CFRP shear strengthening system for steel bridge girders

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\begin{abstract}
This paper presents an investigation undertaken to study the effectiveness of using small-diameter CFRP strands for shear strengthening of steel bridge girders. The study includes a comprehensive experimental program to study effects of the CFRP reinforcement ratio and orientation of the strands. An analytical model, calibrated by the experimental tests, was used to provide design recommendation. Results of the study showed that the proposed strengthening system is effective in increasing the shear capacity of steel bridge girders and there was no sign of CFRP debonding or rupture failure commonly observed by CFRP laminates up to approximately 80% of the steel yield stress.
\end{abstract}

1. Introduction

Use of FRP materials has gained wide acceptance worldwide for strengthening of concrete structures and bridges due to their interesting benefits [1,2,3]. There is also a growing demand for strengthening steel structures and bridges due to increasing of the load demand or reduction of the load-carrying capacity due to corrosion of steel [3]. Use of externally bonded FRP materials for strengthening steel structures did not progress as the use of FRP for strengthening concrete structures due to the lower elastic modulus of typical FRP material relative to steel [3]. However, the recent production of high-modulus Carbon FRP (CFRP) laminates with an elastic modulus similar to or higher than that of steel offers a promising alternative for externally bonded strengthening of steel structures [4,5].

CFRP is a composite material consisting of fibers commonly carbon, glass, basalt or aramid embedded in a resin matrix [6]. A critical issue in strengthening of structures using externally bonded FRP composite systems is failure due to debonding of the strengthening materials [7]. Due to the uncertainties and the sudden nature of the typical debonding failure experienced between the FRP composite and steel substrate, since the laminates are only bonded to the substrate from one side, numerous studies were conducted experimentally and analytically to investigate the bond behavior [8,9,10]. Flexural strengthening of steel beams is typically used as initial step to understand the bond mechanism between the CFRP and steel substrate. Many researches have also explored substantial enhancement in flexural capacity and stiffness of strengthened steel members using externally bonded high-modulus CFRP materials [3,11,12], and [13]. Also, effectiveness of using the recent innovative pre-stressed CFRP plates is proven for strengthening steel structures [14,15], and [16]. However, to increase the total load-carrying capacity of a strengthened steel member, it is often necessary to also increase the shear capacity along with the increased flexural capacity. Despite this, there is very little research published on shear strengthening of steel structures using externally bonded CFRP systems.

The typical failure mode of the steel web of steel bridge girders is buckling in the direction of the principal compressive stress of the applied shear. Thus, the shear capacity of a steel bridge girder can be increased by enhancing the buckling resistance of the web panel. To date, the published research on the FRP shear strengthening of steel bridge girders is very limited. Patnaik et al. [17] reported that the shear capacity of a steel I-beam could increase by up to 26% when the web is strengthened with high tensile unidirectional CFRP laminate. However, the failure mode was governed by debonding of the CFRP laminate from the beam web. Okeil et al. [18,19], and [20] conducted serval studies to investigate the shear strengthening using T-shaped pultruded GFRP sections used as a stiffener. The results of these tests showed that the GFRP could increase the shear capacity up to 56% and the observed failure mode was debonding of the T-shaped pultruded GFRP [3]. Narmashiri et al. [21] published a research report on the use of CFRP strips to strengthen the web of steel beams using different reinforce-ment ratio. The research results showed that the shear capacity of the steel I-beam increased by up to 51% and the failure mode governed by debonding of the CFRP strips.
This paper presents the research undertaken to study the effect in flexural and compressive strengthening of steel plates. Previous research using the same CFRP strands have already demonstrated excellent behavior and very effective for strengthening effect in flexural and compressive strengthening applications of steel members [12,22,3], and [23]. The CFRP strands are stitched together with a gap between each strand allowing the adhesive to completely encapsulate each strand resulting in a superior bond behavior [3].

This paper presents the research undertaken to study the efficiency of these small-diameter high-modulus CFRP strands to enhance the shear strength of steel bridge girders and the development of a proposed guideline for field application.

2. Experimental program

2.1. Material properties

2.1.1. Steel

Dog-bone steel coupon specimens, cut from built-up steel beam specimen, were prepared and tested in tension according to ASTM A370 [24] using a universal testing machine (UTM). Elongation of the coupons was measured by an extensometer and the applied load was measured directly by the UTM load cell. A total of four coupons were tested. The average of the measured tensile properties is summarized in Table 1.

Table 1.

<table>
<thead>
<tr>
<th>Nominal thickness (mm (in.))</th>
<th>Yield strength (MPa (ksi))</th>
<th>Modulus of elasticity (MPa (ksi))</th>
<th>Yield strain (mm/mm (in./in.))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (3/16)</td>
<td>380 (55)</td>
<td>186,000 (27,000)</td>
<td>0.00204</td>
</tr>
</tbody>
</table>

Table 2.

Measured tensile properties of small-diameter high-modulus CFRP strands [3].

<table>
<thead>
<tr>
<th>Strand area (mm² (in²))</th>
<th>Rupture strain (mm/mm (in./in.))</th>
<th>Rupture stress (MPa (ksi))</th>
<th>Elastic modulus (MPa (ksi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.14193 (0.00177)</td>
<td>0.0032</td>
<td>807 (117)</td>
<td>255,000 (37,000)</td>
</tr>
</tbody>
</table>

The strains at the mid-point of each tested panel was measured by electrical resistance strain gauge rosettes. Two strain gauges were attached to the un-strengthened control panel, with one strain gauge on each face [3]. Total of four strain gauges were attached at the mid-point of each strengthened panel; one strain gauge on each face of the substrate steel web, and one on each outer face of the CFRP composite. The out of plane deformation of each test panel was measured by an OptotrackCertus motion capturing system and linear string potentiometers. The OptotrackCertus motion capturing system uses InfraRed Emitting Diodes (IRED) to measure the deformation. A total of 23 IREDs were placed along the vertical and horizontal center line at one side of the test panel with a spacing of 75 mm (3 in.). Five linear string potentiometers were attached to the four mid-edges and mid-point of the test panel on the other face of IRED targets. The layout of the
instrumentation was used to measure the behavior of the test panels is shown in Fig. 5.

2.4. Strengthening system Application [3]

Application of the CFRP strands started by sandblasting the steel and cleaning the surface with acetone. The installation process started by covering the surface with primer resin which was applied and left to cure at least two hours. The strain gauge rosettes were attached to the center of each side of the test panel after the primer was applied and the panel was cleaned using pressurized air [3]. After the primer resin was fully cured, polyurea putty was applied and left to cure for at least six hours. The epoxy and CFRP strands were finally applied while the steel girder was in the vertical orientation to simulate field condition. After applying the epoxy layer, the CFRP strands were bonded to the test panel according to the prescribed orientation. The lead wires for the strain gauge rosette attached to the steel face of the panel were passed through the gap between the strands. The CFRP strands were firmly bonded to the surface.
pressed against the steel panel using hand rollers until the excess epoxy was squeezed out to remove any air pockets. A second layer of epoxy was applied on the top of the CFRP strands. Finally, the strengthened panel remained in a control environment for at least seven days to cure before testing. The application process is illustrated in Fig. 6 [3].

2.5. Test scheme

A total of 12 tests were carried on four steel web panels are summarized in Table 4. The factors included in this study were fiber orientation and CFRP reinforcement ratio. Each panel was tested three times. First, a control test without strengthening. Second, a strengthened test with one layer of CFRP material on each face. Third, a strengthened test after installation of the second layer of the CFRP on each face. The applied concentrated load point and supports were moved to create the test configuration for each test. To prevent steel yielding, loading was stopped when the maximum measured steel strain in the test steel panel reached 1600 με (micro-strain). The orientation of the HM CFRP strands used in each test panel is illustrated schematically in Fig. 7.

3. Test results

3.1. Shear buckling

Fig. 8 shows a flat plate simulating typical web of steel plate beam of large span bridge considering shear stresses distributed uniformly along the four edges. The stresses induce equivalent principal stresses in tension and compression as shown in Fig. 8. Orientation of the tension and compression are at 45 degrees with respect to the shear stresses. These type of loading conditions induces buckling in the form of waves or wrinkles inclined at about 45 degrees [22,30].

When a plate is initially imperfect and is not flat, it deflects before reaching the theoretical buckling load (Pb). Due to the plate imperfection the behavior shows a gradual increase of load with increasing in-plane or lateral deformation. The transition point between pre-buckling and post-buckling behavior vanishes as shown in Fig. 9 and experienced in plate tests. Moreover, at loads far beyond buckling load (Pb) the curve may approach the curve for flat plate as shown in Fig. 9 [22,31].

3.2. Measured principle strain

The total applied shear load and the measured principle strain at...
mid-point of the tested panel strengthened with CFRP strands are shown in Fig. 10 (a) through (d). The graphs shown for each test panel present the results of the panel before strengthening, the strengthened panel with one layer of CFRP strands on each face, and the panel strengthened with two layers of CFRP strands on each face [3]. The shear resisted by the strengthened panel for one and two layers is compared to the control test result before yielding of the steel. The results demonstrated the effectiveness of the externally bonded small-diameter CFRP strands in increasing the shear strength before yielding of the steel web. The measured shear strength can be measured by the increase of the load resistance at any selected value of strain in the figures. The CFRP strands reduced the principle compression strain in the web at the same magnitude of applied shear, which ultimately leads to increased shear capacity. Further, it can be seen in all Fig. 10 that regardless of the CFRP strand orientation, increasing the number of CFRP layers increases the shear capacity of the web.

The percent increase in shear strength for the different CFRP strand orientations considered relative to the control test for the same panel is shown in Fig. 11. The results show that one and two layers of the CFRP strands can increase the shear resistance by up to 46% and 91%, respectively. It is also confirmed that regardless to the reinforcement ratio, aligning the CFRP strands in the principal compressive stress direction improves the efficiency of the strengthening system by reducing out of plane deformation and delaying elastic/inelastic buckling. However, since CFRP strands are currently manufactured in standard sheets of 500 mm (20 in.) width [22], applying strands with an angle of 45° could be ineffective for web plate more than 0.7 × 0.7 m (28 × 28 in.) due to wastes of the material. Therefore, using vertical scheme for one layer and then attaching additional layers orthogonal to the bottom layer is recommended.

### Table 4

<table>
<thead>
<tr>
<th>Test name</th>
<th>Panel no.</th>
<th>No. of CFRP layers per face</th>
<th>Fiber orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-Control</td>
<td>I</td>
<td>0</td>
<td>– (Horizontal)</td>
</tr>
<tr>
<td>I-0-1HM</td>
<td>I</td>
<td>1</td>
<td>0 (Horizontal)</td>
</tr>
<tr>
<td>I-0-90-2HM</td>
<td>I</td>
<td>2</td>
<td>0-90 (Orthogonal Grid)</td>
</tr>
<tr>
<td>II-Control</td>
<td>II</td>
<td>0</td>
<td>– (Horizontal)</td>
</tr>
<tr>
<td>II-90-1HM</td>
<td>II</td>
<td>1</td>
<td>90 (Vertical)</td>
</tr>
<tr>
<td>II-90-2HM</td>
<td>II</td>
<td>2</td>
<td>90 (Vertical)</td>
</tr>
<tr>
<td>III-Control</td>
<td>III</td>
<td>0</td>
<td>– (Horizontal)</td>
</tr>
<tr>
<td>III-45-1HM</td>
<td>III</td>
<td>1</td>
<td>45 (Compressive Direction)</td>
</tr>
<tr>
<td>III-45-2HM</td>
<td>III</td>
<td>2</td>
<td>45 (Compressive Direction)</td>
</tr>
<tr>
<td>IV-Control</td>
<td>IV</td>
<td>0</td>
<td>– (Horizontal)</td>
</tr>
<tr>
<td>IV-45-1HM</td>
<td>IV</td>
<td>1</td>
<td>45 (Compressive Direction)</td>
</tr>
<tr>
<td>IV- ± 45-2HM</td>
<td>IV</td>
<td>2</td>
<td>± 45 (Orthogonal Grid)</td>
</tr>
</tbody>
</table>

Fig. 6. Strengthening system application, (a) Application primer resin on sandblasted steel panel, (b) Application of polyurea putty, (c) Application of CFRP composite [3].

mid-point of the tested panel strengthened with CFRP strands are shown in Fig. 10 (a) through (d). The graphs shown for each test panel present the results of the panel before strengthening, the strengthened panel with one layer of CFRP strands on each face, and the panel strengthened with two layers of CFRP strands on each face [3]. The shear resisted by the strengthened panel for one and two layers is compared to the control test result before yielding of the steel. The results demonstrated the effectiveness of the externally bonded small-diameter CFRP strands in increasing the shear strength before yielding of the steel web. The measured shear strength can be measured by the increase of the load resistance at any selected value of strain in the figures. The CFRP strands reduced the principle compression strain in the web at the same magnitude of applied shear, which ultimately leads to increased shear capacity. Further, it can be seen in all Fig. 10 that regardless of the CFRP strand orientation, increasing the number of CFRP layers increases the shear capacity of the web.

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#### 3.3. Load-Lateral deformation

The mid-point net lateral deformation at the of the web panels relative to the edge points under the applied shear is shown in Fig. 12 (a) through (d). These results reflect the effectiveness of the different orientation in increasing the overall stiffness of the steel web. The percentage increase of lateral stiffness for all four sets of tests are shown in Fig. 13. The behavior clearly indicates that increase of the lateral stiffness is related to increase of the reinforcement ratio for all CFRP strand orientations. Results also showed that regardless to the reinforcement ratio, CFRP strands oriented parallel to the compressive stress direction have the highest increase in lateral stiffness followed by CFRP strands oriented vertically. Discrepancy in the shear capacity increase and the lateral stiffness increase of the similar test configurations are due to the differences in the plate imperfection observed for the test plates [22].
3.4. Deformed shape

Typical measured net lateral deformed shape along the vertical and horizontal center lines for the tested panels strengthened in direction of the principal compressive stresses is shown in Fig. 14. The lateral deformed shapes are shown for the control, one layer and two layers of HM CFRP prior to steel yielding using the Optotrak system [3]. The results are similar for all the panels tested. The deformed shapes indicate that the lateral deformation decreased by increasing the reinforcement ratio of the CFRP strengthening system at the same load level. Furthermore, adding more layers of the CFRP strands induces less distortion of deformed shape. It should be noted that despite the lateral deformation, there was no sign of CFRP debonding or rupture up to approximately 80% of the steel yield stress.

4. Analytical model

Reported research related to the use of small-diameter CFRP strands to increase the compressive and shear strength of steel plates indicated that finite element models and simple hand calculations are capable to predict the behavior and increase of strength using this system [22]. Use of the transformed section method to calculate the shear strength of the panel strengthened by CFRP strands is presented in this section. The following well-known elastic relationship is used to calculate the shear stress in the panel.

\[ \tau = \frac{VQ}{I_{t}t_{t}} \]

where,

\[ I_{t} = I_{s} + \sum_{i=1}^{n} \frac{E_{s}t_{s}}{E_{i}}I_{i} \]

\[ t_{t} = t_{s} + \sum_{i=1}^{n} \frac{E_{s}t_{s}}{E_{i}}t_{i} \]

\( \tau \) is the shear stress for the strengthened specimen with one or two layers of CFRP strands, \( V \) is shear force, \( Q \) is first moment of area, \( E_{s} \) and \( E_{i} \) are elastic modulus of steel and the compressive elastic modulus of each CFRP layer, respectively. \( I_{s} \), \( I_{i} \), and \( t_{s} \) are moment of inertia of the transformed cross-section, moment of inertia of steel, and thickness of each CFRP layer. CFRP compressive elastic modulus of the witness panels was used in calculations. Also, Tresca criteria was used to calculate shear stress from steel normal stress and later calculate the theoretical shear strength [32]. It is worth noting that the proposed analytical approach is not considering the effects of the CFRP strands orientation and plate imperfections. This approach is proposed to conservatively use simple equation for design purposes without considering complexities of the composite system. The predicted shear resistance is compared to the measured values for all tested specimen, including the control and strengthened plates, as shown in Fig. 15 [3]. Each point higher than dashed line clearly indicate that design value is lower that experimental value supporting conservative design. The comparison indicates that for the design purposes, the shear load can be sufficiently estimated using composite transformed section properties of the strengthened panel [3].
5. Conclusions

This paper examined the effectiveness of small-diameter CFRP material for shear strengthening of steel bridge girder. Based on the test results, it can be concluded that the HM CFRP is effective in increasing the shear capacity of steel girders with no de-bonding failure [3]. Detailed conclusions can be summarized as follows,

Fig. 9. Typical behavior of steel plate under pure shear with and without imperfection [22,31].

Fig. 10. Applied shear vs. principle steel strain for web panels strengthened with HM CFRP at an angle of (a) 0–90°, (b) 90°, (c) 45°, and (d) ±45°.
(1) The HM small-diameter CFRP strand is an effective material for increasing the shear capacity of steel bridge girders.

(2) The strengthening system offers excellent bonding behavior. No debonding failure was observed up to approximately 80% of the steel yielding.

(3) The effectiveness of the strengthening system increased by increasing the CFRP reinforcement ratio.

(4) Use of the proposed strengthening system increases the initial lateral stiffness of the strengthened plate.

(5) Applying the CFRP strands in direction of principle compressive stresses gives the most effective strengthening orientation. However, to avoid waste of material and labor cost, it is recommended to apply first layer of CFRP material in vertical direction and then attach additional layers orthogonal to the bottom layer.

(6) The simple analytical method is accurate enough to estimate the shear capacity of the test results of the composite cross section.
Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.engstruct.2018.08.038.

References


