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The Effect of Geometric Nonlinearity on the Seismic Performance of Steel Plate Shear Wall (SPSW) Systems

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Abstract: Recently, steel plate shear wall (SPSW) systems have attracted a lot of attention to be used as reliable lateral load resisting systems in areas of high seismicity. The main problem associated with the analysis and design of SPWS systems, particularly in high-rise buildings, is that the structural model cannot be numerically converged due to the effects of geometric nonlinearity using thin-walled webs while experiencing significant membrane actions in shell elements. The present study examines whether neglecting the geometric nonlinearity on the numerical modeling of SPSW system affects the accuracy of the models. This study confirms that neglecting the geometric nonlinearity in the numerical models can significantly overestimate the seismic capacity of SPSW systems between 10% and 17% depending on the height of the building considered. This modeling issue can be proved extremely critical in modeling tall buildings equipped with SPSW systems while the geometric nonlinearity is ignored in order to help the large model to converge.

Keywords: Steel plate shear wall (SPSW); Finite element method; Numerical modeling; Large displacement; Geometric nonlinearity

1. Introduction

The 1994 Northridge and 1995 Kobe earthquakes brought to structural engineering significant changes in terms of the seismic design philosophy and practice of engineering structures; certainly more than any other earthquakes in recent years [**Error! Reference source not found.**]. A vast majority of research studies have been done into identifying the problems with the pre-Northridge lateral seismic resisting systems and further developing new ones. The most significant post-Northridge development was the birth and development of new beam-to-column connections (e.g., [**Error! Reference source not found.**–**Error! Reference source not found.**16]), the so-called post-Northridge connections, as well as new lateral seismic resisting structural systems (e.g., [**Error! Reference source not found.**17–31]).

One of the proposed structural systems that has been widely used in a significant number of buildings after the Northridge and Kobe earthquakes is the steel plate shear wall (SPSW) system. Fig. 1 presents four samples of conventional of SPSW systems in use in the United States [**Error! Reference source not found.**19–**Error! Reference source not found.**22]. The main function of this lateral load resisting system is to resist the horizontal shear forces induced by earthquake excitations and high winds [**Error! Reference source not found.**18]. This lateral load resisting system comprises of three main parts including: (a) a thin steel infill plate (web plate), (b) the boundary columns (vertical boundary elements), and (c) the horizontal floor beams (horizontal boundary elements) [**Error! Reference source not found.**19]. The SPSW system is designed in a way that the web plates buckle in shear intentionally. Therefore, the lateral load resistance is provided through the development of a diagonal strut-tie field action of the web plate, which has ductile behavior and is desired to absorb some energy, alike the diagonal brace systems [**Error! Reference source not found.**19]. The use of SPSW system significantly reduces the induced seismic demand on the structural frames due to its ductility, continuity, and inherent redundancy associated with this simple but beneficial system [**Error! Reference source not found.**29].

In order to design the SPSW system, three methods have been proposed including: (i) the strip method [**Error! Reference source not found.**32], (ii) the plate-frame interaction (PFI) method [**Error! Reference source not found.**3–**Error! Reference source not found.**34], and (iii) the equivalent truss method [**Error! Reference source not found.**35]. For the design of buildings equipped with SPSW systems, it is common to use the strip method when employing commercial finite element (FE) software. Shell elements are usually applied for modeling the thin web plate. The property of the shell elements is then modified in a way that it will be able to resist against seismic loads in tension. The main problem associated with this type of analysis when using SPSW systems in high-rise buildings is that the model cannot converge due to the effects of nonlinear geometry using thin-walled plates while experiencing significant membrane actions in shell elements. To solve this problem and to get the model converged, it is common to remove the effect of nonlinear geometry in similar structural models. This solution, at first glance,

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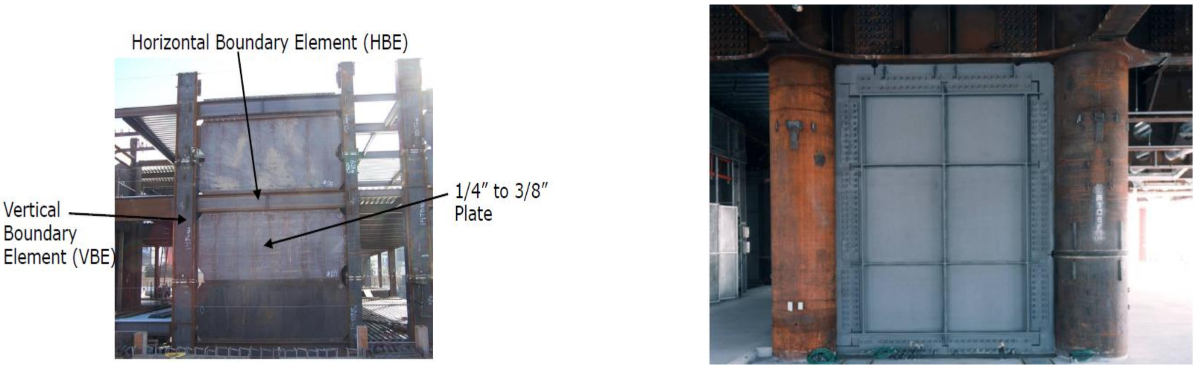
seems attractive as it is convenient to develop the finite element (FE) models and run less time expensive analysis. However, it is apparent that this approach may underestimate the induced seismic demand in the structural elements–which is essentially not desired by the performance-based earthquake engineering approach.

The aim of this study is to evaluate the effect of the geometric nonlinearity on the seismic performance of structures with different heights (from low- to high-rise buildings) equipped with SPSW systems. For this, first, the applied structural models are verified through comparative studies between the numerical results of the current study and experimental tests found in the literature. Following, the influence of neglecting the nonlinear geometry on the computational model is evaluated. Therefore, the effect of geometric nonlinearity and the degree of variation of the structural responses when the geometric nonlinear is overlooked is comprehensively examined in the present study.



a) Unstiffened, slender-web SPSW b) Stiffened web plate SPSW

c) Stiffened SPSW with a central perforation d) SPSW with opening

Fig. 1. Different samples of SPSW [**Error! Reference source not found.**19–**Error! Reference source not found.**2]

2. Numerical Modeling of SPSW for Purpose of Design and Motivation for the Present Study

The infill plate found in SPSW systems buckles first, under low shear forces which are induced by the earthquake. Then, lateral forces developed in SPSW systems are resisted through the formation of tension fields. Therefore, the model of SPSW systems should be able to capture the aforementioned behavior appropriately. As it was noted in Rezai [36], SPSW systems are usually modeled using the shell elements expecting to buckle under shear. Additionally, in the numerical modeling both material and geometric nonlinearity should be considered. The principle role of the geometric nonlinearity in the numerical models of SPSW systems is to correctly capture the buckling in the infill plate. In commercial software such as ABAQUS, LS-DYNA, and ANSYS, the geometric nonlinearity can be included in the numerical model. However, when designing a building, using such software is impractical and uncommon. Engineers use conventional software for the analysis and design of structural systems such as ETABS and SAP2000, GSA Oasys, Stadd Pro, Robot, etc., in which it is not a common practice to perform explicit FE analyses with 3D discretized FE models and include the geometric nonlinearity in the structural modeling. Because of this, there is a need to develop a method which considers the effect of geometric nonlinearity when conducting a classic structural analysis and using demanding large models. A simplified method has been proposed by Rezai et al. [**Error! Reference source not found.**36] for modeling SPSW systems in such programs. This method facilitates the structural analysis and design of the buildings equipped with SPSW systems and enables the designer to use SPSW systems along with other structural elements such as beams and columns. The proposed method implements the concept of pure tension fields or the well-known strip model. Hence, the method does not account for the shear carried by the thin-walled steel panels before the panel buckling. The method involves the following steps:

1- Computing the angle of inclination (α) for the tension strips using the following equation [**Error! Reference source not found.**32]:

$$(\tan\alpha)^4 = \frac{1+\frac{tL}{2A_C}}{1+th_s\left(\frac{1}{A_b}+\frac{h_s^3}{360\,I_C L}\right)} \tag{1}$$

where h_s is the height of the story, A_b is the cross-sectional area of the beam, t is the thickness of the infill panel, L is the bay width. In addition, A_c and I_c are the cross–sectional area and moment of inertia of the boundary columns, respectively.

2- Reorienting the in-plane local axes for the shell elements or infill plates in in the structural analysis software (e.g., ETABS, SAP2000, etc.) based on the specified inclination angel defined in the previous step. The inclination angle is usually assumed about 45 degrees with respect to the horizontal line. However, it is suggested to use Eq. (1) to consider the effect of different parameters, which are identified as effective in the angle of strip inclination.

3- Assigning orthotropic material properties to the shell element instead of using commonly used isotropic material properties. This enables to model the buckling of the compression diagonal in the infill plates. Also, different moduli of elasticity are assigned to the applied shell elements in different directions. In the compression diagonal, it is usually conventional to assign much less stiffness than that for the steel material. Therefore, due to the low stiffness of compression diagonal in comparison to the tension diagonal, a negligible shear will be developed in the compression diagonal. This simulates the actual behavior of the compression diagonal, which its capacity is negligible due to its buckling. In this direction, 2% to 5% of the modulus of elasticity for steel material should be allocated to the compression side. When it comes to the tension diagonal, the full modulus of elasticity for steel material should be considered. Furthermore, in engineering practice, the local axes of 1 and 2 are usually assigned to the tension and compression diagonals, respectively.

Using the above mentioned methodology for the structural modeling of SPSW systems helps to correclty capture the accurate behavior of SPSW systems. However, many designers are not willing to adopt this approach due to some numerical problems that may encounter on the structural models. In these cases, the geometric nonlinearity in the structural models is neglected. This study attempts to examine to what degree neglecting the geometric nonlinearity can impact the predicted capacity of SPSW systems. Consequently, ABAQUS is employed herein while four different frames with 1, 4, 6, 9, and 12 stories are considered to examine the effect of the geometric nonlinearity on the capacity of SPSW systems tested under a monotonic loading through a nonlinear (material and geometry) static analysis. Two different types of SPSW systems are also examined including a diagonally stiffened SPSW system with a central perforation, and a perforated SPSW system. Then, the results of 1-story numerical models are verified with the experimental ones.

3. Numerical Modeling

To create the numerical models of SPSW, the general-purpose finite element software ABAQUS V 6.14 [**Error! Reference source not found.**38] is employed in this study. The shell element (S4R) with 4-node doubly curved, reduced integration and hourglass control as well as five Gauss integration points through the thickness of shell, is applied. This element can provide the enhanced simulation of the complex web plate response. S4R also allows transverse shear deformation and, thus, the transverse shear becomes very small as the shell thickness decreases. In order to facilitate the buckling in the web plate and consequently the development of the tension-strut field action, an initial out-of-plane imperfection is applied when modeling the web plates. As addressed by Webster [**Error! Reference source not found.**39], to determine the initial imperfection an eigenvalue bulking analysis is required. In this regard, the Riks method is implemented to take local and lateral buckling into account. Then, an initially scaled deformation in the shape of the first bulking mode is imposed on the numerical model to account for the imperfection as suggested in [**Error! Reference source not found.**40, **Error! Reference source not found.**41].

In order to simulate the material behavior of all components including beams, columns, web plate, and stiffeners in the FE model, elastic-plastic material properties with isotropic hardening is selected. For the numerical modeling, two assumptions are made to facilitate web plate modeling. First, it is assumed that the web plate is tied to the columns and beams (boundary elements). This implies that the phenomena of web plate slip and web plate tearing are not considered in this simulation process. As it will be discussed later, the similarity between the experimental and numerical models, in case that the mentioned phenomena are neglected, show that they are not so significant. Second, conservatively, it is assumed that all elements including frames and web plates display a pure isotropic hardening. The results of Webster [**Error! Reference source not found.**39] shown that the isotropic and kinematic hardening parameters can vary from one plate to another depending on its thickness.

4. Validation of the Numerical Models

In this study, two systems, including a diagonally stiffened SPSW system with a central perforation and a perforated SPSW system, are considered to verify the efficacy of the numerical models. Experimental tests carried out by Vian et al. [**Error! Reference source not found.**1–**Error! Reference source not found.**2], and Alavi and Nateghi [**Error! Reference source not found.**0] are implemented herein to compare with the elaborated FE models. The first specimen is the diagonally stiffened SPSW system with a central perforation. The details and the mechanical properties of the applied diagonally stiffened SPSW system with a central perforation are available in [**Error! Reference source not found.**0]. For this study, first, the effect of mesh size on the behavior of this SPSW system is studied using pushover analysis. In Fig. 2, the base shear versus displacement for diagonally stiffened SPSW system with a central perforation, considering five different configurations for mesh size, is displayed. From the results, it appears that the 80mm mesh size provides the best option for mesh size. Also, as will be explained later, the numerical model with mesh size of 80 mm produces the closet responses to the experimental data. Thus, this mesh size is selected for numerical model of diagonally stiffened SPSW with a central perforation. In addition, the deformed shape of the considered SPSW system with different mesh configuration is depicted in Fig. 3.

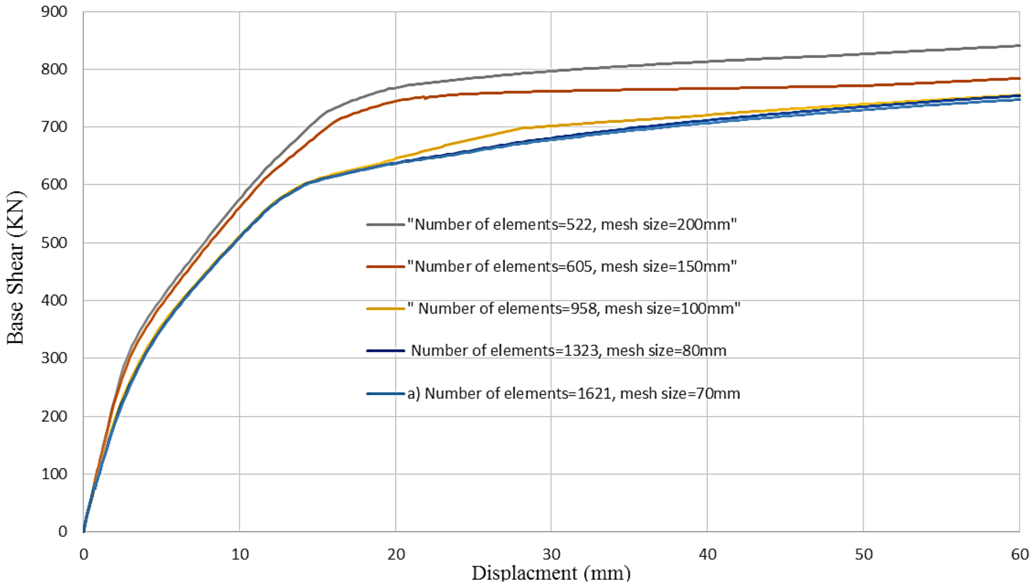
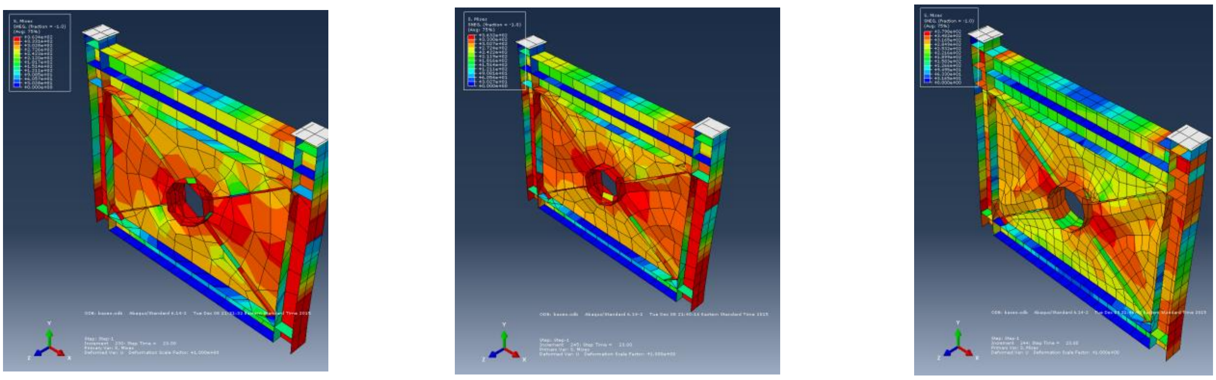


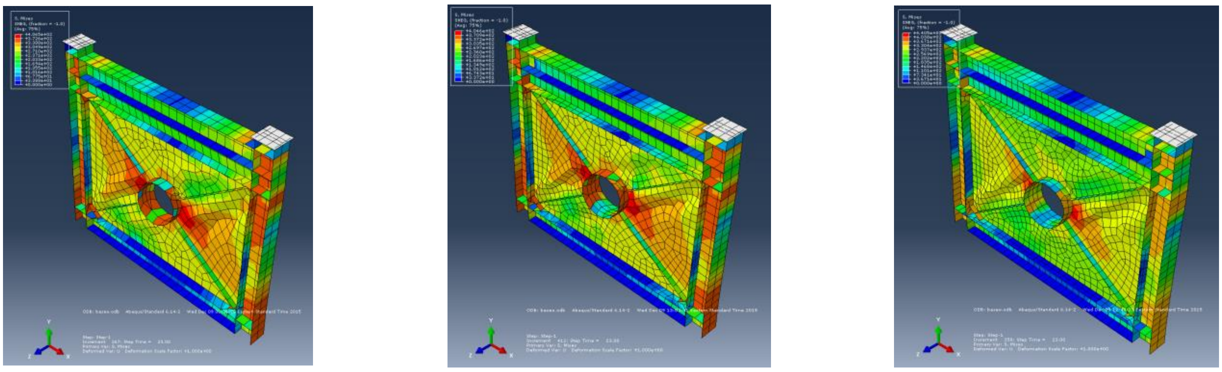
Fig. 2. Base shear versus displacement curve for diagonally stiffened SPSW with different mesh size



Number of elements=522, mesh size=200mm

Number of elements=605, mesh size=150mm

Number of elements=958, mesh size=100mm



Number of elements=1323, mesh size=80mm

Number of elements=1621, mesh size=70mm

Number of elements=2024, mesh size=60mm

Fig. 3. The deformed shape of diagonally stiffened SPSW with different mesh size

In the experimental test done by Alavi and Nateghi [**Error! Reference source not found.**20], the loading history of the ATC-24 [**Error! Reference source not found.**2] test protocol (presented in Fig. 11 in [**Error! Reference source not found.**0]) was used to load the specimens, which it is also used in this study. Also, the cyclic loading pattern in the test and the analytical modeling is controlled by the displacement at the top of the frame. Hysteretic plots of base shear versus displacement at the top of SPSW system from both the numerical model and experimental test are presented and compared in Fig. 4. Satisfactory agreement between experimental results and FE analyses is found. Thus the results of the FE analysis are suitable and in line with these obtained from the experimental tests. The deformed shapes of the specimen from the FE model at the drift ratio (displacement to the height of specimen) of 4.4% are compared with these from the experimental study in Fig. 5, demonstrating the buckling shape of the considered SPSW specimen. As seen, the deformed shape predicted by the numerical model is similar to the final buckling shape mode observed in the test.

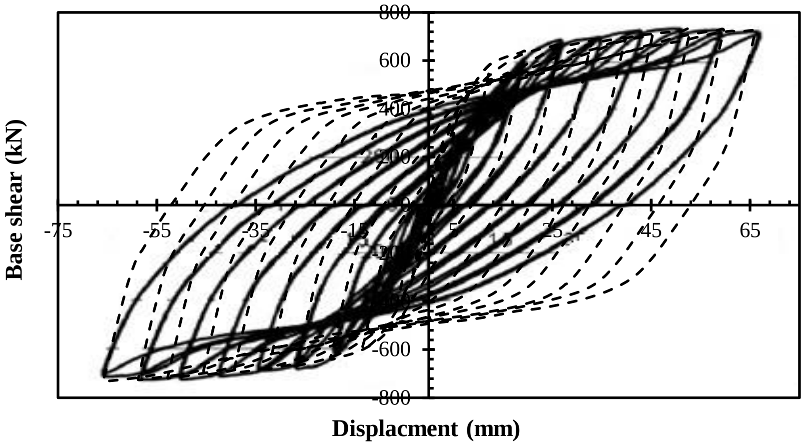


Fig. 4. Experimental (Alavi and Nateghi [**Error! Reference source not found.**20]) and numerical base shear versus displacement curve (experimental results in the solid line and finite element results in the dashed line)

Fig. 5. The deformed shape of the specimen from the experimental test (Alavi and Nateghi [**Error! Reference source not found.**20]) and numerical model at 4.4% drift.

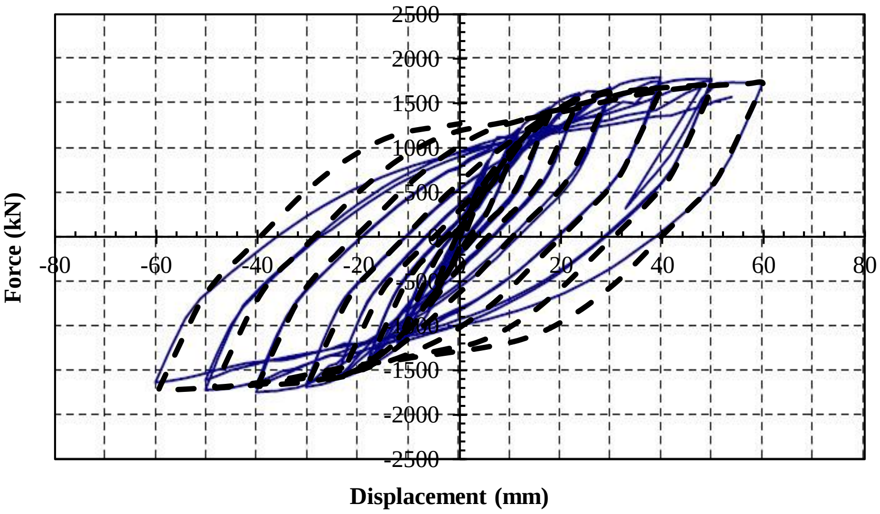


Fig. 6. Experimental [**Error! Reference source not found.**21–**Error! Reference source not found.**2] and numerical base shear versus displacement curve (experimental results in the solid line and finite element results in the dashed line)

The second specimen used to validate the applied numerical model is a perforated SPSW system without any stiffeners, which its seismic performance has been tested experimentally by Vian et al. [**Error! Reference source not found.**1–**Error! Reference source not found.**2]. The loading history of ATC-24 [**Error! Reference source not found.**42] test protocol is used to perform the cyclic loading. In the numerical model, lateral in-plane displacements are applied at the floor levels in proportion to the same ratio used in the test. In Fig. 6, the hysteretic plot of base shear versus displacement obtained from the numerical simulation is compared to that resulted from the experimental test. The results of FE model are suitably in agreement with those obtained from the experimental tests demonstrating the accuracy of the elaborated FE model.

5. The Influence of Geometric Nonlinearity

In the previous section, the finite element models were verified through establishing a comparison between the numerical and experimental results. In this section, these elaborated models are applied to evaluate the importance of the geometric nonlinearity on the seismic performance of SPSW systems. For this purpose, two different cases are considered with respect to material and geometric nonlinearity. In the first scenario, the geometric and material nonlinearity are both considered in the finite element model. When it comes to the second scenario, only the material nonlinearity is taken into account, while the geometric nonlinearity is neglected in the finite element model.

In order to estimate the capacity of the structural systems different methods have been proposed including: nonlinear static analysis, nonlinear dynamic analysis, and incremental dynamic analysis [**Error! Reference source not found.**43–**Error! Reference source not found.**45]. The last two solutions involve using ground motion records and considering record-to-record variability, which are computationally demanding. On the other hand, many studies have shown that nonlinear static analysis can provide a good estimate of the structural seismic capacity, particularly in case of first-mode dominated structure. Therefore, for the purpose of the present study, nonlinear static pushover analysis is employed to compute the capacity of specimens in terms of base shear. Monotonic loading is applied to push the top of specimens to a specified displacement. Fig. 7 presents the base shear against the lateral displacement for the diagonally stiffened SPSW system for two aforementioned scenarios. The effect of large displacements on the seismic response of SPSW system is investigated. As it is clear, neglecting the influence of geometric nonlinearity leads to the underestimation of the displacement given an applied force. As an example for the applied load of 700 KN, the displacement is underestimated about 35%. From another viewpoint, the capacity of SPSW system is overestimated if the geometric nonlinearity is neglected. As seen, the estimated capacity neglecting the large displacement in the SPSW FE model is about 10% more than the predicted capacity when both material and geometric nonlinearity is included. The study concludes that incorporating large displacement in SPSW systems might lead to the overestimation of their nonlinear performance. During an earthquake, this effect may become significant, especially when is combined with considerable vertical loads and must, therefore, be included in the analyses.

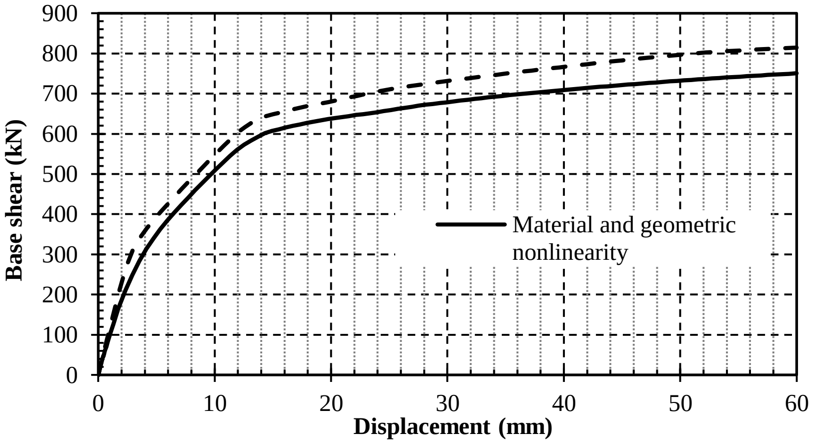


Fig. 7. The effect of large displacement on the seismic response of diagonally stiffened SPSW system

This process is repeated for specimens with a different number of stories to evaluate the effect of large displacement on the seismic performance of SPSW systems. The considered specimens are from four different structures including 4-, 6-, 9-, and 12-story buildings. These buildings are designed for a high-risk seismic zone according to ASCE 7-10 and a combination of SPSW and moment resisting systems is used as a lateral supporting system. The SPSW system for all buildings is modeled according to the method described earlier (about finite element modelling of SPSW), and both types including diagonally stiffened and perforated SPSW systems are examined. Then, a nonlinear static pushover analysis is performed for each specimen to estimate the importance of geometric nonlinearity on the seismic capacity of SPSW systems. For this purpose, the top of each specimen is pushed up to a specified displacement. Then, the base shear versus top displacement of specimens is recorded, like those presented in Fig. 7. Next, the difference between the nonlinear capacity of all specimens considering and neglecting geometric nonlinearity are computed and presented in Table 1. As would be expected, in all cases the capacity of SPSW systems is overestimated if the nonlinear geometry is overlooked in the FE models. As seen, the percentage of overestimation increases as the number of stories rises implying that this issue is more important in the case of high-rise buildings. Notably, one limitation of the present study is that the gravity load is not considered in the pushover analysis. The effect of large displacement in the nonlinear capacity of SPSW will be more significant if the destabilizing action of gravity load is taken into account. However it is attempted to ignore this factor and generalize the results (i.e., independent of the system size). In general, the results indicate that neglecting the geometric nonlinearity in the structural models of structural buildings which are equipped with SPSW systems may cause overestimation of the nonlinear capacity. Therefore, it is advised that this effect should be included in the modeling. If considering this phenomenon leads to instability of the structural model, it is suggested that the analysts use the results of Table 1 and decrease the capacity of the SPSW systems in design by the corresponding percentage. Therefore, following this study, SPSW systems used in multi-story frames should be designed for higher lateral seismic demand to those reported in Table 1. In another option, the designer can reduce the estimated capacity for SPSW systems by about 15% to reach a safe design.

Table 1. The percentage of overestimation of the capacity for SPSW systems when geometric nonlinearity is neglected

Story	Diagonally stiffened SPSW	Perforated SPSW
1	10%	9%
4	12%	12%
6	13%	12%
9	15%	15%
12	16%	17%

6. Concluding Remarks

These studies addressed a problem associated with the analysis and design of the steel plate shear wall (SPSW) systems in high-rise buildings. The problem is that the structural model of high-rise buildings equipped with SPSW systems cannot be numerically converged. This problem, in fact, is because of the effects of nonlinear geometry in thin-walled webs while experiencing significant membrane actions in shell elements. To solve the aforementioned problem in practice (not in academic), it is conventional to analyze the structural model without considering the impact of nonlinear geometry in the structural models. It is well accepted that this solution overestimate the seismic capacity of the SPSW systems. This study quantifies to what degree neglecting nonlinear geometry in the structural models of SPSW systems can over predict their seismic capacity. Finally, the paper suggests a very simple practice-orientated method to consider the effect of the geometric nonlinearity in the estimated seismic capacity of SPSW systems. Based on the numerical studies performed investigating the impact of large displacements (i.e. geometric nonlinearity) on the seismic performance of structural systems with SPSW systems, the following conclusions can be drawn:

(1) The FE models are verified through establishing a comparison between analytical and experimental results.

(2) The results confirmed that the geometric nonlinearity has an important influence on the response of SPSW systems. Neglecting the geometric nonlinearity in FE modeling underestimates the lateral displacements recorded - especially when combined with the considerable vertical (gravitational) load. Hence, in the case of severe earthquakes, this simplification can cause the instability of structures if combined with the destabilizing effect of gravity loads.

(3) It is suggested that, particularly for high-rise buildings, the geometric nonlinearity should be taken into account in the design process to estimate the developed seismic demand. In the case of large displacement lead to model convergence issues, the analyst can use the results of the present study to increase the developed seismic demand and, then, design the structural systems. In addition, the computed lateral displacements should be increased in the case where the impact of large displacements is not taken into account.

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