Shear Strengthening of Prestressed Concrete Bridge Girders Using Bonded CFRP Sheets

R. Hutchinson*, D. Donald*, A. Abdelrahman*, S. Rizkalla*

* ISIS Canada, University of Manitoba, Winnipeg, Manitoba, Canada R3T 5V6

Abstract

The use of heavier trucks demands upgrading of a twenty-nine year old prestressed concrete bridge in Manitoba, Canada. The use of Carbon Fibre Reinforced Polymer (CFRP) sheets for shear strengthening could provide a low-cost solution due to a reduction of construction time and traffic interruption.

An experimental program has been undertaken to investigate the use of bonded CFRP sheets for the shear strengthening of I-shaped concrete AASHTO girders. Seven 1:3.5 scale model precast prestressed concrete girders are tested to failure at both ends to determine the most efficient shear strengthening scheme. The bond properties of the CFRP systems are evaluated using eighteen specially designed concrete specimens strengthened with CFRP. Test results suggests that shear strengthening using CFRP sheets is an efficient rehabilitation solution for the bridge. This paper presents test results and design recommendations for the use of this technique on this particular girder shape.

1. Introduction

The city of Winnipeg, Manitoba, Canada, is considering upgrading a twenty-nine year old bridge in response to the demand for using 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. Analysis using the current AASHTO Code indicates that the shear strength of the girders is not sufficient to withstand the new 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.

An experimental program has been undertaken at the University of Manitoba, Canada, to test scale models of the I-shaped bridge girders strengthened with CFRP sheets. Seven prestressed concrete beams were tested to failure at each end to determine the most
efficient strengthening scheme. The contribution of the CFRP sheets to the enhanced shear capacity of the girder has been examined with emphasis on the effect of this particular girder shape. Since the bond between the sheets and the concrete is a critical component of this strengthening method, a series of bond specimens have been tested in order to determine the bond characteristics. This paper summarizes test results available to date and recommendations for the use of this strengthening technique on the I-shaped girders.

2. Experimental Program

Seven 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 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 Figure 1. The compressive strength of the concrete at the time of testing ranged from 44 to 55 MPa. The beams were pretensioned with 7-wire steel strands with a diameter of 13 mm and an ultimate tensile strength of 1860 MPa. To increase the flexural capacity and avoid premature failure due to flexure, non-prestressed strands were also provided.

The beams were designed to carry the same shear stress at ultimate as the girders of the bridge. The stirrup shape used for the first series of four beams is shown in Figure 1 and is identical to those used in the bridge girders. An alternate straight-legged stirrup shape, shown in Figure 2, was used for the second series of beams. The spacing of the stirrups was identical in all of the test beams.

![Figure 1. Test Beam Dimensions](image1)

![Figure 2. Alternate Straight-legged Stirrups](image2)

One beam from each series, Series I with bent stirrup legs and Series II with straight-legged stirrups, were tested as control beams. The remaining beams were strengthened using the three different types of CFRP sheets indicated in Table 1. The beams were tested to failure at each end to determine the most efficient strengthening scheme.
Table 1. Properties of the CFRP Sheets

<table>
<thead>
<tr>
<th>Property</th>
<th>Type A*</th>
<th>Type B*</th>
<th>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>Fibre 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
+ All properties reported for composite fiber and resin sheets

During testing of the first end of the control beam with bent stirrup legs, premature failure occurred due to the shape of the stirrups. An outward force was observed by spalling of the concrete cover as shown in Figure 3. This force is the resultant of the tensile forces in the vertical and diagonal legs of the stirrups and causes the stirrup to straighten. To control this outward force, the second end of the control beam in Series I was strengthened by a clamping scheme as shown in Figure 4.

![Spalling of Concrete Cover](image1)

![Straightening of Stirrups](image2)

![Outward Force Resultant](image3)

![Steel Sections](image4)

![Bolted Through Web](image5)

Figure 3. Premature Stirrup Failure

Figure 4. Web Clamping Scheme

Prior to application of the CFRP sheets, the concrete surface of one beam was prepared using a grinder, wire brush and high pressure air for cleaning the surface after grinding. The surfaces of the remaining beams were prepared using a high pressure water-blasting technique. Any sharp corners on the beams were rounded using a grinder.

The CFRP sheets were applied to the beams using well defined procedures and proprietary products supplied by each manufacturer. An epoxy primer was first 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 or an epoxy resin with additional filler material. For the majority of the beams, the epoxy resin was applied to the surface of the beam followed by the CFRP sheets and a second layer of epoxy resin was applied as a top coat. In the case of multiple layers of sheets, the top coat served as a base coat for the next
layer of CFRP sheets. For one beam, the Type C 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.

The test beams were strengthened using one layer of 250 mm wide CFRP sheets with the fibres oriented either vertically or diagonally at 45°. A gap of either 20 or 100 mm was provided between each sheet to allow drainage of any moisture accumulation. The vertical or diagonal 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. For some beams, a 220 mm wide horizontal CFRP sheet was applied on the top of the vertical or diagonal sheets. The effect of using two layers of diagonal sheets was also examined.

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 beams were tested using monotonic load and stroke control.

**Bond Specimens**

The bond specimens consisted of 100 x 275 x 900 mm reinforced concrete prisms strengthened on opposite faces with 200 mm wide CFRP sheets and subjected to uniaxial tension as shown in Figure 5. Due to the arrangement of the internal reinforcing, cracking of the concrete was initiated at mid-height of the specimen as shown in Figure 6. For some specimens, steel reinforcement crossing the crack was used to simulate the effect of stirrups in order to evaluate load sharing between the CFRP sheets and the stirrups. In all specimens, the sheets were applied with the continuous longitudinal fibres parallel to the applied load while the orientation of the crack and the steel reinforcement crossing the crack was varied as shown in Figure 6. The effect of multiple layers of CFRP sheets on the bond characteristics was also examined.

![Figure 5. Bond Test Set-up](image-url)
Figure 6. Section Through Typical Bond Specimens

The CFRP sheets were applied to the bond specimens using the same procedures and two surface preparation techniques as described previously for the test beams. The CFRP sheets, steel reinforcing crossing the crack, and the concrete used for the bond specimens were all selected to have similar properties as the materials used for the test beams.

The bond specimens were tested under monotonic loading and stroke control. Instrumentation was applied on both sides of the specimens to measure the ultimate strain in the CFRP sheets at failure, the length of sheet over which stress is effectively transferred to the concrete, and the distribution of axial strain both along the length and across the width of the sheets.

3. Test Results and Discussion: Beam Series I

The first series of four beams have been tested to failure at each end for a total of eight tests. The beams in this series were reinforced using stirrups with a shape that is identical to those used in the existing bridge. The strengthening schemes used for these beams and the experimental parameters examined in each test are described in Table 2. Also provided in Table 2, is a comparison of the ultimate shear failure load, $V_u$, and the initial shear cracking load, $V_c$. Typically, $V_c$ is determined by the load corresponding to the initiation of the first diagonal cracks. However, since the presence of CFRP sheets made the observation of cracks difficult, $V_c$ was determined as the load corresponding to first measurements of strain in the stirrups.
Table 2. Comparison of Specimen Parameters and Test Results: Beam Series I

<table>
<thead>
<tr>
<th>Strengthening Scheme</th>
<th>Gap Size (mm)</th>
<th>CFRP Thickness (mm)</th>
<th>Surface Preparation</th>
<th>$f_c'$ (MPa)</th>
<th>$V_c$ (kN)</th>
<th>$V_u$ (kN)</th>
<th>$(V_u)<em>{test}$ $(V_u)</em>{control}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (none)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>46</td>
<td>66</td>
<td>137</td>
<td>1.00</td>
</tr>
<tr>
<td>Clamped Stirrups</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>46</td>
<td>66</td>
<td>174</td>
<td>1.27</td>
</tr>
<tr>
<td>Vertical CFRP</td>
<td>100</td>
<td>0.11 A</td>
<td>grinding</td>
<td>53</td>
<td>74</td>
<td>151</td>
<td>1.10</td>
</tr>
<tr>
<td>Vertical CFRP</td>
<td>20</td>
<td>0.11 B</td>
<td>hydro-blast</td>
<td>44</td>
<td>76</td>
<td>161</td>
<td>1.17</td>
</tr>
<tr>
<td>Diagonal CFRP</td>
<td>100</td>
<td>0.79 C</td>
<td>hydro-blast</td>
<td>55</td>
<td>72</td>
<td>177</td>
<td>1.29</td>
</tr>
<tr>
<td>Diagonal CFRP</td>
<td>20</td>
<td>0.11 B</td>
<td>hydro-blast</td>
<td>44</td>
<td>76</td>
<td>173</td>
<td>1.26</td>
</tr>
<tr>
<td>Horiz. &amp; Vert. CFRP</td>
<td>100</td>
<td>0.11 A</td>
<td>grinding</td>
<td>53</td>
<td>74</td>
<td>185</td>
<td>1.34</td>
</tr>
<tr>
<td>Horiz. &amp; Diag. CFRP</td>
<td>100</td>
<td>0.79 C</td>
<td>hydro-blast</td>
<td>55</td>
<td>72</td>
<td>186</td>
<td>1.36</td>
</tr>
</tbody>
</table>

In all tests, flexural shear cracks were observed within the shear span and extended toward the top flange at ultimate. Figure 7 shows the control beam at failure. Just prior to failure, spalling of the concrete cover was observed due to the outward tensile force resultant causing straightening of the bent corner of the stirrups.

Due to the shape of the stirrups, only one of the stirrups in the control beam reached yield before failure occurred due to spalling of the concrete cover and straightening of the adjacent stirrups.

Figure 7. Series I Control Beam at Failure

The clamping scheme applied to the second end of the control beam was effective in preventing failure due to straightening of the stirrups. All of the measured stirrup strains were significantly higher than those observed for the control beam. The distribution of forces between the clamped stirrups was improved, contributing to a 27% increase in the ultimate shear capacity, $V_u$, when compared to the control beam.

For the beams strengthened with vertical sheets, two different types of CFRP sheets with similar thicknesses and material properties were used. Two different surface preparation techniques and two gap sizes were used, as shown in Table 2. The ultimate shear capacity, $V_u$, of the beam with the smaller gap size increased by 17%, while only a 10% increase was observed for the beam with the larger gap size. In both beams, failure was initiated by straightening of the stirrups and debonding of the CFRP sheets above and below the
diagonal cracks. Debonding of the CFRP sheets was less extensive on the beam prepared using hydro-blasting when compared with the beam using the grinding technique.

The thickness and material properties of the two types of CFRP sheets used for the diagonal configurations vary significantly as shown in Tables 1 and 2. The gap size was also varied for these two tests while the surface preparation technique was not. For both beams, similar 26% and 29% increases in ultimate shear capacity, $V_u$, were achieved. Due to the shape of the girder, debonding and straightening of the CFRP sheets was observed on both beams at the lower part of the thin web. After the test, the CFRP sheets were removed to examine the stirrups. Due to the efficiency of the diagonal CFRP contribution and the resulting reduced stress in the stirrups at ultimate, the stirrups did not straighten significantly.

The efficiency of the diagonal CFRP sheets is illustrated in Figure 8. The stirrup strain at any level of applied shear is lower for the beams with diagonal sheets. Although the beam with horizontal and vertical sheets reached a higher ultimate shear load, the stirrup strain was greater. Figure 8 also shows that in spite of the larger gap size, the beam with thicker sheets exhibited lower stirrup strains and therefore a greater contribution from the CFRP sheets at the same level of applied shear load.

Both beams with a horizontal CFRP sheet applied on top of the vertical or diagonal sheets, achieved similar 34% and 36% increases in ultimate shear capacity, $V_u$. Figure 9 shows the beam with horizontal and vertical sheets at failure. Similar to the beams with vertical CFRP sheets only, the beam with both horizontal and vertical sheets, demonstrated spalling on the lower part of the thin web due to the outward force in the stirrups at this location. Due to the
presence of both horizontal and vertical sheets, however, spalling was observed at a higher load level than in the control beam or the beam with vertical sheets only. For the beam with both horizontal and diagonal sheets, debonding and straightening of the diagonal sheets was observed at the lower part of the thin web similar to the beams with diagonal sheets only, however, the observed debonding was less extensive.

**Conclusions**

Seven ten meter long prestressed concrete beams and eighteen smaller bond specimens were tested to determine the most efficient shear strengthening scheme using CFRP sheets for I-shaped girders. The beams are scale models of existing bridge girders which require shear capacity upgrading in order to carry increased truck loads. Test results available as of January 1998 suggest that shear strengthening using CFRP sheets is an efficient solution for the bridge. The following conclusions are based on this preliminary analysis of test results available at the time of submission of this paper:

1. CFRP sheets are effective in reducing the tensile force in the stirrups under the same applied shear load, delaying or preventing a premature failure due to straightening of the bent stirrup legs. The clamping scheme was also effective in preventing straightening of the stirrups and premature failure.

2. The reduced gap size for beams with vertical CFRP sheets increased the improvement in ultimate shear capacity from 10% to 17%. The use of hydro-blasting for surface preparation reduced the extent of debonding of the sheets.

3. Diagonal CFRP sheets are the most efficient configuration in reducing the tensile force in the stirrups at the same level of applied shear load. The ultimate shear capacity was increased by 26% to 29% with the application of diagonal sheets. Due to the shape of the girder, debonding and straightening of the CFRP sheets was observed on the lower part of the web in beams with diagonal sheets.

4. The application of a single layer of horizontal CFRP sheets on top of the vertical or diagonal sheets was shown to increase the ultimate shear capacity by 34% to 36%.

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