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ESTIMATION OF LATERAL FORCE CONTRIBUTION OF BOUNDARY ELEMENTS IN STEEL PLATE SHEAR WALL SYSTEMS

A. Verma[1], D.R. Sahoo[2]

[1] PhD Candidate, Department of Civil Engineering, Indian Institute of Technology Delhi, New Delhi 110016; email: abhi.vrock@gmail.com
[2] Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Delhi, New Delhi 110016; email: drsahoo@civil.iitd.ac.in

Abstract

Steel plate shear walls (SPSWs) are used as lateral force-resisting systems in new and retrofitted structures in high-seismic regions. Various international codes recommend the design of SPSWs assuming the entire lateral load to be resisted by the infill plates. Such a design procedure results in significant over-strength leading to uneconomical and inefficient use of materials. This study is focused on the estimation of contribution of boundary elements in resisting the lateral force considering their interaction with the web plates of SPSW systems. Initially, the relative contribution of web plates and boundary frames is computed for a single-bay single-story frame with varying rigidity and end connections of boundary elements. Nonlinear static analyses are carried out for the analytical models in OPENSEES platform to quantify this contribution. Later, this study is extended to the code-based designed 3-, 6- and 9-story SPSWs of varying aspect ratios. Based on the results obtained, a new design procedure is proposed taking the lateral strengths of the boundary frames into account. Nonlinear time-history analyses are conducted for forty recorded ground motions representing the DBE and MCE hazard levels to compare the interstory and residual drift response and yield mechanisms of SPSWs designed as per current practice and the proposed methodology. Finally, an expression has been proposed to predict the lateral force contribution of the infill plate and the boundary frame of SPSWs.

Keywords: Boundary elements; Lateral force; Seismic analysis; Seismic design; Steel plate shear wall.

1. Introduction

Steel plate shear walls (SPSWs) are used as lateral force-resisting systems in new and retrofitted structures located in high-seismic regions. A typical SPSW consists of an infill (web) steel plate surrounded by Vertical Boundary Elements (VBEs) and Horizontal Boundary Elements (HBE). The web plate is connected to the boundary elements through the fish plates. Various international codes [1], [2] recommend the design of SPSW assuming the entire lateral load to be resisted by the infill plates. The boundary elements are then designed, following the capacity-based concepts, for the axial load and bending moment demand computed based on the expected ultimate strengths of web plates. Such a design procedure results in significant over-strengths leading to uneconomical designs of SPSWs.

Past experimental studies [3], [4] concluded that a significant amount of lateral force is resisted by the boundary frames in SPSWs. The studies showed that the lateral load share of the boundary frames could be as large as about 40% for a single-story SPSW, which may be reduced to a value of 25% for a four-story frame. [5] used a plastic analysis method to quantify the load share between frame and infill and derived an expression to estimate the fraction of load resisted by the infill plates of SPSW systems. It was assumed that the boundary elements of SPSW were designed as per the capacity-based approach where the plastic hinges would be restricted to the beam ends only.

Further, the interaction of web plates with the boundary elements has not been explicitly considered in these studies. To summarize, the contribution of boundary elements in resisting the lateral forces in the event of earthquakes should not be neglected in the design procedure. However, the absence of proper guidelines in quantifying this contribution allows the designers to conservatively assume the entire story shear to be carried only by the web (infill) plates of SPSWs. Hence, it is necessary to carry out a detailed study on the quantification of lateral load share of boundary frames of SPSW systems.

2. Research objectives

This study is focused on the contribution of boundary elements in resisting the lateral force considering their interaction with the web plates of SPSW systems. The main objectives of this study are (i) to estimate the relative share of lateral forces between the web plates and boundary elements of SPSWs, (ii) to study the effect of lateral stiffness of boundary elements with various boundary conditions on the lateral load resistance of SPSWs, (iii) to propose a revised design procedure for SPSW considering the contribution of boundary elements, and (iv) to evaluate the seismic performance of modified-designed SPSWs under the design basis earthquake (DBE) and the maximum considered earthquake (MCE) hazard levels.

3. Estimation of lateral loads resisted by infill plates

In case of the perfectly-rigid boundary elements which do not deform under the inward pull exerted by the web plates under lateral loading, the distribution of stresses is fairly uniform throughout the web plate. In such a case, the percentage of load carried by the web remains constant along its height. In the actual practice, the stress distribution in infill plates is not uniform due to the in-plane flexibility of boundary elements. This leads to the variations in the share of lateral load resisted by the infill plates over the story height. In order to understand the contribution of boundary elements in SPSW system under lateral loading, a simplified SPSW has been considered for the analytical investigation as discussed in the following sections.

A single-story single-bay SPSW having a bay width of 3.05 m and a story height of 3.96 m (aspect ratio = 0.77) is considered. Four analysis cases are studied in which the column rigidity and the end connections of boundary elements are varied. Fig. 1 shows the layouts of all considered analysis cases schematically in which infill plates are represented as multiple strips. Steel sections W18X71 and W14X211 are used as HBEs and VBEs, respectively, in case of the flexible boundary frames. A constant web plate thickness of 1.59 mm has been used in all analysis cases. These analysis cases are modelled in computer software OPENSEES [6]. Web plates are modelled as truss elements with elastic-plastic behavior for a material yield stress of 323 MPa. For the boundary elements, force-based beam-column elements are used for a material yield stress of 345 MPa. Strain-hardening ratio of 2% has been considered in both cases. The details of modelling technique adopted in this study are discussed later.

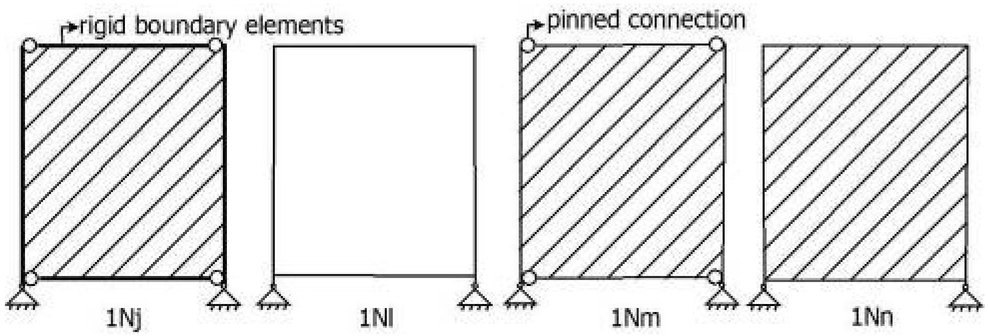


Fig. 1 - Strip models adopted for analysis of design cases

Model 1Nj represents an ideal case with pinned beam to column connections and very stiff boundary elements, in which all the strips of the web plate have the same strain and thus yielded at the same instance resulting in a distinct yield point. The flexibility of boundary frame in case of the model 1Nm causes non-uniform strain distribution on the web strips resulting in a progressive yielding of truss elements. As shown in Table 1, this results in smaller magnitudes of initial stiffness and yield strength of the model 1Nm as compared to the model 1Nj. The lateral strength of model 1Nn is found to be nearly same as the algebraic sum of the lateral strengths of the models 1Nl (frame action) and 1Nm (plate action). Assuming all strips of web plate yield at the same instance, as in case of the model 1Nj, the values of lateral strength as well as initial stiffness of SPSWs are overestimated.

Table 1 - Shear strength and initial stiffness of single story SPSWs

Model	1Nj	1Nl	1Nm	1Nn
Initial stiffness (kN/m)	946350	478079	583270	1257966
Yield Strength (kN)	775	595	534	1110
Base shear at 2% drift (kN)	840	1004	829	1821

The relative contribution of infill plates and boundary frames to the lateral resisting capacity of a SPSW can be derived from the forces exerted on the boundary elements due to the tension-field action in web plate at the deformed configuration of single-story SPSW. As shown in the Fig. 2(a), the P-Delta bending moment due to transverse load (downward pull) on HBEs at a lateral drift (Δ) impose a negative shear on the boundary frame for the equilibrium. If σ_y is the yield stress of plate, t is the plate thickness, α is the angle of inclination of the tension field, and E is the modulus of elasticity, the vertical component (w_v) of force per unit length applied by the infill, assuming the yielding of the entire plate, can be expressed as follows:

$$w_v = \sigma_y t \cos^2\alpha \qquad \text{(without strain-hardening)} \qquad (1)$$

$$w_v = \left(\sigma_y + bE\left(\frac{\Delta}{H}\right)\sin\alpha\cos\alpha\right) t\cos^2\alpha \qquad \text{(with strain-hardening)} \qquad (2)$$

The total downward force on the HBE, F can be given by $F = w_v L$. Considering the free body diagram of any VBE, the in-plane moment equilibrium yields the following equation:

$$\frac{F}{2}\Delta - \frac{P}{2}H = 0 \tag{3}$$

Where, P = shear to be resisted by the frame and H = the height of SPSW.

$$P = \frac{F\Delta}{H}; \quad P = w_v L \frac{\Delta}{H} \tag{4}$$

The additional force to be resisted by the infill plate can be given by:

$$P = \left(\sigma_y + bE\left(\frac{\Delta}{H}\right)\sin\alpha\cos\alpha\right) tL \left(\frac{\Delta}{H}\right)\cos^2\alpha \tag{5}$$

The proposed equation can be used with good accuracy to estimate the P-delta force in the boundary elements of SPSW. In a multi-story building, neglecting the difference in α at any two consecutive floors, the additional lateral force for any ith floor can be given as follows:

$$P_i = -\left(\sigma_y + bE\left(\frac{\Delta_i}{H}\right)\sin\alpha\cos\alpha\right)(t_{i+1} - t_i)L\left(\frac{\Delta_i}{H}\right)\cos^2\alpha \tag{6}$$

This negative shear imposed by the boundary frames causes additional lateral load demand on the infill plates of SPSW systems. This indicates that the contribution of infill plate under lateral load can exceed 100%. It should be noted that the proposed equations do not take the flexural deformation of boundary elements into account. The predicted negative shear resisted by the boundary frame with pinned ends have been compared with the analytical results as shown in Fig. 2(c).

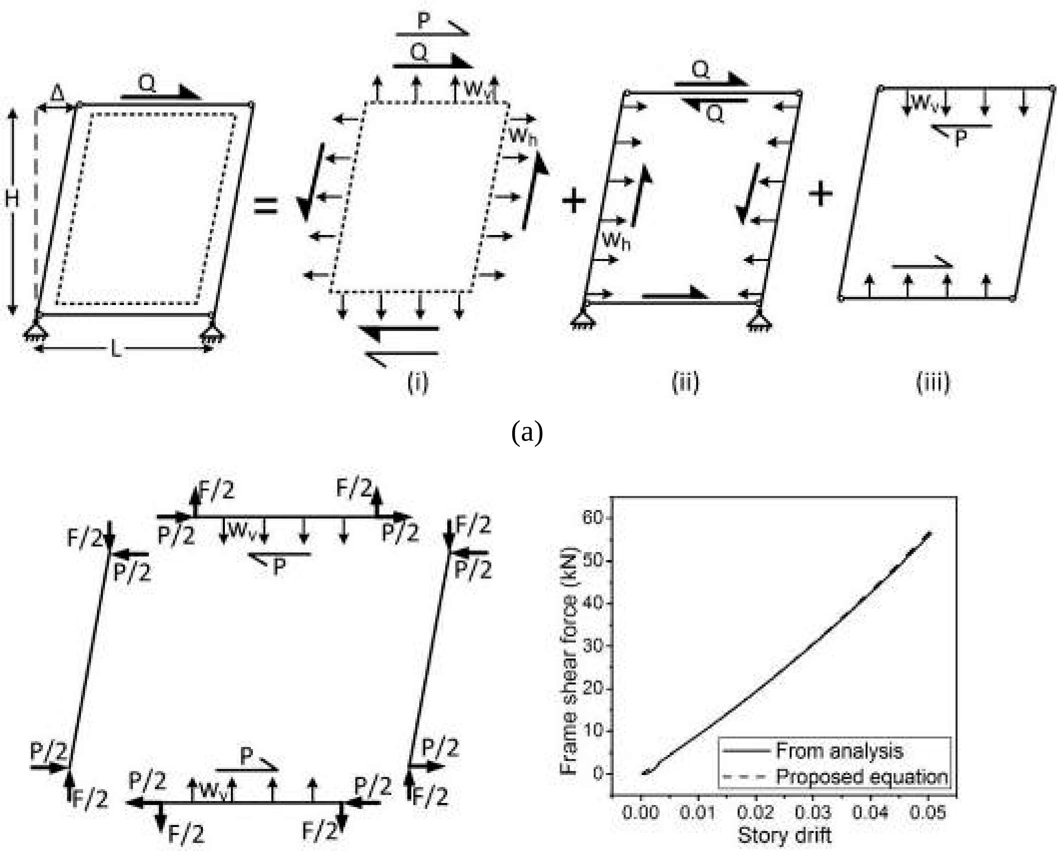
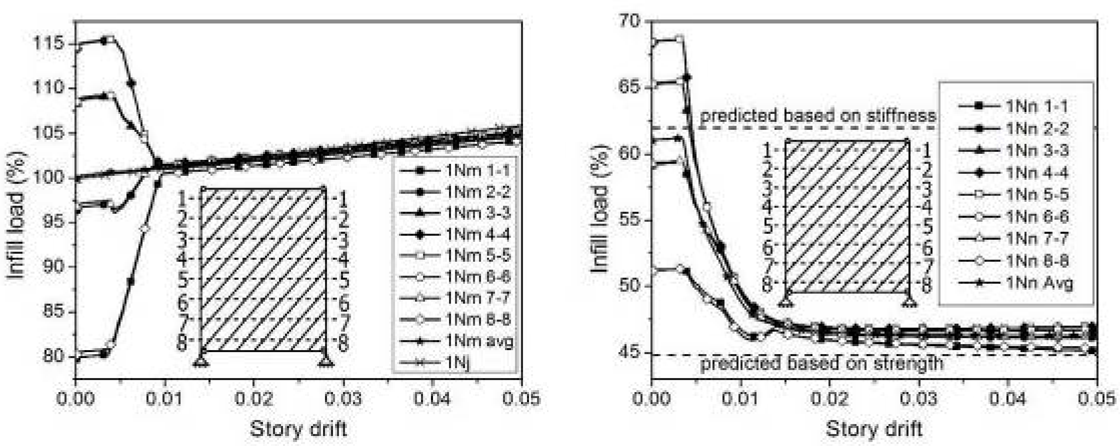


Fig. 2 - Lateral load resistance offered by infill plate and boundary frame and comparison of predicted story shear with analytical results

Nonlinear static analyses results are also used to investigate the variation of lateral load resisted by the web plate over its depth. The lateral load carried by the plate at any particular section is obtained by adding the horizontal components of the axial forces in the tension strips. Fig. 3(a) shows the percentage of load resisted by the infill plate for the model 1Nm. Before the onset of yielding, strips carry the maximum lateral load of nearly 115% at the section at mid-height of the model 1Nm, whereas at the top and the bottom the strips carry nearly 80% of the lateral load. The lateral load share of the strips at the middle section is reduced, whereas that at the top and the bottom keep increasing after the onset of yielding of infill plates. Beyond 1% drift level, when the boundary frame and all the strips have yielded, the strips of the model 1Nm carry nearly the same percentage of lateral load throughout the height till 5% drift level. The average value of lateral loads carried by the strips of model 1Nm is found to be nearly same as that of the model 1Nj in which lateral load resisted by the web plate varies linearly from 100 to 105% in the drift range of 0-5%. Model 1Nn with the moment-resisting connections between the boundary elements represents a typical SPSW system in which the lateral load is resisted by both the boundary frame and the web infill. Similar to the model 1Nm, the lateral load carried by the infill plate for the model 1Nn also varies along the height for small drift values and is nearly constant at higher drifts as shown in Fig. 3(b). Table 1 shows the base shear and initial stiffness values of all the analytical models. The fraction of lateral load carried by the infill is controlled by the relative stiffness of the frame and the infill plates at the smaller drift levels, and by their relative strengths at the higher drift levels. The ratio of initial stiffness of model 1Nl to the model 1Nn is found to be 0.38, which implies that for the model 1Nn, the infill is expected to carry about 62% of the load initially. Similarly, the ratio of the base shear values of the corresponding models is computed as 45% at a drift level of 2%. These values represent the upper and lower limits of lateral load share by the infill plates of the model 1Nn, which approximately matches with the analytical results as shown in 5(b). It should be noted that similar results can also be obtained if the base shear values of models 1Nm and 1Nn are considered to predict the post-yielding load share. As expected, the rule of superposition does not hold good for the initial stiffness of models 1Nl, 1Nm and 1Nn since the distribution of tension field is not same.



(a) (b)

Fig. 3 - Comparison of lateral load resisted by infill plates of (a) 1Nj and 1Nm, (b) 1Nn

4. Lateral load resistance of multi-story SPSW systems

4.1. Details of study frames

To quantify the share of lateral load resisted by the web plates of multi-story SPSWs, three low-to-medium rise (3-, 6- and 9-story) SPSWs designed as per current practice are considered for the analytical study. The building plan of these frames, as shown in Fig. 4(a), are similar to the 3-story SAC building [7]. These SPSWs are referred to as narrow (N), medium (M) and wide (W), respectively. The thickness of infill plate required at each story is computed by assuming the entire shear force to be resisted by it. Capacity-based design is used to determine the forces in the boundary elements. For this purpose, yield strength of the web is multiplied by a material overstrength factor (Ry) equal to 1.3. HBEs are designed following the procedure suggested by [8] in order to avoid the formation of in-span plastic hinges. A column-tree approach is used to find the axial force and bending moment demands in VBEs

4.2. Modelling and validation

A computer software OPENSEES is used to evaluate the seismic performance of the study frames. The web plates are modelled as tension only strips inclined at an angle (α) to the vertical in both the directions. Hysteretic uniaxial material with distributed plasticity is used to define the tension-only properties of web strips with a strain-hardening ratio of 2%. The boundary frames are modelled as force-based BeamColumn element with fiber section of Steel02 material with 2% strain-hardening. In order to validate the analytical models, a four-story SPSW test specimen previously tested by [9] is modelled in the OPENSEES platform to compare its hysteretic response with the test results. Fig. 4(b) shows the comparison of the hysteretic response of the specimen predicted by OPENSEES with the experimental result. The analytical model successfully predicted the lateral stiffness, peak loads and post-yield behaviour.

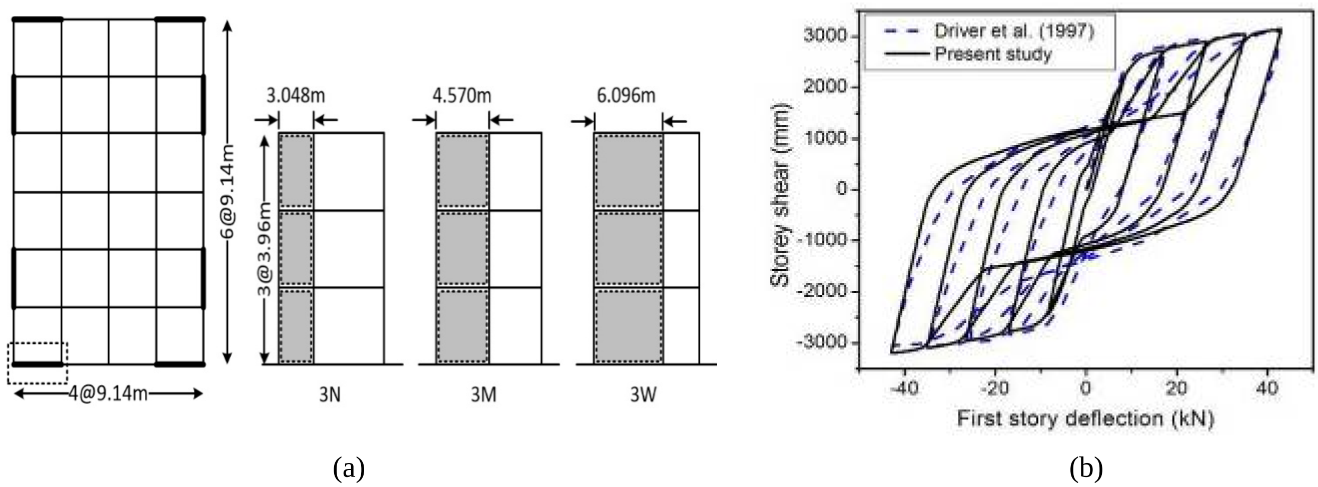


Fig. 4 – (a) Building plan of study frame and typical elevations of 3-story SPSWs (b) Comparison of predicted hysteretic response with the test results

4.3. Nonlinear static analysis

Pushover analysis is carried out to estimate the percentage of lateral load resisted by the web plates and the boundary frames. While the lateral load share of infill plates of 3-story SPSWs varies in the range of 52.5-58.9%, the corresponding range for the 6-story SPSWs is noted as 62.0-71.8%. The narrow SPSWs in both 3- and 6-story frames exhibited a relatively higher lateral load share by the infill plates. Similarly, the web plates of 9-story SPSW system resisted 63.6-72.8% of story shear. Thus, apart from slightly conservative results obtained for 3-story SPSW, the contribution of lateral force resisted by the boundary frames of low-to-medium rise SPSWs lie in the range of 25-40%, which is in good agreement with past experimental studies. A minor change is noticed in the percentage of load share of the web plates with the variation in their aspect ratios. In addition, the lateral load share of infill plates is increased with the increase in the frame height. Over-strength factor can be defined as the ratio of peak lateral strength to the design yield strength. The over-strength factor values are computed to be greater than 3.0 for all aspect ratios of SPSWs designed as per current practice. Without considering the contribution of boundary frames in resisting the lateral loads in the design results in higher values of overstrength of SPSWs. Thus, an economical design of SPSWs can be achieved by considering a reduced value of design base shear for the estimation of web plate thickness. Therefore, all the study frames are redesigned for the reduced values of design base shear. 3-story SPSWs are redesigned for two smaller values, namely, 65% and 80% of the design base shear, whereas the 6-story SPSWs are redesigned for the reduced design base shear values of 75% and 80%. Similarly, the 9-story SPSW has been redesigned for 80% of the design base shear. These considered design base shear values are marginally higher than the maximum values of lateral load share of infill plates as obtained from the analytical study.

Nonlinear static analyses of SPSWs designed for the reduced values of design base shear are carried out to investigate the lateral strength, overstrength and hinge mechanisms of the SPSWs considered in this study. A minor increase in the lateral load share of infill plates is noticed for 3-story SPSWs. However, the overall percentage of lateral load share of web plates of SPSWs is found to be in the range of 55-75%. Thus, the contribution of lateral force resisted by the boundary frames of low-to-medium rise SPSWs lie in the range of 25-45%, which is in a good agreement with past experimental studies. Though the effects of aspect ratio of infill plates is relatively less significant in terms of lateral strength of SPSWs, their effectiveness in controlling the drift response and hinge formations under the dynamic loading conditions is discussed in the following section.

5. Verification of seismic response of modified-designed SPSWS

In order to investigate the seismic performance of SPSWs designed considering the full as well as reduced design base shear, nonlinear time-history analyses are carried out for forty SAC ground motions (LA01-40) representing the Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) hazard levels [10]. The ground motions are scaled to match the design response spectra in the range of the fundamental time periods of SPSWs considered in this study.

Fig. 5 (a) and (b) show the average values of maximum interstory drift response (MISDR) of 3-story SPSWs under DBE and MCE hazard levels. The SPSWs designed for 100% and 80% of design base shear satisfy the limiting values of ISDR. However, the maximum values of MISDR for the SPSWs designed for 65% of design base shear are found to be 2.3% and 4.5% under DBE and MCE hazard levels, respectively. These values can be considered as acceptable seismic performance of SPSWs though they marginally exceed the limiting drift values. Except the 3-story narrow-SPSW designed for 65% of the design base shear, all 3-story SPSWs exhibit a peak residual drift ratio of less than or nearly 0.2%. Fig. 6 shows the material used in the SPSWs designed for full base shear. As shown in Fig. 6(a), the weight of material increases with increase in the aspect ratio of 3-story SPSWs. The narrow SPSW system uses smaller HBE sections as compared to other two systems which results in relatively higher value of residual drift. The steel tonnage usage is higher for the wide SPSWs in which larger span of HBEs require heavier beams making the structure more expensive. However, no significant difference in the drift response is noted between the wide and medium SPSWs in case of 3-story frames.

Even though the considerably heavier columns are used in 6N SPSW as compared to the 6M and 6W SPSWs, as shown in Fig. 5 (c) and (d), all 6-story SPSWs designed for reduced base shear, with the exception of narrow SPSWs, show satisfactory drift response under seismic loading. However, all 6-story SPSWs exhibit peak residual drift ratios of less than 0.3% under the DBE hazard level. Material weight of 6W SPSW is found to be marginally more than the 6M SPSW due to the heavier HBEs, as in case of 3-story SPSW. The heavier HBEs cause a reduction in the peak value of MISDR of SPSWs.

Fig. 5 (e) and (f) show the drift response of 9-story SPSWs designed for full as well as reduced base shear. Though the 9-story wide SPSW uses less steel tonnage as compared to the 9-story medium SPSW, better interstory drift response is noted in the former case. The 9-story wide SPSWs designed with 100% as well as 80% of design base shear value exhibited peak MISDR values of less than 2% under the DBE hazard level. The 9-story medium SPSWs marginally exceeded this limiting value. All 9-story SPSWs exhibit peak MISDR values of less than 4% under the MCE level ground motions and the peak residual drift of less than 0.2%. This shows that both medium and wide SPSWs designed based on the reduced value of design base shear exhibit the satisfactory seismic performance on reduction of base shear by 80%.

The hinge mechanism in the boundary frames of 3-, 6- and 9-story SPSW were found to be acceptable for all medium and wide SPSWs. But hinge rotation of columns for narrow SPSWs at few locations reached upto 0.02 rad. Thus it is observed that the current capacity based design procedure remains inadequate to prevent the plastic hinge formations in the VBEs of narrow SPSWs. If the proper hinge mechanism is ensured, low-to-medium rise SPSWs can be economically designed considering the reduced base shear of 80%. In addition, this design base shear can be further reduced for the design of SPSWs depending on the number of stories and the aspect ratio of web plates.

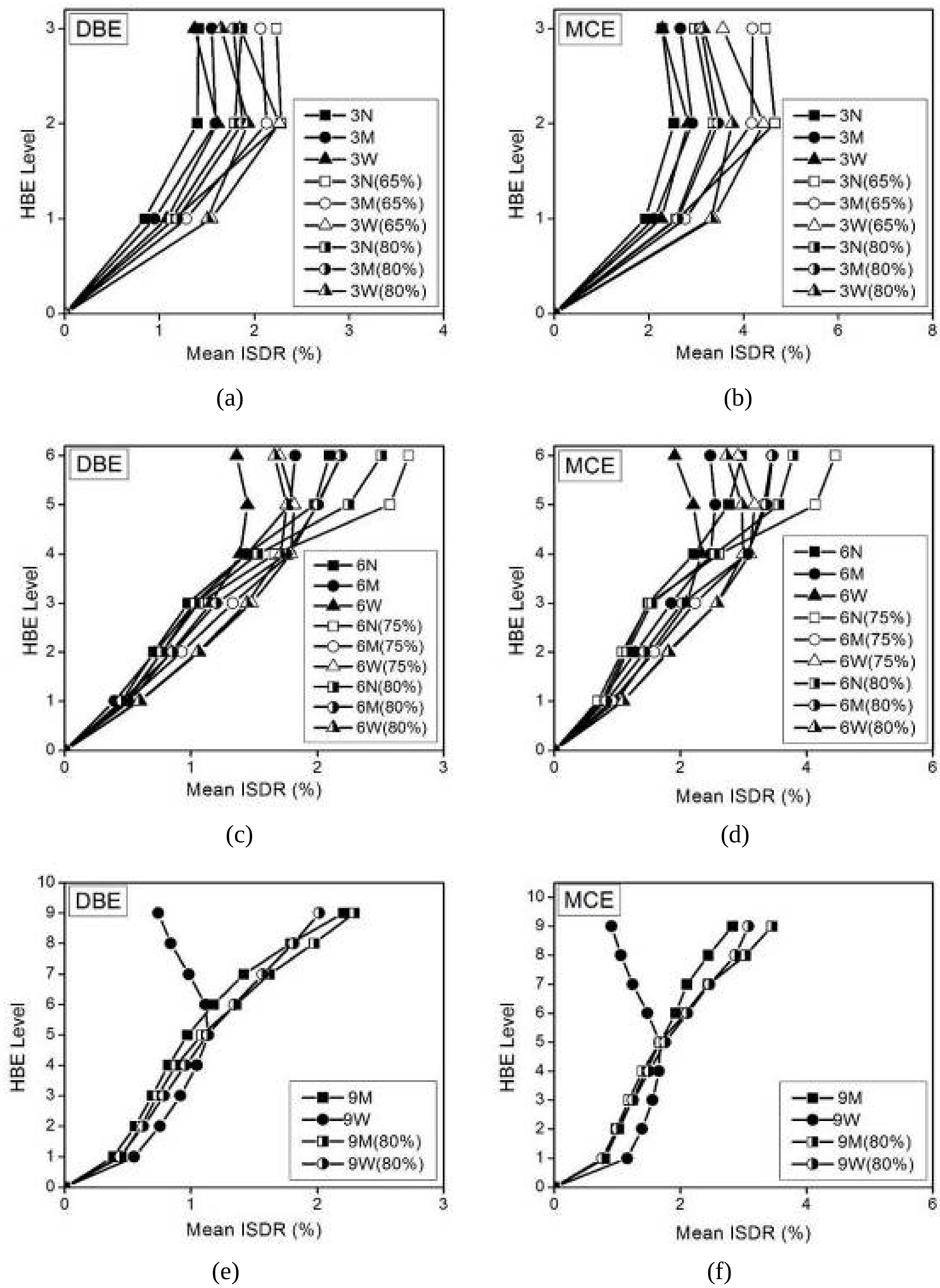
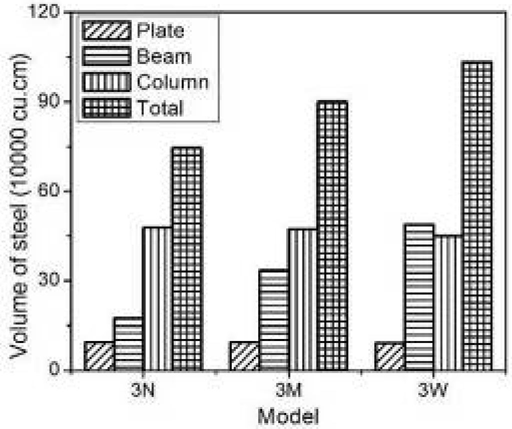
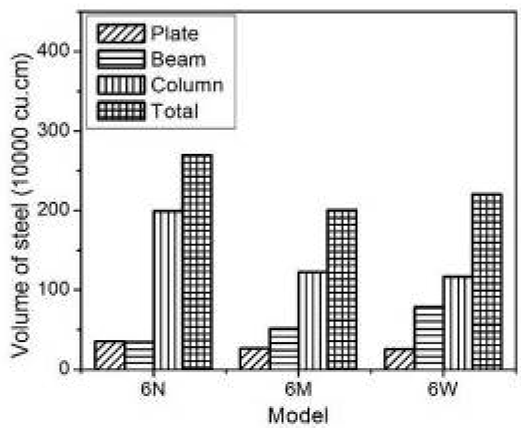


Fig. 5 - Variation of drift response of 3- 6- and 9-story SPSWs



(a)



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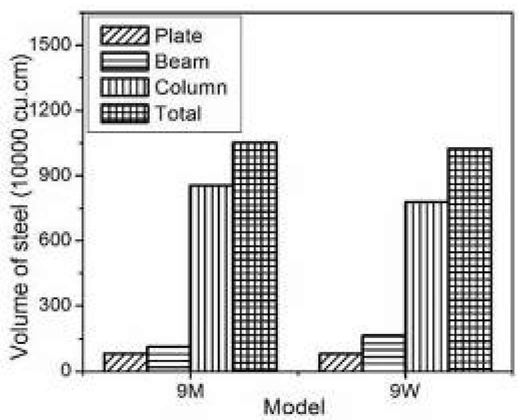


(c)

Fig. 6 - Steel tonnage of 3- 6- and 9-story SPSWs

6. Proposed expression for lateral load share of infill plates

[5] derived an equation to estimate the fraction of load resisted by the infill assuming that the SPSWs are designed using the capacity design approach in which the plastic hinge formation are restricted to beam ends only. For SPSWs without the reduced beam sections at the plastic hinge locations, the equation reduces to:

$$K = \left[1 + \frac{1}{2} \times \frac{A}{\tan\alpha}\right]^{-1} \qquad (7)$$

Where K is the fraction of load carried by the plate, A is the aspect ratio of SPSW panel, and α is the tension field angle. As the behavior of SPSW is found to be less sensitive to the minor variations in the value of α, K largely depends on the aspect ratio only. However, as noted in the present study, the value of K is found to be varying with number of stories as well. The data obtained from the pushover analysis is used to quantify the percentage load carried by the infill plates in this study. In order to estimate the lateral load share of infill plates of SPSWs, a semi-empirical equation is proposed based on the analytical results as follows:

$$\rho = \gamma + 100\left[1 + \frac{\beta}{2}\frac{A}{\tan\alpha}\right]^{-1} \qquad (8)$$

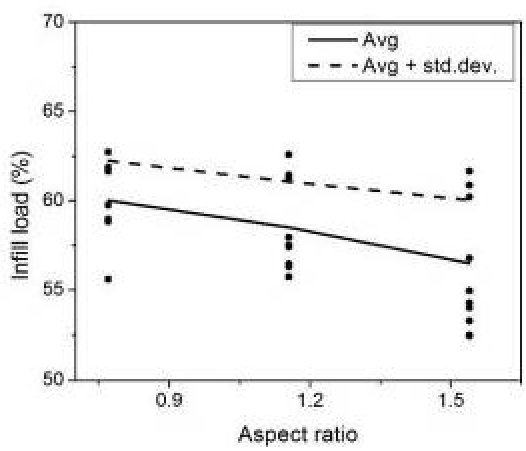
Where ρ is the percentage load carried by the infill plates, and β and γ are empirical constants.

Usually, an average value of α is used for all the stories in seismic design and analysis of a SPSW. The variation of α is very small for SPSWs having same aspect ratios at different story levels. Values of β and γ are obtained such that the root mean square error is minimized for the points representing the mean+standard deviation plots in Fig. 7. β represents the dependency of ρ on the aspect ratio of SPSW, whereas γ accounts for the vertical shift of the line due to introduction of β and also due to the number of stories in the SPSW. The values of β are found to be 0.34 and 0.05 for the 3- and 6-story SPSWs, respectively. The corresponding value of γ are found to be -23.3 and -27.2. Fig. 8(a) shows the comparison of the proposed expressions for the 3- and 6-story SPSWs with Eq. (7) suggested by [5]. The number of stories in a SPSW significantly affects the percentage load resisted by the infill.

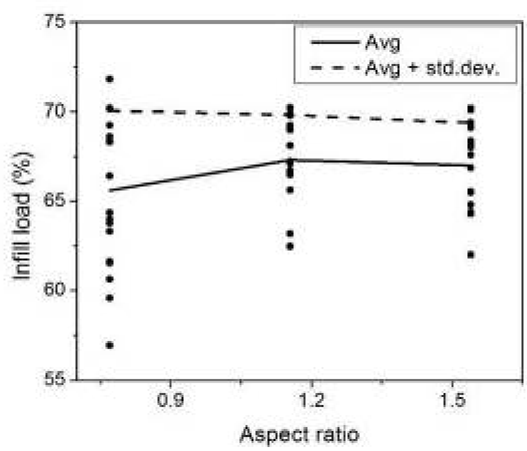
As discussed earlier, the percentage of lateral load resisted by the infill plates of a single-story SPSW in the elastic region is dependent on the relative stiffness of the boundary frame and the web plates. Since the accurate prediction of the story stiffness of boundary frames of multi-story SPSWs is a tedious process, a simple approach is followed to calculate the stiffness of boundary frame and the web plate. The story stiffness of boundary frames of SPSWs is computed using the computer software OPENSEES. The lateral stiffness of infill plates is calculated using the following expression assuming uniform development of tension-field action throughout the plates as follows:

$$K_{infill} = \frac{Elt}{h}\sin^2\alpha\cos^2\alpha \tag{9}$$

The infill plate stiffness is normalized with the frame stiffness. As shown in Fig. 8(b), a relationship exists between the normalized stiffness and the percentage of lateral load resisted by infill in elastic region of 3-, 6-, and 9-story SPSWs. Linear lines are used for curve fittings between the lateral load share of infill plates and the normalized stiffness of SPSWs. The regression coefficients (R^2-values) for the 3-, 6-, and 9-story SPSWs are found to be 0.84, 0.74 and 0.72, respectively.

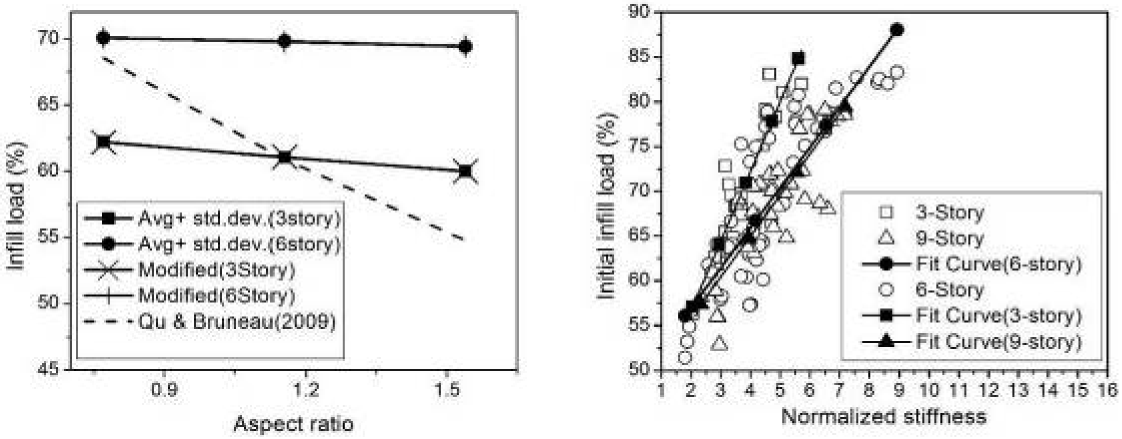


(a)



(b)

Fig. 7 - Load share of web plates of (a) 3-story, and (b) 6-story SPSWs of varying aspect ratios



(a) (b)

Fig. 8 - Proposed relationship of lateral load share of infill plates with (a) aspect ratio, and (b) normalized elastic stiffness ratio

7. Conclusions

The following conclusions can be drawn from this study.

- The downward force applied on the HBEs by the infill plates creates an additional demand on the SPSW due to the P-delta effect.
- The share of lateral load resisted by infill plate depends on the aspect ratio of the infill plates and the number of stories. In order to estimate the lateral load share of infill plates of SPSWs, a semi-empirical equation has been proposed based on the analytical results.
- The lateral load share of infill plates of 3-story SPSWs varies in the range of 52.5-62.7%, the corresponding range for the 6-story SPSWs is noted as 60.6-71.8%. Similarly, the web plates of 9-story SPSW system resisted 63.6-72.8% of story shear. The narrow SPSWs in both 3- and 6-story frames exhibited a relatively higher lateral load share by the infill plates.
- The current design procedure remains insufficient to prevent hinge formations in the VBEs of narrow SPSWs. All other SPSWs designed using the capacity based design approach show acceptable plastic mechanism. In case of 3-story, the drift response of narrow SPSWs is comparable to the medium and wide SPSWs except for a slightly higher residual drift. For taller frames, narrow SPSW may prove to be uneconomical and still perform worse when compared to wider SPSWs.

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