STRENGTHENING OF STRUCTURAL STEEL CHANNELS BY DIFFERENT CFRP WRAPPING CONFIGURATIONS-FINITE ELEMENT ANALYSIS

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Abstract

The structural steel open channel sections, which are widely used in many constructions have been designed with the main purpose of giving large resistance to bending while the torsional strengths are known to be relatively small. Accordingly, to increase the flexural strength and stiffness of this structural section, Carbon Fibre Reinforced Polymer (CFRP) has been used. The present study is to evaluate the performance of strengthening of the structural steel channel using different schematics of CFRP wrapping configurations. Furthermore, it aims to check out the optimum scheme to resist buckling using a finite element approach. The results of the analysis indicate that the adopted technic of a total number of five models including the control model is successful. The mode of failure is different and relies on the scheme of CFRP configurations. Models with skin CFRP have a combined action of bending and torsion failure mode. Besides, their ultimate load capacity is less than the closed scheme of CFRP but greater than that of the control model. When the number of CFRP layers becomes two and due to the orthogonal direction of the fibres, the flexural stiffness increases, the confinement effect provided by CFRP layers enhances the torsional stiffness of the model and decreases the vertical and lateral deflections. Consequently, the more number of CFRP layers, the more enhancement of buckling load capacity. The increase in the torsional stiffness offers sufficient resistance against the twisting; a matter that modifies the failure manner. This indicates that understanding the CFRP failure modes is useful in finding solutions for retarding the failures.

Keywords: ANSYS, Buckling resistance, CFRP, Finite element analysis, Steel Section Channel, Strengthening.
1. Introduction

Strengthening and retrofitting using Carbon fibre reinforced polymer (CFRP) composites have been of increasing interest and acceptance in civil engineering applications. This is due to their high strength-to-weight ratio, good durability, and to the combination of adhesive bonding of a flexible shape. The effectiveness of using externally bonded CFRP composites to improve the strength of structural steel members has been dealt with by many researchers [1-4]. Teng et al. [5] presented a critical review and interpretation of the available research studies on CFRP-strengthened steel structures. Ekiz and El-Tawil [6] studied the buckling behaviour of the steel members strengthened with CFRP wraps and they proposed a strengthening method that can provide enough lateral support to these members to allow them to yield in compression and to continue deforming in further than elastically. Peiris [7] found that when using ultra-high-modulus of CFRP to strengthen steel members, gave strength capacity more than that involved with normal CFRP. Kabir et al. [8] studied the effect of CFRP strip layers’ orientation on improving the bearing capacity of the structural circular hollow steel member. They found that using double CFRP strips along with one transverse layer gave strength capacity and stiffness more than that with one CFRP layer along with two layers in the transverse direction. Siwowski and Siwowska [9] found that the failure modes of the strengthened beams including CFRP plate debonding or plate rupture, depend on the strengthening system and some parameters, such as that of CFRP modulus of elasticity, endplate anchoring, and of plate prestressing level.

Selvaraj et al. [10] conducted an experimental investigation to study the strength enhancement in the structural steel channel section strengthened by different CFRP wrapping configurations. The researchers found that the effectiveness of the closed section can be further improved by increasing the unidirectional CFRP layers prior to the final wrapping by the bidirectional fibres. This study was extended by Selvaraj and Madhavan [11, 12] to improve the failure modes. They further found that CFRP strengthening techniques can significantly improve the flexural moment capacity compared to the bare open specimen. Such an improvement can be done by converting the lateral-torsional buckling (LTB) mode of failure due to yielding. In addition, they found that the closed wrapped configuration with an additional layer of bi-directional CFRP fabric provides the higher strength and stiffness compared to the control and skin wrapped specimen due to the confinement of hoop direction fibres.

Most of the available studies focused on strengthening or retrofitting using CFRP for I or hollow steel sections and a few for channel steel sections. Consequently, it is important to study experimentally and numerically the performance of the channel steel sections strengthened or retrofitted by CFRP. Furthermore, it has been noticed that the closed-form section of the channels wrapping by CFRP instead of the open channel section is necessary to increase the torsional resistance of these sections.

The aim of the present study is to examine the performance of the structural steel channel that is strengthened by different CFRP wrapping configurations using a finite element analysis. The main parameter that should be taken into account is the number of CFRP layers and configuration to reach the optimum scheme of CFRP; a matter that increases the strength capacity of the channel and improves the behaviour and buckling mode of failure by transforming the open cross-sections to close ones.
2. General Description of Test Specimens and Loading Condition

The studied numerical evaluation of specimen was for a standard channel steel section with dimensions of 100×50 mm and 1400 mm long, web thickness of 5 mm, and with an average top and bottom flange thickness of 7.5 mm. Four different schemes of CFRP wrapped around the open channel and an additional one as a control model for comparisons were adopted. The first scheme of CFRP was a skin wrapped by keeping the steel section open with unidirectional and bidirectional. The third model was closed and wrapped by single CFRP layer, and the fourth model was also closed, but wrapped with double CFRP layers; Table 1 of list descriptions about the model and CFRP properties: Thickness (0.25 mm), tensile strength (4000 MPa), tensile modulus (240000 MPa) and elongation (1.8%).

<table>
<thead>
<tr>
<th>Model mark</th>
<th>CFRP layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>*NA</td>
<td>Control</td>
</tr>
<tr>
<td>C2</td>
<td>One direction layer</td>
<td>Skin open-wrap</td>
</tr>
<tr>
<td>C3</td>
<td>Two direction layer</td>
<td>Skin open-wrap</td>
</tr>
<tr>
<td>C4</td>
<td>One layer</td>
<td>Close-wrap</td>
</tr>
<tr>
<td>C5</td>
<td>Two layers</td>
<td>Close-wrap</td>
</tr>
</tbody>
</table>

*Not applicable

The load was applied at the one-third of the span by two application points at each 400 mm from simple supports with 100 mm overhang at both sides so that the centre to centre span become 1200 mm as shown in Fig. 1(a). The vertical and lateral deflection of the tested specimens was measured by LVDT (Linear Variable Displacement Transducer) at the mid-span of the specimen, as shown in Fig. 1(b). For more information about the test, refer to Selvaraj and Madhavan [11].

Fig. 1. Experimental setup: (a) Test specimen, (b) Location of deflection measurements [11].
3. Numerical Evaluation by Finite Element Analysis Approach

Finite element method was selected for analysing the composite beam models by ANSYS version 18.20 [13]. SOLID185 and SOLSH190 were adopted to simulate the steel channel section and CFRP, respectively. The steel nodes at the interaction with CFRP have the same nodes. Accordingly, there is no slip developed between the contact surfaces where the glue is assumed to be enough to make them fully interacted, and work as a unit. The accuracy of the solution as an applied load follows the Newton-Raphson iterative method with 5% tolerance with displacement control. The applied load was divided into sub-steps and the model mesh was selected to reduce the solution time and give an accurate solution. According to Selvaraj and Madhavan [11], the finite element simulation and models are developed to match the actual experimental test data and conditions.

As reported previously, during the experimental loading process, there was not any debonding or slip between the steel and CFRP; so, the method that adopted common nodes between the steel and CFRP in the finite element numerical simulation has a limited impact on the analytical results. The scheme and layout of the channels are shown in Fig. 2. Figures 3 and 4 show the 3D finite element model with and without a mesh for a channel section. Whereas, Fig. 5 shows CFRP skin that was wrapped for the models C2 and C3 and Fig. 6 shows the close wrapped CFRP for the models C4 and C5.

![Fig. 2. Models: (a) Dimensions of the channel, (b) Opened cross-section with one direction layer skin wrap, (c) Opened cross-section with two direction skin wrap and (d) Closed cross-section with closed wrap.](image)

![Fig. 3. Finite element model.](image)  ![Fig. 4. Finite element model mesh.](image)
The mesh size for the longitudinal direction was 50 mm, the height 20 mm and the flange was 5 mm as shown in Fig. 4. These meshes were selected based on the accuracy results with their adopted verification for the experimental work. The support condition at the left has pinned that restraint the vertical and longitudinal directions while the right support is a roller that restraints only in the vertical direction. The load is distributed and applied on the nodes of the upper plates that matched the experimental tests. The nonlinear material analysis for the steel section is assumed to behave as an elastic-full plastic and linear for CFRP.

\[ \frac{b}{t} < 0.56 \left( \frac{E}{f_y} \right) \]  

(1)

Based on AISC-360-16 [14], the ratio of width to thickness is \((b/t)\), in which, \((b)\) is the width of the channel and \((t)\) is the flange thickness; \((50/7.5)\), which is 6.67 less than that yields from Eq. (1), so that the section is a non-slender element:

\[ \frac{b}{t} < 0.38 \left( \frac{E}{f_y} \right) \]  

(2)

where, \(E\) is the modulus of elasticity and \((f_y)\) is the yield tensile strength of the steel section. To check out whether the channel section is compact or not according to Eq. (2), one should follow the following when the section is compact.

Besides, \((hw/tw)\) ratio is 17, which is less than that yields from Eq. (3) for flexural. Accordingly, the section is considered compact.

\[ \frac{hw}{tw} < 3.76 \left( \frac{E}{f_y} \right) \]  

(3)

4. Analysis and Discussing the Results

The failure mode of the tested specimen \(C1\) is shown in Fig. 7, while the deflection manner for the model of \(C1\) is shown in Fig. 8, in which, the maximum applied load is 65 kN with a deflection at this load reaching 34.88 mm. Figure 9 represents the bending stress at the compression and tension along with the model. Figure 10 shows the variations of the principle stress \((\sigma_1)\) as the maximum first principle stress in the plane of zero shear stress. Figure 11 shows the side view of the model that represents the lateral-torsional buckling (LTB) mode of failure for the control specimen, which has an opened and unsymmetrical cross-section with small or no torsional resistance against twisting. Figure 12 depicts model \(C2\) that is wrapped by a single CFRP in one direction and only at the skin, the deflection, bending stress, principle stress and torsion layout as shown in Figs. 13 to 16, respectively.
Fig. 7. Failure mode of test specimen C1 [11].

Fig. 8. Deflection for model C1.

Fig. 9. Bending stress for model C1.

Fig. 10. First principle stress for model C1.

Fig. 11. Torsional of whole model C1.

Fig. 12. Failure mode of test specimen C2 [11].
The deflection at the maximum applied load of 70 kN is 14.93 mm. The maximum bending stresses occur at the location of a maximum bending moment at the centre and under the points of the applied loads. The first principle of stress is shown in Fig. 15 that represents the maximum principle stress in the zero shear stress planes, and within the limit of Von Misses criteria. Lateral torsional buckling occurs due to the lack of symmetry of the cross-section as shown in Fig. 16.

Figure 17 depicts model C3 that is wrapped by a double skin of CFRP in two directions, the deflection, bending stress, principle stress and in the torsion layout as shown in Figs. 18 to 21, respectively. The deflection at the maximum applied to load 72 kN is 12.43 mm with maximum bending stress at the centre and under the points of the applied loads. The first principle of stress is shown in Fig. 20 is within the limit of Von Misses criteria. Torsion occurs due to the lack of symmetry the cross-section shown in Fig. 21.

The results of the models C4 and C5 are shown in Figs. 22 to 31, which state clearly the deflection, bending stress, principle stress and torsion respectively. Model C4 is wrapped with CFRP around the whole cross-section along the channel in a single direction while model C5 is wrapped with double CFRP in two directions. The maximum load applied on the model C4 is 76 kN; it yields a deflection of 9.66 mm while model C5 is 86 kN with 9.64 mm. No torsional effects occur in the models C4 and C5, this is due to the presence of CFRP wrap around the whole section along with the models that work like a box. The load-vertical and lateral deflection behaviour of all models are shown in Figs. 32 and...
33. The load-deflection curves at different load levels in the experimental study were used to verify the validity of the numerical model. Besides the numerical analysis results are listed in Table 2 and compared with the experimental results obtained by Selvaraj and Madhavan [11].

The load-deflection behaviour of the models C2 and C3 with a skin warp gave an increase in the load capacity as compared with the control model, however, had less than the closed scheme of CFRP. The increases in the load capacity with the increase in the number of layers of CFRP lead to an increase in the flexural stiffness of the composite channel.

This is because CFRP can delay the flange local buckling mode of failure of the thin-walled steel channels through the confinement effect provided by the hoop directional fibres when wrapped. In addition, the increase in torsional stiffness offers sufficient resistance against twisting.

This results in a change in the failure mode from the lateral-torsional buckling to combined lateral-torsional buckling and yielding failure that increases the stiffness and strength of the specimen in comparison with the opened cross-section shapes. Thus, the load-deflection performance for open skin wrapped models is the same as the control model. This is because they are still open models but there is an increase in their load capacity. The deflections increase more rapidly after 90% from the ultimate load because the model cannot resist the torsional effects.

![Fig. 17. Failure mode of test specimen C3 [11]](image)

![Fig. 18. Deflection for model C3.](image)

![Fig. 19. Bending stress for model C3.](image)
Fig. 20. First principle stress for model C3.

Fig. 21. Torsional of whole model for model C3.

Fig. 22. Failure mode of test specimen C4 [11].

Fig. 23. Deflection for model C4.

Fig. 24. Bending stress for model C4.

Fig. 25. First principle stress for model C4.

Fig. 26. Torsional of whole model for model C4.
Fig. 27. Failure mode of test specimen C5 [11].

Fig. 28. Deflection for model C5.

Fig. 29. Bending stress for model C5.

Fig. 30. First principle stress for model C5.

Fig. 31. Torsional of whole model for model C5.

Fig. 32. Load-vertical deflection for models.

Fig. 33. Load-lateral deflection for models.
5. Parametric Study

In this paper, the behaviour of CFRP wrapped steel channel sections under loading was investigated using numerical simulation validated using existing experimental data. After validating the developed models, a parametric study was conducted to investigate the influence of the number of CFRP layers on ultimate load, deflection and buckling behaviours and associated failure modes.

The analysis was performed considering three CFRP layers as full interaction performance of composite beams under the same load for C2 and C4 models. The behaviour of vertical and lateral deflections obtained from the analysis are shown in Figs. 34 and 35. Model results are listed in Table 3. The increase in layers up to three reduces the vertical and lateral deflections for skin open-wrapped (PS1) as 39.99 and 33.93% and for close-wrapped (PS2) as 40.99 and 58.92% respectively. Figures 29 and 30 show that the models PS1 and PS2 have the same behaviour of the models C2 and C4 but differ in vertical deflections and lateral displacements values at the same applied load due to the increase in the number of CFRP layers that gave more confinements to the models and increases in load capacity. Therefore, the performance up to inflexion point is linear and after that, the curve slope decreases due to the loss in strength because of a decrease in stiffness of the composite channel. Then, the deflections increase more rapidly after 90% from the ultimate load because of the model does not resist the torsional effect.

![Fig. 34. Load-vertical deflection for parametric study.](image)

![Fig. 35. Load-lateral deflection for parametric study.](image)

<table>
<thead>
<tr>
<th>Model mark</th>
<th>Load (kN)</th>
<th>% Increase in load control</th>
<th>Numerical vertical deflection (mm)</th>
<th>Experimental vertical deflection (mm) [11]</th>
<th>Vertical deflection numerical/experimental</th>
<th>Numerical lateral deflection (mm)</th>
<th>Experimental lateral deflection (mm) [11]</th>
<th>Lateral deflection numerical/experimental</th>
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<tbody>
<tr>
<td>C1</td>
<td>65</td>
<td>---</td>
<td>34.88</td>
<td>33.00</td>
<td>1.05</td>
<td>10.22</td>
<td>9.75</td>
<td>1.04</td>
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<tr>
<td>C2</td>
<td>70</td>
<td>7.69</td>
<td>14.93</td>
<td>14.50</td>
<td>1.02</td>
<td>10.08</td>
<td>10.60</td>
<td>0.95</td>
</tr>
<tr>
<td>C3</td>
<td>72</td>
<td>10.77</td>
<td>12.43</td>
<td>13.00</td>
<td>0.96</td>
<td>8.48</td>
<td>8.75</td>
<td>0.97</td>
</tr>
<tr>
<td>C4</td>
<td>76</td>
<td>16.92</td>
<td>9.66</td>
<td>10.50</td>
<td>0.92</td>
<td>1.85</td>
<td>1.90</td>
<td>0.97</td>
</tr>
<tr>
<td>C5</td>
<td>86</td>
<td>32.31</td>
<td>9.64</td>
<td>10.25</td>
<td>0.94</td>
<td>0.99</td>
<td>1.10</td>
<td>0.90</td>
</tr>
<tr>
<td>Mean</td>
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<td></td>
<td></td>
<td>0.98</td>
<td></td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>Standard division</td>
<td>0.059</td>
<td>0.053</td>
<td></td>
<td></td>
<td>0.004</td>
<td></td>
<td></td>
<td>0.003</td>
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<tr>
<td>Variance</td>
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<td></td>
<td></td>
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</table>
Table 3. Analysis results of the parametric study.

<table>
<thead>
<tr>
<th>Model mark</th>
<th>Load (kN)</th>
<th>Vertical deflection (mm)</th>
<th>Lateral deflection (mm)</th>
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<tbody>
<tr>
<td>C2</td>
<td>70</td>
<td>14.93</td>
<td>10.08</td>
</tr>
<tr>
<td>C4</td>
<td>76</td>
<td>9.66</td>
<td>1.85</td>
</tr>
<tr>
<td>PS1</td>
<td>70</td>
<td>8.96</td>
<td>6.66</td>
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<tr>
<td>PS2</td>
<td>76</td>
<td>5.70</td>
<td>0.76</td>
</tr>
</tbody>
</table>

6. Conclusions

The following conclusions are drawn from the present study.

- The models revealed to yield a reasonable comparison to the available test results, including load-deflection response and mode of failure. Simulation results demonstrated a marked improvement in the buckling behaviour of steel members reinforced with CFRP system compared to the bare one.
- The control model performance under the effect of the applied load did not show buckling up to 80%, in which, the model was stable. Accordingly, the model became weak and lost the flexural stiffness.
- The load-deflection behaviour showed that the models were stable up to 85.52% and 81.44% from the ultimate load for the closed wrapped models.
- A closed double CFRP wrapped model has the highest flexural and torsional stiffness among all CFRP wrap configurations. The total stiffness of the structure has been enhanced due to the combined effect of the CFRP in both directions. Moreover, the open skin wrapped models have an increase compared to the base model.
- The mode of failure for the studied models is different and relays on the number of CFRP layers and wrap configurations; and
- Understanding CFRP failure modes are useful in finding the solutions for the retarding the failures and in choosing a CFRP strengthening technique that helps to avoid the undesirable failures.

Nomenclature

- \( b \) Width of channel
- \( E \) Modulus of elasticity of steel section
- \( f_y \) Yield tensile strength of steel section
- \( h_w \) Web height of channel section
- \( t \) Flange thickness
- \( t_w \) Web thickness of channel section

References


