EXPERIMENTAL NON-DESTRUCTIVE TESTING OF FRP MATERIALS, INSTALLATION, AND PERFORMANCE, DALLAS COUNTY BRIDGE, MISSOURI, USA

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Abstract: The FRP (Fiber Reinforced Polymer) retrofit of a concrete bridge in Missouri provided the opportunity to use new and existing technologies to test the FRP materials installations, and performance. Four different parameters were investigated; concrete substrate surface roughness, FRP fiber alignment, FRP delamination, and FRP bond pull-off strength. Results of testing to date are presented, and long term monitoring plans will be given.

Surface substrate roughness measurements of sand blasted surfaces were made, on selected locations of the bridge abutments and bents, as well as the bridge deck, using a newly developed laser profilometer. The roughness measurements are compared to the "idealized surface roughness", and compared against any future delamination, from pull-off tests and natural delamination.

FRP fiber alignment measurements were made using an imaging techniques that measures the angle between control lines and special tracers embedded in the FRP materials.

FRP delamination testing was done using a specially modified impact echo tester, on production surfaces and on surfaces with artificially created delaminations. All test sites are referenced with respect to previously determined substrate roughness measurements. Tests will be done every six months for the next five years.

FRP bond Pull-off strength testing was done using a specially designed Pull-off tester. Testing will be done to a working load, Pull-off failure is anticipated only for defective materials or installation. Pull-off plugs were installed on selected locations on the bridge and referenced to roughness measurements. Testing will be done every six months for the next five years.

Introduction: The use of fiber reinforced polymers (FRP) for reinforcement of concrete members has emerged as one of the most promising technologies in materials and structural engineering to repair and strengthen our nation's infrastructure (1,2,3,4,5,6,7). Current Federal Highway Administration (FHWA) statistics indicate that approximately one-fifth of our nation's bridges constructed between 1950 and 1960 are structurally deficient (8). Of these, the vast majority are composed of reinforced or pre-stressed concrete. Much of the deterioration is attributed to aggressive environments and durability related issues. In particular, for highway structures where de-icing salts are predominantly used, corrosion related problems associated with mild steel reinforcing or pre-stressing strands has stood out as a major contributor to the deterioration.

Fiber reinforced polymers are ideally suited for repair and strengthening of concrete structures in aggressive environments due to their non-corrosive, non-magnetic characteristics. They have high tensile strength to weight ratio and high elastic limit. Externally applied FRP sheets or laminates are bonded directly to a concrete surface with an epoxy providing additional flexural or shear strength capacity depending on the application and fiber alignment. This significantly increases the load carrying ability of a structural component and/or structural system.

Although durability-related concerns for new structures can be addressed using modern techniques that include cathodic protection, epoxy-coated reinforcing, and non-corrosive materials, existing deficient structures must be rehabilitated and upgraded in a cost effective way with minimal disruption to service. Research has shown that repair of concrete structures with FRP products including externally applied FRP materials has proved to be a viable and cost effective alternative to traditional repair and strengthening techniques to upgrade deficient structures to meet today's design standards (3,4,5,6,7,8,9).

In 2003 the Missouri Department of Transportation contracted to retrofit five county bridges with FRP materials. This paper deals with non-destructive of FRP material performance on one of the bridges.

Concrete Substrate Surface Roughness: The roughness of the concrete pre-FRP-installation substrate has been identified as a critical factor that affects bond behaviour between the FRP and the concrete (10,11,12). Using a newly developed laser profilometer (13) (Figure 1) a preliminary relationship between roughness (defined as I_a or micro average inclination angle of the profile) has been established (12) (Figure 2). A preliminary optimum value of I_a has been established.

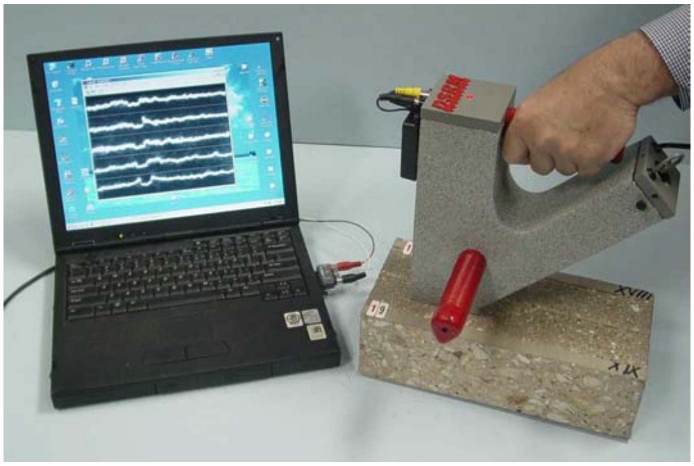

Figure 1: New laser profilometer.

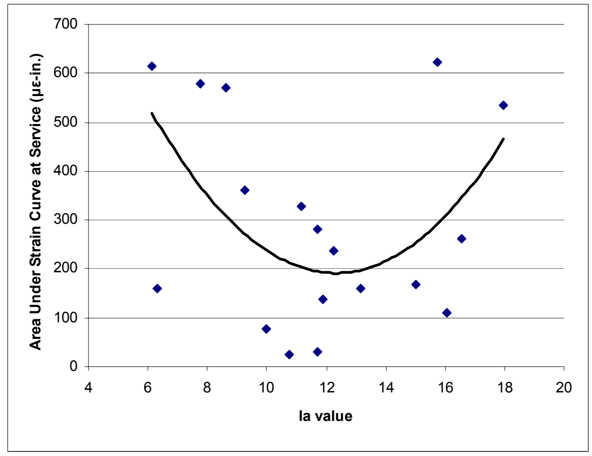

Figure 2. Relationship between roughness (I_a) and stiffness (area under strain curve).

FRP Fiber Alignment: The alignment of FRP fibers as installed has also been identified as an indicator of FRP performance. Yang et al. (14) indicate that a misalignment of 5 degrees or more can significantly affect the performance of the repair. A method of measuring the installation alignment of the FRP sheets was developed. A chord is stretched along the designed alignment of FRP sheets that have tracers woven into them (Figure 3). Using imaging software, the angle between the tracer and the chord is measured to determine if it is greater than 5º misalignment (Figure 4).

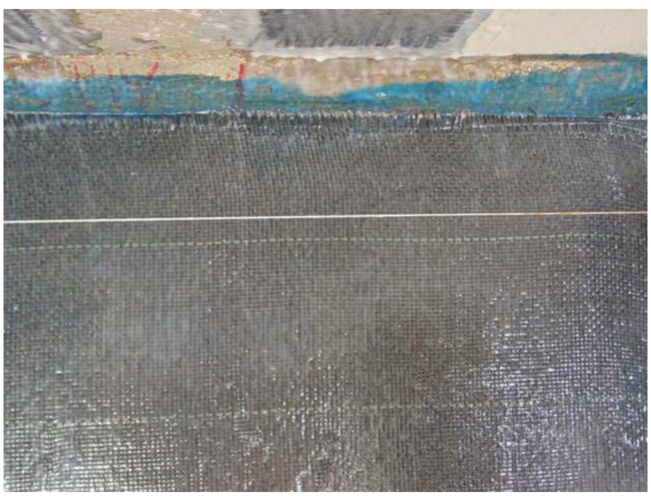

Figure 3: FRP sheets with yellow tracer and overlain by white chord.

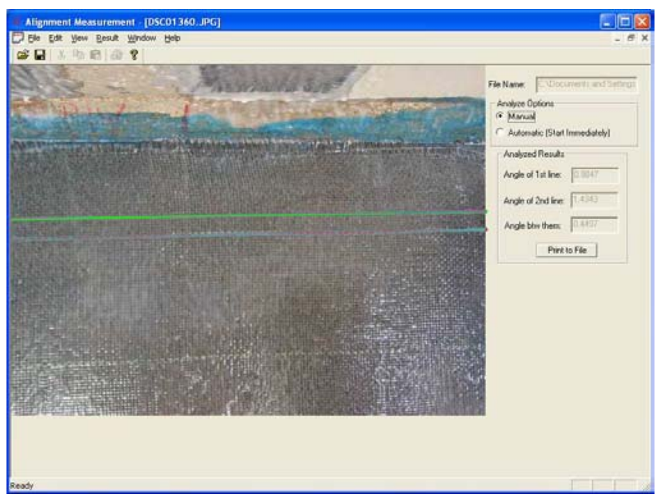

Figure 4: Measurement of angle between the tracer and the chord.

FRP Delamination: Delamination of the FRP materials after installation results in decreased stiffness and decreased load bearing ability (15). A delamination with a surface area of 1 square inch is believed to be the threshold for which repair should be considered. To measure delaminations, an Olson Instruments impact echo tester (figure 5) was specially modified with an air coupled receiver (Figure 6), and frequency domain analysis was employed to uniquely identify delaminated areas.

Figure 5: Olson Instruments impact echo tester.

Figure 6: Impact echo tester modified with air coupled receiver.

FRP Bond Pull-off: Longevity of the epoxy bond between the FRP and concrete substrate is also important to the long term performance of the FRP reinforcement. An experimental non-destructive Pull-off test has been devised. This test is related to a destructive Pull-off methodology (Figure 7) using a plug epoxied to the FRP surface which requires that the Pull-off surface be isolated by cutting through the FRP (Figure 8). In the non-destructive version, the surface is not cut and isolated, and the plug is not loaded to failure but to a fixed load that is ideally 60% of the average failure load. Although the tendency is for the failure to occur at the plug/FRP interface, the failure can take place at the FRP/concrete interface if it is weaker.

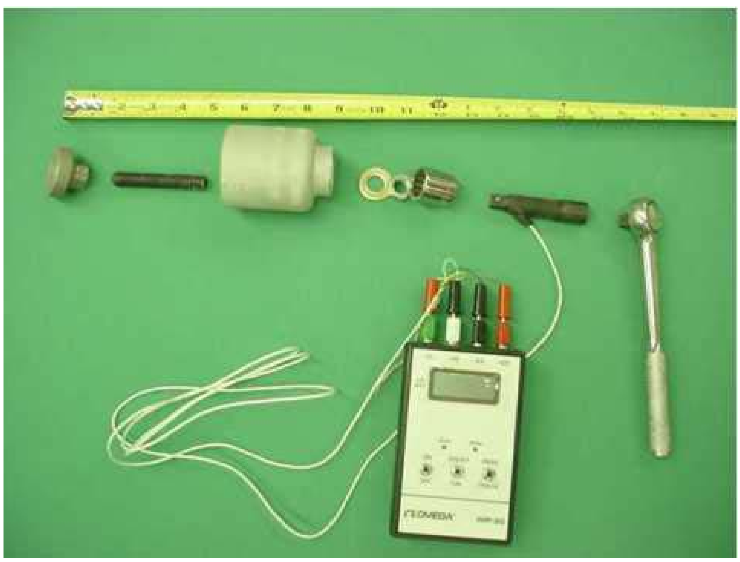

Figure 7: Components of the Pull-off tester.

Figure 8: Pull-off tester; destructive testing.

Figure 10: Roughness measurements on the bridge deck.

Results: During the fall of 2003, this Dallas County bridge was retrofitted with FRP laminates as well as other reinforcing materials. The bridge was heavily instrumented, and many measurements were made.

1. Concrete surface roughness measurements were made after sand blasting and prior to FRP sheet application on one section of the bridge deck using the laser profilometer (Figure 10). Measurements were made on a grid on 1foot centers.
2. Fiber alignment measurements were made after FRP sheet application, and before painting. Transparent epoxy was used to make the tracers more visible (Figure 11).
3. Test sections of FRP materials were applied on one abutment and one bent. These were sandblasted to specified differing roughnesses (Figure 12), and roughness was characterized prior to FRP sheet installation. Delaminations were forced under the sheets installed in these test sections by air injection (Figure 13). These delaminations were measured and will be re-measured every six months.
4. Pull-off plugs were installed over the FRP sheets on one section of the bridge deck (Figure 14) and on various test sections Figure 16. The substrate roughness under each plug has been measured (plug locations were selected to sit above a wide variety of substrate roughnesses). Non-destructive Pull-off tests will be conducted every 6 months.

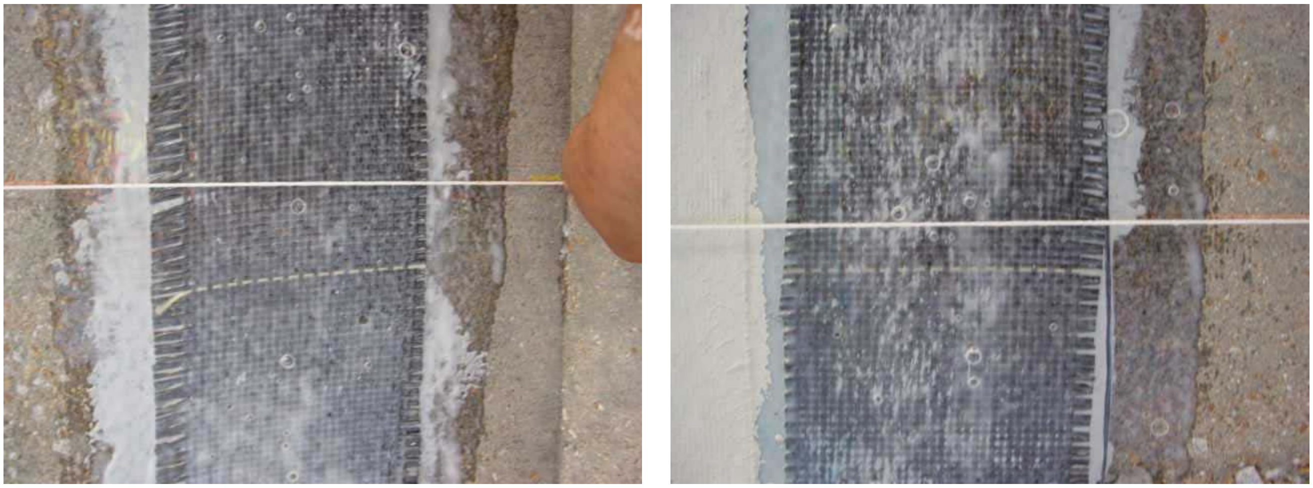

Figure 11: Alignment errors of 7.2 and 0.9º, respectively.

Figure 12: Surface preparation by sandblasting.

Figure 13: "Forced" delamination by air injection.

Figure 14: Pull-off plug installed on the bridge deck

Figure 15: Pull-off testing.

R/C	1	2	3	4	5	6	7
1	7.0	7.3	7.5	9.0	7.9	8.8	8.2
2	12.2	7.6	7.6	7.9	9.4	8.8	10.2
3	8.0	7.6	7.5	8.1	7.4	9.3	8.2
4	7.1	7.0	8.0	7.5	9.3	8.2	9.5
5	7.6	8.7	8.4	7.1	7.9	7.7	7.0
6	6.9	7.4	4.6	6.8	9.2	10.7	9.0
7	6.8	7.3	7.8	7.2	7.1	8.5	8.2
8	7.7	7.1	7.1	7.2	8.8	8.0	9.1
9	10.5	9.4	7.8	8.9	7.8	9.6	8.4
10	9.9	10.6	10.7	10.1	7.3	7.2	7.5
11	9.1	6.6	8.3	7.9	6.9	8.6	7.7
12	7.1	7.7	7.4	7.7	7.7	8.8	8.0
13	7.3	8.0	7.2	8.8	7.3	7.7	6.7
14	6.9	7.5	7.5	9.7	7.3	7.5	7.0
15	9.4	7.7	7.9	7.6	7.6	6.9	8.2
16	7.1	8.1	8.6	7.4	7.3	6.9	8.4
17	6.7	6.4	8.3	8.4	8.5	7.7	7.2

Table 1: I_a (º) roughness results on one section of the bridge deck.

Concrete Substrate Surface Roughness: Roughness measurements were made on 4 sections of the bridge deck (Figure 10). Measurements were made on 12" centers, an example of a set of measurements is given in Table 1. Table 2 shows the mean and standard deviation of the measured roughness.

The mean values which are around 8º reveal that the roughening sandblasting done by the contractor was in general below the optimum value for bond performance (12º). The variability was very low, but is probably due to the fact that very little material was removed by the sandblasting, and that the final roughness was similar to the original cast roughness of the concrete.

Section	Mean Ia (º)	Standard Deviation
1	7.9	1.3
2	8.5	1.0
3	8.0	1.2
4	7.5	1.1

Table 2. Mean and standard deviation Ia roughness for the four sections of the bridge deck

FRP Fiber Alignment: Fiber alignment measurements (Figure 11) were taken on four sections of the bridge deck. In all 421 measurements were made. The mean alignment error was 3.6º with a maximum error of about 11º. Almost 25% of the measurements indicated alignment errors over 5º. In fairness to the contractor, these thin strips of bi-direction fabric are difficult to keep aligned. In tests with of a broad sheet applied to the center girder, the alignment error in 12 measurements was about 1.2º, with no measurements above 5º.

FRP Delamination: Impact echo delamination testing found all the major planned delaminations. An example is given in Figure 16. A few small delaminations (less than 1 square inch) were not identified because the sampling was on 1 in on centers. However, some small delaminations that were not intentionally installed, were identified using the impact echo testing.

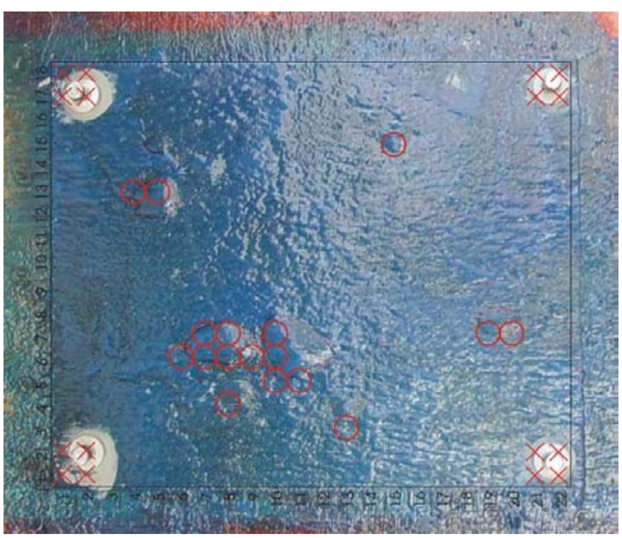

Figure 16: Delamination Measurements overlain on image of test FRP strip #4.

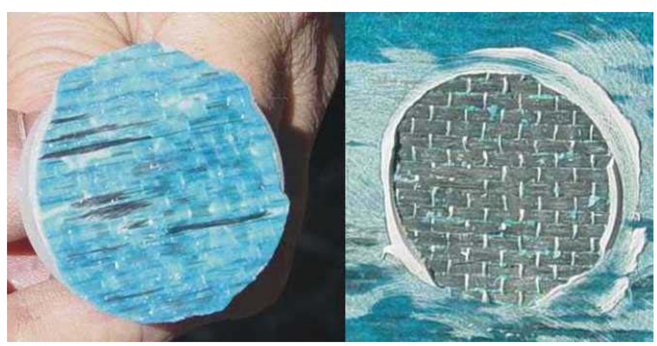

Figure 17: Pull-off plugs separating at the FRP/epoxy interface.

FRP Bond Pull-off: The FRP (destructive) Pull-off tests done to date, all failed at the interface between the FRP sheet and to covering epoxy (Figure 17). The average Pull-off load for 10 samples was found to be 9745 lbs. For future non-destructive testing, the plugs will be loaded to 6500 lbs (2/3 of the average strength), every 6 months.

Discussion: *Concrete Substrate Surface Roughness:* The surface roughness measurements were quick, easy to make and easy to interpret. The surface roughness was found to be below optimal, although the contractor would not have known what optimal was. Timing of this measurement is important, as the measurements need to done after sand blasting and before FRP installation.

FRP Fiber Alignment: The fiber alignment measurements were also quick and easy. There is a special requirement for FRP sheets with highly visible tracer fibers, running in the load bearing direction. Also the use of transparent (clear) epoxy is recommended, so that the fibers are more visible. This creates a potential problem for the contractor, because with out the dye in the epoxy, it is difficult to determine when complete mixing has been attained.

FRP Delamination: The impact echo delamination measurements were successful in identifying the "forced" delaminations. In addition, some small unplanned delaminations were found. Delamination measurements are somewhat time consuming, taking some 30 minutes to measure a 2.75 square foot section at 1" centers. In addition the sampling points have to be marked in some way before measurements can take place.

FRP Bond Pull-off: The bond Pull-off tests to determine max loads have all failed above the FRP, between the FRP and the epoxy. Although it is expected poor quality epoxy/installation will result failure at lower loads, and perhaps at the FRP/concrete interface, this has not yet been verified.

Conclusions: Experiment non-destructive testing of the FRP materials and installation has been undertaken in conjunction with the MODOT retrofitting of this Dallas County bridge. Early results show that is possible, with minimal effort, to provide quality control for FRP installation by verifying both the concrete substrate preparation (sandblasting) and the FRP fiber alignment.

The impact echo testing was able to identify all the delaminations introduced into the installed FRP sheets, as well as a few unintentional one, although the testing takes a significant amount of time. The usefulness of the Pull-off testing has not yet been determined.

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