VALIDATION OF FRP COMPOSITE TECHNOLOGY TRHOUGH FIELD TESTING

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Abstract: This paper identifies assessment techniques for critical parameters relative to installation and performance of fiber reinforced polymer (FRP) materials as a way to strengthen structurally deficient concrete bridges. Various Nondestructive Testing (NDT) techniques, representing viable solutions for identification and monitoring of such critical parameters on structural members strengthened with FRP, were implemented in a research program consisting of five upgraded concrete bridges in the State of Missouri. The research program was designed to provide information on installation aspects such as optimal roughness of the concrete substrate surface, fiber alignment, FRP debonding, FRP-concrete bond quality, concrete cracking, and FRP strain level. These parameters are related to both initial and long-term performance of a bridge structure. The five upgraded concrete bridges strengthened with composite materials are to be monitored semiannually for five years, including load tests. The NDT evaluation mainly focused on one of the bridges, where three different FRP strengthening systems were used.

Introduction: Fiber-reinforced polymer (FRP) as an emerging strengthening technology for concrete structures has been tested and proven successful because of its inherent characteristics [1, 2, 3] such as corrosion resistance, high strength, light weight and anticipated long-term durability. However, some important installation and performance issues remain to be fully understood. In order to make FRP composites as popular as conventional strengthening materials, it is necessary to develop suitable methods for quality control (QC) and long-term monitoring. Even though FRP systems are relatively easy to install, they are also highly susceptible to handling and construction errors. The purpose of this paper is to explain what issues have been recognized as critical and need to be monitored with NDT technologies. Methods for QC must meet basic requirements to be suitable for effective field use such as: simplicity, ease of handling, and lack of complex and/or heavy equipment.

A five-bridge strengthening program, using five variations of composite strengthening techniques, was undertaken to offer a comprehensive case study, addressing several aspects of installation and long-term monitoring. The project is intended to validate the use of FRP materials, and carbon FRP (CFRP) in particular, to strengthen structurally-deficient concrete bridges. As part of a five-year long monitoring program, an NDT research will be concentrated on one structure, namely bridge P-0962 in Dallas County, MO (Table 1).

Table 1. Bridge P-0962 in Dallas County, MO.

Side View of the Bridge

Approach to the Bridge

RC Bent, Girders and Slab

BRIDGE FEATURES

- Total length is 127 ft. Height of the bridge is 18 ft. Width of deck is 23 ft.
- Deck consists of three RC T-beams spaced 9 ft on centers. All spans have three transverse beams
- The thickness of the slab is 6 in.
- Concrete is in good condition. No spalling detected. Abutments and piers are in good condition.
- Load Posting: trucks over 18 ton, 15 mph on the bridge

The five bridges are distributed over three Missouri Department of Transportation (MoDOT) Districts. The candidate structures were selected in consultation with the respective District Offices. None of the bridges to be strengthened lie on the same route. Four structures, including P-0962, are of the T-beam type and one is of the solid slab type. Of the four T-beam bridges, one has a four-girder supported deck, while the others, including P-0962, have a three-girder supported deck. In this group, P-0962 is a more recent structure in terms of age (1956 construction). Four FRP system technologies and a steel fiber reinforced polymer (SRP) system were used for the flexural strengthening of the five structures. Shear strengthening, when necessary, was always in the form of externally bonded laminates installed by manual lay-up. The four FRP technologies were as follows:

- Externally bonded FRP laminates installed by manual lay-up
- Adhered pre-cured FRP laminates
- Near surface mounted FRP bars
- Mechanically fastened FRP laminates

This investigation covered aspects such as measurement of concrete surface roughness, evaluation of bond properties, investigation of fiber alignment, and detection of delaminations and concrete cracking. For this purpose, some strengthening was conducted with intentional defects at non-critical locations. Additionally, in-situ load testing prior to and after the strengthening was implemented on each of the five bridges. The intention of these load tests is to determine possible degradation of stiffness over the time. The overall performance of a strengthened bridge superstructure is evaluated by comparing the behavior before and immediately after the strengthening to that over a reasonably long period of time.

The information and data collected during all phases of the upgrade, that is: initial assessment, design, construction, inspection and monitoring are to be used for the development of specifications and guidelines written in technical language for future strengthening projects.

In the following section, a brief introduction to FRP materials is provided. After that, critical parameters related to an FRP strengthening project are described. This paper is closely related to the following five companion publications presented at this conference:

- Experimental Nondestructive Testing of FRP Materials, Installation, and Performance
- Nondestructive Testing Of Dallas County Bridge
- Experimental Nondestructive Testing of FRP Materials, Installation, and Performance
- Use of the Total Station for Serviceability Monitoring of Bridges with Limited Access
- Embedded Fiber Optic Sensing For Bridge Rehabilitation

FRP Material: Fiber reinforced polymer materials are composites consisting of millions of thin and high strength fibers embedded in a polymeric resin (Figure 1) [3]. Fibers in an FRP composite are the load –carrying elements, while the resin maintains the fibers together and aligned as a compact unit, also protecting them against the environment and possible damage. Among commercially available fibers, carbon fibers exhibit the highest strength and stiffness when compared with steel. The type of fiber is selected based on mechanical properties and durability requirements, while the type of resin depends upon environmental and constructability needs. Perhaps the most relevant property of CFRP composites for construction use is their resistance to corrosion that allows having them installed on the concrete surface.

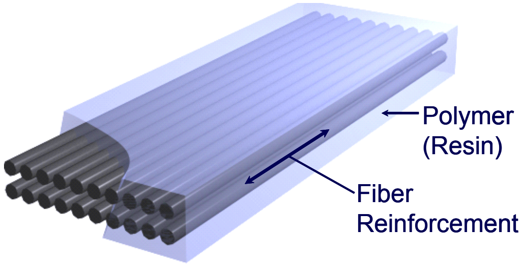


Figure 1. Representation of FRP Material.

FRP laminates have been used worldwide to strengthen, repair or add ductility to existing concrete bridges and buildings in the last fifteen years. Currently, the Federal Highway Administration (FHWA) and State Departments of Transportation (DOT) are trying to advance FRP technology to contribute to the rebuilding of the US transportation infrastructures. The idea is to avoid replacement, whenever possible, by rehabilitating and maintaining the existing and deficient bridges [1, 2].

Critical Issues on FRP Strengthening: In the following sections, critical issues related to any FRP project are described such as evaluation of bond properties, investigation of fiber alignment, detection of debonding, optimal surface roughness, growing of crack and voids and degree of resin curing. A short description of the NDT techniques under development and being applied in the context of the aforementioned research program is presented. In particular, of the five upgraded bridges, the one in Dallas County, MO (Bridge P-0962) was selected for validation of most of the NDT technologies.

Fiber Alignment*:* An FRP laminate exhibits its maximum strength and stiffness in the direction of the fibers. For unidirectional laminates such as the one shown in Figure 1, unintentional misalignment can be introduced during the construction process, especially on irregular geometries. These misalignments are almost unavoidable. The influence of degradation of strength and stiffness by any deviation from proper alignment was studied [4, 5] and recommendations for design and construction specifications were made. Acceptance criteria have been specified [6] as the maximum level of defect allowable. Fiber misalignment of more than 5 degrees (approximately 1 in/ft [800 mm/m]) from that specified in the design affects system performance. Misalignment above this level should be detected in the field by an inspector as quickly and easily as possible. Although visual inspection by the naked eye is possible, it is too dependent on the experience of the individual inspector.

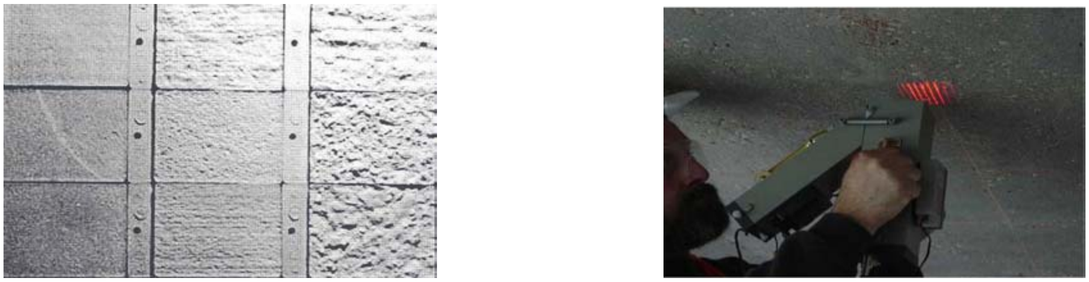
The process of installation of FRP laminates on a selected bridge was monitored and fiber misalignment was detected with the NDT method briefly described here and presented in details in Reference [7]. Fiber plies with tracers were installed using transparent epoxy on deck and girder on one span of the bridge (Figure 2). Image analyses were used to measure the angle between the fiber and tracer using a white string reference. Digital pictures from ordinary cameras could be used to measure fiber alignment to an accuracy of less than 1 degree. A simple imaging test allows the measurement of the misalignment. Immediately after installation, a colored string is stretched along the proper orientation of the fibers, and a simple digital photograph is taken. The digital photograph is then input into a computer program, which automatically measures the angle between the tracers and the string to an accuracy of less than 1 degree.

Figure 2. Fiber Misalignment Detection.

Optimal Surface Roughness: The bond between FRP and concrete is crucial to the effectiveness of the strengthening technique and is related, among other things, to the quality and surface roughness of the substrate material to which the FRP is applied. Failure, in the form of peeling of the FRP reinforcement from the concrete surface can result if the optimal bond surface is not obtained. The load-bearing capacity of the strengthened member is greatly compromised when delamination occurs at the substrate level [16, 17, 18]. The overall performance of the structural system and parameters that control delamination depend highly upon this roughness quality. Laboratory results have indicated that concrete surface roughness is one of the key factors that affect bond behavior [8]. The substrate surface should not be too smooth or too rough. Too smooth of a surface may results in poor bonding. On the other hand, too rough of a surface may require the application of expensive and time-consuming-to-apply fillers. Therefore, if surface roughness is measured accurately prior to FRP application, and adjusted if necessary in order to achieve an 'optimum' roughness, reliable bond strength could be achieved for the system. This concept has great potential as optimal roughness determines the loading level at which delamination between two materials can occur.

Surface preparation of reinforced concrete (RC) structures to provide a clean and suitable roughened surface may be accomplished with various techniques that include sandblasting, water jetting and grinding. Abrasive sandblasting was used to clean the concrete surfaces for the bridge investigated in this project. The sandblasting also removed detrimental substances such as dust, dirt, laitance, oil and any curing substance left over the surface. Because there are no means to effectively measure roughness of concrete, surface roughness profiling can be used to determine whether the concrete surface preparation has been effective. An "optimal" concrete surface roughness has been established to be CSP 3 (Concrete Surface Profile number 3) as defined by the International Concrete Repair Institute (ICRI) [8]. Figure 3-a shows a model for different profiles as defined by ICRI. The samples are ordered by column from 1 to 9 (top to bottom and left to right) in order of increasing roughness.

A prototype laser profilometer (Figure 3-b) has been developed at the University of Missouri – Rolla (UMR) to rapidly and accurately quantify the roughness of the prepared surface prior to installation of the FRP. This device and its features are presented in details in Reference [7]. The profilometer is a portable device that characterizes a roughened surface by means of laser light and transmits the image to a laptop computer used for analysis.



a) Plastic Model Concrete Surface Profile. b) Roughness Detection by Laser Profilometer

Figure 3. Roughness Surface

Detection of Debonding: Debonding between the FRP laminate and concrete substrate may occur due to improper installation, improper resin curing, presence of moisture near the concrete surface, impact damage, etc. Durability of adhesion between composite laminate and concrete substrate is related to initiation and propagation of cracks in the interface region [16]. Personnel training is essential to eliminate or minimize the presence of poorly adhered areas. Analytical and experimental studies regarding bond characteristics have been presented for different FRP strengthening techniques [16, 17, 18]. According to specifications prepared by the American Concrete Institute (ACI) [6], sounding of the strengthened areas is acceptable to check for voids, bubbles and delaminations. Inspection methods should be capable of detecting delaminations of 2 in^2 (1300 mm^2) or greater. Delaminations smaller than 2 in^2 (1300 mm^2) are permissible, so long as the defective area is less than 5% of the total laminate area and there are no more than 10% such delaminations per 10 ft^2 (1 m^2). Delaminations less than 25 in^2 (16,000 mm^2) may require resin injection or ply replacement. Large delaminations greater than 25 in^2 (16,000 mm^2) can affect the performance of installed FRP. In this case, all voids, bubbles, and delaminations are to be repaired by epoxy injection or replacement of the fiber ply/s.

For the bridge inspected in this research program, strengthening systems were installed with intentional defects at non-critical locations as shown in Figure 4 [9] and three different NDT detection techniques, based on new approaches developed at UMR, were used for monitoring. The techniques are explained in detail in References [7, 9, and 10] and are briefly summarized here.

Figure 4. Intentional Delaminations on FRP Laminates.

A modified impact echo technique [7] was used to indicate delaminations. In particular, an Olson Instruments impact echo tester was specially modified with an air coupled receiver and frequency domain analysis was employed to uniquely identify delaminated areas.

Using a plug epoxied to the FRP surface, it is possible to determine the quality of the bond between FRP and concrete. This standard test method [12] requires that the pull-off surface be isolated by cutting through the FRP and is therefore destructive. In the non-destructive version [7], the surface is not cut and isolated, and the plug is not loaded to failure but to a pre-determined load.

Near-field microwave NDT was used for quick, on-site, real-time and repeatable detection of disbonds between the FRP laminate and concrete substrate [10]. The new measurement system uses a fully automated scanner and signal processing section. The system allows the operator to scan areas of interest to generate microwave images that can be identified as potential debond areas.

Strain Measurement: Strain measurement is an important parameter to determine continuity in deformation between FRP and substrate material and for evaluation of overall structural behavior [19]. Strains can indicate the presence of debonds and cracks, but also allow to determine the “real” stress distribution through the selected material. In order to detect flexural strains in concrete, internal steel reinforcing bars, and FRP reinforcement of the deck and one girder in the central span of the selected bridge, fiber optic sensors were installed as described in detail in Reference [13]. The sensor system is designed for long-term health monitoring of the FRP reinforcement with emphasis on field security and data acquisition. Also electrical strain gauges were installed close to the optical sensors for comparison. Strains are monitored during load testing, which allows to correlate vertical displacements to deformations measured under such a test.

Although almost all the NDT research was concentrated on bridge P-0962, in one other bridge the FRP technology termed mechanically fastened FRP laminates was used without repairing the concrete substrate that was substantially deteriorated. This technology consists of FRP strips anchored to the concrete substrate where surface preparation of the substrate is not necessary because the mechanism of load transfer is attained by fasteners and not by adhesion. Electrical strain gauges were installed and strain and displacements are to be monitored to determine how rapidly the concrete deterioration process may continue and to assess the overall behavior and safety of the structure.

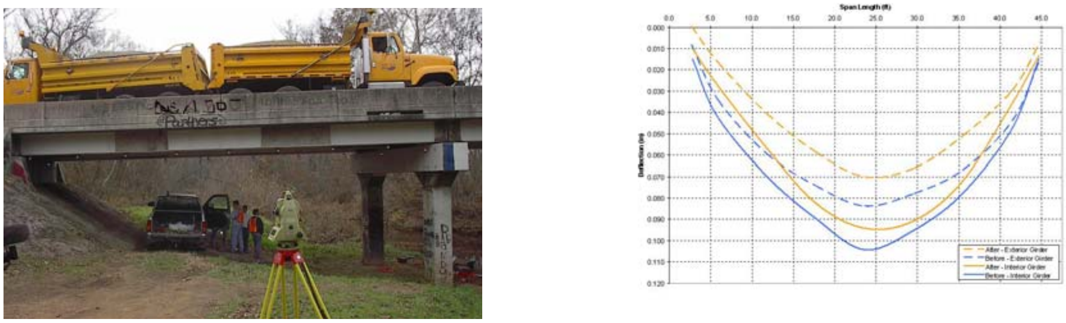
Degree of Resin Curing: Curing of resins is a phenomenon dependent on time and temperature. Resins cured in the field can take several days to reach full cure. Temperature extremes or fluctuations can retard or accelerate the resin cure time. Relative cure of the resin can be evaluated in-situ by physical observation of resin hardness and viscosity. Real-time, in-situ monitoring for quality control of the polymer cure process is of great interest. In particular, epoxy resin reinforced with carbon fibers designed as a strengthening system for structures, demands excellent mechanical properties.

Cracking: Concrete structures always have cracks. Moreover, bridges are subjected to fatigue and cyclic loads that may generate additional cracks on structural members. Some of these cracks tend to stabilize through time. If FRP is applied on an area where cracks of considerable magnitude can appear, an evident process of debond and rupture may occur. Coaxial crack sensors were installed on the deck soffit of bridge P-0962 in order to detect cracking even below the visible range [20]. Sensors are placed in a groove and grouted in place. A time-domain reflectometer (TDR) is connected to one or both ends of the sensor and a series of electronic pulses are sent through the sensor. TDR then records the reflected image, which shows the location and size of a crack when the sensor experiences a deformation.

Long-term Global Performance: To determine the global structural performance, in-situ load tests were performed before and immediately after strengthening of the five bridges. Such tests will also be repeated every six months over a period of five years using a novel non-contact deflection monitoring technique based on high performance surveying equipment or Total Station, as described in details in Reference [11]. Deflections were measured at several locations, transversely at mid-span and longitudinally along an exterior and its adjacent interior girder. The static load tests were performed using standard trucks.

The Total Station sends a laser ray to the reflecting magnet-mounted prisms, and, by comparing the displacement with fixed reference points outside the structure, the operator can determine how much the element has moved in a three-dimensional array.

More important than the small increase in stiffness recorded after strengthening is the monitoring of the response over time. In fact, repeated load tests may show structural degradation resulting in a change in the deflection response, leading to a more detailed investigation and, if necessary, repair of the structure [14, 15]. Typical results of load tests, before and immediately after strengthening, are shown in Figure 5. It can be seen that after the application of the FRP reinforcement, a marginal decrease in deflection is obtained. Subsequent tests over a period of five years will be compared to these two baselines.



a) Surveying Equipment. b)Deflection Before and After Strengthening

Figure 5. Load Testing.

Results and Discussion: Preliminary results of the NDT program applied to the project show initial good performance. Nevertheless, in a validation program for this emerging technology, a more accurate assessment can only be done over an extended period of time.

Conclusions: The main objective of this paper is to show to NDT researchers some of the critical parameters associated with health monitoring of FRP strengthened structures and how they were tackled by a UMR research team. This paper has identified and explained potential critical issues of field validation of this emerging technology that can be monitored with NDT technologies. Field identification and monitoring of potential installation and subsequent problems in composite materials by NDT techniques is more than a necessity.

Even though FRP systems are easy to install, they are also highly dependent and susceptible to handling and construction errors. Methods for QC must have basic attributes to be suitable for widespread use such as simplicity, ease of handling, and lack of complex and/or heavy equipment. A five-year five bridge research program was designed to identify and monitor critical parameters such as optimal surface roughness, fiber alignment, strain, debonding, crack opening, and long-term performance. All bridges will be monitored semiannually by repeated load tests.

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