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Analysis approach for composite steel plate shear walls (CSPSW) reinforced with CFRP

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ABSTRACT

Steel plate shear walls (SPSWs) have been conducted as a capable system for resisting lateral forces induced on structures by wind and earthquakes. Adding concrete covering is a way of improving the behavior of SSWs. Studies by researchers indicated that, by using the concrete layer, stress is better distributed in the steel plate and the tension field lines are developed in a wider region. The only difference between the traditional system and the composited steel plate shear wall with the concrete system is that, in the latter, there is a gap between the concrete wall and the boundary columns and beams. In the traditional system, there is no gap, and the concrete directly rests against the boundary columns and beams. This seemingly simple modification resulted in a significant improvement in performance as well as an increase in ductility and damage mitigation. Some researchers showed that the carbon fiber-reinforced polymer (CFRP) would enhance the structural behavior of SPSWs. Nevertheless, no simple approach has been presented for composite SPSWs (CSPSWs) reinforced with CFRP. In the present research, the nonlinear behavior of CSPSW is determined and a method of analysis is proposed. The comparison between the findings of this approach and those of the finite element method (FEM) indicates that the proposed method is more accurate and its relevant computations take less time compared to the FEM. This model provides a good understanding of the interactions that might occur among different components of the system. It is also able to predict the overall pushover response, which is used in the nonlinear analysis of CSPSW systems.

1. INTRODUCTION

Composite steel plate shear wall (CSPSW) reinforced with carbon fiber-reinforced polymer (CFRP), a layer of CFRP is placed on both sides of the infill steel plate. Results have shown (Hatami *et al.*, 2012) that the CFRP enhances the structural parameters of

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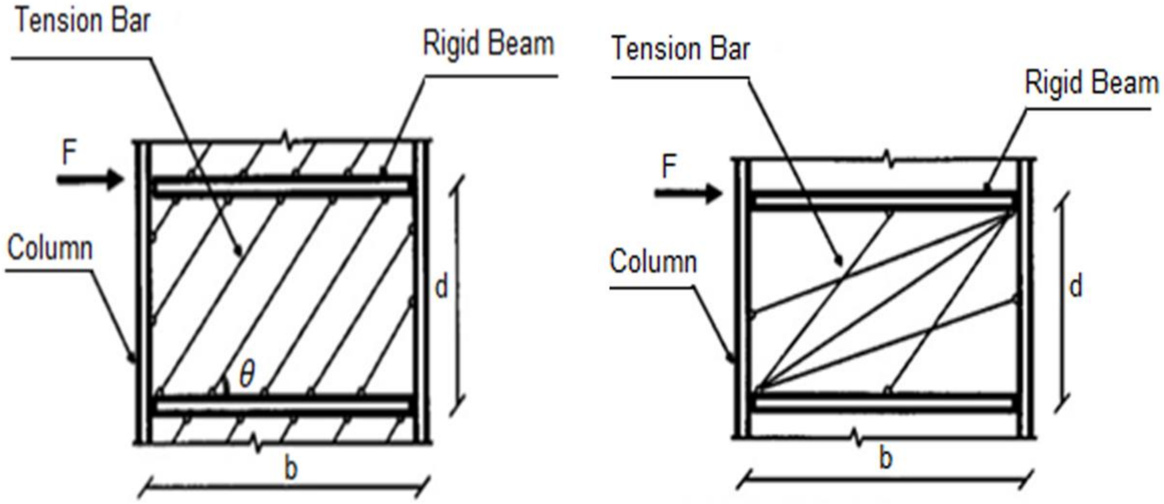
SPSW in the elastic and inelastic zones. In the present study, a method of predicting the nonlinear behavior of CSPSW is presented and its structural characteristics are addressed. Using the linear analysis, a graph is sketched to display the behavior of CSPSW in the inelastic zone.

1.1 Previous works on analysis methods

Several researchers (Timler and Kulak, 1983; Thorburn *et al*., 1983; Driver *et al*., 1998) have studied the behavior of SPSW. Based on the results, the strip model concept represents the SPSW as a series of inclined strip members. Each strip is allocated an area equal to the product of the strip width and the plate thickness. Fig. 1(a) shows the strip model. Since the stripe was developed based on the truss members, it can be used easily via SAP2000 and Etabs software. The models have been suggested by Canadian Steel Design Standard (CAN/CSA-S16-01, 2001). UBC's researchers presented a multi-angle strip model for SPSW using nonlinear analysis. This model is shown in Fig. 1(b) (Rezai, 1999). The researchers indicated that the analysis predictions were close to cyclic test results as well as shake table tests.



a) Strip model used in the Canadian Steel Design Standard (CAN/CSA-S16-01, 2001)

b) Multi-angle strip model proposed by Rezai (1999)

Fig. 1 Strip model representing steel plate walls

Several researchers have used the finite-element formulation with both geometric and material nonlinearities to model the complex wall-frame interactions (Caccese *et al*., 1993). The results of the finite element analysis (FEA) show a somewhat stiffer load-deformation relationship for SPSWs, compared to the experimental results. In general, this discrepancy can be attributed to either plate imperfection or the residual stresses created by the welding of the steel panel to the frame. Sabouri-Ghomi *et al*. (2005) developed a general method (PFI method) for the analysis and design of SPSWs with different configurations, including walls with or without openings, with thin or thick plates, and with or without stiffeners. The strip model is mostly limited to SPSWs with thin plates. Also, the strip model, although appropriate for the practical analysis of thin plates, is not directly applicable to other types of plates. Conversely, even though the PFI method is suitable for the analysis of other types of plates, it is not directly applicable to CSPSWs. In this paper, a new method for evaluating the shear capacity and shear stiffness of a given CSPSW is proposed. The obtained results of this approach are compared with those of the finite element method (FEM). The comparison shows that the proposed method produces similar results to the FEA; nevertheless, it is much faster and requires less computation.

2. MODELING

The nonlinear analyses were performed in the ANSYS version 12 finite element package. To achieve sufficient accuracy, all the samples have been chosen by using the SHELL 181 element (an adequate shell element for composite layers) with 6 degrees of freedom (DOF) at every node. Mesh formation has been such that at common points, structural nodes are established and coupled with each other using the capability of the software. In reality, as a result of the fabrication, welding, and assembling processes, the thin infill plates are already in a distorted and buckled shape when being installed. To perform a geometrical and material nonlinear analysis and also to consider imperfections, a technique in the nonlinear FE modeling has been implemented. In doing so, first, an elastic analysis was carried out and after evaluating the buckling modes; the dominant mode was introduced to the software. For evaluating the convergence of the results, two force and moment convergence criteria were employed. The analysis process was performed based on the Full Newton-Raphson approach. The isotropic hardening rule has been utilized for material behavior.

3. VALIDATION of FEM RESULTS

For this meaning, a simple detached infill plate with dimensions 3000x3000x3 mm under pure in-plane shear loading was meshed into various number of elements; and their buckling stresses were compared with Eq. (2) to the classical formula as given in Eq. (1). The results of the FE modelling was compared to verify the numerical modelling.

$$\tau_{cr} = \frac{K_v.\pi^2.E}{12.(1-\vartheta^2)} \qquad (1)$$

$$\begin{cases} K_v = 5.34 + \frac{4}{(d/b)^2} & \frac{d}{b} \leq 1 \\ K_v = 4 + \frac{5.34}{(d/b)^2} & \frac{d}{b} > 1 \end{cases} \qquad (2)$$

where K_v is the shear buckling coefficient. The coefficient is related to the geometry of the SPSW and boundary condition. The dimensions of the panel, d and b, are shown in Fig. 1. The difference of errors determined by comparing the FE results to the theoretical value for different numbers of incorporated mesh elements has been indicated in Fig. 2. Regarding Fig. 2, mesh with 30x30 elements is selected.

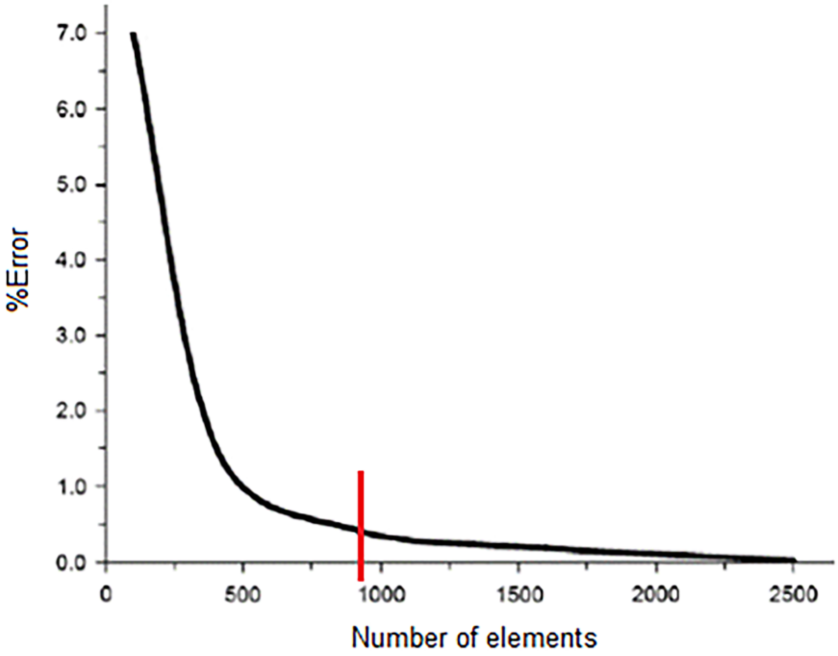


Fig. 2 FE mesh number sensitivity analysis

After measuring the optimum FE meshing, the SPSW was modeled. By comparing the numerical analysis results with the experimental results (Nateghi-Alahi and Khazaei-Poul, 2013), the numerical models were validated for the analyzing and modeling of scaled specimens. Fig. 3 compares the load-displacement curves obtained in the numerical analysis and experimental tests.

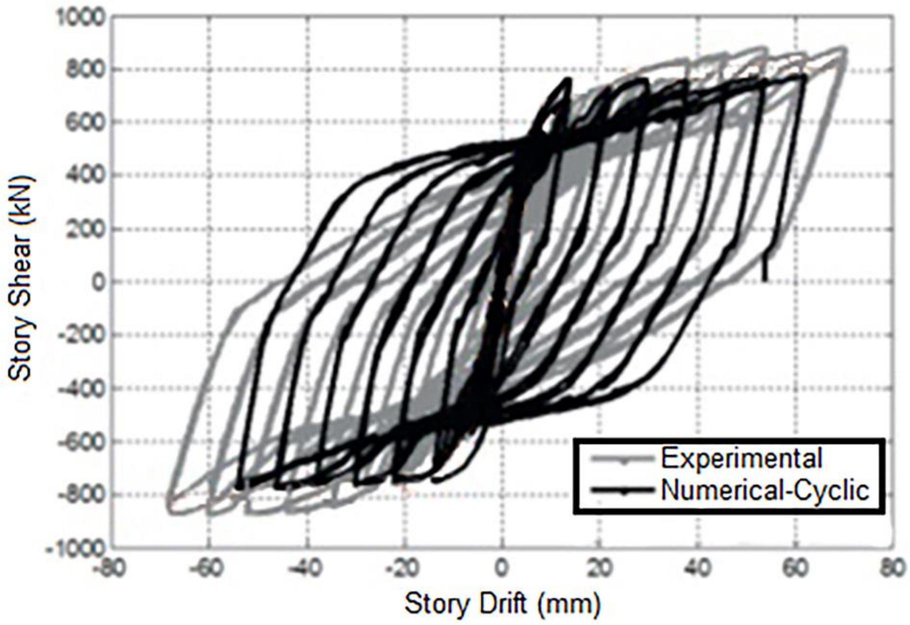


Fig. 3 Comparison of FE modeling with test

4. NUMERICAL MODELS

After verifying the numerical results with the experimental results, for predicting the pushover response of the CSPSW, many numerical specimens are selected (see Table 1) to the accuracy of the presented method. All the specimens are 3 m in height and 7 mm in thickness for the steel plate. Also, 2 mm thick fiber polymers are selected. The CFRP angle in Table 1 is attached to the infill plate illustrated in Fig. 4.

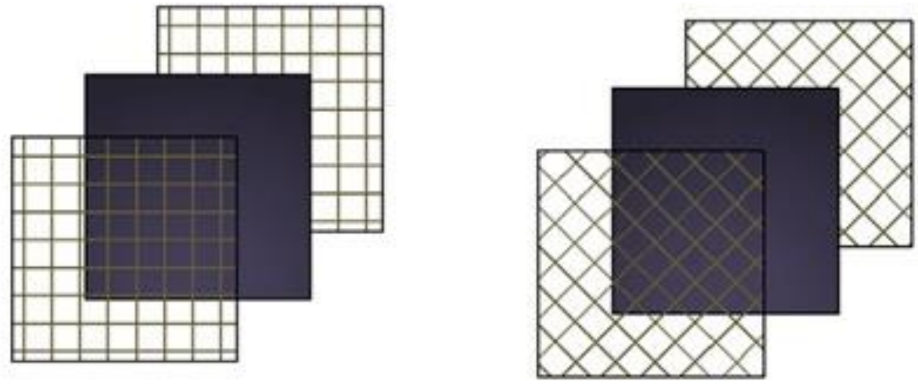


Fig. 4 Fiber angle of CSPSW

Table 1 Properties of FE models

Model name	Type of wall	Fiber Angel (Deg.)	Wall width (mm)
CS-33	CSPSW	Laterally and longitudinally	3000
CS-35	CSPSW	Laterally and longitudinally	5000
CS-36	CSPSW	Laterally and longitudinally	6000
CS-33-30	CSPSW	30	3000
CS-33-45	CSPSW	45	3000
CS-33-60	CSPSW	60	3000
CS-33-90	CSPSW	90	3000
CS-35-30	CSPSW	30	5000
CS-35-45	CSPSW	45	5000
CS-35-60	CSPSW	60	5000
CS-35-90	CSPSW	90	5000
CS-36-30	CSPSW	30	6000
CS-36-45	CSPSW	45	6000
CS-36-60	CSPSW	60	6000
CS-36-90	CSPSW	90	6000

It should be noted that the CFRP layers attached only to two sides of the infill steel plate. On the other hand, the infill steel plate is covered by CFRP layers. The steel members (beam, columns, and infill plate) have been made out of structural steel ST37 with a yield stress of 240 MPa, Elasticity Modulus of 206 GPa. Also, the material properties of CFRP layers have been used as fracture stress of 3800 MPa, and Elasticity Modulus of 240 GPa. The dimensions of beams and columns are selected as in Fig. 5. The specimens are named according to the type of shear wall used, the dimensions, and the fiber angle. So, the first notations refer to the type of shear wall (CS for the composite shear wall), the next two notations refer to the dimensions of the panel (b, d) and the last two notations refer to the angle of fibers.

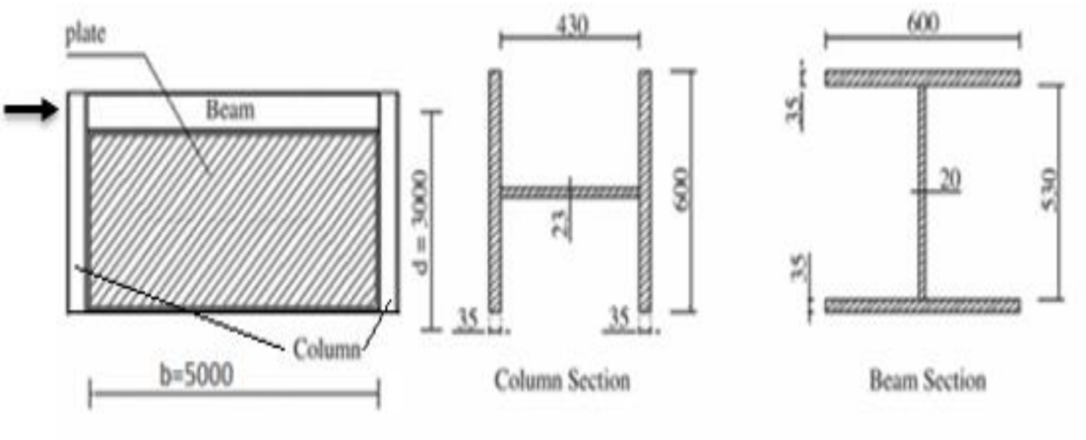


Fig. 5 Geometrical parameters of specimen

5. PROPOSED MODEL for CSPSW ANALYSIS

5.1 Basic assumptions

A typical story of a multi-story structure with a CSPSW can be represented as an isolated panel, for which the following assumptions are made:

- The columns with enough rigidity are used around the infill plates. Due to this assumption, the columns support the infill plate to develop tension field action.

- Regarding Ref. Nateghi-Alahi and Khazaei-Poul (2013), difference between the tension-field intensities in adjacent stories is ignored.

- The effect of stress due to flexural behavior (global bending stresses) on the shear buckling stress of the steel plate is disregarded.

- The principle of superposition applies.

- In the CFRP-CSPSW system, a layer of CFRP increases the number of diagonal tension-field lines.

5.2 Predicting the pushover curve

To determine the pushover curve of the CFRP-CSPSW systems, a simple equation is presented in this section. Eqs. (3)-(13), which are used in this method, have been explained in detail in Figs. 6-7.

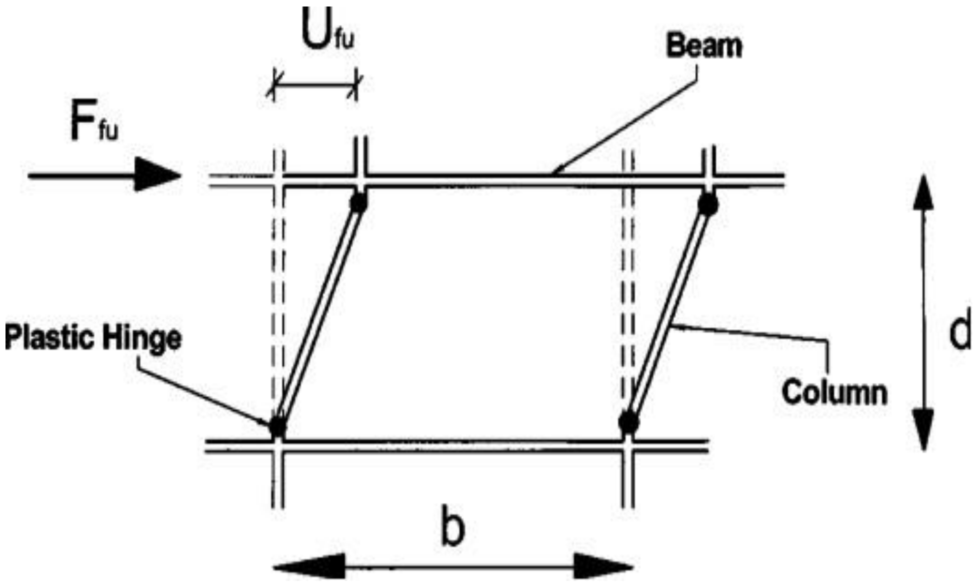


Fig. 6 Frame idealization (Nateghi-Alahi and Khazaei-Poul, 2013)

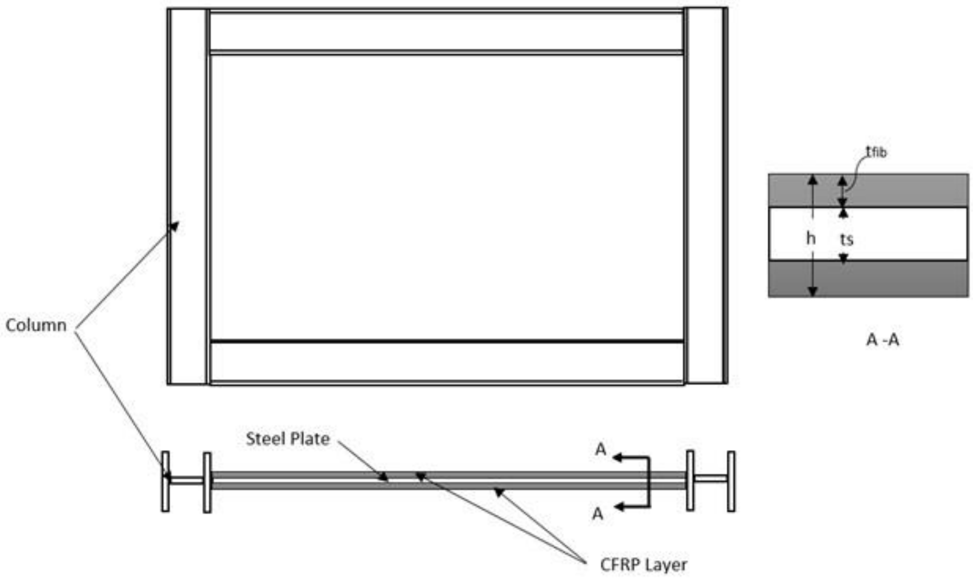


Fig. 7 CFRP-CSPSW

Since it was assumed that the frame around infill plates is moment resistant frame, the beam to column connections are fixed. Point A is shown in Fig. 8, this point is obtained using F_{fu} and U_{fe} from Eqs. (3)-(4), respectively. K_f is computed through Eq.

(5). The slope of line OA in Fig. 8 is the stiffness of the frame, and the load-displacement diagram of the frame is therefore defined. The lateral shear strength, lateral shear displacement, and shear stiffness of the frame are expressed as Hatami *et al*. (2012):

$$F_{fu} = \frac{4.M_{pf}}{d} \tag{3}$$

$$U_{fe} = \frac{M_{pf}.d^2}{6EI_f} \tag{4}$$

$$K_f = \frac{24EI_f}{d^3} \tag{5}$$

Point B is calculated using Eqs. (6)-(10). The shear displacements (in-plane displacements) of the steel plate and CFRP sheet are equal, and this is an idealization of the parallel spring's principle. This principle is used to calculate the shear strength and displacement of the steel sheet covered by the CFRP. Therefore, Eqs. (6)-(10) (Eqs. (6)-(8) have been derived, and Eqs. (9)-(10) are based on PFI method) are derived by combining the PFI method, the parallel springs principle, the numerical results, the classic equations of shells and plates, sandwich panel's behavior and several other experimental factors. Experimental and numerical studies (Rezai, 1999) have shown that the layers of CFRP increase the number of diagonal tension-field lines and intensify the elastic buckling of the steel plate. Therefore, the shear buckling stress and shear strength of the system are affected.

$$\tau_{cr} = \frac{K.\pi^2}{b^2.t} \cdot D \tag{6}$$

$$D = \frac{E_s.{t_s}^3}{12(1-\vartheta^2)} + 1.5(t_{Fib}.h).(2E_1 + \frac{G_{12}}{2}) \tag{7}$$

$$F_{tw} = \tau_{cr}(1 + \sqrt{6.75 + {F_{ys}}/{\tau_{cr}}} \tag{8}$$

$$U_w = \left(\frac{\tau_{cr}}{G_s} + \frac{2F_{tw}}{E_s}\right).d \tag{9}$$

$$F_w = (\tau_{cr} + 0.5F_{tw})b.t \tag{10}$$

The panel has shown in Fig. 8 can be obtained separately for the plate and the surrounding frame, and then by superimposing the two shear load-displacement diagrams can be obtained. Using the von Mises yield criterion, the stress distribution provides a lower bound for the strength of the web plate, knowing that the surrounding frame members are strong enough to sustain the normal boundary forces associated with the tension-field. The values of Points C and D are calculated using Eqs. (11)-(13).

$$F_p = K_f.U_w + F_{wu} \tag{11}$$

$$K = F_p/U_w \tag{12}$$

$$F_c = F_{fu} + F_{wu} \tag{13}$$

Points E and F are also obtained from Fig. 8. In this diagram, the slope of the curve is changed at displacement equal to Δ = 0.005d and Δ = 0.015d.

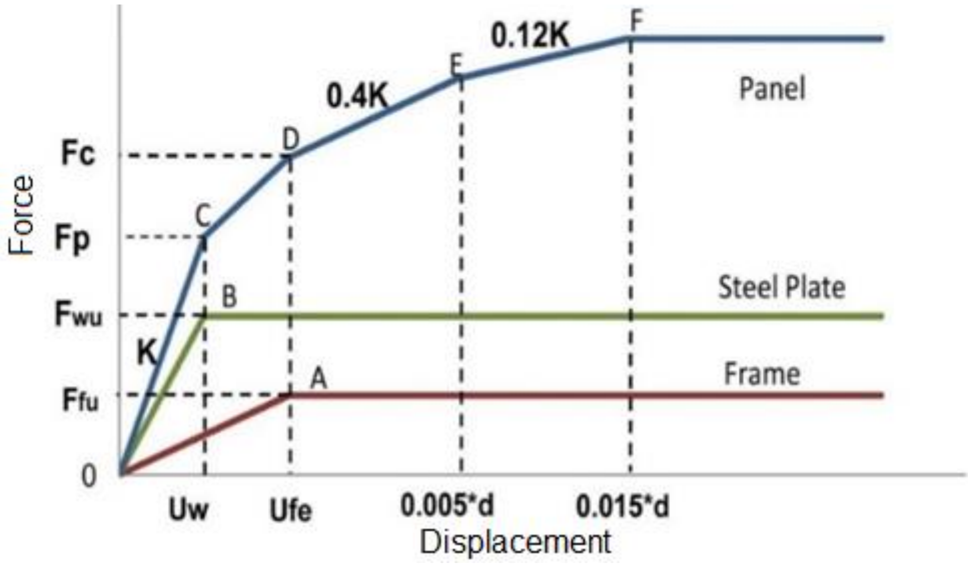


Fig. 8 Load-Displacement diagram

6. RESULTS and DISCUSSION

Fig. 9 shows the results of the proposed method compared with those of the FEM model, showing a good convergence. The proposed method estimates the load-displacement curve (pushover response) of the CFRP-CSPSW. This comparison shows close agreement between the developed method results with FEM results.

To obtain the load-displacement curves using different fiber angles of CFRP, only *K* is modified. The modification of *K* had been defined as follows (Hatami *et al*., 2012):

$$K\theta = \left(\frac{\theta exp4}{10000000} - \frac{\theta exp3}{200000} + 0.001\theta exp2 - 0.0148\theta + 1\right)K \tag{14}$$

Eq. (14) has been derived by fitting the results obtained from the specimens. In this relation, K is calculated from Eq. (12). The results of the FEM (ANSYS program) and the proposed method (Simplified) have been compared in Figs. (10)-(12). The comparison shows a convergence between the results. The main advantage of the proposed method over the FEM is that the proposed method is very simple (does not require any software for ordinary calculations) and is much faster in obtaining the results.

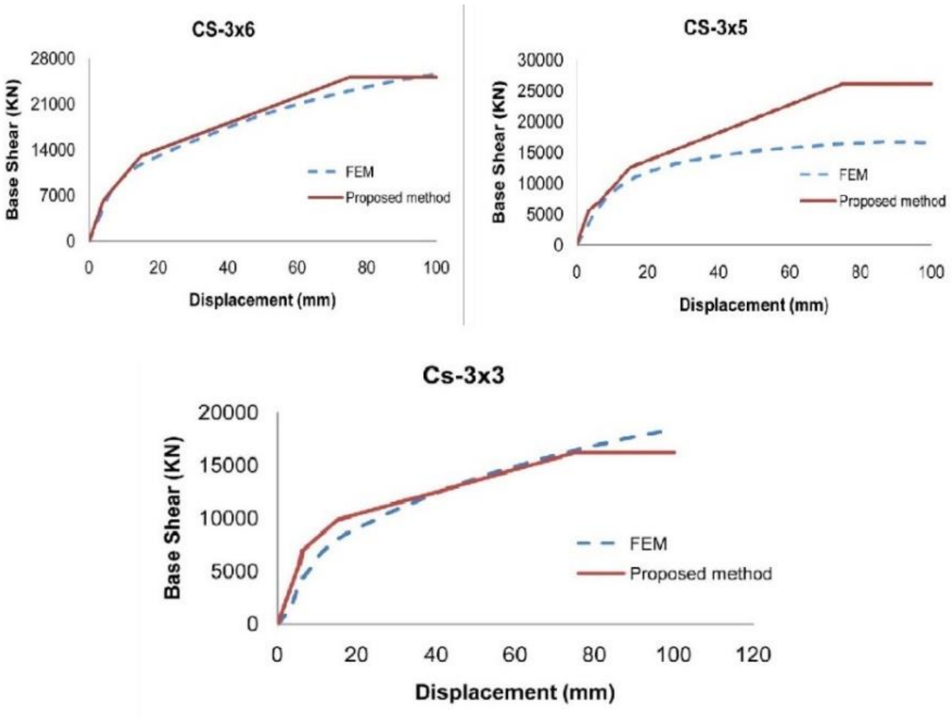


Fig. 9 Comparing the proposed equation results with FE results

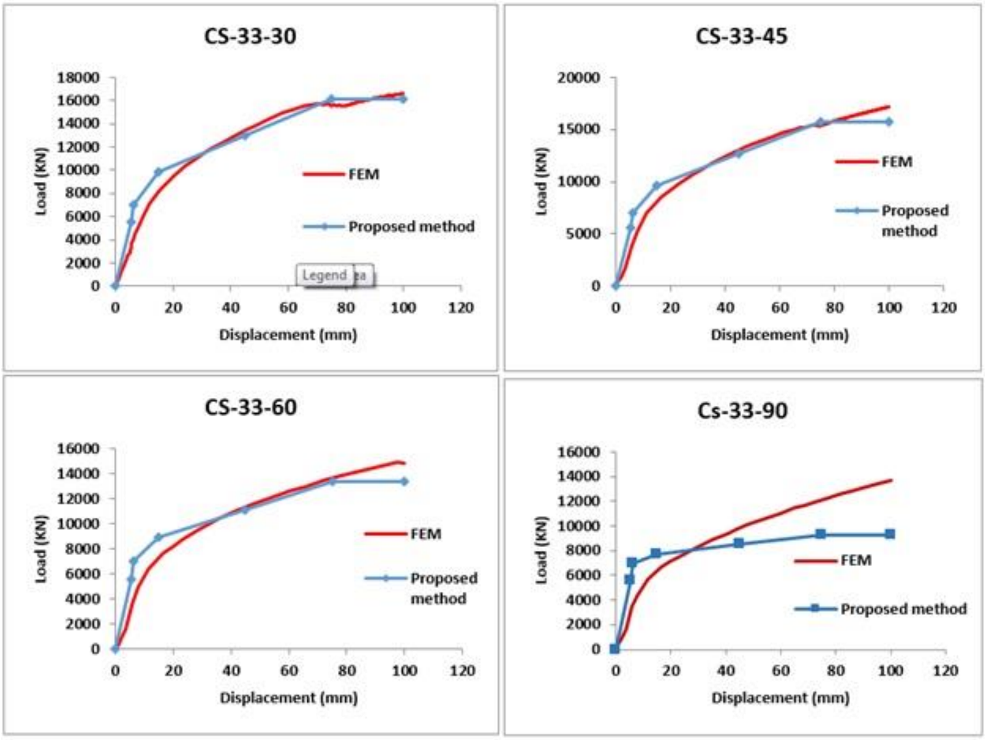


Fig. 10 Comparison of proposed method results with FEM-CS-33-Fiber angle

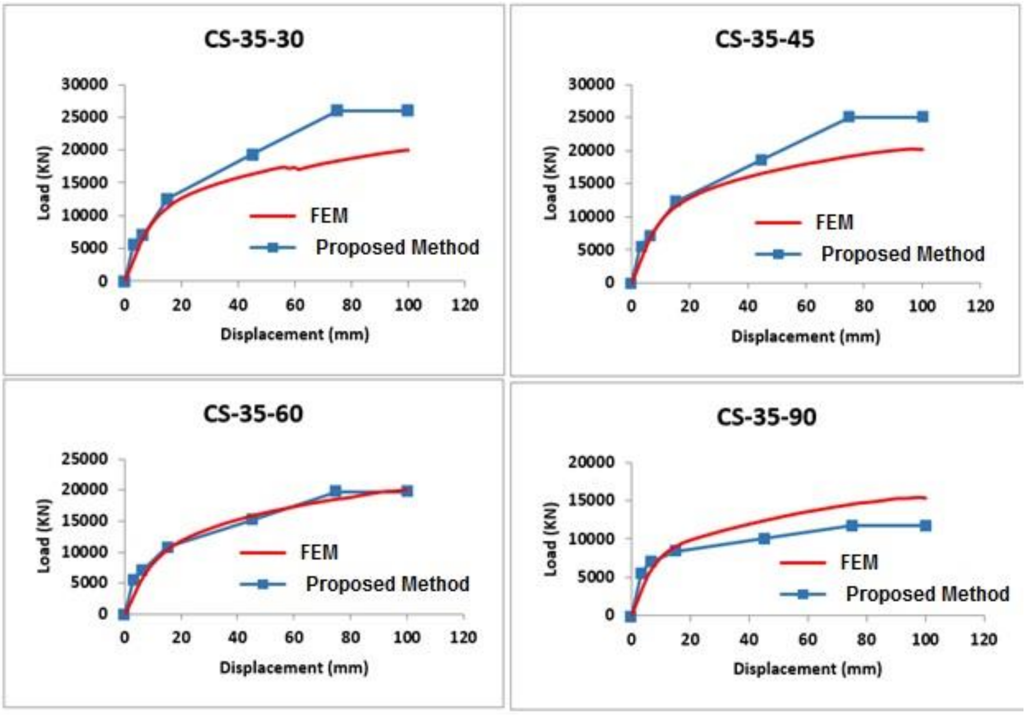


Fig. 11 Comparison of proposed method results with FEM-CS-35-Fiber angle

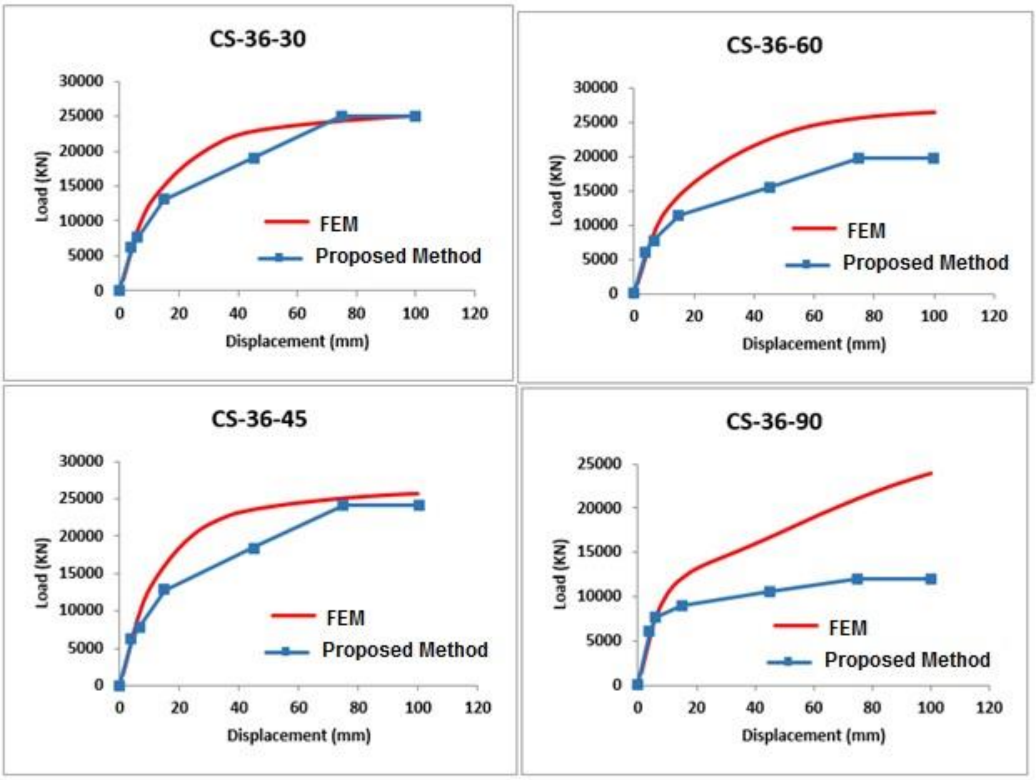


Fig. 12 Comparison of proposed method results with FEM-CS-36-Fiber angle

6. CONCLUSIONS

In the present study, the behavior of SPSW reinforced by fibers was investigated numerically and parametrically. There, summarized findings are presented as follows:

- An analytical model was suggested to determine the behavior of CSPSWs with varying angles of polymer fibers.
- To obtain the load-displacement curves using different angles of CFRP fibers, only the stiffness needs to be modified.
- Finally, some equations have been suggested to calculate the nonlinear behavior of the CSPSW system using the linear analysis approach.

ACKNOWLEDGMENTS

The generated or used data required to reproduce these findings of this study will be made available from the corresponding author upon reasonable request. This research received no external funding. All authors have no conflict of interest to declare the research described in this paper.

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