SHEAR STRENGTHENING USING CFRP SHEETS
FOR A PRESTRESSED CONCRETE HIGHWAY BRIDGE
IN MANITOBA, CANADA

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SUMMARY

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 as well as the effect of the various parameters studied on the shear behaviour of the girder. This paper presents preliminary conclusions and recommendations for the use of this strengthening technique on this particular girder shape.

1. INTRODUCTION

The city of Winnipeg, Manitoba, Canada, is considering an upgrading of the Maryland bridge in response to the demand for 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 while the flexural strength of the I-shaped girders is adequate, the shear strength of the girders is not sufficient to withstand the increased 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. Compared with conventional methods, this technique provides a low-cost solution and reduces construction time without traffic interruption.

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 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. The stirrup shape, shown in Fig.2, was identical to those used in the bridge girders with the dimensions scaled down accordingly.

One of the beams was tested as a control beam while the remaining three beams were strengthened with CFRP sheets and tested at each end to determine the most efficient shear 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.
Prior to application of the CFRP sheets, the concrete surface of the remaining three beams was prepared using two different techniques, grinding and high pressure water blasting. The three beams were then strengthened at each end using one layer of 250 mm wide CFRP sheets with the fibres oriented either vertically or diagonally at 45 degrees. The 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 a minimum of 100 mm. A gap was provided between each vertical or diagonal sheet to allow drainage of any moisture accumulation. To study the effect of the gap size, 20 mm and 100 mm gaps were used. On one end of two beams, a single layer sheet of 220 mm wide CFRP with the continuous carbon fibres in the horizontal direction was applied on top of the vertical or diagonal sheets. The CFRP sheets were applied to the beams using well defined procedures recommended by each manufacturer and proprietary products supplied by each manufacturer [1].

2.1 Material Properties

Three different types of CFRP sheets were used in this experimental program, the Tow Sheet FTS-C1-20 manufactured by the Tonen Corp. of Japan, the Replark™ Type 20 sheet manufactured by the Mitsubishi Chemical Corp. of Japan, and the Tyfo™ S Fibrewrap™ sheets manufactured by the Hexcel Fyfe Co., U.S.A. The material properties of the three types of sheets are given in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Tonen</th>
<th>Mitsubishi</th>
<th>Hexcel Fyfe</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 (millistrain)</td>
<td>15.1</td>
<td>14.8</td>
<td>10.0</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 under stroke control. Electrical strain gauges were used to monitor the strain in the stirrups and the distribution of the strain in the CFRP sheets.
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 as described in Table 2 below. Also provided in Table 2, are the ultimate shear failure loads, $V_u$, and the initial shear cracking load, $V_e$, determined by the load corresponding to the initiation of the first inclined cracks as described elsewhere [1].

Table 3: Comparison of Specimen Parameters and Test Results

<table>
<thead>
<tr>
<th>Strengthening Scheme:</th>
<th>Gap Size (mm)</th>
<th>CFRP Thickness (mm) &amp; Type</th>
<th>Surface Prep.</th>
<th>$f'_c$ (MPa)</th>
<th>$V_e$ (kN)</th>
<th>$V_u$ (kN)</th>
<th>$\frac{(V_u)}{(V_e)_{control}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (none) Clamped Stirrups</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>Vertical CFRP Vertical CFRP</td>
<td>100 20</td>
<td>0.11 T 0.11 M$^*$</td>
<td>grinding hydro-blast</td>
<td>53 44</td>
<td>74 76</td>
<td>151 161</td>
<td>1.10 1.17</td>
</tr>
<tr>
<td>Vertical CFRP Vertical CFRP</td>
<td>100 20</td>
<td>0.79 H$^<em>$ 0.11 M$^</em>$</td>
<td>hydro-blast hydro-blast</td>
<td>55 44</td>
<td>72 76</td>
<td>177 173</td>
<td>1.29 1.26</td>
</tr>
<tr>
<td>Diagonal CFRP Diagonal CFRP</td>
<td>100 20</td>
<td>0.11 T 0.11 M$^*$</td>
<td>grinding hydro-blast</td>
<td>53 44</td>
<td>74 76</td>
<td>185 186</td>
<td>1.34 1.36</td>
</tr>
<tr>
<td>Horiz. &amp; Vert. CFRP Horiz. &amp; Diag. CFRP</td>
<td>100 100</td>
<td>0.11 T 0.79 H$^*$</td>
<td>grinding hydro-blast</td>
<td>55 55</td>
<td>72 72</td>
<td>186 186</td>
<td>1.36 1.36</td>
</tr>
</tbody>
</table>

Key: T - Tonen, M - Mitsubishi, H - Hexcel Fyfe

In all eight tests, flexural shear cracks were observed within the shear span and extended toward the top flange at ultimate. 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 in the control beam.

Fig. 4: Control Beam at Failure

Fig. 5: Straightened Stirrups
3.1 Effect of the Stirrup Clamping Scheme

The clamping scheme applied to the second end of the control beam was effective in controlling the outward force in the stirrups. Although the cracking pattern was similar to that observed in the control beam, there was no spalling of concrete due to the clamping of the stirrups. In the control beam, only one of the stirrups monitored was observed to have reached its yield strain of 2.8 millistrain at failure, while all of the clamped stirrups monitored during testing of the second end were observed to have yielded. The improved distribution of higher forces in the clamped stirrups contributed to the observed 27 % increase in the ultimate shear capacity, $V_u$, when compared to the control beam.

3.2 Beams Strengthened with Vertical CFRP Sheets

Two types of CFRP sheets with similar thicknesses and material properties were used for the beams strengthened with vertical sheets. Two gap sizes and surface preparation techniques were also used as shown in Table 2. The ultimate shear capacity, $V_u$, of the beam with the 20 mm gap size increased by 17 % compared with the control beam, while only a 10 % increase was observed for the beam with the 100 mm gap size. It should be noted that the reduced gap size resulted in a 32 % increase in the area of sheets per unit length of beam. The contribution of the vertical sheets with the reduced gap size could also be influenced by the use of hydro-blasting for surface preparation which, according to other researchers [2], results in better bond between the sheets and the concrete.

In both beams, failure was initiated by straightening of the stirrups and debonding of the CFRP sheets above and below the diagonal cracks. For the beam with the surface prepared by hydro-blasting, debonding of the CFRP sheets appeared to be less extensive just prior to failure when compared with the beam prepared using the grinding technique.

The maximum recorded stirrup strains were similar and ranged from 2.0 to 2.6 millistrain for stirrups in both beams. The maximum strains measured in the CFRP sheets were also similar, ranging from 3.0 to 5.5 millistrain, which suggests that the force transferred to the sheets through bond was not significantly influenced by the different surface preparation techniques used. However, it can be concluded from various reports of strain distribution in CFRP sheets bonded to concrete [1,2,3], that the bond stresses are highly localized which may result in an observed maximum strain that is lower than the actual maximum strain occurring at other locations in the CFRP. Additional bond tests are proposed to further evaluate the effect of the different surface preparation techniques and types of CFRP sheets on the bond performance of the CFRP strengthening systems used in this experimental program.

3.3 Beams Strengthened with Diagonal CFRP Sheets

The thickness and material properties of the two types of CFRP sheets used for the diagonal configurations vary significantly as shown in Table 1 and Table 2. The
gap size parameter 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. On both beams, debonding and straightening of the CFRP sheets was observed at the lower part of the thin web. Unlike the beams with vertical sheets only, the diagonal sheets remained bonded near the top of both beams at ultimate. 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 evident when comparing stirrup strains for the beams in Fig.6. 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. Fig. 6 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.

The strain in the diagonal sheets on each beam can also be used to demonstrate the increased contribution of the thicker sheets. At an applied shear load of 150 kN, a maximum strain of 4.07 millistrain was measured in the Mitsubishi sheets. Based on the modulus of elasticity reported by Mitsubishi, this strain represents a stress of 936 MPa in the Mitsubishi sheet at this location as shown in Fig. 7. For the same level of shear resisting force, the stress in the Hexcel Fyfe sheet would be only 130 MPa due to the increased thickness. Based on the modulus of elasticity reported by Hexcel Fyfe, the strain in the Hexcel Fyfe sheet would be only 1.71 millistrain.

![Fig. 6: Stirrup Strain vs Applied Shear](image)

![Fig. 7: Stress & Strain for Equivalent Force in CFRP](image)
During the test, at an applied shear load of 150 kN, the maximum strain at a similar location in the Hexcel Fyfe sheet was found to be 2.13 millistrain rather than 1.71 millistrain, suggesting that the thicker diagonal sheet contributes more shear resisting force at the same level of applied shear load.

3.4 Horizontal CFRP Sheets Combined with Vertical or Diagonal Sheets

Both beams with a single layer of horizontal CFRP sheets applied on top of the vertical or diagonal sheets, achieved similar 34% and 36% increases in ultimate shear capacity, $V_u$, when compared with the control beam. It should be noted that the level of applied load causing shear failure in both beams is within 5% of the load predicted to cause flexural failure in the beam.

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. Spalling was observed at a higher load level due to the presence of both horizontal and vertical sheets. 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. In both beams at ultimate, rupture and some debonding of the CFRP sheets was observed very close to the top of the beam. There did not appear to be any significant bond problem between the CFRP and the concrete.

4. CONCLUSIONS

Four 10 m long pretressed beams were 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. The clamping scheme was effective in controlling the outward force in the stirrups. When compared with the control beam, higher stirrup forces were distributed to more stirrups within the shear span, allowing the stirrups to yield and contributing to a 27% increase in the ultimate shear capacity.
3. The reduced gap size for beams with vertical CFRP sheets provided more area of CFRP per unit length of beam and increased the improvement in ultimate shear capacity from 10% to 17%. Use of the hydro-blasting surface preparation technique may also have contributed to the improvement in the shear capacity and will be evaluated further in proposed bond tests.

4. 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.

5. Thicker diagonal CFRP sheets appear to contribute more shear resisting force than thinner sheets at the same level of applied shear load. The effect of the different types of CFRP sheets used on the bond performance will be evaluated further in proposed bond tests.

6. 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% which approaches the flexural capacity of the beam.

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REFERENCES

