SHEAR STRENGTHENING USING FRP SHEETS FOR
A HIGHWAY BRIDGE IN MANITOBA, CANADA

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ABSTRACT: The use of heavier trucks demanded upgrading of a twenty-seven year old bridge in Winnipeg, Manitoba, Canada. Analysis of the precast prestressed concrete girders using the current AASHTO Code indicates a deficiency in the shear capacity. Shear strengthening using Carbon Fibre Reinforced Polymer (CFRP) sheets provides a low-cost solution by increasing the speed of construction and reducing traffic interruption when compared with conventional methods. Due to a lack of information on the use of CFRP sheets for shear strengthening of I-shaped concrete AASHTO girders, an experimental program has been undertaken at the University of Manitoba. Four ten meter long scale model prestressed concrete girders have been tested to failure at both ends, using six configurations for three types of CFRP. The contribution of the CFRP sheets to the enhanced shear capacity of the girder has been evaluated. This paper presents preliminary conclusions and recommendations for the use of this strengthening technique on this particular girder shape.

KEYWORDS: AASHTO, CFRP, concrete, girder, prestressed, shear, strengthening

1. INTRODUCTION

The city of Winnipeg, Manitoba, Canada, is considering an upgrading of the Maryland bridge in response to the demand for using increasingly heavier truck loads. The twin five-span continuous prestressed concrete structures were designed in 1969 according to the American Association of State Highway and Transportation Officials (AASHTO) Code. Rehabilitation analysis using the current AASHTO Code indicates that while the flexural strength of the I-shaped girders is adequate, the shear strength of the girders is not sufficient to withstand the increased truck load. Carbon Fibre Reinforced Polymer (CFRP) sheets provide an excellent solution for shear strengthening since they are light-weight, corrosion-free, and have a high tensile strength. When compared with conventional methods, this technique provides a low-cost solution due to significant reduction of construction time without traffic interruption.

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Due to a lack of information on the use of CFRP sheets for shear strengthening of I-shaped concrete AASHTO girders, an experimental program has been undertaken at the University of Manitoba, Canada, to test scale models of the Maryland bridge girders strengthened with CFRP sheets. Four prestressed concrete beams are tested to failure at each end to determine the most efficient strengthening scheme. This paper summarizes preliminary test results and recommendations for the use of this strengthening technique on this particular girder shape.

2. EXPERIMENTAL PROGRAM

Four prestressed concrete girders were tested at the University of Manitoba, Canada. The ten meter long beams are 1:3.5 scale models of the I-shaped Maryland bridge girders. All of the beams had a depth of 415 mm with a top slab of 480 mm wide and 60 mm deep as shown in Fig.1 and Fig. 2. The slabs were cast a minimum of seven days after the casting of each beam. The beams were pretensioned with three 13 mm straight steel 7-wire strands and one draped strand. Two non-prestressed 13 mm steel 7-wire strands were provided to increase the flexural capacity of the beams to avoid premature failure due to flexure. The stirrup spacing and configuration were the same in all of the test beams. The beams were designed to carry the same shear stress at ultimate as the Maryland bridge girders within the maximum stirrup spacing requirements. The stirrup shape, shown in Fig.2, was identical to those used in the bridge girders with the overall dimensions and bar diameter scaled down accordingly.

One of the beams was tested as a control beam while the remaining three beams were strengthened with three different types of CFRP and six configuration schemes. The beams were tested at each end to determine the most efficient strengthening scheme. Due to the configuration of the stirrups, which are identical to the bridge, an outward force was observed by spalling of the concrete cover of the control beam. This force is the resultant of the tension forces in the vertical and diagonal legs of the stirrups. To control this outward force, the second end of the control beam was strengthened by a clamping scheme as shown in Fig.3.

![Fig. 1 Test Beam Fabrication](image1)

![Fig. 2 Test Beam Dimensions](image2)

![Fig. 3 Clamping Scheme](image3)
2.1 MATERIAL PROPERTIES

The test beams were fabricated by Lafarge Canada Inc., Winnipeg, Manitoba, Canada. The compressive strengths of the concrete at the time of testing of the beams ranged from 44 to 53 MPa. Seven wire steel strand with a diameter of 13 mm was used for both the prestressed and non-prestressed flexural reinforcement. The ultimate tensile strength of the steel strand is 1860 MPa. The stirrups consisted of undeformed 5.5 mm diameter bars which were tested at the University of Manitoba and found to have an average yield strain of 0.0028, an average yield stress of 640 MPa and an average modulus of elasticity of 225 GPa. Three different types of CFRP sheets were used in this experimental program. The material properties of the three types of sheets are given in Table 1.

Table 1 Material Properties of CFRP Sheets

<table>
<thead>
<tr>
<th>Property:</th>
<th>Beam MB2: (Type A)*</th>
<th>Beam MB3: (Type B)*</th>
<th>Beam MB4: (Type C)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Thickness (mm):</td>
<td>0.11</td>
<td>0.11</td>
<td>0.79</td>
</tr>
<tr>
<td>Fiber Areal Weight (g/m²):</td>
<td>200</td>
<td>200</td>
<td>660</td>
</tr>
<tr>
<td>Tensile Strength (MPa):</td>
<td>3350</td>
<td>3400</td>
<td>760</td>
</tr>
<tr>
<td>Tensile Strength (N/mm width):</td>
<td>390</td>
<td>375</td>
<td>600</td>
</tr>
<tr>
<td>Tensile Modulus (GPa):</td>
<td>235</td>
<td>230</td>
<td>76</td>
</tr>
<tr>
<td>Strain at Rupture:</td>
<td>0.0151</td>
<td>0.0148</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*All properties reported for dry fiber sheets

2.2 TEST SET-UP

Testing was conducted at the Structural Engineering and Construction R&D Facility, University of Manitoba. The simply supported beams were subjected to two equivalent non-symmetric point loads. The shear span of 1940 mm was kept constant for all of the tests while the overall span was varied in order to test both ends of each beam. The monotonic static load was applied using a MTS 5000 kN testing machine under stroke control.

Electrical strain gauges with a gauge length of 5 mm were used to monitor the strain in the stirrups and the distribution of the strain in the CFRP sheets. Demec stations were used to measure flexural strains at the top and bottom of the beam within the shear span. In regions of high shear stress, U-shaped PI gauges were used to form rosettes for strain measurement in three directions on the web at the location of the stirrups. Linear Variable Deflection Transducers (LVDT) were used to measure deflection. The strain in the prestressed and non-prestressed strands was also monitored using electrical strain gauges.
The second test beam was strengthened using one layer of 250 mm wide vertical CFRP sheets with a 100 mm gap between each sheet to allow drainage of any moisture accumulation. The vertical CFRP sheets were applied on each side of the cross-section from the top of the beam immediately below the slab to the underside of the beam where they were overlapped for a minimum length of 100 mm. The other end of the beam was strengthened with a single layer sheet of 220 mm wide CFRP with the continuous carbon fibres in the horizontal direction on the top of the vertical sheets. Type A CFRP sheets were used for the second beam. The surface was prepared prior to application of the sheets using a grinder, wire brush and high pressure air for cleaning the surface after grinding.

One end of the third test beam was strengthened by one layer of 250 mm wide CFRP sheets with the fibres oriented diagonally at 45 degrees. The sheets were applied on each side of the beam and overlapped on the underside of the beam. A 20 mm gap was provided between each diagonal sheet. The second end of the third beam was strengthened using one layer of 250 mm wide vertical CFRP sheets similar to the second beam, but with a gap of 20 mm between sheets. Type B CFRP sheets were used for the third beam. The surface of the beam was prepared using a high pressure water blasting technique, however, some grinding was required to round any sharp corners on the beam.

The fourth test beam was strengthened using one layer of 250 mm wide CFRP sheets with the fibres oriented diagonally at 45 degrees. As with the previous beams, the sheets were applied on each side and overlapped on the underside of the beam. A 100 mm gap was provided between each diagonal sheet similar to the second test beam. The other end of the beam was strengthened with a single layer sheet of 220 mm wide CFRP with the continuous carbon fibres in the horizontal direction on the top of the diagonal sheets. The fourth beam was strengthened using Type C CFRP sheets. Similar to the third test beam, the surface of the beam was prepared using a high pressure water blasting technique and grinding to round any sharp corners on the beam.

The CFRP sheets were applied to the beams using well defined procedures recommended by each manufacturer and proprietary products supplied by each manufacturer. Following the surface preparation for each beam, an epoxy primer was applied to the surface of the beam to seal the concrete. After setting of the primer, any significant surface irregularities were filled using an epoxy putty on the second and third beams and an epoxy resin with additional filler material on the fourth beam. Additional grinding was required after setting of the putty to achieve a smooth surface on the second and third beams. For the second and third beams, the epoxy resin was applied to the surface of the beam followed by the CFRP sheets. After the first layer of epoxy resin had impregnated the carbon fibres, which could be noticed by penetration of the epoxy through the first sheet in some areas, a second layer of epoxy resin was applied as a top coat. In the case of multiple layers of sheets, the top coat of epoxy resin served as a base coat for the next layer of CFRP sheets. For the fourth beam, the CFRP sheets were impregnated with epoxy resin in a separate resin bath prior to application on the beam and subsequent layers were applied using the same technique.
3. TEST RESULTS AND DISCUSSION

The first end of the control beam was tested to failure without strengthening and the second end was tested using a clamping scheme to control the outward force in the stirrups. The remaining beams were tested at each end using different CFRP strengthening schemes. A summary of specimen parameters and a comparison of the test results are given in Table 2.

<table>
<thead>
<tr>
<th>Beam Mark</th>
<th>Specimen Description</th>
<th>Surface Preparation</th>
<th>$f'_c$ (MPa)</th>
<th>$V_c$ (kN)</th>
<th>$V_u$ (kN)</th>
<th>$(V_u)/(V_{u,control})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB1-1</td>
<td>Control Beam</td>
<td>n.a.</td>
<td>46</td>
<td>66</td>
<td>137</td>
<td>1.00</td>
</tr>
<tr>
<td>MB1-2</td>
<td>Clamping of Stirrups</td>
<td>n.a.</td>
<td>46</td>
<td>66</td>
<td>174</td>
<td>1.27</td>
</tr>
<tr>
<td>MB2-1</td>
<td>Horizontal &amp; Vertical FRP</td>
<td>grinding</td>
<td>53</td>
<td>74</td>
<td>185</td>
<td>1.34</td>
</tr>
<tr>
<td>MB2-2</td>
<td>Vertical FRP - 100 mm Gap</td>
<td>grinding</td>
<td>53</td>
<td>74</td>
<td>151</td>
<td>1.10</td>
</tr>
<tr>
<td>MB3-1</td>
<td>Diagonal FRP - 20 mm Gap</td>
<td>water-blast</td>
<td>44</td>
<td>76</td>
<td>173</td>
<td>1.26</td>
</tr>
<tr>
<td>MB3-2</td>
<td>Vertical FRP - 20 mm Gap</td>
<td>water-blast</td>
<td>44</td>
<td>76</td>
<td>161</td>
<td>1.17</td>
</tr>
<tr>
<td>MB4-1</td>
<td>Horizontal &amp; Diagonal FRP</td>
<td>water-blast</td>
<td>55</td>
<td>72</td>
<td>186</td>
<td>1.36</td>
</tr>
<tr>
<td>MB4-2</td>
<td>Diagonal FRP -100 mm Gap</td>
<td>water-blast</td>
<td>55</td>
<td>72</td>
<td>177</td>
<td>1.29</td>
</tr>
</tbody>
</table>

Table 2 provides a comparison of the ultimate shear failure load, $V_u$, and the initial shear cracking load, $V_c$, for all tests. The shear cracking load could be typically determined by the load corresponding to the initiation of the first inclined cracks. Since the presence of CFRP sheets made the observation of cracks difficult, $V_c$ was determined from the measured strain of the stirrups and the concrete using strain gauges and rosette PI gauges, respectively.

As can be seen in Table 2, the presence of both horizontal and vertical CFRP sheets improved the ultimate shear capacity, $V_u$, of the beam by 34 %, while both horizontal and diagonal sheets increased the shear capacity by 36 %. The ultimate shear capacity was also enhanced with the application of one layer of vertical sheets alone. A 10 % increase was observed for the beam with widely spaced vertical sheets, while an increase of 17 % was observed for the beam with closely spaced vertical sheets. The application of a single layer of diagonal CFRP sheets increased the ultimate shear capacity 26 % for beam MB3-1 with closely spaced diagonal sheets and 29 % for beam MB4-2 with widely spaced diagonal sheets. This behaviour can be attributed to the use of a thicker type of CFRP sheet for beam MB4-2 as shown in Table 1. The clamping scheme that was applied to the web of beam MB1-2 was effective in controlling the outward force in the stirrups and increased the ultimate shear capacity by 27 %.

3.1 CRACK PATTERNS AND FAILURE MODES

In all tests, flexural cracking began at the location of the applied concentrated loads. Flexural shear cracks were then observed within the shear span during all eight tests. At ultimate, the flexural shear cracks extended towards the top flange of the beams.
Fig. 4 shows the control beam at failure. Prior to failure, spalling of the concrete was observed at the lower part of the web due to the outward tensile force resultant causing straightening of the bent corner of the stirrups. Fig. 5 illustrates the straightening behaviour of the stirrups.

![Fig. 4 Control Beam MB1-1 at Failure](image1)

![Fig. 5 Stirrup Straightening in Beam MB1-1](image2)

Debonding of the CFRP sheets was observed on beams MB2-2 and MB3-2 with vertical sheets only. After zones of debonding were observed above and below the diagonal cracks, the beam continued to carry increasing shear load. Similar to the control beam, spalling was observed on the lower part of the thin web just prior to failure. However, in both beams, the spalling was observed at a higher load level due to the presence of the vertical CFRP sheets and the load sharing between the stirrups and the CFRP. In both beams, failure was initiated by increased debonding of the CFRP sheets and straightening of the stirrups. Debonding of the CFRP sheets was less extensive just prior to failure of beam MB3-2 when compared with beam MB2-2 with more widely spaced sheets and a different method of surface preparation.

For beams MB3-1 and MB4-2 with diagonal sheets only, debonding of the CFRP sheets was observed at the lower part of the thin web. Fig. 6 illustrates the location of debonding just prior to failure of beam MB4-2. In both beams at ultimate, the CFRP sheets debonded and straightened near the lower part of the web, but remained bonded near the top of the beam. After completion of the test, the CFRP sheets were removed to examine the condition of the stirrups. The stirrups did not straighten significantly due to the efficiency of the diagonal CFRP contribution and the resulting reduced stress in the stirrups at ultimate.

Beam MB2-1 with both horizontal and vertical CFRP sheets, demonstrated spalling on the lower part of the thin web due to the outward force in the stirrups at this location. Spalling was observed at a higher load level than the control beam or the beams with vertical sheets only due to the presence of both horizontal and vertical sheets. Failure was initiated by the straightening of the stirrups and resulted in rupture and some debonding of the CFRP sheets very close to the top of the beam as shown in Fig. 7. There did not appear to be any significant bond problem between the CFRP and the concrete.
For beam MB4-1 with both horizontal and diagonal sheets, debonding of the CFRP sheets was observed at the lower part of the thin web similar to the beams with diagonal sheets only. However, debonding was less extensive just prior to failure when compared with the beams with diagonal sheets only. Similar to the beam with horizontal and vertical sheets, rupture and some debonding of the CFRP sheets was observed very close to the top of the beam.

3.2 LOAD SHARING BETWEEN CFRP SHEETS AND STEEL STIRRUPS

Load sharing between the sheets and the stirrups is evident when comparing the stirrup strain versus applied shear for the four beams shown in Fig.8. The stirrup strain at any level of applied shear after cracking is significantly higher in the control beam stirrup when compared with those beams strengthened with CFRP sheets. In addition, a comparison of stirrup strains in the beams with diagonal sheets and the beam with horizontal & vertical sheets illustrates the efficiency of the diagonal CFRP sheets. Although the beam with horizontal and vertical sheets reached a higher ultimate shear load, the strain in the stirrup was greater at load levels below ultimate when compared with the beams with diagonal sheets. Fig.8 also illustrates the effect of using a thicker CFRP sheet. The beam with thicker diagonal sheets and a larger gap demonstrated a lower strain in the stirrups and therefore a greater contribution from the CFRP sheets at the same level of applied shear load.
4. CONCLUSIONS

Four 10 m long pretensioned beams were fabricated and tested to determine the most efficient configuration and type of CFRP sheets that can be used to strengthen existing AASHTO girders for shear. The beams are scale models of the Maryland bridge girders which require shear capacity upgrading in order to carry increasing truck loads. Preliminary results have been presented and suggest that shear strengthening using CFRP sheets is an efficient solution for the Maryland bridge. The following conclusions and recommendations are based on preliminary analysis of test results available at the time of submission of this paper:

1. Due to the shape of the stirrups used in the original bridge girders, an outward force is created under increasing tensile force in the stirrups causing spalling off of the concrete cover followed by straightening of the stirrups and sudden failure. CFRP sheets are effective in reducing the tensile force in the stirrups under the same applied shear load.

2. With the application of one layer of widely spaced vertical CFRP sheets, the ultimate shear capacity of the beam, \( V_u \), was increased by 10% when compared with \( V_u \) of the control beam reinforced with stirrups only. Reducing the gap between vertical sheets from 100 mm to 20 mm provided a 17% increase in the ultimate shear capacity.

3. The application of one layer of diagonal CFRP sheets increased the ultimate shear capacity of the beams by 29% and 26% for the beams with widely spaced and closely spaced diagonal sheets, respectively. The higher ultimate shear capacity in the beam with widely spaced sheets is attributed to the increased thickness of the CFRP sheets.

4. The application of both horizontal and vertical CFRP sheets improved the ultimate shear capacity of the beam, \( V_u \), by 34%. Applying a horizontal layer over one layer of diagonal sheets provided a 36% increase in the ultimate shear capacity of the beam.

5. Diagonal CFRP sheets are more efficient than the horizontal and vertical CFRP sheet combination in reducing the tensile force in the stirrups at the same level of applied shear load. Diagonal CFRP sheets are an efficient shear strengthening scheme with the same ease of application as the vertical CFRP sheets and less material with fewer layers than the horizontal and vertical sheet combination.

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