FRP FOR SHEAR STRENGTHENING OF AASHTO BRIDGE GIRDER

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ABSTRACT
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 ISIS Manitoba at the University of Manitoba using seven scale-model pretensioned concrete girders in composite action with the deck slab. The first set of four beams were representative of a typical bridge girder reinforced with an outward bent-legged shaped stirrup occasionally used by the precast industry for convenient casting. The other three beams were reinforced using the more commonly used straight-legged stirrup shape. Beams were strengthened with three different types of CFRP sheets using ten different configurations. The program also included a series of bond specimens tested to determine the bond characteristics of CFRP sheets to the concrete surface as affected by the surface preparation, shape of the girders, as well as load-sharing with the embedded steel stirrups. Test results are used to verify a rational approach introduced to define the shear resistance of the CFRP sheets in addition to the concrete and stirrup shear resisting contributions for pretensioned concrete members.

The paper describes the experimental program, test results, failure mechanisms and the effectiveness of each configuration of CFRP sheets. Design guidelines and recommendations on the use of CFRP for shear strengthening of AASHTO bridge girders are presented.

INTRODUCTION

The use of heavier trucks demands that the shear capacity of a twenty-nine year old prestressed concrete bridge in Winnipeg, Manitoba, Canada be upgraded. Carbon Fibre Reinforced Polymer (CFRP) sheets provide a low-cost solution for shear strengthening due to a reduction in construction time and minimal interruption of traffic. An experimental program was undertaken at the University of Manitoba, Canada, to test scale models of the I-shaped AASHTO bridge girders strengthened with CFRP sheets. In order to investigate the bond characteristics of CFRP sheets to concrete, fifteen tension specimens were also tested. This paper summarizes the beam test results, the bond test results to date, and presents a rational model introduced to predict the shear capacity of I-shaped pre-tensioned concrete beams strengthened with CFRP sheets.

EXPERIMENTAL PROGRAM

Beam Test Specimens
Seven pretensioned concrete girders were tested to failure at each end for a total of fourteen beam tests. The ten meter long beams are 1:3.5 scale models of the I-shaped AASHTO 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. To ensure shear failure and avoid premature flexural failure, non-pretressed strands were also provided. CFRP laminate strips were applied to the underside of three beams to further increase the flexural capacity.
The four Series B beams were reinforced with bent-legged steel stirrups similar to those used in the existing bridge girders, as shown in Fig. 1. The straight-legged stirrups shown in Fig. 2 were used for the three Series S beams.

![Diagram of beams and stirrups]

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 and an overall span of 9.7 m or 6.0 m. 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 in each series 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>
</tr>
<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>
</tr>
</tbody>
</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>Gap* (mm)</th>
<th>CFRP Type</th>
<th>CFRP Strip</th>
<th>Span (m)</th>
<th>f(_c)' (MPa)</th>
<th>V(_{test}) (kN)</th>
<th>(\frac{V_{test}}{V_{control}})</th>
<th>Beam Mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.7</td>
<td>46</td>
<td>137</td>
<td>1.00</td>
<td>B-Control</td>
</tr>
<tr>
<td>Clamped</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.0</td>
<td>46</td>
<td>174</td>
<td>1.27</td>
<td>B-CL</td>
</tr>
<tr>
<td>Vertical</td>
<td>-</td>
<td>100</td>
<td>A</td>
<td>-</td>
<td>6.0</td>
<td>53</td>
<td>151</td>
<td>1.10</td>
<td>B-Vert100</td>
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<tr>
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<td>-</td>
<td>20</td>
<td>B</td>
<td>-</td>
<td>6.0</td>
<td>44</td>
<td>161</td>
<td>1.18</td>
<td>B-Vert20</td>
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<tr>
<td>Diagonal</td>
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<td>100</td>
<td>C</td>
<td>-</td>
<td>9.7</td>
<td>55</td>
<td>185</td>
<td>1.35</td>
<td>B-Vert-H</td>
</tr>
<tr>
<td>Horizontal</td>
<td>-</td>
<td>20</td>
<td>C</td>
<td>-</td>
<td>9.7</td>
<td>44</td>
<td>173</td>
<td>1.29</td>
<td>B-Diag100</td>
</tr>
<tr>
<td>Diagonal</td>
<td>Horizontal</td>
<td>100</td>
<td>C</td>
<td>No</td>
<td>9.7</td>
<td>55</td>
<td>186</td>
<td>1.36</td>
<td>B-Diag20</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Layer 1 Config.</th>
<th>Layer 2 Config.</th>
<th>Gap* (mm)</th>
<th>CFRP Type</th>
<th>CFRP Strip</th>
<th>Span (m)</th>
<th>f(_c)' (MPa)</th>
<th>V(_{test}) (kN)</th>
<th>(\frac{V_{test}}{V_{control}})</th>
<th>Beam Mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.0</td>
<td>57</td>
<td>213</td>
<td>1.00</td>
<td>S-Control</td>
</tr>
<tr>
<td>Diagonal</td>
<td>-</td>
<td>20</td>
<td>B</td>
<td>Yes</td>
<td>6.0</td>
<td>50</td>
<td>233</td>
<td>1.09</td>
<td>S-Diag-1</td>
</tr>
<tr>
<td>Horizontal</td>
<td>Diagonal</td>
<td>20</td>
<td>B</td>
<td>Yes</td>
<td>6.0</td>
<td>59</td>
<td>234</td>
<td>1.10</td>
<td>S-Diag-2</td>
</tr>
<tr>
<td>Diagonal</td>
<td>Horizontal</td>
<td>20</td>
<td>B</td>
<td>Yes</td>
<td>6.0</td>
<td>50</td>
<td>247</td>
<td>1.16</td>
<td>S-Diag-H</td>
</tr>
<tr>
<td>Diagonal</td>
<td>Clamped</td>
<td>20</td>
<td>B</td>
<td>Yes</td>
<td>6.0</td>
<td>59</td>
<td>272</td>
<td>1.28</td>
<td>S-Diag-CL</td>
</tr>
</tbody>
</table>

* Size of gap between FRP sheets
The beams in both series were strengthened using 250 mm wide CFRP sheets with the fibres oriented vertically or diagonally at a 45° angle, as described in Tables 2 and 3. 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 beam B-CL, without any FRP sheets. In order to control the outward force in the diagonal CFRP sheets on beam S-Diag-CL, the same clamping scheme was applied at both the top and bottom of the web. The 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.

Bond Test Specimens
Two types of tension specimens, Rectangular and Single-Flanged, were used to investigate the bond characteristics of CFRP sheets to concrete. A total of six Rectangular tension specimens and nine Single-Flanged tension specimens were tested to study the effect of concrete surface preparation, concrete surface configuration, crack orientation, and load sharing between the external CFRP sheets and internal steel reinforcing.

Each Rectangular specimen consists of a 100 x 275 x 900 mm block of reinforced concrete strengthened on two faces with one layer of 200 mm wide Type B CFRP sheets, as shown in Fig.4. The Single-Flanged tension specimens were also strengthened on two faces with one layer of Type B CFRP sheets and were designed to simulate the lower web of an AASHTO I-shaped girder, as shown in Fig. 5. For both specimen types, the internal steel is designed to produce a crack at a predetermined angle and location. Some specimens include additional steel reinforcing across the crack to simulate the presence of stirrups. The concrete surface of two Rectangular tension specimens was prepared by grinding while the surface of the remaining Rectangular specimens and all of the Single-Flanged specimens were prepared using a hydro-blasting technique. The average compressive strength of the concrete used for the bond test specimens was 52 MPa for the Rectangular specimens and 41 MPa for the Single-Flanged specimens.
Each bond test specimen is statically loaded using stroke control. Pin-ended connections and rotating couples ensure an even distribution of tensile force to the two tension bars protruding from each end of each specimen. The distribution of strain in the CFRP sheets is measured using three columns of electric strain gauges, as shown in Fig. 4 and Fig. 5.

BEAM TEST RESULTS

All of the test beams failed in shear with inclined shear cracks typically occurring at an angle of 30°. For all of the beams strengthened with CFRP sheets, concrete remained bonded to the CFRP sheets over most of the beam at failure, indicating that shear-tension failure occurred in the concrete substrate.

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 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. Test results for the Series B beams are presented in more detail elsewhere. (Hutchinson et al. 1997).

Comparison of Series S and Series B
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, however, shows an increase in shear capacity of 18 percent for beam S-control. This increase is attributed to the use of a slightly larger diameter bar for the straight-legged stirrups compared to the bent-legged stirrups.

Series S 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.

Diagonal Configuration – Beam S-Diag-1 is shown in Fig. 6 at failure. 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.

Fig. 6- Beam S-Diag-1 at Failure
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 for Series S Beams
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. 7. The maximum value of the FRP contribution, $V_{f_{max}}$, 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. 8. For S-Diag-1, the FRP contribution also reaches $V_{f_{max}}$ 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.

![Graph](image1.png)

Fig. 7- FRP Contributions for Beam S-Diag-2

![Graph](image2.png)

Fig. 8- FRP Contributions for Series S Beams

BOND TEST RESULTS

Rectangular Tension Specimens
For the Rectangular specimens prepared using the grinding technique, shear-tension failure occurred in the in the concrete substrate. Failure began near the crack and propagated along the length of the sheet. For the specimens prepared using hydro-blasting, failure occurred due to rupture of the FRP sheets. A summary of the test results is provided in Table 4 for all of the Rectangular tension specimens.

<table>
<thead>
<tr>
<th>Surface Prep.</th>
<th>Steel Across Crack</th>
<th>Crack Angle</th>
<th>Ave. Max. FRP Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding</td>
<td>no</td>
<td>0</td>
<td>0.0040</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.0042</td>
</tr>
<tr>
<td>Hydro-Blasting</td>
<td>no</td>
<td>0</td>
<td>0.0044</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.0046</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>0</td>
<td>0.0046</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.0051</td>
</tr>
</tbody>
</table>
The strain distribution in the FRP sheets for two of the Rectangular specimens is shown in Fig. 9. The length of sheet over which stress transfer is effective, or the effective bond length, is illustrated in Fig. 9 by a change in FRP strain over this length. As shown in Fig. 9, the effective bond length observed in this experimental program is typically between 75 mm and 100 mm. The peak strain measured in the hydro-blasted specimens was only 50 percent of the ultimate rupture strain of the material as listed in Table 1, and slightly higher than the peak strain observed for the specimens prepared using grinding.

![Fig. 9- Strain Distribution in FRP Sheets: Rectangular Tension Specimens](image1)

![Fig. 10- Load-Sharing Ratio vs Applied Load: Rectangular Tension Specimens](image2)

Based on the strain measured in the FRP sheets and the internal steel stirrups, the ratio of the load carried by the FRP sheet to the load carried by the steel stirrups, $P_{\text{fr}} / P_{\text{steel}}$, is calculated and plotted in Fig. 10. The load-sharing ratio observed prior to cracking is equivalent to the stiffness ratio of the two types of reinforcement, $(AE)_{\text{fr}} / (AE)_{\text{steel}}$, since the strain in the two materials is equivalent at this stage. After cracking however, the load-sharing ratio increases significantly due to the shorter effective bond length of the FRP sheets when compared to the development length of the steel stirrups.

**Single-Flanged Tension Specimens**

Testing of the Single-Flanged tension specimens is currently underway and will be completed by May 1999. Only specimens without internal reinforcing crossing the crack have been tested to date. As anticipated, the general mode of failure for these specimens is peeling at the interior corner of the simulated AASHTO girder cross-section immediately after cracking. Maximum strains observed in the FRP sheets range from 0.002 to 0.003 for the specimens tested to date.

**FRP STRAIN DISTRIBUTION MODEL**

For I-shaped AASHTO girders, 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. A model for the strain distribution in FRP sheets bonded to I-shaped cross-sections is introduced based on the FRP strain distribution measured during the beam tests at the initiation of failure, $V_{f_{\text{max}}}$.

The FRP strain distribution measured during testing is shown in Fig. 11 (a) for beam S-Diag-1 and Fig. 11 (b) for beam S-Diag-H, both compare well with the strain distribution model at $V_{f_{\text{max}}}$ which is also shown in Fig. 11. After straightening of the FRP sheets is initiated at $V_{f_{\text{max}}}$, the average strain in the FRP sheets is reduced as shown in Fig. 11 (a) and (b) and a decrease in the shear resistance provided by the FRP sheets occurs, as shown in Fig. 8. The nominal shear strength provided by the FRP sheets is
therefore taken as the maximum FRP contribution which occurs just prior to straightening of the FRP sheets, \( V_{f_{\text{max}}} \), and is calculated based on the FRP strain distribution model.

\[ \varepsilon_{f_{\text{ave}}} = \frac{\varepsilon_{f_{\text{max}}} (d/2) + 0.5 (d_f - d/2)}{d_f} \]  

(1)

Based on test results for I-shaped sections, the maximum strain in the FRP sheets at failure, \( \varepsilon_{f_{\text{max}}} \), for a single layer diagonal sheet of Type B FRP with or without a horizontal sheet is 0.004, as shown in Fig. 11 (a) and (b). Appropriate values for the maximum FRP strain, \( \varepsilon_{f_{\text{max}}} \), vary depending on the FRP sheet configuration and stiffness as discussed in the following sections.

**Effect of FRP Sheet Stiffness**

Based on a series of shear bond tests, (Maeda et al. 1997) suggest that the maximum strain in an FRP sheet, \( \varepsilon_{f_{\text{max}}} \), developed over an effective bond length, \( L_{fe} \), is reduced with an increase in the stiffness of the FRP sheet as follows:

\[ \varepsilon_{f_{\text{max}}} = L_{fe} C \]  

(2)

Where,

\[ L_{fe} = \exp[6.134 - 0.580 \ln(t_f E_f)] \]

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

Since Eq. (2) is based on bond failure due to shear stresses only, Eq. (2) 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. (2) can be used to predict the maximum strain in two layers of diagonal sheets, \( (\varepsilon_{f_{\text{max}}})_2 \) layers, based on the value obtained for a single layer of diagonal sheets, \( (\varepsilon_{f_{\text{max}}})_1 \) layer of 0.004, as follows:
\[
(\varepsilon_{f,\text{max}})^{2 \text{ layers}} = 0.004 \exp[6.134 - 0.580 \ln(t_f E_f)]^2 \text{ layers} \exp[6.134 - 0.580 \ln(t_f E_f)]^1 \text{ layer}
\]  

Fig. 12 shows the measured FRP strain distribution at \( V_f \text{ max} \) for beam S-Diag-2, with two layers of diagonal sheets. Eq. (3) 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. 13. Eq. (3) is also used to determine the maximum strain for Type C FRP sheets, \((\varepsilon_{f,\text{max}})_{\text{Type C}}\), based on the value obtained for Type B sheets, \((\varepsilon_{f,\text{max}})_{\text{Type B}}\) of 0.004.

![Graph showing FRP strain distribution](image)

*Fig. 13- FRP Strain Distribution: Beam S-Diag-2*

![Graph showing ratio of measured strain](image)

*Fig. 14- 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 vertical component of the maximum strain of 0.004, in the diagonal sheets as follows:

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

(4)

The value for the maximum strain in the vertical FRP sheets calculated using Eq. (4) compares well with the maximum strain observed in the Single-Flanged tension-type bond specimens tested to date.

**STIRRUP STRAIN AT FAILURE**

In predicting the shear strength of reinforced concrete members, it is typically assumed that the steel stirrups have yielded at ultimate. However, for I-shaped sections strengthened with FRP sheets, failure due to straightening of the FRP sheets 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. The strain in the stirrups, \( \varepsilon_{se} \), occurring at \( V_{f,\text{max}} \) can be predicted based on the average strain in the FRP sheets, \( \varepsilon_{f,\text{ave}} \), as follows:

\[
\varepsilon_{se} = \varepsilon_{f,\text{ave}} \sin \alpha_f \gamma_{fs}
\]

(5)

Where \( \gamma_{fs} \) 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, \( \varepsilon_{se,\text{ave}} \), and is determined experimentally.
For the beams in this experimental program, the ratio γ_{fs} is determined based on measured strains and is shown in Fig. 14. As shown in Fig. 14, the strain ratio γ_{fs} is typically greater than 1.0 prior to the initiation of failure due to straightening of the FRP sheets. Based on the beam tests conducted in this experimental program, γ_{fs} = 1.5 is proposed. Other researchers have reported values for γ_{fs} greater than 1.0 based on beam test results (Miyachi et al. 1997, Sato et al. 1996, Uji 1992); however, further investigation is required to confirm appropriate values for γ_{fs}.

For the bond tests conducted to date, higher strain ratios have been obtained as illustrated in Fig. 10. The strain ratios obtained with the single-crack tension specimens are in the range of 3.0 to 4.0 and are comparable to the strain ratios obtained during the early stages of shear cracking in the beams. After multiple shear cracks develop and propagate during the beam tests, the strain ratio decreases as shown in Fig. 14.

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 max}:

$$V_n = V_c + V_{se} + V_{f max}$$

The contribution provided by the FRP sheets, V_{f max}, is illustrated in Fig. 15 and can be determined using the following expression:

$$V_{f max} = \frac{\varepsilon_{f ave} E_f 2n_f t_f w_f d_f (\cot \theta + \cot \alpha_f)}{s_f} \sin \alpha_f$$

![Diagram of FRP sheets](image)

Fig15.- Contribution to Shear Resistance Provided by FRP Sheets

The effective stirrup contribution, V_{se}, is based on the strain in the stirrups, ε_{se}, which occurs at the initiation of failure in the FRP sheets, V_{f max}, and is determined as follows:

$$V_{se} = \varepsilon_{se} E_s A_v \frac{d \cot \theta}{s} \quad \text{where} \quad \varepsilon_{se} \leq \varepsilon_{sy}$$

(8)
The proposed model is used to predict the shear capacity of the test 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. A comparison of Series B and Series S test results versus predictions for $V_{\text{frax}}$ is shown in Fig. 16 (a) and (b), respectively.

*Fig. 16 (a) - Test Results vs Predicted Shear Capacity: Series B*

*Fig. 16 (b) - Test Results vs Predicted Shear Capacity: Series S*
CONCLUSIONS

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 AASHTO girders. Fifteen tension-type bond specimens were tested to characterize the bond between the CFRP sheets and the concrete. 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. Based on the experimental work completed to date, the following conclusions are drawn:

1. For I-shaped AASHTO girders, failure is initiated by straightening of the FRP sheets. Failure typically occurs due to shear-tension failure within the concrete substrate, which is subjected to both shear and peeling forces at the interior angle located on the bottom of the web.

2. Failure occurs prior to a uniform distribution of strain in the FRP sheets, and a FRP strain distribution model is proposed based on experimental results. The maximum strain developed in the FRP sheets depends upon the configuration and stiffness of the FRP sheets.

3. Due to improved bond and a shorter effective bond length for FRP sheets when compared to the bond length for steel stirrups, the strain in the FRP sheets is higher than the strain in the steel stirrups crossing the crack. Since the steel stirrups may not have reached yield at the initiation of failure, the strain in the stirrups should be determined based on the strain in the FRP and typical strain ratios between the FRP and the steel observed experimentally.

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