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Original Research Article

A STUDY ON THE SIGNIFICANCE OF THE DESIGN PARAMETERS OF STEEL PLATE SHEAR WALLS SUBJECTED TO MONOTONIC LOADING

Saeed HONARMAND[1], Peyman HOMAMI[1]*, Vahidreza GHAREHBAGHI[1],
Ehsan NOROOZINEJAD FARSANGI[2]
[1]Kharazmi University, Tehran, Iran
[2]Graduate University of Advanced Technology, Kerman, Iran

Abstract

Steel plate shear walls (SPSWs) as a resistant system against lateral loads have a high potential for earthquake energy dissipation. Due to the uncertainties of loading, construction, and installation of SPSWs, it is vital to investigate the importance of each component and achieve higher accuracy in design and the implementation of these members. In this paper, a sensitivity analysis is carried out to determine the significance of important uncertainties. The results denoted that the most important parameters affecting the loading capacity of the SPSWs are height, thickness, length, Young's modulus of the wall material, flange, and web thickness of the column, respectively.

Keywords: steel plate shear walls (SPSWs), sensitivity analysis, Mote-Carlo simulation, seismic loads, monotonic loading, uncertainties

1. INTRODUCTION

Over the years, Steel plate shear walls (SPSWs) has been attracted by engineers' attention as lateral force-resisting systems in structures. These systems have considerable potential for absorbing lateral forces such as those due to earthquakes

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[1*] Corresponding author: Tehran, IRAN , Kharazmi University, Assistant Professor Peyman Homami, e-mail: homami@khu.ac.ir

and wind, especially in tall buildings. Moreover, it can be utilized along with concrete frames to improve the system's lateral rigidity [1, 2]. Hence, this demanding phenomenon, which is rapidly trending in the world, found its way through the construction of new buildings as well as reinforcement of existing structures, especially in seismic prone countries like the United States and Japan in the early 1980s [3].

A typical SPSW consists of thin steel plates or infill panels (ranging from 4.75 to 12.5 mm) bounded by beams and columns as horizontal boundary elements (HBEs) and vertical boundary elements (VBEs) [4]. The beam-column connections can be applied with either simple shear or moment-resisting connections jointed by weld, bolt, or both. Fig. **1** denotes the main components of a conventional SPSW system (Fig. 1).

Generally, SPSWs are categorized into stiffened and unstiffened [5]. At the first of emerging, the SPSWs had many stiffeners to avoid buckling and improving the wall's shear bucking capacity. Over decades, scholars have conducted numerous analytical and experimental investigations and realized that post-buckling of unstiffened plates leads to higher ductility and a more efficient manner in SPSWs [6]. Since, under incremental lateral forces, the steel plate is subjected to buckling in shear and forming post-bucking diagonal tension fields. Subsequently, this mechanism causes the structures to show higher strength, higher initial lateral stiffness, and an appropriate energy dissipation capacity [7].

Many sources of uncertainties exist during the designing procedure, including material strength, environmental loads, human errors, and approximations in the numerical modes. Although there are some studies regarding the uncertainties of SPSWs [8, 9], they all considered the uncertainties derived from earthquakes and not the structural system itself [10-12]. Hence, the objective of this study is to identify the important uncertain parameters and indicating important variables that should be considered for design. To this end, the Monte Carlo simulation as a computational approach of analysis is used, which deploys statistical sampling techniques to obtain a probabilistic approximation to the solution of a model. It is a method in which the analyst creates a large number of sets of randomly generated values for the uncertain parameters and calculates the performance function for each set [13]. It can be used to estimate the possible outcomes of an uncertain problem. Monte Carlo simulation helps to carry out a sensitivity analysis with the potential to identify the correlation of input variables in a mathematical model. It provides practical information for simulated models through identifying parameters with the most impact on the results of a system [14].

Considering the above preface, this study on SPSW includes the following sections. First, a finite element (FE) model of an unstiffened SPSW is presented. Afterward, the model is validated via an experimental specimen. Next, the parameters of the steel wall are defined, and the sensitivity analysis is conducted.

Finally, the results are presented for further discussion, and the important parameters are indicated.

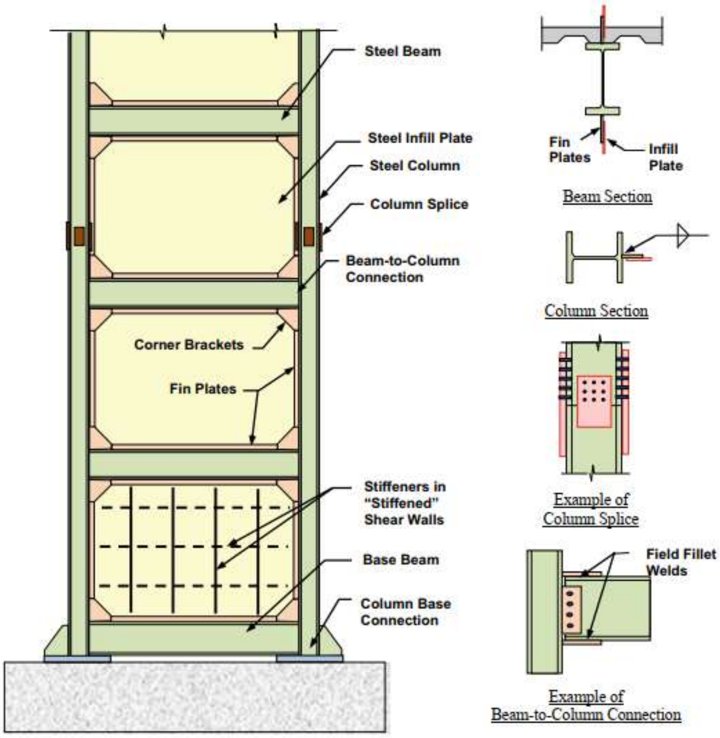


Fig. 1. Main components of a conventional SPSW [15]

2. NUMERICAL SIMULATION

In order to investigate the performance and determination of the effectiveness of the design parameters in the behavior of SPSWs, a one-story frame has been investigated. The model has been evaluated experimentally by Sabouri and Sajjadi [16] in order to study and determine the behavior and energy absorption of the wall. In that study, three specimens were studied, including the surrounding moment frame and the SPSW with and without stiffeners. The dimensions, size, and materials used as the boundary elements (beams and columns), plate, and stiffing plate were identical in those three specimens. In this paper, the SPSW without stiffeners has been studied, and the experimental results are deployed for validation (Fig. **2**).

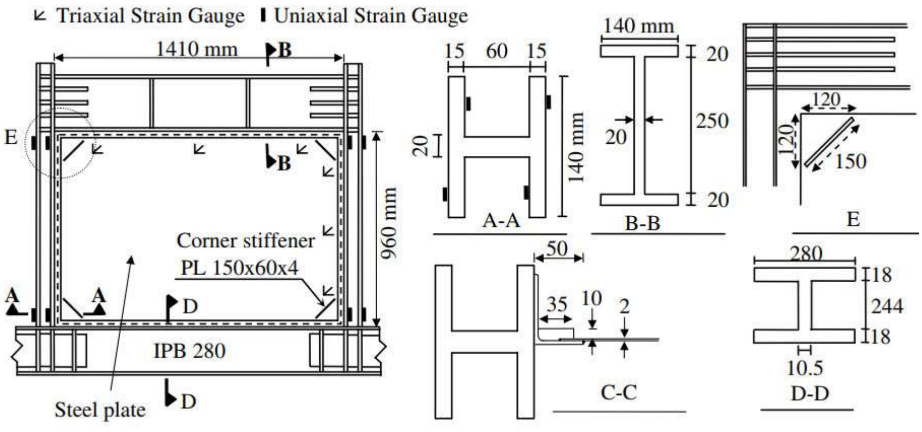


Fig. 2. Specification of SPSW (without stiffeners) [16]

A Finite element model (FEM) composed of SPSW and the surrounding frame has been simulated in the software as depicted in Fig. **4**. To define the material behavior, a bi-linear model is utilized, and strain hardening has been considered (Fig. 3).

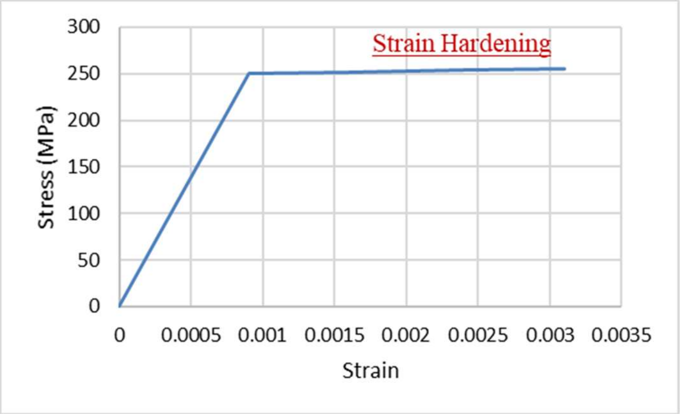


Fig. 3. A sample Bi-linear material behavior

The experimental reference specimen consists of three types of steel materials with different yielding and ultimate stress and is deployed for modeling of components (Fig. **4**. FE model of the SPSW Table **1**). In this paper, the SHELL181 element has been used for modeling the steel wall, which is broadly used for modeling SPES and also is suitable for modeling thin to moderately shell structures [17]. This element has four nodes with six degrees of freedom, translations in the direction of X, Y, Z, and rotation around X, Y, Z for each node. The mapped mesh method is applied to the model for better accuracy, as depicted in Fig. **4** [17].

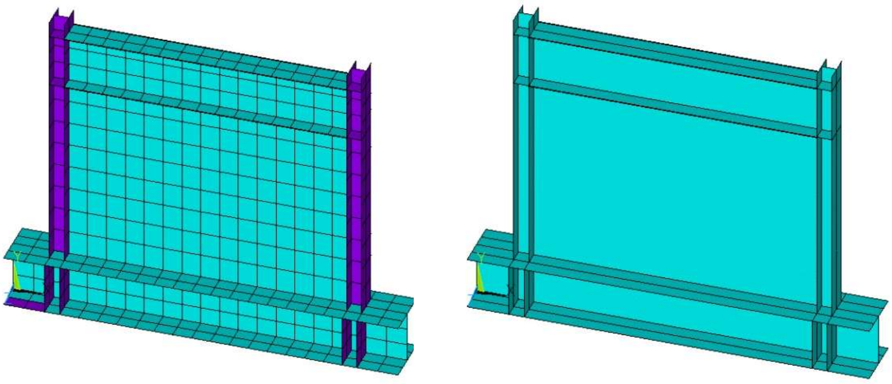
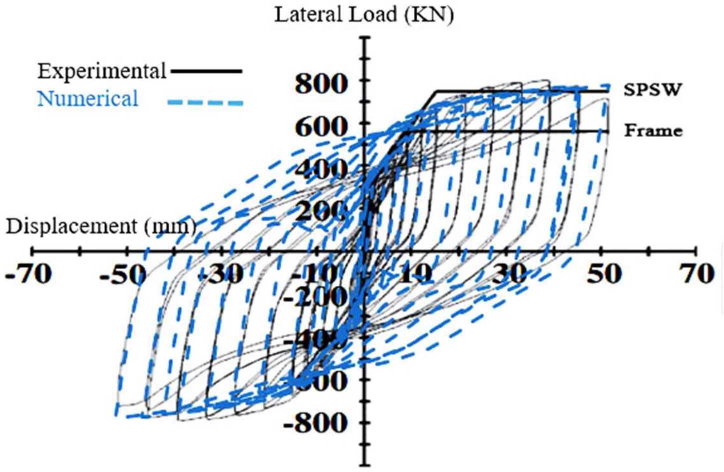


Fig. 4. FE model of the SPSW

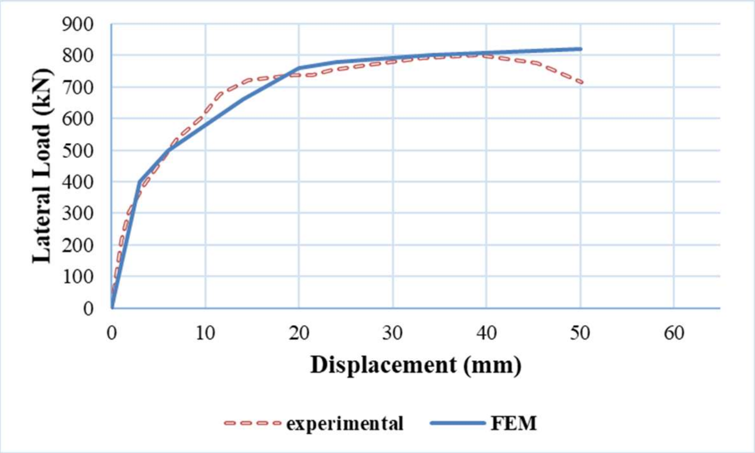
Table 1. Material Properties of SPSW [16]

Component	Yield Stress (MPa)	Ultimate Stress (MPa)	Steel Grade (DIN)
Plate	192.4	277.2	St 14
Column/Beam	414.9	551.8	St 52
Stiffeners	258.3	390.4	St 37

Turning simulation verification, the FE model has been compared with the experimental specimen in terms of hysteresis and pushover curve shown in Fig. **5** (a & b). As shown, there are some minor differences between the two models, which is due to modeling simplifications such as not modeling welding, connections, corners stiffeners, and fishplates. Notably, this difference does not affect the results of sensitivity analysis since the general behavior of the wall is the case of this paper. Moreover, the deformed shape of the SPSW is compared with the reference model, and it provides appropriate compatibility in terms of deformation and behavior (See Fig. **6**).

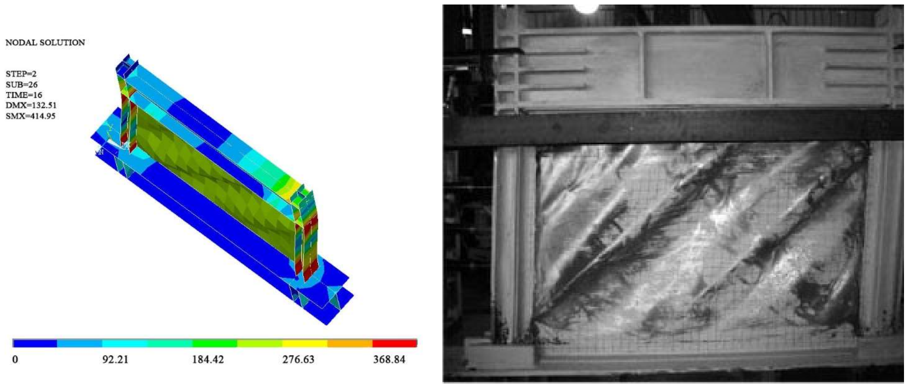


a) Hysteresis curve



b) Pushover curve of SPSW

Fig. 5. Model verification via Hysteresis and pushover curve



(a) (b)

Fig. 6. Compatibility of the deformed shape of models

a) FE Model b) Experimental Specimen [16]

3. SENSITIVITY ANALYSIS

In this section, the parameters of the SPSW are defined in order to deploy in the Monte-Carlo simulation. To this end, the authors utilized a FE software for statistical and sensitivity analysis. Using Monte-Carlo simulation and the Latin Hypercube Sampling (LHS) method, the software is capable of calculating the effect of variation of parameters, which is defined with a definite parabolic distribution[18]. The LHS method deploys stratification of the probability distribution functions of random variables and needs much less of simulations in comparison with the original type of Monte-Carlo simulation [19].

The output of the analysis can be depicted as the significance of each of these variables in percentage. In this paper, a total number of 22 uncertain parameters, including material properties and dimensions of the components, are studied (see Table 2).

The random variables are defined based on the probability distribution and coefficients presented in Table 3. After defining the uncertainty parameters, the simulated SPSW is pushed via a monotonic lateral load, and the sensitivity analysis is carried out. The considered response in the probabilistic analysis is the horizontal displacement of the wall.

Table 2. Studied parameters in SPSW sensitivity analysis

Parameter	Definition	Notation	Parameter	Definition	Notation
1	Height	H	12	Width of thecolumn's web	WCW
2	Length	L	13	Width of the bottombeam's flange	WFBB
3	Flange thickness of column	TFC	14	Width of the topbeam's flange	WFTB
4	Web thickness of column	TWC	15	Width of the bottombeam's web	WWBB
5	Flange thickness of bottom beam	TFBB	16	Width of the topbeam's web	WWTB
6	Flange thickness of top beam	TFTB	17	Yielding stress of beam and column	YSCB
7	Plate thickness of wall	TPS	18	Yielding stress of wall's plate	YSWL
8	Stiffener thickness	TSB	19	Yielding stress of stiffeners	YSSTIF
9	Web thickness of bottom beam	TWBB	20	Young's modulus of beam and column	YOCB
10	Web thickness of top beam	TWTB	21	Young's modulus of wall's plate	YOPL
11	Width of the column's flange	WCF	22	Young's module of stiffeners	YOSTIF

Table 3. Variation Coefficients

Parameter	Distribution	Variation Coefficient	Reference
Section dimensions	Normal	0.150	[20]
Yielding resistance of steel materials	Normal	0.102	[21]
Young's modulus	Log-normal	0.100	[22]

4. RESULTS AND DISCUSSION

In the previous sections, the numerical model of SPSW is presented, and the study parameters are introduced. Herein, the sensitivity analysis is carried out, and the variables that play a more significant role in determining the capacity of the SPSW are categorized and reported. During the analysis, using more iterations and sampling leads to more accurate results. In contrast, with increasing the number of iterations, the analysis time will increase. In this paper, the number of iterations is set to 1000. The result of sensitivity analysis is shown in Fig. **7**.

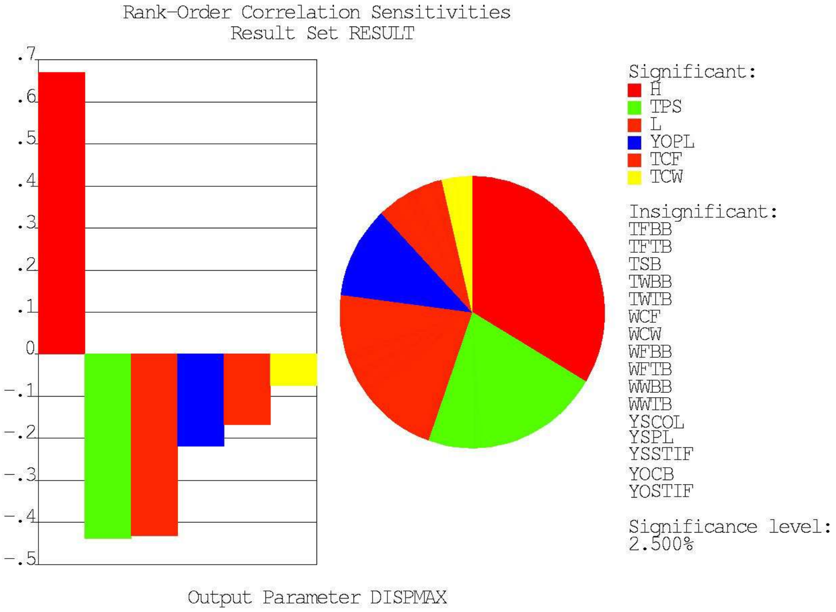


Fig. 7. Result of sensitivity analysis (1000 iterations)

Subsequently, the most significant parameters in the SPWS having higher impacts on the capacity of SPSW would be height (H), thickness of the wall (TPS), length (L), Young's modulus of wall's plate (YOPL), flange thickness of column (TCF), and web thickness of the column (TCW), respectively. Moreover, the mean and standard deviation (STD) of the displacement of SPSW versus the lateral is depicted in **Błąd! Nie można odnaleźć źródła odwołania.**. Consequently, it can be observed that the expected response of the SPSW with an error of about 5% is located between the upper and lower bounds.

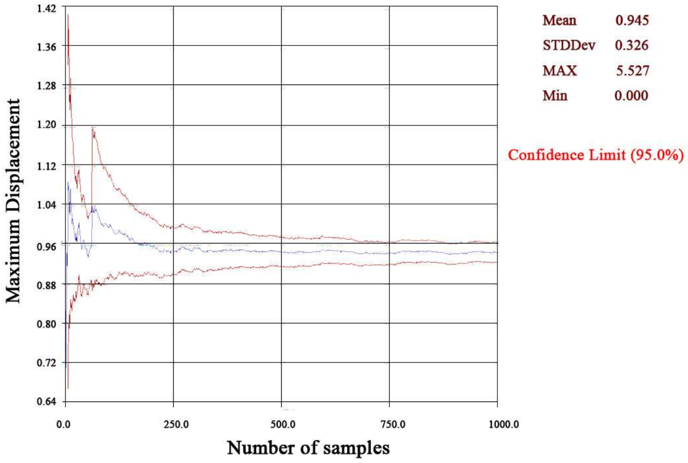


Fig. 8. Mean values of displacement (1000 iterations)

Finally, to determine and plot the capacity curve of SPSW, the upper and lower limits of the model are calculated for the incremental lateral load. During this increase, the lateral load at each step is subjected to iterative Monte Carlo analysis. As a result, the capacity curve for the two limits is denoted in Fig. 9. For the purpose of comparison, the experimental pushover curve for a load of 700 KN is shown in the Figure. It is indicated that the experimental results are located within the mentioned bounds of the capacity curve. The Figure shows that the upper and lower limits of the SPSW initial stiffness are 255.3 and 90.9 kN/mm, respectively. It also shows that the upper and lower limits of the SPSW ultimate strength are 850 and 620 kN, respectively.

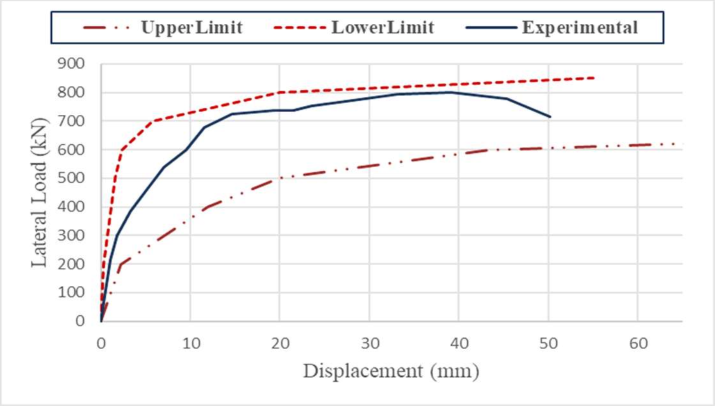


Fig. 9. Capacity curve for each bound

5. CONCLUSION

This research focused on unstiffened SPSW and was subjected to monotonic loading. In this study, the authors attempted to investigate the significance of various parameters of SPSW in terms of affecting the capacity curve. To this end, a one-story SPSW was simulated through a FEM and was verified with an experimental specimen. Afterward, a total number of 22 uncertain parameters such as height, length, thickness of the wall, etc., were defined to carry out a Monto-Carlo simulation. The wall was subjected to a monotonic loading, and the corresponding capacity curve was obtained under incremental lateral load. Subsequently:

- The most significant parameters affecting the capacity curve were identified as the panel height, thickness, panel length, and Young's modulus of the wall material coupled with the flange and web thickness of the column, respectively.
- The significance of the SPSW strength sensitivity to the panel height, plate thickness, and panel length is more than 2 times greater than its sensitivity to the Young modulus and the flange and web thicknesses of the columns.
- It was shown that in the presence of the assumed uncertainties, the upper limit of the SPSW initial stiffness is almost 2.5 times its lower limit.
- The upper limit of the SPSW ultimate strength was almost 20% greater than its lower limit due to the considered random variables.
- It was observed that the under-investigated uncertainties potentially are capable of causing a more significant decrement of the SPSW strength and stiffness relative to their potential to enhance its behavior.

Future studies can carry out on stiffened wall types and deploy cyclic loading to identify the significance of uncertain parameters

Conflict of Interest

The authors declare that they have no conflict of interest.

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