NONDESTRUCTIVE TESTING OF DALLAS COUNTY BRIDGE IN MISSOURI, USA

M. Ekenel[1], J. J. Myers[1]
[1] Center of Infrastructure Engineering Studies (CIES), Department of Civil Engineering, University of Missouri-Rolla, Rolla, MO 65409, USA

Abstract: Fiber reinforced polymer (FRP) composites are getting a wide range of application areas in bridge rehabilitations because these materials are less affected by corrosive environmental conditions, known to provide longer life and require less maintenance. However, there are still some concerns about their long-term performance because currently limited data exists. Moreover, the quality control and quality assessment of these new rehabilitation systems still need to be further improved and standardized. A recent rehabilitation application by using carbon fiber reinforced polymer (CFRP) and steel reinforced polymer (SRP) laminates took place in a bridge located in Dallas County, Missouri, by the Missouri Department of Transportation (MoDOT) and the Center for Infrastructure Engineering Studies (CIES) at the University of Missouri-Rolla. An investigation has been carried out in this bridge to provide installation criteria for FRP strengthening of civil structures. This investigation covers measurement of surface preparations, evaluation of bond properties by pullout tests, detection of fiber alignment, and detection of delaminations formed between concrete substrate and carbon fiber reinforced polymer (CFRP) by non-destructive testing equipments. Several nondestructive testing systems were performed such as impulse-echo, ultrasonic, and microwave to detect and image the delaminations. This paper explains the concerns about bridge rehabilitation systems and how the bridge was prepared before and after strengthening with CFRP for the nondestructive testing purposes. This bridge will be under investigation for five successive years.

Introduction and Background: Recently, rehabilitation projects to increase the life expectancy of existing bridges has seen rapid growth because the replacement of a bridge is becoming a large burden for state DOT's. The main reasons include the growth in construction costs, increased losses due to disruption of traffic during the new construction, and increased public disturbance. The rehabilitation of many deficient bridges are performed by utilizing new generation materials such as carbon fiber reinforced polymers (CFRP) because of their superior performance including high stiffness-to-weight ratio and low installation costs which can offset the higher material costs. Moreover, these materials poses more corrosive resistance as compared to conventional materials such as steel plates, hence expected to provide a longer service life and require less maintenance. However, currently very limited data exists about the long-term behavior and performance of such materials [1]. Even though numerous laboratory experiments have been completed, these cannot perfectly simulate actual bridge conditions in a controlled laboratory environment. This is primarily because of the conditions that could happen in a bridge environment simultaneously such as UV light exposures, weathering, and traffic conditions, unlike that of laboratory conditions where the temperature is ambient and no direct sunlight exposure exist. Moreover, natural disasters, such as flood and earthquakes, can also contribute to these factors and may cause significant amount of damages. Some of the most common questions about bridge rehabilitation with FRP laminates are surface roughness, fiber alignment, bond strength and presence of air voids and delaminations between CFRP and concrete substrate.

Because the CFRP strengthening works as an 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 substrate concrete. The bond strength between an FRP sheet and concrete influences the structural behavior of concrete elements strengthened with FRP sheet bonding. The American Concrete Institute (ACI) Committee 440.2R document requires bond strength of minimum 1.4 MPa and failure mode of the concrete substrate [2].

The surface roughness has also a great influence on bond strength. Therefore, it is necessary to determine an evaluating method for concrete surface roughness and to describe the relations between bond strength and various surface roughness indexes [3]. The most common method in performing surface preparation is sand blasting. The surface roughness of concrete can be varied by changing the application methods, such as, adjusting the amount of sand discharged from the nozzle or the distance between surface and nozzle.

Another type of structural deficiency is air voids or delaminations between CFRP laminate and concrete substrate. Any kind of these surface defects may effect and significantly weaken the structural integrity and performance of the system; moreover may limit the life expectancy of the structure [2, 4-8]. Delamination can be caused by several reasons such as presence of moisture in the concrete, significant changes in temperature during curing, and improper application. An undetected delamination may also cause fracture of the material [9]. The American Concrete Institute (ACI) Committee 440.2R document requires the evaluation of delaminations and air voids between multiple plies or between the FRP system and the concrete with a minimum detectable size of 1300 mm^2. Some other criteria from ACI Committee 440 may be noted as: total delamination area should be less than 5% of the total laminate area and no more than 10 delaminations per 1 m^2, large delaminations (greater than 16,000 mm^2) should be repaired by cutting away and applying an sheet patch, and delaminations smaller than 16,000 mm^2 maybe repaired by resin injection or ply replacement. Senthilnath (2001) reported that ACI Committee 440 requirements are very conservative [10]. He also reported an insignificant growth in delamination sizes after fatigue testing for 2-million cycles without environmental conditioning.

Fiber alignment is an important issue which should be investigated during and after FRP placement because the performance of unidirectional FRP laminates is highly dependent on fiber orientation with respect to applied load direction. Depending on the severity of the misalignment, the difference between actual strength and stiffness of the FRP from assumed nominal values may become critically high and may cause of rejection of the system [11]. ACI 440.2R-02 reports that fiber misalignment of more than 5 degrees as compared to design drawings should be evaluated for acceptance [2].

One of the main concerns about bridge rehabilitation is early determination of above mentioned problems to ensure safety and to assist management of bridge system. Since quality of the FRP products is very consistent and satisfactory because of the quality assurance systems of manufacturers, the main remaining issue is quality of work performed during rehabilitation or strengthening. The conventional methods involve visual inspection or destructive testing; however, it is obvious that visual inspection cannot provide quantitative and objective information and destructive testing may have adverse effects on integrity of bridges. As an example of these conventional testing is the coil tap test of delaminations. This method involves basically using a small hammer or a steel bar to tap the FRP bonded surface (after curing) to detect air voids because a perfectly bonded FRP generates a different audible noise from that which is not. However, even though this method is low technology and simple, it is more subjective and less reliable because it needs an employee with a discerning ear [6, 8]. Hence, efficient, reliable, cost-effective, portable, hand-held nondestructive testing (NDT) devices, which do not compromise the structural integrity during the inspection of rehabilitation work, are in demand [12-14]. Moreover, this device must be user-friendly and the outcomes of these devices must be easy to interpret [15]. Several NDT methods are currently available such as impact-echo, microwave, thermography, and ultrasonic; however, they should be validated before used and all factors affecting their reliability identified. In order to serve this purpose, FHwA established a NDE methods validation center (NDEVC) in McLean, Virginia [16]. However, Starnes (2003) reports that, currently, there are no standard NDT procedures that controls the quality and assess the integrity of bonded FRP composite systems used in civil engineering applications [17]. One of the purposes of the work described in the paper was to create an environment and system to test the NDT methods in delamination inspection of CFRP utilized bridge rehabilitations, such as impact-echo, microwave, and ultrasonic.

Surface Preparation: Improper surface preparation may result in debonding or delamination of the FRP system and may cause a decrease in the design strength of the retrofit. Several different locations have been selected on the bridge abutment and two bents on the Dallas County Bridge. Surface preparations with various roughnesses were applied on these locations before placement of CFRP laminates. Based on the evaluation of available data, specification limits will be detailed relating to optimal surface roughness limits for maximum bond conditions. The work of this investigation will not only address the substrate (concrete) and FRP interface issue, but also repair of damaged and/or deteriorated regions and materials prior to the installation of bonded FRP laminates. The plan view of bridge is shown in Figure 1.

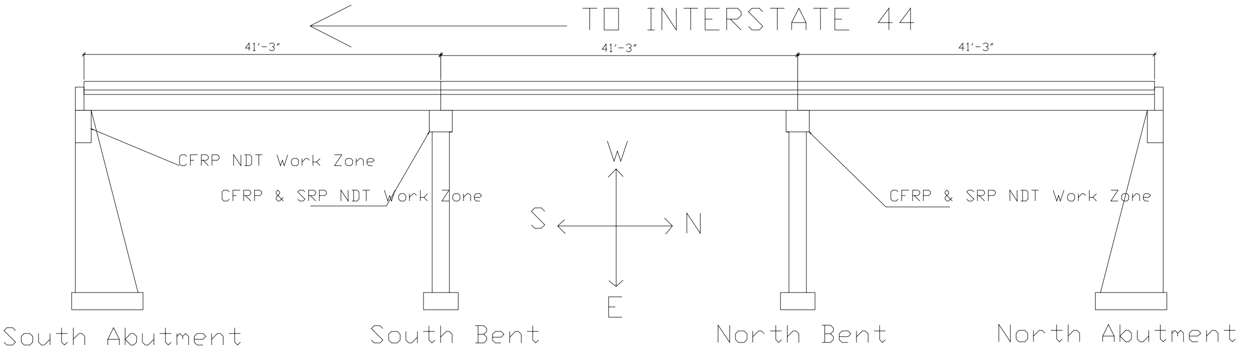


Figure 1. Plan view of Dallas County Bridge, Missouri

Six different locations were selected on the south abutment and five different surface roughnesses were applied by contractor for study. Surface preparation was performed using a sand blasting technique. The sand used was carbon-based material, obtained from a coal plant by-product. One location was left unroughened to serve as a control unit. This location was cleaned using a wire brush to remove any dirt. The surface roughness of concrete was varied by adjusting the distance between surface and nozzle. All five locations have been scanned to determine the surface roughnesses of each relative to control unit, which had no preparation. Representative pictures are shown in Figure 2. The plan of abutment is presented in Figure 3.

Figure 2. Surface Preparation on Abutment

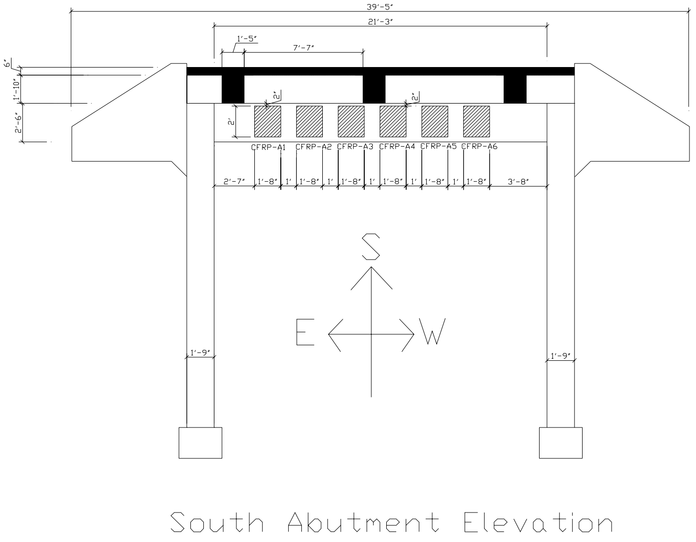


Figure 3. Plan View of South Abutment

Four different locations were selected on the south side view of the south bent cap, these spots prepared by surface roughening (see Figure 4), two additional spots selected on north side of same bent, these locations were left without any preparation (see Figure 5). Surface preparation is also applied to east and west side views of the south bent cap.

Four different locations have been selected from north side of north bent. This side of north bent was prepared by utilizing surface roughening. No surface roughening applied at the spot located on the west side of the north bent. All the spots were scanned using a laser stripping device developed by the Rock Mechanics Non-destructive testing group to determine the suitable amount of surface roughening to obtain the desirable surface roughness for the test patches. Figure 6 represents the north side view of north bent.

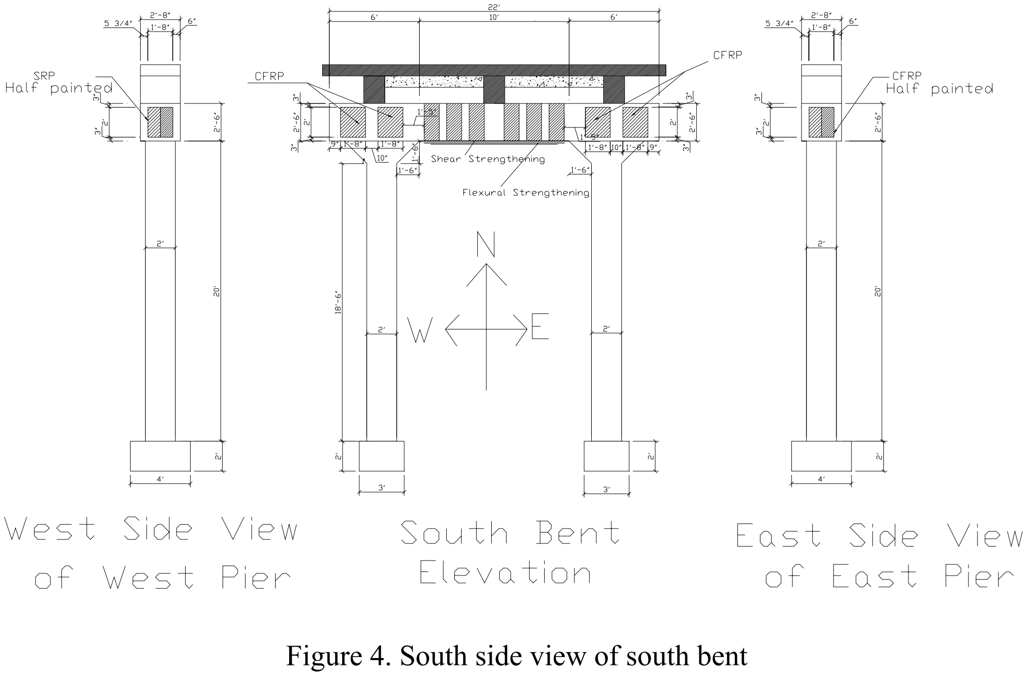


Figure 4. South side view of south bent

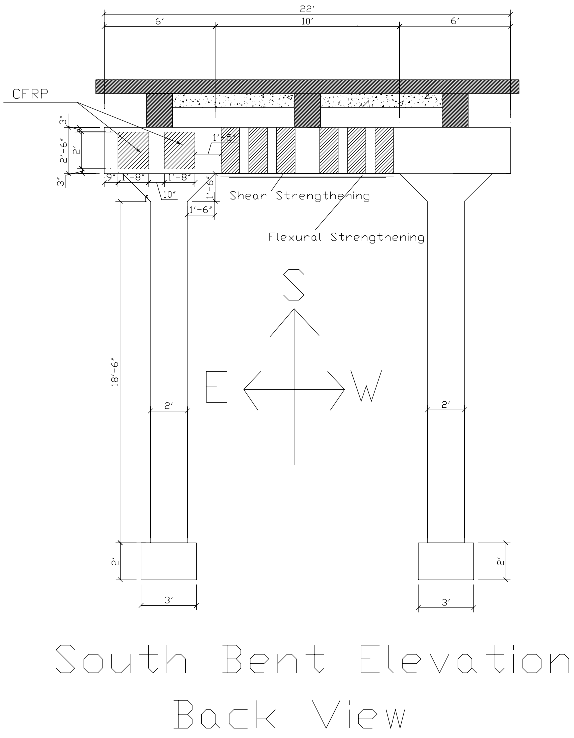


Figure 5. North side view of south bent

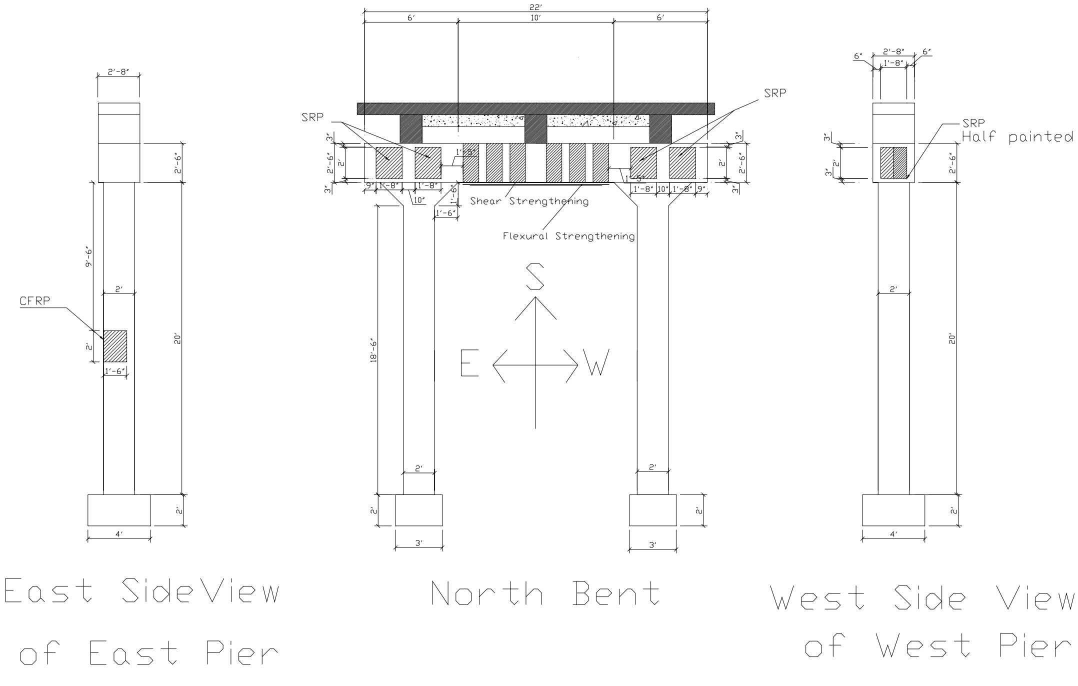
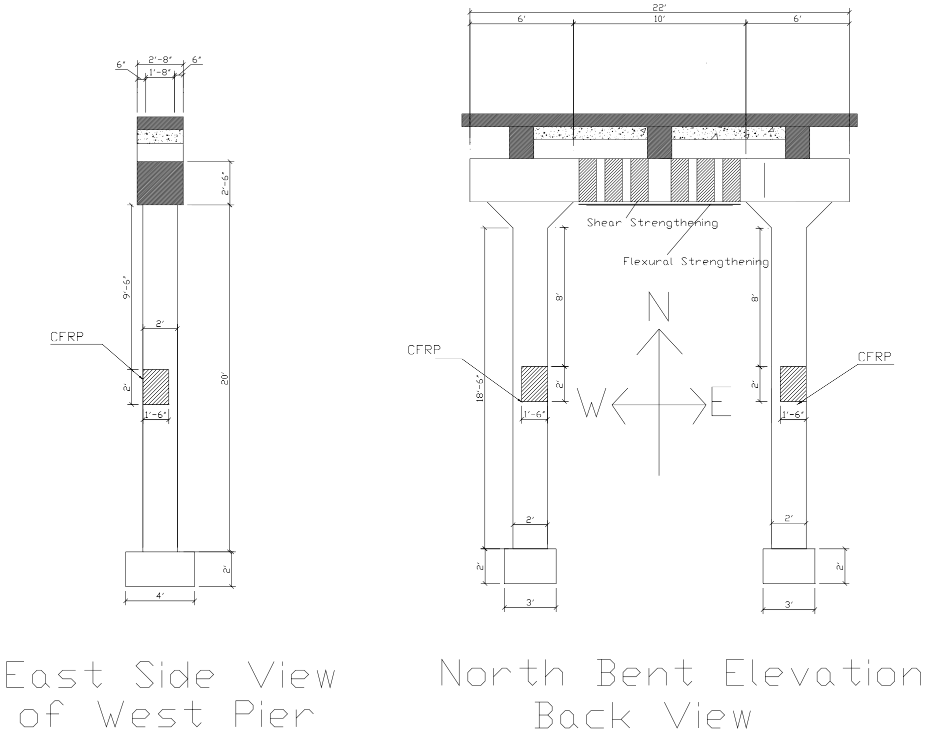


Figure 6. North side view of north bent

Delaminations: One of the purposes of this investigation was to develop reliable and capable methods to detect voids and delaminations of a specified maximum size in FRP repair systems. The finding of this investigation will help for a better understanding of permissible size of individual detectable delaminations, their location in the structure, and delamination area over a given structure. Severe environmental conditioning effects, coupled with fatigue loading, will also be addressed.

For this investigation, 15 CFRP laminates with dimensions of 20”x24” were installed on various spots of abutment and bents. Six CFRP laminates were installed on south abutment, on the same surfaces where roughness studies were installed. Four of the CFRP laminates were placed on the south side and one on the east side of the south bent (see Figure 7). These laminates were installed on roughened surfaces. Two other CFRP sheets were placed on north side of the same bent. These sheets were installed on un-roughened surfaces and will serve as control samples. Finally, two CFRP sheets were placed on the corners of the lower part of north bent columns, as shown in Figure 7. These sheets were placed close to water level in order to study the wet-soak and freeze-thaw effect for next five years.



East Side View
of West Pier

North Bent Elevation
Back View

Figure 7. South side view of north bent

Figure 8. CFRP laminates with delaminations on south abutment and north bent

Delaminations were created on all CFRP laminates. Delaminations were formed by applying pressured air beneath CFRP sheet when the epoxy was in fresh state. Because it was hard to control pressured air, the number and the sizes of the delaminations could not be controlled. The final shapes were formed by rolling a roller spike around delaminations. Each single CFRP sheet contained different size and numbers of delaminations. Figure 9 shows how the delaminations were formed.

Figure 9. Creating delaminations

SRP Placement: Six steel fiber reinforced polymers (SRP) were also placed. Four of the SRP were installed on north side view of north bent. These locations were prepared by roughening. The final two SRP sheets were placed on the west sides of the north and south bents, one on each. The one on the south bent was placed on a roughened surface, while the one on the north bent was placed on un-roughened surface. These SRP laminates will be visually inspected for five successive years.

On-going Events: Rock Mechanics nondestructive group from UMR placed pullout test plates on four corners of each CFRP sheet [18]. These plates will be pulled out within five years to investigate the bond strength over time. Some examples are shown in Figure 8. Moreover, the same NDT group placed a special woven CFRP fabric that is externally bonded to a structural element by the wet lay-up method and enables to measure the angle of the fiber misalignment. Delaminations have been scanned by echo-impact [18], microwave technology [19] and ultrasonic NDT devices. These measurements will continue for five successive years and the results will be compared with each other.

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References:

1. Miceli, M., Horne, M. R., Duke, C. D., "*Health Monitoring of FRP Bridge Decks*" Advanced Nondestructive Evaluation for Structural and Biological Health Monitoring, Proceedings of SPIE, V. 4335, 2001, pp. 100-105.
2. ACI 440.2R-02, "*Guide for Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*", American Concrete Institute, 2002.
3. Mitsui, M., Fukuzawa, K., Numao, T., Fuda, I., *"Relations Between Surface Roughness Indexes and Bond Strength Between CFRP Sheets and Concrete*" Journal of the Society of Materials Science, Japan, V. 49, N. 6, June 2000, pp. 685-691.
4. Kim J. Y., De Flaviis, F, Jofre, L, Feng, M. Q., "*Microwave-Based NDE of FRP-Jacketed Concrete Structures*" International SAMPE Symposium and Exhibition (Proceedings), V.46 I 2001, pp. 439-450.

5. Hughes, D., Kazemi, M., Marler, K., Zoughi, R., Myers, J.J., Nanni, A., *"Microwave Detection of Delaminations Between Fiber Reinforced Polymer (FRP) Composite and Hardened Cement Paste,"* Proceedings for the 28th Qualitative Nondestructive Evaluation Conference, Brunswick, Maine, July 29-August 3, 2001.
6. Newman, J., Zweben, C., "*Nondestructive Inspection of Composite-Strengthened Concrete Structures*" 47th International SAMPE Symposium, V. 47, May 2002, pp. 691-702.
7. Akuthota, B., Hughes, D., Zoughi, R., Myers, J.J. Nanni, A., *"Near-Field Microwave Detection of Disbond in Fiber Reinforced Polymer Composites Used for Strengthening Concrete Structures and Disbond Repair Verification,"* American Society of Civil Engineering – Journal of Materials in Civil Engineering, (In Press).
8. Shih J. K. C., Tann, D. B., Hu, C. W., Delapk, R., Andreou, E., "*Remote Sensing of Air Blisters in Concrete-FRP Bond Layer Using IR Thermography*" International Journal of Materials and Product Technology, V.19, Nos. 1-2, 2003, pp. 174-187.
9. Gros, X. E., Takahashi, K., "*Non-destructive Characterization of Delaminated Areas at Interfaces Between Plies in Carbon Fiber/epoxy Laminates with Foucault Currents*" Composite Interfaces, V. 7, N.3, 2000, pp. 177-192.
10. Senthilnath, P. S., Belarbi, A. J., Myers, J. J., "*Performance of CFRP Strengthened RC Beams in the Presence of Delaminations and Lap Splices under Fatigue Loading*," Proceedings-Composites in Construction: 2001 International Conference, Porto, Portugal, October 2001.
11. Yang, X., Nanni, A., Haug, S., Sun, C. L., "*Strength and Modulus Degradation of CFRP Laminates from Fiber Misalignment*" Journal of Materials in Civil Engineering, V. 14, N. 4, July/August 2002, pp. 320-326.
12. Washer, G., "*Developments for the Non-destructive Evaluation of Highway bridges in the USA*" NDT & E International, V. 31, N. 4, 1998, pp. 245-249.
13. Washer, G., "*Developing NDT Technologies for Highway Bridges*" Materials Evaluation, V. 57, N. 11, 1999, pp. 1151-1161.
14. Tawhed, F. W., Gassman, S. L., "*Damage Assessment of Concrete Bridge Decks using Impact-Echo Method*" ACI Materials Journal, V. 99, N. 3, May 2002, pp. 273-281.
15. Prine, W. P., "*Problems Associated with Nondestructive Evaluation of Bridges*" SPIE Volume 2456: ND evaluation of Aging Bridges and Highways, Oakland, California, 1995, pp. 46-52.
16. Phares, B. M., Washer, G. A., Moore, M. E., "*FHwA's Nondestructive Evaluation Validation Center, A National Source*" Transportation Research Board No. 1680, Paper N. 99-1020, 1999, pp. 74-76.
17. Starnes, M. A., Carino N. J., Kausel, E. A., "*Preliminary Thermography Studies FRP Quality Control of Concrete Structures Strengthened with FRP Composites*" Journal of Materials in Civil Engineering, ASCE, 2003, pp. 266-273.
18. Maerz, N., "*Experimental Nondestructive Testing of FRP Materials, Installation, and Performance, Dallas County Bridge, Missouri, USA"*, Submitted for 16th World Conference on Nondestructive Testing, Montreal, Canada, August-September 2004.
19. Zoughi, R., "*Microwave Field Measurement of Delaminations and Their Growth in CFRP Concrete Members in a Bridge*" Submitted for 16th World Conference on Nondestructive Testing, Montreal, Canada, August-September 2004.