Shear Strengthening of AASHTO Bridge Girders Using CFRP Sheets

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Synopsis:

This paper summarizes research findings on the use of carbon fibre reinforced polymer (CFRP) sheets for shear strengthening of pretensioned AASHTO bridge girders. The research includes an experimental program conducted at the University of Manitoba using scale models of pretensioned concrete girders in composite action with the deck slab. The beams were strengthened with three different types of CFRP sheets using ten different configurations and were tested to failure.

The paper describes the experimental program, test results, failure mechanisms and the effectiveness of each configuration of CFRP sheets. A rational model is introduced to define the contribution of the CFRP sheets to the shear resistance in addition to the contributions provided by the stirrups and the concrete for I-shaped pretensioned concrete members. Test results are used to verify the proposed model.
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INTRODUCTION

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 provides a low-cost solution due to a reduction in construction time and minimizing traffic interruption. An experimental program was undertaken at the University of Manitoba, Canada, to test scale models of the I-shaped bridge girders strengthened with CFRP sheets. This paper summarizes the test results and presents a rational model introduced to predict the shear capacity of I-shaped pre-tensioned concrete beams strengthened with CFRP sheets.

EXPERIMENTAL PROGRAM

Seven pretensioned concrete girders were tested to failure at each end. The ten meter long beams are 1:3.5 scale models of the I-shaped bridge girders. All beams had an overall depth of 475 mm including a 60 mm deep top slab, as shown in Fig. 1. The beams were pretensioned with 13 mm diameter steel strands. Non-prestressed strands were also provided to avoid flexural failure and ensure shear failure. CFRP laminate strips were applied to the underside of three beams in Series S to further increase the flexural capacity.

The Series B beams were reinforced with bent-legged steel stirrups similar to those used in the existing bridge girders, as shown in Fig. 1. Straight-legged stirrups, shown in Fig. 2 were used for the Series S beams. The stirrup spacing was identical for both series.

Fig.1- Series B Beam  Fig.2- Series S Stirrup
The simply supported beams were tested under monotonic loading and stroke control with a shear span of 1940 mm. One beam from each series was tested as a control beam. The remaining beams were strengthened using the three different types of CFRP sheets described in Table 1. Tables 2 and 3 provide a summary of the parameters evaluated and the test results for the Series B beams and Series S beams, respectively.

**Table 1- Material Properties of 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>
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<tr>
<td>Tensile Strength (MPa)</td>
<td>3350</td>
<td>3400</td>
<td>760</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>
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</table>

*properties for dry fiber sheets, +properties for composite fiber and resin sheets

**Table 2- Parameters and Test Results: Series B**

<table>
<thead>
<tr>
<th>Layer 1 Config.</th>
<th>Layer 2 Config.</th>
<th>$s_f$ (mm)</th>
<th>CFRP Type</th>
<th>$f_c'$ (MPa)</th>
<th>$V_{test}$ (kN)</th>
<th>$\frac{V_{test}}{V_{control}}$</th>
<th>Beam Mark</th>
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<tr>
<td>None</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>46</td>
<td>137</td>
<td>1.00</td>
<td>B-Control</td>
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<td></td>
<td>Clamped</td>
<td>-</td>
<td>-</td>
<td>46</td>
<td>174</td>
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<td>B-CL</td>
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<tr>
<td>Vertical</td>
<td></td>
<td>350</td>
<td>A</td>
<td>53</td>
<td>151</td>
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<td>B-Vert100</td>
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<td>270</td>
<td>B</td>
<td>44</td>
<td>161</td>
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<td>B-Vert20</td>
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<tr>
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<td>450</td>
<td>C</td>
<td>55</td>
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<td>B-Diag100</td>
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<td>Diagonal</td>
<td>370</td>
<td>B</td>
<td>44</td>
<td>173</td>
<td>1.26</td>
<td>B-Diag20</td>
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<td>Clamped</td>
<td>370</td>
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<td>59</td>
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<td>S-Diag1-</td>
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<td>Horizontal</td>
<td>370</td>
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<td>234</td>
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<td></td>
<td>Clamped</td>
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<td>B</td>
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<td>247</td>
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<td>S-Diag-H</td>
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<tr>
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<td>370</td>
<td>B</td>
<td>50</td>
<td>272</td>
<td>1.28</td>
<td>S-Diag-CL</td>
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</tbody>
</table>

**Table 3- Parameters and Test Results: Series S**

Beams in Series B and S were strengthened using 250 mm wide CFRP sheets with the fibres oriented vertically or diagonally at a 45° angle. The sheets were applied on each side of the cross-section just below the slab and overlapped on the underside of the beam. For some beams, a 220 mm wide horizontal sheet was applied on the top of the vertical or diagonal sheets. The effect of two layers of diagonal sheets was also examined.
The clamping scheme shown in Fig. 3 was used to control the outward force in the bent-legged stirrups of one case and CFRP sheets in a second case. This outward force is the resultant of the tensile forces in the vertical and diagonal legs of the shear reinforcement, and causes the sheet or stirrup to straighten.

**TEST RESULTS**

All of the test beams failed in shear with inclined shear cracks occurring typically at 30°. For all of the beams strengthened with CFRP sheets, concrete remained bonded to the CFRP sheets over most of the beam at failure, as shown in Fig. 4, indicating that shear failure occurred in the concrete substrate rather than debonding of the sheets.

**Series B Beams** -- Only one of the stirrups in beam B-Control reached yield before failure occurred due to straightening of the bent-legged stirrups. The clamping scheme applied to beam B-CL was effective in controlling the outward force in the stirrups and all of the stirrups reached yield before failure. For all Series B beams, the CFRP sheets reduced the strain in the stirrups at any level of applied shear load, as shown in Fig. 5, and increased the shear capacity, as shown in Table 2. Due to the shape of the girder, straightening of the CFRP sheets was observed prior to failure. Detailed test results of Series B are presented elsewhere. (1)

**Control Beams** -- Comparison of beams S-Control and S-NoFRP indicates that using CFRP laminates to increase the flexural capacity increased the shear capacity by only 3 percent, which falls within experimental limits, as shown in
Table 3. A significant increase in the shear capacity, equivalent to 50 percent, is observed when comparing beams S-Control and B-Control. This increase is partly due to the premature failure of beam B-Control caused by straightening of the bent stirrup legs. A comparison of beams S-Control and B-CL shows an increase in shear capacity of 18 percent due to the use of a slightly larger diameter bar for the straight-legged stirrups.

**Diagonal Configuration** -- Failure of beam S-Diag-2 is shown in Fig. 4. Comparison of beams S-Diag-1 and S-Diag-2 suggests that the second layer of diagonal sheets did not increase the shear capacity significantly. Both beams exhibited straightening of the diagonal sheets due to the shape of the girder. As a result of the straightening behaviour, the diagonal CFRP sheets were not fully effective and the increase in ultimate shear capacity for these beams was only 9 percent and 10 percent, respectively, when compared to beam S-control.

**Diagonal-Horizontal Configuration** -- Beam S-Diag-H, strengthened with a horizontal sheet on top of a single layer of diagonal sheets, achieved a 16 percent increase in shear capacity. The straightening of the FRP sheets was not as extensive when compared with beams S-Diag-1 and S-Diag-2.

**Clamped Diagonal Configuration** -- The clamping scheme applied to beam S-Diag-CL effectively controlled the straightening of the diagonal CFRP sheets. The measured strains in the clamped diagonal sheets reached higher levels than those recorded for the other beams. The 28% increase in ultimate shear capacity does not represent the full potential of the strengthening scheme, since failure of the beam occurred outside of the strengthened zone.

**FRP CONTRIBUTIONS**

The strains measured in the steel stirrups and CFRP sheets are used to determine the shear resisting force provided by each component at different levels of applied shear load. The measured contributions for beam S-Diag-2 are shown in Fig. 6. The maximum value of the FRP contribution, \( V_{r\,\text{max}} \), at an applied shear load of 190 kN, represents the initiation of straightening of the FRP sheets. The FRP contribution begins to drop off as straightening continues. At this stage, the stirrup contribution increases more rapidly, until complete failure of the beam occurs at 234 kN.

The FRP contribution to shear resistance for all Series S beams is shown in Fig. 7. For S-Diag-1, the FRP contribution also reaches \( V_{f\,\text{max}} \) at the initiation of sheet straightening followed by a decrease in the FRP contribution. For beam S-Diag-H, the contribution of the diagonal sheets reaches a constant level and does not decrease significantly prior to failure. The FRP contribution for the clamped sheets of S-Diag-CL shows a constant increase until failure.
PROPOSED RATIONAL MODEL

The shear strength, $V_n$, of a reinforced concrete beam with externally bonded FRP sheets can be calculated as the sum of the shear resisting contributions of the concrete, $V_c$, the steel stirrups, $V_{se}$, and the FRP sheets, $V_{f\text{\text{}}\text{\text{}}\text{\text{\text{}}\text{\text{}}}\text{\text{}}}\text{max}$:

$$V_n = V_c + V_{se} + V_{f\text{\text{}}\text{\text{}}\text{\text{\text{}}\text{\text{}}\text{\text{}}}\text{max}}$$  \hspace{1cm} (1)

The contribution provided by the FRP sheets, $V_{f\text{\text{}}\text{\text{}}\text{\text{\text{}}\text{\text{}}}\text{max}}$, is illustrated in Fig. 8 and can be determined using the following expression:

$$V_{f\text{\text{}}\text{\text{}}\text{\text{\text{}}\text{\text{}}}\text{max}} = \varepsilon_{f\text{\text{}}\text{\text{}}\text{\text{\text{}}\text{\text{}}\text{\text{}}}\text{ave} E_f 2n_f t_f w_f d_f (\cot \theta + \cot \alpha_f) \sin \alpha_f$$  \hspace{1cm} (2)

![Fig.8- Contribution to Shear Resistance of FRP Sheets](image_url)
In determining the contribution to shear resistance provided by FRP sheets, the two modes of failure shown in Fig. 9 a) and b), introduced by others, are considered. Due to the shape of the cross-section examined in this experimental program, a third mode of failure was observed and is proposed in this paper for I-shaped cross-sections, as shown in Fig. 9 c). The values for $d_r$ and $\varepsilon_{f\text{ave}}$ depend on the mode of failure, and are determined based on the FRP sheet configuration and the shape of the cross-section, as shown in Fig. 9.

**Fig. 9(a)**

$\varepsilon_f = \varepsilon_{f\text{ave}}$

Effective bond length, $L_{fe}$

**Fig. 9(b)**

$\varepsilon_f = \varepsilon_{f\text{ave}}$

**Fig. 9(c)**

$d/2$

$\varepsilon_{f\text{ave}}$

Zone of failure initiation

$\varepsilon_{f\max}$

Shear peeling

**Fig. 9 - Basic Modes of Failure for Bonded FRP Sheets**
The first mode of failure shown in Fig. 9 (a) is rupture of the FRP sheets and typically occurs at stress levels lower than the ultimate tensile strength of the FRP sheet. For applications where the FRP sheets cannot be completely wrapped around the beam cross-section, the bond between the FRP sheet and the concrete is critical. Failure of the bond mechanism is the second mode of failure shown in Fig. 9 (b) and typically occurs due to shear-tension failure within the concrete substrate. For the I-shaped section shown in Fig. 9 (c), the tensile forces developed in the FRP sheets subject the concrete substrate to peeling forces as well as shear forces. Failure typically occurs within the concrete substrate due to straightening of the FRP sheets, prior to the development of a uniform strain distribution in the sheets.

For the first two modes of failure shown in Fig. 9 (a) and (b), methods for determining $d_r$ and $\varepsilon_{fave}$ have been introduced by others.\(^{(2,3)}\) For I-shaped sections, the average strain in the FRP sheets at failure, $\varepsilon_{fave}$, is based on a constant strain of $\varepsilon_{fmax}$ extending $d/2$ from the bottom of $d_r$ and decreasing to zero at the top of $d_r$, as shown in Fig. 9 c). The average FRP strain for I-shaped sections can be determined as follows:

$$\varepsilon_{fave} = \varepsilon_{fmax} \left[ \left( \frac{d}{2} \right) + 0.5 \left( d_r - \frac{d}{2} \right) \right]$$

As observed during testing, the strain distribution shown in Fig. 9 (c) occurs just prior to straightening of the FRP sheets. After straightening of the FRP sheets is initiated, the average strain in the FRP sheets is reduced and a decrease in the shear resistance of the FRP sheets occurs, as shown in Fig. 7. The nominal shear strength provided by the FRP sheets, $V_{fmax}$, is calculated using Eq. (2) and Eq. (3) and is based on the maximum FRP contribution which occurs just prior to straightening of the FRP sheets.

For the first two basic modes of failure described in Figs. 9 (a) and (b), the average FRP strain at ultimate, $\varepsilon_{fave}$, is typically greater than the stirrup yield strain, $\varepsilon_{sy}$.\(^{(2,3)}\) Consequently, most models assume that the steel stirrups have yielded at ultimate. However, for I-shaped sections, failure due to straightening of the FRP sheets is initiated at a lower level of FRP strain and may occur prior to yielding of the stirrups. Therefore, the effective stirrup contribution, $V_{se}$, is based on the strain in the stirrups, $\varepsilon_{se}$, which occurs at the initiation of failure in the FRP sheets, $V_{fmax}$, and is determined as follows:

$$V_{se} = \varepsilon_{se} E_s A_s d \cot \theta$$

where $\varepsilon_{se} \leq \varepsilon_{sy}$ \(\text{Eq. (4)}\)

**Maximum FRP Strain** – Based on test results for I-shaped sections, the maximum strain in the FRP sheets at failure, $\varepsilon_{fmax}$, is 0.004. This value for $\varepsilon_{fmax}$ applies to a single layer diagonal sheet of Type B FRP with or without a horizontal sheet. Figs. 10 (a) and (b) show the measured FRP strain distribution.
at $V_{f_{\text{max}}}$, for beams S-Diag-1 and S-Diag-H, respectively. The model FRP strain distribution, based on $\varepsilon_{f_{\text{max}}}$ of 0.004, is also shown in Figs. 10 (a) and (b), and compares well with the measured strain distributions.

**Effect of FRP Sheet Stiffness** -- Based on a series of shear bond tests, Maeda et al. (4) suggest that the maximum strain in an FRP sheet, $\varepsilon_{f_{\text{max}}}$, developed over an effective bond length, $L_{\text{fe}}$, is reduced with an increase in the stiffness of the FRP sheet as follows:

$$\varepsilon_{f_{\text{max}}} = L_{\text{fe}} C \quad (5)$$

Where,

$$L_{\text{fe}} = \exp[6.134 - 0.580 \ln(t_{\text{r}} E_d)]$$

$$C = \text{constant strain rate of } 110 \times 10^{-6} /\text{mm}$$

Since Eq. (5) is based on bond failure due to shear stresses only, Eq. (5) overestimates $\varepsilon_{f_{\text{max}}}$ for FRP sheets subjected to shear and peeling forces. However, the relationship between maximum strain and sheet stiffness given in Eq. (5) can be used to predict the maximum strain in two layers of diagonal sheets, $(\varepsilon_{f_{\text{max}}})_{2 \text{ layers}}$, based on the value obtained for a single layer of diagonal sheets, $(\varepsilon_{f_{\text{max}}})_{1 \text{ layer}}$ of 0.004, as follows:

$$\frac{(\varepsilon_{f_{\text{max}}})_{2 \text{ layers}}}{(\varepsilon_{f_{\text{max}}})_{1 \text{ layer}}} = \frac{0.004 \exp[6.134 - 0.580 \ln(t_{\text{r}} E_d)]_{2 \text{ layers}}}{\exp[6.134 - 0.580 \ln(t_{\text{r}} E_d)]_{1 \text{ layer}}} \quad (6)$$

Fig. 11 shows the measured FRP strain distribution at $V_{f_{\text{max}}}$ for beam S-Diag-2, with two layers of diagonal sheets. Eq. (6) was used to determine $(\varepsilon_{f_{\text{max}}})_{2 \text{ layers}}$ for the model strain distribution, which is in good agreement with the measured strain distribution, as shown in Fig. 11. Eq. (6) is also used to determine the
maximum strain for Type C FRP sheets, \((\varepsilon_{f_{\text{max}}}^{c})_{\text{Type C}}\), based on the value obtained for Type B sheets, \((\varepsilon_{f_{\text{max}}}^{c})_{\text{Type B}}\) of 0.004.

![Image](image-url)

**Fig. 11- FRP Strain Distribution:**
Beam S-Diag-2

**Fig. 12- Ratio of Measured Strain:**
FRP Sheets vs Stirrups

**Effect of FRP Sheet Configuration** -- The maximum strain in the FRP sheets oriented vertically can be predicted based on the maximum strain, \(\varepsilon_{f_{\text{max}}}^{c}\), of 0.004, in the diagonal sheets as follows:

\[
(\varepsilon_{f_{\text{max}}}^{c})_{\text{Vertical}} = (\varepsilon_{f_{\text{max}}}^{c})_{\text{Diag}} \sin 45^\circ
\]  

(7)

The shear resistance of vertical Type B FRP sheets, \(V_{f_{\text{max}}}^{c}\), can be determined using Eq. (7), Eq. (3) and Eq. (2) with \(\alpha_{f} = 90^\circ\).

**Effective Stirrup Strain at Failure** -- The strain in the stirrups, \(\varepsilon_{se}\), occurring at \(V_{f_{\text{max}}}^{c}\) can be predicted based on the average strain in the FRP sheets, \(\varepsilon_{f_{\text{ave}}}^{c}\), as follows:

\[
\varepsilon_{se} = \varepsilon_{f_{\text{ave}}} \sin \alpha_{f} / \gamma_{fs}
\]  

(8)

Where \(\gamma_{fs}\) is determined based on test results and is defined as: the ratio of the vertical component of average strain in the FRP sheets, \(\varepsilon_{f_{\text{ave}}} \sin \alpha_{f}\), to the average strain in the steel stirrups, \(\varepsilon_{se_{\text{ave}}}\). For the beams in this experimental program, the ratio \(\gamma_{fs}\) is determined based on measured strains and is shown in Fig. 12. As shown in Fig. 12, the ratio \(\gamma_{fs}\) is typically greater than 1.0 prior to the initiation of failure due to straightening of the FRP sheets. Based on the strains measured in this experimental program, \(\gamma_{fs} = 1.5\) is used for the proposed model. Other researchers have reported values for \(\gamma_{fs}\) greater than 1.0 (5,6,7); however, further investigation is required to confirm appropriate values for \(\gamma_{fs}\).
RELIABILITY OF THE PROPOSED MODEL

The proposed model is used to predict the shear capacity of both the Series B and the Series S beams. The measured shear crack angle of 30° is used for all of the beams. The ACI expression for the concrete contribution for prestressed beams is used and was found to be in good agreement with the test results. Since the objective is to accurately predict observed test results, rather than to calculate a conservative design solution, no load or resistance factors are used in the calculations.

Fig. 13 a) provides a comparison of test results versus predictions for the shear capacity of the Series B beams. For the Series S beams, a comparison of test results versus predictions for $V_{f_{\text{max}}}$ is shown in Fig. 13 b). For both beam series, the predicted shear capacities are in good agreement with the test results.

![Fig. 13 a) - Test Results vs Predicted Shear Capacity: Series B](image1)

![Fig. 13 b) - Test Results vs Predicted Shear Capacity: Series S](image2)
SUMMARY

Seven ten meter long prestressed concrete beams were tested for shear failure at each end to determine the most efficient shear strengthening scheme using CFRP sheets for I-shaped girders. A rational model for predicting the shear capacity of I-shaped girders strengthened with CFRP sheets is introduced and found to be in good agreement with test results.

The proposed model considers the following:

1. For I-shaped cross-sections, the maximum shear resistance of the FRP sheets, \( V_{r \text{ max}} \), is achieved just prior to straightening of the sheets due to shear and peeling forces.

2. For I-shaped cross-sections, failure typically occurs prior to the development of a uniform strain distribution in the FRP sheets.

3. The maximum strain developed in the FRP sheets at failure is reduced with an increase in the stiffness of the FRP sheets.

4. For I-shaped cross-sections, failure may initiate prior to yielding of the stirrups. The shear resistance provided by the stirrups, \( V_{se} \), is calculated based on the average strain in the FRP sheets at the initiation of failure.

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REFERENCES


