16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 3996
Registration Code: S-N1464557747

Performance-based Seismic Evaluation of Structural Insulated Panels

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Abstract

Structural Insulated Panels (SIPs) represent an example of an energy-efficient structural system. They are composed of an insulation core, such as expanded polystyrene (EPS), with both traditional and novel facing materials such as plywood, oriented strand board (OSB), cement mortar, or steel. Developed over 60 years ago, SIPs are extensively used throughout Europe and North America. However, there is limited information available about the seismic behavior of SIPs. Therefore, their application in seismically hazardous regions is limited due to unacceptable performance as demonstrated by few cyclic tests. Seismic performance of a building constructed from SIPs is evaluated in this study using the performance-based earthquake engineering (PBEE) methodology developed by the Pacific Earthquake Engineering Research (PEER) Center. Several quasi-static and hybrid simulation tests have recently been conducted at University of California, Berkeley to quantify the earthquake response of SIPs. The results of these tests are used in the structural and damage analyses stages of the PEER PBEE methodology. The considered building for this study is a hypothetical two-story single-family house-over-garage building made of SIPs. The building is assumed to be located in San Francisco Bay Area, California, where such buildings are prevalent. Particularly, loss curves are obtained for this building constructed using different nail spacing. From the previously conducted tests, the nail spacing was observed to have considerable effect on the seismic response of SIPs. Results of the PBEE analyses indicated the importance of nail spacing on the seismic performance of a single-family house and highlighted that the usage of SIPs in highly seismic areas can be increased by improving the construction and design details. Increased usage of SIPs is expected to be influential in accelerating the construction process and enhancing the energy-efficiency of the built environment in seismic regions.

Keywords: construction details, hybrid simulation, PEER performance-based earthquake engineering methodology, single family homes, structural insulated panels.

1. Introduction

30~40% of all primary energy in the world is consumed by buildings. Furthermore, buildings are considered to account for 40~50% of all greenhouse gas emissions [1]. Energy consumed by buildings can be separated into three components: Embodied energy, Operating energy and Demolition energy. Embodied energy is the energy employed for construction of the building, including the energy content of all the building materials and energy used at the time of erection, construction and renovation of the building. Operating energy is the energy required for proper functioning of a building to meet the needs of the occupants. It consists of several components, such as the energy for thermal (i.e., Heating, Ventilation and Air Conditioning (HVAC) systems), lighting, domestic hot water and the energy for running appliances. Demolition energy is the energy required to demolish the building and transport the waste material to landfill sites and/or recycling plants. A literature survey on the life cycle energy use of 73 case study buildings from 13 countries indicated that the operation energy is significantly larger than all other components, with 80~90% of the total building life-cycle energy [2]. One of the important contributors of operation energy of buildings is the thermal energy consumption. Thermal insulation features of a building is generally enhanced by improving the building envelope, i.e. the façades and the roof. Thermal insulation in wood framed buildings is conventionally achieved by the use of insulation material, such as fiberglass or wood foam, placed in between the vertical studs. However, the vertical wood studs introduce thermal bridges, reducing the efficacy of the insulation material. Furthermore, air infiltration cannot be significantly reduced in this conventional way of insulation [3].

As opposed to a steel or reinforced concrete moment frame, where the façade is geometrically separated from the structural frame, in wood framed buildings, the façade is integrated with the structural system, as indicated in Fig. 1. Therefore, it is a rational approach to develop a structural system with inherent thermal resistance features for wood construction. Structural insulated panels (SIPs) represent an example of an energy efficient structural system developed using this design approach.

SIPs consist of two outer skins and an inner core of insulating material, which are bonded together to form a monolithic wall unit. The insulation core consists of expanded polystyrene (EPS) or urethane foam, while the outer skins are typically plywood, oriented strand board (OSB), cement mortar, or steel, Fig. 2.

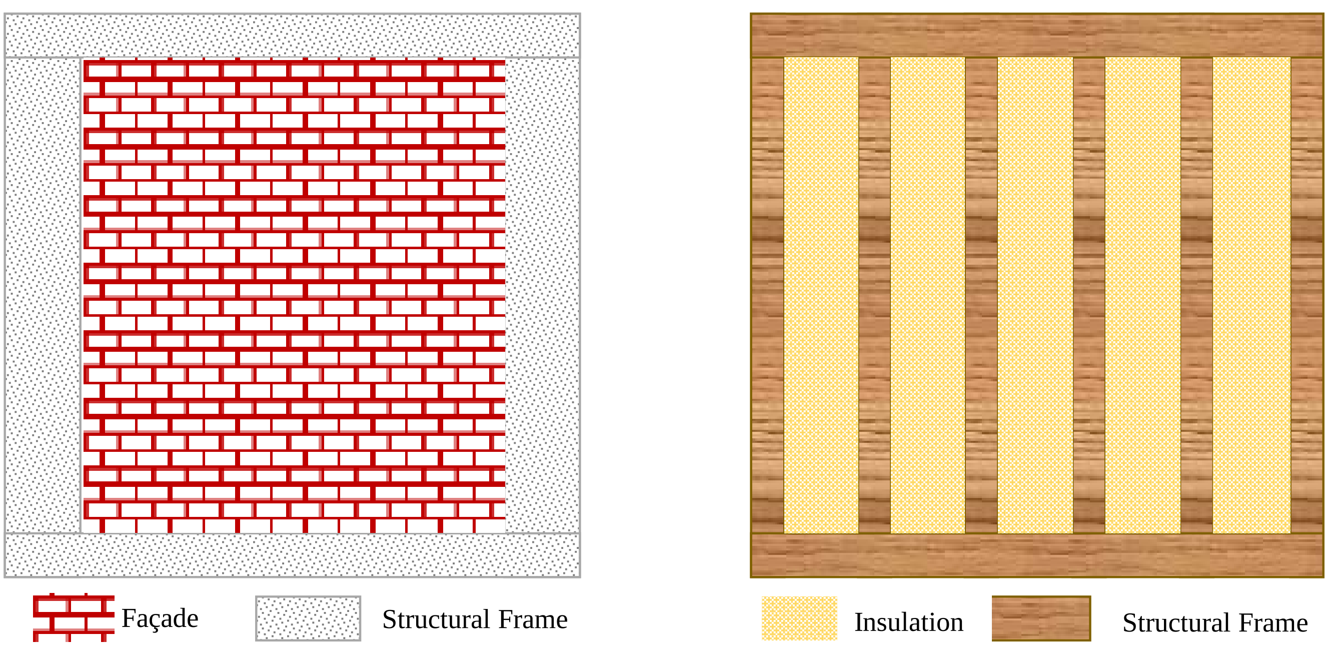


Fig. 1 – Structural frame geometrically separated from the façade in reinforced concrete construction (left), structural frame and the façade geometrically integrated in wood framed construction (right)

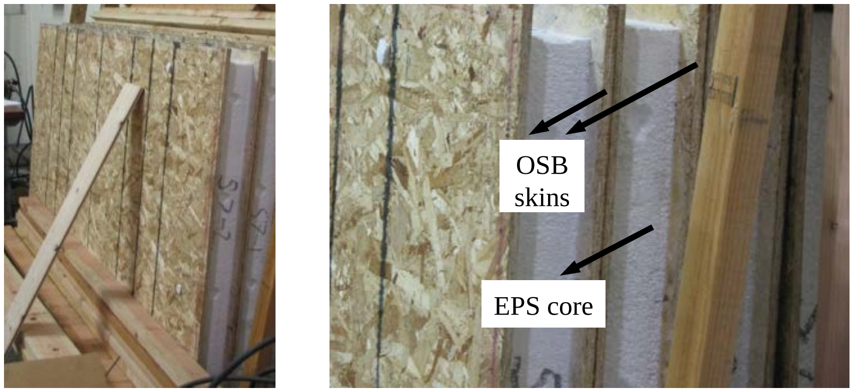


Fig. 2 – Structural insulated panels with ESP core and OSB skin

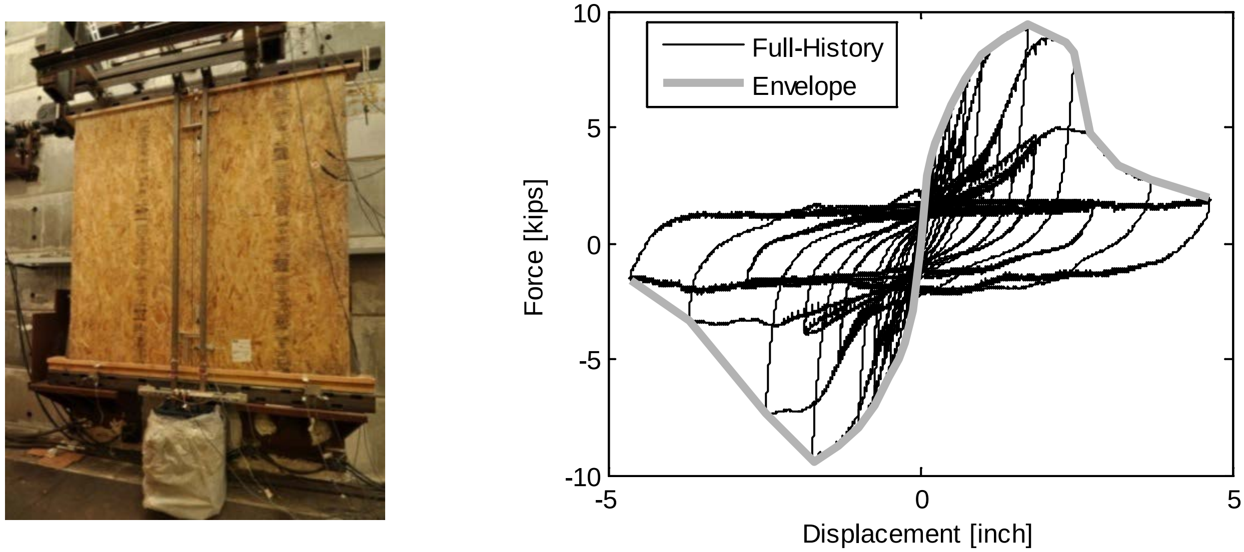
Developed over 50 years ago, SIPs are extensively used throughout Europe and North America. Although the thermal features of SIPs are well-established [3-5] and there are a reasonable number of experimental and analytical response of SIPs subjected to wind and snow loading, there is considerably limited information available about the seismic behavior of SIPs. The International Building Code (IBC) [6] and ASCE 7-10 [7] do not directly address SIPs. The International Residential Code for One- and Two-Family Dwellings [8] limits the use of SIPs to only one- and two-story family dwellings, and to only the Seismic Design Categories A through C. While there is a growing database of SIPs tests, the seismic performance of SIPs has not yet been evaluated on a systems level. A performance-based seismic evaluation of a hypothetical two-story single-family house-over-garage building, made of SIPs, is conducted in this study. The performance-based earthquake engineering (PBEE) methodology developed by the Pacific Earthquake Engineering Research (PEER) Center is employed in the conducted PBEE analyses. A test program consisting of several quasi-static and hybrid simulation (HS) tests to quantify the earthquake response of 8 ft × 8ft SIPs have recently been completed at the University of California, Berkeley. The results of these tests are used in the structural and damage analyses stages of the PEER PBEE methodology. Particularly, loss curves are obtained for the considered hypothetical building constructed from SIPs using 3 and 6 inch nail spacing.

2. Experimental Program

The conducted experimental study consisted of cyclic and HS tests of 8ft × 8ft SIPs using the setup shown in Fig. 3a. The test matrix and the global envelope response of the tested specimens are shown in Table 1 and Fig. 4, respectively. Interested readers can find more detailed information about the pursued experimental program in [9]. The complete force-deformation of one of the specimens is plotted together with the corresponding envelope in Fig. 3b. From this figure, it is observed that the nail spacing has the most significant effect on the seismic response. Therefore, the effect of nail spacing on the seismic performance of a single-family house is investigated in this paper as discussed below.

Table 1 – Test matrix for the experimental program pursued in [9]

Specimen	**Protocol**	**Gravity**	**Nail spacing [in]**	**Remarks**
S1	CUREE	No	6	Conventional wood panel
S2	CUREE	No	6	-
S3	CUREE	Yes	6	-
S4	HS	Yes	6	Near-fault pulse-type ground motion (GM)
S5	HS	Yes	3	Near-fault pulse-type GM
S6	CUREE	Yes	3	-
S7	HS	Yes	3	Long duration, harmonic GM
S8	HS	Yes	3	Near-fault GM; 3 stories computational substructure



(a) (b)

Fig. 3 – (a) Test setup, (b) Complete force displacement history and envelope curve for S3

3. Performance-based Earthquake Engineering Analyses

The PEER PBEE methodology is a second generation PBEE method developed to improve the first generation methods [10]. The main features of the PEER methodology are as follows:

- Performance of a structure is determined in a rigorous probabilistic manner by considering all sources of uncertainty that affect the performance.
- Performance is defined with decision variables (DV) which reflect global system performance.
- Performance is defined with DVs in terms of the direct interest of various stakeholders.

PEER PBEE methodology consists of four analysis stages, i.e. hazard, structural, damage, and loss [11]. The methodology focuses on the probabilistic calculation of system performance measures meaningful to facility stakeholders by considering the four stages of analysis in an integrated manner, where uncertainties are explicitly considered in all stages. The outcome of each of the four stages is either a probability (or probability of exceedance, POE) distribution. The probabilities determined in each stage are combined using Eq. (1). The damageable parts of a facility are divided into damageable groups consisting of components affected by the same EDP in a similar manner, e.g. structural or non-structural components. Global collapse of a structure is treated separately in this methodology since its probability does not change from one damageable group to another. Eq. (1), which resemble the well-known triple integration, referred to as the PEER PBEE framework equation in [10], is applicable only for the case of a single damageable group and no global collapse. A fourth summation is included to consider the presence of different damageable groups in Eq. (2). The most general format of the formulation is given in Eq. (3) for the case of multiple damageable groups and global collapse.

$$P\left(DV^n\right) = \sum_m \sum_i \sum_k P\left(DV^n \middle| DM_k\right) p\left(DM_k \middle| EDP^i\right) p\left(EDP^i \middle| IM_m\right) p\left(IM_m\right) \tag{1}$$

$$P\left(DV^n\right) = \sum_m \sum_j \sum_i \sum_k P\left(DV_j^n \middle| DM_k\right) p\left(DM_k \middle| EDP_j^i\right) p\left(EDP_j^i \middle| IM_m\right) p\left(IM_m\right) \tag{2}$$

$$P\left(DV^n\right)=\sum_m\left(\sum_j\sum_i\sum_k P\left(DV_j^n\middle|DM_k\right)\,p\left(DM_k\middle|EDP_j^i\right)\,p\left(EDP_j^i\middle|IM_m\right)p\left(NC\middle|IM_m\right)+P\left(DV^n\middle|C\right)p\left(C\middle|IM_m\right)\right)\;p\left(IM_m\right) \qquad (3)$$

where $p(IM_m)$ is the probability of the m^{th} value of the earthquake intensity measure (IM), determined as an outcome of hazard analysis, $p(EDP_j^i|IM_m)$ is the probability of the i^{th} value of the EDP utilized for the j^{th} damageable group, when the m^{th} value of IM occurs (outcome of structural analysis), $p(DM_k|EDP_j^i)$ is the probability of the k^{th} Damage Measure (DM) when subjected to the i^{th} value of the EDP utilized for the j^{th} damageable group (outcome of damage analysis), and $P(DV_j^n|DM_k)$ is the POE of the n^{th} value of the DV for the j^{th} damageable group when the k^{th} DM occurs (outcome of loss analysis). Moreover, $p(C|IM_m)$ and $p(NC|IM_m)$ are the probabilities of having and not having global collapse, respectively, under ground motion (GM) intensity IM_m. Finally, $P(DV^n|C)$ is the POE of the n^{th} value of DV in the case of global collapse. It is noted that index j is dropped in Eq. (1) since this equation represents the case of a single damageable group.

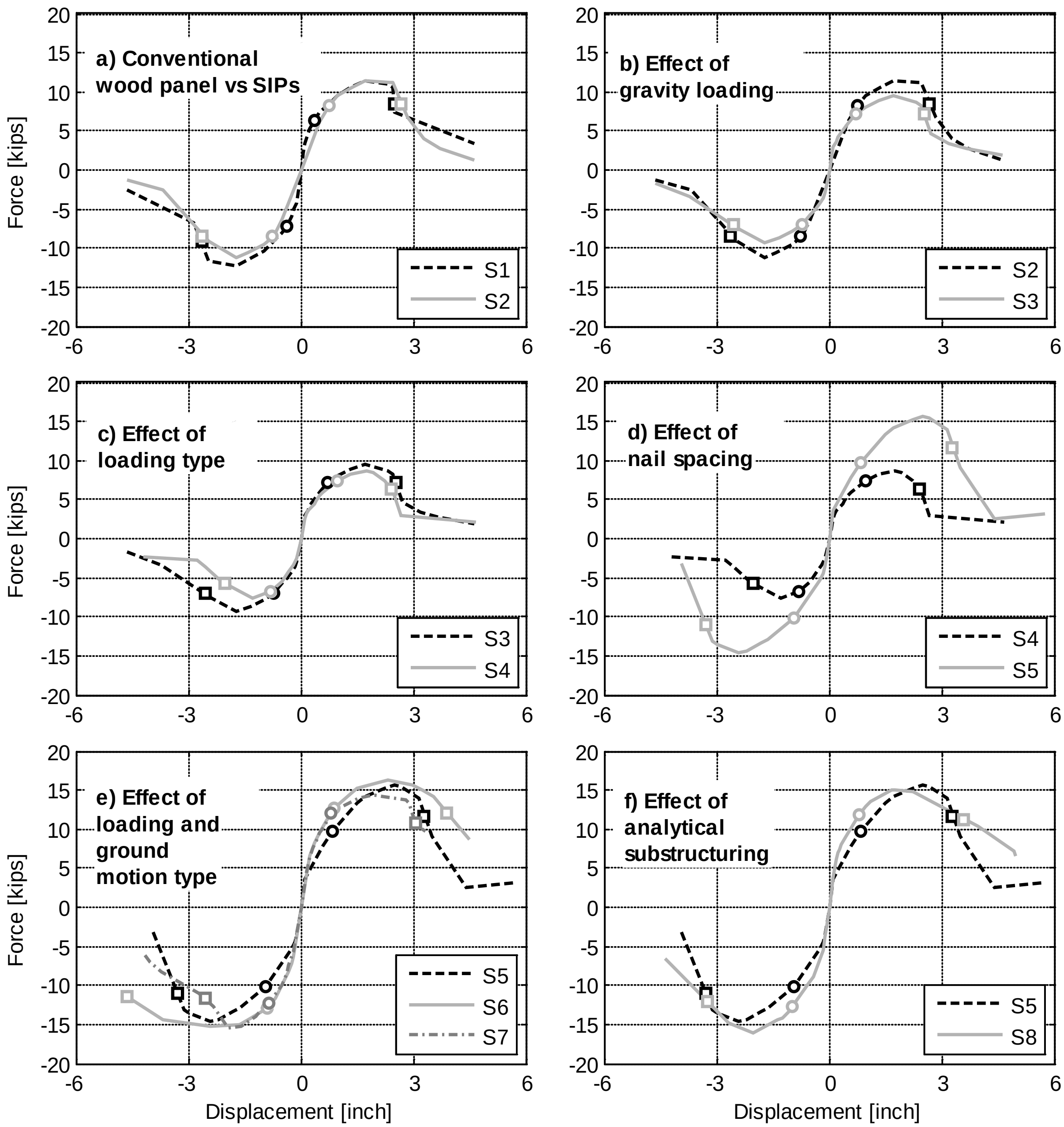


Fig. 4 – Envelope curves of specimens tested in [9]

Equations 1-3 consider all possible scenarios of earthquake hazard, where each hazard level has a specific probability of occurrence during a considered time span, e.g. 50 years, as calculated from hazard analysis. However, in some situations, it may be useful to determine the loss in the case of a specific hazard level certainly taking place during the considered time span. These situations where the probability of the considered hazard level is 1.0 may arise if the considered structure is an important public facility, or if the return period of the considered hazard level is likely to be completed within the considered time span. In such cases, the POE is represented with Eq. (4), where IM_m is the considered intensity level. Specific hazard levels are considered in this study. Therefore, Equation 4 is utilized for the conducted PBEE analyses.

$$P(DV^n) = \sum_j \sum_i \sum_k P\left(DV_j^n \middle| DM_k\right) p\left(DM_k \middle| EDP_j^i\right) p\left(EDP_j^i \middle| IM_m\right) p\left(NC \middle| IM_m\right) + P\left(DV^n \middle| C\right) p\left(C \middle| IM_m\right) \tag{4}$$

Details of the different stages of the PBEE analysis, conducted on a hypothetical two-story single-family house-over-garage building made of SIPs, are described in the next sections along with the combination of analyses.

3.1 Hazard Analysis

Hazard analysis is conducted to describe the earthquake hazard in a probabilistic manner, considering nearby faults, their magnitude-recurrence rates, fault mechanism, source-site distance, site conditions, etc., and employing attenuation relationships, such as GM prediction equations. The end result of hazard analysis is the hazard curve, which provides the POE of each possible value of an intensity measure (GM parameter) for the considered site. In this study, the hazard curve is not computed since the PBEE analyses are conducted for specific scenarios. The considered scenarios are the earthquake events with 2%, 10% and 50% POE in 50 years and are referred to as Maximum Considered Earthquake (MCE), Design Earthquake (DE) and Serviceability Earthquake (SE), respectively. The two-story single-family house-over-garage building is assumed to be located in San Francisco Bay Area, where such buildings are prevalent. Particularly, the building is assumed to be located at a site in Oakland with stiff soil (site class D with reference shear wave velocity = 180 to 360 m/s), where the spectral accelerations corresponding to the short (0.2 sec) and long (1.0 sec) periods are 2.2g and 0.74g, respectively. It is noted that these spectral accelerations are representative of many locations in California [12]. Forty 2-component GM records, which were selected by Baker et al. [13] to match the uniform hazard spectrum at each of these three hazard levels at the considered site, are used in the structural analysis stage, which is described in the next section.

3.2 Structural Analysis

A 13.5-ft×19.5-ft two-story single-family house-over-garage building made of SIPs is investigated with the PEER PBEE methodology. A different structural configuration of this structure, constructed from conventional wood-frames, was previously tested on the PEER shaking table [14], Fig. 5. In the structural analysis stage, this building is modeled in OpenSees [15] using spring elements as shown in Fig. 6. The force-displacement relationship of each spring is obtained from the HS tests conducted as part of the experimental program described in Section 2. Two models are developed that are constructed from SIPs specimens S4 and S5 in Table 1, constructed with 6 and 3 inch nail spacing, respectively. Analytical models of the springs in OpenSees are calibrated to match the results of the conducted HS tests. The *Hysteretic* material in OpenSees is utilized to model the springs. The results from the HS of specimen S5 and simulation of the corresponding analytical model are plotted in Fig. 7. As can be seen from this figure, the calibrated spring model is capable of accurately reproducing these HS test results.

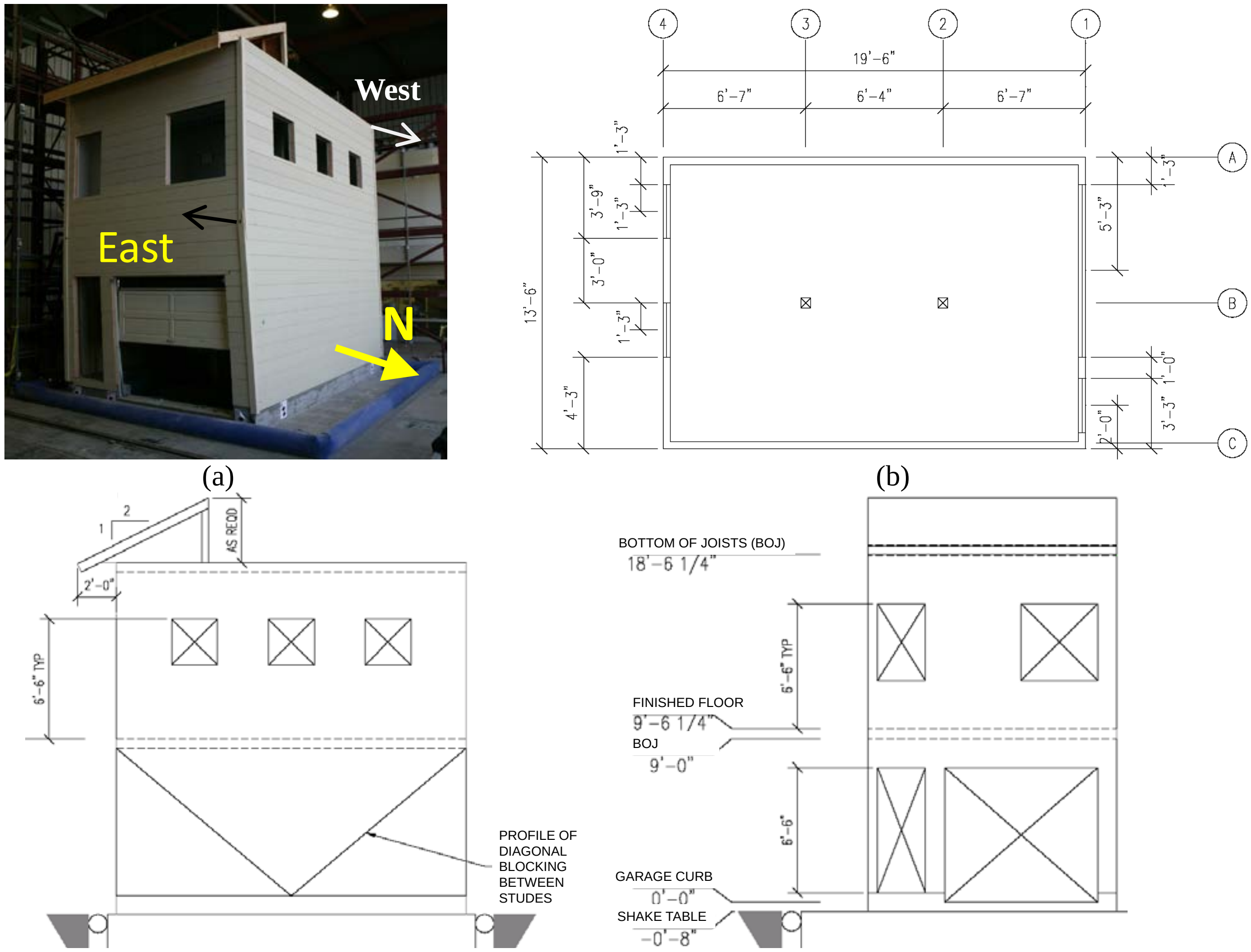


Fig. 5 – Two-story single-family house-over-garage building: (a) Photo of tested structure on PEER shaking table, (b) plan view, (c) elevation views

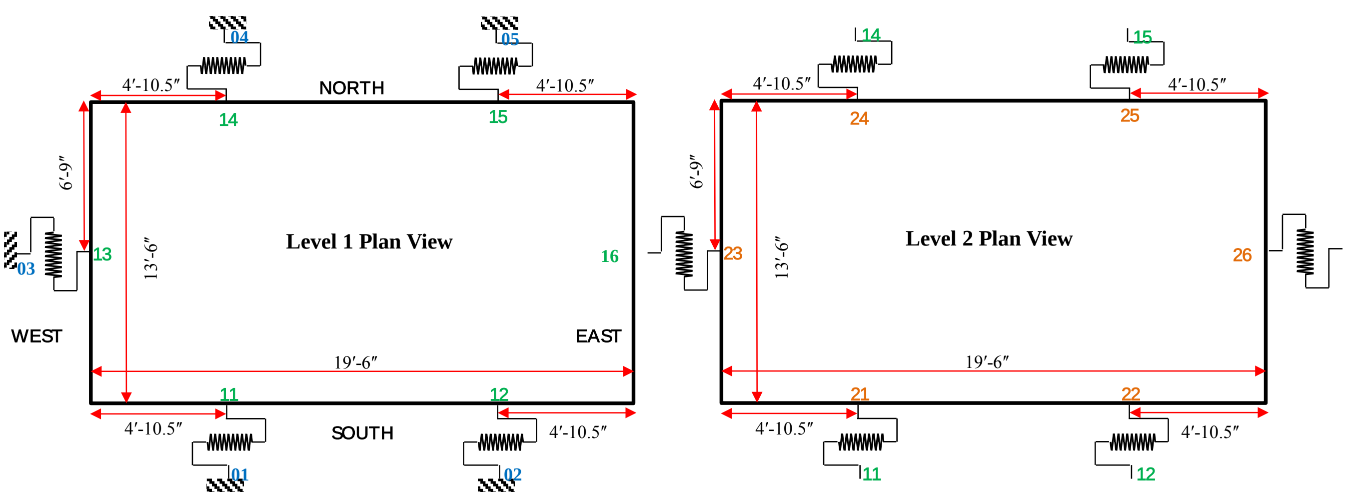


Fig. 6 – 3D analytical model using spring elements

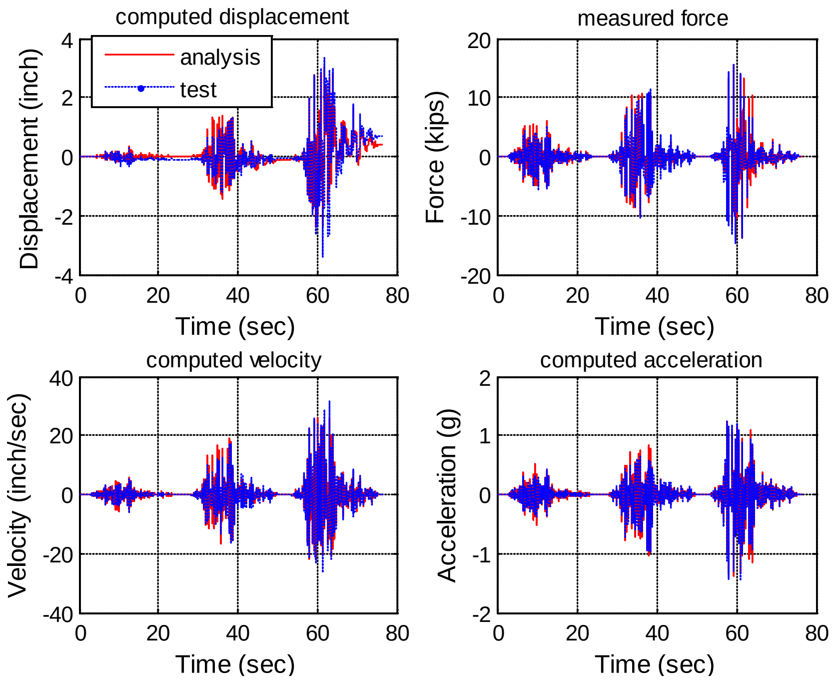


Fig. 7 – Comparison of results from the HS of specimen S5 and the corresponding analytical model

Two versions of the 3D analysis model shown in Fig. 6 are constructed using force-displacement relationship corresponding to that of specimens: (1) S4 constructed with 6 inch nail spacing, and (2) S5 constructed with 3 inch nail spacing. Nonlinear time history analyses (NTHA) of these two versions of the 3D model are conducted for 40 two-component GMs in each of the three considered hazard levels using OpenSees [15].

Probabilities of engineering demand parameters (EDPs) are determined in structural analysis, where each damageable group has a specific EDP associated with it. Therefore, the damageable groups and corresponding EDPs are defined as a part of the structural analysis stage. Two damageable groups are considered for the investigated structure: (1) structural components, and (2) non-structural components. Maximum peak interstory drift ratio (MIDR) and maximum peak floor acceleration (PFA) along the height are considered as the EDPs for structural and nonstructural groups, respectively. It is noted that the MIDR and PFA values are computed for each spring to consider the increase of EDPs due to the increased torsion resulting from the presence of the garage opening. For each of the considered hazard levels, lognormal distribution is assumed for both of the considered EDPs with the median and coefficient of variation (COV) values of EDPs obtained from the NTHA. The probability distributions for the 3 inch nail spacing configuration are plotted in Fig. 8. It is noted that the median and COV values are computed from the analyses that do not lead to collapse. To determine whether an analysis leads to collapse, resulting roof displacements are compared to the collapse roof displacements obtained from pushover analyses using the same analytical models. For this purpose, the pushover analysis conducted in North-South direction is used since this is the critical direction due to asymmetry caused by the garage opening on the East side of the building in the first story (Fig. 6). The pushover curve developed for the 6 inch nail spacing configuration is plotted in Fig. 9, where the collapse displacement is determined to be 4.2 inches. It is noted that the developed pushover curve is multilinear because of the multilinear nature of the *Hysteretic material* that is used to define the springs in OpenSees. It is further noted that other damage states are also marked in this figure, which are used in the damage analysis stage to determine the story drifts corresponding to different structural damage states. The collapse probabilities are computed by dividing the number of GMs that lead to collapse by the total number of GMs, i.e. 40.

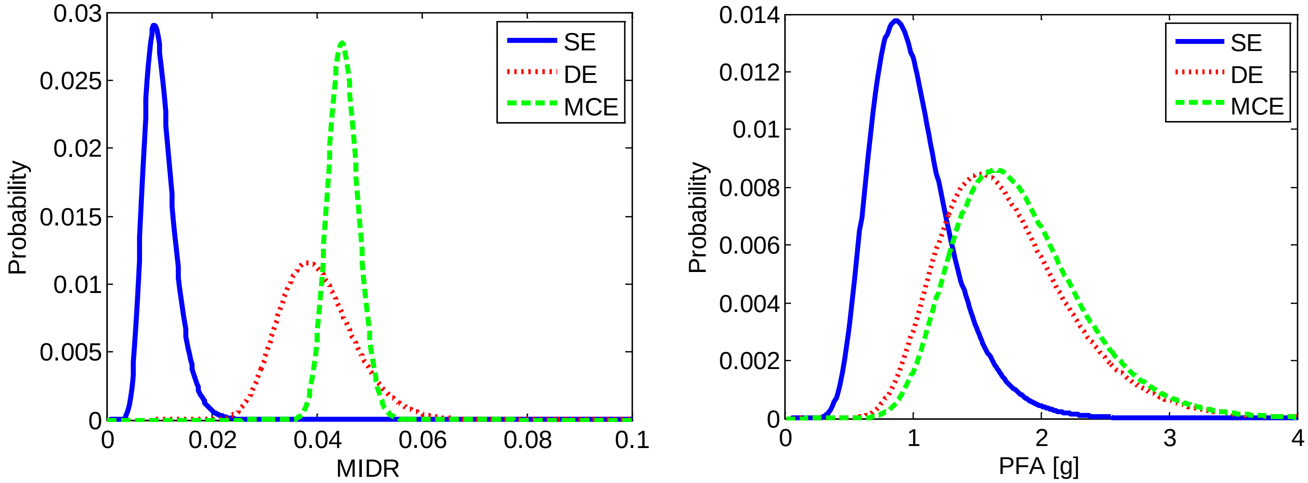


Fig. 8 – Probability distributions of the EDPs of the building with 3 inch spacing for different intensity levels

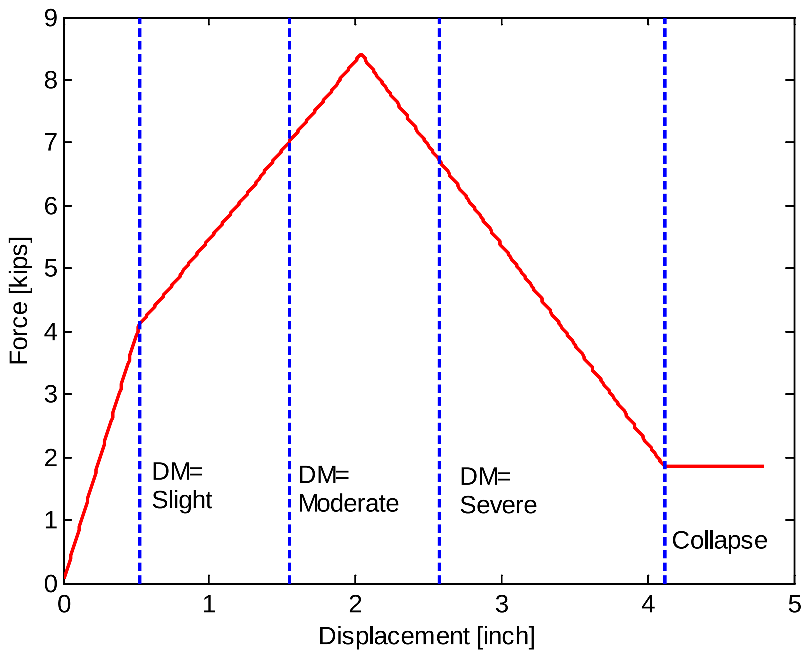


Fig. 9 – Pushover curve of the building constructed from SIPs with 6 inch nail spacing

3.3 Damage Analysis

Fragility functions are obtained for the two damageable groups in damage analysis. Damage measures (DMs) considered for the structural components are slight, moderate, and severe damage, while the DMs for the nonstructural components are based on the damage states for (1) DS1: *unsecured fragile objects on shelves with unknown restraint*, and 2) DS2: *desktop electronics including computers, monitors, stereos, etc. on smooth surfaces* defined in FEMA-P58 [16, 17]. The former damage state corresponds to lower EDPs compared to the latter.

The probability of a damage level given a value of the EDP, $p(DM_k|EDP_{ji})$, is assumed to be lognormal. Median and COV values for the damage levels of structural and non-structural components of the building are shown in Table 2. Values for the structural components are obtained from the conducted pushover analyses as the EDP values in the pushover steps corresponding to the roof displacements that define various DMs shown in Fig. 9, while those for the nonstructural components are gathered from the FEMA-P58 document [16, 17]. The resulting fragility curves for structural and non-structural components are shown in Fig. 10.

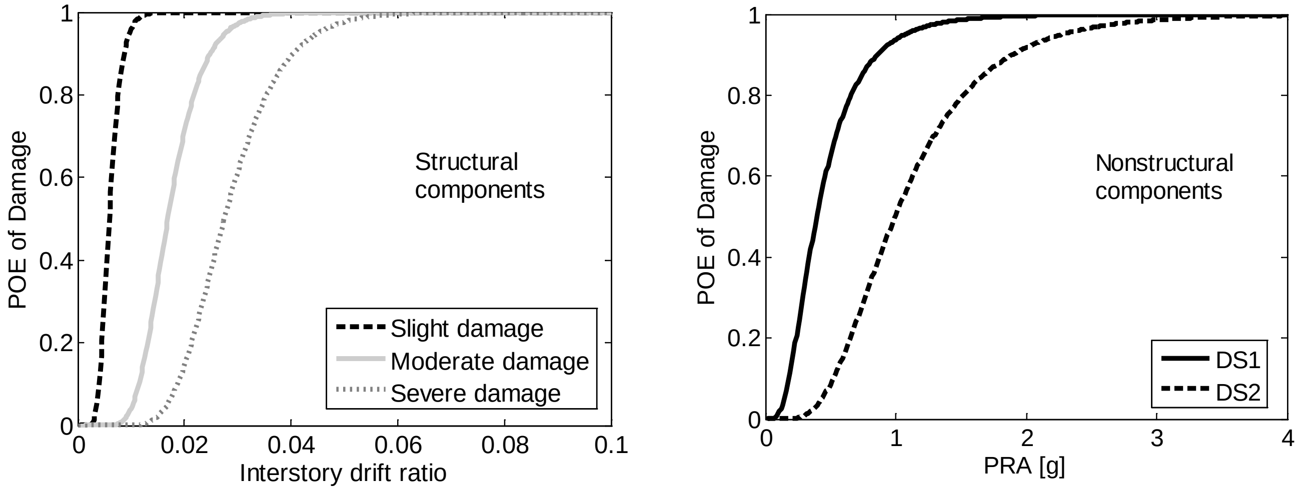


Fig. 10 – Fragility curves for structural and nonstructural components

Table 2 – Median and COV of EDPs for different damage levels of the investigated building

Component	Damage level	EDP	Median	COV
Structural	Slight	MIDR	0.006	0.30
	Moderate	MIDR	0.017	0.30
	Severe	MIDR	0.028	0.30
Non-structural	Falling of unsecured fragile objects with unknown restraint	PFA (g)	0.4	0.6
	Falling of desktop electronics on smooth surfaces	PFA (g)	1.0	0.5

3.4 Loss Analysis

Monetary loss normalized by the building replacement cost is chosen as the considered DV. Because the investigated building is a hypothetical one, there is no specific information available regarding the losses. However, evidences from recent earthquakes, such as the 2014 South Napa earthquake, indicate that the losses of single family houses due to nonstructural components are generally larger than those due to the structural components. Accordingly, median values of DVs for the first and second non-structural DMs are accepted to be respectively 0.3 and 0.6, while those of the structural DMs are accepted to be 0.1, 0.2, and 0.4 for the light, moderate, and severe damage states, respectively. COV of the loss functions for all the damage states are set to be 0.3. Probability of the chosen DV in case of global collapse is assumed to be lognormal with the median of 1.0 and COV of 0.1.

3.5 Combination of Analyses

Loss curves of the buildings constructed with SIPs using 3 and 6 inch nail spacing are computed with Eq. (4) for the three considered intensity levels and are plotted in Fig. 11. Probability of the losses are not small even for the SE level mainly due to the soft story formation and increased torsion because of the garage opening in the East side of the first story, which was also observed during the shaking table tests conducted in [14]. The two buildings with 3 and 6 inch nail spacing have similar loss curves for the SE and MCE intensity levels. The two curves are similar for the MCE level mainly because most of the MCE GMs lead to collapse of the buildings. In the SE level, only one GM leads to the collapse of both buildings. In terms of EDPs, the MIDR is larger for the 6 inch nail spacing, while the floor accelerations are similar. Differences in the MIDR lead to the slightly reduced losses for the 3 inch configuration. The effect of nail spacing is clearly observed in the loss curves for the DE intensity level. In this level, 37 of the 40 GMs lead to the collapse of the building with 6 inch nail spacing, while only 9 GMs lead to collapse of the building with 3 inch nail spacing. Furthermore, the EDPs of the building with 6 inch nail spacing are significantly larger than those of the building with 3 inch nail spacing. Therefore, the losses of the building with 6 inch nail spacing are considerably larger than those of the building with 3 inch nail spacing for the DE level. From the lower right side of Fig. 11, it is observed that the MCE loss curve of the building with 3 inch nail spacing is close to the DE loss curve of the building with 6 inch nail spacing, which indirectly implies that the difference of (6-3=3) inch in nail spacing is equivalent to a difference of (10-2=8) % POE of hazards in 50 years for the considered SIPs building.

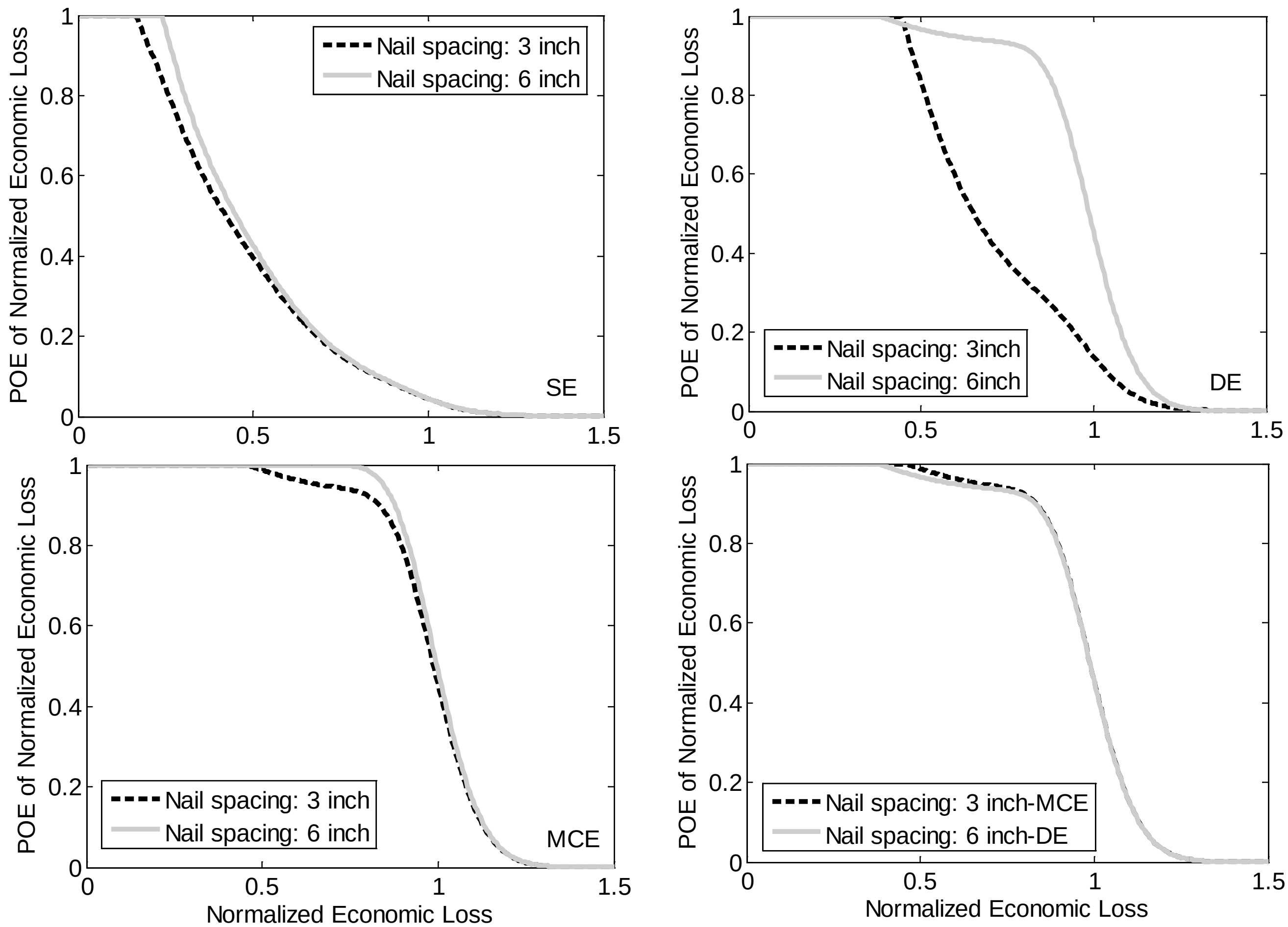


Fig. 11 – Loss curves of the investigated building configurations for different earthquake intensity levels

4. Summary and Conclusions

The seismic performance of a two-story single-family house over garage building is explored in this paper. Using PEER PBEE methodology, loss curves are computed for the two configurations of the building constructed with 6 inch and 3 inch nail spacing. Concluding remarks are listed as follows:

- Conducted NTHA indicate that the investigated two-story single family house over garage building is subjected to soft story formation and significant torsion, which increase the interstory drifts and floor accelerations. Similar remarks were observed during the shaking table tests conducted in [14].
- Loss curves of the buildings with 3 inch and 6 inch nail spacing are similar to each other for the serviceability and maximum considered earthquake levels.
- Losses of the building with 3 inch nail spacing are considerably smaller than those of the building with 6 inch nail spacing for the design earthquake level.
- MCE loss curve of the building with 3 inch nail spacing is close to the DE loss curve of the building with 6 inch nail spacing, which indirectly implies that the difference of 3 inch in nail spacing is equivalent to a difference of 8% POE of earthquake hazard in 50 years.
- The obtained results clearly indicate the importance of design and construction details, such as nail spacing, on the economic losses of single family houses and highlight that the usage of SIPs in highly seismic areas

can be increased by improving the construction and design details to benefit from its rapid construction and energy-efficiency benefits.

5. Acknowledgements

The authors acknowledge the financial support under the Intra-University Transaction No. 6815031 from the LBNL under Contract No. DE-AC02-05CH11231 of the US-DOE. The technical support of Dr. Richard C. Diamond is greatly appreciated. The presented research was also partially supported by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) program. The SIPs were donated with help of Mr. Bill Wachtler, SIPA, and Mr. Jim Whalen, PFB Corporation.

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