SEISMIC PERFORMANCE ASSESSMENT OF A SEVEN-STORY WOOD-STEEL HYBRID BUILDING

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ABSTRACT :

Performance based seismic design (PBSD) is a design paradigm which is beginning to be applied for steel and concrete structures. The ability of PBSD to incorporate various types of performance requirements and account for innovative construction techniques makes it a powerful tool, particularly in the design of new structural configurations. Modern mixed-use mid-rise wood frame buildings (4-8 stories) are ideal for combining a steel moment frame (SMF) at the first and/or second level to open the lower levels up for retail shops with wood used for the upper residential levels. The SMF provides enough strength for gravity load to support the upper levels, while providing substantial ductility and shear capacity. The interaction between the SMF and wood components for mid-rise woodframe buildings has not been adequately studied. The system behavior is not explicitly accounted for in existing building codes, other than the standard requirements for stiffness between successive story levels (e.g. IBC). In this paper, a seven-story structure, whose 1st-story is assumed to be a steel SMF supports six upper stories made of light-frame wood construction, is used as an example to illustrate a logical PBSD procedure which can be applied to these types of "hybrid" structures. The basic idea is that with the preliminary design of the wood portion of the building known, the effective stiffness of the steel frame can be determined based on the desired performance, which was assumed to be correlated with peak inter-story drift. Through this numerical study, the application of PBSD to wood-steel hybrid structures was illustrated and verified.

KEYWORDS: Performance evaluation, Steel-wood hybrid structure, Effective stiffness, Drift limit

1. INTRODUCTION

Woodframe construction is commonly used for residential construction throughout North America. However, for mid-rise woodframe structures, such as multi-family residential structures, hotels, and condominiums, the current International Building Code (IBC) (2006) only allows woodframe structures to be three stories or four stories if sprinklers are included in the design. Assuming fire requirements can be dealt with, there is some concern that many of these multi-family mixed-use buildings may not perform as well as expected during a major earthquake, partially due to the need/desire to provide many large openings in the lower levels. Performance Based Seismic Design (PBSD) is a new design philosophy which is, by the vast majority, considered as an important step forward in earthquake engineering design. The performance of the structure under specified hazard levels are explicitly considered and numerically examined in PBSD. The non-structural component contributions are also considered in the analysis and performance in PBSD. PBSD provides an opportunity to include new analysis methods and technologies in seismic design.

In this paper, the performance based design of a wood-steel hybrid mid-rise building was conducted with the design procedure outlined in Figure 1. The six-story woodframe structure, termed herein as the Capstone building, was originally designed as a condominium building in California using the IBC (2006) methodology. Adding a steel SMF under the Capstone building can provide the large openings at the 1st-story which meets the mixed-use requirements of many of these types of buildings. A simplified shear building model was used in this paper to search for the effective stiffness of the SMF needed to achieve several different performance requirements under several different seismic intensity levels. This searching procedure was performed within a probabilistic PBSD framework using multiple time history analyses (SAPWood User's Manual, www.engr.colostate.edu/NEESWood/sapwood). After the stiffness was identified, the SMF story and all the woodframe structure components based on the preliminary design were used to build a detailed three-dimensional system model in SAPWood. The final structure performances were verified through Multi-IDA (Vamvasikos and Cornell, 2002) with this comprehensive numerical model.

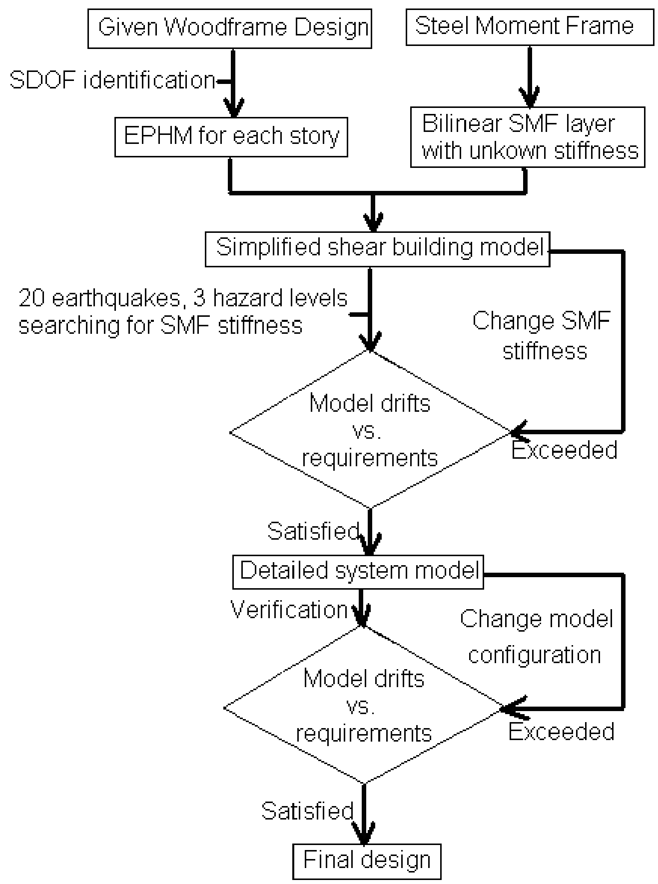

Figure 1 PBSD procedure used in this study

2. CAPSTONE BUILDING

This upper six-story woodframe structure sitting on top of the SMF was designed to have 23 single family dwelling units. The lower five stories have four apartments and the top story was designed to have three luxury apartments. A tapered joist roof with a 0.91m (3 ft) parapet with service equipment was including in lieu of a metal plated truss roof since this would be more typical in an urban setting.

The preliminary design of the wood portion of the building was based on the International Building Code (IBC, 2006) and American Society of Civil Engineers Standard 7-05 (ASCE, 2005). The three dimensional model of Capstone building is shown in Fig 2 and the basic design parameters for Capstone building are presented in Table 1.

Table 1 Approximate building dead loads

Building Assembly	Estimated Dead Load Pa (psf)
Roof/Ceiling (1 Hour Rated)	886 (18.5)
Floor (1st - 5th Levels – 1 Hour Rated)	1173 (24.5)
Floor (6th Level – 1 Hour Rated)	1269 (26.5)
Balcony	1197 (25)
Exterior Wall w/ WSP Bracing (1 Hour from Interior Only)	527 (11)
Interior Wall w/o WSP Bracing (Unrated)	383 (8)
Interior Wall w/ WSP Bracing (1 Hour Rated Both Sides)	527-622 (11-13)

Note: WSP – Wood Structural Panel

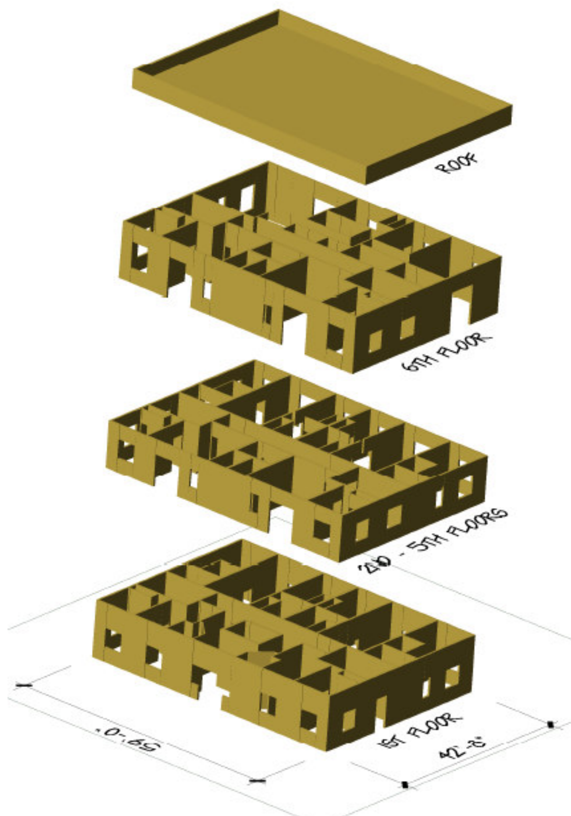

Figure 2 3-D of Capstone building (upper six stories of wood)

3. NUMERICAL ANALYSIS

3.1. Shear Building Model

In the simplified analysis of the hybrid structure, the force-based design of the building without the SMF was adopted as the preliminary design for the wood upper-structure, i.e. assumed not to change. A detailed numerical model was built with floor details and shearwall configurations in the SAPWood v1.0 software package. Then, a simplified shear building model was developed to identify the initial stiffness for the SMF story under various performance requirements. The hysteresis of each global story degree of freedom in the shear building model was identified by forcing each level through a displacement protocol numerically. A bilinear element was selected to represent the behavior of the SMF with initial stiffness, K0, which is the independent design variable to be identified, the post yield stiffness which is the dependent design variable, Ky, and was set equal to 1/8 K0 based on experimental data, and the yield displacement, Dy, which was set equal to 1% of the height of the SMF story. For the upper woodframe structure, the evolutionary parameter hysteretic model, Evolutionary Parameter Hysteretic Model (EPHM) (Pang et al., 2007), was selected to represent the hysteresis of the wood stories in the shear building model. Figure 3 depicts the simplified shear building model used in the search procedure. The EPHM parameters were obtained from the quasi-static identification process mentioned earlier in both the x- and y-direction. The parameters of the bilinear model are sought using the PBSD procedure. Once the shear building model was set up, multi-record incremental dynamic analysis (IDA) (Vamvasikos and Cornell, 2002) was performed using the shear building model in each direction with 20 ordinary ground motion records at three different hazard levels.

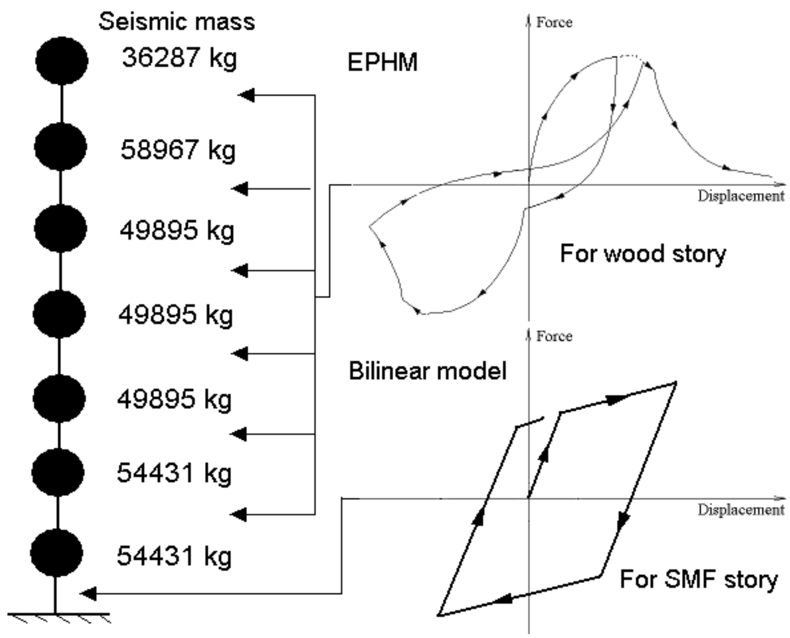

Figure 3 Shear building model simplification

The hazard levels consisted of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), were defined based on the probability of exceedance (PE) of 50%, 10%, and 2% in 50 years, respectively (ASCE 41, 2006). The performance requirements for steel moment frames and woodframe structures in ASCE 41-06 are listed in Table 2 and the newly proposed drift requirements in NEESWood project is listed in Table 3 which increased the drift limit for woodframe structure at CP level to 4% for ordinary ground motions. If more than seven earthquake ground motions were used in the evaluation, these requirements were set for the median of the maximum inter-story drifts.

Table 2 Performance requirements in ASCE 41-06

	IO	LS	CP
SMF	0.7%	2.5%	5%
Wood	1%	2%	3%

Table 3 Probabilistic performance requirements for woodframe structure

Hazard level	Performance requirement
50%/50 years	Mean of peak drifts ≤1%
10%/50 years	Mean of peak drifts ≤2%
2%/50 years (OGM)	80% of peak drifts < 4%
Near fault ground motion records (optional)	50% of peak drifts < 7%

Note: OGM stands for ordinary ground motion records.

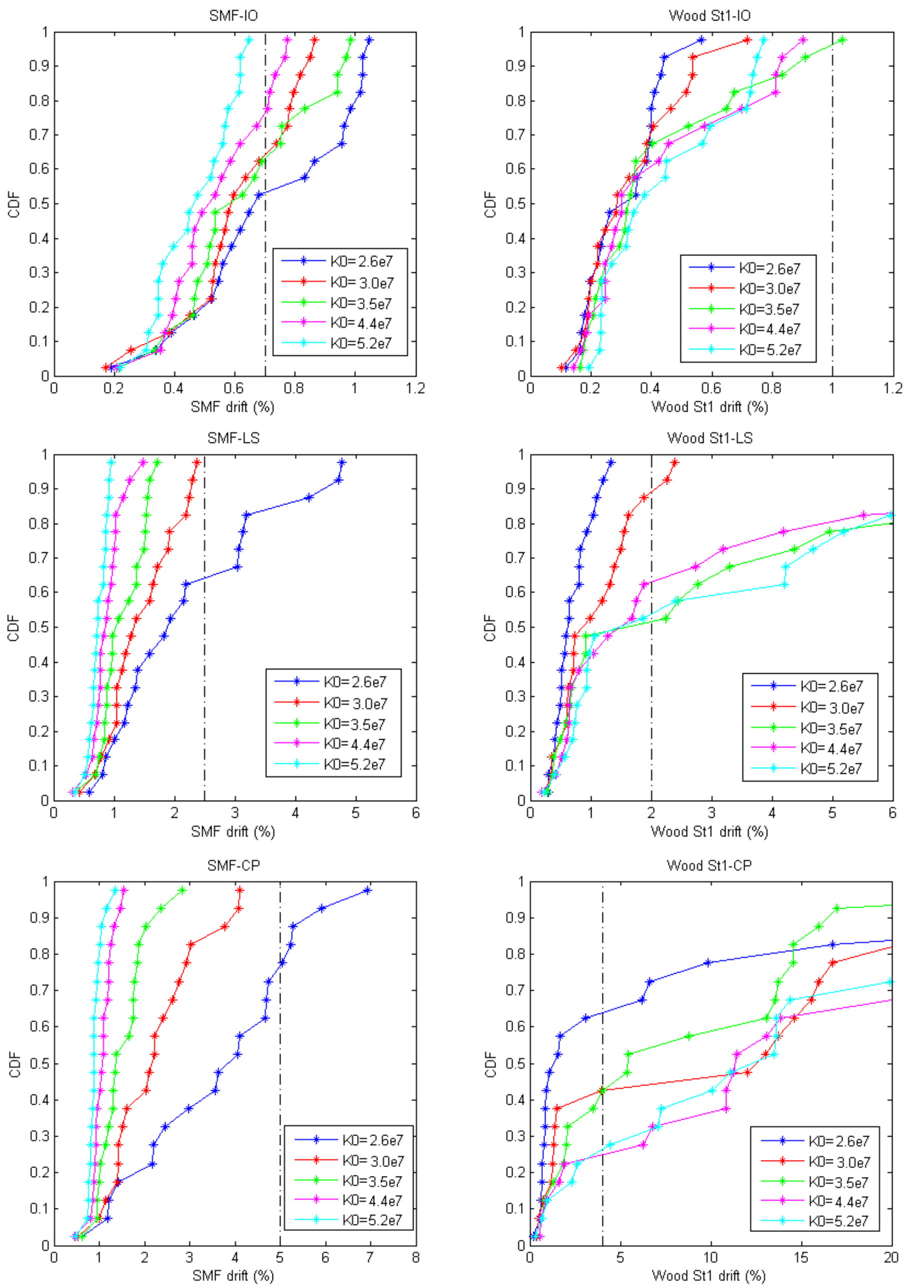

Figure 4 Maximum inter-story drift distribution for steel and wood (x-direction)

The maximum inter-story drift distribution for the SMF and 1st-story of the woodframe portion of the structure in the x-direction, determined to be the critical location and direction, are shown in Figure 4. The assumption is made here that if the inter-story drift requirements are satisfied then the structure will perform satisfactory. The performances for all the design configurations at the IO level were generally acceptable and the design was clearly controlled by the LS and CP level requirements. An interesting observation is that when the stiffness of the SMF increased, the drift of the woodframe structure also increased while the drift of the SMF decreased. Thus, the SMF story almost serves as a partial isolator due to its high level of ductility. The probability of the model drifts satisfying the performance requirements listed in Table 2 at different hazard levels for the SMF and wood stories are listed in Table 4. If no modification was made on the wood upper stories, an initial stiffness of 2.6e7 N/m (1.5e5 lb/in) would be selected for the SMF layer. The drifts of the structure at CP level controlled the stiffness selection, which are shown bolded in Table 4.

Table 4 Probability of Non-exceedance

K0 (N/m)	IO		LS		CP	
	SMF	Wood	SMF	Wood	SMF	Wood
2.6e7	55%	100%	65%	100%	**80%**	**65%**
3.0e7	65%	100%	100%	87%	100%	45%
3.5e7	65%	98%	100%	50%	100%	45%
4.4e7	80%	100%	100%	63%	100%	23%
5.2e7	100%	100%	100%	53%	100%	25%

3.2. System Model

After the initial stiffness of the steel story was identified using the shear building model, a comprehensive 3-D numerical model was built in SAPWood. This model included the details of the floor plan and shearwall configurations for the woodframe structure. In this detailed model, the SMF was modeled by using two bilinear elements in each direction. The parameters of the bilinear element in each direction produced an effective story stiffness equal to 2.6e7 N/m (1.5e5 lb/in). The seismic mass added by the SMF story was assumed to be equal to the 1st-story of wood. Then a Multi-IDA was also performed using 20 ordinary ground motions at IO, LS, and CP level. It should be mentioned that the earthquake excitations in the numerical analysis are applied simultaneously in both x- and y-direction, and the intensity level in both directions is the same. This perfectly matched input in both directions might increase the response of the building compared to the one direction shear building analysis.

The maximum inter-story drift distribution for the SMF and 1st-story of wood are shown in Figure 5 for both directions. It is obvious that the SMF produces most of the displacement during earthquake excitation at the IO level. However, along with the increase in the seismic intensity level, the failure of the structure would most likely be triggered by a soft story mechanism at the 1st-story of the wood. Similar to Table 4, the probability of satisfying performance requirements in ASCE 41-06 are listed in Table 5. Comparing these two tables, it can be observed that the probability results of the simplified shear building model are different from the detailed system model. However, they are felt to be close enough to justify the preliminary design procedure using the simplified shear building model. Some drifts from the bi-axial system model were higher than that of the shear building model at the same hazard level. This result might be caused by the use of simultaneous bi-axial excitation inputs in both directions of the detailed model.

Table 5 Probability of non-exceedance

	IO		LS		CP	
	X	Y	X	Y	X	Y
SMF	45%	45%	58%	55%	92%	80%
Wood st1	100%	100%	78%	83%	42%	48%

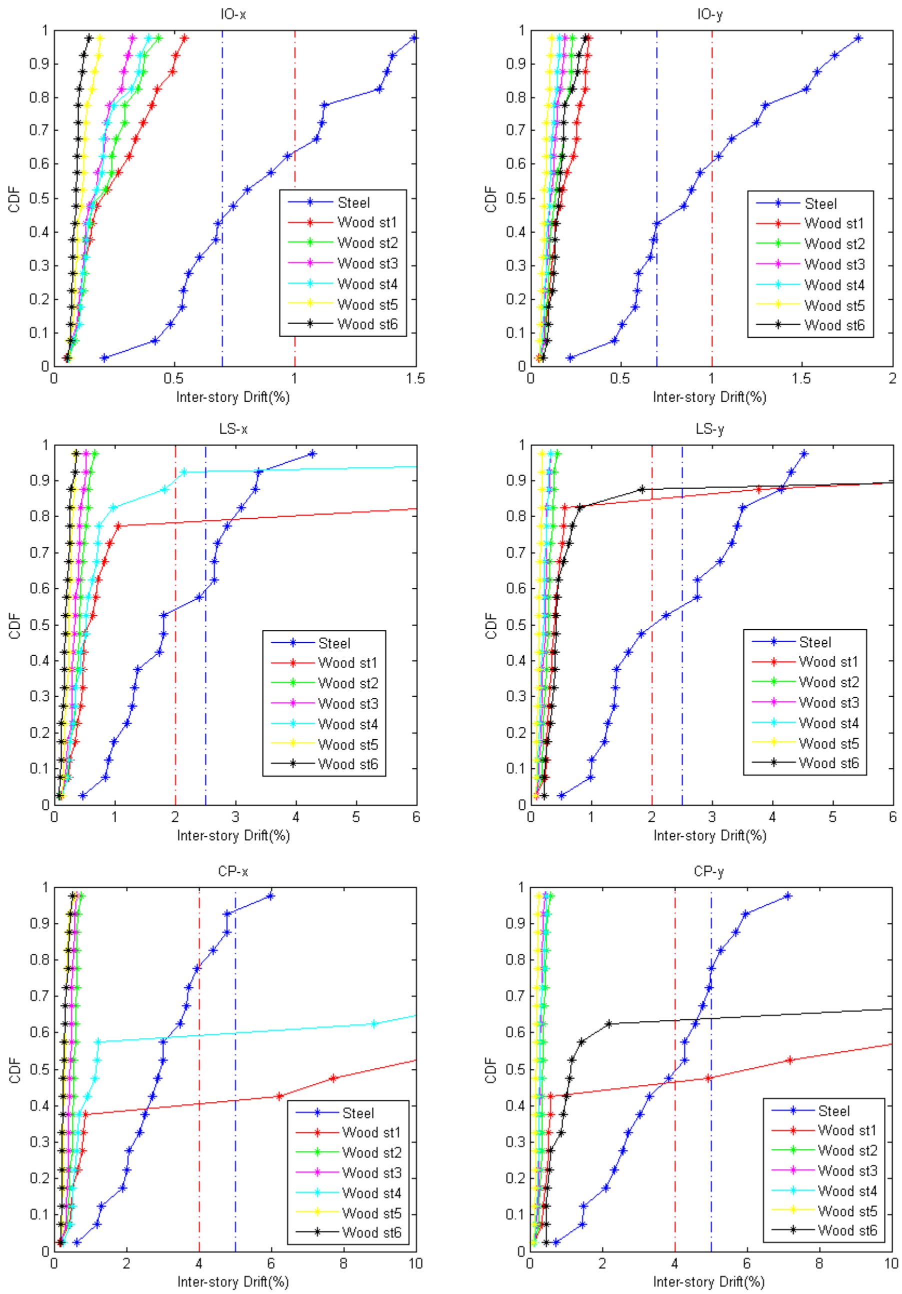

Figure 5 Maximum inter-story drift distributions in both directions

It can be seen from the table 5 and figure 5 that the SMF at story level 1 satisfied the performance requirements at both the LS and CP hazard levels, with the performance very close to the requirements at the IO level. The wood structure median drifts were very close to the performance requirements for the CP level but satisfied the IO and LS levels completely. The results presented in table 5 are for the configuration with the performance closest to the requirements.

4. CONCLUSION

Based on the numerical analysis on the hybrid structure, the following conclusions can be reached:

(1) The simplified design procedure based on the shear building model can provide a good estimation of the initial stiffness of the SMF story. The performance of the simplified model is close to the comprehensive system model.

(2) Without changing the design of woodframe structure, the final design for the stiffness of SMF story was obtained so that the drift requirements for both the wood and steel structure were satisfied (or closely matched) for all of the hazard levels. This result was verified with multi-record IDA results from a detailed system model.

(3) There is a complimentary interactive relationship between the SMF and woodframe structure peak drifts, as expected. When the stiffness of the SMF is increased, the peak drifts for the SMF tend to decrease while the peak drifts in the first story of wood tend to increase. This is likely because the isolation effect provided by the ductile SMF is reduced allowing higher forces into the first story of wood.

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