Analytical Study of Building Height Effects over Steel Plate Shear Wall Behavior

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Abstract

In the latest three decades, the steel plate shear walls (SPSW) system has emerged as a promising lateral load resisting system for both construction new buildings and retrofit of existing buildings. This system has acceptable stiffness for control of structure displacement, ductile failure mechanism and high energy absorption. This paper will quantify the effect of increasing the height over analytical behavior of SPSW (height effect). Considering abundant emergence of high-rise buildings all over the world in recent years and their need for strengthening, the importance of the studies presented in this paper cannot be overemphasized for optimum height usage of SPSW lateral resisting system. The study was performed through design of four models of dual system with special moment frames capable of resisting at least 25% of prescribed seismic forces. In this article, structure buildings consisting of 5, 10, 15 and 20 stories have been modelled. Results consisting of story shear absorption, support reaction forces, lateral story displacement and drift indexhave investigated for different cases. Results show that SPSW absorbs more shears at the lower stories than top stories. Furthermore, axial reaction of edge supports experience decreasing rate corresponding to increase in the story numbers. Drift magnitude of steel plate shear wall with the 5 stories has the maximum value at the top story while the systems with the 10 and the 15 stories have maximum drift at lower stories.

Keywords: Steel Plate Shear Wall (SPSW), dual system, high-rise buildings

1. Introduction

In the latest three decades, the steel plate shear walls (SPSW) system has emerged as a promising lateral load resisting system for both construction new buildings and retrofit of existing buildings (especially in high-rise buildings). This system has acceptable stiffness for control of structure displacement, ductile failure mechanism and high energy absorption.

There are several numerical and experimental studies to quantify the structural behavior of SPSW [1-13]. In a research program which Elgaali and Caccese carried out in 1990, ten steel shear wall specimens subjected to the cyclic loads have been studied. Specimens were 3-story and one span and they differed with each other in plate thickness and beam to column connection type. In the middle of test, columns due to weak design were buckled and also this connection showed a behavior similar to the rigid connection due to inaccurate implementation [4]. In the years 1991 and 1992, Sabouri & Roberts tested 12 small-scale shear panel specimens which had thin plate. Each specimen was loaded subjected to the tensile and compressive

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cyclic loads on the opposite diagonals which were applied to the corners. He concluded that strength and stiffness of shear panels is decreased by opening dimensions increase in a linear way [1, 5]. In 1998, Driver tested a 4-story steel shear wall on a scale of 1/2 which had rigid beam to column connections subjected to quasistatically cyclic loading. Purpose of this test was study of a multi-story steel shear wall subjected to cyclic loads. Equivalent lateral loads were applied on the level of each story cyclically and specimen subjected to cyclic loadings until maximum ductility. Finally, test ended due to the weld fracture at the bottom of column of specimen [6].

In 2001, Astaneh-Asl and Zhao studied two stories steel shear walls specimens subjected to cyclic loads which. Half of one coupled steel shear wall and tubular steel columns filled with concrete was included in the specimens. Specimens showed good ductility and stable hysteresis behavior along with suitable energy absorption [9]. In 2002, Matteis, Landofel and Mazolani studied effect of steel shear panels which had low yielding limit on the seismic response of two 7-story steel moment resisting frames: (1) Frames which are specified by their members which have great over-strength (Ω) and lateral elastic resistance of story approximately is more than design shear of story. (It means that frames have been designed according to stiffness needs). (2) Frames which are specified by rather low lateral resistance compared with design forces (It means that frames basically have been designed according to strength needs). These frames were subjected to three recorded accelererograms which are: 1940 El Centro earthquake record (E-W component) – 1952 Taft earthquake record (S 69 E component) and 1968 Hachinohe earthquake record (N-S component) [13].Their results are:

Low-yield shear panels may strongly enhance the seismic performance of steel frames. While acting as hysteretic dampers, they supply a large source of energy dissipation, which results in a limitation of plastic deformation demand to the primary structure.

Beneficial effect of low-yield shear panels appear to be significantly dependent on both yield strength ratio ρ and second stiffness ratio a. When applying relevant design strategies, in order to optimize the structural response of the whole system, the impact of such indices should be checked. Anyway, it has been shown that also shear panels characterized by low relative strength (low value of ρ ratio) allow a significant improvement of seismic performance Degradation effects of the hysteretic behavior of low-yield shear panels may produce a reduction of panel structural contribution, especially for large frame story deflections.

Application of low-yield shear panels appears to be particularly effective in case of primary structures characterized by limited lateral rigidity and reduced over strength. In fact, in such a case, shear panels may behave as stiffening devices also, rather than as hysteretic dampers only. Therefore, the contribution provided by shear panels could be profitably taken into account when performing the serviceability limit state check of the primary structure, which, according to Euro codes, usually has a strong impact on the design of steel frames.

In 2003, Behbahanifard [14] tested a 3-story steel shear wall specimen on a scale of 0.5 subjected to cyclic loads along with gravity loads. In fact, tested specimen was upper part of 4-story specimen which Driver had tested. Regarding that specimen was subjected to a plastic deformation history in the previous test, so evaluation of previous test effect on the general performance of specimen was one of the purposes of this test [14]. In 2004, Vian and Bruneau [15] tested 3 steel shear wall specimens subjected to cyclic loads which low-strength steel had been used in their panel's plates and reduced section had been used in the ends of beams. Some holes were created in the plates of the two specimens. In order to decrease its total strength compared with specimen without opening, considerable numbers of holes were created in plate of one of the specimens. In another specimen one opening in the shape of quadrant was created in the corner of panel. In this specimen, around the opening was reinforced due to transferring plate forces into circumferential beams and columns [15]. In 2005, Kharrazi [16] tested two steel shear wall specimens subjected to cyclic loads with the help of Ventura and in consultation with Sabouri. Mild steel (energy absorbent steel) and structural ordinary steel were used in plate of panels in these specimens. Also, high strength steel was used in frame of the specimen. Height to width ratio of panels was chosen more than one. Panels behaved stable and they showed high total strength, elastic and post-buckling stiffness, ductility and high energy absorption.

In 2008, Sabouri and Gholhaki [1] tested two ductile 3-story thin SPSW on a scale of 1/3 subjected to cyclic loads. These walls have two types of beam to column connection, rigid (SPSW-R) and simple (SPSW-S). Also, mild steel (energy absorbent steel) and high strength steel had been used in plate of panels and columns, respectively. Each of these specimens which had rigid and simple connections was subjected to 31 and 19 cyclic loads respectively which 25 and 13 cycles of these numbers were carried out in the nonlinear range, respectively. Before failure of specimen and ending of the test, first story displacement of specimens which had rigid and simple connections was 10 and 11 times larger than their first yielding displacement, respectively. Specimens had remarkable ductility (6.63 and 8.24, respectively), high primary stiffness and high energy absorption and their hysteresis loops have shown a stable behavior. Usage of mild steel (energy absorbent steel) in plate of panels is a reason that extraordinary energy is absorbed in large displacements. Moreover, in the middle of tests and until their ending had not been seen any signs of local or general buckling in the columns. The results have shown that type of beam to column connection had some effects on the ductility factor, strength and absorbing energy, but it has no considerable effect on the primary stiffness [1].

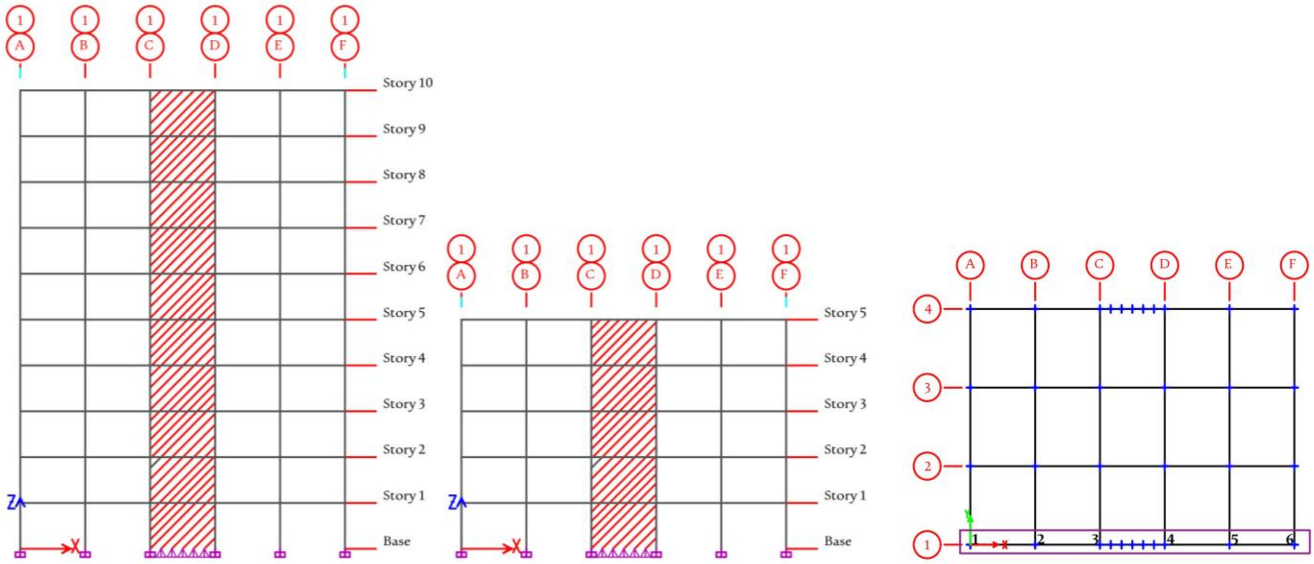
In 2009, Siddhartha Ghosh, Farooq Adam, Anirudha Das [17], during their researches about designing of steel shear walls and regarding that predications of seismic codes for these systems are based on elastic force design method, have suggested seismic design method based on the performance that proposed PBSD method for SPSW systems is based on relative inelastic lateral displacements and yielding mechanisms which are chosen already. Suggested method is tested in a 4-story building with different dimensions ratios of steel panels for lateral relative displacement subjected to earthquake mappings of Northridge recorded in Salmer station, Kobe, Japan recorded in Kijima station and Kobe, Japan recorded in Takarazuka station. Actual inelastic drift demands are created close to selected drifts. Totally, displacements diagrams compared with selected yielding mechanism in maximum responses. Proposed design method has been a proper method for design of steel shear walls [17].

This paper will quantify the effect of increasing the height over analytical behavior of SPSW. The study was performed through design of four models of dual system with special moment frames capable of resisting at least 25% of prescribed seismic forces. Structure buildings consisting of 5, 10, 15 and 20 stories have been modeled. Results consisting of story shear absorption, support reaction forces, lateral story displacement and drift index have investigated for different cases.

2. Model Assumptions

In order to quantify effect of increasing height of building on analytical behavior of SPSW, four MRF building with different stories (5, 10, 15 and 20) have been modelled using Etabs 8.5.1. For more details of the models, see Fig. 1(a). In all models the story height was 3.5 m and lateral load was applied in the X direction.

Lateral loads were distributed on the model heights according to the UBC-94 code. The frames were controlled based on the AISC ASD-89 provisions. The analyses included one equivalent static analysis and one non-linear static analysis for selected frame. Lateral loads were applied in X direction. All steel elements are modelled using ST-37 where the elasticity modulus is 210 GPa and poison ratio is 0.3. Locations of the studied frames are shown in Fig. 1(b).

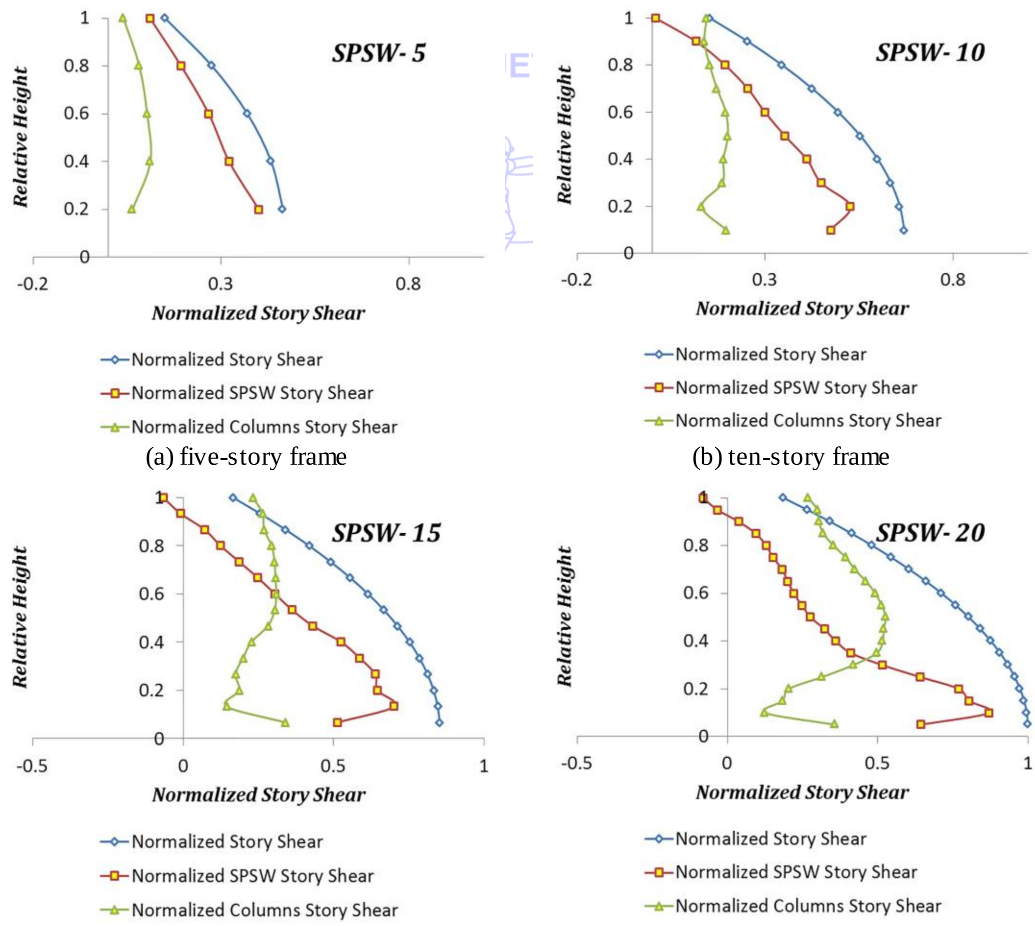


(a) Location of SPSW in 10 and 5 story frames (b) key plan, location of studied frame

Fig. 1 Elevation and plan of modeled structures

3. Results and Discussion

In this study, all stories shear forces were normalized to shear force at the first story. As it is shown in Fig. 1(b), this comparison was made for frame 1. Drift and lateral displacement of all stories were normalized to the roof drift. Shear lag in different stories were also normalized to the axial force of the columns in the first story of sample.



(a) five-story frame (b) ten-story frame

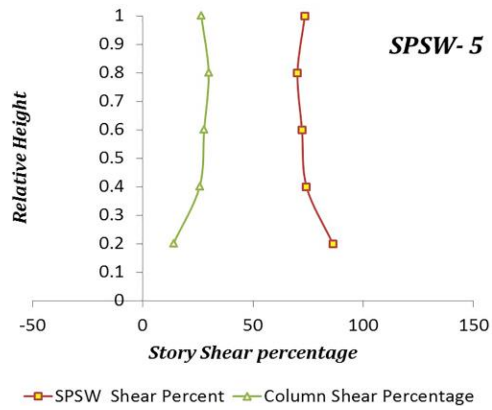
(c) fifteen-story frame (d) twenty-story frame

Fig. 2 Normalized story shear force, the shear force absorbed by walls, and also the force in the columns

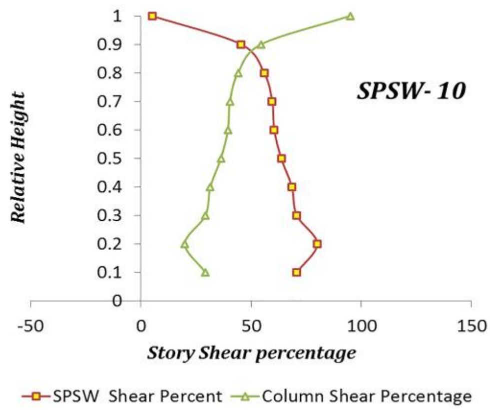
One of the most important parameters to quantify the performance of SPWS is amount of the absorbed shear force at different stories by these walls. Fig. 2 illustrates the normalized story s hear force, the shear force absorbed by walls, and also the force in the columns in different story levels.

According to Fig. 2, ratio of carrying stories shear force by steel shear wall is higher in the lower stories. For example, for the SPSW-10 the ratio of carrying shear force by sear wall at the last floor (floor 10) is zero, and the value is negative for two last stories in SPSW-15 and SPSW-20. This means that the existence of SPSW at upper floors not only cannot assistance to absorb story shear forces but also can lead to absorb more than 100% of shear force by columns at these floors. Fig. 3 is presented to clarify the issue, in which the shear absorption percentage of steel plate shear walls and columns is determined. As it is sh own in Fig. 3, in the model SPSW-5 steel shear wall absorbed more than 70% of stories shear. This absorbed ratio reaches to 86% in the first story. However, columns in this structure absorb at maximum up to 30% of the story shear. In SPSW -10, 70% to 80% of shear is distributed to steel plate shear walls in lower stories, but in upper stories, especially on the top story, shear distribution is much reduced. For example, shear distribution is reduced to 5% on the top story.

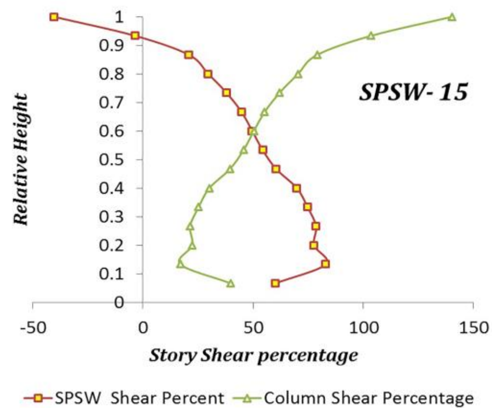
In other words, steel plate shear walls have little effect in absorbing story shear force in SPSW -10. It can be seen that in the last two stories story shear in steel plate shear walls is a negative value, and it is more than 100% in the story columns in SPSW-15 and SPSW-20. This confirms that in high-rise building and in the up floors the steel shear wall not only could not be suitable to absorb the story shear but also could increase the story shear. In the last two stories of SPSW -15, shear distribution to steel plate shear walls is -3% and -40%, respectively, and it is 103% and 140%, respectively, in the columns of these stories. In the last two stories of SPSW-20, shear distribution compared to steel plate shear walls is also -13% and -44%, respectively, while it is 113% and 144%, respectively, in the columns of these stories.



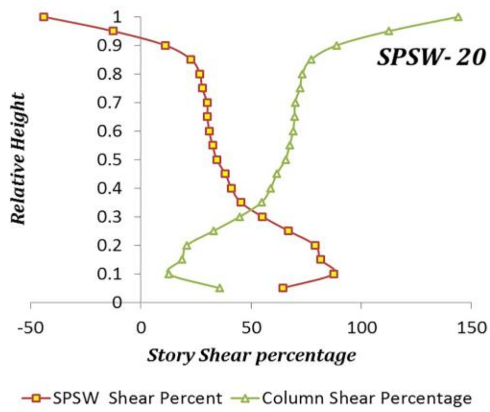
(a) five-story frame



(b) ten-story frame



(c) fifteen-story frame

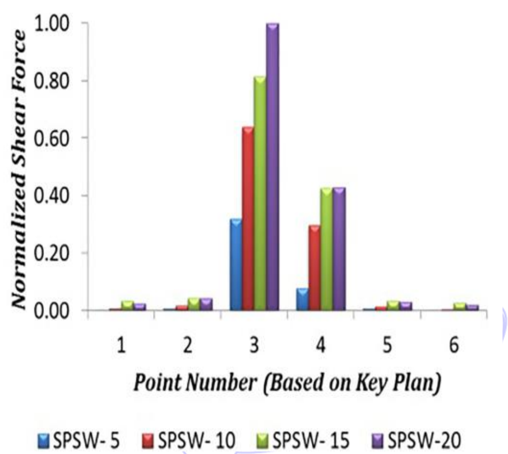


(d) twenty-story frame

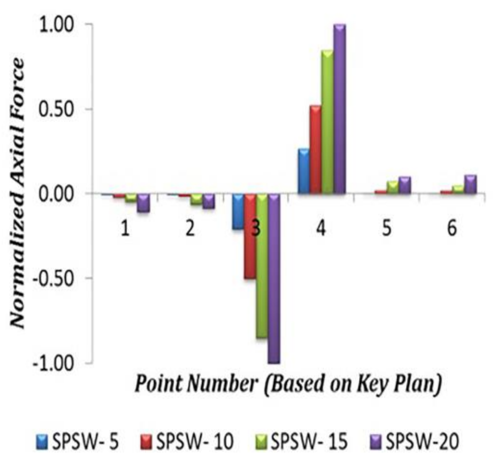
Fig. 3 Percentage of story shears absorption by steel plate shear walls and columns

The support reactions in structures including braced frame, concrete shear walls and steel plate shear walls are important, as in these structures some phenomena, such as uplift, are possible which should be controlled. In order to have a better perception of behavior of the steel shear wall, support reactions of frame no. 1 (see Fig. 1(b)) is presented in Fig. 4. As observed in Fig. 4(a), there is a significant amount of wall shear force in two supports 3 and 4 under earthquake Ex, and it does not depend on the number of stories in the structure. It is also observed that, regardless of the number of stories, in supports 1, 2, 5 and 6 there is an insignificant amount of wall shear force, which can be ignored.

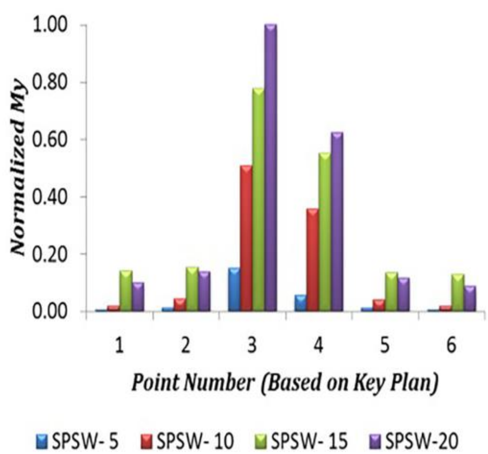
In Fig. 4(b), it can be observed that regardless of the height of structure, and there is a significant amount of tensile and compressive axial force in two edge columns of SPSW than corresponding values of other columns in the same frame. It is also observed that contrary to the shear force of supports (Fig. 4(a)); their axial force is directly proportional to the increase in stories and is increased linearly. The significant axial force in edge columns of steel plate shear walls confirms the necessity of u plift control in these structures. The importance of this issue is increased by increasing the nu mber of stories. It can also be seen in Fig. 4(c) that changes in bending moments of columns are almost identical to shear force of supports. Given that the behavior of steel plate shear walls is identical to tensile strips, higher shear force and bending moment in column 3 compared to column 4 can be justified in Figs. 4(a) and 4(c).



(a) Shear force



(b) axial reaction

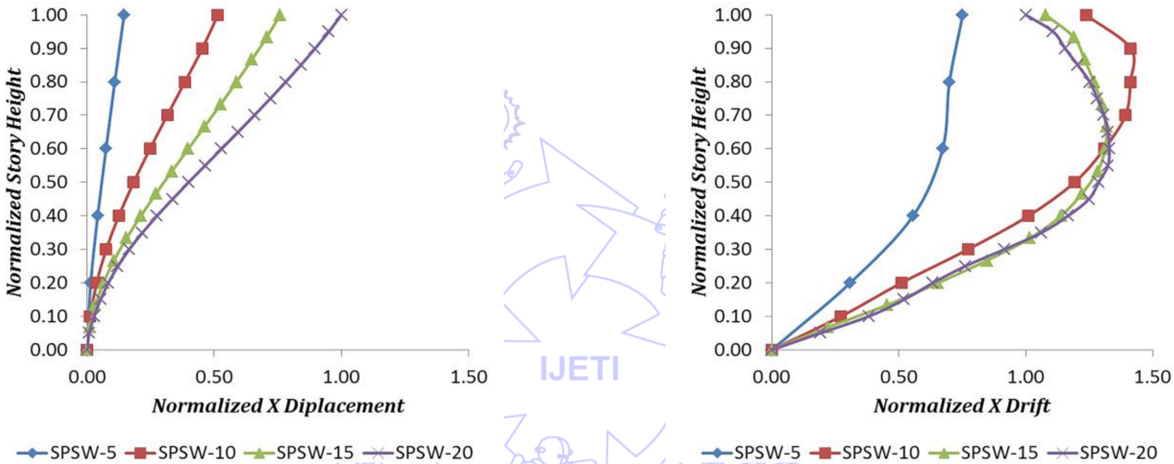


(c) created bending moment

Fig. 4 Internal force in supports 1 to 6 in frame 1

Shear support reactions are decreased by increasing the number of stories, so that the value in SPSW-10 is twice more than SPSW-5. The corresponding value is 1.28 times more in SPSW-15 and SPSW-10, and is 1.23 times more in SPSW-20 and SPSW-15. Axial support reactions are also decreased by increasing the number of stories, so that the value is 1.98 times more in SPSW-10 than SPSW-5. The corresponding value is 1.61 times more in SPSW-15 and SPSW-10, and is 1.18 times more in SPSW-20 and SPSW-15. Values of support moment reactions around axis Y are corresponding to the values of shear reaction, and axial support reactions are decreased by 3.38, 1.52 and 1.29, respectively.

Displacement and drift of structures are among the service design criteria, i.e., too much drift will damage non-structural components and will cause insecurity during the application of lateral forces such as wind and earthquake. Steel plate shear walls can significantly reduce the two. In Fig. 5(a), it can be observed that roof displacement in SPSW-5 is only 15% of that in SPSW-20, while roof displacement in SPSW-10 and SPSW-15 is respectively 51% and 76% of that in SPSW-20. According to this process, it can be found that although roof displacement is increased 250% by increasing the number of stories from 5 to 10, it is increased 48% and 32%, respectively, by increasing the number of stories from 10 to 15 and from 15 to 20. Hence, it can be concluded that with an increase in stories, displacement of structures grows at a lower rate. It is also observed that lateral displacement in SPSW-5 is completely bending and displacement in SPSW-10, SPSW-15, and SPSW-20 moves toward the shear mode with increasing the height.



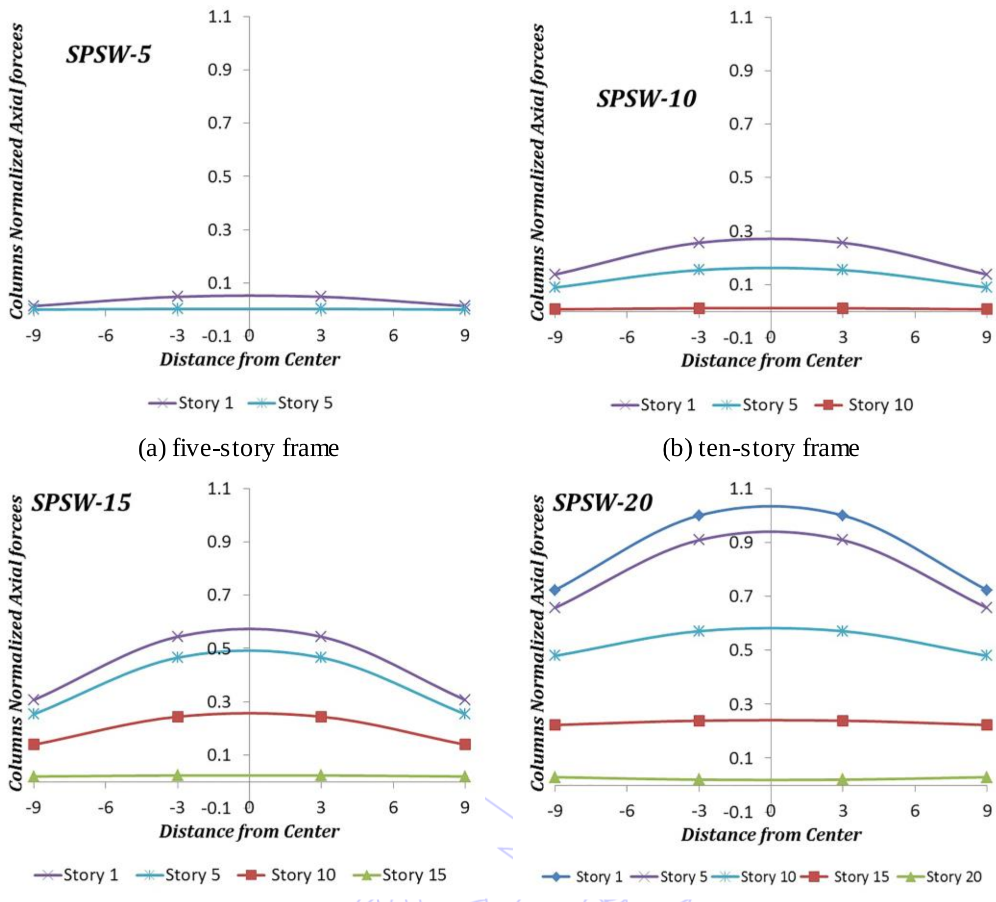
(a) Normalized lateral displacement of structures based on displacement in the last story in SPSW-20

(b) normalized lateral drift of structures according to lateral drift in the last story in SPSW-20

Fig. 5 Normalized lateral displacement and drift

Fig. 5(b) shows the normalized drift of structures according to the drift of roof in SPSW-20. As observed, drift of roof has the maximum value in SPSW-5, while in SPSW-10 the maximum drift occurs at 0.9 of height, and at 0.6 of height for two other structures. The drifts of structure are highly matched in SPSW-15 and SPSW-20, suggesting the convergence of structures drifts with increased height. As observed, maximum drift is related to SPSW-10.

Shear lag is an important parameter in high-rise structures. A dimensionless parameter called lag index was defined to evaluate the results of analysis of structures. According to the definition, axial force of edge columns shows shear lag index of these columns compared to the values of middle columns [14]. Columns under earthquake loading EX in frame F were studied to examine the results of shear lag index. According to Fig. 6, shear lag index is normalized to middle column of the first story in SPSW-20, which is under the highest axial force. According to Fig. 6, axial force of edge columns in the first and fifth stories is 28% less than middle columns in SPSW-20. This value for columns of stories 10, 15 and 20 is 16%, 7% and -45%, respectively. As observed, shear lag index is decreased by increasing the number of stories, so that the axial force of edge columns on the top story is more than the middle column. The axial force of edge columns in stories 1, 5, 10 and 15 compared to middle columns in same stories is 44%, 46%, 43% and 17%, respectively, in SPSW-15. The value for stories 1, 5 and 10 in SPSW-10 is 46%, 42% and 37%, respectively, and in SPSW-5 for stories 1 and 5 is 71% and 73%, respectively.



(a) five-story frame (b) ten-story frame

(c) fifteen-story frame (d) twenty-story frame

Fig. 6 Normalized shear lag index compared to middle columns in SPSW-20 in various stories

4. Conclusions

The main objective of this study was to quantify the effect of increasing the height over analytical behavior of the steel plate shear walls (SPSW). The study was performed through design of four models of dual system with special moment frames with different stories (5, 10, 15 and 20). Lateral loads were distributed on the heights of the structures according to the UBC-94 code. The frames were controlled based on the AISC ASD-89 provisions. Two different analyses were applied to the structures; one equivalent static analysis and one non-linear static analysis. The following conclusions can be drawn from the study:

- In all models with different story levels, steel plate shear walls and columns around them have good performance on the lower stories of structures and absorb the majority of story shear, while in the upper stories, the absorption is decreased.
- By increasing the height of the structures, the percentage of absorbed shear by columns around steel plate shear walls is increased.
- Supports axial reactions are decreased by increasing the numbers of stories while, bending moment reactions around y axis of supports are decreased by increasing the number of stories.
- In 5-story frame, the maximum drift is observed at roof. For 15- and 20-story frames the maximum value of drift is happened at middle of the frame's height.
- It is observed that shear lag index is decreased by increasing the number of stories. The axial force of edge columns on the top story is more than the middle column.

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