Behavior and Characteristics of Innovative Composite Plate Shear Walls

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Abstract

Fiber reinforced polymer (FRP) bonding has been investigated as an innovative method for enhancing behavior of thin steel plates subjected to in-plane shear. The steel plate undergoes post-buckling and inclined tension field forms in the plate at a certain angle. Carbon fibers can be oriented at the angle of tension field in the plate and significant results can be obtained by strategic fiber orientation and clever placement of FRP strips.

A finite element analysis research program was conducted and a steel plate shear wall model was designed. A global design rule has been taken into consideration in every model which dictates that complete yielding of the infill steel plate must precede any failure or hinging in the boundary frame and that hinging in the column must be the last step. Modeling and analysis of the steel shear wall was carefully validated with some of the most renowned laboratory tests available in the literature. Four-node shell elements with material and geometric nonlinearity were used and damage initiation and propagation in the FRP layer is considered in the model.

The optimum angle of fibers is found to be in the direction of tension field in the plate and increases of over 20% have been observed in strength and enclosed area under the load-displacement curve and 10% in stiffness of the shear wall. The FRP layer is found to participate in load carrying mainly after the steel plate has completely yielded and fiber damage and stress distribution are observed along the diagonal and corners of the plate.

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Keywords: shear wall; FRP; steel plate; composite; buckling.

1. INTRODUCTION

Steel plate shear wall (SPSW) has been widely accepted as an efficient lateral resistant system in the last decades. In the early years the design philosophy and the common practice was to restrain the shear...
buckling of the steel plate by the use of steel stiffeners in a way that shear yielding would precede any instability phenomenon. The result was strong and stiff SPWSs with large energy dissipation capacity and full spindle shape hysteresis loops with little pinching. In 1983 researchers in Canada showed that a thin steel plate without stiffeners would be an acceptable system and the cost reduction associated with the omission of stiffeners was considered to outweigh the resulting strength and stiffness loss (Thorburn et al. 1983; Timler and kulak 1983). The behavior of this system has been fully studied through laboratory tests and finite element (FE) simulations throughout the world (Roberts and Sabouri-Ghomi 1991; Driver et al. 1997; Astaneh Asl 2001; Vian et al.(1) 2009; Vian et al. (2) 2009).

In SPWS systems with thin infill plates, the plate will undergo shear buckling as soon as the plate is loaded and a post-buckling phenomenon similar to that in a plate girder web will produce an inclined path for shear transfer through tension strips. The instabilities of the plate will result in pinched hysteresis loops and limited energy dissipation capacity as measured by the area enclosed by the loops while the wall is loaded in a cyclic regime. Furthermore the out-of-plane deformation of the plate resulting from the buckles will result in damage to the architectural decorations. Consideration of these behavioral issues has resulted in researches focusing on restraining the plate buckling using either stiffeners or a reinforced concrete layer as out-of-plane restraint (Astaneh-Asl 2002; Rahai and Hatami 2009).

In this paper a new method has been proposed and investigated which partially restrains the buckling of the plate, increases the critical shear buckling stress, limits the out-of-plane movement of the plate and increases the shear capacity and stiffness of the system. In the proposed method, a fiber reinforced polymer (FRP) layer will be attached to the steel plate which will provide partial stiffening of the steel plate.

2. METHOD OF STUDY

This study is numerical in nature and a number of models have been constructed and analyzed using the finite element method. The accuracy of the simulation and the calculations has been carefully investigated and verified through comparisons with several experimental examples.

To verify the modeling of a SPWS and the nonlinearity and post-buckling phenomenon in its behavior, two examples of the famous laboratory tests were selected and simulated using the ABAQUS finite element package. The first example is the four-storey shear wall tested in the University of Alberta (Driver et al. 1997). S4R shell elements with material and geometric nonlinearity were used and an imperfection following the first buckling mode of the system was applied to the model with maximum deflection of 20 mm to simulate the real imperfect conditions. Shear force of the first storey was monitored and plotted against first storey in-plane displacement and comparison of the FE pushover curve with the laboratory hysteresis curves is shown in figure 1.

The second example is the one-story perforated shear wall recently tested in Taiwan by the researchers of the University of Buffalo (Vian et al. 2009). Perfect agreement between the FE results gained in this verification and both the FE and experimental results reported by Vian et al. (Vian et al. 2009) is demonstrated in figure 2.
In order to investigate the effect of the proposed strengthening scheme on a common steel plate shear wall system, a one-story model was produced. The frame centerline dimensions of the wall are 4500 mm by 3000 mm and the thickness of the steel plate is 4mm. The beam-column connection is made by connecting the cross section of the beam to the column face to represent a moment resisting connection. The beam and column sections are W14x120 and W14x342 respectively. The steel material is considered as elasto-perfectly plastic with $f_y=235$ MPa.

Design of the frame is done considering some basic presumptions. As specified by AISC341-05, the plate must undergo considerable plastic deformations before any significant plasticity occurs in the frame (AISC 2005). Also the wall is expected to tolerate 2.5% story drift while plasticity is accepted only at the ends of the HBEs and the VBE bases (AISC 2005). Von-Mises stress distribution shown in figure 3 shows significant plasticity in the plate while the boundary elements remain elastic and plasticity at the ends of the beams and the base of the column at 2.5% drift.
The steel plate is then strengthened using a carbon fiber reinforced polymer (CFRP) wrap covering the whole plate. The CFRP material has linear behavior. Failure of CFRP material is considered in the model using the Hashin failure criteria within ABAQUS. When the failure criteria are met in an element, the element is removed from the model and its stiffness will be omitted in the following steps. This damage evolution is done through a fracture mechanics approach using fracture energies of the material and a special damage stabilization scheme to reduce numerical instabilities. The mechanical properties of the CFRP material and the parameters related to damage evolution used in the analysis are shown in tables 1 and 2 respectively.

Table 1: Mechanical properties of CFRP material

<table>
<thead>
<tr>
<th>E11(GPa)</th>
<th>E22(GPa)</th>
<th>G12(GPa)</th>
<th>V12</th>
<th>Xt (MPa)</th>
<th>Xc (MPa)</th>
<th>Yt (MPa)</th>
<th>Yc (MPa)</th>
<th>S (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>10</td>
<td>5</td>
<td>0.3</td>
<td>1500</td>
<td>1200</td>
<td>50</td>
<td>250</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 2: Fracture energies of CFRP material

<table>
<thead>
<tr>
<th>Gf,t (N/mm)</th>
<th>Gf,c (N/mm)</th>
<th>Gm,t (N/mm)</th>
<th>Gm,c (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>25</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Where E11 and E22 are the moduli of elasticity of the CFRP in the fiber and transverse directions and Xt, Xc, Yt, Yc and S represent longitudinal tensile, longitudinal compressive, transverse tensile, transverse compressive and shear strength respectively. In table 2 G_{f,t}, G_{f,c}, G_{m,t}, G_{m,c} represent the fracture energies of fibers in tension and compression and matrix in tension and compression respectively.

The CFRP wrap consists of two plies whose fiber orientation angles are Θ and -Θ when Θ is measured from the horizontal direction. The thickness and fiber orientation of the plies are changed to investigate the optimum configuration. Figure 4 shows the fiber orientation of the plies on the steel plate shear wall.

First assuming thickness of 0.5 mm for each ply, the fiber orientation angle is changed from 0° to 90° in 5° increments and the shear wall is pushed for each angle and the shear force vs. in-plane lateral displacement is obtained. The 35° and 75° degrees angles give the highest and lowest pushover curves which are plotted with the no-CFRP shear wall curve in figure 4. For each of the curves four performance parameters including the initial stiffness, the enclosed area under the curve, the yield shear force and the ductility factor are calculated and plotted in figure 5. The yield shear force is calculated by idealizing each pushover curve by an elasto-perfectly plastic curve in a way that the areas under the real and idealized curves become equal. The ductility factor is obtained by dividing the maximum displacement corresponding to 2.5% drift by the yield displacement. The yield displacement is that corresponding to the intersection of the initial stiffness inclined branch with the yield plateau.
As the diagrams of figure 5 show, the best results regarding strength, stiffness and enclosed area under the curves can be obtained in Θ=35. This result will be discussed later in chapter 3. Figure 5 shows that while increases in strength and stiffness are expected by reaching the optimum angle; the ductility of the system is subject to decrease. To determine the amount of each of the parameters for different ply thicknesses, the shear wall model is strengthened with different ply thicknesses oriented at (35/-35) directions. Table 3 and figure 6 show the parameters calculated in this section. All of the parameters
except ductility are increased with higher thicknesses of plies and the rate of their increase is higher than the rate of decrease in SPSW ductility.

![Diagram](image1)

**Figure 6:** Performance parameters of SPSW with plies at 35°/-35° for different ply thicknesses

<table>
<thead>
<tr>
<th>Thickness of each ply (mm)</th>
<th>Enclosed Area Increase (%)</th>
<th>Stiffness Increase (%)</th>
<th>Yield shear increase (%)</th>
<th>Ductility decrease (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>7.0</td>
<td>2.2</td>
<td>7.5</td>
<td>4.8</td>
</tr>
<tr>
<td>0.5</td>
<td>12.2</td>
<td>4.4</td>
<td>12.9</td>
<td>7.5</td>
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<tr>
<td>0.75</td>
<td>16.1</td>
<td>6.6</td>
<td>17.0</td>
<td>8.8</td>
</tr>
<tr>
<td>1</td>
<td>19.6</td>
<td>8.9</td>
<td>20.6</td>
<td>9.6</td>
</tr>
</tbody>
</table>

### 3. Discussion of Results

The angle of inclination of the tension field measured from vertical in the post-buckling phase of a SPSW behavior is determined using equation (1) which is based on the work by Thorburn et al. (Thorburn et al. 1983).

\[
\tan \theta = \frac{1 + t_n L \left[ \frac{1}{2} \frac{L^3}{A_p} + \frac{L^2}{120 t_n h} \right]}{1 + t_n h \left[ \frac{1}{A_p} + \frac{h^2}{360 t_n L} \right]}
\]
where $t_w$, $L$, $h$, $A_c$, $A_b$, $I_c$, $I_b$ are plate thickness, distance between columns centerlines, distance between beams centerlines, column and beam cross sectional areas and column and beam moment of inertia respectively.

Using this equation for the model, the angle of inclination of tension field is calculated as 59.3º which agrees with the 55º angle obtained from the graphical inspection of the FE model. As graphs of figure 5 show, the maximum yield shear force, enclosed area and stiffness of the composite model were obtained in plies with the angle of 35º measured from horizontal which is in fact the angle of inclination of the tension field. This shows that bonding CFRP warps is most efficient when the fibers are oriented in the direction of dominant tension stress in the plate. Observing and comparing the stress distributions in the steel plate in both models, no significant difference can be seen which confirms that the steel plate has a large stiffness compared with the composite layer and the FRP layer does not participate in load carrying actively unless the plate has fully yielded. When yielding is spread over the whole plate surface, the composite layer will develop stresses in the direction of the tension field and when the failure criteria are met, the FRP elements will undergo damage. The damage pattern for the fibers in tension in a 1 mm thick ply at 35º orientation is shown in figure 7 together with distribution of principal stresses in the layer at 2.5% drift.

![Figure 7: Tensile fiber damage (left) and principal stress distribution (right) in 35º FRP layer with t=1 mm at 2.5% drift](image)

4. Conclusions

A finite element model of a one-storey SPSW was produced and verified with experimental data and then the infill plate was strengthened using an FRP wrap with two plies at $(\Theta/-\Theta)$ directions. The optimum angle of the fibers was found to be 35º which is the angle of inclination of the tension field in the steel plate. The thickness of one ply is increased from 0.25 mm to 1 mm for $\Theta=35º$ and it was found that the shear capacity of the system can be increased from 7.5% to 20% compared to bare steel. Although ductility of the system is decreased, the rate of its decrease is slower than the increase of strength and stiffness of the system and is no more than 10% at worst. The FRP layer does not change the stress distribution in the steel plate significantly but when the plate has yielded completely, it will actively carry loads in the direction of the tension field. Damage to fibers is expected in the corners of the plate and in the direction of the tension field due to stress concentrations and spread of tension stress to the diagonal of the plate.

References

Council, Moraga, CA.


