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Title: Effect of Varied Surface Roughness, Putty Thickness and Concrete Strength on the Interfacial Bond Strength of FRP to Concrete

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Effect of Varied Surface Roughness, Putty Thickness and Concrete Strength on the Interfacial Bond Strength of FRP to Concrete

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Abstract. The use of bonded fiber reinforced polymer (FRP) sheets for upgrade or repair of aging and deteriorating concrete structure has emerged as a viable and cost effective method. Previous research has identified several items that influence FRP-concrete bond strength including concrete strength, type of FRP laminate, the number of layers of the FRP laminate, and the bonding agent or epoxy saturant used. To date, limited research has been conducted on studying the influence of surface preparation (i.e. surface roughness) on bond performance. To that end, an experimental program was undertaken to investigate the effect of a broad range of surface roughnesses and putty thickness on bond strength. A laser profilometer device has been developed at the University of Missouri-Rolla that can characterize surface roughness using laser stripping and image analysis. This devise was used in conjunction with water-jet technology to create a broad range of surface roughnesses that were evaluated within the context of this study. The effects of surface roughness on bond performance for two different commercially available externally bonded laminate systems were investigated. These systems were separated into two series of tests. In total 62 specimens were produced, utilizing three test methods to study bond behavior, namely a flexure test and two surface tests (torsion and pull-off). The different grades of roughness were obtained from water jetting using the rotary jet method. The effect of surface roughness and putty thickness on the bond performance of FRP sheets to concrete is presented in this paper.

Keywords. FRP Interfacial Bond Behavior, Surface Roughness, Putty Thickness, Surface Characterization.

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.

OVERVIEW OF SURFACE CHARACTERIZATION

It has been reported that one of the critical factors that affects the bond behavior between FRP and concrete is surface roughness [1]. In order of obtain the maximum bond strength, there is an optimal level of surface roughness required. The measuring of surface roughness is broken into three types by the American National Standards Institute (ANSI). Those types are contacting methods, taper sectioning, and optical methods. The work presented herein utilizes an optical method to characterize surface roughness.

Optical Methods

Optical methods include optical reflecting instruments, light microscopy, electron microscopy, speckle metrology, interferometry and laser profilometry [2].

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 (Shen, 2002). 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 [2]. Maerz et al. [2] reported that among all parameters analyzed by the imaging software program, 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:

$$i_A = \frac{1}{n}\sum_{i=1}^{n}\left|I_j\right| \qquad [1]$$

where,
n = number of evenly spaced sampling points
I = inclination angle between points along sampling line

Some of the later developments in the optical method research have led the International Concrete Repair Institute (ICRI) to produce 9 plastic models of concrete surface profiles (CSP) which are illustrated in **Fig. 1** with measured i_A values. All of the profiles are identified by a number ranging from 1 (smooth) to 9 (very rough), and replicate the degree of roughness considered for coating applications of up to .25-in. (6.35 mm). While actual concrete surface textures have been produced that visually match the ICRI models, the i_A values obtained from the ICRI models and actual concrete are quite different.

Previous research has reported that a control specimen with no roughening, and a standard trowel finish produce an i_A value of approximately 6 [1]. The measured roughness of the plastic samples cannot be directly compared to the measured roughness of real concrete surfaces. The plastic samples, although they look like faithful reproductions of real surfaces, do not have reproduced in them the high frequency roughness that is found in real surfaces. As the profilometer measures both high and lower frequency roughness, it is not surprising that the two measurements do not correlate. For the research discussed herein, the i_A value will be the parameter measured for the roughness index on all samples.

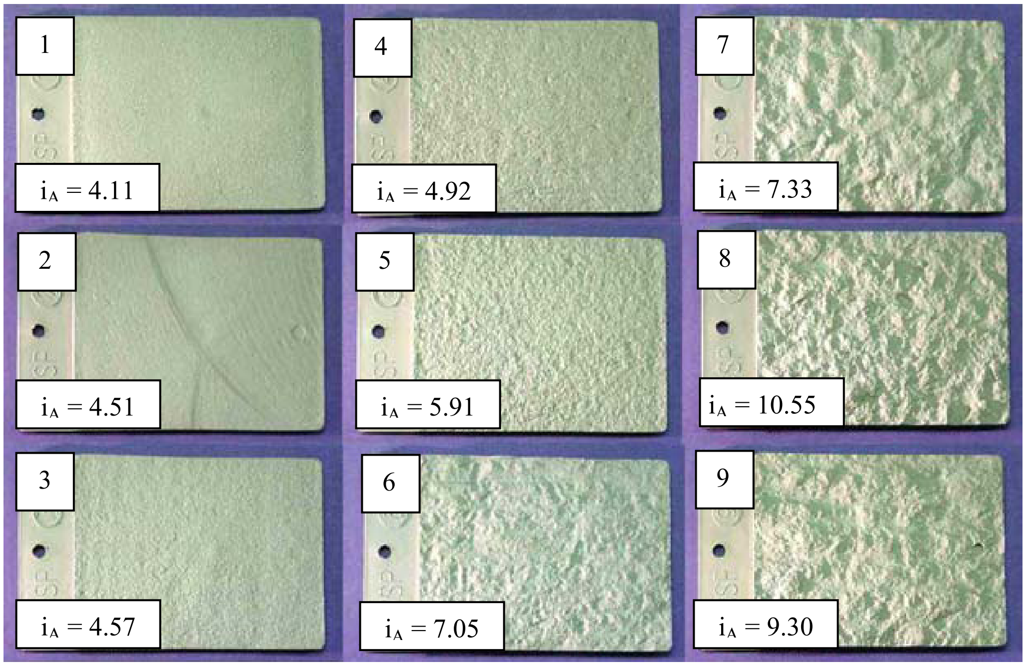


Fig. 1 – ICRI's 9 plastic models with accompanying measured i_A values.

METHODS OF SURFACE PREPARATION

A typical concrete rehabilitation job consists of: damage analysis, surface preparation and application of protective coating or strengthening systems [3]. It has been reported that surface preparation can significantly increase the bond between concrete and FRP. Many methods exist to attain the roughness, but the most common types in Civil Engineering are the use of manual tools, blasting using sand or other media, and water jetting.

The most commonly used manual tools are air chisels, disk sanders, and hand breakers. The air chisel and hand breaker both prepare the surface by impacting the surface with chisel points which crush the laitance. These patterns created are very irregular and coarse, but this also crushes the aggregate in the substrate. Disk sanders are used to smooth out the projections created by the roughening, which comes out much more regular than those samples created by the use of the air chisel or the hand breaker.

Three types of blasting are available, namely steel shot blasting, sandblasting, and dry blasting. Each uses a different media to produce similar results by spraying these materials onto the concrete surface, crushing the laitance.

Water jetting was first done in 1952 by Stephens while working in the cutting and cleaning industry. It has been improved and studied extensively since that time, and has become one of the most common methods used to prepare the concrete surface to improve the bond strength between the concrete and FRP.

PREVIOUS RELAVENT LITERATURE

Chajes et al. [4] 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. [5] 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 [6] studied the effect of the quality of the concrete on the bond of CFRP sheets. Three failure modes were observed: shearing of the concrete, delamination, and FRP rupture. When the compressive strength of the concrete was low, for example, less than 3560 psi (24.8 MPa), failure occurred in the concrete. Delamination occurred when the compressive strength was high or when a shear type test was conducted. It was also found that the bond strength increased as the concrete compressive strength increased.

De Lorenzis et al. [7] studied the bond between FRP sheets and concrete by using an inverted T-beam in a flexure test. The beam included a saw-cut along the bottom of the entire section, and a steel hinge in the top. This was done in order to allow for the compression moment arm of the section to be a known value during testing. De Lorenzis' research reported an effective bond length of 3.65-in. (93 mm), which is within the range of other reports of the effective bond length being between 3 and 4-in. (76 and 102 mm). The reported failure mechanism for all specimens was a failure of the concrete-adhesive interface with the bonded length not affecting the ultimate load, which confirms the existence of an effective bonded length. It is important to note that the compressive strength for De Lorenzis' specimens exceeded 6000-psi (41.4MPa). Myers et al. [8] conducted laboratory tests on externally strengthened RC beams subjected to environmental conditioning with sustained loading and found that conditioning and sustained load affected the bond capacity over time. Myers et al. [9] also reported the effects that environmental conditions during installation can have on bond performance.

EXPERIMENTAL PROGRAM

Test Matrix.

The research program discussed herein consisted of sixty-two (62) RC beams. The specimen dimensions are detailed in **Table 1.** Among them, fifty-two (52) were tested for Surface Roughness Effects (SRE) on bond strength between Fiber Reinforced Polymer (FRP) sheets and concrete. The cross sections of the beams used for SRE tests were 6 x 9 x 24-in. (152 x 203 x 610-mm) and 7 x 9 x 24-in. (178 x 203 x 610 mm) for Phase I and Phase II respectively. The other 10 beams, with cross section 6 x 9 x 24-in. (152 x 203 x 610 mm) were tested for Putty Thickness Effects (PTE) on bond strength between FRP and concrete. All the beams were designed according to the requirements of ACI 318-99. All the beams used in this research study were reinforced with 2-#2 (6 mm) steel rebars with 1.5-in (38.1 mm) bottom cover with no shear reinforcement.

Table 1 – Specimens used in this study.

	SRE Specimens		Phase III PTE Specimens
	Phase I	Phase II	
Dimension (inch)	6 x 9 x 24	7 x 9 x 24	6 x 9 x 24
Number of Specimens	24	28	10
Surface Treatment Method	Water Jet	Water Jet	
Target Strength (psi)	3000	4000	5000
Strength at 28 days (psi)	2830	3930	5570
Strength prior to test (psi)	2910	4110	5840

Conversion Units: 1 psi = 6.89 kPa, 1-in. = 25.4 mm

SRE and PTE Test Matrix: Phase I, II and III

In each phase of the SRE test, the specimens were divided into two series based upon the strengthening system selected, designated herein as Series I and Series II. Two strengthening systems utilizing CFRP were investigated, namely, System M and System T. CFRP sheets were applied to specimens in each series. For each series, half of the specimens were utilized for surface tests, while the other half was subjected to flexural testing. For the PTE test, only System M CFRP was studied. Detailed information for specimens used in each phase is provided in **Table 2**. For the PTE test, putty thickness investigated for each specimen is shown in **Table 3**.

Table 2 – Information for specimens used in Phase I and II.

	Series 1 - System M			Series 2 - System T		
	Flexural Test	Surface Test		Flexural Test	Surface Test	
		Pull-off Test	Torsion Test		Pull-off Test	Torsion Test
Phase I No. of Specimens	6	6		6	6	
Phase II No. of Specimens	7	7		7	7	
Phase III No. of Specimens	5	5		NA	NA	
4 term Key: Example **4M-3-P** – ***Term 1*** refers to the target concrete compressive strength in ksi; ***Term 2*** **M** or **T** refers to strengthening system; ***Term 3*** refers to the roughness grade (0 to 6); ***Term 4*** **F**, **P** or **T** refers to the test: flexural test, pull-off test, or torsion test respectively.						

Conversion Units: 1-in. = 25.4 mm

Table 3 – Putty thicknesses for specimens used in PTE test.

Specimen Designation	Putty Thickness (inch)
P-0	0
P-1	1/32
P-2	1/16
P-3	1/8
P-4	1/4

Conversion Units: 1in. = 25.4mm

Materials.

Materials used in this research study included concrete, reinforcing steel and two systems CFRP sheets and epoxy resins.

Concrete.

The RC beams used in this study were cast in the Engineering Research Laboratory (ERL), Structural Engineering Laboratory at the University of Missouri-Rolla (UMR). The beams were sub-divided into 3 types, type I through type III, with target strength of 3000 psi (20.7 MPa), 4000 psi (27.6 MPa), and 5000 psi (34.5 MPa), each. The low end compressive strength was selected to see what role surface roughness might play on low strength concrete.

Concrete compression cylinders, with dimensions 4-in. (102 mm) diameter by 8-in. (203 mm) length, were made according to ASTM C31-95 for each batching process. All cylinders were tested in according with ASTM C39-94 at 28 days after casting and within 3 days of testing of the corresponding specimens. The specific mix design adopted for each type in this research study is shown in **Table 4**. The slump of the concrete was 4-in. (102 mm).

Table 4 – Mix design for Type I to III concrete specimens.

Mix Design	Coarse Aggregate [1] (pcy)	Fine Aggregate [2] (pcy)	Water (pcy)	Cement [3] (pcy)	W/C Ratio	Slump (in)
Type I 3000 psi	1620	1483	303	516	0.59	4
Type II 4000 psi	1800	1235	240	500	0.48	4
Type III 5000 psi	1750	1245	270	658	0.41	4

Conversion Units: 1pcy = 0.593 kg/m^3; 1-in. = 25.4mm
Note: **1:** Havin Coarse Aggregate; **2:** Havin Roha Sand; **3:** Portland Cement, Type I.

Reinforcing Steel.

Two #2 (6 mm) diameter steel rebars were provided on the tension side of the specimen for pre-cracking. For flexural tests, the steel rebars were pre-cut along the pre-crack to isolate and study the bond characteristics of the FRP sheets. The properties of the steel were provided by the supplier. The yield strength of the steel was 96 ksi (661.4 MPa) and the MOE was 29,000 ksi (199960 MPa).

Fiber Reinforced Polymer (FRP) Sheets.

Two different series of carbon fiber reinforced polymer (CFRP), namely Series I and II, were used in this experimental program. MbraceTM CF 130 used in Series I is a high tensile strength carbon fiber manufactured by Master Builder Inc. located in Cleveland, OH. TyfoR SCH-35 CFRP was used in Series II. Tyfo CFRP was supplied by Fyfe Co. LLC, a composite company located in San Diego, CA. The sheets used in this program were unidirectional single-ply FRP sheets. The properties of the sheets used in this study are presented in **Table 5**. ASTM test method D-3039 was followed to characterize their properties.

Table 5 – MBrace ^{TM} CF 130 CFRP and Tyfo^{R} SCH-35 CFRP properties.

Property	Typical Test Value	
	MBrace CF 130	**Tyfo^{R} SCH-35**
Ultimate tensile strength in Primary fiber direction, ksi (MPa)	550 (3790)	143.7 (991)
Elongation at ultimate	1.67%	1.26%
Tensile Modulus, psi (GPa)	33×10^{6} (228)	11.4×10^{6} (78.6)
Ultimate tensile strength 90 degrees to primary fiber (psi)	0	0
Laminate thickness, in. (mm)	0.0065 (0.165)	0.035 (0.889)

CFRP are manufactured by pyrolizing polyacrylonitrile (PAN) based on precursor fiber at very high temperatures. For example, MBrace ^{TM} CF 130 was pyrolized at approximately 2700 °F (1500 °C). The result of the pyrolization process is a highly aligned carbon fiber chain. The carbon fiber filaments are assembled into untwisted tows that are then used to create a continuous unidirectional sheet.

Epoxy Resins including Primer, Putty and Saturant.

MBrace primer.

For structures repaired by MBrace CFRP sheets, the first coat applied to the concrete surface is a 100% solids epoxy based primer. MBrace primer is applied to provide adequate bond to the base concrete. The primer is formulated to penetrate the pores of the concrete and provide the bond. According to MBrace Engineering Design Guidelines (1998), primer should be applied only when the base concrete is sufficiently clean and dry.

MBrace putty.

For structures repaired by MBrace CFRP, if the surface has bug holes or defects after cleaning, MBrace putty is suggested to be used to fill these holes and defects up to 0.25-in. (5 mm) according to MBrace Engineering Design Guidelines (1998). Mbrace putty can also be used for leveling and patching small holes.

Epoxy saturant.

MBrace saturant and Tyfo saturant were used separately in Series I and Series II. Saturant is used to impregnate the dry fibers. It maintains the fibers in their intended orientation and under strain distributes stress to fibers. The saturant also protects the fiber from abrasion and environmental effects. MBrace saturant is formulated to quickly wet the fibers and hold the tow sheet in place while the system cures. Properties of MBrace related epoxy resins are shown in **Table 6**.

Table 6 – Net MBrace Resin Properties According to ASTM D-638[2].

Property	MBrace Primer	MBrace Putty	MBrace Saturant
Maximum Stress, psi (MPa)	2500 (17.2)	2200 (15.2)	8000 (55.2)
Stress at Yield, psi (MPa)	2100 (14.5)	1900 (13.1)	7800 (53.8)
Stress at Rupture, psi (MPa)	2500 (17.2)	2100 (14.5)	7900 (54.5)
Strain at Maximum Stress	0.400	0.060	0.030
Strain at Yield	0.040	0.020	0.025
Strain at Rupture	0.400	0.070	0.035
Elastic Modulus, psi (MPa)	104,000 (715)	260,000 (1790)	440,000 (3035)
Poisson's Ratio	0.48	0.48	0.40

Note: properties determined at 72°F (22°C) and 40% relative humidity.

For structures repaired with Tyfo CFRP, there is no primer resin nor putty used. The only resin used is Typo ^{R} S saturant. For rough surface, FYFE Co. LLC suggested the use of cabosil mixed with saturant to apply on the first cover of concrete surface. Property data for Typo ^{R} S saturant provided by the supplier is as shown in **Table 7**.

Table 7 – Resin Properties for Typo ^{R} S Saturant.

Property	Method	Properties
Tensile Strength, psi (MPa)	ASTM D-638 Type 1	10,500 (72.4)
Tensile Modulus, psi (GPa).		461,000 (3.18)
Elongation	ASTM D-638 Type 1	5.0%
Flexural Strength, psi (MPa)	ASTM D-790	17,900 (123.4)
Flexural Modulus, psi (GPa)	ASTM D-790	452,000 (3.12)

Note: Tensile strength is obtained at 70°F (21°C), with crosshead speed of 0.5-in.(13 mm)/min.

Test Methods and Surface Preparation

Surface preparation was done by water jetting. Six grades of surface roughness were obtained, with four specimens at each grade for investigation. Beams used for flexural tests and surface tests had the same grade surface roughness as shown in **Table 8**. The beams for all specimens were fabricated with two-#2 (6 mm) diameter undeformed bars as shown in **Fig. 2**. The longitudinal steel reinforcement was provided primarily for the flexural series of tests such that the specimens could be pre-cracked prior to strengthening to avoid shear failure. The beams were pre-cracked under single point loading by applying the cracking load 28 days after fabrication. Installation procedure of FRP sheets recommended by the manufacturer was strictly adhered to while applying the two types of sheets.

Table 8 – Resulting Average i_A Values from Waterjetting.

Roughness Grades	Phase I i_A values	Phase II i_A values
Control (0)	5.7	4.7
I (1)	8.4	8.5
II (2)	10.7	10.9
III (3)	12.3	11.7
IV (4)	13.7	13.4
V (5)	15.6	14.0
VI (6)	NA	15.5

Beams for flexural tests were externally strengthened with 1.5-in. (38 mm) wide *System M* laminates (Series I) and 1.0-in. (25 mm) wide *System T* laminates (Series II). All these beams were provided with 1.5-in. (38 mm) width end u-wraps of respective FRP sheets for anchorage between FRP strips and concrete. Beams for surface tests were strengthened with single CFRP ply of 3-in. (76 mm) wide laminate respective for both series.

Flexural Test Set-up

After completion of surface preparation and FRP application, the longitudinal steel reinforcement was cut prior to testing at the pre-crack location. This was done to isolate the FRP laminate so its bond behavior could be more directly studied. The beams were tested under two point bending in a Tinius-Olsen™ testing machine as illustrated in **Fig. 2**. Strain and crack growth were recorded through the use of strain gages and extensometer. The data were collected by an electronic acquisition system and processed by LABVIEW 6.0® software. Four strain gages were attached to FRP sheets as illustrated in **Fig. 3** for monitoring strain in the sheets. An extensometer was attached across the pre-initiated crack to monitor the crack growth while testing.

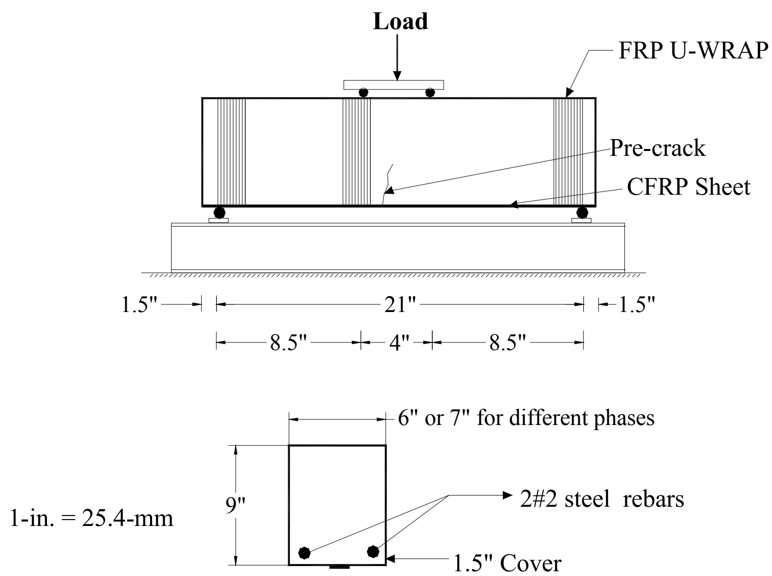


Fig. 2 – Specimen and Test Set-up for Flexural Tests.

Surface Test Set-up

The pull-off test was carried out on specimens that had a roughened surface at least 3-in. (76 mm) wide to accommodate the laminates to insure the roughened surface was located through out the location of the bonded laminate. Two days after the beams were strengthened, 3 adhesives fixtures of 1.6-in. (41 mm) in diameter were attached to the surface of the FRP with epoxy adhesive. After the epoxy cured, a core drill was used to isolate the adhesion fixture from the surrounding FRP. Next, the test apparatus was attached to the adhesion fixture and aligned to apply tension perpendicular to the concrete. A constant force rate was applied to the adhesion fixture and recorded until the adhesion fixture detaches from the surface. Two types of failure modes, concrete failure in tension or partially concrete failure and partially FRP delamination, were found in this study. Failure stresses were calculated based on the measured pull-off load at failure divided by the bonded disc area.

For the torsion test, the torque was applied to the special probe using a calibrated torque-wrench. Test probes were glued to the FRP with epoxy adhesive. Similar to the pull-off test, the FRP was cut along the perimeter of the probe using a small grinder. Torsion was applied using a calibrated torque wrench with a series of hinges. The average shear stresses were then calculated (see **Eq. 2**) by taking average of the readings obtained in a particular series where T is the torque measured at failure and R is the diameter of the disc.

$$\tau_{average} = \frac{T}{\pi R^3} \qquad [2]$$

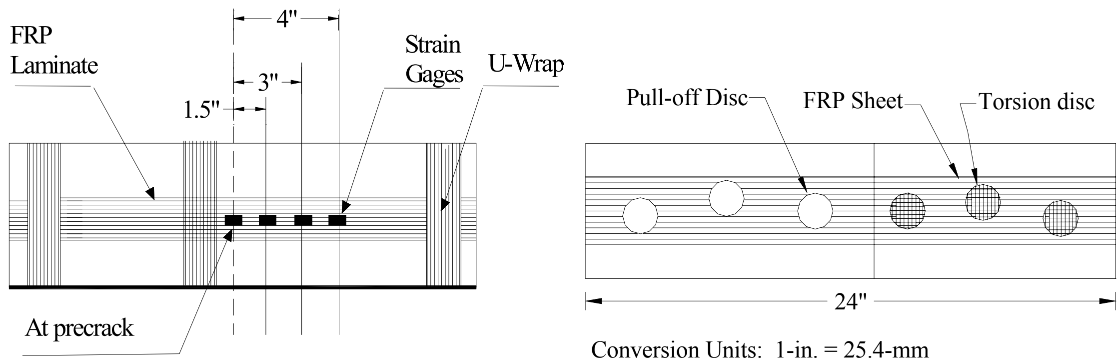


Fig. 3 – Flexural test set-up (left) and surface test set-up (right).

EXPERIMENTAL TEST RESULTS AND DISCUSSION

Flexural Tests

For the flexural test of 4000 psi (27.6 MPa) series specimens, peeling or de-bonding of the sheet was the primary failure mode of the specimens. During the loading process, there was a clear indication of the peeling of the laminate in the form of a sharp sound at the onset of the peeling. The degradation in the bond with the increase in load can be seen from the specimens in both series, as illustrated in **Figs. 4** and **5** respectively. These are representative strain-load profiles for each series. As illustrated in the figures, it can be observed that the strains values increase at a much more rapid rate with load for the 4T6 and 4M6 specimen as compared to 4T4 and 4M3 specimen due to the high roughness of the grade VI (6) surface.

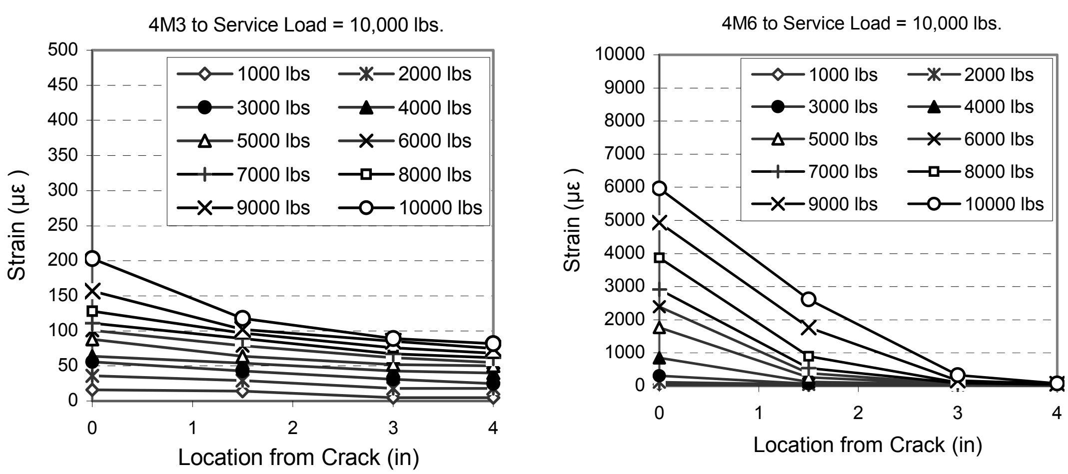


Fig. 4 – Strain vs. Load for Series I 4M3 and 4M6 *(System M).*

To get a broad picture of the degradation in bond between FRP and concrete, the strains in FRP sheets are plotted with the distance from the crack at service load (60% of ultimate load). Ultimate load was obtained by averaging the ultimate load of each specimen. **Fig. 6** illustrates the strains level for *Series I and II* respectively. The figure illustrates that a roughness grade from 3 to 5 (i_A values from 12 to 14) for Series I and from 4 to 5 (i_A values from 13 to 14) for Series II will result in more efficient bond transfer at service load. It was also observed for Series I, that the non-textured surface - control specimen (4M0) exhibited poorer bond transfer compared to textured specimens 4M1, 4M2 and 4M6 at service load. In terms of failure load (see **Table 10**) the control specimen (4M0) failed at 13.7 kips (61.1 kN).

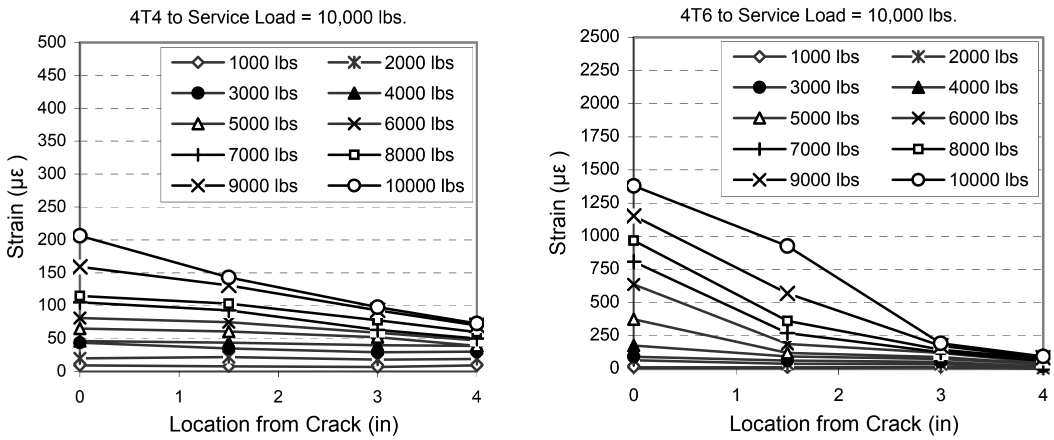


Fig. 5 – Strain vs. Load for Series II Specimens 4T4 and 4T6 *(System T)*.

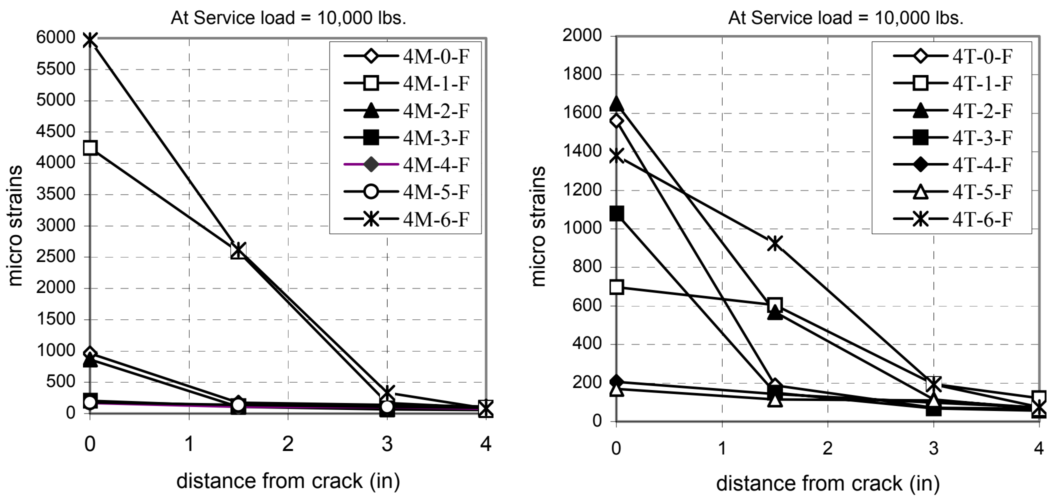


Fig. 6 – Micro Strain at Service Load for 4000 psi Series I (left) and Series II (right).

Table 10 – Flexural test results for System M and T specimens in 4000 psi Series.

Specimen ID	Strain SG1 at service load, 7000 lb (με)	Ultimate Load (lb)	Ultimate Strain at Crack (με)	Failure Mode
4M-0-F	961	13,740	6131	Peel-off
4M-1-F	4245	16,003	10686	Peel-off
4M-2-F	862	14,352	7885	Peel-off
4M-3-F	203	16,680	12285	Peel-off
4M-4-F	168	14,006	8566	Peel-off
4M-5-F	180	15,090	6060	Peel-off
4M-6-F	5970	17,260	12356	FRP Rupture
4T-0-F	1562	13,809	5195	Peel-off
4T-1-F	697	16,365	4423	Peel-off
4T-2-F	1651	14,149	8594	Peel-off
4T-3-F	1080	19,894	6021	Peel-off
4T-4-F	206	14,296	4482	Peel-off
4T-5-F	169	14,002	4129	Peel-off
4T-6-F	1381	17,919	5345	FRP Rupture

Conversion Units: 1-lb. = 4.45 N

The maximum load for all of the other specimens varied between 14.0 to 17.3 kips (62.3 to 76.8 kN) in both series. A similar trend was observed for *System T*. The bond strength and capacity of the non-textured control specimen was clearly lower than the textured specimens indicating that surface roughness improves the bond performance.

For the flexural test of 3000 psi (20.7 MPa) series specimens, peeling was the failure mode for all of the specimens. **Fig. 7** illustrates the strain level for the Series I and II specimens respectively and **Table 11** reports the failure loads and associated strain values. It may be noted that the surface roughness plays a much less significant role at lower concrete strength levels (<3000 psi) based on the observed strain and failure load values obtained.

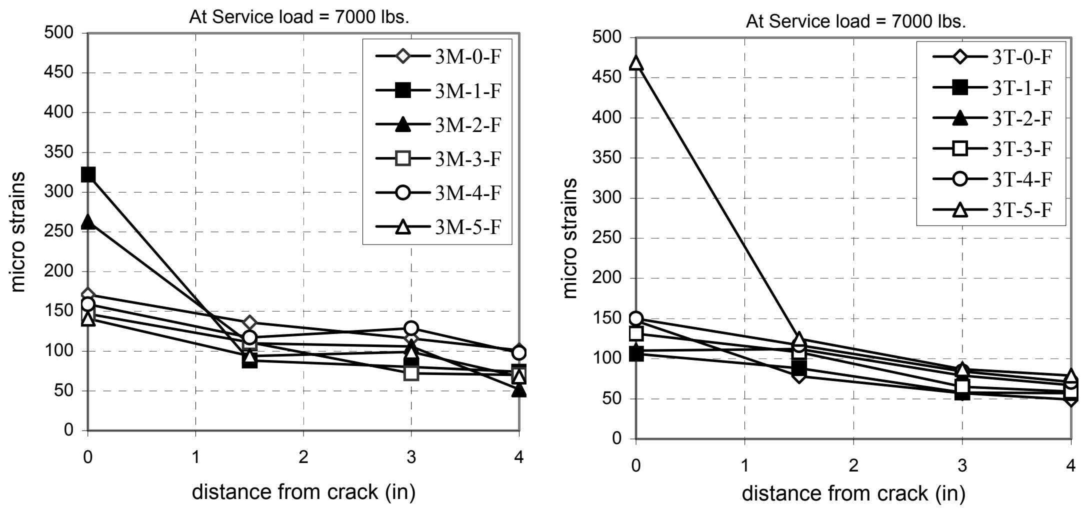


Fig. 7 – Micro Strain at Service Load for 3000 psi Series I (left) and Series II (right).

Table 11 – Flexural test results for System M and T specimens in 3000 psi Series.

Specimen ID	Strain SG1 at service load, 7000 lb (με)	Ultimate Load (lb)	Ultimate Strain at Crack (με)	Failure Mode
3M-0-F	171	11952	9688	Peel-off
3M-1-F	322	11321	10519	Peel-off
3M-2-F	263	11833	7864	Peel-off
3M-3-F	147	13685	11715	Peel-off
3M-4-F	159	11163	10670	Peel-off
3M-5-F	141	10053	9033	Peel-off
3T-0-F	147	9881	4910	Peel-off
3T-1-F	106	13023	7248	Peel-off
3T-2-F	110	12534	6124	Peel-off
3T-3-F	131	11347	7200	Peel-off
3T-4-F	150	13423	7020	Peel-off
3T-5-F	469	11331	8968	Peel-off

Conversion Units: 1-lb. = 4.45 N

Surface Tests

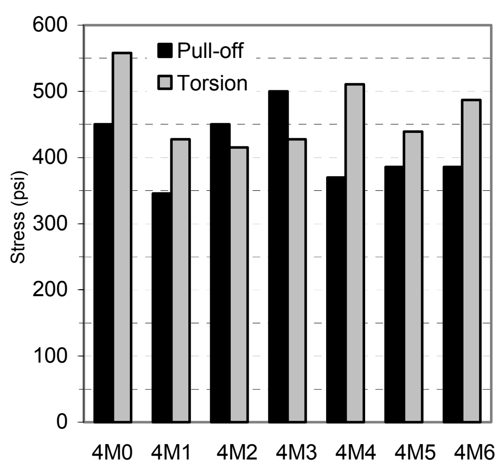
Phase I and II surface pull-off and torsion test results are presented in **Table 12**. The average stress values are a result of three surface tests under each test method. The standard deviation (SD) and coefficient of variation (cv) are presented.

The results for 4000 psi (27.6 MPa) series specimen surface tests are illustrated in **Fig. 8**. There was a large degree of scatter and variation observed within the tests conducted. No clear trend between surface roughness and bond strength was observed. Clearly, the surface test methodologies used were not appropriate to distinguish the influence of surface texture on bond performance since the failure mode predominately occurred at the interface within the concrete. The tests do clearly demonstrate that the ACI [10] minimum required bond strength of 200 psi (1.4 MPa) was satisfied at all surface roughness levels.

Table 12 – Pull-off and Torsion test results for System M and T specimens in Phase I and II.

Specimen ID	Average Stress σ (psi)	Standard Deviation (psi)-(cv)	Specimen ID	Average Stress σ (psi)	Standard Deviation (psi)-(cv)
4M-0-P	450	56 (12.3%)	3M-0-P	370	14 (3.7%)
4M-1-P	345	37 (10.7%)	3M-1-P	450	111 (24.7%)
4M-2-P	450	56 (12.3%)	3M-2-P	353	28 (7.8%)
4M-3-P	500	31 (6.1%)	3M-3-P	385	0 (0%)
4M-4-P	369	56 (15.1%)	3M-4-P	417	74 (17.6%)
4M-5-P	385	0 (0%)	3M-5-P	403	28 (6.9%)
4M-6-P	385	0 (0%)	3T-0-P	289	0 (0.0%)
4T-0-P	377	85 (22.4%)	3T-1-P	337	48 (14.2%)
4T-1-P	225	28 (12.3%)	3T-2-P	321	28 (8.6%)
4T-2-P	225	37 (16.3%)	3T-3-P	361	42 (11.5%)
4T-3-P	377	85 (22.4%)	3T-4-P	321	14 (4.3%)
4T-4-P	337	48 (14.3%)	3T-5-P	297	14 (4.7%)
4T-5-P	353	56 (15.7%)	3M-0-T	415	41 (10.8%)
4T-6-P	458	0 (0%)	3M-1-T	510	74 (14.5%)
4M-0-T	557	21 (3.6%)	3M-2-T	462	21 (4.5%)
4M-1-T	427	71 (16.7%)	3M-3-T	522	41 (8.1%)
4M-2-T	415	21 (4.7%)	3M-4-T	451	143 (25.7%)
4M-3-T	427	36 (8.3%)	3M-5-T	427	21 (4.0%)
4M-4-T	510	54 (10.7%)	3T-0-T	415	21 (4.9%)
4M-5-T	439	21 (4.7%)	3T-1-T	510	41 (8.1%)
4M-6-T	486	21 (4.2%)	3T-2-T	462	0 (0%)
4T-0-T	391	36 (9.1%)	3T-3-T	522	21 (3.9%)
4T-1-T	391	0 (0%)	3T-4-T	451	41 (9.1%)
4T-2-T	439	21 (4.7%)	3T-5-T	427	0 (0%)
4T-3-T	403	41 (10.2%)			
4T-4-T	510	54 (10.6%)			
4T-5-T	451	41 (9.1%)			
4T-6-T	557	21 (3.7%)			

Conversion Units: 1 psi = 6.89 kPa; * The failure mode for all specimens was within the concrete substrate.



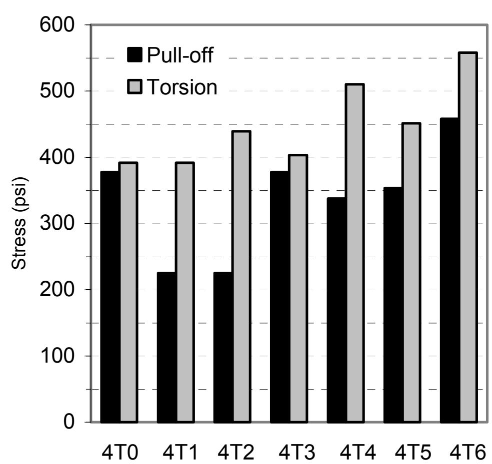


Fig. 8 – 4000 psi Surface Test Result for Series I (left) and Series II (right).

The results for the 3000 psi (20.7 MPa) series specimen surface tests are illustrated in **Fig. 9**. The average pull-off and torsion stress values on average were slightly lower for the 3000 psi (20.7 Mpa) series compared to the 4000 psi (27.6 MPa) series. No clear trends developed with the surface tests regarding surface roughness effects.

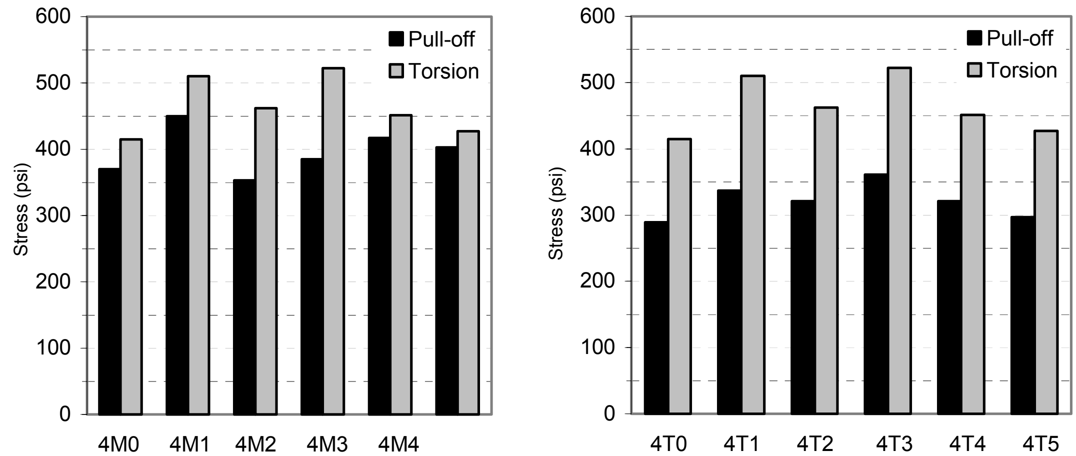


Fig. 9 – 3000 psi Surface Test Result for Series I (left) and Series II (right).

Putty Thickness (PTE) Tests

The bond between concrete and FRP sheets was evaluated by strengthening concrete beam with FRP sheets under different putty thickness conditions. The surface of all the specimens was wire-brushed before applying putty and FRP in this series of tests. A difference in behavior between specimen P-0-F (No Putty) and specimens P-1-F/P-2-F was noted. Under service load, strain gage readings on P-1-F and P-2-F was much larger compared to the values recorded on specimen P-0-F (see **Fig. 10**). This can be attributed to the putty thickness. For specimen P-1-F and P-2-F, the putty thickness is too thin and shows elastic behavior, like a plastic sheet attached to the concrete surface. Once under bending, the "putty sheet" will slide from the concrete surface resulting in large strain readings. Specimen P-3-F and P-4-F show a similar behavior as P-0-F during the testing.

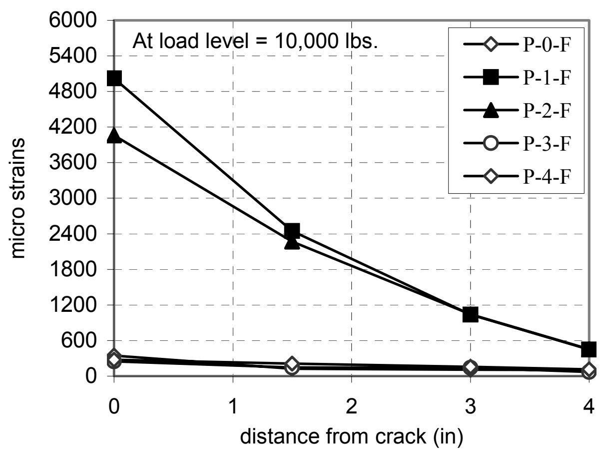


Fig. 10 – Micro strains at service load for PTE tests.

Pull-off evaluation exhibited a complete concrete substrate failure behavior for every specimen tested. **Fig. 11** illustrates the surface test failure stresses. High variability was observed in the measurement for each specimen as discussed in Phase I/II. For the torsion test, FRP delamination occurred in each case, but there is no significant relationship between shear stress and putty thickness. It can be concluded that surface tests used in this study cannot precisely predict the bond behavior between FRP and concrete as discussed in Phase I/II.

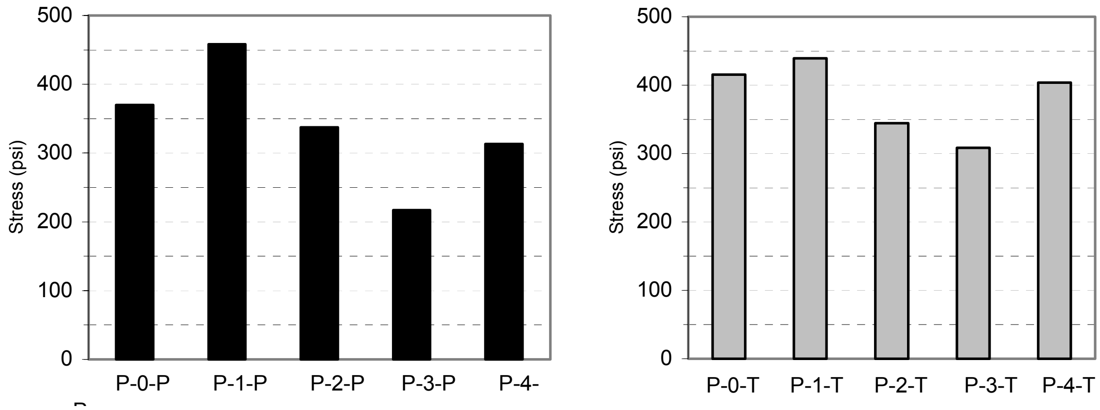


Fig. 11 – Surface Test Result for PTE Tests Pull-off (left) and Torsion (right).

Based on the flexural tests conducted herein, putty guidelines may be suggested. If the putty thickness is too thin [less than 0.112-in. (3.2 mm)], sliding of FRP at service level may occur. Therefore, if there are no significant bug holes or voids larger than 0.25-in (6.5 mm) in diameter, putty is not recommended. For large holes or voids, putty should be used to fill these holes or voids. Once the larger mil thickness of putty cures, composite interlock action between putty and concrete surface can prevent FRP sliding. When putty is used, the putty thickness should be thicker than 0.12-in. (3.2 mm) above the concrete surface to provide interlock. As a result, when the putty cured, a more rigid putty layer can form and avoid the elastic behavior of "putty sheet". Within the evaluation conducted herein, the maximum limit of putty thickness was not studied. Future research needs to be conducted to provide a guideline for maximum putty thickness that can be applied on the structural repairs.

Correlation and Variations between Surface Test Methods

Fig. 12 illustrates the correlation between the average pull-off stress and average torsion stress of all specimens used in phase I/II plus data obtained from previous research [11]. A trend line using the above data is plotted as illustrated in **Fig. 12**. Theoretically, there should be a linear relationship between the averaged pull-off stress and the averaged torsion stress from each specimen. The resulting correlation index ($R^2 = 0.5703$) from the reported data illustrates a mediocre relationship between the pull-off test and torsion test method.

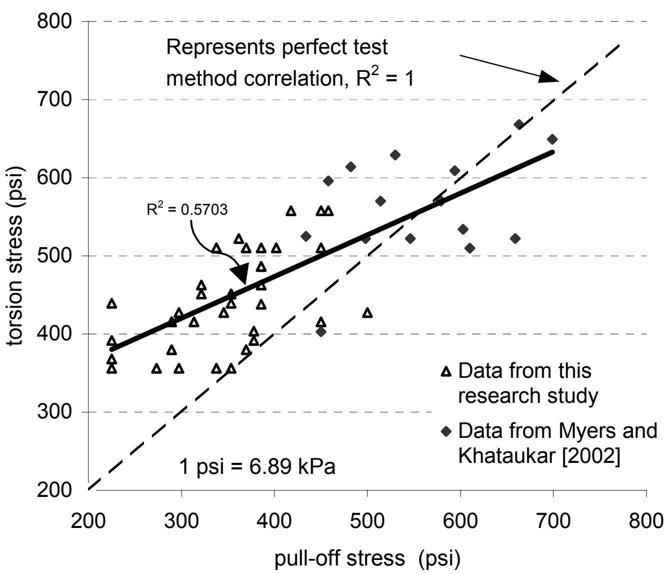


Fig. 12 – Average pull-off stresses vs. average shear stresses.

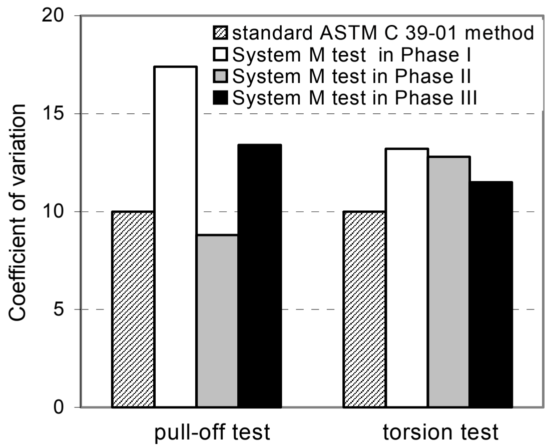


Fig. 13 – Comparison of COV and the requirement for standard concrete compressive strength test.

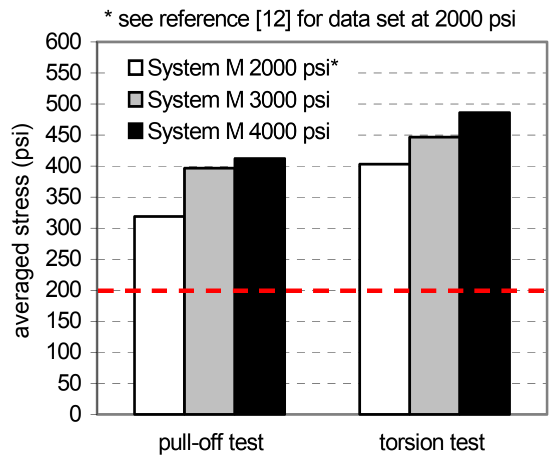
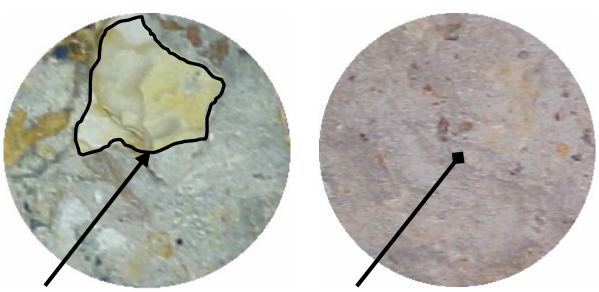


Fig. 14 – Averaged stresses for System tests in different phases.

Fig. 13 illustrates the comparison between the results of System M from this research study and the requirement for standard concrete compressive strength test [ASTM C-39-01]. It can be observed that, except for the result of the pull-off test in Phase II, all the test results show a higher coefficient of variation (CV) compared to the required CV (10%) for concrete [ASTM C 39-01]. **Fig. 14** presents the average stresses for System M at varying concrete strengths. The observed trend shows as the concrete compressive strength increases the stresses in both pull-test and torsion test increase, but the increase is not proportional to compressive strength. System T investigation shows a similar behavior as system M investigation.

A conclusion can be made that surface tests used in this study cannot precisely predict the bond behavior between FRP and concrete. This is related to several issues including the non-homogenous nature of the concrete (different cement/aggregate ratio near the surface) and the nature of the test method. **Fig. 15** illustrates two failure modes when using pull-off test at different locations on specimen 3M-1-P. It may be observed that there is a large aggregate on the left disc surface (disc (1)). The final pull-off stress for disc (1) is approximately 1.5 times of the pull-off stress for disc (2). The effect of concrete substrate material can have a dramatic effect on the predicted bond strength using the pull-off test method.



Large coarse aggregate near the surface | **Complete substrate failure within the paste**

3M-1-P (disc 1) | **3M-1-P (disc 2)**

Fig. 15 – Representative pull discs from different positions of 3M-1-P.

CONCLUSIONS

An experimental investigation was conducted to study the bond behavior and the modes of failure of RC beams, strengthened with CFRP sheets, under flexural tests and surface tests. The parameters investigated in this program were surface roughness and putty thickness. The following can be concluded based on flexural test results observed herein:

- For concrete compressive strength lower than 3000 psi (20.7 MPa), surface preparation does not significantly improve the flexural behavior for specimens strengthened with either System M or System T CFRP. This is due to "premature" concrete substrate failure behavior for low compressive strength concrete (see **Fig. 16**).
- For concrete compressive strength higher than 4000 psi (27.6 MPa), surface preparation can increase the bond connection for specimens strengthened with both System M and System T CFRP within limits. As surface roughness increases above i_A of 14, bond connection will decay for compressive strength higher than 4000 psi (27.6 MPa) as schematically illustrated in **Fig. 16**.

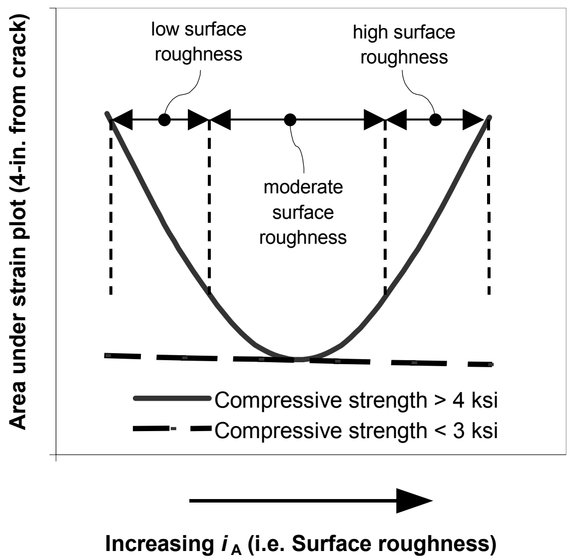


Fig. 16 – Trends for area under strain plot at service load.

- For both series, FRP delamination was the dominate failure mode under flexural tests as expected.
- For CFRP ***System M***, surface roughness from grade III to grade V (Ia value from about 12.0 to 14), and for CFRP ***System T***, surface roughness from grade IV to V (Ia from 13 to 14) exhibited optimal bond adhesion between CFRP and concrete for the testing program undertaken herein.
- Flexural test result shows that applying putty does not increase the flexural behavior. For those specimens with putty thickness less than 0.112-in. (3.2 mm), the flexural behavior has less capacity than those with putty thickness greater than 0.112-in. (3.2 mm) or without putty.
- When putty is used, the putty thickness should be thicker than 0.12-in (3.2 mm) above the concrete surface to provide interlock.

The following can be concluded based on flexural test results observed herein:

- Surface tests used in this study did not indicate any clear trends regarding surface roughness or putty thickness. This is related to several issues including the non-homogenous nature of the concrete (different cement/aggregate ratio near the surface) and the nature of the test method.
- Surface test methods did indicate a general relationship between concrete strength and the surface tests, but the COV was generally higher than 10% indicating the variability of the test method.
- The correlation between the pull-off and torsion test methods indicated a moderate correlation with a R^2 value of 0.57.
- All surface tested specimens resulted in a concrete substrate failure.

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