Use of FRP as Shear Reinforcement for Concrete Structures

by

Emile Shehata, Ryan Morphy, and Sami Rizkalla

Corresponding Author:

Emile Shehata
ISIS Canada Network of Centres of Excellence,
University of Manitoba, Winnipeg, Manitoba, Canada, R3T 5V6
Phone: (204) 474-8506  Fax: (204) 474-7519
E-mail: shehata@cc.umanitoba.ca

Keywords: Fibre Reinforced Polymer (FRP); Carbon FRP; Glass FRP; stirrups; shear; bend; bent zone;
This paper summarizes an experimental program conducted to examine the structural performance of FRP stirrups for shear reinforcement of concrete structures. The research is part of a comprehensive program undertaken to construct 100-foot girders of a highway bridge prestressed and reinforced for shear using FRP reinforcement. A total of six beams were tested to study the behavior and the mode of failure. Three beams were reinforced by CFRP stirrups, one reinforced with GFRP stirrups, one reinforced with steel stirrups and last beam without shear reinforcement. The main variables were the stirrup spacing and the type of the material. Due to the unidirectional characteristics of FRP, significant reduction of the strength relative to the ultimate tensile strength parallel to the fibres is introduced by bending. A total of 40 specially designed specimens were tested to examine the bent effect on the stirrup capacity, along with four control specimens reinforced with steel stirrups. The variables considered in the second study are the type of the material, bar diameter, configuration of the stirrup anchorage, and embedment length. Descriptions of the experimental program, test results and design recommendations are presented.

INTRODUCTION

Deterioration of concrete structures due to the corrosion of steel reinforcement has led to the need for an alternative type of reinforcement such as Fibre Reinforced Polymers (FRP). Stirrups used for shear reinforcement are normally located as an outer reinforcement with respect to the flexural reinforcement and therefore are more susceptible to severe environmental effects due to the minimum concrete cover provided. In some cases, stirrups are even exposed from the beam surface to provide composite action with the slab which is normally cast at a later stage. During this period corrosion
could be serious. Fibre reinforced polymers (FRP) are non-corrosive materials and have recently been used as reinforcement to overcome the corrosion and deterioration of concrete structures. Bountiful research has been reported on the use of FRP as longitudinal reinforcement including their implementation in several structures and bridges. The use of FRP for shear reinforcement has not yet fully been explored and the current available data is insufficient to formulate unified design guidelines. The current investigation was conducted as part of a complete research project to evaluate the use of CFRP as main and secondary reinforcement for a highway bridge, being built at Headingley, Manitoba [1].

Due to the diagonal nature of shear cracks, the induced tensile forces are typically oriented at an angle with respect to the stirrups and consequently the stirrups’ tensile strength in the direction of the fibres cannot be fully developed [2]. Bending of FRP stirrups to develop sufficient anchorage could also lead to a significant reduction of the capacity [3,4,5].

**RESEARCH SIGNIFICANCE**

This research program provides design guidelines for the use of FRP as stirrups for shear reinforcement of concrete structures. Based on an experimental investigation using different types of material, stirrup spacing, bar diameter, stirrup anchorage and embedment length, the strength of FRP stirrups is proposed. Test results were used to evaluate the strength of FRP stirrups as affected by the embedment length and bending of the bars to achieve the appropriate anchorage. Direct comparisons were made between FRP bars and steel bars when used as shear reinforcement.

**EXPERIMENTAL PROGRAM**

**Materials**

Three types of FRP reinforcement were used in this experimental program, Carbon FRP Leadline bars produced by Mitsubishi Chemical corporation, Japan, Carbon Fibre Composite Cables (CFCC) produced by Tokyo Ropes, Japan, and Glass FRP C-BAR produced by Marshall Industries Composites Inc., Lima, Ohio. Figure 1 shows the various types of the FRP bars. Table 1 shows the characteristics of FRP reinforcements, as reported by the manufacturing companies, including the 6.35 mm steel bars used for the control specimens. The FRP stirrups were delivered prefabricated. It is reported that the curing process of the FRP stirrups included a heating process which could affect the strength of the stirrups at the bent zone. Figure 2 shows the different configurations of the FRP stirrups used in this experimental program. The steel stirrups, used in this experimental program, have the same configuration as the GFRP stirrups, however, they
were produced as a continuous bar. The concrete used had an average 28-day compression strength of 50 MPa, and an average tensile strength of 4 MPa, based on splitting test of concrete cylinders.

**CFRP**
- CFCC 7-wire  5.0 mm
- CFCC single wire  5.0 mm
- CFCC 7-wire  7.5 mm
- Leadline (rect. section) 5x10 mm

**GFRP**
- C-BAR  12 mm

Figure 1. Carbon and Glass FRP Bars Used for the Stirrups

Figure 2. Stirrup Configurations
Table 1. FRP and steel bars properties

<table>
<thead>
<tr>
<th>Type of Bar</th>
<th>CFRP</th>
<th>CFCC</th>
<th>GFRP</th>
<th>Deformed Steel bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leadline bar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rect. sec.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5x10mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal diameter $d_b$ (mm)</td>
<td>5.0</td>
<td>5.0</td>
<td>7.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Nominal area $A_b$ (mm²)</td>
<td>38.48</td>
<td>15.20</td>
<td>10.10</td>
<td>30.40</td>
</tr>
<tr>
<td>Guaranteed strength $f_{gs}$ (MPa)</td>
<td>1800</td>
<td>1842</td>
<td>1782</td>
<td>1875</td>
</tr>
<tr>
<td>Ultimate tensile strength $f_{uu}$</td>
<td>N/A**</td>
<td>2170</td>
<td>1810</td>
<td>1910</td>
</tr>
<tr>
<td>Elastic modulus $E$ (GPa)</td>
<td>140</td>
<td>143</td>
<td>137</td>
<td>137</td>
</tr>
<tr>
<td>Maximum strain $\varepsilon_{uu}$ (%)</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* yield strength
** Not available

Panel Specimens

A total of 40 specially designed specimens using different types of CFRP, GFRP and steel stirrups were tested. The configuration and dimensions of a typical specimen are shown in Figure 3. The embedment length within the blocks was varied by using different lengths of plastic tube for debonding which was secured in place using duct tape as shown in Figure 3. The dimensions of each concrete block were 200 x 250 x 200 mm. The free length of the stirrup between the two blocks was kept constant as 200 mm.

![Diagram of Panel Specimens](image)

Figure 3. Details of Panel Specimens

Three different embedment lengths, $l_d$, were selected for this study, as given in Table 2. Two types of specimen details were tested in this study, as shown in Figure 3. For Type A specimens, the anchored end of the stirrup was debonded to simulate the performance
of stirrups with a standard hook. In Type B specimens, the stirrups were debonded only at the continuous end of the stirrup.

Table 2. Panel Specimens

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Nominal diameter db (mm)</th>
<th>Effective diameter de = \sqrt{\frac{4A_b}{\pi}} (mm)</th>
<th>(r_b/d_b)</th>
<th>Embedment length (l_d) (mm)</th>
<th>Stirrup anchorage type</th>
<th>Failure stress (f_u) (MPa)</th>
<th>(f_{u}/f_{ig})</th>
<th>Mode of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFCC</td>
<td>5 mm (7-wire)</td>
<td>3.59</td>
<td>3.0</td>
<td>150</td>
<td>A</td>
<td>2145</td>
<td>1.20</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td>1975</td>
<td>1.11</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>916</td>
<td>0.51</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>B</td>
<td>2145</td>
<td>1.20</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td>2156</td>
<td>1.21</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>1455</td>
<td>0.82</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>5 mm (single wire)</td>
<td>4.40</td>
<td>3.0</td>
<td>150</td>
<td>A</td>
<td>1957</td>
<td>1.06</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td>1973</td>
<td>1.07</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>983</td>
<td>0.53</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>B</td>
<td>1957</td>
<td>1.06</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td>1949</td>
<td>1.06</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>1187</td>
<td>0.64</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>7.5 mm (7-wire)</td>
<td>6.22</td>
<td>3.0</td>
<td>150</td>
<td>A</td>
<td>1900</td>
<td>1.01</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td>1421</td>
<td>0.76</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>798</td>
<td>0.43</td>
<td>B</td>
</tr>
<tr>
<td>Leadline</td>
<td>Rect. sec. (5x10mm)</td>
<td>7.0</td>
<td>3.0</td>
<td>150</td>
<td>B</td>
<td>1242</td>
<td>0.69</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td>1335</td>
<td>0.74</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>715</td>
<td>0.40</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>B</td>
<td>1163**</td>
<td>0.65</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td>988</td>
<td>0.55</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>858</td>
<td>0.48</td>
<td>B</td>
</tr>
<tr>
<td>C-BAR</td>
<td>12.0 mm</td>
<td>12.0</td>
<td>4.0</td>
<td>150</td>
<td>B</td>
<td>586</td>
<td>0.82</td>
<td>SP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>346**</td>
<td>0.49</td>
<td>B</td>
</tr>
<tr>
<td>Steel</td>
<td>6.35</td>
<td>6.35</td>
<td>3.0</td>
<td>150</td>
<td>A</td>
<td>770</td>
<td>1.28</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td>757</td>
<td>1.26</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>593</td>
<td>0.99</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>B</td>
<td>770</td>
<td>1.28</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(r_b+d_b)</td>
<td></td>
<td>669</td>
<td>1.12</td>
<td>B</td>
</tr>
</tbody>
</table>

* Mode of failure: M between the concrete blocks; B at bent; E rupture at end of debonding inside the block; SP splitting of the concrete blocks

** reported for both type A and type B specimen configurations

*** average value for two typical specimens

Test Procedure - The test setup, shown in Figure 4, consisted of a 500kN (112.5kip) hydraulic jack, used to apply the relative displacement between the two concrete blocks.
and a 333kN (75 kip) loadcell to measure the applied load. Electrical strain gauges and 50mm-extensometers were attached to each leg of the stirrup.

![Image of test setup - Panel Specimens](image)

Figure 4. Test setup - Panel Specimens

**Beam Specimens**

A total of six beams were tested. Three beams were reinforced for shear by CFRP Leadline stirrups, one beam was reinforced by GFRP C-BAR stirrups, one beam reinforced by steel stirrups, and the last beam without shear reinforcement. The cross section of the tested beams was a T-section with a total depth of 560 mm and a flange width of 600 mm as shown in Figure 5. The beams were reinforced for flexure using six non-prestressed 15 mm (0.6 in.) steel strands with high yield strength and relatively low dowel resistance compared to conventional steel bars. Beams were designed to fail in shear while the flexural reinforcement is within the elastic range to simulate the linear behavior of FRP. The beam without shear reinforcement was used as a control beam to account for all concrete contribution including the dowel action of the steel strands used for flexural reinforcement which are normally weaker than conventional steel reinforcement. The beams consisted of a 5.0 meter simply supported span with 1.0 meter projections from each end to avoid bond-slip failure of the flexural reinforcement. The shear span was taken as 1.50 m, corresponding to a shear span-to-depth ratio of 3.2. Only one shear span was reinforced with FRP stirrups, while the other shear span was reinforced using closely spaced steel stirrups, as shown in Figure 5. The stirrup spacings used for the CFRP stirrups were 0.5, 0.33, and 0.25 of the effective depth d. Details of the tested beams are summarized in Table 3.
**Test Procedure** - Two equivalent symmetric loads were applied to the simply supported beam specimens through a strong spreader beam, using an MTS universal testing machine. A monotonic static load was applied using stroke control mode. Instrumentation of the beam included Linear Voltage Displacement Transducers (LVDTs) for deflection measurement, displacement gauges (PI gauges) for strain measurements on the concrete surface, and electric strain gauges attached to the stirrups. 200mm-PI gauges were mounted on the web surface in three directions, as shown in Figure 6, to evaluate the shear crack width and slide.

![Diagram of beam specimens](image)

Figure 5. Details of Beam Specimens

<table>
<thead>
<tr>
<th>Beam ID</th>
<th>Stirrups</th>
<th>$E_f/E_s$</th>
<th>Spacing</th>
<th>Shear rft ratio $\rho_v = A_v/b.s$</th>
<th>Mode of failure</th>
<th>Measured $\nu_s = (V_s - V_{cr})/b.d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1</td>
<td>----------</td>
<td>1</td>
<td></td>
<td>0.40 %</td>
<td>S - DT</td>
<td>---</td>
</tr>
<tr>
<td>Beam 2</td>
<td>Steel</td>
<td>d/2</td>
<td></td>
<td>0.40 %</td>
<td>S - Y</td>
<td>3.27 MPa</td>
</tr>
<tr>
<td>Beam 3</td>
<td>CFRP</td>
<td>d/2</td>
<td></td>
<td>0.24 %</td>
<td>S - R</td>
<td>3.34 MPa</td>
</tr>
<tr>
<td>Beam 4</td>
<td>Leadline</td>
<td>d/3</td>
<td></td>
<td>0.36 %</td>
<td>S - R</td>
<td>4.33 MPa</td>
</tr>
<tr>
<td>Beam 5</td>
<td>GFRP</td>
<td>0.70</td>
<td></td>
<td>0.47 %</td>
<td>S - R</td>
<td>4.89 MPa</td>
</tr>
<tr>
<td>Beam 6</td>
<td>GFRP</td>
<td>0.21</td>
<td></td>
<td>0.71 %</td>
<td>S - R</td>
<td>3.55 MPa</td>
</tr>
</tbody>
</table>

* S-DT : diagonal Tension failure; S-Y : shear failure initiated by yielding of the steel stirrups; S-R: shear failure initiated by rupture of the FRP stirrups
TEST RESULTS AND DISCUSSION

Stirrup Capacity

Test results of the 40 concrete block specimens tested in this study are given in Table 2 including the measured stresses in the stirrups at failure and the failure mode.

CFCC stirrups - For the 7.5 mm CFCC stirrups, the largest diameter used in this study, it was noticed that regardless of the embedment length $l_d$ used, failure occurred at the bent zone. However, for the longest embedment length, the measured strength was found to be equal to the guaranteed strength $f_{tg}$ parallel to the fibres. For the smallest embedment length, the measured strength was only 43 percent of the guaranteed strength in the direction of the fibres. For smaller diameter CFCC stirrups, different modes of failure occurred as listed in Table 2. It should be mentioned that the ultimate tensile strength $f_{tu}$ parallel to the fibres for CFRP bars is always higher than the guaranteed value $f_{tg}$ reported by the manufacturer. Results indicated that for a sufficient embedment length of 150 mm or more, the stirrup could develop the full strength in the direction of the fibres.

Leadline stirrups - For the different values of radius of bend $r_b$, failure always occurred at the bent zone as a result of bond loss between the fibres and the outer resin coating of the bar. None of the tested Leadline stirrups achieved the guaranteed strength parallel to the fibres. The strength at the bend could be as low as 40 percent of the strength parallel to the fibres.
C-BAR stirrups - A total of 15 typical specimens were tested for an embedment length of \( r_b + d_b \), in order to examine the variability of the test results. All of the tested specimens failed at the bent zone, giving an average strength of 346 MPa, and a standard deviation of 26 MPa. Results indicated that the strength at the bend is about 49 percent of the guaranteed strength parallel to the fibres.

Eq. (1) proposed by the JSCE [6], for a \( r_b/d_b \) ratio of 3.0, used in this investigation predicts a stirrup strength \( f_u \) of 45 percent of the guaranteed strength \( f_{ig} \) at the bend which is close to the values measured in this investigation.

\[
f_u = (0.05 \frac{r_b}{d_b} + 0.3) f_{ig}
\]

where \( r_b \) is the radius of the bend for a nominal diameter \( d_b \) of the FRP bent bar.

Effect of Embedment Length

In general, test results indicated that decreasing the embedment length decreases the strength capacity of the stirrups. The strength reduction is attributed to a reduction of the bond along the length leading to exposure of the bent portion of the stirrup to the load. For the small diameter CFCC stirrups, with \( d_b \) ranging from 5 to 7.5 mm in this study, it is suggested that a 150 mm embedment length could be sufficient to eliminate direct stressing of the bent portion of the stirrups, therefore, the guaranteed strength in the direction of the fibres can be fully developed. A summary of the stirrup strength as a result of varying the embedment lengths for the different types of CFRP stirrups considered in this study is given in Table 2.

To establish a relation between the embedment length \( l_d \) and the strength of the stirrups \( f_u \), the relationship is presented in dimensionless format with respect to the effective bar diameter \( d_e \) and the guaranteed strength \( f_{ig} \) parallel to the direction of the fibres, respectively, as shown in Figures 7 and 8. This relationship indicates that the reduction in the strength starts below a certain value of \( l_d/d_e \) ratio for each type of stirrup. This value was found to be in the range of 20 for the CFCC type A stirrups and 15 for type B stirrups. Using the value of \( l_d/d_e \) of 5.0 typically provided at the bend, the measured average strength for CFCC stirrups using type A and B were 50 and 74 percent, respectively, as shown in Figure 7. Figure 8 indicates that the limiting value for \( l_d/d_e \) for the Leadline stirrups to achieve the guaranteed strength \( f_{ig} \) parallel to the direction of the fibres is 35. Using a small development length could reduce the strength to 40 percent, as shown in Figure 8. The given equations in Figures 7 and 8 can be used to evaluate the strength capacity of the stirrups \( f_u \) with smaller embedment lengths than the recommended values. Testing of additional panel specimens reinforced by GFRP is currently in progress to evaluate the development length for the GFRP C-BAR stirrups.
Figure 7. Effect of embedment length $l_d$ on strength of CFCC stirrups

Figure 8. Effect of embedment length $l_d$ on strength of Leadline stirrups

**EFFECT OF STIRRUP ANCHORAGE**

Significant reduction in the stirrup capacity was observed in type A anchored stirrups (standard hook) as compared to type B anchored stirrups, as shown in Figure 7. This reduction is attributed to possible slip at the hook leading to initiation of failure at a lower stress level in this zone.
BEAM TESTS

All the tested beams failed in shear by rupture of the FRP stirrups at the bent zone, as shown in Figure 9 and yielding of the steel for the control beam. A summary of the beam test results is presented in Table 3.

![Failure at bent](image)

Figure 9. Beam specimen at failure and close-up

**Contribution of FRP Stirrups** - The shear capacity of a concrete beam without shear reinforcement, $V_{cr}$, is always measured as the applied load which causes the initiation of the first shear crack. At this stage, the major shear crack width increases dramatically. The contribution of the FRP stirrups to the shear carrying capacity of concrete beams was evaluated based on the difference between the measured ultimate shear load $V_u$ and the measured load at the initiation of the first crack $V_{cr}$. Based on the 45-deg truss model, which is adopted by many codes (e.g. ACI318-95 eq. 11-5), the stirrup capacity at failure $f_u$ can be determined as follows:

$$f_u = \frac{(V_u - V_{cr}) s}{A_v d}$$  

(2)
where, \( A_s \) is the area of the stirrups, \( s \) is the stirrup spacing, and \( d \) is the effective beam depth. Figure 10 shows the stirrup capacity at failure for the different spacing values, \( s \), used in this study. Test results indicate that strength of the stirrups could be as low as 54 percent of the strength in the direction of fibres. It was also observed that for closely spaced stirrups, there is a higher chance for the diagonal cracks to intersect the bent zone of the stirrups which could lead to a lower shear carrying capacity of the stirrups.

![Graph showing the effect of stirrup spacing on stirrup stress at failure](image)

**Figure 10. Effect of stirrup spacing on stirrup stress at failure**

**General Behavior and Shear Cracking** - At the early stage of loading, flexural cracks were observed in the region of pure bending at the same load level for all of the tested beams. With a further increase in load, additional flexural cracks were formed in the shear spans between the applied load and the support. The shear cracking load was monitored by three techniques in addition to the visual observation of cracks. The three techniques were based on monitoring of the stirrup strains, the surface concrete strain within the shear span, and the concrete strains along the web.

After shear cracking, the behavior of the beams was influenced by the shear reinforcement. The reading of the PI gauges mounted on the web were used to determine shear crack width along the gauge length, as illustrated in Figure 11. Considering the PI gauges in diagonal and vertical directions, the shear crack width \( w \) can be determined as follows:

\[
w = \left( \sqrt{2} \Delta_D - \Delta_V - 0.5l \varepsilon_{ct} \right) \sin \theta + \left( \Delta_V - 0.5l \varepsilon_{ct} \right) \cos \theta
\]

where, \( \theta \) is the measured crack angle to the horizontal axis of the beam, \( l \) is the gauge length, \( \varepsilon_{ct} \) is maximum tensile strain of concrete \( (0.1 \times 10^{-3}) \), and \( \Delta_D, \Delta_V, \Delta_D \) are the displacements measured by the PI gauges, as described in Figure 11. Similar equations can be used to determine the shear crack width by considering either \( \Delta_D \) and \( \Delta_H \) or \( \Delta_V \) and
The shear vs. crack width for the beams reinforced with CFRP stirrups are shown in Figure 12, compared with the control specimens. It can be seen in Figure 12 that low values of crack width were observed for beams with a higher shear reinforcement ratio $\rho_v$. It is also observed that the beam with 0.4% steel stirrups falls between the two beams with CFRP stirrups of 0.36% and 0.47%. Therefore, it can be concluded that the beam with CFRP stirrups could have the same behavior as the beams with steel stirrups despite the relatively low elastic modulus of the CFRP material.

Figure 11. Determination of Shear Crack Width

Figure 12. Shear vs. Crack width - Beams with CFRP Stirrups
For the same stirrup spacing of 0.5 d, Figure 13 shows the shear vs. crack width for three beams reinforced with CFRP, GFRP, and steel stirrups. It can be seen in Figure 13 that the beam with GFRP stirrups with double the shear reinforcement ratio $\rho_v$ behaves similarly to the one with steel stirrups. Doubling the shear reinforcement ratio $\rho_v$ minimized the effect of the low elastic modulus of the GFRP material $E_r$, which is about 20% of $E_s$. It can be also seen that high crack width values were observed for the beam with CFRP stirrups, even though the stiffness index $\{E_r\rho_v\}$ is higher for this beam than the one reinforced with GFRP stirrups.

![Figure 13. Shear vs. Crack width - Beams with Stirrup Spacing = d/2](image)

**CONCLUSIONS**

Fourty specially designed specimens and six reinforced concrete beams were tested. The effects of the embedment length, bar diameter, and stirrup anchorage on the performance of the FRP stirrups were investigated. Based on the results of the experimental program, the following conclusions can be drawn:

1. A decrease in the embedment length $l_d$ of the stirrup increases the possibility of failure at the bent zone of the stirrup resulting in an average strength 40 percent of the strength in the direction of the fibres.

2. A limiting value for the embedment length to diameter $l_d/d_c$ ratio of 20 for the CFCC type A stirrups (standard hook), 15 for the CFCC type B stirrups and 35 for the Leadline stirrups is sufficient to develop the full guaranteed strength of the stirrups in the direction of the fibres. For an embedment length to diameter ratio less than the limiting values, the strength can be predicted using the proposed equations.

3. Failure in the Leadline specimens is mainly due to loss of bond between the fibres and the outer resin coating. The same conclusion was also observed for the beams reinforced for shear by Leadline stirrups.
(4) Using small spacing of stirrups to increase the shear capacity of beams, could increase the chance for shear cracks to intersect the bent zones and consequently cause a significant reduction of the stirrups capacity.

(5) Based on the beam tests and using practical spacing for the stirrups, it is recommended to limit the strength of CFRP stirrups to 50 percent of the guaranteed strength parallel to the direction of the fibres.

(6) The relatively inexpensive GFRP stirrups could be a good alternative for shear reinforcement.

ACKNOWLEDGMENTS

Funds for this program were provided by the ISIS Canada Network of Centres of Excellence on Intelligent Sensing for Innovative Structures and Natural Sciences and Engineering Research Council of Canada (NSERC). Special thanks extended to Mr. Moray McVey for his valuable contribution in constructing and testing of the specimens.

REFERENCES


