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.

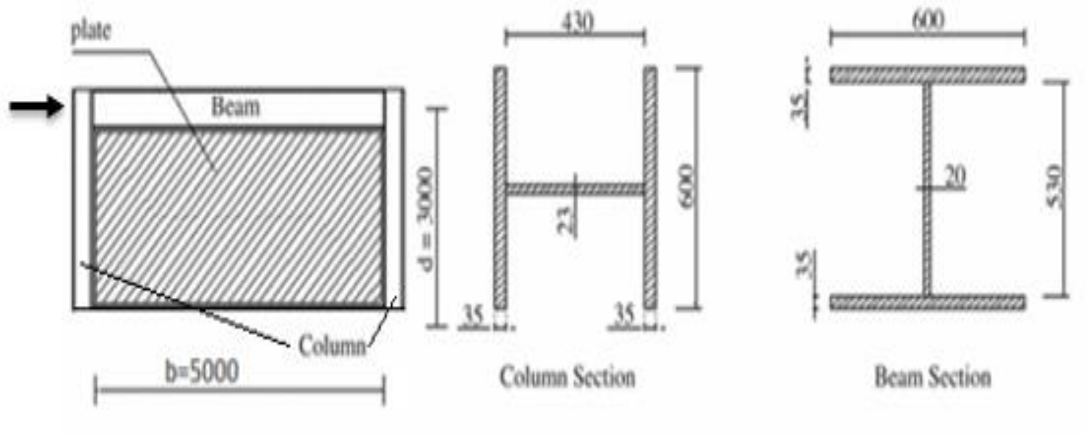

Fig. 5 Geometrical parameters of specimen

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.

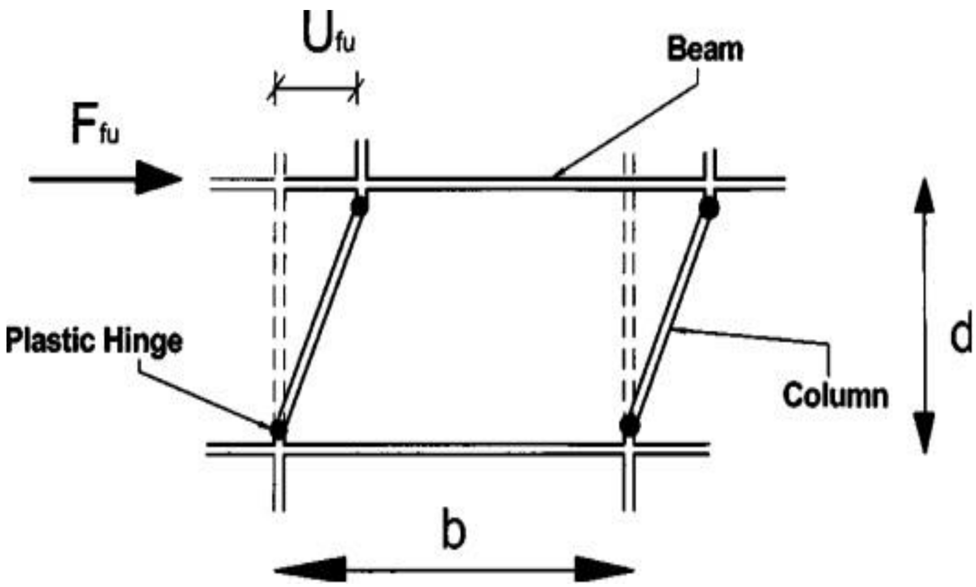

Fig. 6 Frame idealization (Nateghi-Alahi and Khazaei-Poul, 2013)

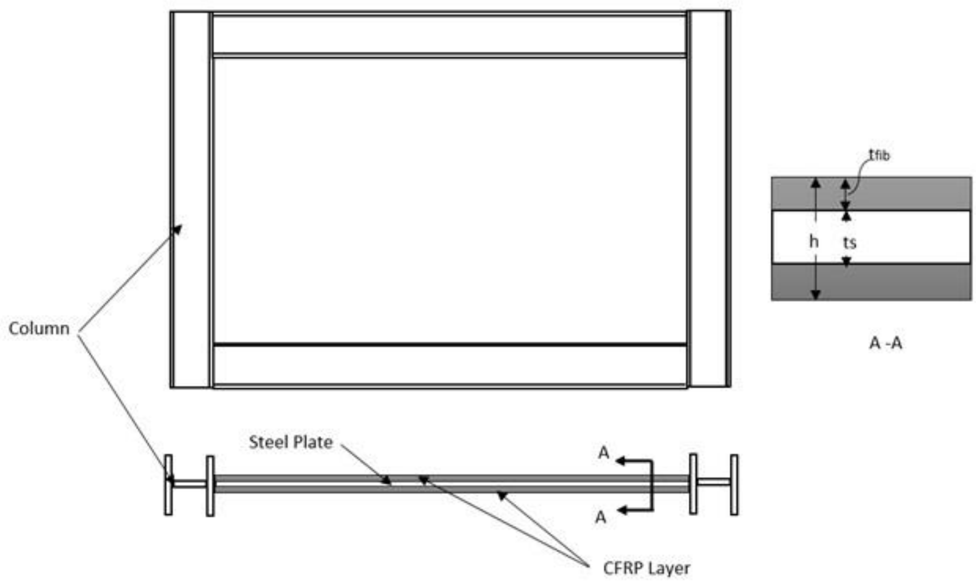

Fig. 7 CFRP-CSPSW

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).

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

$$K = F_p/U_w \quad (12)$$

$$F_c = F_{fu} + F_{wu} \quad (13)$$

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.

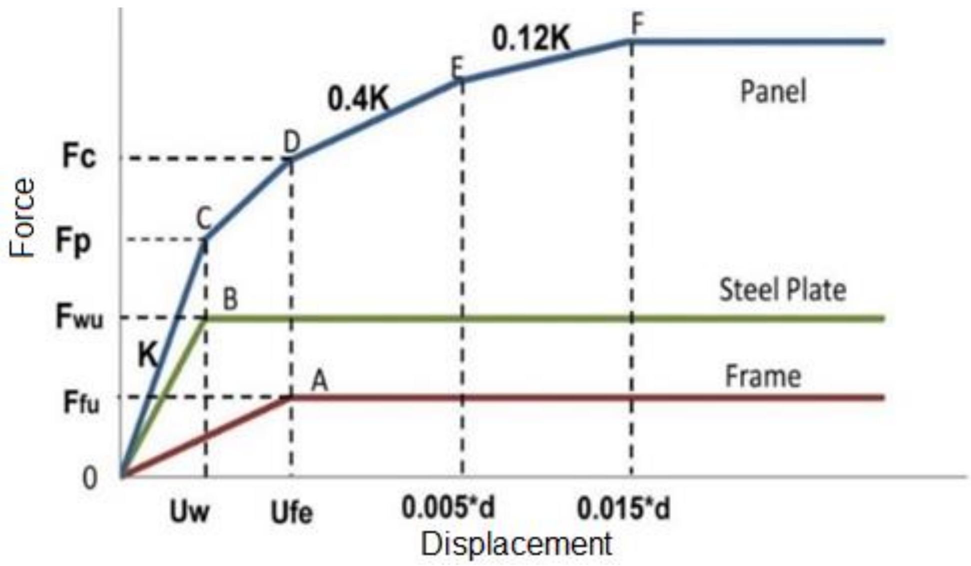

Fig. 8 Load-Displacement diagram

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):

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

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.

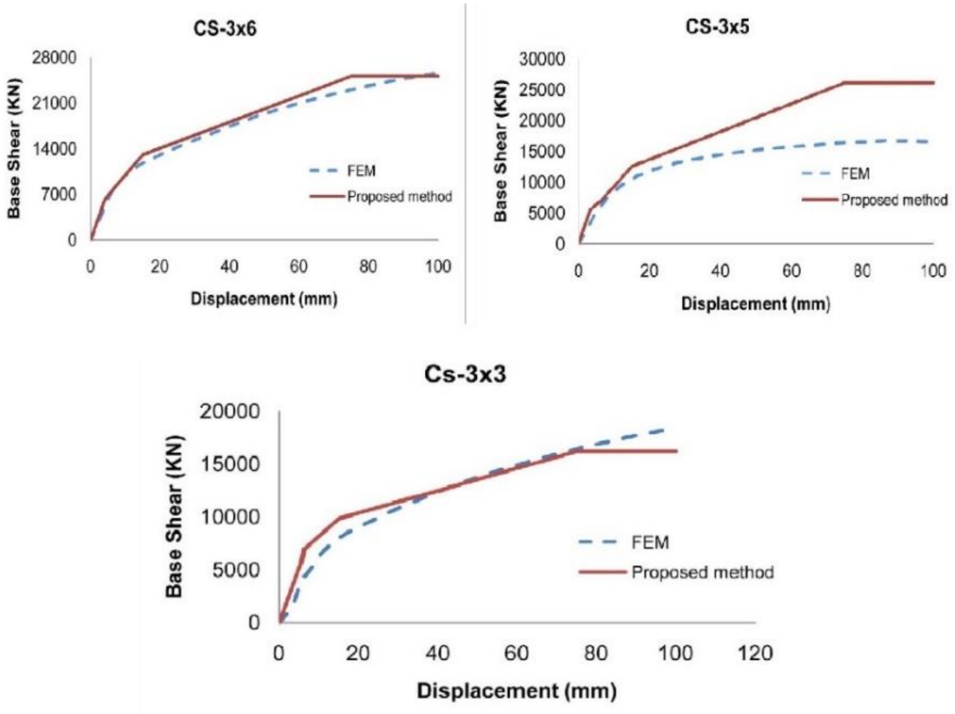

Fig. 9 Comparing the proposed equation results with FE results

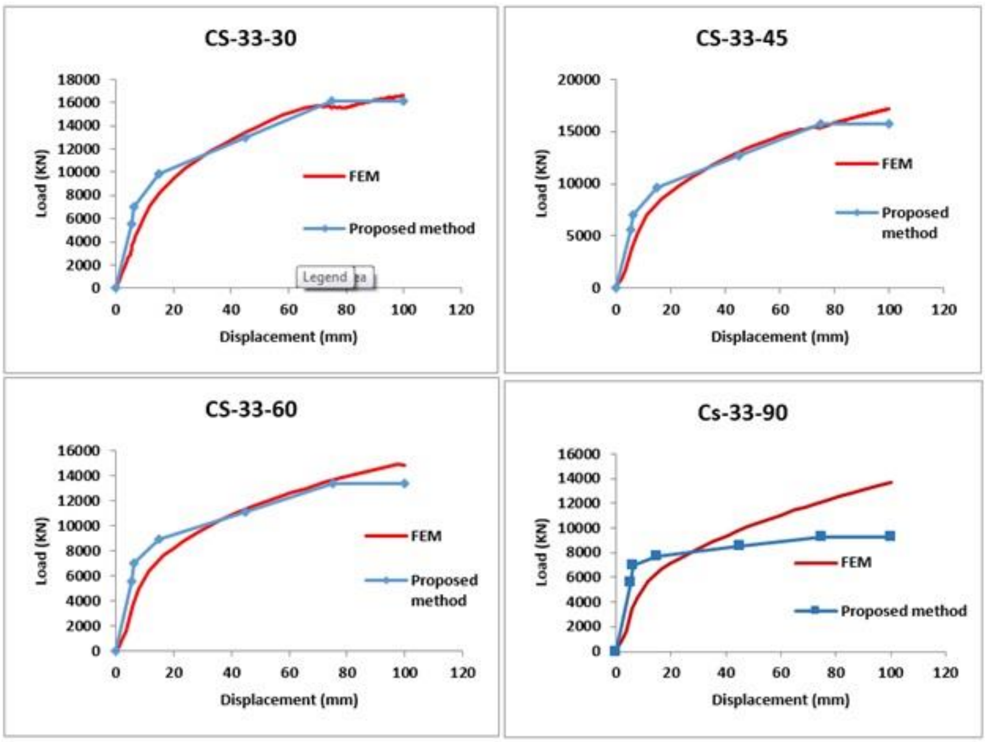

Fig. 10 Comparison of proposed method results with FEM-CS-33-Fiber angle

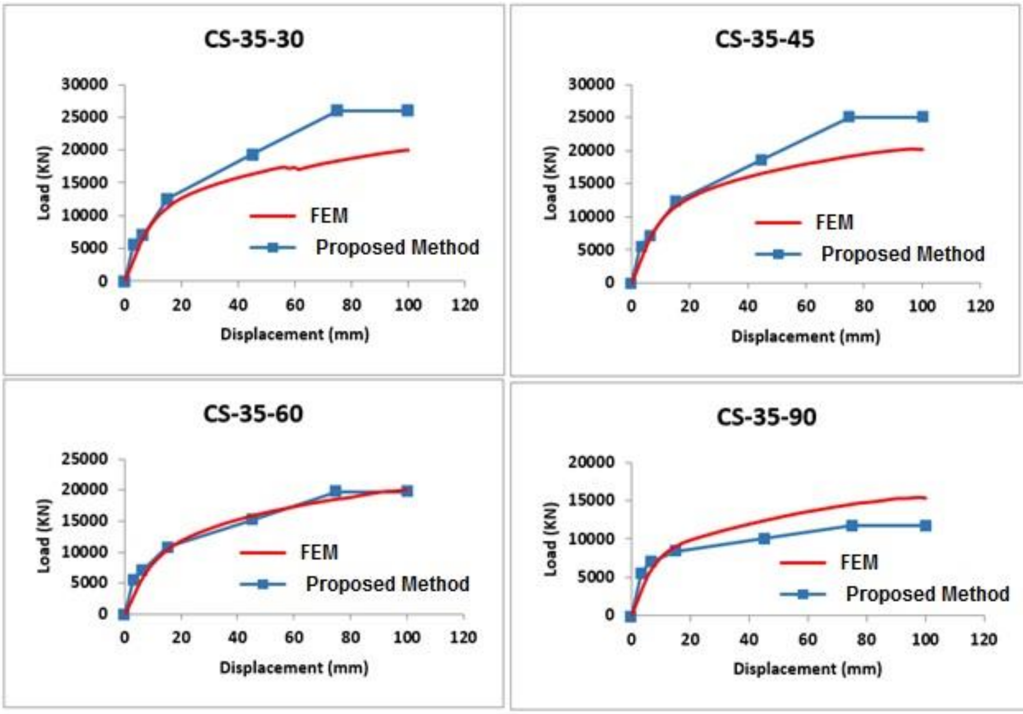

Fig. 11 Comparison of proposed method results with FEM-CS-35-Fiber angle

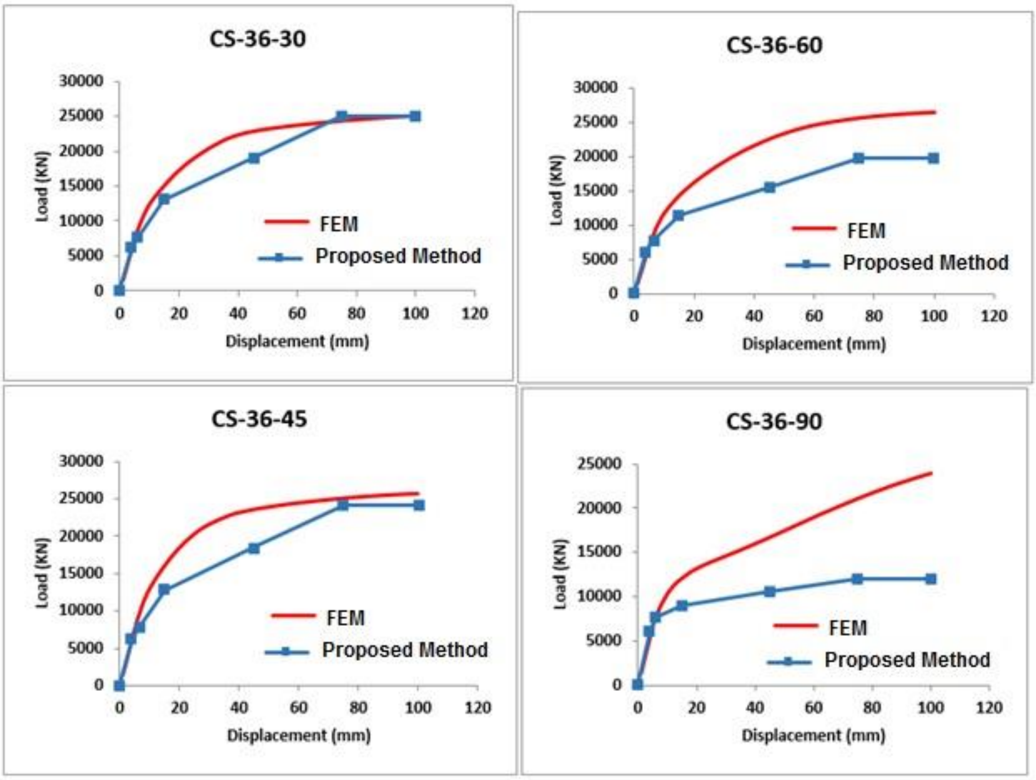

Fig. 12 Comparison of proposed method results with FEM-CS-36-Fiber angle

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.

REFERENCES

Hatami, F., Ghamari, A., Rahai, A. (2012), "Investigating the properties of steel shear walls reinforced with Carbon Fiber Polymers (CFRP)," *J. Constr. Steel Res.*, **70**(6), 36-42. https://doi.org/10.1016/j.jcsr.2011.07.010.

Timler, P.A., Kulak, G.L. (1983), "Experimental study of steel plate shear walls," Structural engineering report No 114. Edmonton (AB): Department of Civil Engineering, University of Alberta, Canada. https://doi.org/10.7939/R3C24QV49.

Tromposch, E.W., Kulak, G.L. (1987), "Cyclic and static behavior of thin panel steel plate shear walls," Structural Engineering Report, **145**, University of Alberta, Edmonton, Alta, Canada.

Driver, R.G., Kulak, G.L., Kennedy, D.J.L., Elwi, A.E. (1998), "Cyclic tests of four-story steel plate shear wall," *J. Struct. Eng.*, **124**(2), 112-20. https://doi.org/10.1061/(ASCE)0733-9445(1998)124:2(112).

CSA-S16-01 (2001), "Limit State Design of Steel Structures," Canadian Standards Association CAN/CSA-S16-01, Mississauga, Ontario, Canada.

Rezai, M. (1999), "Seismic behaviour of steel plate shear walls by shake table testing"; PhD Dissertation, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, 1999. https://open.library.ubc.ca/terms_of_use.

Caccese, V., Elgaaly. M., Chen, R. (1993), "Experimental study of thin steel-plate shear walls under cyclic load," *J. Struct. Eng.*, **119**(2), 573-587. https://doi.org/10.1061/(ASCE)0733-9445(1993)119:2(573).

Sabouri-Ghomi, S., Ventura, C., Kharrazi, M.H. (2005), "Shear analysis and design of ductile steel plate walls," *J. Struct. Eng.*, **131**(6), 878-1316. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:6(878).

Nateghi-Alahi, F., Khazaei-Poul, M. (2013), "Analytical study on the strengthened steel plate shear walls by FRP laminate," *Procedia Eng.*, **54**, 377-386. https://doi.org/10.1016/j.proeng.2013.03.034.