STRENGTHENING OF STEEL BEAMS USING TRIANGULAR END TAPERED CFRP STRIPS

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ABSTRACT
Beams are structural elements which might need strengthening due to different reasons such as incorrect designing, wrong implementation, excessive loading, and functional changes. There are various methods for strengthening steel beams. One of modern methods is application of Carbon Fibre Reinforced Polymer (CFRP). Since one of problems of strengthening with CFRP strips is high stress created at the tips of CFRP strips, this research tries to study a solution for removing or retarding of this problem. The end stress reduction is studied by selecting triangular shape pieces with different dimensions and angles at the end of CFRP strip used for flexural strengthening. To this end, five steel beam specimens with the same length and thickness of CFRP along with various dimensions of triangular shapes were used to study and model the end stress by ABAQUS V6.11 software. Modelling method was three dimensional (3D) and analysis method was non-linear static. The results showed that the shapes of end cutting have considerable effect for stress and strain distribution at the tip of CFRP strips and this method leads to noticeable reduction of stress and strain in that stress intensity in beam specimens with jaggy ends is less than those with non-jaggy ends. Reduction of stress intensity leads to delay in debonding phenomenon at the tip of CFRP strips.

Keywords: Strengthening, CFRP, Debonding, ABAQUS

INTRODUCTION
Structural strengthening using Fibre Reinforced Polymer (FRP) is one of methods in that various researches have been conducted on them in the last two decades around the world. Most of these researches have focused on concrete structure strengthening. Increasing flexural resistance using FRP is one of modern strengthening methods within the interest area of a noticeable number of researchers. The first usage of Carbon Fibre Reinforced Polymer (CFRP) composite was in ship industry in ports and harbours in order to avoid the possible accidents with harbour walls and to reduce the damage. From then onward, these laminations have been used more in industry when CFRP laminations entered construction industry (Gablbraith et al., 1995). In the past, most usages of CFRP were on concrete structures in particular on bridges but the first structure strengthened by CFRP lamination in the world was Hythe Rail Bridge in England (Luke et al., 2001). Bonaci and Maalejm (2001) were among the first people who studied the behaviour of FRP-strengthened concrete beams (Bonaci et al., 2001). Fanning and Kelly (2001) studied the behaviours of FRP-strengthened beams accurately. They were able to calculate the ultimate rise of these beams accurately (Fanning et al., 2001). Themosen et al., (2004) analyzed flexural break mode of FRP-strengthened concrete beams. They, after doing various experiments, realized that the length of FRP lamination plays an important role in their flexural resistance (Thomsen et al., 2004). Patnaik and Bauer studied the effect of flexural and shear strengthening in steel beams by CFRP coverage. Beams which went under the flexural strengthening test by CFRP on tension flange, 30 percent increased load bearing capacity were observed. Moreover, when CFRP laminations were placed in beam webs to study the shear of CFRP laminations, 62 Percent increased shear capacity of beam was observed (Patnaik et al., 2004). Deng (2004) realized that a considerable number of normal stresses occur at the end of laminates. These stresses were observed in the distance of 20 mm from lamination ends (Deng et al., 2004). Al-Emrani (2005) showed that two types of break mode happen at the end of laminations including: a) layers shear stress break at the end of layers, b)

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debonding failure which is related to maximum shear at the end of CFRP (Al-Emrani et al., 2005). Hilderbrand showed that using one reverse thin cut and filling it by adhesive at the end of CFRP leads to reduction of shear and stress of end CFRP layers (Hilderbrand et al., 1994) Deng and Lee have proved that debonding happens as a result of reaching maximum internal stress to critical value at the end of layer (Deng et al., 2007).

Higuín et al., (2009) studied the transversal shear along with CFRP thickness. In their research, Haghani and his colleagues studied six specimens numerically where each of them enjoyed various end cutting angles as well as different cutting angle in attaching adhesive to CFRP strip and they compared the maximum stress values in the form of three stresses including shear stress, layer stress, and main stress (Haghani et al., 2009). Rizkalla and his colleagues in 2008 studied different square and thinned shapes along with circled end in order to study the end shear of CFRP on concrete –steel composite beams. He tested various mechanical ties on specimen beams in order to study the stress near CFRP strips. The thicknesses were 2.9, 3.2, and 4 mm. The results showed substantial reduction at the end of CFRP laminations. Strain reduced by 59 percent at end CFRP for end thinned shapes even though creation of such cutting is difficult especially for CFRP (Rizkalla et al., 2008).

The effect of end shear in CFRP thickness on flexural strengthening of steel beams were studied by Linghoff where the thickness of layers were investigated in that the effect of end cutting was 4 mm and end CFRP was thinned for 135 mm. He realized that the load bearing capacity reduced in comparison with situation where beam end was without thinning (Linghoff et al., 2009). Narmashiri et al., (2010) studied the effect of using mechanical ties to avoid debonding. Ties included one plate restrained with four bolts to steel. Four specimens were studied where two specimens were restrained with end ties and the only difference lied in the length of connecting lamination. The results show that using mechanical ties increased the load bearing capacity by 24 percent compared to that of non-strengthened one (Narmashiri et al., 2010). Narmashiri et al., (2011) studied the effects of using CFRP by laboratory and software studies. One of their researches studied various failure modes on CFRP-strengthened beams. They studied four modeled specimens in laboratory and 3D modeling with Finite Element Analysis software. The results reveal four various break modes including cutting under loading, end debonding, debonding under load, end CFRP strips exfoliation (Narmashiri et al., 2011). Mohammedi and Kadhim studied the effects of various CFRP lengths for strengthening steel beams and they showed that length change is effective on debonding (Mohammed et al., 2012). Narmashiri et al., studied the effect of CFRP thickness on stress. Furthermore, they studied the difference of 2D and 3D modeling. Their results showed noticeable difference in the analysis of results for 2D and 3D states (Narmashiri et al., 2011).

Since stress intensity at CFRP end leads to debonding phenomenon and reduces CFRP efficiency, in this study, various triangular shapes for CFRP ends were used to reduce stress intensity and consequently to delay or to prevent debonding.

Material and Specimen Specifications

In this research, to reduce the end stress of CFRP strips, five beam specimens with different end cutting s were used for flexural strengthening of the steel beam.

Figure 1: Specifications of CFRP specimens used in this research
To this end, B1 specimen was rectangular end and as control one and B2, B3, B4, and B5 enjoyed triangular end shapes. Specimen specifications are shown in figure (1). It is noteworthy that CFRP length and thickness are fixed for all beam dimensions.

**Specification of Steel Beam**

Steel beam of IPE160; length of 2350 mm, ultimate strength of 370 MPa, and ultimate strain of 13.5 percent and in the form of non-linear, was modeled in the software. Geometrical shape of beams are in figure (2) and (3). Specification of steel beam is shown in Table (1).

**Table 1: Dimensions and material properties of steel I-beam**

<table>
<thead>
<tr>
<th>Steel I-section – mild steel IPE-160</th>
<th>Steel I-section dimensions (mm)</th>
<th>Modulus (N/mm²)</th>
<th>Stress (N/mm²)</th>
<th>Yielding (F_y)</th>
<th>Ultimate (F_u)</th>
<th>Strain (ε_y) %</th>
<th>Ultimate (ε_u) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width 82, High 160, Flange thick 7.4, Web thick 5.0</td>
<td></td>
<td>200,000</td>
<td>250</td>
<td>370</td>
<td>0.12</td>
<td>13.5</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2: Geometrical characteristics and support used in this research**

** Specification of CFRP**

To strengthen steel beam under pure flexural, CFRP composites; length of 1000 mm, width of 50 mm with elasticity modulus of 210000 MPa, strip thickness of 1.4 mm, and isotropic Poisson coefficient of 0.12; was used. The length of stress-strain graph of these materials shows linear elastic behavior until the breakage point without yielding and they do not show a non-linear behavior in modeling. This is why elastic mechanical properties of these materials are inserted in to software. The CFRP specifications are illustrated in Table (2).
Adhesive Specifications

Adhesive provides the transferring path of cutting between steel surface and composite materials and leads to identical performance of composite and the beam. The CFRP strengthening strips are attached to steel beam using especial epoxy with thickness of one mm and elasticity modulus of 11520 MPa. Adhesive specifications are illustrated in Table (3).

Table 2: Dimensions and material properties of CFRP strips

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Dimensions (mm) length</th>
<th>Elasticity modulus (N/mm²)</th>
<th>Tensile strength (N/mm²)</th>
<th>Strain at break</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.4</td>
<td>1000</td>
<td>210,000</td>
<td>2400</td>
<td>1.35%</td>
</tr>
</tbody>
</table>

Table 3: Dimensions and material properties of adhesive

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>Compressive strength (N/mm²)</th>
<th>Tensile strength (N/mm²)</th>
<th>Shear strength (N/mm²)</th>
<th>Bond strength (N/mm²)</th>
<th>Adhesive strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>Thick.</td>
<td>Length</td>
<td>E-modulus</td>
<td>Strength (7 days)</td>
<td>E-modulus</td>
</tr>
<tr>
<td>50</td>
<td>1.0</td>
<td>100</td>
<td>5485</td>
<td>11,520</td>
<td>22.7</td>
</tr>
</tbody>
</table>

Modeling and Analysis by Software

ABAQUS V6.11 software was used for modeling where steel beam, stiffeners, CFRP laminations, and adhesive were considered 3D and Solid with element of TET 10 nodes for modeling and non-linear static analysis was used to reach the break state. Moreover, linear and non-linear features of materials were taken in to account and the obtained results are listed in Table (4). To check the validity of software, two specimen beams were compared with those of Narmashiri et al., (2012) where laboratory specimens of F1 and F2 were accurately validated (Figures 4 and 5).

Figure 4: Validation of vertical displacement at the mid-span (experimental and numerical)
RESULTS AND DISCUSSION

According to Table (4) and Figure (6) Which are obtained from result analysis, ultimate stress value for B1 specimen strengthened by 1000-mm CFRP strip and rectangular end with width of 50 mm is 591 MPa. In B2 specimen enjoying 20 mm-height triangular ends, the ultimate stress is almost as much as rectangular shape (control beam specimen). Increasing the height of CFRP end triangle, it is observed that noticeable reduction ultimate stresses in CFRP strips in that the stress reduction intensity was by 39 % for heights of 100 mm avoiding the occurrence of debonding at end CFRP. According to Figure (7) showing E33 strain in 100 mm end of CFRP strip, the lowest strain in B5 specimen enjoying jaggy end triangle is observable compared to other specimens and 44 percent reduction happened in comparison with B1 specimen. Since the highest amount of stress intensity happens in loading zones, debonding happens in end zones in most cases proving the necessity of reducing end stresses.
Figure 7: E33 strain along the end 100 mm of CFRP strip

Figure 8: Stress concentration at CFRP tip

Table 4: Results of specimen analysis with CFRP strips with the length of one meter and various end shapes

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen name</th>
<th>CFRP length (mm)</th>
<th>Maximum stress of Mises in end 100 mm of CFRP strip (MPa)</th>
<th>Percentage of increase / stress reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1</td>
<td>1000</td>
<td>591</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>B2</td>
<td>1000</td>
<td>604</td>
<td>+2%</td>
</tr>
<tr>
<td>3</td>
<td>B3</td>
<td>1000</td>
<td>552</td>
<td>-7%</td>
</tr>
<tr>
<td>4</td>
<td>B4</td>
<td>1000</td>
<td>409</td>
<td>-31%</td>
</tr>
<tr>
<td>5</td>
<td>B5</td>
<td>1000</td>
<td>248</td>
<td>-39%</td>
</tr>
</tbody>
</table>
Research Article

Conclusion
Using CFRP strips have got high effect on load-bearing capacity as well as steel beam resistance; however, the occurrence of Debonding phenomenon at CFRRP tips due to stress concentration reduces the appropriate performance of such polymers. In this study, to avoid debonding, five steel beams with various triangular shapes were used to reduce end strengthening stresses where increasing the height of end triangle leads to observation of dramatic reduction of stresses compared to rectangular condition. In B5 specimen, with end 100 mm-height triangles, intensity of stress reduction is 39% in comparison with control beam (rectangular end shape). Also, jaggy end triangle (B5) has lower strain compared to other states. This research shows that stress intensity of jaggy triangle CFRP end is less than that of non-jaggy triangle.

ACKNOWLEDGEMENT
The study presented here was financially supported by Islamic Azad University, Zahedan Branch, Zahedn, Iran and Iranian Construction Engineering Organization, Sistan and Baluchestan Province, Zahedan, Iran. Authors would like to record their appreciation for the supports.

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