Alkhrdaji, T. and A. Nanni, "Surface Bonded FRP Reinforcement for Strengthening/Repair of Structural Reinforced Concrete," Proc., ICRI-NRCC Workshop, Baltimore, MD, Oct. 30, 1999, 19 pp.

SURFACE BONDED FRP REINFORCEMENT FOR STRENGTHENING/REPAIR OF STRUCTURAL REINFORCED CONCRETE

Tarek Alkhrdaji and Antonio Nanni

Center for Infrastructure Engineering Studies (CIES)
University of Missouri-Rolla
223 Engineering Research Lab
1870 Miner Circle
Rolla, MO 65409-0710

INTRODUCTION

Current studies indicate that the use of advanced composites for structural application is expected to increase exponentially in the next few years (1). The market growth will mainly stem from the increased need for repair/strengthening of deficient structures and for new infrastructure systems that last longer and cost less to maintain. In general, concrete structures may need strengthening due to deterioration (e.g., corrosion of steel reinforcement), design/construction errors, a change in functional use or loading, or for code-mandated upgrade (e.g., seismic). The selection of the structural strengthening/repair method is strongly affected by labor, shutdown costs and time, and site constraints.

The wide spread use of FRP technology for structural applications is hindered by the lack of standard material test methods, comprehensive materials and construction specifications, and design guidelines.

Two techniques for surface reinforcement for reinforced concrete (RC) structural members are addressed in this paper; namely, externally bonded laminates and near surface mounted rods. Some of the construction related issues influencing the performance of both techniques are identified. A project involving the full-scale strengthening with FRP and testing to failure of a highway bridge is used to illustrate the field application and construction process of the two strengthening techniques. The performance and effectiveness of these techniques are demonstrated by comparing the test results of the strengthened and the unstrengthened structural members.

FRP COMPOSITES

FRP composites can be manufactured in many shapes and forms. Applications of FRP composites in civil/infrastructure engineering are diverse and may include internal reinforcement, structural elements, and externally bonded reinforcement. For concrete reinforcement, the most popular forms of FRP are smooth and deformed bars, prestressing tendons, and pre-cured and cured-in place laminates/shells (2). FRP bars and tendons are currently produced with sizes and deformation patterns similar to those of steel bars and strands. FRP composites are light in weight, which means they are easier to transport and install. They are corrosion-resistant and therefore perform better in terms of long-term durability and maintenance cost. FRP pre-cured and cured-in-place laminates/shells and sheets are used for external concrete reinforcement (3) and FRP shells have been used as jackets for columns (4).

RP strengthening is currently being marketed in the form of systems. The system concept includes not only the constituent materials (e.g., fibers and resins), but also the installation technique, design guide, and contractor training.

FRP AS EXTERNAL REINFORCEMENT FOR REINFORCED CONCRETE MEMBERS

One advantage of surface FRP reinforcement in repair and strengthening application is the speed and ease of installation. Labor, shut-down costs, and site constraints typically offset the material cost of FRP, making FRP strengthening systems very competitive with traditional strengthening techniques such as steel plate bonding and section enlargement. The short-term and long-term performance of surface FRP reinforcement systems is highly affected by bond characteristics and the long-term performance is very sensitive to the process in which the material is stored, handled, installed, and cured. Surface FRP reinforcement require a high level of process control. Hence, there is a need to identify the construction parameters that affect overall structural performance and to verify the quality of the construction process. Table 1 provides a list of the parameters of interest for the case of externally bonded laminates. Some of these parameters are discussed in the following section.

Installation of Externally Bonded Laminates

Surface bonded FRP includes two possibilities: pre-cured and cured-in-place laminates (manual lay-up). For the latter, a surface primer is applied first to the concrete prepared surface to fill micro-cavities. After the primer is cured, a layer of putty is applied to level uneven spots and fill surface cavities. The recommended resin is then mixed and applied to the concrete surface in a thin uniform layer using a roller. A fiber sheet (pre-impregnated or dry) is cut to the desired length and width and pressed to the concrete using a “bubble roller”. This act eliminates the entrapped air between the fibers and resin and ensures the impregnation of the FRP sheet with resin. Attention should be paid when installing the FRP sheet since poor orientation of the fibers generally reduces the strength of FRP (5). After the ply is installed, a second layer of impregnating resin is applied. In the case of multiple plies, the process is repeated. Inspection of the bonded laminates for voids and spots of delamination is conducted after the full cure. Repair techniques may include resin injection or ply replacement, depending upon the size and number of delaminations and their locations. Following repairs, the laminate should be re-inspected and the results contrasted with those of the initial inspection to show that the repair was properly accomplished.

Most FRP strengthening systems are deceptively simple to install. Improper installation by inadequate mixing of components, not saturating the fibers, misaligning the fibers, etc. is not easily avoided without careful attention. Quality control tests and inspection should be performed regularly to ensure proper installation and performance of the system.

<u>Surface Profile and Strength</u> – Quality bond between bonded FRP reinforcement and concrete is crucial for the strengthening technique to be effective. Before applying the FRP system, the levelness of the concrete surface should be ensured. Low spots should be filled with the appropriate epoxy and high spots should be ground flat. If the FRP follows the contour of the

irregular concrete surface, the curvature of the laminate may initiates pull-out forces, creating a localized delamination and jeopardizing the strength of the system. Bridging over protuberances, such as formwork marks, may result in stress concentration and cause the fibers to rupture at load levels lower than anticipated in design.

TABLE 1. REPAIR/STRENGTHENING WITH PRE-CURED AND CURED-IN PLACE LAMINATES

Construction	
Substrate Condition	Surface Profile
	Surface Strength
	Intimate Contact
	Presence of Moisture or Frost
	Moisture Vapor Transmission
	Crack Injection
	Moving Cracks
Materials and Material Handling	Dust Control
	Fiber Irregularities
	Storage
Installation	Epoxied Surface Smoothness
	Unattended Epoxy Surfaces
	Fiber Alignment
	Voids/Delaminations
	Cure Time Limits
	Corner Radius
	FRP Strip Spacing
	Bonded Length
	Lap Splice Length
Inspection Devices and Methods	Surface Roughness Test
	Pull-off Test (Bond)
	Torque Test (Bond)
	Voids/Delaminations Test
End Anchorage	Installation Purpose
	Anchor Details
Durability	
Aggressive Environment	Freeze-thaw Cycles
	Extreme Thermal Gradients (non-freeze)
	UV Exposure
	Relative Humidity
	Long-term Exposure to Salts

To ensure adequate bond behavior, there is a need for the characterization of concrete. A roughness index can be used to determine the adequacy of prepared concrete surfaces for FRP applications. One approach is to use the Concrete Surface Profiles (CSP) as defined by the International Concrete Repair Institute (ICRI) (6). These profiles replicate degrees of roughness, which were considered for the purpose of application of coatings and sealers up to a thickness of 0.25 inch (6 mm). Each profile carries a CSP number ranging from a base line of 1 (nearly flat) through 9 (very rough). Previous research has indicated that concrete surface roughness is a key factor that can affect bond characteristics of epoxy with concrete (7). Concrete surface is usually sandblasted prior to the installation of the FRP strengthening/repair system to remove dust, laitance, and other loose materials. However, bond failure may occur even though concrete surface has proper roughness. This mode of failure is possible when the surface concrete has low strength causing the failure to initiate prematurely.

Crack Injection – Depending on their width, small cracks should be either pressure injected with epoxy or left untreated. Large cracks should be saw-cut and then filled with epoxy. The limit separating the three approaches may depend on technical (e.g., viscosity of the epoxy), structural, and economical considerations (8). In certain cases, field conditions may call for the application of FRP materials to concrete members while subjected to service loads (open cracks if any). When the system is curing or after it is fully cured, the load level can decrease and the composite material may experience localized deformation at a crack location. This may result in stress concentration and delamination.

Bonded Length - In order to attain composite action, the bonded length of the laminate should be such that the design capacity is attainted at the critical sections. The development length can be defined as the shortest length necessary to attain failure of the reinforcement (19). The designer should follow the recommendations of the FRP system supplier.

Lap Splices - Fiber sheets are usually packaged in rolls that may contain hundreds of feet of the material. Due to constructability and geometric reasons, the splicing of FRP sheets may be necessary. For example, in the case of column wrapping, the use of lap splices is necessary to ensure effective confinement and continuity of the wrap. In general, the length of the lap splice depends on the type of fiber material, stiffness of the FRP composite, and type and thickness of the resin. Adequately lap-spliced laminates should be able to develop the full capacity of the composite material thus ensuring the design strength of the system.

Installation of Near Surface Mounted Bars

The use of near surface mounted (NSM) FRP bars is an attractive method for increasing the flexural and the shear strength of deficient reinforced concrete (RC) members. This strengthening technique is practical since the anchorage of the mounted bars into adjacent members is feasible. In addition, application of NSM FRP bars does not require surface preparation work. In certain cases, using NSM bars can be more practical than using externally bonded FRP laminates. For example, when the end anchorage of the FRP reinforcement is an essential design requirement or when the installation of laminates involves extensive surface preparation work.

Installation of the NSM bar is achieved by grooving the surface of the concrete. Traditionally, surface mounted reinforcement is placed parallel to the existing reinforcement. The grooves may have a square cross section with dimensions equal to the diameter of the FRP bar plus one eighth of an inch per side to allow for embedment. Concrete can be grooved by making two parallel saw cuts on the concrete surface using conventional tools and technology. The two cuts will have predetermined depth and are spaced at a distance equal the required width of the groove. The concrete in between the two cuts is then chipped off, thus creating the groove. The groove is cleaned (e.g., pressured air) to remove all loose particles and dust. To apply the NSM bar, each groove is initially filled half way with a high viscosity binder (e.g., epoxy paste) compatible with the FRP systems. The high viscosity binder ensures easier field execution, especially for the case of over-head application. An FRP bar is then placed into the groove and lightly pressed in place. This action forces the paste to flow around the bar and cover the sides of the groove. The bar can be held in place using wedges at an appropriate spacing. The groove is then filled with the same binder and the surface is leveled. A cross section showing details of the final product is shown in Figure 1.

Since the effectiveness of the near surface mounted bars is strictly related to the quality of bond between the reinforcement and the surrounding material, the performance of the bond between NSM FRP bars and concrete is crucial for this technique to be effective. The following are some of the construction parameters that have an influence on the bond properties of NSM bars.

<u>Surface Preparation</u> – Groove cleanness, application of a primer coating, and concrete strength are all factors that can affect bond characteristics between the paste (e.g., epoxy) and the concrete. Surface preparation is important because the tensile stresses are transmitted from the concrete to the FRP bar through the binding paste by means of tangential stresses.

<u>Type of Bar</u> – The bar parameters that affect the performance of the system may include bar diameter, type of FRP, and surface condition. Bond strength and the mechanism of bond failure are expected to be influenced particularly by the surface condition of the bar.

<u>Dimensions of Groove</u> - Increasing the groove depth may increase the strength by preventing or delaying splitting of the epoxy paste. The optimum groove depth can be attained as a trade off between the two opposite needs of performance (large groove) and constructability (small groove). This optimum value may be expressed as a ratio between groove size and size of the FRP bar. Based on the research and field experience of the authors, it is recommended that the minimum groove size be taken as the dimensions of the FRP bar plus 0.25 inch (6 mm).

DEMONSTRATION PROJECT

Demonstration Bridge

Prior to its demolition, a reinforced concrete bridge was strengthened and tested to failure. The bridge was built in 1932 and consisted of three simply supported decks made of 18 in. (460 mm) thick solid reinforced concrete slabs with an original roadway width of 25 ft (7.6 m). Each simply supported deck spanned 26 ft (7.9 m). The bridge deck was supported by two abutments and two bents. Each bent consisted of two piers connected at the top by a RC cap beam. The longitudinal reinforcement of the bridge deck consisted of #8 (25 mm) deformed steel bars at 5 in. (127 mm) spacing while the transverse reinforcement consisted of #4 (13 mm) deformed steel bars at 18 in. (460 mm) spacing. The piers had a 2 by 2 ft (0.6 × 0.6 m) square cross-section and reinforced with four #6 (19 mm) deformed steel bars. The transverse reinforcement consisted of #2 (6 mm) steel ties at 18 in. (457 mm) spacing. The piers were supported by 4 by 4 by 2.5 ft (1.2 × 1.2 × 0.75 m) square spread footings. In general, the condition of the bridge was good and no major damage (e.g., corrosion of reinforcement or concrete spalling) was observed. Two of the three bridge decks were strengthened with externally bonded reinforcement. The first was strengthened using externally bonded carbon FRP sheets and the second using near surface mounted carbon FRP rods. The decks were tested to failure under static load. The piers, originally designed for gravity loads, were seismically upgraded using near–surface mounted carbon FRP rods, as well as jackets made of unidirectional carbon FRP sheets. The piers were tested to failure under cyclic static loading.

Bridge Strengthening

All strengthening work was carried out on the bridge while in service. Bridge upgrading was rapid with no interruption of traffic flow. A crew of three workers carried out the installation of FRP reinforcement for the decks and the piers of the bridge over a period of seven working days.

Decks - Two of the bridge decks were strengthened to the same level of nominal capacity using the two strengthening techniques discussed earlier. Based on the material properties provided by the Missouri DOT, the as built capacity of the decks was 78.5 k-ft/ft (349 kN-m/m). Based on analysis, a strengthening to approximately 101.7 k-ft/ft (452.3 kN-m/m) was sufficient to upgrade the bridge decks to carry HS20-modified truck load.

The design of externally bonded carbon FRP sheets called for eight, 20-in (500 mm) wide, single-ply CFRP strips to be applied to the deck soffit. The strips were evenly spaced over a width of 25 ft (8.2 m) and ran the entire length of the deck. The FRP strengthening system was installed by a specialty contractor. Prior to the CFRP sheets installation, the concrete surface was prepared according to manufacturer’s specifications. Laitance and dirt were removed by abrasive blasting. Bug holes and small surface voids were exposed prior to filling with epoxy filler. CFRP sheets were installed by the wet lay-up procedure. After allowing for cure, the system was inspected for voids and delaminations. Pull-off tests were conducted as a quality control measure to ensure adequate bond with the concrete.

The second deck was strengthened to the same level using near-surface mounted FRP rods. The required number of near-surface mounted reinforcement was determined to be 20 rods spaced at 15 in. (375 mm). The NSM reinforcement considered in this project consisted of CFRP rods with surface roughened by sandblasting to improve bond properties. The rods were embedded in 20 ft (6.6 m) long, ¾” (19 mm) deep, and $^{9}/_{16}$” (14 mm) wide grooves cut onto the soffit of the bridge deck parallel to its longitudinal axis as shown in Figure 2. Groove dimensions were chosen based on the previous experience of the research team. The rods were grouted in place using a viscous epoxy paste. Appropriately spaced wedges were used to hold the rods in place until the epoxy cured.

For all decks, electrical strain gages were applied to the steel and FRP reinforcement to monitor the reinforcement strain during testing.

Piers - Many bridges constructed prior to 1970 were designed for gravity loading only, with no consideration to seismic vulnerability. An investigation of the capacity of the piers of such bridges usually reveals that the piers may lack the flexural strength, shear strength, or ductility to resist an earthquake. Research on columns wrapped with FRP composites indicate that this can significantly improve the shear and axial capacity of the columns as well as their ductility. Wrapping with FRP is less effective for rectangular members than for circular (10). FRP sheets bonded to the surface of the columns with fibers oriented along the longitudinal axis have a minimal or no effect on the flexural capacity of the column. Mainly, because the critical sections for flexure are usually located at the top and the bottom of a column, where an adequate anchorage of the sheets is not possible.

The computed lateral load capacity of the bridge piers for shear and flexure were 76 kips (338 KN) and 14 k (62 KN), respectively. Seismic performance category (SPC) B was selected for the analysis, since it is representative of existing bridges in Missouri (11). Based on this approach, the required lateral load capacity of the bridge piers was determined to be 36 kips (178 KN). This preliminary investigation indicated that the piers were adequate for resisting the shear forces induced by an earthquake, while a deficiency existed in flexural capacity. To this effect, two of the four bridge piers were strengthened for flexure using near-surface mounted CFRP rods. Pier #2 had 14 rods mounted on two opposite faces, 7 on each face, while pier #4 had 6 rods, 3 on each face. They were fully anchored (minimum 15 in., 375 mm) to the footing to ensure that the full capacity of the strengthened section be attained at the base of the column. For this, 16-in (400 mm) deep holes were drilled into the footings, aligned with the grooves on the column sides. The grooves and the drilled holes were then filled with a viscous epoxy grout and the carbon FRP rods were installed. Another layer of epoxy grout was then applied and the surface was leveled. Finally, the two columns were wrapped with 4-ply, 20 in. (500 mm) wide, CFRP jacket. Pier #3 was externally jacketed with six plies of glass FRP sheets while pier #1 was used as a benchmark. All FRP jackets were installed by wet lay-up. The FRP covered the entire height of the columns with the fiber direction perpendicular to the column axis. The corners of the rectangular piers were rounded to prevent stress concentrations in the FRP composite and also to prevent the formation of voids. Available literature recommends that the sharp corners of rectangular members be rounded to a minimum of 0.5 inch (13 mm) radius (12).

Test Results

Decks - Each of the three spans was tested to failure by applying quasi-static load cycles. Four 200-kips (90-tons) hydraulic jacks were used to apply the static load, as shown in Figure 3. The magnitude of the maximum load used in each successive load cycle was incremented until failure of the deck was achieved. Deck deformations as well as strain in the steel bars, CFRP bars, and CFRP sheets were measured at different locations.

The mode of failure of each deck was dependent on the strengthening scheme and occurred after the yielding of the original steel reinforcement. For the deck with NSM rods, failure was initiated by the rupture of some CFRP rods at the location of the widest crack. The failure mode of the deck strengthened with CFRP laminates was a combination of rupture and peeling of laminates. As for the reference deck, the classical mode of failure of yielding of steel reinforcement followed by the crushing of concrete at ultimate was attained. The deck strengthened with CFRP laminates had a capacity of 134.1 k-ft (181.8 kN-m). The deck strengthened with NSM rods showed the highest capacity with a failure load of 147.1 k-ft (200 kN-m). The capacity of the unstrengthened deck was 114.6 k-ft (155.4 kN-m) at failure. The higher than anticipated capacity of the reference deck was related to the difference between the actual and assumed material properties. The initial analysis was based on the material properties recommended by the Missouri DOT database for bridges built in the 1930's. Concrete cores and steel coupons were only obtained after the bridge was closed to traffic after strengthening. Upon testing of the specimens, it was found that the actual concrete strength was 8147 psi (56.2 kN) compared to 2300 psi (15.9 kN) from the DOT database, whereas for steel the actual yield strength was 43,333 ksi (299 kN) compared to 30,000 ksi (207 kN) from the DOT database.

<u>Piers</u> - The piers were tested to failure by applying cyclic lateral loads to the pier cap beams. To achieve this, the central portion of the cap beam was removed and a hydraulic jack was inserted in the gap while a second jack was attached to a reaction frame confining the piers cap beam, as shown in Figure 4. The two jacks were used alternately to create a cyclic loading condition. A 10-in strip of each deck was saw-cut along the longitudinal axis of the bridge to allow for the relative displacement of the piers. In order to reduce the superstructure/substructure interaction, the bridge decks supported on piers 3 and 4 were jacked up and lubricated steel plates were inserted between the deck and the cap beam.

Failure loads of bridge piers exceeded in magnitude the predicted loads. For pier #1 (unstrengthened), the applied lateral load at failure was 79 kips (351 KN) and the maximum lateral displacement at the top of the pier was around 0.61 in. (15.5 mm). For pier #2, the failure was initiated by a crack which occurred at the column flare where the mounted rods were terminated followed directly by the yielding of steel reinforcement. The applied lateral load at failure was 81 kips (360 KN) and the lateral displacement at the top of the pier varied from 0.058 in. (1.5 mm) just before cracking to 0.116 in (2.9 mm) at loading termination. For pier #3, cracks occurred simultaneously at the top and the base of the pier (see Figure 5) at about 65 kips (289 KN). Failure was initiated by rupture of the mounted FRP rods at the base of the column at 86 kips (382 KN) with a maximum lateral displacement at the top of 0.86 in. (21.8 mm). As for pier #4, the pier started to rotate as a rigid body at 50 kips (222 KN). The test was terminated when the lateral displacement exceeded 1.5 in. (38.1 mm). This variation in failure modes and lateral load capacity may be related to the effect of superstructure/substructure interaction, variation in the boundary conditions of each pier (e.g., rotation stiffness), and the skew effect of the bridge bents. The behavior of the bridge piers is currently the subject of comprehensive analysis and will be reported in future publications.

CONCLUSION

The objective of this research program was to demonstrate the use of two FRP strengthening techniques of externally bonded FRP laminates and near surface mounted (NSM) FRP rods. Prior, to demolition, a full-scale bridge was strengthened using the two techniques. Test results indicate that both techniques are effective in increasing the flexural capacity of the bridge decks and bridge piers. Test results also indicate that the capacity and failure modes of the bridge piers are closely related to the superstructure/substructure interaction and the pier boundary conditions.

Applications of the two methods of strengthening may not be suited for every case but it does provide practitioners with an additional effective tool to upgrade reinforced concrete structures. Prior to installing surface bonded FRP reinforcement, attention should be directed toward investigating the surface concrete on which the composites are to be bonded. Until standard specifications are generated, the designer should refer to appropriate documentation for required concrete surface strength, concrete surface preparation, and installation process.

Research and development is continuing to refine the design methods, installation procedures, and quality control tests of FRP surface reinforcement to provide the construction industry with science-based procedures. In the interim, a judicious use of composites can provide substantial benefits.

ACKNOWLEDGEMENTS

This project was made possible with support received from the Missouri Department of Transportation (MoDOT), Mid-America Transportation Center (MATC), and the University of Missouri-Rolla/University Transportation Center (UMR-UTC). Master Builders Technologies, Cleveland, OH, and Structural Preservation Systems, Baltimore, MD, provided and installed the FRP systems, respectively.

REFERENCES

(1) Saadatmanesh, H. and Ehsani, M. R., Editors, “Fiber Composites in Infrastructure,” *Proceeding of the Second International Conference on Composites in Infrastructure (ICCI-98)*, 1998, Tucson, Arizona
(2) ACI Committee 440, “State –of-the –Art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures,” *American Concrete Institute*, Detroit, Michigan, 1996, 68 pp.
(3) Nanni, A., “Carbon FRP Strengthening: New Technology Becomes Mainstream,” Concrete International, American Concrete Institute, Vol. 19, No. 6, June 1997, pp. 19-23.
(4) Xiao, Y. and Ma, R., “Seismic Retrofit of RC Circular Columns Using Prefabricated Composite Jacketing,” *Journal of Structural Engineering* - ASCE, Vol. 123, No. 10, 1997, pp. 1357-1364.
(5) Naval Facilities Engineering Service Center, “Navy Advanced Composite Technology in Waterfront Infrastructure,” Special Publication SP-2046-SHR, Port Hueneme, 1998.
(6) International Concrete Repair Institute, “Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings and Polymer overlays,” Guideline No. 03732, 1997, Sterling, Virginia, 41 pp.
(7) Miller, B., “Bond Between Carbon Fiber Reinforced Polymer Sheets and Concrete”, MSc. Thesis, Department of Civil Engineering, University of Missouri – Rolla, Rolla, MO, 1999, pp. 138.

(8) Trout, J., *Epoxy Injection in Construction*, The Aberdeen Group, Addison, Illinois, 1997, 80 pp.
(9) Bizindavyi, L., and Neale, K. W., “Experimental and theoretical investigation of transfer lengths for composite laminates bonded to concrete Structures,” Composite Materials, Structural Systems, Telecommunication Towers Proceedings, Annual Conference - Canadian Society for Civil Engineering. Vol. 6, 1997, Montreal, Quebec, Canada, pp. 51-60.
(10) Kestner, J.T., Harries, K.A., Pessiki, S.P., Sause, R., and Ricles, J.M., 1997, Rehabilitation of Reinforced Concrete Columns Using Fiber Reinforced Polymer Composite Jackets, Lehigh University, ATLSS Report 97-07, Bethlehem, PA, 1997, 196 pp.
(11) Standard Specifications for Highway Bridges, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1996.
(12) Master Builders Technologies, (1998), “MBrace Composite Strengthening System - Engineering Design Guidelines,” Second Edition, Cleveland, OH, 1998, pp. 140.

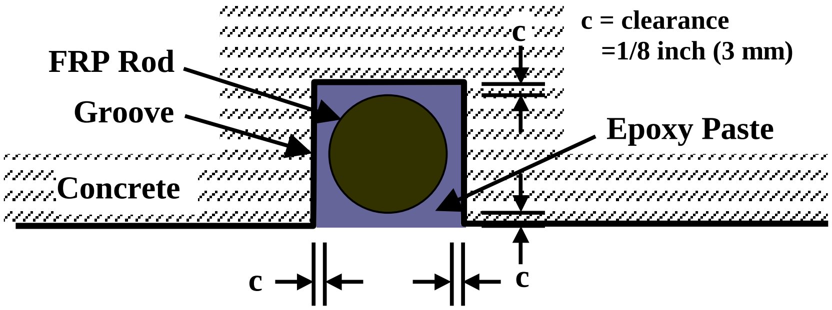

Figure 1. Installation details of the near surface mounted FRP rod

Figure 2. Mounting the NSM FRP rods on bridge deck soffit.

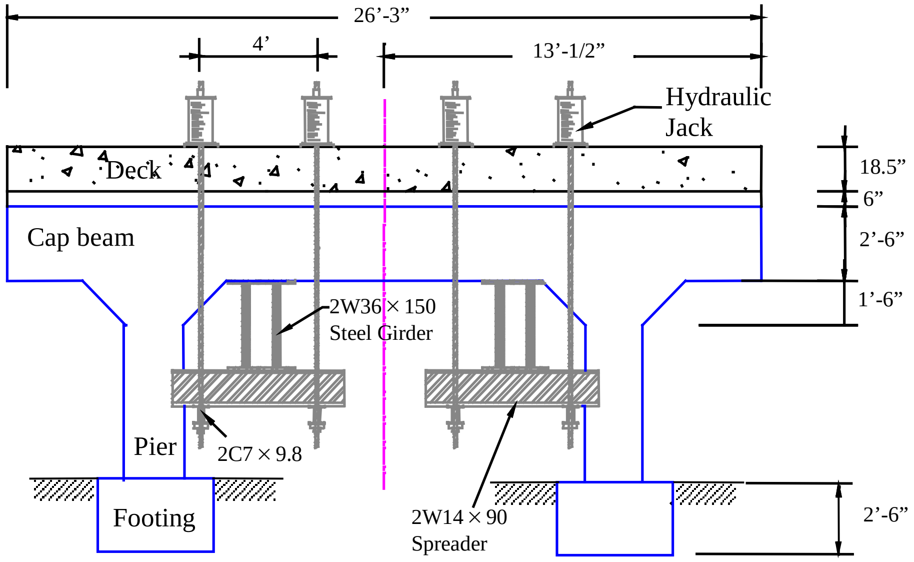

Figure 3. Static load test setup for bridge decks.

Figure 4. Test setup for cyclic loading for bridge piers.

(a) Rupture of FRP rods at the base of the column.

(b) Cracking at the top of the column.

Figure 5. Failure condition of pier #3.