Strengthening of Deficient Steel Box-Shaped Compressive Members Using CFRP

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ABSTRACT
Background: Nowadays, because of construction and repair costs, maintenance of structures is indispensable. Several factors such as design and calculation errors, lack of proper installation, change structures application, fatigue, corrosion and events such as earthquake, fire and environmental conditions reduce their durability, which renew and restore to its original function is inevitable. One of the proper materials for strengthening is Carbon Fibre Reinforced Polymer (CFRP). This paper presents an investigation on the effect of CFRP for strengthening of short steel box-shaped members with initial horizontal and vertical deficiency. Thirteen specimens with variety of parameters such as length, width and position of deficiency, and strengthening techniques were investigated to study amount of CFRP and strengthening methods to reform the performance. Three-dimensional (3D) modeling and nonlinear static analysis method using ABAQUS software were utilized. The results of research on the use of CFRP fibers to strengthening of short steel box-shaped members with initial deficiency indicate, the fibres have significant effects on increasing load bearing capacity and ductility and, also prevent deficiency propagation.

INTRODUCTION

The first researches in this area began in the early 1980s in Switzerland and its results was used in the strengthening of reinforced concrete bridges in 1991. Though, researches for Fibre Reinforced Polymer (FRP) applications to steel structures has started recently regardless of the crucial requirement for the restoration of steel structures such as beams, columns, bridges and buildings. In the initial researches, steel plates were applied for external strengthening. It presented some problems such as increase of self-weight, required heavy lifting equipment to install the plates in position, trouble in shaping and fitting in complex profiles and complication in bonding/welding and moreover added plates are susceptible to corrosion which causes an increase in future maintenance expenditures. In comparison, recovery using FRP composites do not reveal any of these problems and performs to be an excellent solution.

Strengthening of circular hollow sections (CHS) with FRP by Teng and Hu [14] and Hong et al. [5] under axial compression, Doi et al. [2] under bending and compression, Zhao et al. [16] and Xiao et al. [15] on concrete filled CHS has revealed substantial enhancement in strength and stiffness of steel members with externally bonded CFRP. Shaat and Fam [9] found, transverse Carbon Fibre Reinforced Polymer (CFRP) layers are effective in confining the outward local buckling of short columns and that the load capacity increased by 18 % for short columns and 13 – 23 % for slender columns. Also, they recognised three usual failure modes for short steel hollow section columns strengthened by CFRP which are (a) delamination between the steel and the longitudinal CFRP at the end of the column, (b) rupture of the transverse CFRP adjacent the corners and (c) delamination between the steel and the transverse CFRP, and for long steel hollow section columns strengthened by CFRP, the delamination and crushing of the CFRP at an internal buckling location was observed.

In a research by Tao et al. [12] up to two layers of CFRP jackets to strengthening of steel hollow sections subjected to axial compression were utilized. Results indicated that increase in load carrying capacity of the circular columns were much more than rectangular columns. He et al. [4] investigated Behavior of circular, concrete-filled solid and hollow steel columns. It resulted CFRP gains ductility and ultimate strength and,
increase of layers showed more strength, and full wrapping developed the stiffness. The CFRP strengthening has demonstrated higher buckling load and compressive load bearing capacities. Sundarraja and Prabhu [10] studied on concrete filled steel tubular (CFST) with Horizontal wrapping of CFRP strips. Twenty-seven specimens were externally bonded with 50 mm width of CFRP strips with a spacing of 20 mm, 30 mm and 40 mm. When the spacing between the CFRP strips increase, due to inadequate confining pressure by the FRP, the buckling was happened in the unwrapped area. They found out, more layers of CFRP had better performance to control axial deformation and, appropriate spacing of CFRP strips is essential to delay the buckling, axial load carrying capacity and axial stress–strain behavior of columns.

Feng et al. [7] experimented different cross-sectional shapes and strengthened using mortar-filled FRP tubes. After strengthening, the mid-height failure modified to local damage at the steel end. In addition, enhancement of ductility and load carrying capacity by up to 877% and 44–215% observed, respectively. Prabhu and Sundarraja [8] conducted tests on concrete filled steel tubular columns strengthened by CFFRP strips with two different spacing. CFRP strips prevent the lateral deformation and postpones the local buckling of steel tube. Increase of CFRP layers raise axial deformation control up to 66.24% and load bearing capacity up to 1.5 times than the capacity of the steel section alone, furthermore, the load bearing capacity generally relies on the appropriate spacing between the CFRP strips. By 30 mm spacing were shown CFRP rupture failure, though when increasing the spacing, the columns were failed by local buckling without any rupture. Teng and hu [13] investigated FRP-jacketed thin cylindrical shells under combined axial compression and internal pressure. Results showed FRP jacketing is an effective strengthening method for elephant’s foot collapse failure near the support. Application of FRP outcome a large increases in ductility and energy absorption capacity but limited increases in the ultimate load, which is appropriate in seismic retrofitting.

Bambach et al. [1] researched on square hollow sections (SHS) cold-formed steel were made-up by spot welding, strengthened by CFRP under axial compression. The SHS were fabricated by spot-welding and had plate width-to-thickness ratios between 42 and 120, resulting in plate slenderness ratios between 1.1 and 3.2. It revealed that the using CFRP to slender sections increases axial capacity, strength-to-weight ratio, and elastic buckling stress up to 4 times. Haedir and Zhao [3] presented strengthening effectiveness CFRP in strengthened tubular short columns. Combination of hoop and longitudinal CFRP in a slender tube improved yield capacity of tube. Higher amount of CFRP has more efficiency on strength and provide a degree of confinement to postpone buckling of the thin steel walls. Kalavagunta et al. [6] researched on axially loaded cold formed lipped channel steel section strengthened with CFRP on the web and full section. Due to peeling and debonding of the CFRP, reduced capacity and premature failure happened. Ultimate load was increased in web strengthening and full sections by 10.26% and 16.75%, respectively. Sundarraja and Sivasankar [11] investigated on spacing of CFRP strips and number of layers in strengthening of hollow structural steel (HSS) tubular columns. Improvement in load bearing capacity and ductility were observed. More transverse CFRP sheets outcome higher load carrying capacity, stiffness and increased axial deformation in comparison with longitudinal CFRP sheets.

From the past research, it found out that there have been investigations on using CFRP as a strengthening material for steel members and also external wrapping of FRP considerably improved the strength and stiffness of the steel tubular members. Furthermore, more experiments are necessary to develop a useful combination of fibre orientation, number of layers and arrangement in applying CFRP layers on repairing or strengthening of deficient members under compression. The aims of this research are to evaluate the achievability of Strengthening of deficient steel box-shaped members subjected to compression by unidirectional CFRP and to develop a suitable repair method using CFRP material. The specimens were modelled and analysed using ABAQUS software.

**MATERIALS AND METHODS**

In order to investigate the CFRP effects and strengthening technique, one non-strengthened control member and twelve strengthened members with different layers and arrangement of CFRP sheets are chosen.

2.1 Materials:

2.1.1. Steel tube:

In this research, square hollow steel tube with a dimension of 90×90 mm was used. The dimension of the selected steel section and the test setup are also indicated in Fig. 1. In order to make deficiency, a horizontal and vertical slot was created at the both of middle and corner of steel tubes, which these deficiency patterns are shown in Fig. 2. The thickness and length of the square hollow steel tube were 3 mm and 270 mm, respectively. By coupon tests, the yield and ultimate strength of steel tubes predicted 270 and 282 N/mm$^2$, respectively.

2.1.2. Carbon fibre:

CFRP has been extensively used for strengthening structural elements because of its high tensile strength. SikaWrap®-230 C, a unidirectional high strength carbon fibre, was used in this study. It is a standard modulus
CFRP fibre with modulus of elasticity of 238 kN/mm² and tensile strength of 4300 N/mm². The thickness of the fibre was 0.131 mm.

Fig. 1: Test setup and dimensions of steel member.

Fig. 2: Deficiency patterns.

2.1.3. Adhesive:
The epoxy must be strong to endure the high stress generated during loading. In order to obtain good bonding between steel tube and carbon fibre, Sikadur®-330 was used in this study. It is 2-part epoxy impregnation resin, comprised a resin and a hardener with the 4:1 mixing ratio.

2.2 Description of specimens:
Amongst 13 specimens, 8 were externally bonded by CFRP Sheets, and 5 remaining are unbonded which 4 specimens of them have deficiency. Two different fibre layouts were investigated: one layer being placed transversely (i.e. around the SHS perpendicular to the direction of axial load) with one layer longitudinally (i.e. in the direction of axial load), henceforth called 1T1L; and two layers transversely with two layers longitudinally called 2T2L. The transverse layer was placed first, bonded directly to the steel, and the longitudinal layer second; then for the 2T2L specimens another transverse layer followed with the final longitudinal layer. Specifications, load bearing capacities and deficient details of the members are shown in Table 1. Dimensions of steel tubes are the same for all specimens. The specimen Control is non-deficient and not strengthened which used as the control member.

2.3 Numerical simulation:
To model the specimens, the full 3D simulation using ABAQUS software was performed. Steel tube, CFRP sheets, and adhesive were modeled in three dimensions and solid form. Tetrahedron quadratic (10 nodes) elements for steel tube, and Hex quadratic (20 nodes) elements for adhesive and CFRP were used. Good bonding behavior between the steel tube, adhesive, and CFRP sheets was defined. The materials’ linear and nonlinear properties were applied. The CFRP sheets material properties were defined as linear and orthotropic
because CFRP materials have linear properties and they were unidirectional. The steel tube were defined as nonlinear properties.

Table 1: Specifications, load bearing capacities, and deficient dimension of the beams.

<table>
<thead>
<tr>
<th>No</th>
<th>Specimen</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Position</th>
<th>CFRP layers</th>
<th>Load bearing Capacity</th>
<th>Increase/Decrease (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>292.6</td>
<td>-</td>
</tr>
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<td>2</td>
<td>MHD</td>
<td>60</td>
<td>20</td>
<td>Middle Horizontal</td>
<td>N/A</td>
<td>240.6</td>
<td>-17.77</td>
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<tr>
<td>3</td>
<td>MHD-1T1L</td>
<td>60</td>
<td>20</td>
<td>Middle Horizontal</td>
<td>2</td>
<td>267.1</td>
<td>-8.71</td>
</tr>
<tr>
<td>4</td>
<td>MHD-2T2L</td>
<td>60</td>
<td>20</td>
<td>Middle Horizontal</td>
<td>4</td>
<td>296.7</td>
<td>1.40</td>
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<tr>
<td>5</td>
<td>CHD</td>
<td>60</td>
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<td>Corner Horizontal</td>
<td>N/A</td>
<td>238.2</td>
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<tr>
<td>6</td>
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<td>60</td>
<td>20</td>
<td>Corner Horizontal</td>
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<td>259.1</td>
<td>-11.44</td>
</tr>
<tr>
<td>7</td>
<td>CHD-2T2L</td>
<td>60</td>
<td>20</td>
<td>Corner Horizontal</td>
<td>4</td>
<td>291.3</td>
<td>-0.44</td>
</tr>
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<td>8</td>
<td>MVD</td>
<td>180</td>
<td>20</td>
<td>Middle Vertical</td>
<td>N/A</td>
<td>273.9</td>
<td>-6.39</td>
</tr>
<tr>
<td>9</td>
<td>MVD-1T1L</td>
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<td>20</td>
<td>Middle Vertical</td>
<td>2</td>
<td>297</td>
<td>1.50</td>
</tr>
<tr>
<td>10</td>
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<td>Middle Vertical</td>
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<td>326.8</td>
<td>11.68</td>
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<tr>
<td>11</td>
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<td>N/A</td>
<td>249.9</td>
<td>-14.59</td>
</tr>
<tr>
<td>12</td>
<td>CVD-1T1L</td>
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<td>2</td>
<td>276.9</td>
<td>-5.36</td>
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<tr>
<td>13</td>
<td>CVD-2T2L</td>
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<td>20</td>
<td>Corner Vertical</td>
<td>4</td>
<td>319.7</td>
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</table>

In order for verifying, the specimens 50×50×2 plain (non-strengthened), 50×50×2 1T1L (strengthened with 2 layers of CFRP), and 50×50×2 2T2L (strengthened with 4 layers of CFRP) from (Bambach and Elchalakani, 2007) with good agreement were validated. The results of Load-Displacement as shown in Fig. 3. Presented that the full-3D modelling case and non-linear analyses applied in this research had high accurateness with the experimental tests.

**RESULTS AND DISCUSSION**

3.1 Effects of Deficiencies:
According to Table 1, it was found out that deficiency reduce load bearing capacity by 1.5-18.59 %. Results clarify which corner deficiency is more critical in contrast to middle one and horizontal deficiency decreases local bearing capacity much more than vertical deficiency, although specimens with horizontal deficiency have lesser area of slot.

3.2 Load bearing capacity:
This investigation is carried out with the aim of reforming performance of deficient members. From the test results, it can be seen that CFRP plays a vital role in increasing the load carrying capacity of box-shaped members. Local buckling was observed nearer to the edge of deficiency as shown in Fig. 4. It was observed that all specimens confined by CFRP wraps showed a considerable increase in ultimate load bearing capacity by 19.31-27.93. The axial load carrying capacity of all retrofitted specimens is presented in Table 1 along with the percentage increase in it compared with the control specimens. It can be understood that from Figs. 5 to 8, there is a significant increase in axial capacity and ductility resulting from CFRP applications. In addition, there is more gain in increasing of load carrying capacity when the number of layers of CFRP fabrics was increased. Among the strengthened specimens, the members confined with four layers of CFRP obtained higher ultimate load when compared to columns confined with two layers of CFRP and the unbonded member.
Fig. 4: Stress intensity and local buckling near to deficiency; a: CHD-Plain, b: CHD-1T1L.

Fig. 5: Load-Displacement curves for specimens with middle horizontal Deficiency.

Fig. 6: Load-Displacement curves for specimens with corner horizontal Deficiency.

Fig. 7. Load-Displacement curves for specimens with middle vertical Deficiency.
In this research, CFRP sheets for strengthening of box-shaped members with initial deficiency to gain load bearing capacity were applied. Two scheme of strengthening were carried out, and unidirectional CFRP orientation in both the longitudinal and transverse directions assisted the procedure. The results of force-displacement diagrams obtained from finite element method demonstrate that using CFRP significantly improve the compressive members performance. For all strengthened members, it is obviously observed that strengthening with externally bonded CFRP fibres under axial loads can arise the ductility of the strengthened columns compared with the non-strengthened ones and also, more number of CFRP layers play significant role in confining or delaying the local buckling, and subsequently load carrying capacity increase. Finally, this study showed CFRP sheets are able to surmount the strength weakness and performance of deficient compressive members.

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