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Development of Earthquake Vulnerability Functions and Risk Curves for Low and Mid-rise Hotel Buildings using a Performance-based Loss Estimation Framework

A. Safiey[1], W. Pang[2], M. Javanbarg[3], K. Rokneddin[4], E. Ziaei[5]

[1] *Research Assistant, Glenn Department of Civil Engineering, Clemson University, 139 Lowry Hall, Clemson, SC 29634-0911, USA, asafiey@clemson.edu*

[2] *Associate Professor, Glenn Department of Civil Engineering, Clemson University, 312 Lowry Hall, Clemson, SC 29634-0911, USA, wpang@clemson.edu*

[3] *Manager, Cat Management and Analytics Center of Excellence, AIG, NY, USA and Adjunct Faculty, Glenn Department of Civil Engineering, Clemson University, Lowry Hall, Clemson, SC 29634-0911, USA, Mohammad.Javanbargh@aig.com*

[4] *Senior Research Scientist, Cat Management & Analytics Center of Excellence, AIG Property Casualty, 1650 Market St., 38th Floor, Philadelphia, PA 19103, Keivan.Rokneddin@aig.com*

[5] *PhD Candidate, Glenn Department of Civil Engineering, Clemson University, 131 Lowry Hall, Clemson, SC 29634-0911, USA, eziaei@clemson.edu*

Abstract

The concept of performance-based earthquake engineering has gained significant attentions in both the research and engineering communities. The development of a performance-based seismic loss assessment framework, known as the FEMA P-58 method, allows one to estimate the potential financial losses of a building using performance-based engineering method. This research employs a seismic loss estimation framework derived using the P-58 method to estimate the monetary loss of a mid-rise wood-frame hotel building which is assumed to be located in Napa Valley, California. A 3D structural model representative of the dynamic behavior of the wood-frame hotel was created and subjected to Incremental dynamic analysis (IDA). The structural demands (peak inter-story drifts, peak floor accelerations etc.) obtained from the IDA were utilized in the developed loss estimation framework to assess losses of structural and non-structural components as well as content damages. Preliminary results such as the cumulative loss functions for given intensities and annual risk curve (annual exceedance probability versus monetary loss) are presented and discussed.

Keywords: loss assessment, light-frame wood, performance based earthquake engineering, FEMA P-58

1. Introduction

Performance-based earthquake engineering (PBEE) has gained increasing recognition and applications in recent years. One of the key milestones for PBEE is the development of the FEMA P-58 methodology, a framework for assessing the building specific seismic performances through engineering principles [1]. The FEMA P-58 report series contain loss estimation examples for reinforced concrete moment frames, steel moment frames and masonry structures. Example applications of the P-58 methodology are also presented using a companion computer program for P-58, known as PACT (Performance Assessment Calculation Tool). PACT is a graphical user interface tool developed to streamline the implementation of the P-58 methodology. While the examples presented in the P-58 reports are for steel, concrete and masonry buildings, a significant portion of the North American building stock is light-frame wood construction. This paper presents the development of a performance-based loss estimation framework derived from the P-58 methodology and its application to develop loss (vulnerability) function for a four-story wood-frame hotel building.

The losses incurred by the 2014 South Napa earthquake (M_w = 6.0) in California, US were estimated to be between \$362 million and \$1 billion USD [2][3]. A survey of the seismic performance of buildings and nonstructural components in the 2014 South Napa earthquake is available in [4]. While the post-earthquake reconnaissance report [2] focuses mainly on the behavior of unreinforced masonry buildings, a significant portion of the buildings affected by the South Napa earthquake is light-frame wood construction. To evaluate the risk from possible future events, this paper adopts the stochastic framework of P-58 to evaluate the exceedance probabilities of losses.

2. Building Description and Dynamic Response Model

The example study building is a four-story hotel constructed in accordance to the modern US seismic codes (Fig. 2). The main lateral load resisting system of the hotel is light-frame wood shear wall. The building is 14.6 m (48 ft) wide, 29.3 m (96 ft) long and 12.8 m (42 ft) tall with a plate-to-plate story height of 3.2 m (10.5 ft). The total seismic weight of the building is 4320 kN (971 kips). The perimeter shear walls are sheathed with wood structural panels, and finished with gypsum wallboards in the interior and stucco on the exterior. All partition walls (non-shear walls) are assumed to be covered by gypsum wallboards on both faces. The first three periods of the building model are 0.58s, 0.55s, and 0.54s, which correspond to translational mode in the North-South direction, translational mode in the East-West direction and torsional mode, respectively (Fig. 2).

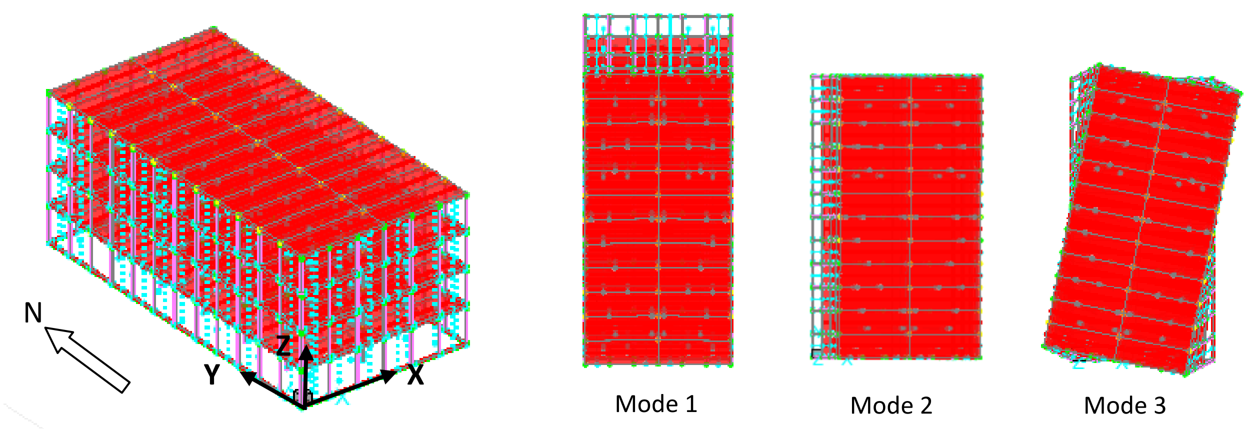

Fig. 1 – 3D building model for the case study 4-story wood-frame hotel.

The dynamic response of the 4-story wood-frame hotel is modeled using a nonlinear dynamic analysis software called Timber3D developed at Clemson University. The Timber3D model is based on co-rotational formation [4] and large displacement theory, which makes it suitable for modeling the dynamic responses under very large deformations and simulated collapse with P-Delta effect. Fig. 3 shows the pushover curves of the building. The peak base shear coefficients (normalized by total building weight) are about 0.39 and 0.35 for the North-South and East-West directions, respectively.

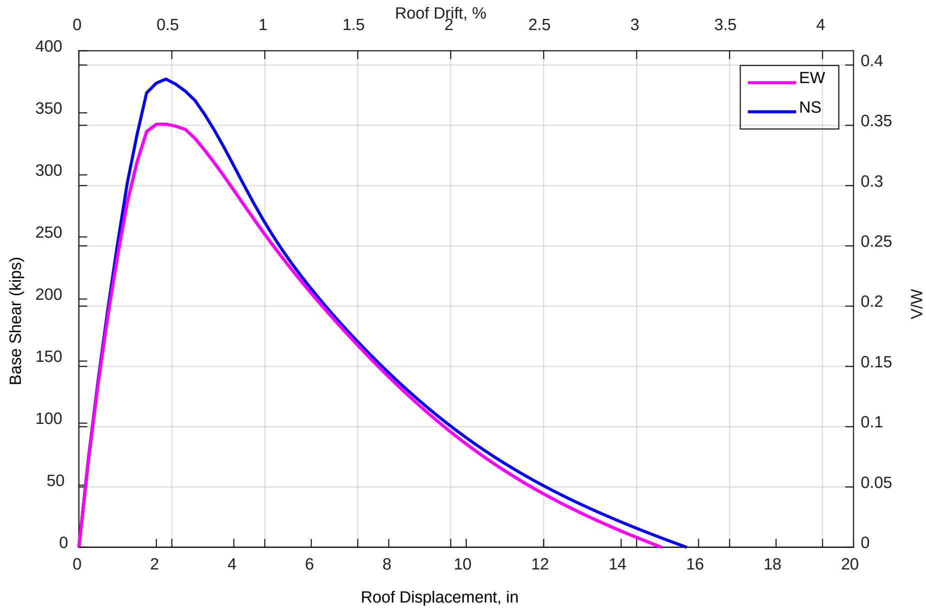

Fig. 2 – Monotonic pushover curves of the 4-story wood-frame hotel.

Incremental dynamic analysis (IDA) using nonlinear response history procedure is utilized to quantify the engineering response quantities (peak inter-story drifts, peak floor accelerations, etc.) of the building under different hazard levels. An ensemble of 22 pairs of bi-axial far field ground motions developed as part of the FEMA P-695 project [5] was utilized in this study. Fig. 4 shows the individual response spectra of the FEMA P-695 ground motions scaled to median S_a of 1.5 g at T_n of 0.25s.

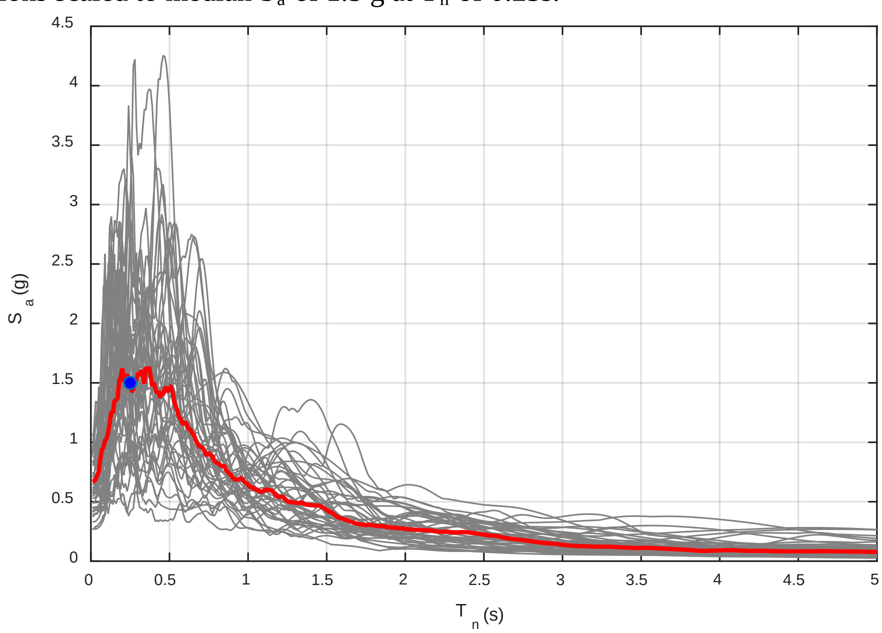

Fig. 3 – FEMA P-695 far field ground motions scaled to median Sa of 1.5g at T_n = 0.25s.

The IDA was carried out by scaling the median of the P-695 response spectrum at T_n of 1.25s from 0.1g to 3.0g with increments of 0.1g. This procedure results in a total of 1320 nonlinear response history analyses required in a complete set of IDA. The Clemson University super computer (Palmetto Cluster) was utilized for the IDA. The IDA results in terms of peak roof drift versus median scaled S_a are presented in Fig. 5.

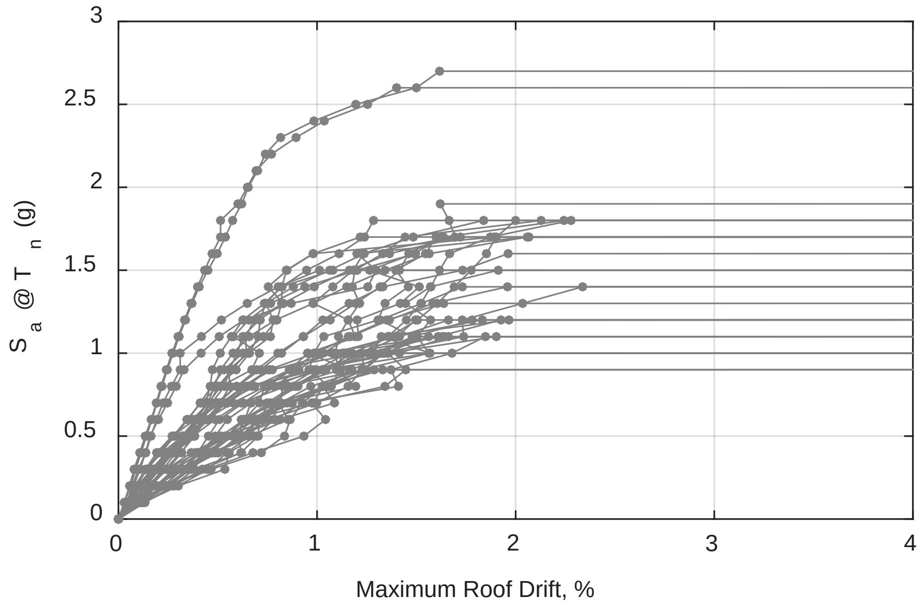

Fig. 4 – Incremental dynamic analysis (IDA) curves.

Fig. 6 shows the collapse fragility curve for the 4-story hotel building. The data points shown in Fig. 6 were obtained from the IDA results (see Fig. 5). Note that the raw collapse data points include only the ground motion or record-to-record uncertainty. The final collapse fragility curve shown in Fig. 6 was determined using the FEMA P-695 procedure [5], which accounts for the total uncertainty of the building. The collapse fragility curve and engineering demand parameters (EDP), which include the maximum acceleration, drift and residual drifts in each story, are utilized for loss assessment.

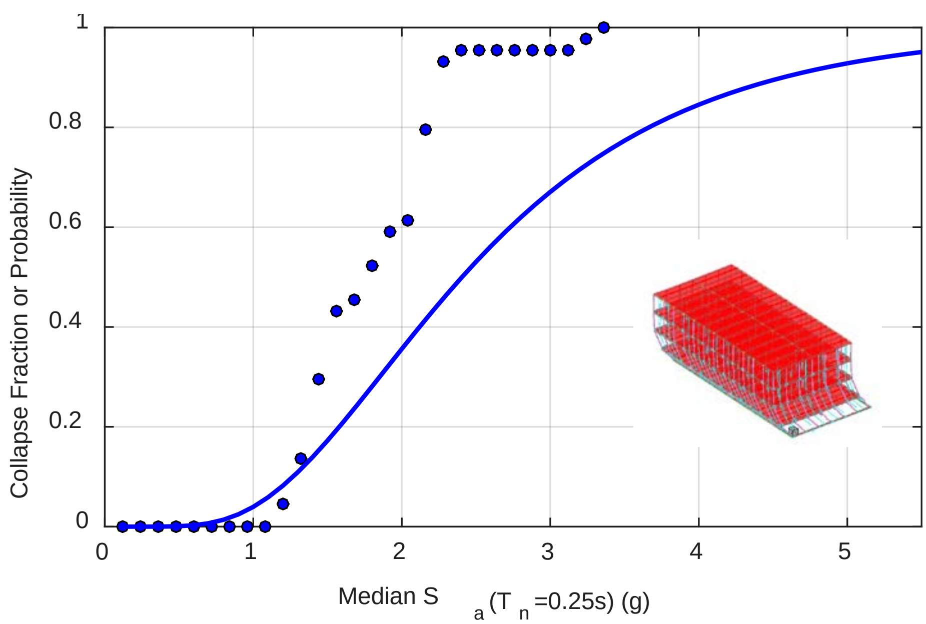

Fig. 5 – Collapse fragility curve and an example deformed shaped of the building model at incipient collapse.

3. Performance Model

The objective of the "Performance Model" is to translate the engineering demand parameters into quantifiable seismic performances (e.g. translation of damage into monetary loss). In this study, a MATLAB code is developed to conduct loss estimation. The loss estimation procedure is depicted graphically in Fig. 7. The performance model requires Monte Carlo simulations (MCS) to be carried out. In each realization of MCS, two checks of 'collapse' and 'reparability' need to be conducted. The Collapse state is being checked using fragility collapse curve obtained from IDA (see Fig. 6). Reparability is being checked against the corresponding reparability fragility curve as prescribed by FEMA P-58. The reparability fragility curve is characterized using residual drift and it is modeled using a lognormal distribution with a median residual drift of 1% and a logarithmic standard deviation of 0.3.

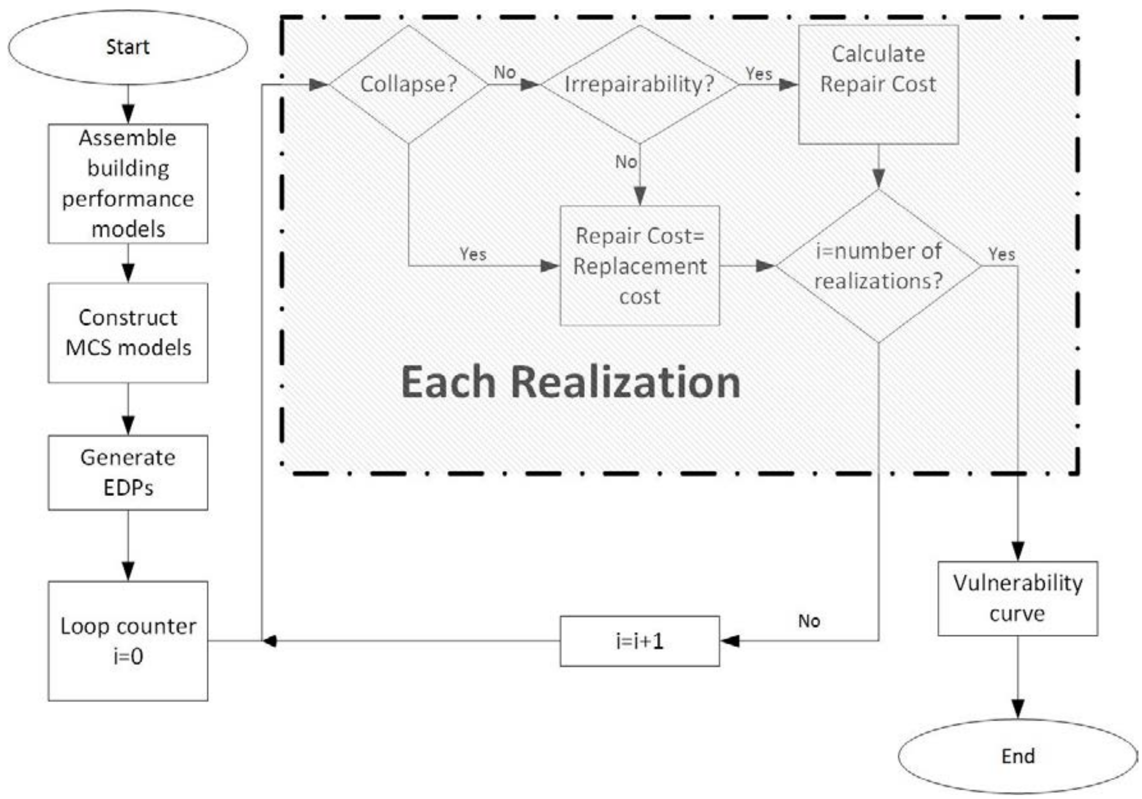

Fig. 6 – Flowchart of the loss assessment procedure.

In the "Performance Model", a building is treated as an assembly of components, either 'vulnerable' or 'rugged.' In order to assess the potential loss, seismically vulnerable components within the building must be identified. This task highly demands for engineering experience and discerning judgement. The list of major vulnerable components for a typical hotel and the corresponding quantity of each vulnerable component are listed in Table 1. FEMA P-58 Volume 1 Appendix F presents normative quantities which could be used to populate the list of components for select building types. In this research, the inventory list furnished by the tool is adopted as the starting point and the list was further modified based on consultation with a practitioner/engineer. Table 1 presents the inventory list of vulnerable components totaling 19 items. The consequence functions for these components are adopted from the database of FEMA P-58 [1].

Each ground motion excites simultaneously the structure in two horizontal directions resulting in a set of EDPs for each ground motion. The peak EDP for each of the horizontal directions is used to estimate the loss of components that are direction dependent. For components that are not direction sensitive (e.g. sprinkler system), the maximums of the two horizontal EDPs were utilized for loss estimation.

Table 1 – List of vulnerable componentes.

#	Component	Abridged Description	Quantity*	Ground Floor	Typical Floor	Roof
1	B1071.021	Light framed wood walls	16.8	-	x	x
2	B2022.001	Curtain Walls	67.2	-	x	x
3	C1011.011a	Wall Partition: gypsum + wood studs	2.76	-	x	x
4	C3011.001a	Wall Partition: gypsum + wall paper	1.33	-	x	x
5	C3032.003c	Suspended ceiling	2.76	-	x	x
6	D2021.013a	Cold water piping	0.07	-	x	x
7	D2022.013a	Hot water piping – small diameter	0.737	-	x	x
8	D2022.023a	Hot water piping – large diameter	0.14	-	x	x
9	D2031.013b	Sanitary waste piping	0.437	-	x	x
10	D3041.011c	HVAC Duct	0.23	-	x	x
11	D3041.032c	HVAC Drops / Diffusers	3.69	-	x	x
12	D3041.041b	Variable air volume box	2.76	-	x	x
13	D5012.021a	Low voltage switchgear	0.23	-	x	x
14	D4011.023a	Fire sprinkler piping	1.014	-	x	x
15	D4011.033a	Fire sprinkler drop	0.55	-	x	x
16	C3021.001p	Generic flooding	1000	-	x	x
17	E2022.010	Content with unknown restraint	20	x	x	-
18	E2022.013	Content with low friction surface	20	x	x	-
19	B3011.011	Concrete roof tile	32	-	-	x

*: units as per FEMA P-58[1].

4. Results

The results of the seismic performance assessment were amalgamated in two types, namely vulnerability curve and risk curve. The vulnerability curve, which is also called ‘performance function’ in accordance to the FEMA P-58 terminology, presents monetary loss versus probability of non-exceedance for a given hazard intensity measure (e.g. spectral acceleration). The vulnerability curve is site independent. It can be convoluted with the site hazard curve to obtain the ‘risk curve’ or ‘time-based performance function’. Fig. 8 shows the vulnerability curves of the case study 4-story wood-frame hotel. In this study, the hotel is assumed to be located in Napa valley of California, US. The hazard curve of a location in Napa valley is obtained from the USGS database. Interpolation was carried out to construct the hazard curve corresponding to the fundamental vibration period of the structure as plotted on Fig. 9. The vulnerability curves were convoluted with the hazard curve to develop the risk curve as shown on Fig. 10. The final annual risk curve can be used to price the insurance premium accordingly based on building specific and site specific information.

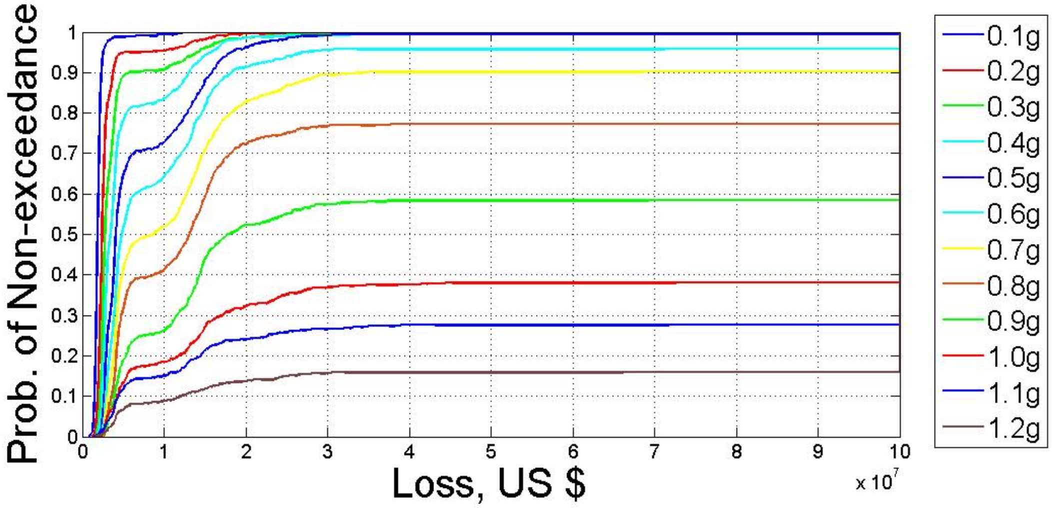

Fig. 7 – Vulnerability curves of the 4-story hotel.

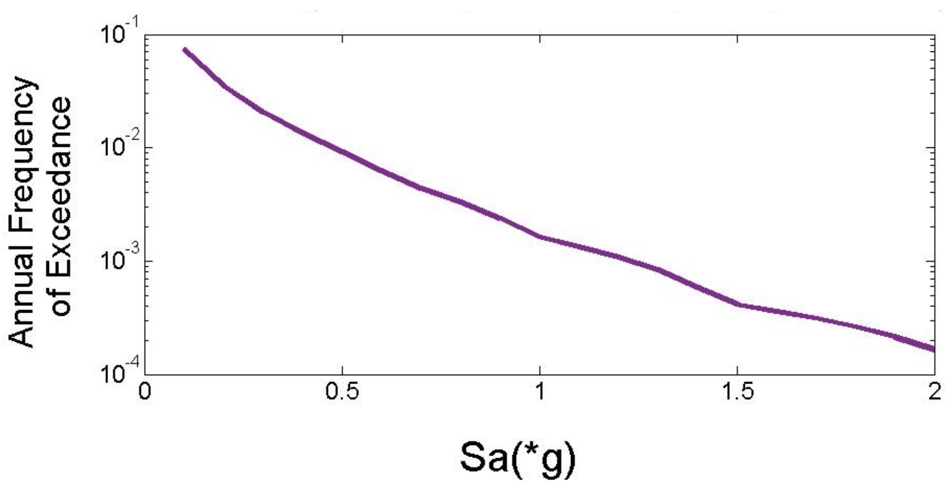

Fig. 8 – Hazard curve of a location in Napa valley, California, USA.

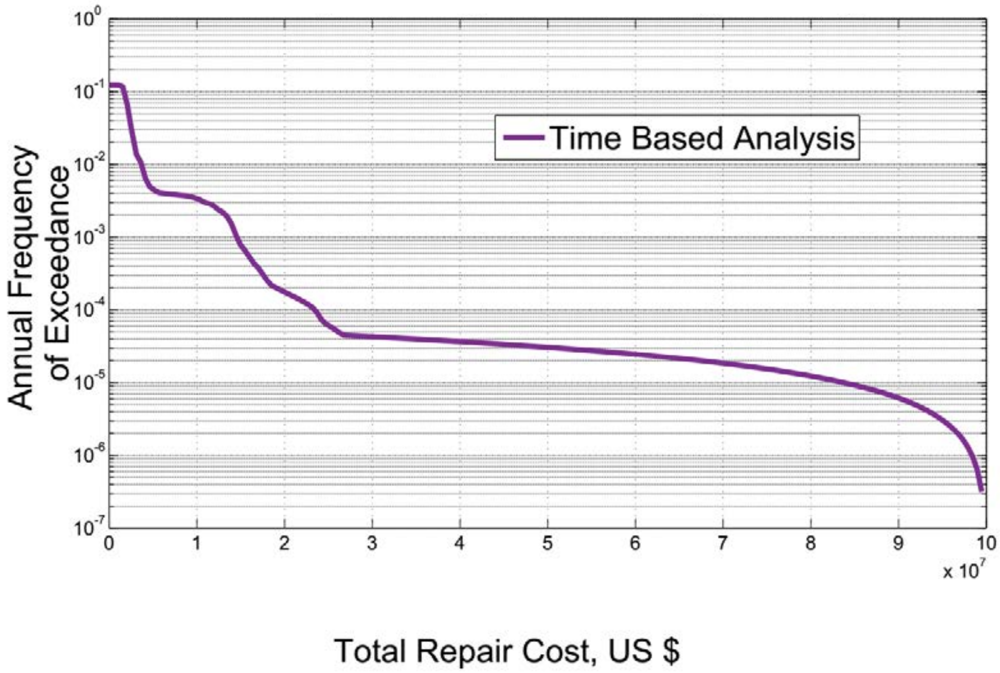

Fig. 9 – Annual risk curve of the 4-story hotel.

5. Conclusion and Findings

This paper presents the preliminary results of a pilot study on developing site independent vulnerability curves and site dependent risk curve for a vintage 4-story light-frame wood hotel. This is the first step of an ongoing collaborative research project between the Clemson University and AIG (American International Group). The overarching goal of the research is to develop a performance-based earthquake engineering method for loss estimation and use the framework to develop vulnerability curves for different types of building systems. These vulnerability functions will then be incorporated into a GIS-based hazard tool for regional loss assessment of building portfolios.

Catastrophe models for the insurance industry heavily rely on empirical methods to develop vulnerability functions out of past claims data. While analytical models are also used for this purpose, the application of performance-based earthquake engineering as outlined in the P-58 framework is in its infancy. Moreover, empirical or analytical vulnerability curves for generic building types which are developed for loss estimation for a large portfolio of buildings do not accurately represent the response of specific sites or buildings types. In addition, generic vulnerability curves are primarily suitable for more frequent minor to moderate seismic events where there are more data available for calibration. For infrequent and large events, the performance-based framework provides enhanced methods for site-specific risk assessment. Therefore, the presented research can provide a more reliable estimate of potential losses for irregular buildings and infrequent large magnitude earthquakes where past claims data are scarce and limited.

7. References

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