Research Article

Effect of Strengthening of Steel Beams with Variable Length by Using Carbon Fiber

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In this research, four steel beams were fabricated and tested to understand the influence of their strengthening (by using carbon fiber) with various span lengths on load deflection, load-strain, and ultimate load responses. All tested beams have the same cross-sectional area, and they are all strengthened by using intermediate stiffeners and cover steel plate at top flange to insure that failure will occur at the bottom flange. The tested steel beams are divided into two groups according to their clear span lengths 1400 and 1900 mm, and each group is subdivided into two beam cases based on whether they are strengthened by carbon fiber or not. From this study, it was found that the load deflection and load-strain curves for the beams strengthened by carbon fiber are stiffer than the original beams (without carbon fiber) with similar clear span lengths (this behavior was more obvious with smaller lengths). Moreover, the load deflection and load-strain responses have shown that beams became stiffer when the effective length is reduced (with and without carbon fiber), and this behavior was more apparent with the beams strengthened by carbon fiber. On the contrary, from the results of ultimate load of the beams, it can be concluded that the percentage of increase in ultimate load for the beam strengthened by carbon fiber is increased with the decrease in its span length. One could also conclude that when the effective length decreases, the ultimate load was increased and the percentage of this increasing is magnified with the presence of carbon fiber.

1. Introduction

The most important properties of steel are great durability and formability, good yielding, tensile strength, and thermal conductivity, so steel is considerably the most useful material for building structures with a strength of approximately ten times that of concrete due to its high strength and uniformity [1]. CFRP laminates have been used over the last two decades in the structural field as a workability construction material providing additional skill for modernizing and increasing the strength of structures’ elements because of their economical and structural toughness, performance, and homogeneous properties [2]. FRP laminates have widely been used in structural repair and strengthening techniques for buildings and bridges in the recent years. The superior properties of CFRP laminate such as high Young’s modulus, high tensile strength, high strength to weight ratio, high stiffness to weight ratio, and good durability have made them a good alternative to the traditional repair and strengthening materials. Many studies have recently been performed on the strengthening of steel-composite beams by the bonding of FRP laminates to the tension flange of a simply supported beam [3–17]. These studies have demonstrated that significant strength gains and, in some cases, significant stiffness gains can be obtained using adhesively bonded FRP laminates. However, flexural strengthening of steel beams by using FRP usually suffers problem in the form of debonding at the end of the FRP laminate. This is normally attributed to the very high stress and strain intensity that occurs at the end of the laminates [3, 12, 18].

In order to improve the behavior of steel beams, many researchers have studied CFRP materials trying to attain their
full capacity. First, some of them have used “prestressing of CFRP strip” [10]. Second, others have used “splicing finite length of CFRP strips” (near the support [10] and with a variable length at midspan [19]). Third, researchers have used CFRP sheet wrapped around the tension flange and part of the web [20]. Fourth, researchers have manipulated the properties (elastic modulus, tensile stress, strain at rupture, and thickness) of CFRP plates [14]. Last, researchers used various CFRP strip lengths with the same length of strengthened steel beams in order to have (and investigate) different modes of CFRP strip failures [21].

Some researchers have demonstrated techniques to overcome this problem (debonding at the end of the CFRP laminates) for steel structures by using a tapered CFRP end cutting shape [12,22–28]. Using a longer CFRP laminate reduces the bending moment at the ends and hence the magnitude of the stress level [29], but this is not economic because of the high cost of CFRP laminates. Applying mechanical end anchorage at the end of the CFRP laminates by using a three-piece clamping system for steel-concrete composite bridges increased the resistance against peeling and deboning. The application of steel plates and bolts as a CFRP end anchorage for steel I-beams improved the load-carrying capacity and decreased the strain and deformation of the whole beam [30].

2. Research Significance

The objective of this study is to get much information and better understanding for the behavior of steel I-beams strengthened by CFRP laminates as compared with the reference (original) steel beam in order to improve their performance.

3. Experimental Work

3.1. Material Properties

3.1.1. Steel Section and Steel Plate Test Symbols. An I-shaped steel member commonly used in structural frames. Flanges of I shape are designed to provide strength in a parallel level, while the web provides strength in a perpendicular level. Table 1 shows dimension and properties of the steel section used in this study.

The direct tension test of the steel specimen was performed at the laboratory of civil engineering department in the college of engineering at Mustansriyiah University by using the hydraulic universal machine with a capacity of 1200 kN according to ASTM A370-2014 [31] as shown in Figure 1, and test results of the specimen are listed in Table 2.

3.1.2. Cover Plate and Stiffeners. To make sure that the failure mode in the steel beam is of yielding type in the bottom flange (in a plastic hinge manner) and to prevent lateral bulking in top flange, a steel cover plate (8 × 65 × 1500) mm for beams C1 and C2 or (6 × 65 × 1250 mm) for beams B1 and B2) is welded on the external surface of the top flange; besides, an intermediate stiffener with dimension (6 × 22 × 86) mm is welded on both sides of the web parallel to the loading direction. These plates are assisted to prevent web crippling at midspan section and also provide lateral stability for the steel beams as shown in Figure 2.

3.1.3. CFRP Laminates and Adhesive. Sika CarboDur® S plates are made from a carbon fiber-reinforced polymer (CFRP) laminates, and it has been taken into account in design computations of all strengthened structural elements. Sika CarboDur® S plates are glued to steel beams as external strengthening by using Sikadur®-30 epoxy resins. The mechanical and physical properties of Sikadur resin are listed in Tables 3 and 4.

3.1.4. Surface Preparation and CFRP Installation. The efficiency of strengthening steel beams with externally bonded laminates depends primarily on the bond strength between the CFRP and the steel beam. To insure tight bonding between steel beam and CFRP laminates, the surface of the steel beam should be free from paint and any isolating material such as dust, dirt, and oil. To prepare the steel beam before gluing CFRP laminates (width = 25 mm and thickness = 1.2 mm), the surface should be subjected to fillings as a first step preceding CFRP adhesion. All surface pores or cavities on beam flanges surfaces are then filled with Sikadur®-30 epoxy resin to enhance the continuity for the bonded surface and to ensure proper tight bonding at the surface defect locations. After that, the first coat of Sikadur®-30 epoxy is spread on the steel surface. Mechanical properties for Sikadur®-30 epoxy are given in Table 3, and the whole fabric surface is shown in Figure 3.

3.2. Testing Program

3.2.1. Specimen Description. The parametric variables involved in this study focus generally on the existence of CFRP laminates. Four steel beam specimens were tested and subjected to one-point load bending, and half of these beams were strengthened by CFRP laminates, and the others were not strengthened and considered as references beams. All specimens have similar I sections, with a 8 × 65 × 1500 mm or 6 × 65 × 1250 mm steel cover plates, a 6 × 22 × 86 mm intermediate stiffener, and 1400 or 1900 mm span lengths, respectively. Table 5 shows the description of the steel beam specimens used in this study.

3.2.2. Deflection Monitoring. Deflection of the tested beam specimens had been recorded using one dial gauge with 30 mm capacity and 0.01 mm accuracy placed at midspan under the concentrated point load. The testing process was monitored to assign the exact dial reading at each required time accurately. Locations of the dial gauges are shown in Figure 4.

3.2.3. Strain Reading in Tested Beams. Longitudinal strain at bottom flange is one of the parameters taken into account in this study. Strain readings were achieved by using one TML strain gage and switching box, and readings are recorded from the beginning of load application until failure occurs.
### Table 1: Dimension and properties of the steel section*.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Thickness (mm)</th>
<th>Radius of curvature (mm)</th>
<th>Cross-sectional area ( (\text{mm}^2 \times 10^2) )</th>
<th>Mass per meter (kg/m)</th>
<th>Moment of inertia ( (\text{mm}^4 \times 10^4) )</th>
<th>Yielding strength, ( F_y ) (MPa)</th>
<th>Ultimate tensile strength, ( F_u ) (MPa)</th>
<th>Elongation at break (in 200 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H×B</td>
<td>( t_1 )</td>
<td>( t_2 )</td>
<td>( r )</td>
<td>Ag</td>
<td>8.1</td>
<td>250</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>100×55</td>
<td>4.1</td>
<td>5.7</td>
<td>7</td>
<td></td>
<td>10.3</td>
<td></td>
<td></td>
<td>22.6</td>
</tr>
</tbody>
</table>

*Supplied by the manufacturer.

### Figure 1: Direct tension test for steel plate. (a) Testing machine. (b) Specimen. (c) Specimen dimensions.

### Table 2: Mechanical properties of the specimen test based on the direct tension test.

<table>
<thead>
<tr>
<th>Standard specification</th>
<th>Yielding strength, ( F_y ) (MPa)</th>
<th>Ultimate tensile strength, ( F_u ) (MPa)</th>
<th>Elongation at break (in 200 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test results</td>
<td>265</td>
<td>410</td>
<td>22.6</td>
</tr>
<tr>
<td>Limitation of ASTM A36 mild/low carbon steel</td>
<td>≥250</td>
<td>≥400</td>
<td>≥20</td>
</tr>
</tbody>
</table>

### Figure 2: Details of the cover plate and stiffeners on a tested steel beam.
The strain gauge is fixed at the upper surface of the bottom flange (40 mm) shifted from midspan as shown in Figure 4.

3.2.4. Testing Procedure and Load Measurements. All tests were performed in the laboratory of civil engineering department in the college of engineering at Mustansiriyah University (MFL). A universal hydraulic machine of 3000 kN capacity was used. Steel beams were tested under one concentrated point load at midspan with a clear span of 1900 and 1400 mm. The applied machine piston load was

<table>
<thead>
<tr>
<th>Curing time</th>
<th>25°C Tensile strength in flexure (N/mm²)</th>
<th>55°C Curing temperature</th>
<th>55°C Tensile Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 d</td>
<td>&gt;12s</td>
<td>~38</td>
<td>—</td>
</tr>
<tr>
<td>3 d</td>
<td>&gt;20</td>
<td>~40</td>
<td>~14</td>
</tr>
<tr>
<td>7 d</td>
<td>&gt;25</td>
<td>~42</td>
<td>~17</td>
</tr>
</tbody>
</table>

Modulus of elasticity in tension ~42 (+25°C)

*Supplied by the manufacturer

<table>
<thead>
<tr>
<th>E modulus (N/mm²)</th>
<th>Mean value</th>
<th>5% fractal value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>170000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>165000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tensile strength</th>
<th>Mean value</th>
<th>5% fractal value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2900</td>
</tr>
</tbody>
</table>

*Supplied by the manufacturer.

Table 5: Description of the tested steel beams.

<table>
<thead>
<tr>
<th>Beam designation</th>
<th>Clear span (mm)</th>
<th>CFRP laminates</th>
<th>Length of CFRP laminate (cm)</th>
<th>CFRP length/clear span length</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1900</td>
<td>Without CFRP</td>
<td>133</td>
<td>0.7</td>
</tr>
<tr>
<td>C2</td>
<td>1900</td>
<td>With CFRP</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>B1</td>
<td>1400</td>
<td>Without CFRP</td>
<td>98</td>
<td>0.7</td>
</tr>
<tr>
<td>B2</td>
<td>1400</td>
<td>With CFRP</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 3: Description details of tested steel beams.
transformed to a knife edge load (over the steel beam width) by the use of a 100 mm diameter steel rod. A deflection dial gauge of 0.01 mm accuracy with 30 mm capacity was fixed in the designated location (at midspan) and reset to zero. Load progression for all tested beam specimens was due to 5 kN load increment. The strain gauge and dial gauge readings were recorded at each load increment. Measurements were recorded until the failure of the beam occurs when the applied load indicator was dropped while deformation increased. The test machine and instrumentation details are shown in Figure 4.

4. Experimental Parametric Studies

In order to investigate the effectiveness of the mechanical action of carbon fiber on the strengthening of steel I-beams and the effect of their clear span length, four samples were tested under single point load bending test. These beams were divided into two groups according to their clear span lengths. Each group consisted of two specimens with and without strengthening with carbon fiber with the same clear span each. All specimens had the same dimensions of I section, intermediate stiffener, and steel cover plate on top flange. The experimental deflection and longitudinal strain readings for the tested beams were recorded and monitored (through the use of a single dial gauge fixed at midspan and a single TML strain gauge fixed at the upper surface of the bottom flange (40 mm) shifted from midspan) since time of load application until failure occurs.

4.1. Effect of Carbon Fiber with Various Clear Span. In order to improve the strengthened steel beams, three actions were performed in this research trying to obtain the full capacity of the CFRP strips:

(a) Adding a 1.25 m × 65 mm × 6 mm plate welded at the top flange to prevent the failure from occurring in the compression flange and to insure that the failure will occur at the bottom flange which is strengthened by CF.

(b) The highest ratio of CFRP length/span length used was equal to 0.7.

(c) The small width of CFRP strips (25 mm) is used to obtain the full capacity of them, pursuant to the following study: Sallam et al. [9] have concluded that the strengthened beam by one CFRP strip of a width of 70 mm bonded to the lower face of the tension flange revealed less load-carrying capacity than that of the I-beam strengthened by two separate CFRP strips of which each strip width of 30 mm bonded to the lower face of the tension flange due to the premature occurrence of debonding in the constant moment region [9].

4.1.1. Load Deflection Response of the Steel Beams Tested. Figures 5 and 6 illustrate the load deflection response of the tested beams with and without strengthening by carbon fiber having an effective length of 1400 and 1900 mm (B1 and B2, and C1 and C2), respectively, as displayed in Table 5. The load deflection curves in these figures reveal that beams strengthened by carbon fiber are stiffer than the reference beam (without carbon fiber) at the same clear span (this behavior is more clear when increasing the load). Moreover, the mentioned figures show that the effect of carbon fiber (which makes the load deflection curve straighter) is increased when the effective length is reduced.

4.1.2. Load-Strain Response of the Steel Beams Tested. Figures 7 and 8 present the effect of using CFRP laminates on the load-strain response of steel beams having clear spans 1.4 m and 1.9 m, respectively. Both figures show an identical response at the elastic region, while at the plastic region, the role of carbon fiber in improving the beam stiffness is considerable, which means that the benefit of carbon fiber existence in improving beam stiffness starts when load values enter the plastic region and it is magnified gradually until failure occurs. Moreover, when comparing load results of the two figures, one can notice that load values (with and without carbon fiber) are reduced when clear spans are decreased.

4.1.3. Ultimate Load of the Steel Beams Tested. Table 6 and Figure 9 display the ultimate load of the tested steel beams. The results show that the usage of CFRP increases the ultimate load of beams (C2 and B2) as compared with the reference beams (B1 and C1), respectively. This improvement could be attributed to the role of the carbon fiber in increasing the beam stiffness, and hence, increasing the load-carrying
capacity of the strengthened beams is represented by the increase in ultimate loads. The results also reveal that the percentage of increase in ultimate load was 38.88% when the clear span is 1.9m and 52.17% when the clear span is 1.4m, which means that the percentages of increasing in ultimate load (when using carbon fiber) are increased when the clear span is reduced.

4.2. Effect of Clear Span Length with and without Carbon Fiber Strengthening

4.2.1. Load Deflection Response of the Steel Beams Tested. Figures 10 and 11 illustrate the influence of span length on the load deflection response for the tested beams with and without strengthening by carbon fiber. The mentioned figures reveal that (for the same load level) the deflection is decreased when span length is decreased, and this behavior becomes more obvious as long as load level increases. Moreover, one can notice that this behavior is identical for beams with and without strengthening by carbon fiber. The mentioned figures also show that (for the same load level) the deference between the deflection values for beams strengthened by carbon fiber (B2 and C2) is smaller than the difference between the deflection values of the beams not strengthened by carbon fiber (B1 and C1).

4.2.2. Load-Strain Response of the Steel Beams Tested. Figures 12 and 13 illustrate the influence of span length on the load-strain response for the tested beams with and without strengthening by carbon fiber. The mentioned figures reveal that (for the same load level) the longitudinal strain is reduced when span length is decreased, and this behavior becomes more obvious as long as load level increases. Besides, this behavior is seemed conformable for beams with and without strengthening by carbon fiber. The mentioned figures also reveal that (for the same load level)
the deference between the strain values for beams strengthened by carbon fiber (B2 and C2) are smaller than the difference between strain values of the beams not strengthened by carbon fiber (B1 and C1).

4.2.3. Ultimate Load of the Tested Beams. Table 7 and Figure 14 show the effect of clear span length on the ultimate load of the tested beams. The results show that the ultimate load is increased when clear span is reduced. They

<table>
<thead>
<tr>
<th>Beam designation</th>
<th>Clear span (mm)</th>
<th>Ultimate load (kN)</th>
<th>Percentage of increase in ultimate applied load</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1900</td>
<td>45</td>
<td>—</td>
</tr>
<tr>
<td>C2</td>
<td>1900</td>
<td>62.5</td>
<td>38.88</td>
</tr>
<tr>
<td>B1</td>
<td>1400</td>
<td>57.5</td>
<td>—</td>
</tr>
<tr>
<td>B2</td>
<td>1400</td>
<td>87.5</td>
<td>52.17</td>
</tr>
</tbody>
</table>

Figure 9: Effect of using CFRP on ultimate load with various clear spans.

Figure 10: Effect of clear span length of the beam on load deflection response without carbon fiber strengthening.

Figure 11: Effect of clear span length of the beam on load deflection response with carbon fiber strengthening.

Figure 12: Effect of clear span length of the beam on load-strain response without carbon fiber strengthening.

Figure 13: Effect of clear span length of the beam on load-strain response with carbon fiber strengthening.

the deference between the strain values for beams strengthened by carbon fiber (B2 and C2) are smaller than the difference between strain values of the beams not strengthened by carbon fiber (B1 and C1).
also show that the percentages of this increase (in ultimate load) for beams with and without strengthening by carbon fiber are 27.77% and 40%, respectively, which means that the percentage of increase in ultimate load is enlarged with the existence of carbon fiber at bottom flange (tension zone).

5. Modes of Failure

Figure 15 shows that the failure modes in all steel beams (with and without CFRP strengthening laminates) are flexural failure modes (in a form of a plastic hinge in middle span) when steel yielding occurs at the bottom flange (as a result of the addition of the cover steel plate at the top flange). On the contrary, the failure modes for CFRP laminate beams were of debonding type as can be clearly seen in the tension zone of beams B2 and C2 in Figure 15, noting that this type of failure was sudden (maybe) because of the stress concentration occurred at the ends of the carbon fiber. This outcome is in lined with the following studies: one major problem of strengthened steel beams is the presence of high interstitial stresses near the end of the composite laminate which might govern the failure of the strengthening schedule [32]. Also, end debonding was occurred because of high concentration of stress and strain intensities on adhesive at the CFRP tips [27, 28].

6. Conclusions

From studying the experimental results of the tested steel beams, the following conclusions can be obtained:

### Table 7: Effect of clear span length on ultimate load with and without carbon fiber strengthening.

<table>
<thead>
<tr>
<th>Beam designation</th>
<th>Clear span (mm)</th>
<th>Ultimate load (kN)</th>
<th>Percentage of increase in ultimate load</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1900</td>
<td>45</td>
<td>—</td>
</tr>
<tr>
<td>B1</td>
<td>1400</td>
<td>57.5</td>
<td>27.77%</td>
</tr>
<tr>
<td>C2</td>
<td>1900</td>
<td>62.5</td>
<td>—</td>
</tr>
<tr>
<td>B2</td>
<td>1400</td>
<td>87.5</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 14: Effect of clear span length on ultimate load with and without carbon fiber strengthening.

Figure 15: Shapes of failed tested beams.
(1) When using carbon fiber in the tension zone of steel beam, the ultimate load (as an indicator to the flexural strength) was increased and the percentage of increase in ultimate load was increased with reducing span length.

(2) When the span length of the steel beam is reduced, the ultimate load (flexural strength) is increased and the percentage of this increase is enlarged with the existence of carbon fiber.

(3) When using carbon fiber in the tension zone, the load deflection response shows that the strengthened beams become stiffer than the reference beams, and the effect of using carbon fiber (to make the strengthened beams stiffer) is magnified with decreasing their span lengths.

(4) When the span length of steel beam is reduced, the load-deflection response shows a stiffer behavior. This response (behavior) is seemed identical for beams with and without strengthening by carbon fiber.

(5) When using carbon fiber in the tension zone (bottom flange) of the beams, the longitudinal strain in this zone is decreased, and this decreasing is enlarged with reducing span length of beams.

(6) When span length of the beam is reduced, the longitudinal strain in the tension zone is also decreased. This behavior is similar for beams with and without carbon fiber strengthening.

Data Availability

The data used to support the findings of this study are available from the authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References


