Effect of Environmental Conditions on Bond Strength between CFRP Laminate and Concrete Substrate

by J.J. Myers and M. Ekenel

Synopsis: Limited information is known about the effects of environmental conditions during installation on quality and performance of the bond between carbon fiber reinforced polymer (CFRP) reinforcement and substrate material. This research study investigates the effect of surface moisture, relative humidity and temperature on the bond strength between concrete and CFRP reinforcement. Three test methods including a surface pull-off bond test, a surface shear-torsion bond test, and a flexural test were used to evaluate the bond performance of the FRP fabric under various installation conditions. Test results revealed that the high surface moisture content, extreme humidity and extreme low temperature can be detrimental to bond strength. Although the high temperature improved the bond strength, it is not recommended because of decreased set-time and saturant workability. Based on the results presented in this paper, a maximum allowable limit on surface moisture content, relative humidity, and temperature of 4.3%, 82%, and 90°F, respectively, at installation is recommended.

Keywords: bond strength; CFRP strengthening; durability; frost effect; moisture; temperature

ACI member **John J. Myers** is an Associate Professor at the University of Missouri-Rolla. He received his BAE from The Pennsylvania State University; MS and Ph.D. from University of Texas-Austin. His research interests include high performance concrete and use of fiber-reinforced polymers in structural repair and strengthening applications. He is a member of ACI Committees 201, 342, 363, 440, E801, E802, and E803. He is the current sub-committee co-chair of 440L (durability of FRP concrete structures) and chair of E801.

ACI member **Mahmut Ekenel** is a Post-Doctoral Research Fellow in the Dept. of Civil, Arch. and Envir. Engineering at the University of Missouri-Rolla. He received his BS from Seljuk University, Turkey; MS from Southern Illinois University-Carbondale and PhD from UMR. His research interests include high performance concrete, durability and non-destructive testing of advanced construction materials used in structural rehabilitation and strengthening.

INTRODUCTION

Because of the need to repair and retrofit deteriorating infrastructure in a rapid fashion, the potential market for using fiber-reinforced composites for repair is now being realized to a greater extent in recent years. Numerous successful applications using fiber-reinforced polymer-matrix composites in the construction industry have been reported. The key properties that make carbon fiber reinforced reinforcement (CFRP) materials suitable for structural strengthening are excellent resistance to corrosion, high strength-to-weight ratio, and reduction in labor costs. However, one factor inhibiting greater widespread implementation is the lack of quality control for installation. Hence, understanding the behavior and installation conditioning of CFRP materials is essential in the development of quality control specifications.

Because CFRP strengthening can provide additional flexural or shear reinforcement, the reliability for this material application depends on how well they are bonded and can transfer stress from the concrete component to CFRP laminate. Ideally designers desire a CFRP laminate that is perfectly bonded to the concrete substrate. The bond strength between an FRP fabric and concrete influences the structural behavior of concrete elements strengthened with these FRP materials. Hence, the American Concrete Institute (ACI) Committee 440.2R document requires minimum bond strength of 200 psi (1.4 MPa) and a failure mode within the concrete substrate [ACI 440.2R-02]. A limited database of information exists on the effects of environmental conditions during installation on quality and performance of the bond between the CFRP reinforcement and substrate material. The effect of moisture and temperature of the concrete surface on the bond strength between concrete and CFRP reinforcement is not well understood or documented and therefore was investigated in this study. It was observed by many researchers that the presence of moisture vapor transmission or backside water ingress can cause air pockets under the CFRP laminate during installation. This phenomenon was related to the vapor transmissions resulting from entrapped moisture in the concrete after being exposed to high temperatures. Formation of air pockets prior to the full cure of the system will reduce the efficiency of the system and, if undetected and not properly treated or repaired, could cause premature failure of the system. The behavior of FRP bonded concrete may also vary with the variation of temperature, presence of saline conditions, relative humidity …etc.; therefore, this study was initiated.

LITERATURE REVIEW

Very limited literature is currently available on the effect of environmental conditions on bond strength between FRP materials and concrete substrate during installation process. Much of the research found in available literature was related to durability aspects. Several of these durability related references are discussed herein as they relate to bonded FRP-concrete substrate issues. Raiche (1998) investigated the long-term behavior of composite materials used to reinforce concrete beams. The effects of moisture, temperature and de-icing salts were investigated in this study. No significant differences were observed in elastic modulus for the composite materials before and after environmental exposures. The mechanical properties of the CFRP product were found to be less influenced by the environmental exposures than those of the GFRP product, despite higher water absorption. The combined effect of moisture and temperature was more aggressive than the presence of de-icing salt for all laminates.

Sen (1999) presented results from a two-year exposure study to evaluate the durability & performance of the epoxy bond formed with concrete and carbon fiber-reinforced polymers (CFRP) in a marine environment and also the effects of exposure on material properties degradation. Four different environments were studied: combined wet/dry cycles and hot/cold cycles in 5% salt-water; wet/dry cycles in 15% salt water; outdoor conditions; and air-conditioned laboratory conditions. Bond degradation was least for outdoor exposure and greatest under wet/dry cycles which suggests that moisture absorption by the epoxy is potentially more detrimental to bond durability where CFRP is used for repair. The researcher noted that surface preparation and proper application of epoxy following recommended procedures is essential for the long-term integrity of the CFRP/epoxy/concrete bond. The effect of freeze-thaw cycles on the bond durability between FRP plate strengthening and concrete was studies by Green (2000). The results indicated that the bond between CFRP strips and concrete is not significantly damaged by up to 300 freeze-thaw cycles. However, Ren (2003) performed freeze-thaw tests on concrete structures strengthened with FRP sheets and concluded that the bond strength between concrete and FRP sheets decreases under the freeze-thaw cycles. Miller (1999) studied the bond between CFRP sheets and concrete. He concluded that the bonded length of the CFRP sheet had no affect on the bond strength of the CFRP sheets. Concrete strength did not affect the bond strength.

Grace (2004) reported that many researchers concluded as the long term exposure of FRP strengthened RC beams to humidity may cause a significant decrease in their load carrying capacity, and even short-term exposure of CFRP to humidity may significantly degrade the beam strengthening system. Grace himself concluded that the most significant reduction was caused by long-term exposure to 100% humidity. Staunton (1982) notes that the moisture effectively plays the role of a resin plasticizer which softens the matrix and lowers the glass transition temperature; moisture has a potentially degrading effect on matrix material. It was also noted that moisture absorption also effectively lowers the mechanical properties. The effect of aggressive environments on fatigue resistance of CFRP strengthened RC beams was studied by subjecting the test members to freeze-thaw, extreme temperature, UV light exposure, and relative humidity cycles before fatigue cycling under service loads (Ekenel, 2004). It was noted that all beams survived 2-million fatigue cycles without showing significant bond degradation between composite and substrate. However, significant stiffness degradation was observed in the conditioned specimens. Toutanji (1997) reported that the FRP strengthened specimens subjected to wet-dry cycling showed less improvement in load carrying capacity as compared to the specimens kept at room temperature. This was attributed to the degradation of the epoxy, which led to the weakening of the bond between concrete specimen and FRP sheets. Al-Salloum (2001) exposed glass FRP strengthened beams to wet-dry normal water, wet-dry saline water, wet-dry alkaline, and high temperature environments. He concluded no significant degradation in the flexural strength and rigidity arising out of that environmental exposure was noticed.

RESEARCH OBJECTIVES

This study investigated the effect of moisture and temperature of concrete surface on the bond strength between concrete and FRP reinforcement. This was investigated by varying the moisture and temperature of the concrete surface prior to FRP application. Surface tests in the form of pull-off and shear-torsion were conducted to evaluate the bond performance. The bond performance in the presence of frost at the surface of the concrete was also evaluated by surface and flexure tests. The end result was to develop allowable limits for these environmental conditions at the time of FRP fabric installation.

EXPERIMENTAL PROGRAM

Test samples and material properties

The test samples were divided into two groups: surface test samples (Type I) and flexural test samples (Type II). All concrete specimens had the dimensions of 6 in. x 6in. x 24 in. (152 mm × 152 mm × 610 mm). Two #2 (0.250 mm. diameter) and two #3 (0.375 mm. diameter) steel bars were used as tension reinforcement in Type I and Type II specimens, respectively. The yield strength of the steel used in Type I and Type II specimens was 96 and 104 psi (661.4 and 717 MPa), respectively. The compression strengths of test specimens were measured according to ASTM C 39 at test-age and determined as 6,500 and 6,422 psi (44.8 and 44.2 MPa) for Type I and II, respectively. The dimension of the CFRP fabric was 23 in. x 5.5 in. (584 mm × 140 mm), thus covering 88% of the concrete face as illustrated in Figures 1 and 2. Systems M and T were the two different commercially available strengthening systems used in the experimental program. The properties of System M and T CFRP laminates are presented in Table 1. Type II beams were pre-cracked at 28 days after casting under 3-point bending to ensure flexural crack in the mid-span prior to strengthening and to be representative of an in-service structural member. CFRP u-wraps were applied on the ends and adjacent to the crack location on one side for flexural test specimens. The u-wraps at the ends were applied to provide anchorage to the existing CFRP flexural strengthening. The u-wrap near the crack was applied to avoid duplication of instrumentation. The flexural test set-up is illustrated in Figure 2.

Test matrix

The test matrix contained three phases. Type I concrete beams were used for Phases I and II of this study. Type II beams were used for Phase III of this study. The relative humidity (RH) and ambient temperature for all seasons for five distantly different regions in the United States were studied to develop appropriate ranges of conditioning for study. The regions included a hot dry location of Phoenix, Arizona, to a hot humid Houston, Texas to an extremely cold location of International Falls, Minnesota (NCDC, 2003). Phase I was carried out to identify a surface moisture content level at which the bond between concrete and FRP performed well. The surface moisture content was measured by a commercially available calibrated moisture-meter. Table 2 shows the surface moisture contents studied for two commercially available systems, (systems M and T). The test specimen was first saturated in water for a minimum of 3 days until the concrete specimen was fully saturated. The beam was then taken out and an average moisture reading was recorded with the help of a calibrated moisture meter until the desired surface moisture level for testing was obtained. The specimen was then weighed to correlate percent moisture content.

The test matrix for phase II focused on the RH of concrete. The test specimens started at a RH of 98% and proceeded in decreasing order of RH during installation of CFRP to identify a level at which the bond between concrete and CFRP performed well. Table 3 shows the RH of the specimens at installation. This RH was maintained throughout the matrix hardening process. The strengthening took place in an environmental chamber where the RH could be precisely controlled and maintained. All specimens were brought to equilibrium within the environment prior to strengthening.

Phase III was divided into two groups as high and low temperature, the highest and lowest limits were set as 120°F (49°C) and 20°F (-7°C), respectively. The testing program is shown in Table 4. The high temperature specimens were conditioned in an oven at a constant temperature for 10 hours prior to strengthening. The low temperature specimens were conditioned in an exterior environment for temperature ranges between 20°F (-7°C) to 40°F (4°C) for 10 hours prior to strengthening.

Test methods

Two types of tests were performed under surface tests category, namely, pull-off and shear-torsion tests. Test adhesive fixtures were applied two days after the primary strengthening occurred. Four adhesives fixtures with 1.625 in. (41.2 mm) diameter were attached to the surface of the FRP with epoxy adhesive (see Figure 1). After the epoxy cured, a core drill was used to isolate the adhesion fixture from the surrounding FRP by drilling to a depth between 0.13 in. (3.3 mm) and 0.25 in. (6.35 mm). Next, the pull off test apparatus was attached to the adhesion fixture and aligned to apply tension perpendicular to the concrete, as illustrated in Figure 3. A constant force rate of 150 lb/sec. (0.67 kN/sec.) was applied to the adhesion fixture and recorded until the adhesion fixture detaches from the surface. There are three types of possible failure modes: the failure of concrete in tension, failure of the epoxy glue attaching the adhesion fixture to the FRP, or the delamination of the FRP from the concrete. The shear-type torsion test is a relatively new method to qualify the bond strength (Myers, 2002). For the shear-torsion test, the torque was applied to a special probe using the torque-applying adhesive, as illustrated in Figure 4. Torsion was applied using a calibrated torque wrench with a series of hinges until the failure. The torque reading at failure was recorded. The shear stress was calculated as $\tau = T/\pi R^3$, where T is the torque and R is the outer diameter of torsion disc. The average shear stress was then calculated by taking the average of all the readings for a respective test specimen irrespective of the mode of failures. Flexural test were applied after pre-cracking, strengthening and conditioning the beams. The flexural steel reinforcing in the beam was cut at the location of the crack to study the bond behavior of FRP (see Figure 2). Strain in the FRP fabric was observed with the aid of strain gauges, respectively.

EXPERIMENTAL TEST RESULTS

Phase I test results

System M and T pull-off tests - The bond performance of four beams strengthened with FRP sheets were evaluated using a pull-off test. Each value presented is the average of three tests. Figure 5 illustrates representative pull-off discs of the specimens as indicated. Figure 6 illustrates the average test results for each conditioned System M and T specimens and standard deviations. The System M specimen strengthened at 5.05% moisture meter reading behaved very poorly in terms of both the failure stress and performance of substrate material. All of its discs had complete CFRP peeling. The control and 1M-3.50 specimens exhibited a good bond performance in terms of failure stress as well as substrate material. Similar to M specimens, the System T specimen 1T-3.50 performed well in terms of bond behavior, which exhibited concrete failure.

System M and T shear-torsion tests - The bond performance of four specimens strengthened with FRP sheets were evaluated using shear-torsion test. Each value presented is the average of three tests. Figure 7 illustrates the average test results for each conditioned System M and T specimens and standard deviations. Even though all System M discs exhibited similar bond performance in terms of failure stress; it may be noted that the samples with lower surface moisture contents tend to have higher failure stresses. In addition to the failure stress, each disc was inspected in terms of where the failure occurred; namely FRP delamination, concrete substrate failure, or some % of each. The distribution of the failure mode was determined using a software package which enabled the authors to obtain a percentage of concrete and FRP from the surface tests. Only samples from specimen 1M-3.37, with the lowest surface moisture content, exhibited a complete concrete substrate failure. Specimens of 1T-4.26 and 1T-3.80 had a failure mode that consisted of approx. 40% FRP substrate (delamination) failure and may be categorized as poor bond performance in terms of the failure mode. The performance of specimen 1T-3.50 was good in terms of the average shear stress as well as the percentage of FRP failure (29%).

Phase II test results

System M and T pull-off tests - The bond performance of five beams strengthened with System M and T FRP sheets was evaluated by using pull-off tests. Each value presented is the average of three tests. Figure 8 illustrates the average test results for each conditioned System M and T specimens. In general, the results show a trend in that the FRP-concrete bond performance decreases as the installation relative humidity increases. The specimen 2M-65 had optimal bond performance in terms of substrate material and 2M-75 exhibited optimal bond performance in terms of failure stress. As for T specimens, it should be noted that the FRP sheet of the specimen strengthened at 98% installation RH peeled off completely while grinding the perimeter of the discs. Thus, it indicated very poor FRP-concrete bond. There was a significant amount of difference in percent FRP substrate failure between specimens strengthened at 65% RH and at 75% RH and higher (increase from 28% to 100%). Specimen 2T-82 exhibited relatively higher results in terms of failure stresses.

System M and T shear-torsion tests - The bond performance of five beams strengthened with System M and T FRP sheets was evaluated using a shear-torsion test. Each value presented is the average of three tests. Figure 9 illustrates the average test results for each conditioned System M and T specimens. It can be observed from the average stress of all the specimens that the bond performance of the specimen 2M-98 is the poorest within all M specimens. Even though all the M specimens had partial FRP failure, 2M-65 showed the highest failure load. Figure 9 also illustrates the average test results for each conditioned System T specimen. It was observed from average failure stress as well as the bond performance of substrate material that the performance of FRP with concrete is poorest at 89%, whereas the bond performance of 2T-65 in terms of substrate material was optimal. The results did not indicate any particular trend in terms of failure loads; however, the percent FRP substrate failure was lower for lower humidity levels such as 26% for the sample 2T-65.

System M and T flexural tests - The bond performance of four Type II specimens strengthened with System M FRP sheets at different installation RH were evaluated using flexure tests. Test results for this series are summarized in Table 5. As seen in this Table, the lower humidity sample exhibited higher failure load. The post-failure visual inspection also showed a good bond between concrete and FRP sheet which is demonstrated by peeling of most of the concrete cover with the sheet and the texture of the peeled off concrete was rough and angular. Figure 10 and 11 illustrate the strain vs. strain gauge (SG) location diagram for the specimen 2M-65F and 2M-89F, respectively. Both of the graphs show a trend in which the strain value in each of the strain gauge increase as the load increases and distance from crack decreases. The highest load considered here is approximately 40-60% of the ultimate load capacity to represent the behavior at slightly above service loads. Figure 10 illustrates insignificant difference between the strain values of SG 3 and SG 4. For a load of 3500 lb (15.6 kN), SG 3 exhibited approximately 8% strain value of SG 1 and approximately 6% strain value of SG 2. SG 4 exhibited strain values that were less than 30 micro-strains. All strain gauges of Figure 11 exhibited higher strain values than that of Figure 10. After the visual inspection, it was observed that the sheet of the specimen 2M-89F peeled off with less amount of concrete without any rough or angular texture indicating that the RH of 89% had a detrimental effect on the bond between FRP and concrete. Specimens 2M-82F and 2M-75F exhibited similar behavior to 2M-89F with the exception that the sheet had more concrete. The sheet of specimen 2M-75F resembled that of specimen 2M-82F. The specimen 2M-65F had FRP rupture indicating optimal bond between FRP and concrete.

System T test results for this series are summarized in Table 6. As seen in this Table, the lowest humidity sample showed the highest flexural strength. After visual inspection of the sheet of specimens of 2T-89F and 2T-82F, it was observed that they were peeled off with slight concrete cover. The sheet of specimen 2T-75F peeled off without any concrete on it indicating poor bond performance. The specimen 2T-65F had FRP rupture demonstrating optimal bond between FRP and concrete.

Phase III test results

Phase III of the experimental program focused on evaluating the bond performance of FRP strengthened concrete at various installation temperatures (Table 4). This phase was sub-divided into extreme high and low temperatures. The control specimens were strengthened and tested under ambient lab temperature of 70°F (21°C) ± 3°F (2°C). The reason that T specimens were not tested at all temperature levels was on the basis of bond performance observed at 120°F (49°C) for System T and the comparative results for System M specimens tested at those temperatures. Concrete specimens for surface tests were also strengthened with FRP sheets using System M at low temperatures. Specimen 1M-10 was the specimen designation for the one installed with a thin layer of frost present. System T specimens were not undertaken at a temperature of 20°F (-7°C) or in the presence of frost based on the observations of bond performance tests on System M specimens conditioned and tested under those conditions. The bond performance of FRP strengthened beams was not significantly affected by installation at high temperatures. However, temperatures higher than 100°F (38°C) affected the set time and workability of the saturant used for the two systems investigated. The bond between concrete and FRP sheet was evaluated by stress at failure due to an applied torque or pull-off force. The failure mode and distribution was also observed at failure and recorded. The bond performance of nine beams strengthened with System M FRP sheets was evaluated using pull-off test. Four beams were used for System T strengthening. Each value presented is the average of minimum of three pull-off tests

System M and T pull-off tests - Figure 12 illustrates the average test results for each conditioned specimen. The control specimens exhibited a complete concrete substrate failure. Representative pull-off disc image of a control specimen which exhibited concrete substrate failure is illustrated in Figure 13a. The texture of the concrete substrate was rough and angular also representative of good bond behavior. Representative pull-off disc image of a specimen strengthened with FRP at 10°F (-12°C) in the presence of frost is illustrated in Figure 13b. This figure demonstrates complete debonding between the FRP and concrete substrate.

As illustrated by failure stress level and observed visually, specimen 3M-120 illustrated optimal FRP-concrete bond performance as the failure mode occurred in the concrete substrate. The texture of the concrete substrate was rough and angular also representative of good bond behavior. The same can be mentioned for specimens 3M-105 and 3M-90 although a slight FRP substrate failure (less 15%) was observed for some of the discs. Installation of FRP at 10°F (-12°C), 20°F (-7°C) and to some extent 30°F (-1°C) was more difficult, as the primer and saturant became thicker and its impregnation into the fiber was more difficult. The set time of the saturant and primer clearly decreased although no scientific method was implemented to measure this. Certainly, low temperature installation is not practical from this perspective withstanding direct bond behavior test results. Specimen 3M-30 also did not perform well in terms of substrate material, but did exhibit a high failure stress. Figure 12 also illustrates the average test results for each conditioned System T specimen. The control specimens for System T strengthened at 70°F (21°C) exhibited a 67.7% concrete substrate failure. Each of the discs exhibited partial concrete and FRP failure. Thus, it did not demonstrate optimal bond. Specimen 3T-120 exhibited optimal FRP-concrete bond performance. Each disc exhibited complete concrete substrate failure. Also, the texture of the concrete substrate was rough and angular also representative of good bond behavior. The specimen strengthened with FRP at 30°F (-1°C) resulted in a partial substrate failure. In addition, it exhibited lower stress at failure compared to the control specimen and all other conditioned specimens.

System M and T shear-torsion test - Figure 14 illustrates the average test results for each conditioned System M and T specimens. Similar to the pull-off test, the control specimens (70) exhibited a complete concrete substrate failure demonstrating optimal bond performance in terms of substrate concrete. Specimen 3M-120 exhibited optimal FRP-concrete bond in terms of failure stress and a less optimal bond in terms of substrate material. Specimens 3M-105 and 3M-90 had FRP as well as concrete substrate failure but less optimal as compared to specimen 3M-120. For the low temperature phase, higher FRP substrate percentages were generally observed. Specimen 3M-20 exhibited the poorest performance in terms of substrate material but not in terms of failure stress. The bond performance of specimen 3M-10 in terms of substrate material was slightly better than 3M-20 although its performance in terms of failure stress was poor. Specimen 3M-30 did not perform well in terms of substrate material. All the discs strengthening under conditioning had at least a partial FRP substrate failure.

As for System T specimen, all the discs exhibited a partial FRP substrate failure. The specimen 3T-120 exhibited less optimal bond performance in terms of failure stress when compared to the control specimen, but it exhibited more optimal bond performance in terms of substrate material. The control specimen exhibited more optimal bond performance in both the failure modes. Henceforth, the test results emphasize the relative variability encountered with this test method. Specimen 3T-30 exhibited the poorest bond in terms of failure stress and in terms of substrate material.

System M flexural tests - Eleven Type II specimens strengthened with FRP sheets using System M at different installation temperatures were tested under 4-point bending. Average test results for this series are summarized in Table 7. Control specimen 3M-70F after testing is illustrated in Figure 15. The post-failure visual inspection showed a good bond between concrete and FRP sheet. Concrete cover was peeled off with the sheet demonstrating a good bond with the FRP sheet.

Figure 16 illustrates the strain vs. location diagram for different specimens strengthened with CFRP at high temperatures and at ambient lab temperature (control specimen). Strain gauge 4 (SG4) for specimen 3M-120F failed. Hence a projected line (dashed) has been plotted. At the crack location, specimen 3M-105F had developed approximately 100% higher strain than the control specimen 3M-70F. Specimen 3M-120F developed approximately 40% higher strain than the control specimen. The SG2 on the conditioned specimens developed higher strains compared to SG2 on the control specimen which varied from 40-80%. Strain gauge SG3 on the conditioned specimen developed approximately 7-10 times higher strain than the corresponding strain gauge of the control specimen 3M-70F. The above-mentioned results indicate less efficient bond for the high temperature installed specimens in terms of flexural behavior.

Figure 17 illustrates the strain vs. location diagram for different specimens strengthened with FRP at low temperatures, at ambient lab conditions and specimen strengthened with frost on it. Specimens 3M-40F and 3M-70F (control) had developed the lowest strain when compared to other specimens at 4000 lb. The difference between the strains developed in both the specimens was at the most 25%. Thus, it can be stated that for specimen 3M-40F minimal degradation was observed for this system. Specimen 3M-10F (frost) developed the highest strain from SG1 and SG2. Both the strain gauges developed approximately 3-5 times the strain of control specimen indicating that the frost had detrimental effect on the bond between FRP and concrete. Specimens 3M-30F and 3M-20F developed higher strain values along the monitored region compared to the control specimen. Thus, the low temperature had an adverse effect on the bond between FRP sheet and concrete. Based upon the visual inspection, the sheet for 3M-120F peeled-off with rough texture of concrete. There was a FRP rupture in specimen 3M-105F. The sheet in specimen 3M-90F peeled off with concrete scattered over some portions of the sheet. The sheet in specimen 3M-70F (control) peeled off with concrete which was rough and angular. The quantity of concrete in the sheet of specimen 3M-70F was more than the concrete in the sheet of specimen 3M-120F indicating that the bond performance of the control specimen was better than that of specimen 3M-120F. The result demonstrated that high temperatures did not significantly affect the bond between FRP and concrete.

System T flexure tests - Four Type II specimens, strengthened with System T FRP sheets at different installation temperatures were tested under 4-point bending. Test results for the same are summarized in Table 8. Figure 18 illustrates the strain vs. location diagram for different specimens strengthened with FRP sheets at all kinds of temperatures which included high, low and room temperatures. As illustrated specimen 3T-40F developed the highest strain along the length of the sheet compared to other specimens. All of the low temperature specimens were maintained ± 3°F (2°C) to their target temperature except for specimen 3T-40F that was subjected to a shape temperature drop of 20°F (11°C) during curing. The high variability of temperature during the strengthening and curing process for this specimen seemed to indicate that high temperature variability during installation/curing at low temperature detrimentally affects the bond between FRP and concrete more severely than a relatively constant temperature for System T. Minimal variation was seen between the strain developed in specimen 3T-70F along the length of the sheet indicating that the temperature 30°F (-1°C) did not adversely affect the bond between FRP and concrete. SG1 on specimen 3T-120F developed approximately 15% more strain than the control specimen 3T-120F and SG2 on specimen 3T-120F developed 50% less strain than specimen 3T-120F. This indicated that specimen 3T-120F had a brittle failure, but the high temperature did not detrimentally affect the bond between FRP and concrete. Based on visual inspection, it was observed that specimen 3T-120F failed by FRP rupture. The sheet on control specimen 3T-70F peeled off with rough and angular texture of concrete indicating optimal FRP-concrete bond. The sheet on the specimen 3T-40F peeled off without significant concrete on it indicating a poor bond between FRP and concrete. The sheet on specimen 3T-30F peeled off with more concrete than specimen 3T-40F, but less than control specimen 3T-70F indicating less optimal bond between FRP and concrete.

DISCUSSION & CONCLUSIONS

Based on matched pairs statistical analysis between pull-off and shear-torsion tests data, a 99% confidence interval fell between 4.4 and -149.7. Since zero is within the interval, there is insufficient evidence to conclude there is a difference between the two means. A graph plotted between average pull-off stress and average shear stress for all the tested specimens is illustrated in Figure 19. A trend line using the above data is also plotted. As illustrated in this Figure 19-a, several of the shear-torsion tests yielded higher test results as compared to pull-off test results. Consequently, the shear stress displayed a wider standard deviation compared to the pull-off stress test results. Upper and lower limits (y±s) were drawn around the trend line (y) on this figure using the standard deviation (s) of overall test result and outliners were removed (Figure 19-b). As illustrated in Figure 19-b, the R^2 value is 0.70, which does not represent a strong relationship between pull-off and shear-torsion test results.

The following can be concluded about effect of surface moisture content, relative humidity and temperature on the bond performance:

- Specimens strengthened with a surface moisture content of 100% (5.05% value of moisture-meter) resulted in extremely poor bond behavior based on disc inspection (FRP peeling failure) and pull-off stress at failure.
- Specimens strengthened at a surface moisture reading of 4.3% or lower exhibited satisfactory bond performance based upon the calibrated moisture-meter used within this investigation.
- Specimen strengthened at 82% or lower relative humidity exhibited satisfactory bond performance for the two systems investigated.
- Specimen strengthened at 65% RH during installation exhibited the highest quality bond performance. This was concluded by failure disc inspection and FRP strain level results from the flexure tests for the two systems investigated.
- Less optimal bond performance may be encountered when FRP is installed at a RH of 82% or above.
- Extreme low temperature affected the bond performance of both the systems investigated. It has been observed that, saturant and primer became too viscous for

proper application at extreme low temperatures. Also, high thermal changes during curing at low temperatures indicated some detrimental affects.

- High temperature did not significantly affect the bond in both the commercially available systems investigated although the workability and set time of the saturant was detrimentally affected above 90°F (32°C) installation temperatures.
- It was observed that above 90°F (32°C), the set time and workability of the saturant is negatively affected.

Based on observations of the research program undertaken herein, the following specifications are recommended:

- FRP should not be installed at surface moisture content readings above 4.3% using the commercially available calibrated moisture-meter used in this study.
- FRP sheets should not be installed at or over 82% of substrate relative humidity.
- FRP sheets can be installed within the temperature range between 40°F (4°C) and 120°F (49°C). Installation above 90°F (32°C) should be avoided due to set-time and saturant workability at high temperatures.
- The manufacturer-recommended installation requirements should additionally be considered and supercede limits presented herein.

ACKNOWLEDGMENTS

The authors would like to acknowledge: the Federal Highway Administration (FHwA) under research study DTFH 61-00X-00017; the University Transportation Center (UTC) and the NSF/Industry sponsored Repair of Buildings and Bridges with Composites Cooperative Research Center (RB2C) at the University of Missouri-Rolla (USA). In addition the authors would like to acknowledge Mr. Anand L. Khataukar for his involvement in fabricating and testing the specimens in this research program.

REFERENCES

Al-Salloum Y. A., Alsayed S. H., Almusallam T. H., "Effect of Aggressive Environments on Strength of RC Beams Strengthened with Composite Laminates," 46th International SAMPE Symposium, May 2001, pp. 485-496.

Ekenel, M., Myers, J. J., "Effect of Environmental Conditioning & Sustained Loading on the Fatigue Performance of RC Beams Strengthened with Bonded CFRP Fabrics," Submitted to ACI Materials Journal, September 2004.

Grace, N. F., "Concrete Repair with CFRP," Concrete International, Vol. 26, No. 5, May 2004, pp. 45-52.

Green, M. F., Bisby, L. A., Beaudoin, Y. Labossiere, P., "Effect of Freeze-Thaw Cycles on the Bond Durability between Fibre Reinforced Polymer Plate Reinforcement and Concrete". Canadian Journal of Civil Engineering, V. 27, No. 5, October 2000, pp. 949-959.

Miller, B. and Nanni, A., "Bond Between CFRP Sheets and Concrete," Proceedings, ASCE 5th Materials Congress, Cincinnati, OH, L.C. Bank, Editor, May 10-12, 1999, pp. 240-247.

Myers, J.J., Shen, X., “Effect of Surface Roughness and Putty Thickness on the Bond Performance of FRP Laminates,” Center for Infrastructure Engineering Studies,” Report Number 03-41, October, 2002.

National Climatic Data Center (NCDC), http://www.ncdc.noaa.gov/oa/ncdc.html, web site accessed at 2003.

Raiche, A., “Durability of Composite Materials used as external reinforcement for RC-beams,” Annual Conference of the American Society for Civil Engineering, Regina, Saskatchewan, Canada, 1999, pp. 155-164.

Ren, H., Hu, A., Zhao, G., “Freeze-Thaw Resistance Behavior of Bonded Joints between FRP and Concrete,’ Journal of Dalian University of Technology, V. 43, No. 4, July 2003, pp. 495-499.

Sen, R., Shahawy, M., Mullins, G., Spain, J., “Durability of Carbon Fiber-Reinforced Polymer/Epoxy/Concrete Bond in Marine Environment,” ACI Structural Journal, V. 96, No. 6, November/December 1999. pp. 906-914.

Staunton R., “Environmental Effects on Properties of Composites,” Handbook of Composites, Edited by George Lubin, Van Nostrand Reinhold Publication, 1982.

Toutanji, H. A., Gomez, W., “Durability Characteristics of Concrete Beams Externally Bonded with FRP Composite Sheets,” Cement and Concrete Composites, V. 19, 1997, pp. 351-358.

Table 1 – Properties of CFRP sheets.

Material	Ultimate Strength ksi (MPa)	Elastic Modulus ksi (GPa)	Ultimate Strain (%)
System M	550 (3792)	33,000 (227.5)	1.67
System T	143.7 (990)	14,400 (78.6)	1.26

Table 2 – Various Surface Moisture Contents of System M and T Specimens.

Specimen Designation (M)	Specimen Designation (T)	Moisture Content (1) (%)	Surface Moisture Reading (2)
1M-5.05	-	100	5.05%
1M-4.26	1T-4.26	90	4.26%
1M-3.80	1T-3.80	NA	3.80%
1M-3.50	1T-3.50	NA	3.50%
1M-3.37 (Control)	1T-3.37 (Control)	NA	3.37%

(1) Based on specimen weight by measurement at the time of strengthening.
(2) Based on moisture meter readings (Average of a minimum of 20 surface readings).

Table 3 – Various Relative Humidity of System M and T Specimens.

Specimen Designation (Surface Tests)	Relative Humidity (%)	Specimen Designation (Flexure Tests)	Relative Humidity (%)
2M-98 and 2T-98	98	-	-
2M-89 and 2T-89	89	2M-89F and 2T-89F	89
2M-82 and 2T-82	82	2M-82F and 2T-83F	82
2M-75*and 2T-75*	75	2M-75F* and 2T-75F*	75
2M-65 and 2T-65	65	2M-65F and 2T-65F	65

* Control Samples

Table 4 – Various Installation Temperatures of System M and T Specimens.

Specimen Designation (Surface Tests)	Temperature at the Time of Install. °F (°C)	Specimen Designation (Flexure Tests)	Temperature at the Time of Install. °F (°C)
3M-120 & 3T-120	120 (49)	3M-120F & 3T-120F	120 (49)
3M-105	105 (41)	3M-105F	-
3M-90	90 (32)	3M-90F	-
3M-70* & 3T-70*	70 (21)	3M-70F* & 3T-70F*	70 (21)
3M-40 & 3T-40	40 (4)	3M-40F & 3T-40F	40 (4)
3M-30 & 3T-30	30 (-1)	3M-30F & 3T-30F	30 (-1)
3M-20 & 3T-20	20 (-7)	3M-20F	20 (-7)

* Control Samples

Table 5 – Summary of Flexural Test Results for System M Specimens.

Specimen Code	Strain SG1 at 3500 lbs	Ultimate Load (lb)	Ultimate Strain at Crack	Failure Mode
2M-89F	1167	5875	1840	Peel-off
2M-82F	NA	6225	*	Peel-off
2M-75F	547	7000	2241	Peel-off
2M-65F	887	7200	1906	FRP rupture

* Instrumentation failure during testing (1 lb = 0.0044 kN)

Table 6 – Summary of Flexural Test Results for System T Specimens.

Specimen Code	Strain SG1 at 2500 lbs	Ultimate Load (lbs)	Ultimate Strain at Crack	Failure Mode
2T-89F	98	4125	1549	Peel-off
2T-82F	380	4800	1493	Peel-off
2T-75F	121	3500	521	Peel-off
2T-65F	72	5000	1289	FRP rupture

Note: 1 lb = 0.0044 kN

Table 7 – Summary of Test Results for System M Specimens.

Specimen Code	Strain SG1 at 4000 lb (με)	Ultimate Load (lb)	Ultimate Strain at Crack (με)	Failure Mode
3M-120F	4696	6004	7077	Peel-off
3M-105F	6000	4450	6070	FRP Rupture
3M-90F	6290	5550	7735	Peel-off
3M-70F	3700	7110	7410	Peel-off
3M-40F	4801	8010	10250	FRP Rupture
3M-30F	3733	6302	4637	Peel-off
3M-20F	5047	7326	9249	Peel-off
3M-10F	Specimen Failure	6357	*	FRP Rupture

* Failure of strain gauge prior to ultimate load (1 lb = 0.0044 kN).

Table 8 – Summary of Test Results for System T Specimens.

Specimen Code	SG1 at 60% Ultimate Load (με)	Ultimate Load (lb)	Ultimate Strain at Crack (με)	Failure Mode
3T-120F	2355	4078	5408	FRP rupture
3T-70F	1971	4018	3828	Peel-off
3T-40F	7814	5533	13643	Peel-off
3M-30F	1782	4080	6894	Peel-off

Note: 1 lb = 0.0044 kN

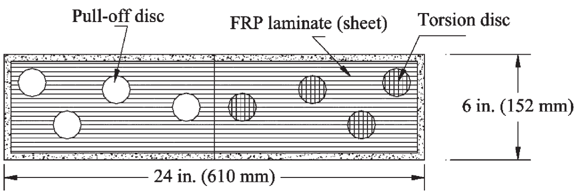


Figure 1 - CFRP strengthened side view of beams used for surface tests.

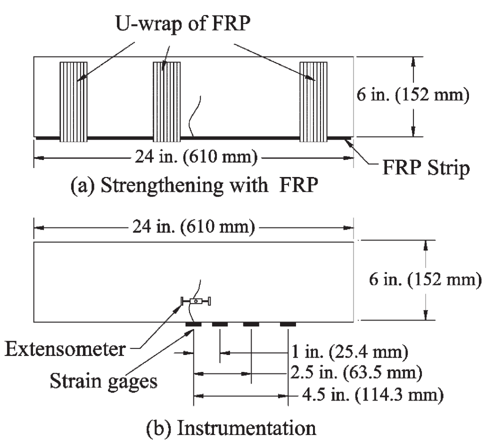


Figure 2 - CFRP strengthened beam used for flexural tests.

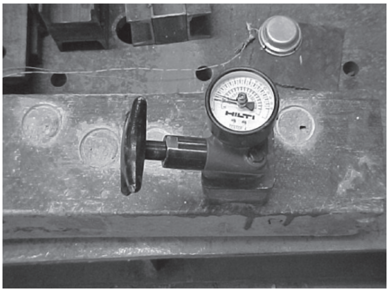


Figure 3 - Pull-off test equipment.

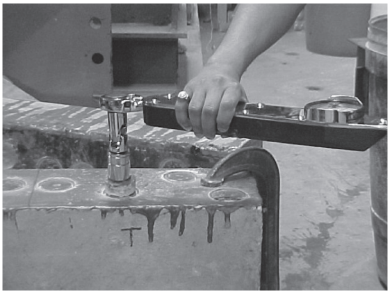
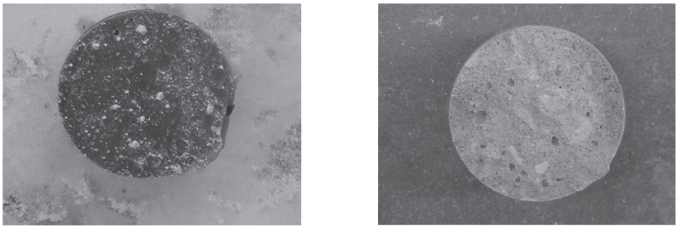


Figure 4 - Application of torque using torque wrench.



(a) (b)

Figure 5 - Representative pull-off disc for specimens (a) 1M-5.05 (b) 1M-3.50.

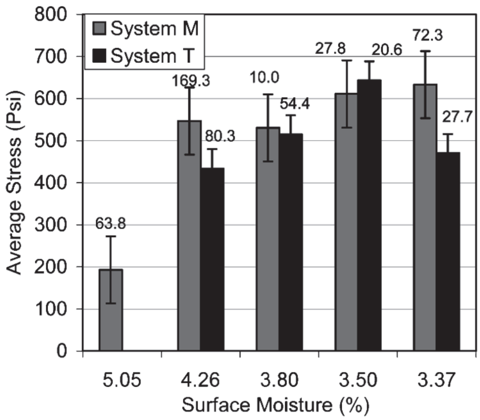


Figure 6 - Pull-off test results (with standard deviations) for system M and T specimens strengthened at various surface moisture contents (1 psi = 0.0069 MPa).

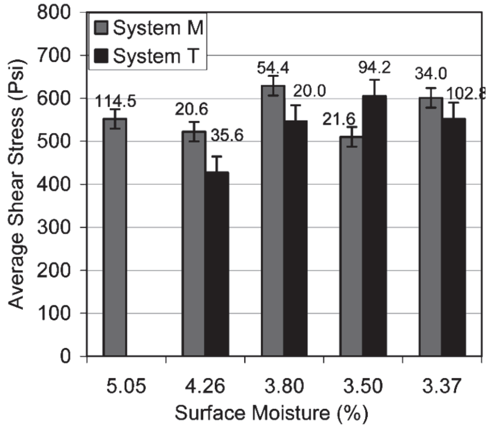


Figure 7 - Shear-torsion test results (with standard deviations) for system M and T specimens strengthened at various surface moisture contents (1 psi = 0.0069 MPa).

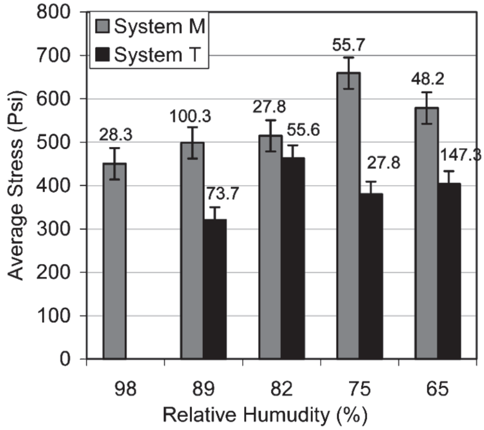


Figure 8 - Pull-off test results (with standard deviations) of system M and T specimens (1 psi = 0.0069 MPa).

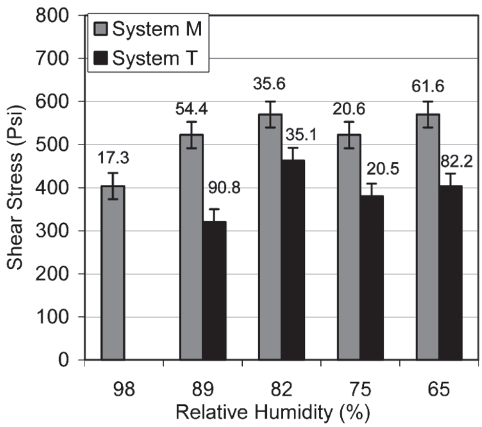


Figure 9 - Shear-torsion test results (with standard deviations) of system M and T specimens (1 psi = 0.0069 MPa).

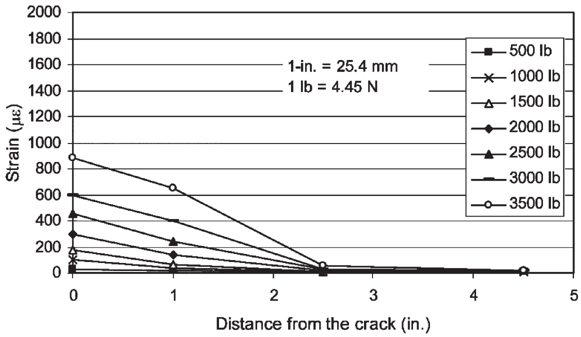


Figure 10 - Strain vs. location graph for specimen 2M-65F.

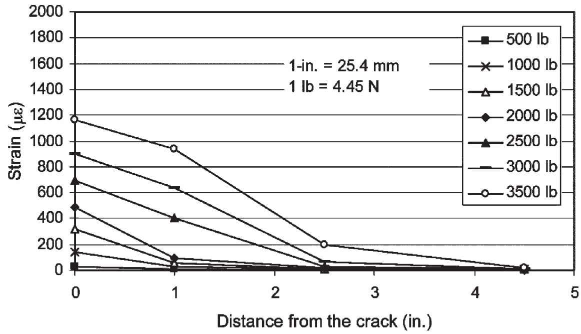


Figure 11 - Strain vs. location graph for specimen 2M-89F.

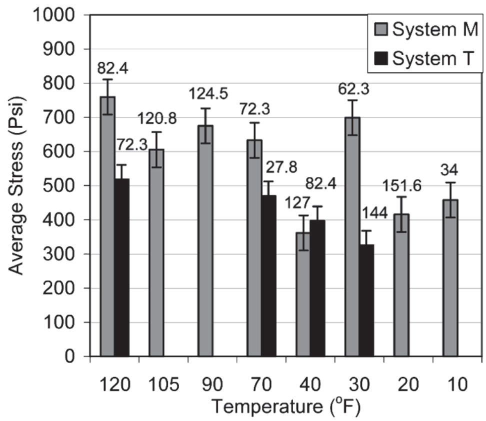


Figure 12 - Pull-off test results (with standard deviations) for system M and T specimens strengthened at extreme installation temperatures (1 psi = 0.0069 MPa).

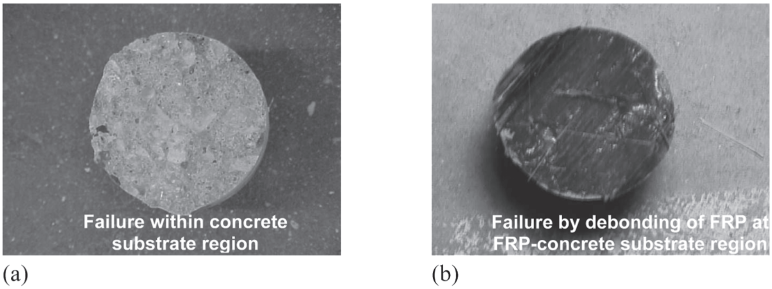


Figure 13 - Representative Pull-off Test Disc for Specimens (a) 3M-70 (b) 3M-10.

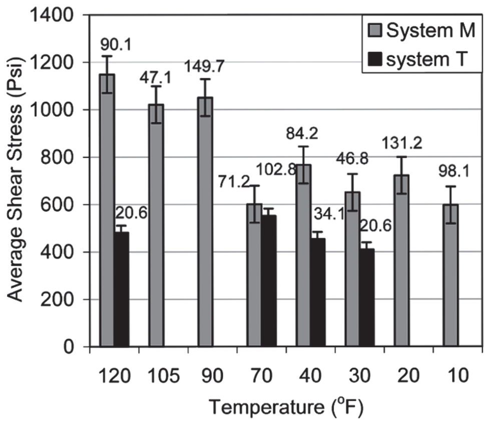


Figure 14 - Shear-torsion test results (with standard deviations) for system M and T specimens strengthened at extreme installation temperatures (1 psi = 0.0069 MPa).

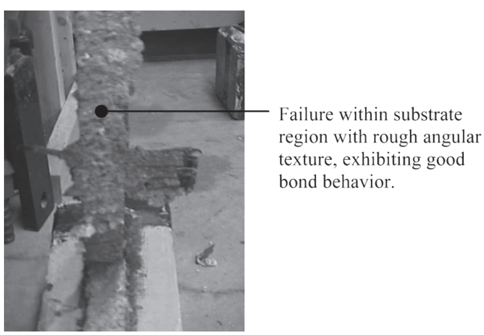


Figure 15 - Specimen 3M-70F after testing.

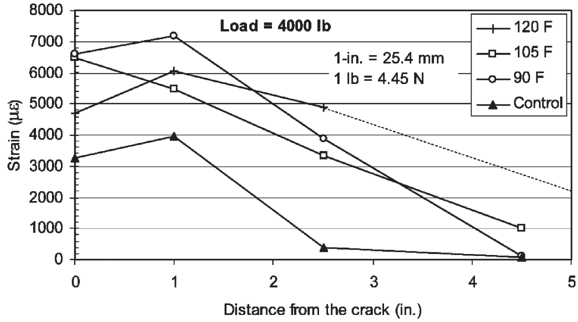


Figure 16 - Strain vs. location diagram for system M high temperature specimens.

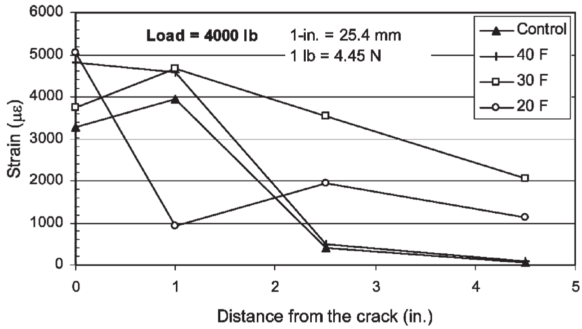


Figure 17 - Strain vs. location diagram for system M high temperature specimens.

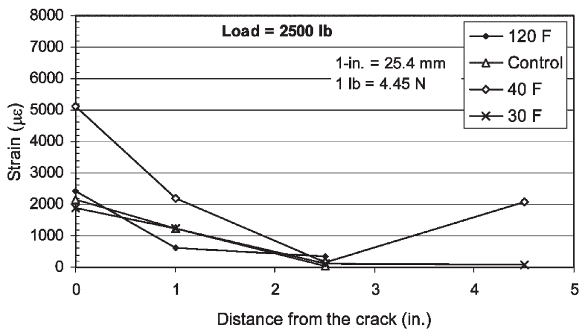


Figure 18 - Strain vs. location diagram for system T.

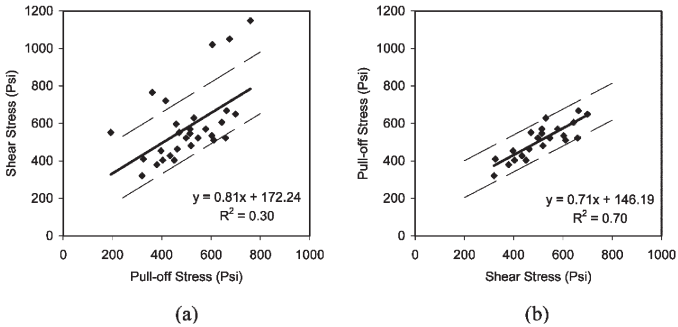


Figure 19 - Relation between average pull-off stress versus average shear stress of Systems M and T samples (1 psi = 0.0069 MPa) (a) rough data, (b) data without outliners.