component replacement cost. Thus the fragility can be decoupled from regional/periodical price fluctuation since the change in new product cost data can be reflected by data sources such as the latest RS Means publication.

An accurate (nonlinear) structural analysis model is essential to the accuracy of the simulation results. The model used in this study was first introduced by Folz and Filiatrault (2001). In this model, the story diaphragm is assumed to be rigid and connected to one another with shearwall components modeled as non-linear hysteretic springs. This model was incorporated in an analysis program SAWS (Folz and Filiatrault, 2004). An alternative model termed the Evolutionary Parameter Hysteretic Model (Pei et al., 2006) was used within a similar software package entitled Seismic Analysis Package for Woodframe Structures (SAPWood). SAPWood is available free at www.engr.colostate.edu/NEESWood/ .

Once the framework to assess lifetime loss is established, the design problem based on the minimization of lifetime loss can take on many forms: the objective is to find the optimized loss for a predetermined construction budget; to find the design that yields optimized initial cost to loss ratio given architectural floor plans; etc. These design problems usually have complicated (or vague) constraints (e.g. predefined architectural floorplans) which may be difficult to represent with mathematical models. Without extensive simplifications and assumptions, the derivation of analytical solutions to the loss minimization problem in PBSD is virtually impossible to perform. However, the modeling error introduced by these simplifying assumptions might greatly undermine the practical value of the solution. On the other hand, simulation techniques based on a trial-and-error design procedure can provide practical solutions to such problems, although they might not be the mathematically minimized solution. In this study, optimized design alternatives for typical woodframe residential floor plans are investigated and compared.

Numerical Example: Two-Story Residential Structure

In this section, alternative designs of a typical two story single family building in North America having a predetermined floor plan will be evaluated based on potential lifetime economic losses. The economical performance of the designs for different lifetime durations will be determined from the analysis results. The floor plan layout for the building is illustrated in Fig. 2. The structure has a total area of about 160 m2 (1700 sq-ft). The seismic mass is assumed to be approximately 240 kg/m2 (50 lb/ft2) at first floor and 120kg/m2 (25 lb/ft2) at the roof level. The lifetime losses covered in this analysis includes the repair/replacement of three types of structural components, namely the exterior shearwalls with OSB panel sheathing, the interior partition walls with gypsum wall board finishing, and doors/windows. For each of these components, different damage fragilities were assigned and different repair/replacement costs were associated. Two different structural configurations were investigated in this example: the first one uses 4/12 inch (100/300 mm) nail spacing (i.e. 100mm on the sheathing panel exterior and 300mm on the field nailing) on all exterior walls (configuration A); and the second uses 6/12 inch (150/300 mm) nail spacing (configuration B). It will be reasonable to assume that design A will be stronger than B and performs better during most of the earthquakes. But the amount of influence this detailing has on the life cycle loss must be estimated through simulation.

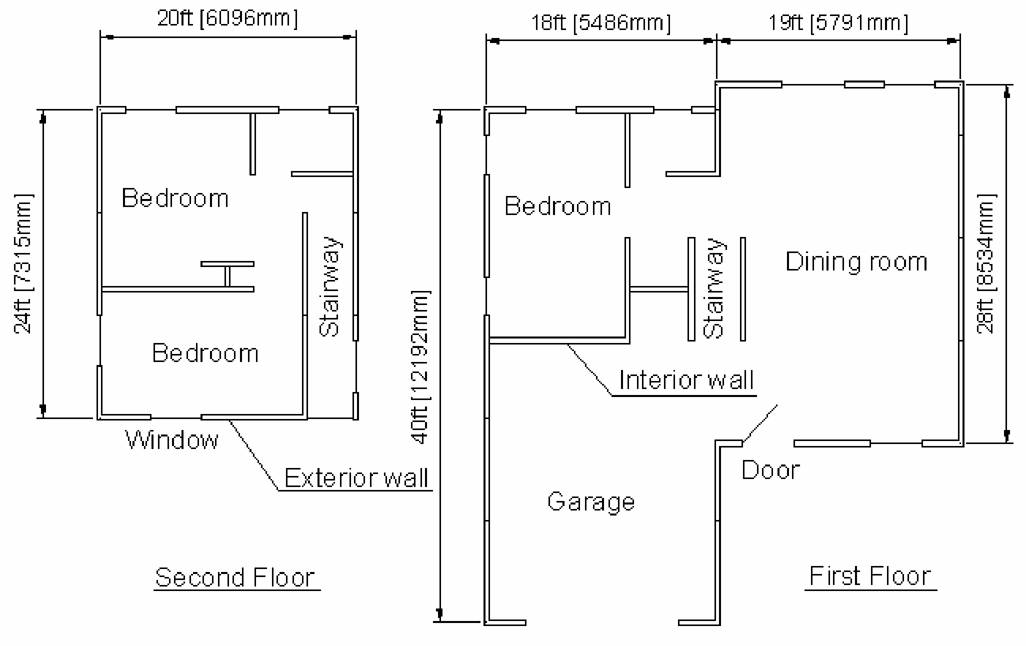

Figure 2. Two-story residential structure.

Ideally, an earthquake database constructed from continuous earthquake monitoring at the location of the structure should be used within the simulation framework. In virtually all cases this is not possible, i.e. practically. In this study a suite of twenty ground motion records was applied to illustrate the implementation of the framework. The earthquake occurrence rate parameter was determined from the United States Geological Survey (USGS) recorded historical earthquakes in the California area from 2001 to 2005. The intensity measure used in this example was the spectral acceleration at 0.3 seconds with 5% damping. The simulation first obtained the relationship between the loss of a single earthquake and the intensity of that earthquake (Eq. 3). Due to the uncertainty in the earthquake hazard, this loss was modeled as a random variable following a lognormal distribution whose parameters were functions of intensity from the regression analysis of the simulated loss data. Note that the cost considered here only includes the cost associated with the construction/installation of the three types of structural components discussed earlier. The cost of other construction tasks such as painting, plumbing work, etc. is not included in this analysis and will be added eventually.

With the model for economic loss in a single earthquake established, the structures' behavior under several typical life time durations was investigated following the simulation scheme discussed in the framework section earlier. The structural life time durations of interest include several different values, specifically 5 years, 30 years, and 75 years. The simulated total structural repair cost data were fit with lognormal distributions and presented in Fig. 3, with some critical statistics listed in Table 1. Because the normalized cost fragility for individual components was used, the cost values in the table were also normalized by the total cost of replacing these components, which differs from the purchasing price of the house. From the results, one can see that design A not only provides a lower mean loss value, but also results in a lower variation in lifetime loss.

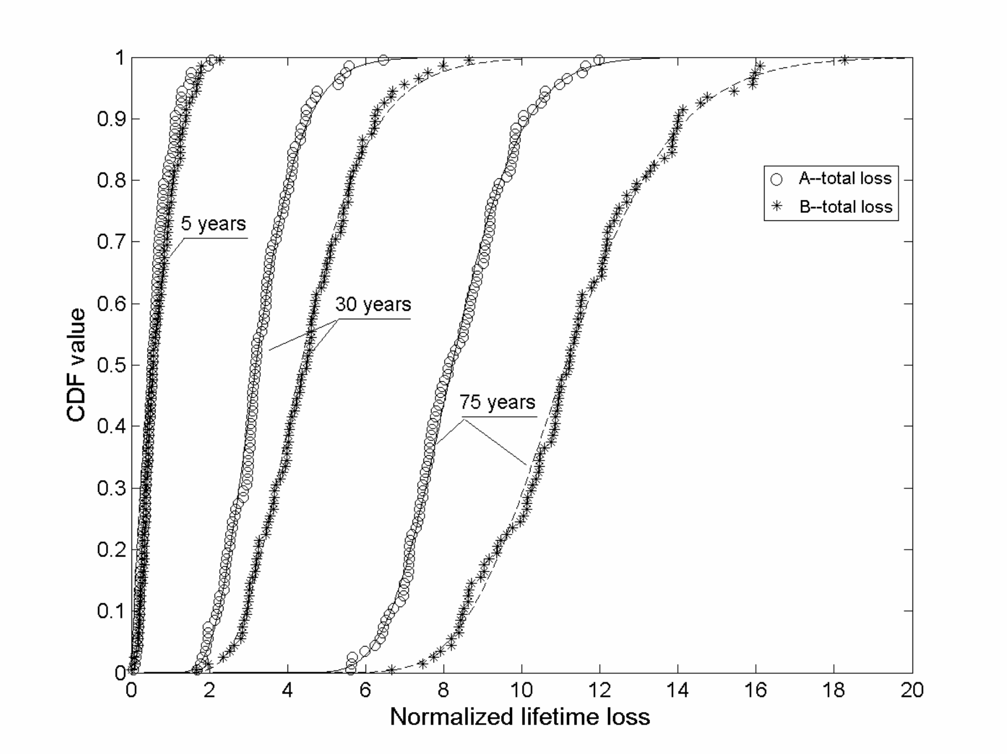

Figure 3. Cumulative Distribution Function (CDF) for Normalized Lifetime loss.

Table 1. Statistics of loss simulation results.

Nailing Design	5 years		30 years		75 years	
	mean	std	mean	std	mean	std
A	0.62*	0.40	3.31	0.92	8.33	1.38
B	0.71	0.46	4.54	1.34	11.33	2.18

*Normalized cost by total replacement cost.

Conclusions

By setting up the Bayesian loss framework and showing the numerical simulation results from two typical residential construction examples, a procedure to perform lifetime loss-based seismic analysis has been demonstrated in this paper. In the case of the illustrative house example, the difference in design detailing significantly affected the performance, i.e. loss, of the structure against earthquake hazard over time. The comparison of the lifetime loss favors the design with stronger exterior walls, as one would expect. The examples show that the potential lifetime loss due to earthquake hazard will depend on structural configuration/design and can be incorporated into a more general second generation performance-based seismic design (PBSD) philosophy that includes losses.

Acknowledgments

This study was supported by the National Research Initiative of the USDA CSREES through grant number 2005-35103-15250.

References

Ang, A.H. and Lee, J.C., 2001. Cost optimal design of R/C buildings. *Reliability Engineering and System Safety* 73(3): 233-238.

Folz, B. and Filiatrault, A., 2001. Cyclic analysis of wood shear walls. *Journal of Structural Engineering* 127(4): 433-441.

Folz, B. and Filiatrault, A., 2004. Seismic analysis of woodframe structures. I: Model formulation. *Journal of Structural Engineering* 130(9): 1353-1360.

Folz, B. and Filiatrault, A., 2004. Seismic analysis of woodframe structures. II: Model implementation and verification" *Journal of Structural Engineering* 130(9): 1361-1370.

Gelman, A., Carlin, J.B., Stern, H.S. and Rubin, D.B., 2004. *Bayesian data analysis. Second edition*. Boca Raton: Chapman & Hall/CRC.

Liu, M., Burns, S.A. and Wen, Y.K., 2003. Optimal seismic design of steel frame buildings based on life cycle cost considerations. *Earthquake Engineering and Structural Dynamics* 32(9): 1313-1332.

Liu, M., Wen, Y.K. and Burns, S.A., 2004. Life cycle cost oriented seismic design optimization of steel moment frame structures with risk-taking preference. *Engineering Structures* 26(10): 1407-1421.

Liu, S.C. and Neghabat, F., 1972. Cost optimization model for seismic design of structures. *Bell System Technical Journal* 51(10): 2209-2225.

Pei, S., van de Lindt, J.W., Rosowsky D.V. and Pang W.C., 2006. Next generation hysteretic models for development of a performance-based seismic design philosophy for woodframe construction. *8th National Conference on Earthquake Engineering*, San Francisco, CA.

Porter, K.A., 2000, Assembly-based vulnerability of buildings and its uses in seismic performance evaluation and risk-management decision-making, *Ph.D. Thesis*, Stanford, CA.

Porter, K.A. et al., 2001. Improving loss estimation for woodframe buildings. *CUREE Publication No. W-01*, CUREE-Caltech Woodframe Project, Dept. of Structural Engineering, Univ. of California, San Diego.

Seible, F., Filiatrault, A. and Uang, C.M., 1999. Proc. Invitational workshop on seismic testing, analysis and design of woodframe construction. *CUREE Publication No. W-01*, CUREE-Caltech Woodframe Project, Dept. of Structural Engineering, Univ. of California, San Diego.

van de Lindt, J.W., Rosowsky, D.V., Filiatrault, A., Symans, M.D. and Davidson, R.A., 2006. The NEESWood project: Progress on the development of a performance-based seismic design philosophy for mid-rise woodframe construction. *World Conference on Timber Engineering*, Portland, OR.