Analytical Study on the Strengthened Steel Plate Shear Walls by FRP Laminate

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Abstract

In this paper, nonlinear behaviour of composited steel plate shear walls by means of glass fiber reinforced polymer (GFRP) laminates under quasi-static loading have been analytically investigated. In that regard, numbers of the tested $\frac{1}{2}$ scaled one-story un-stiffened steel plate shear walls (SPSWs) have been selected and simulated using finite element method, based on the available experimental data in the literature. After calibration of the analytical models, numbers of GFRP layers are added to the steel web plates of SPSWs, and effects of GFRP laminate and the number of layers on the seismic behaviour of steel shear walls are investigated. The results indicate that GFRP laminate increase the ultimate shear capacities of SPSWs, and the secant shear stiffness of the system. Besides, the hysteretic behaviour of the composite steel shear walls have been improved in comparison with the un-stiffened steel shear walls.

Keywords: Composite; Steel plate shear wall; Glass fiber reinforced polymer; Finite element method; Hysteretic.

1. Introduction

Steel plate shear walls can be used in different configurations, such as stiffened, un-stiffened thin steel plate, and composite steel plate. In composite steel plate shear walls fiber reinforced polymer laminate or concrete on one or both sides of the web plate. Concrete layers can improve load carrying capacity of steel plate shear walls by
permitting utilization of the full yield strength of the infill plate. In addition, shear strength of the concrete is effective to increase capacity of system (Astaneh, 2001).

Recent studies show that fiber reinforced polymer (FRP) laminates are effective to enhance load-carrying capacity of damaged or sub-standard steel structures by increasing strength, stiffness and even ductility of steel structural elements. FRP layers have a linear behaviour until failure, so it can increase initial stiffness and ultimate strength of system. On the other hand these layers are useful to increase secant stiffness of SPSWs.

2. Background

During four last decades many experimental and numerical research on seismic performance of un-stiffened and strengthened steel plate shear walls have been carried out and these researches lead to better understanding of this lateral load resistant system.

Wagner 0 is the first researcher who used a complete and uniform tension fields to determine the shear strength of a panel with rigid flanges and very thin web, and inferred that the shear buckling of a thin aluminum plate supported adequately on its edges does not constitute failure. Other researches were also conducted based on this idea to develop an analytical method for modeling of thin SPSWs. Thorburn et al (1983) developed a simple analytical method to evaluate the shear strength of unstiffened SPSWs with thin steel plates and introduced the strip model to represent the tension field action of a thin steel wall subjected to shear forces. Timler and Kulak (1983) modified the formula for the angle of strips inclination with the column by the tests. This method has been implemented into the Canadian design codes (CAN/CSA 2001) and the AISC (2005b) seismic design specifications.

Astaneh-Asl and Zaho [5-6] performed experimental test on the two specimens of three-story composite shear walls under cyclic loads and both specimen showed highly ductile behavior, stable cyclic post yielding performance. He showed the concrete layer produces a better distribution of stress in the steel plate, developing tension field lines in a wider region.

Lubell et al.(2000) tested two single and one 4-story thin SPSWS under cyclic loading and compared the experimental results with the simplified tension field analytical models and found that the models can predict post-yield strength of the specimens well, with less satisfactory in the elastic stiffness results. Caccese and et al. (1993) tested five one-fourth scale models of three-story into the effects of panel slender ratio and type of beam-to-column connection. They reported as the plate thickness increased, the failure mode was governed by column instability and the difference between simple and moment-resisting beam-to- column connection was small. Driver et al. (1998) tested a 4-story large-scale steel plate shear wall specimen with unstiffened panels under cyclic loading to determine its behavior under an idealized severe earthquake event. Robert and Sabouri-Gohomi(1992) conducted a series of 16 quasi-static loading tests on unstiffened steel plate shear panel with central opening. They recommended the ultimate strength and stiffness of a perforated panel can be conservatively approximated by applying a linear reduction factor (1–D/d) to the
strength and stiffness of a similar solid panel, where D is the hole diameter and d is the specimen width.

Berman and Bruneau [11-12] presented plastic analysis method plastic based on the strip models as an alternative for the design of steel plate shear walls. Vian and et al. (2009) performed test on Special Perforated Steel Plate Shear Walls with Reduced Beam Section Anchor Beams under cyclic loading and reported the perforated panel reduced the elastic stiffness and overall strength of the specimen by 15% as compared with the solid panel specimen.

In this paper, nonlinear behaviour of composite steel plate shear walls have been analytically investigated. In that regard, numbers of the tested ½ scaled one-story un-stiffened steel plate shear walls (SPSWs) have been selected and simulated using finite element method, based on the available experimental data in the literature. After calibration of finite element model with experimental model, number layer of GFRP laminate is added to web of infill plate in FEM model and non-linear large displacement analyses on the finite element models have been carried out.

3. Analytical Study

3.1 Basic assumptions in the analysis

The most common failure mode for FRP-strengthened steel plate is debonding and delamination of the FRP laminate (Benachour et al., 2008). In analytical models several assumptions for modeling FRP layers, bond between steel plate and FRP layer and bond between FRP layers are considered. They are summarized as follows:

a) All FRP layers considered are linear elastic.

b) Steel materials considered are nonlinear (multi-linear kinematic hardening)

c) No slip is allowed at the interface of the bond (a perfect bond is considered at the bond between adhesive and steel infill plate interface and between FRP layers).

d) Both a fiber reinforced polymer and adhesive in FEM model are considered as one layer.

e) The adhesive layer is assumed to be thin so that stresses can be considered as constant through the layers thickness.
3.2 Calibration of the numerical models

The analytical method has been validated using the available experimental results in the literature; therefore the SPSW1 specimen of Alavi-Nateghi’s work (Alavi, 2010), Figure 1, is selected and modeled. This SPSWs is ½ scaled one-story specimen with around 2 m width and 1.5 m height of un-stiffened SPSWs. The boundary elements of them were similar, while the infill steel plate thickness is 1.5mm. Each specimen consisted of the standard profile HEB160 columns and beams, as boundary elements. At the top of each specimen, an additional HEB160 was placed on the beam and welded...
along with the flanges, to better anchor the internal panel forces and to contribute with transferring loads of the horizontal jack to the specimen.

In the analysis, multi-linear kinematic hardening model is assigned to boundary element, infill plate, and fish plate. Figure 2 shows that the materials model for boundary element, infill plate, and fish plates. Moreover, in the analysis, initial imperfection based on first buckling mode is assigned to the analytical model. The analytical hysteretic and push-over load-displacement curves from the non-linear finite element modeling with analysis based on nonlinear analysis are presented and compared with experimental model in Figure 3. It is obtained that the used analytical method has been successful to estimate the actual shear capacity of the system and initial stiffness of system in comparison with the experimental results. Different between obtain shear capacity in the analytical and experimental model are less than 5%.

The nonlinear results of Von-Mises yield criterion and out-of-plane deformation in 5.4 displacement is presented in Figure 40.

3.3 Composite steel plate shear walls Analysis

In the previous section, verification of the analytical method with experimental model has been carried out. After verification, the SPSW1 specimen has been strengthened by numbers of GFRP layers with different orientation of GFRP layers (Figure 5). In this study, infill plate is strengthened in four ways. In the SPSW2 and SPSW3 specimens, infill steel plate is strengthened by one layer of GFRP laminate in each side, where the GFRP layers are oriented horizontally and vertically (α = 0 & 90) in the first, in a +45 and -45 degrees inclination with respect to the horizontal beam in the second specimens, respectively (Figure 5-a,b).

![Figure 5. Different types of strengthening of infill steel plate by GFRP layers](image-url)
In the SPSW4 and SPSW5 specimens, infill steel plate are strengthened by two layers of GFRP in each side, where the GFRP layers are oriented horizontally and vertically in the first, in a +45 and -45 degrees inclination with respect to the horizontal beam in the second specimens, respectively (Figure 1-c,d). Details of the analytical models are summarized in Table 1.

In the finite element models, for modeling the GFRP layers and infill plate, element of SHELL181 is used. SHELL181 is a 4-node 3-D element with 6 degrees of freedom at each node. The element has full nonlinear capabilities including large strain and allows defining 255 layers.

The layer information is inputted by using the section command. A failure criterion is available for this element. Shell section is used for modeling composite infill layers (GFRP layers that are attached to infill steel plate). For example, for modeling composite infill plate in the SPSW2 specimen defined shell section with three layers. Kinematic hardening plasticity model has been utilized with multi-linear kinematic hardening material model for the mild steel material that placed in middle layer. Outer layer are considered for modeling two GFRP layers. The GFRP layers are modeled with orthotropic material and considered 0º and 90º as principal direction of the GFRP layers. Tsai-Wu Failure Criterion, which allows nine failure stresses and three additional coupling coefficients, are assigned to GFRP layers.

Mechanical properties of the GFRP laminate, such as young’s modules and tensile strength are summarized in Table 2.

| Analytical models | Number of layers in comosite infill plate | Thickness of laminate and steel plate | Orientation of GFRP | GFRP NO         |
|-------------------|------------------------------------------|--------------------------------------|---------------------|----------------|
| SPSW1             | 1                                        | 1.5 mm / 1 mm                        | -                   | Sika Wrap® Hex 430G |
| SPSW2             | 1                                        | 1.5 mm / 1 mm                        | 0 & 90              | Sika Wrap® Hex 430G |
| SPSW3             | 1                                        | 1.5 mm / 1 mm                        | +45 & -45           | Sika Wrap® Hex 430G |
| SPSW4             | 1                                        | 1.5 mm / 1 mm                        | 0 & 90              | Sika Wrap® Hex 430G |
| SPSW5             | 1                                        | 1.5 mm / 1 mm                        | +45 & -45           | Sika Wrap® Hex 430G |

| GFRP               | Tensile Modulus | Tensile Strength |
|--------------------|-----------------|------------------|
| SikaWrap® Hex 430G | 26493           | 7069             | 537 | 23 |
3.4 Discussion of analytical results

After verification, the SPSW1 specimen has been strengthened by the number of GFRP layers with different orientation of GFRP layers. Hysteretic load-displacement curves for the specimens are presented in Figure 6 (a, b, c and d). In the whole, very good hysteretic performance of the SPSWs and CSPSWs can be noticed. Ultimate shear strength of the SPSW1, CSPSPW2, CSPSPW3, CSPSPW4, CSPSPW5 are equal to 776 kN, 1012 kN (30% increase in shear strength), 1181 kN (52% increase in shear strength), 1193 kN (54% increase in shear strength) and 1365 kN (76% increase in shear strength), respectively. It can be observed that strengthening by GFRP layers can significantly increase the ultimate shear strength of SPSWs. Based on analytical results; ultimate strength of SPSW3 are greater than SPSW2 and also ultimate strength of SPSW5 are greater than SPSW4 and also. These results show that if principal orientation of the GFRP laminate layer lies in the direction of tension field lines, shear capacity of system will be increased.

In Figure 8 and Figure 9, the comparison in terms of cumulative dissipated energy of the all specimens is provided. Analytical results show that GFRP layers are able to increase cumulative dissipated energy of SPSWs. Based on these analytical results it can find out that actually principal orientation of GFRP layer doesn’t have significant
effect in the amount of dissipated energy by specimens. By increasing the number of GFRP layers cumulative dissipated energy are increased.

In Figure 90, the comparisons in terms of secant shear stiffness of all specimens are represented. These analytical result shows that GFRP layers increased secant stiffness of steel plate shear walls. Principal orientation of GFRP layer has an effect in the amount of Secant stiffness of specimen. Maximum secant stiffness of the composite SPSWs in the condition occurs that principal orientation of GFRP layer is parallel with tension fields in infill plate.

These results show that adding GFRP layers can be increased initial stiffness and ultimate strength of steel plate shear walls. Based on FEM results, it can be found out that GFRP layers have increased ultimate strength and initial stiffness of the system. On the other hand, if principal orientation of GFRP layers lies in direction of tension fields of infill plate, initial stiffness, ultimate strength, and secant stiffness of system would be the maximum rates.

Figure 7. Cumulative dissipated energy of the SPSW1, SPSW2, and SPSW3

Figure 8. Cumulative dissipated energy of the SPSW1, SPSW4, and SPSW5

Figure 9. Secant stiffness of the specimens

Figure 10. Equivalent viscose damping ratio of the specimens

In Figure10, the comparison in terms of equivalent viscose damping ratio all specimens are provided. Analytical results show that by strengthening infill plate, equivalent viscose damping ratios of system are decreased. The SPSW1 specimen has a maximum equivalent viscose damping ratio between all specimens. On the other hand, the SPSW5 specimen has a minimum equivalent viscose damping ratio between all specimens. Analytical Results show that if principal orientations of the GFRP layers lie in direction of tension field lines, equivalent viscose damping ratio of the composite SPSWs will be decreased.
3.5 Concluding Remarks

In this study, nonlinear behavior of composited steel plate shear walls by means of glass fiber reinforced polymer (GFRP) laminates have been analytically investigated. The main results can be summarized as follows:

1. The shear capacities and hysteresis curves of the experimental and numerical unstiffened steel plate shear wall are compared. It is found that the simulation outcomes have showed good agreement with the experimental results.

2. The results indicate that strengthened SPSWs by GFRP layer have higher ultimate shear capacities and secant shear stiffness than unstiffened SPSWs.

3. Equivalent viscous damping ratio of the system decreased after strengthen steel plate shear wall by GFRP layers.

4. If principal orientation of GFRP laminate lie in direction of tension field line, shear capacity, secant stiffness of system will be increased.

5. Principal directions of GFRP laminate on the infill plate have a negligible effect in the amount of cumulative dissipated energy.

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