EXPERIMENTAL INVESTIGATION ON FRP SHEETS BONDED TO CONCRETE

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The work presented here forms a part of a larger effort carried out at the University of Alberta to investigate rehabilitation of existing reinforced concrete structures with externally bonded FRP sheets. The effort included physical testing of full-scale specimens, small detailed material tests, field monitoring and numerical analysis. This paper presents a detailed experimental study on the interfacial behavior of fiber reinforced polymer (FRP) sheets when applied to concrete members as external reinforcement. A modified push-apart test method was proposed and tested. The proposed method was compared to the pull-apart test method in separate test series independently investigating the bond behavior and failure mechanism of FRP sheets bonded to concrete. An experimental test method to determine the effective bond length was also proposed and tested. It was concluded that the test methods used affect the test results. Conversion factors and approaches are explored to allow determination of the effective bond length from either method.

INTRODUCTION

Understanding of the behavior of bonded FRP materials is not complete. Recent developments in composite material technologies require not only basic knowledge of the material properties of each new product but also knowledge of the interfacial behavior. The local bond strength when delamination occurs and the average bond strength when the maximum tensile force in the FRP is reached are dependent on many factors such as the bond length, bond width, the stiffness of the bonded sheet, and the concrete strength. Two series of tests were carried out in order to study the effect of the FRP sheet dimensions on the bond behavior. The first series of tests used a modified push-apart specimen, while the second consisted of pull-apart specimens. Both series were instrumented with the objective of assessing the test methods, comparing the results of each method and investigating the strain distribution.

MODIFIED PUSH-APART TEST (S-SERIES)

Each specimen in this series was a rectangular concrete block with a rectangular empty core in the center. Metal sheets were placed along the width of the specimen arms in their center to force the crack to form in that location. The specimen rebar was detailed in such a way to prevent the failure of the inner concrete corner. The arrangement of CFRP sheets bonded to the arms of the specimen eliminates the compression field in the concrete within the test region, on which the sheets are bonded, thus closely simulating a crack in a beam. One side of the FRP sheets has an anchor sheet bonded along the width to force the failure to be on the other (tested) side. Details of the specimen are shown in Figure1.

Strain gauges with 5 mm gauge length were applied to the face of the CFRP sheets on the tested side at various locations in order to measure the strain distribution along the length and width of the CFRP sheets. Each specimen was laid on a flat smooth steel surface on which it was free to slide. A 220 kN capacity hydraulic jack placed in the center of the hollow core applied the load in stroke control with a rate of 0.05 mm/min. A 220 kN capacity load cell located between the hydraulic jack and the steel plate measured the applied load. An LVDT inside the hydraulic jack was used to measure the displacement at the center of the specimen and was also used in

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regulating the stroke applied by the jack. Figure 3 shows a view of the modified push-apart test set-up and instrumentation.

Specimen S2, S3, and S5 all had the same bond widths of 150 mm but different bond lengths of 50, 100, and 150 mm, respectively, in order to study the bond length effect on the bond behavior. The lengths were chosen based on previous studies in the literature\textsuperscript{3,6,7,11}, which showed the effective bond length to range between 60 and 110 mm. Specimens S4 and S5 had a bond length of 150 mm but different bond widths of 100 and 150 mm, respectively, in order to study the bond width effect on the bond behavior.

The CFRP width values were taken based on strip widths typically used in practical beam repairs\textsuperscript{3}. Specimen S1, S3, and S4 all had the same CFRP sheet bond area of 15,000 mm\textsuperscript{2} but each had a different L/w ratio in order to study the FRP sheet L/w ratio effect on the bond behavior. Table 1 lists the variables for the modified push-apart test specimens.

<table>
<thead>
<tr>
<th>Test #</th>
<th>L (mm)</th>
<th>w (mm)</th>
<th>$P_u$ (kN)</th>
<th>$\tau_b$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>75</td>
<td>200</td>
<td>54.81</td>
<td>1.83</td>
</tr>
<tr>
<td>S2</td>
<td>50</td>
<td>150</td>
<td>39.85</td>
<td>2.66</td>
</tr>
<tr>
<td>S3</td>
<td>100</td>
<td>150</td>
<td>56.40</td>
<td>1.88</td>
</tr>
<tr>
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<td>150</td>
<td>100</td>
<td>42.71</td>
<td>1.42</td>
</tr>
<tr>
<td>S5</td>
<td>150</td>
<td>150</td>
<td>53.52</td>
<td>1.19</td>
</tr>
</tbody>
</table>

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**Table 1. Modified Push-apart details**

Figure 1. Mod. push-apart (a) plan (b) side

**Figure 2. Pull-apart specimen layout**

**PULL-APART TEST (P - SERIES)**

Each specimen in this series was a concrete prism with two embedded concentric steel bars in the center. Metal sheets placed at mid height acted as crack initiators when the load is applied. Figure 2 shows typical specimen dimensions and details. Strain gauges were applied on the tested side of specimens P9 through P13 to study the strain distribution along the length and width of the sheets and to compare the results with previous results from the S-series.

Each specimen was placed vertically in the testing machine. The specimen top and bottom bars were secured in the upper and lower head of the MTS machine, respectively, using hydraulic grips. The test was conducted in stroke control with a rate of 0.05 mm/min.

Specimens P1 through P8 were used to investigate an experimental procedure to determine the effective bond length. The FRP sheet width was taken as 100 mm in all eight specimens and the sheet bond length was varied from 0.6 to 2.0 of an estimated effective length $L_e$. The anticipated effective length, $L_e$, was estimated using\textsuperscript{11}:

$$L_e = \frac{25350}{(t_p \cdot E_p)^{0.58}}$$

where $t_p$ and $E_p$ are the FRP thickness in mm and modulus of elasticity in MPa, respectively. The values of $t_p$ and $E_p$ were assumed 0.51 mm and 45,000 MPa, respectively. The value of $L_e$ based on the previously stated values was calculated to be 75 mm.

Specimens P9, P10, and P11 were used to study the bond length effect and had bond lengths of 50, 100, and 150 mm, respectively, but a constant bond width of 150 mm. Specimens P12, P13, P8, and P11 had a bond length of 150 mm and bond widths of 25, 50, 100, and 150 mm, respectively, and were used to study the sheet width effect on the bond behavior. The pull-apart specimens P9 through P13 had the same FRP sheet bond length and width as the specimens in the S-series in order to directly investigate the influence of the test methodology.
The manufacturer's recommendations and procedures. The sheets were bonded to the concrete according to epoxies. The putty used was a two-component epoxy. Two-component, high-modulus, and high-strength series. The primer and resin used were average bond strength listed in Table 1 was calculated by the remaining portion of the sheet is an irregular thin layer. The metal sheet placed in the specimen arm to metal sheet to the concrete while the P-series simulates a failure at which the crack is developed after bonding the CFRP sheets while the P-series simulates a failure at which the CFRP sheets are bonded to a pre-cracked concrete surface. Load Transfer along CFRP Sheet Length

Figure 3 shows typical average strain distributions at the center of the CFRP sheets along the length at different load levels for the S-series. Similar results were obtained from the P-series. The figure shows that as the load increases the strain values increase across an increasing portion of the bond length, indicating that more bond area is mobilized. The strain distribution in the figure also shows a change in trend as the load increases. The strain distribution beyond the 25 mm position is concave at lower loads then transforms into a convex shape as the load reaches 70% of the ultimate load. The change in the strain distribution trend with a large increase in the strain values is similar to a snap-through behavior and signals that debonding of the CFRP sheet is underway. Figure 4 shows the load plotted against the estimated transfer length for specimens S2, S3, and S5. All three had a bond width of 150 mm. The term transfer length is defined here as the distance from the fracture location to the point where the strain is negligibly small. The figure shows that the transfer length increases as the load increases. The increase in the transfer length at the lower load levels was almost constant but the rate then increased rapidly at the higher loads for specimens with bond lengths above the effective length, as seen by the steeper slopes for S3 and S5. The same behavior also occurred in the P-series. Load transfer across CFRP sheet width

Figure 5 shows a typical strain distribution across the CFRP sheet width at the crack location. The figures show that the strain distribution across the sheet width did not have a defined trend as a whole. The strain values at the edge were always higher compared to those at the center of the sheet, while the strain values...
half way between the center and the edge of the sheet fluctuated relative to those at the center. At the crack location, the increase in the average strain value at the edge of the sheet over that at the center of the sheet at ultimate load ranged from 9.3% to 134% and averaged 58% for the S-series. The average value was 39%, excluding S2, which had bi-directional CFRP sheets. For the P-series, the increase in the average strain value at the edge of the sheet compared to that at the center of the sheet at the ultimate load ranged from 8% to 48.6% and averaged 31%.

**Bond Length**

The modified push-apart specimens S2, S3, and S5 had the same bond width of 150 mm, but had bond lengths of 50, 100, 150 mm, respectively. Figure 6 shows the load response plotted against the deflection for these specimens. It was observed from the curves that the specimens had the same trend except for specimen S2, which was pre-cracked and showed a slightly softer behavior. The ultimate capacity also increased with increasing the bond length but to a certain limit. This is apparent from specimens S3 and S5 with bond lengths of 100 mm and 150 mm, respectively, where there was no significant change in the ultimate capacity with the increase in bond length. The same behavior occurred in the P-series as shown in Figure 8, where P10 and P11 exhibit similar strength with larger bond lengths than that of P9. It is concluded that the bonded length beyond a certain distance from the crack causes no increase in the ultimate capacity of the joint. This distance is referred to as the effective bond length. The expression “joint” used here refers to the assembly of concrete, adhesive, and FRP sheet. This conclusion is similar to the findings of other researchers in the literature1, 3, 6, 7, 11.

For a given configuration (sheet width, stiffness, surface conditions, etc.), ultimate strength develops over this effective length, and then debonding propagates through the rest of the sheet without a limit. The value of the effective length depends on many variables of which the most significant, according to the literature, are the sheet stiffness and the concrete tensile strength10. The S-series average bond stress value was 2.06 MPa. The average τ_b values for conventional push-apart tests studied in the literature1, 6 averaged 2.45 MPa. The difference in the τ_b values is due to the different concrete strengths, CFRP stiffness, and test specimens configurations used.

Examination of the strain distribution in the center of the CFRP sheet along the bond length for specimens S2, S3, and S5 shows and for P9, P10 and P11 showed that there was no significant difference between the strain distribution of specimens S3 and S5 and also between those of P10 and P11. This indicates that the strain distribution and magnitude does not change on increasing the bond length beyond the effective bond length. However, the strain values at the crack location were higher for specimens S2 and P9 with a smaller...
bond length. This indicates that specimens S3 and S5 with larger bond lengths had better stress distributions.

Evaluation of the effective bond length should follow the procedure outlined by specimens P1 through P8, in which for a given bond width the bond length was increased at constant increments. This procedure is also adopted in Annex J of the CSA-S806-02 (2002). The load response plotted against the deflection for specimens P1 through P8, with the exception of P6 as discussed previously show the same trend but with different ultimate loads and displacement values. Specimen P7 showed a slightly softer behavior and a reduced ultimate load caused by air voids under the CFRP sheets that created discontinuity in the glue joint and reduced the area. The figure also shows that the maximum displacement increases as the bond length increases, which maybe interpreted as an increase in the ductility of the joint as the bond length increases.

The ultimate loads achieved are next plotted against the bond lengths in Figure 7. A moving average trend line was added and a linear approximation was plotted manually. The linearized moving average trend line is bilinear with an inclined segment and a horizontal segment. The intersection of the segments indicates the location of the effective bond length, which is estimated to be 80 mm in this case.

**Bond Width**

The load displacement responses for specimens S4 and S5 with bond widths of 100 and 150 mm, respectively and with equal bond lengths of 150 mm showed that increasing the bond width in specimen S5 by 50% over that of specimen S4 (from 100 mm to 150 mm) increased the ultimate load by only 25.31%. This resulted in the average bond strength decreasing as the sheet width increased. This conclusion is similar to that of Ueda et al. (1999)12. The behavior is illustrated in more detail in Figure 8, in which the CFRP sheet bond width is plotted against the ultimate load and the average bond strength for specimens P12, P13, P8, and P11, which had bond widths of 25, 50, 100, and 150 mm, respectively but had a constant bond length of 150 mm. The figure shows that the ultimate load increases as the bond width increases. The figure also shows that increasing the bond width decreases the average bond strength to a certain limit at which the bond strength stabilizes with the increase in the bond width. This indicates the existence of an effective bond width beyond which no increase in the average bond strength is obtained. For example, increasing the width of P11 by 50% over that of P8 increased the ultimate load proportionately by 52.6%. This resulted in no change in the average bond strength as the bond width significant increased. This behavior is similar to other findings in the literature6.

The behavior is explained through variable strain distribution across the width as shown above. Higher strains at the sheet edges relative to mid sheet strains are observed in wider sheets, whereas narrow sheets tend to have more uniform strain distributions. Most previous studies3, 2 are based on narrow sheet widths, mostly 25 mm. This results in the average bond stress being higher compared to sheets used in actual practice, which tend to be much wider than 25 mm.

**Test Method**

Both methods considered here are indirect test methods. Both test methods exhibited similar failure modes. The amount of concrete that stayed bonded to the CFRP sheet after failure was different in each test method due to the difference in the crack initiator distance from the concrete face to which the CFRP sheets were bonded. This caused the S-series to behave as an uncracked strengthened member while the P-series behaved as a pre-cracked strengthened member. The load-displacement relationships for specimens in the two test methods with similar bond widths of 150 mm were essentially the same but with different magnitudes as shown in Figure 6.

When one compares the strain distributions along the length of the sheet from both the S-series and the P-series at different load levels. Although the strain
gauge locations were different, there was no significant difference between the strain distributions in the two methods when the load levels were both above or both below 70% of the ultimate load level. When the load level in one method was above 70% the ultimate load while the other method was below that level, there appeared to be a difference in the strain distribution, as shown in the figure at 30 kN.

SUMMARY AND CONCLUSIONS
This paper presents the results of experimental series in which two test methods of CFRP sheets externally bonded to concrete specimens were pulled. The loads, displacements, strain distributions along the length as well as across the width of the sheets were recorded. Sheet widths varied form 25 to 250 mm, whereas the bond length was varied from 50 to 250 mm. A number of observations were made and some conclusions were reached. Most importantly, the existence of an effective bond length beyond which no increase in the bond strength is observed is confirmed. The average bond strength on the other hand was found to decrease with an increase in the width of the sheet. But this is also limited by an effective bond width beyond which the average bond strength remains constant as the sheet width is increased. The effective bond length and the effective bond width do not appear to be related. This observation, however, may require further investigation.

ACKNOWLEDGMENTS
The Authors acknowledge the financial support of the Canadian Network of Centers of excellence on Intelligent Sensing for Innovative Structures (ISIS Canada), the Natural Sciences and Engineering Research Council of Canada (NSERC), and Mitsubishi-Kasei Corp. of Japan.

REFERENCES