EFFECT OF VARIED SURFACE ROUGHNESS AND CONCRETE STRENGTH ON THE BOND PERFORMANCE OF FRP FABRICS

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Abstract: The use of externally bonded fiber reinforced polymer (FRP) fabrics to strengthen and rehabilitate existing concrete structures has recently received a great deal of attention within the Civil Engineering community. Numerous experimental studies have demonstrated the effectiveness of externally bonded FRP strengthened reinforced concrete (RC) structures. The overall performance of the strengthened system depends highly upon the bond quality between the concrete and the FRP laminate. Low bond strength can cause delamination and result in a premature failure of a repaired structure.

Failure of RC members strengthened with FRP fabrics may be caused by crushing of the concrete, rupture of FRP laminate, or by the delamination of the FRP laminate. When a peeling or delamination failure can be avoided, a more effective engagement of the FRP sheet occurs which results in more efficient use of material. To that end, an experimental program was undertaken to investigate the effect of a broad range of surface roughnesses and concrete strengths on bond performance. The specimens used in the study were unreinforced concrete beams and prisms that were externally reinforced with CFRP fabrics after varying surface preparation was completed. The specimens were then tested using either a flexural or direct shear test method. Test results indicated that the strength of the concrete substrate, the surface roughness level, and the roughness technique utilized influenced the bond strength of the FRP laminate. The American Concrete Institute (ACI) 440.2R-02 code implications as they relate to the results obtained are also discussed.

Keywords: Bond, Surface Roughness, Externally Bonded Fiber Reinforced Polymer, Mechanical Roughening Devices.

1 Introduction

Concrete structures throughout the world have deteriorated severely due to chloride induced steel corrosion. Due to this problem, there are many structures that are in need of structural repair or rehabilitation. One of the many attempts to address deficient structures is the application of externally bonded Fiber Reinforced Polymer (FRP) composites.

There are many advantages to using FRP materials for the purpose of structural rehabilitation and repair. Those advantages include a higher strength, the ease and ability to form FRP materials to any size or shape no matter how complex, and their lighter weight. The most important aspect of applying the FRP laminate is the bond between it and the concrete substrate. The bonding agent between the two is the epoxy, and with that bond comes the ability to transfer flexural and shear stresses to the FRP laminate through composite action.

An important variable that affects the bond between FRP and concrete is the roughness of the concrete substrate surface. If the surface is too smooth it may develop a poor bond between FRP and concrete. When the surface is left too rough, putty must be placed under the epoxy which adds cost for labor and materials. Therefore, an optimum level of surface roughness exists to achieve optimal bond strength assuming sufficient substrate strength (concrete) is present.

2 Previous Relevant Literature

A brief literature review of sample studies is presented. Chajes et al. [1] studied the bond and force transfer mechanism in FRP plates bonded to concrete by using a single layer shear specimen. Test results show that surface preparation of the concrete can influence the bond strength. Yoshizawa et al. [2] conducted a study on the effect of the type of concrete surface preparation on the bond of carbon FRP. The concrete surface was roughened using either water jetting or sandblasting. It was found that, compared with sandblasting, the water jetting doubled the capacity of specimen. Horiguchi and Saeki [3] studied the effect of the quality of the concrete on the bond of CFRP sheets. Three failure modes were observed: shearing of the

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2.1 Bond Test Methods

There have been many methods of testing developed to qualify the bond between concrete and FRP. These types include pull-off tests, torsion tests, flexure tests, and shear bond tests.

2.1.1 Pull-off Test

The pull-off test consists of a metallic disc being attached to the FRP surface to be tested by epoxy adhesive. Once the epoxy has cured, a core drill is used to isolate the sample from the surrounding FRP. A perpendicular tension force to the surface of the sample is then applied. The load is applied at a constant rate of 0.67 kN/sec (150 lb/sec) until the adhesion fixture fails from the surface. The bond failure stress may then be determined based on the failure load divided by the contact area.

Myers and Shen [7] reported that this test resulted in complete concrete substrate failure for all samples tested, along with a high variability of tensile failure stresses. This testing method was not chosen for the research discussed herein due to the variability in results previously noted. However, this test method has been used as a bond verification test method often specified at 1.4MPa (200-psi) [8].

2.1.2 Torsion Test

The torsion test consists of a metallic disc being attached to the final epoxy layer of the cured FRP. A torque is then applied and measured until failure of the bond at which point the bond strength may be computed after simplification [7] as the failure torque divided by the disc radius$^3\times\pi$ for a circular disc.

Myers and Shen [7] reported that this test resulted in incomplete concrete substrate failure for all specimens tested in their study with FRP debonding being observed on less than 10% for each. High variability was also reported for this test method.

2.1.3 Flexure Test

The flexure test is among the most popular tests used to conduct this type of research due mostly to the understanding that today’s researchers possess for it. There have been two main types of flexure tests conducted consisting of both three-point and four-point bending. Both of the projects described here used a four-point loading setup. Recent research at the University of Missouri-Rolla (UMR) used an inverted T-beam [4]. The specimen used for this research was different than most flexure tests in that at mid-span of the section there was a saw-cut along the bottom and a steel hinge at the top. Therefore, through this design, the compressive force at the mid-span of the beam was located at the center of the hinge and the internal moment arm was known and constant for any given load level above the cracking load [4]. By doing this, the researchers were able to accurately compute the tensile strength of the FRP.

Myers and Shen [7] also conducted a flexure test method, but on a more regular rectangular specimen. Three compressive strength levels were used, namely 13.8MPa (2000-psi), 20.7MPa (3000-psi), and 27.6MPa (4000-psi) respectively. The beams were reinforced using 2-16mm (No. 2) diameter reinforcing bars with 38.1mm (1.5-in.) bottom cover with no shear reinforcement. Once the concrete had time to cure, and before strengthening with FRP could occur, the reinforcement bars were cut to allow the FRP sheet to become effective. CFRP was applied to the beam in a 38.1mm (1.5-in.) width to the tension face of the beam, and a U-wrap was applied transversely to force failure to the monitored side.

Testing was completed once the beams had undergone surface preparation using water jet and strengthening. Surface roughness on the specimens was varied to study the effect the roughness had on the bond strength. Findings of the work reported that the surface roughness had no significant affect on the failure load while working with concrete that has a compressive strength of less than 20.7MPa (3000-psi), but it did have a significant affect with a compressive strength of 27.6MPa (4000-psi) or higher. All specimens were reported to have a delamination failure.

This type of test was not selected for the research discussed herein due to the lengthy preparation time of the beams.

2.1.4 Shear Bond Test

Several researchers [9,10] including work conducted in this study have used direct shear tests to...
evaluate bond performance. This type of test is further described in the experimental program presented herein.

2.2 ACI 440.2R Externally Bonded Laminate Issues

2.2.1 Flexure Design

For flexural design, the ACI 440.2R design guide defines the knock down factor \( k_m \) that reduces the strain in the FRP to evaluate that would account for peeling phenomenon [9]. The development of the factor \( k_m \) is purely experimental, as tests have been done to evaluate this factor. The equation for the bond dependent coefficient \( k_m \) is given by the following expression:

\[
1 - \frac{nE_f t_f}{360,000} \leq \frac{90,000}{nE_f t_f} \leq 0.090 \quad \text{for} \ nE_f t_f \leq 180,000 \quad \text{(SI Units)} \tag{1a}
\]

\[
1 - \frac{nE_f t_f}{360,000} \leq \frac{90,000}{nE_f t_f} \leq 0.090 \quad \text{for} \ nE_f t_f > 180,000 \quad \text{(SI Units)} \tag{1b}
\]

Where, \( \varepsilon_{Fu} \) is the ultimate strain of the FRP, \( n \) is the number of plies of FRP, \( E_f \) is the MOE of the FRP (MPa), and \( t_f \) is the thickness of the FRP sheet (mm).

2.2.2 Shear Design

For shear design, the ACI 440.2R [8] design guide suggests the maximum effective strain \( \varepsilon_{Fe} \) should be calculated using a bond reduction coefficient \( k_v \) and should be less than or equal to the limited maximum strain of 0.4% for shear strengthening applications. The equation for the bond reduction coefficient is given by the following expression:

\[
\varepsilon_{Fe} = k_v \varepsilon_{Fu} \leq 0.004 \quad \text{(2)}
\]

Where, \( \varepsilon_{Fe} \) is the maximum effective strain in FRP, \( k_v \) is the bond reduction coefficient, and \( \varepsilon_{Fu} \) is the ultimate strain in the FRP.

This bond reduction coefficient \( k_v \) is a function of the wrapping scheme, the stiffness of the FRP system, and the compressive strength of the concrete, and is given by the following expression:

\[
k_v = \frac{k_c k_{Le}}{11,900 \varepsilon_{Fu}} \leq 0.75 \quad \text{(SI Units)} \tag{3}
\]

The active bond length \( L_e \) is the length over which the majority of the bond stress is maintained. This length is given by the following expression:

\[
L_e = \frac{23,300}{\left( n t_f E_f \right)^{1/3}} \quad \text{(SI Units)} \tag{4}
\]

The bond reduction coefficient \( k_v \) also relies on two modification factors, \( k_1 \) and \( k_2 \), that account for the concrete compressive strength and wrapping scheme used, respectively. These items are given by the following expressions:

\[
k_1 = \frac{d_f - L_e}{d_f} \quad \text{for u-wraps} \tag{6}
\]

\[
k_2 = \frac{d_f - 2L_e}{d_f} \quad \text{for two sides bonded} \tag{7}
\]

Where, \( f'c \) is the concrete compr. strength (MPa), \( L_e \) is the active bond length (mm), and \( d_f \) is the depth of the shear FRP reinf. (mm).

2.3 Optical Methods to Characterize Surface Roughness

Optical methods include optical reflecting instruments, light microscopy, electron microscopy, speckle metrology, interferometry and laser profilometry [11].

The method of light microscopy utilizes a thin slit of light to project that beam of light to the surface at an angle of 45°. The image is then recorded at an angle of 90° from the surface being characterized. With a flat surface, the line of light is straight, and as the roughness increases, the line becomes increasingly surging.

Interferometry and speckle metrology make use of interference fringes produced when monochromatic or laser light is reflected off a rough surface and a flat reference surface [7]. With the use of the reference surface, the fringes become only half of the wavelength of the light used, so these types would only be useful on a roughness with small angulations.

Laser profilometry utilizes reflecting laser light off of the surface, and has been used to measure ocean wave profiles. Maerz et al. [11] reported that among all parameters analyzed using imaging software, the micro-average inclination angle \( i_A \) could precisely give the grades of surface roughness. \( i_A \) is defined as the average of the absolute values of the pixel to pixel angles of the stripe profile:

\[
i_A = \frac{1}{n} \sum_{j=1}^{n} |I_j| \quad \text{(8)}
\]

Where, \( n \) = number of evenly spaced sampling points, \( I = \) inclination angle between points along sampling line.

Previous research has reported that a control specimen with no roughening and a standard trowel finish produces an \( i_A \) value of approximately 6 [12]. For the research discussed herein, the \( i_A \) value will be the parameter measured for the roughness index on all samples.

3 Surface Preparation Techniques

3.1 Manual Grinder

A manual grinder was used for phase I of this research study to investigate if similar bond behavior would result compared to other methods such as sandblasting and water jetting. The manual grinder has several different heads; each designed to produce a different roughness level as shown in Figure 1.
A disadvantage with using the manual grinder was that largely differing roughnesses could not be obtained by the grinding process alone. To produce the differing roughnesses on specimens F2 and F3 of phase I, found in Table 1, an air chisel was used to add the variation. The differing grades of roughness for phase I were measured using a laser profilometer. The resulting $i_A$ values are shown in Table 1.

### 3.2 Water Jet

In general terms, water jetting methods can be classified according to the type of water spray and operation nozzle [7]. Water jetting was used to vary roughness for the test specimens in phase II. Myers and Shen [7] went through numerous laboratory trials to obtain the different grades of surface roughness desired for testing. Values of $i_A$ between 8 and 16 were targeted. This selection was based on the equivalent roughness of the International Concrete Repair Institute (ICRI) plastic surface roughness models from CSP2 to CSP7. For this research, samples in the same range of $i_A$ values were selected. Surface preparation by water jet was conducted in the Water jet Laboratory at UMR.

The varying levels of roughness for phase II were measured using a laser profilometer. The resulting $i_A$ values attained for phase II are also presented in Table 1, while Figure 2 shows a representative specimen from phase II.

### 4 Experimental Program

#### 4.1 Test Matrix

The research program discussed herein consisted of three (3) plain concrete T-beams, and twenty-three (23) plain concrete prisms. All surface preparation was done prior to FRP application as detailed previously. 

##### 4.1.1 T-beams

Three (3) T-beam specimens were used for the Surface Roughness Effects (SRE) evaluation using the flexural test method.

### Table 1: Roughness parameters for phase I and II.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>$i_A$ Value</th>
<th>Specimen ID</th>
<th>$i_A$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-F1-9.41</td>
<td>9.41</td>
<td>6-F3-10.11</td>
<td>10.11</td>
</tr>
<tr>
<td>6-F2-9.58</td>
<td>9.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-S1-6.15*</td>
<td>6.15</td>
<td>6-S4-11.68</td>
<td>11.68</td>
</tr>
<tr>
<td>6-S2-10.00</td>
<td>10.00</td>
<td>6-S5-12.23</td>
<td>12.23</td>
</tr>
<tr>
<td>6-S3-11.14</td>
<td>11.14</td>
<td>6-S6-17.96</td>
<td>17.96</td>
</tr>
<tr>
<td>8-S1-6.29*</td>
<td>6.29</td>
<td>8-S10-11.69</td>
<td>11.69</td>
</tr>
<tr>
<td>8-S2-7.75</td>
<td>7.75</td>
<td>8-S11-11.89</td>
<td>11.89</td>
</tr>
<tr>
<td>8-S3-8.29</td>
<td>8.29</td>
<td>8-S12-13.17</td>
<td>13.17</td>
</tr>
<tr>
<td>8-S4-8.3</td>
<td>8.3</td>
<td>8-S13-15.03</td>
<td>15.03</td>
</tr>
<tr>
<td>8-S5-8.36</td>
<td>8.36</td>
<td>8-S14-15.74</td>
<td>15.74</td>
</tr>
<tr>
<td>8-S6-8.64</td>
<td>8.64</td>
<td>8-S15-16.06</td>
<td>16.06</td>
</tr>
<tr>
<td>8-S7-9.28</td>
<td>9.28</td>
<td>8-S16-16.57</td>
<td>16.57</td>
</tr>
<tr>
<td>8-S8-10.26</td>
<td>10.26</td>
<td>8-S17-17.17</td>
<td>17.17</td>
</tr>
<tr>
<td>8-S9-10.75</td>
<td>10.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key: where 6 or 8 is the compressive strength of the concrete (ksi); F stands for flexural test; S stands for direct shear test; and the number is the $i_A$ value (roughness characterization) of the specimen. * - indicates control specimen.

#### 4.1.2 Blocks

Twenty-three (23) block specimens were used for the SRE evaluation using direct shear testing method. There were two sub-groups in the direct shear bond test study. Each group represented a different concrete compressive strength. Both of the groups included blocks with similar $i_A$ values for their roughness.

### 4.2 Test Specimens and Test Set-up

#### 4.2.1 T-beam specimens and test set-up

A plain concrete beam with an inverted T shape, as illustrated in Figure 3, was used in phase I of this study. The beam was simply supported with a span length of 1067mm (42-in.) and a total length of 1219mm (48-in.). A steel hinge at the top and a saw cut at the bottom, both located at midspan, were used to control the distribution of the internal forces. During loading, the saw cut caused a crack to develop at the center of the beam and extend up to the hinge, thus creating a known moment arm. A 51mm (2-in.) wide CFRP strip was bonded to the tension side of the beam. A transverse sheet was placed on one side to force failure on the opposite side of the beam. In addition, the sheet was left unbonded for approximately 51mm (2-in.) on either side of midspan. The bonded length of this strip was 203mm (8-in.). The width and bonded length of the strip were selected by reviewing other reports from research using the identical cross-section as illustrated in Figure 3.
Previous research has indicated that there was no change in ultimate load when increasing the width of the strip from 51mm (2-in.) to 102mm (4-in.), or having a bonded length longer than the effective bonded length, which was reported to be approximately 95mm (3.75-in.).

![Figure 3: T-beam specimen adopted from [4].](image)

After the beams had cured for 10 to 14 days, the CFRP strip was applied after it was roughened using a hand-held motorized-grinder. Once the saturant had cured for a minimum of 3 days, strain gages were applied as shown in Figure 4. The beams were tested using a four-point loading technique in a Baldwin Testing Machine, as shown in Figure 5.

![Figure 4: Strain gauge location for phase I.](image)

A Linear Variable Displacement Transducer (LVDT) was placed at mid-span to monitor deflection of the beam. Strain, deflection and load were recorded by means of an Data Acquisition System (DAS), and processed using LABVIEW 6.0® software. The CFRP sheets were allowed to cure for at least 7 days prior to testing of the beams.

### 4.2.2 Block specimens

The specimen used in phase II consisted of a plain concrete prism with rectangular shape as illustrated in Figure 6. The blocks were tested in tandem, with a separating span of 305mm (12-in.). A hydraulic ram and load cell was used to apply direct shear to the specimens and to monitor the applied load. One block specimen was u-wrapped to control the failure location. Strain gauges were installed on the monitoring block where failure occurred as illustrated in Figure 7.

![Figure 6: Direct shear block specimen.](image)

![Figure 7: Strain gauge location for phase II.](image)

### 4.3 Materials

Materials that were used to perform the research described herein included concrete, CFRP sheets and epoxy resins.

#### 4.3.1 Concrete

The specimens used for all phases of this research were cast at UMR’s Structural Engineering Laboratory. All T-beams cast in phase I had a compressive strength of 43.9MPa (6380-psi) [referred to as Conc. 1]. A target compressive strength of 41.4MPa (6000-psi) was selected since it was felt that this strength level would be representative of in-situ concrete strength prior to strengthening, based on field cores from retrofitted bridge structures in the past.

Phase II was sub-divided into two groups: one at a target concrete strength of 41.4MPa (6000-psi), with a
test-age strength of 43.7MPa (6340-psi) [referred to as Conc. 2]; and the other at a target concrete compressive strength of 55.2MPa (8000-psi), with a test-age strength of 58MPa (8410-psi) [referred to as Conc. 3]. Concrete compression cylinders were made according to ASTM C31-01 for all batches. All concrete was ready-mix concrete supplied by Haven Materials in Rolla, Missouri, USA.

4.3.2 Carbon fiber reinforced polymer sheet

Mbrace™ CF 130 was the Carbon Fiber Reinforced Polymer (CFRP) sheet used in this research. The sheet was a uni-directional single-ply FRP. Manufacturing of this sheet was out of a pyrolyzing polyacrylonitrile (PAN), which is based on a precursor fiber at approximately 2700°F (1500°C). This resulted in a highly-aligned carbon fiber chain, which was then assembled into untwisted tows that were used to make the uni-directional sheet. The composite system used for this research consisted of the CFRP sheet, primer, and saturant. The sheet had an ultimate tensile strength of 4,272MPa (620-ksi), a design tensile strength of 3,790MPa (550-ksi), a modulus of elasticity of 227GPa (33,000-ksi) and a fiber thickness of 0.16mm (0.0065-in.) as indicated by the manufacturer.

5 Experimental Results

5.1 Phase I T-beams

Results for these specimens are summarized in Table 2. This table shows the load at which the beam first cracked at the notched section, the ultimate load, which is the highest load achieved after first cracking, and the average bond strength, which can be calculated by the following equation:

\[ \tau_b = \frac{P_{\text{max}}}{l_b w_f} \]  

Where, \( \tau_b \) is the average bond strength, 
\( P_{\text{max}} \) = maximum load (kN), 
\( l_b \) = bonded length of the CFRP sheet (mm), 
\( w_f \) = width of the CFRP sheet (mm).

The beam was loaded in three steps. The first step was to load the beam to 6.67kN (1500-lbs) followed by the unloading of the beam to 2.22kN (500-lbs) which is labeled 1 on the graphic. This step was in place to ensure the DAS was functioning properly. Following this, the beam was reloaded to the cracking moment, which is labeled 2 on the graphic. The dramatic drop in load at stage 2 simply represents the drop in load due to the cracking of the beam. Finally the beam was then unloaded a second time to 2.22kN (500-lbs) and then reloaded to failure, which is labeled with a 3 on the graphic. A representative load-deflection response for phase I specimens is shown in Figure 8 with test results presented in Table 2.

Failure of specimens occurred as a sudden peeling of the CFRP sheet from the concrete’s surface. Though there was some pre-failure localized peeling in the sheet, as shown by the drops in the load as the deflection increased.

Plots of strain vs. location or distance from the center of the beam were developed to study the bond behavior at varying load levels. Strain levels in the unbonded region were consistent, while the strain in the bonded region decreased as the distance from the crack increased until higher load levels were reached where debonding initiated and failure occurred. A representative example is shown in Figure 9. It may be noted that the spike in strain corresponds to the onset and occurrence of a delamination failure of the bond. Worth noting is that as the \( i_A \) value increased, the apparent bond length, based on measured strain values, also increased.

The last step in phase I was to examine how roughened specimens using a manual grinder compared to specimens tested by previous research efforts that were sandblasted. To compare their respective behavior, the linear relationship of the strain vs. location graphics at the ultimate load level was utilized. This linear relationship has been noted by several other researchers, including Miller [13] and De Lorenzis [4]. For each specimen, a value of the slope (\( d\varepsilon/dx \)) of the linear portion of the strain vs. location plot was found by using experimental data. Reported in Table 3 are the values of \( d\varepsilon/dx \), as well as the load that corresponds to the curve from which that slope was determined. Using Eq. 10, the strain for that load can be calculated, while using Eq. 11 to calculate the experimentally obtained effective length. Eq. 12 can be used to calculate the effective strain, \( \varepsilon_{ef} \) per ACI 440.2R-02.
Table 2: Test results for phase I.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cracking Load kN (lb)</th>
<th>Ultimate Load kN (lb)</th>
<th>Avg. Bond Strength kPa (psi)</th>
<th>Failure Mode</th>
<th>$k_{exp}$</th>
<th>$k_m^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-F1-9.41</td>
<td>11.29 (2536)</td>
<td>8.03 (1804)</td>
<td>779 (113)</td>
<td>Substrate debonding</td>
<td>1.26</td>
<td>0.90</td>
</tr>
<tr>
<td>6-F2-9.58</td>
<td>13.52 (3038)</td>
<td>7.63 (1714)</td>
<td>737 (107)</td>
<td>Substrate debonding</td>
<td>1.27</td>
<td>0.90</td>
</tr>
<tr>
<td>6-F3-10.11</td>
<td>11.02 (2476)</td>
<td>6.80 (1529)</td>
<td>661 (96)</td>
<td>Substrate debonding</td>
<td>1.06</td>
<td>0.90</td>
</tr>
</tbody>
</table>

* ACI 440.2R-02 determined including $C_F$ factor.

$$
\varepsilon_{max} = \frac{P_{max}}{A_f E_f} \quad \text{(experimentally obtained)} \quad (10)
$$

$$
L_{e-exp} = \frac{\varepsilon_{max}}{(d\varepsilon/dx)} \quad (11)
$$

Where, $\varepsilon_{max}$ = strain corresponding to ult. load ($\mu$), $P_{max}$ = ultimate load (kN), $A_f$ = cross-sectional area of the FRP (mm²), $E_f$ = modulus of elasticity of the FRP system (GPa), $L_{e-exp}$ = exp. effective bond length (mm), and $(d\varepsilon/dx)$ = slope of strain distr. curve ($\mu$/mm).

$$
\varepsilon_{fe} = k_m \varepsilon_{fu} \quad \text{(ACI 440.2R-02 obtained)} \quad (12)
$$

Where, $k_m$ = knock down factor.

$\varepsilon_{fu}$ = ultimate strain value from the manuf.

Table 3: Values used to determine $L_{e-exp}$.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$P_{max}$ kN (lb)</th>
<th>$d\varepsilon/dx$ (µ/in)</th>
<th>$\varepsilon_{max}$ (µ)</th>
<th>$L_{e-exp}$ (mm (in.))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-F1-9.41</td>
<td>4.91 (1104)</td>
<td>488</td>
<td>2573</td>
<td>134 (5.27)</td>
</tr>
<tr>
<td>6-F2-9.58</td>
<td>6.50 (1460)</td>
<td>634</td>
<td>3403</td>
<td>136 (5.37)</td>
</tr>
<tr>
<td>6-F3-10.11</td>
<td>4.83 (1086)</td>
<td>332</td>
<td>2531</td>
<td>194 (7.62)</td>
</tr>
<tr>
<td>Average</td>
<td>5.42 (1217)</td>
<td>485</td>
<td>2836</td>
<td>154.7 (6.09)</td>
</tr>
</tbody>
</table>

Note: 1 in. = 25.4mm; 1 lb = 4.45N.

When the effective bond length, $L_e$ values using the manual grinder are compared to identical specimens of similar concrete strength performed by Miller [13] using sandblasting as a surface preparation method, it may be observed that the $L_e$ found experimentally increases from 78mm (3.06-in.) reported by Miller to a value of 134mm (5.27-in.) found for the specimen prepared with an $i_A$ of 9.41 using the manual grinder. The specimens which included the air chisel and manual grinder resulted in even higher $L_e$ values as indicated in Table 3. Analytically, DeLorensi found that the $L_e$ was 93mm (3.65-in.) while other researchers have predicted analytical values in the 76 to 102mm (3 to 4-in.) range.

This suggests that surface preparation using the surface grinder does not enhance the bond characteristics, but rather may in fact be somewhat detrimental to the concrete surface/substrate region. It is believed that using a surface grinder results in some level of microstructure damage to the near surface of the concrete due to the harsher impact and damage to the pore structure of the concrete near the surface. Sandblasting on the other hand may actually enhance the pore structure of the concrete due to the smaller particle size and less harsh impact of the blast medium at the near surface allowing further penetration of primer into the pore structure. Further microscopic studies are recommended to examine the pore structure of the near surface concrete to verify this submission.

Table 2 was used to determine $k_{exp}$ values as reported in Table 2 utilizing the experimental data.

$$
k_{exp} = \frac{\varepsilon_{ult. load}}{\varepsilon_{fe}} \quad (13)
$$

As observed by the failure modes, the roughening of the surface using the manual grinder did prevent a peeling failure of the FRP system within the laminate. Strain levels at failure ranged from 0.21% to 0.32%, which corresponds to 16% to 21% of the strain recorded at failure of previous research studies. Load levels at failure ranged from 6.80kN (1529-lbs) to 8.03kN (1804-lbs), which corresponds to 46% to 54% of the failure loads of the sandblasted specimens, and 28% to 33% of the failure load of a roughened specimen via sandblasting with 12.7mm (1/2-in.) indentations in the concrete surface on identical tests performed by Miller [13]. It may also be noted that the specimen tested by Miller with the 12.7mm (1/2-in.) diameter indentations actually failed in fiber rupture rather than a peeling (debonding) failure. This also indicates and validates the discussion above that the manual grinder which produces a less angular surface (i.e. lower $i_A$ values) with limited pore structure into the concrete as opposed to the method used by Miller is not nearly as effective.

When the $k_{exp}$ values using the manual grinder are compared to the ACI 440-2.R-02 guide limit that suggests a knock down factor ($k_m$) of 0.9 be used for calculating the strain limitation, it may be observed that the provisions appear to be conservative even for the grinder roughened specimens that failed at a lower load compared to identical specimen roughened by other techniques.

5.2 Phase II Blocks

There were two series of specimens (Conc. 2 and Conc. 3) in phase II of the study. All specimens were strengthened with the same materials and bonded...
length. After completing a trial test of three blocks out of Conc. 3, the remaining blocks were strengthened, and then tested. Once all testing was concluded for Conc. 3, it was then decided to move forward with another series, Conc. 2, to see what effect a lower concrete strength would have on bond strength. The results for Conc. 2 tests were limited to 6 blocks, which were picked due to their $i_A$ values being within the range of some gaps in the $i_A$ values from Conc. 3 tests, and are displayed in Table 1 along with Conc. 2 series. All specimens failed due to debonding of FRP. The location of the debonding varied within the substrate region as illustrated in Figure 10.

![Concrete](image1.png)

**Figures:**
- a) Sample 8-S2-7.75 after test (minimal surface prep).
- b) Sample 6-S2-10.0 after test (moderate surface prep).
- c) Sample 6-S6-17.96 after test (rough surface prep).

**Figure 10:** Post test FRP-concrete substrate interface.

In general, specimens without surface preparation (control) or with minimal surface preparation (low $i_A$ values) failed via debonding of FRP from the concrete surface. Specimens with moderate surface preparation ($i_A$ values between 10 and 14) failed within the concrete substrate as shown in Figure 10b, which is the most preferable peeling failure mode. Specimens with very rough surface preparation ($i_A > 14$) failed in a partial substrate fashion with some evidence within the concrete substrate as shown in Figure 10c.

Tables 4 and 5 present both the ultimate failure load and calculated results for phase II study. Debonding of the FRP laminate was the failure mode for all specimens. From the information presented in Tables 4 and 5, it may be observed that the values of the computed $k_{exp}$ ratios, while varying somewhat, are consistently higher for the Conc. 3 samples when compared to the Conc. 2 samples. When examining the $k_{exp}$ factor, it may be observed that the measured value based on experimental results are above 0.75 for all samples.

**Table 4:** Results for phase II conc. 2

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate load, kN (lb)</th>
<th>$k_{exp}$</th>
<th>$k_v$**</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-S1-6.15*</td>
<td>21.6 (4850)</td>
<td>1.5</td>
<td>0.75</td>
</tr>
<tr>
<td>6-S2-10.00</td>
<td>32.2 (7240)</td>
<td>2.3</td>
<td>0.75</td>
</tr>
<tr>
<td>6-S3-11.14</td>
<td>20.0 (4490)</td>
<td>1.4</td>
<td>0.75</td>
</tr>
<tr>
<td>6-S4-11.68</td>
<td>30.4 (6820)</td>
<td>2.1</td>
<td>0.75</td>
</tr>
<tr>
<td>6-S5-12.23</td>
<td>24.0 (5400)</td>
<td>1.7</td>
<td>0.75</td>
</tr>
<tr>
<td>6-S6-17.96</td>
<td>18.5 (4150)</td>
<td>1.3</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Overall Avg.**

|          | 24.4 (5490) | 1.7 | 0.75 |

All specimens failed in debonding; $f'_c=43.7$MPa.

* - indicates control specimen.

** - ACI 440.2R-02 determined including $C_e$ factor.

**Table 5:** Results for phase II conc. 3

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate load, kN (lb)</th>
<th>$k_{exp}$</th>
<th>$k_v$**</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-S1-6.29*</td>
<td>18.5 (4150)</td>
<td>1.3</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S2-7.75</td>
<td>62.9 (14140)</td>
<td>4.4</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S3-8.29</td>
<td>65.5 (14720)</td>
<td>4.6</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S4-8.30</td>
<td>19.0 (4280)</td>
<td>1.3</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S5-8.36</td>
<td>37.3 (8390)</td>
<td>2.6</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S6-8.64</td>
<td>21.4 (4820)</td>
<td>1.5</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S7-9.28</td>
<td>63.8 (14330)</td>
<td>4.5</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S8-10.26</td>
<td>16.3 (3660)</td>
<td>1.1</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S9-10.75</td>
<td>52.8 (11870)</td>
<td>3.7</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S10-11.69</td>
<td>44.5 (9990)</td>
<td>3.1</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S11-11.89</td>
<td>19.8 (4450)</td>
<td>1.4</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S12-13.17</td>
<td>15.9 (3570)</td>
<td>1.1</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S13-15.03</td>
<td>35.7 (8020)</td>
<td>2.5</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S14-15.74</td>
<td>72.3 (16260)</td>
<td>5.1</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S15-16.06</td>
<td>28.7 (6450)</td>
<td>2.0</td>
<td>0.75</td>
</tr>
<tr>
<td>8-S16-16.57</td>
<td>46.2 (10380)</td>
<td>3.3</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Overall Avg.**

|          | 38.8 (8720) | 2.7 | 0.75 |

All specimens failed in debonding; $f'_c=58$MPa.

* - indicates control specimen.

** - ACI 440.2R-02 determined including $C_e$ factor.

The strain value obtained based on the load in some cases exceeds the manufacturer’s strain limit. This suggests that there may have been some inherent
problem with the test method on some specimens. During the testing there did not appear to be any alignment problems or testing complications, but it may be noted that the peeling failure did not occur simultaneously on both sides.

Figure 11 illustrates the average $k$ values for the two concrete strengths, and the relationship between the different roughness levels for both when separated into three major classifications. It can be seen that the $k$ values for the Conc. 3 (58MPa) roughened samples are consistently higher than those of the Conc. 2 (43.7MPa) samples, indicating that there is improved bond performance and a higher safety factor when bonded to a higher concrete strength. The specimens used for the “control grouping” in Figure 11 refer to the specimens without any surface roughness.

\[
y = 9.857x^2 - 240.12x + 1686.5 \quad R^2 = 0.7412
\]

Figure 12: Area under the strain vs. location curve at service load vs. $i_A$ value conc. 2.

\[
y = 6.2782x^2 - 157.86x + 1185.8 \quad R^2 = 0.1111
\]

Figure 13: Area under the strain vs. location curve at service load vs. $i_A$ value conc. 3.

### 6 Conclusions

#### 6.1 Effectiveness of Manual Surface Grinder

The test results showed that surface preparation using the surface grinder does not enhance the bond characteristics, but rather may in fact be somewhat detrimental to the concrete surface/substrate region. Previous researchers have used differing methods of surface preparation than that used in this research, with higher ultimate failure loads compared to those in this study. Because of this, it can be concluded that the sandblasting and indentation method of surface preparation used by Miller [13] is more effective than the manual grinder method used in Phase I of this research.

1. The manual surface grinder method produces a higher effective bond length for the FRP compared to that using sandblasting method or sandblasting method with indentations.
2. Sandblasting appears to open the pores of the concrete to a higher extent allowing the primer of the FRP system to saturate the surface pores whereas the manual surface grinder appears to detrimentally affect the surface structure of the concrete and perhaps induce near surface microcracks. This should be examined in greater detail using microscopic examination.
3. Variation in the application time of the manual surface grinder as well as using different grinding heads specimens, while this research focused on the direct shear specimens.
did not appreciably increase the surface roughness (i.e. increase the iA value).

6.2 Effectiveness of Water Jetting Method

The test results showed that roughening the surface of the concrete using water jetting techniques enhances the bond between the CFRP and concrete substrate; however, there is high variability in the test results obtained. In general, as the iA value increased, the failure load also increased until iA values exceed a value of 14.

Texturing of the concrete surface, as with the water-jet zig-zag pattern, increased the bond strength of the roughened specimens, which provide further anchorage for the primer and saturant, compared to the unroughened (i.e. control specimens) and uniform roughened specimens.

6.3 ACI 440 Code Commentary

The following was concluded based on the test results obtained herein:

- Flexural T-Beam Test: ACI 440.2R for flexural design was conservative when examining the kexp factors computed in Table 2.
- Direct Shear Test:
  1. ACI 440.2R for shear design was conservative when examining the kexp factors computed in Tables 4 and 5.
  2. A higher concrete compressive strength also resulted in a larger safety factor when using the codes equations.

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7 References