

01 Jan 2004

## Design and Technologies for a Smart Composite Bridge

K. Chandrashekhara

*Missouri University of Science and Technology, chandra@mst.edu*

Prakash Kumar

Steve Eugene Watkins

*Missouri University of Science and Technology, watkins@mst.edu*

Antonio Nanni

*Missouri University of Science and Technology*

Follow this and additional works at: [https://scholarsmine.mst.edu/mec\\_aereng\\_facwork](https://scholarsmine.mst.edu/mec_aereng_facwork)



Part of the [Aerospace Engineering Commons](#), [Electrical and Computer Engineering Commons](#), and the [Mechanical Engineering Commons](#)

---

### Recommended Citation

K. Chandrashekhara et al., "Design and Technologies for a Smart Composite Bridge," *Proceedings of the 7th International IEEE Conference on Intelligent Transportation Systems, 2004*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2004.

The definitive version is available at <https://doi.org/10.1109/ITSC.2004.1399035>

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in Mechanical and Aerospace Engineering Faculty Research & Creative Works by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact [scholarsmine@mst.edu](mailto:scholarsmine@mst.edu).

# Design and Technologies for a Smart Composite Bridge

K. Chandrashekhara, Steve E. Watkins, *Senior Member, IEEE*, Antonio Nanni, and Prakash Kumar

**Abstract**—An all-composite, smart bridge design for short-span applications is described. The bridge dimensions are 9.14-m (30-ft.) long and 2.74-m (9-ft.) wide. A modular construction based on assemblies of pultruded Fiber-Reinforced-Polymer (FRP) composite tubes is used to meet American Association of State Highway and Transportation Officials (AASHTO) H20 highway load ratings. The hollow tubes are 76 mm (3 in.) square and are made of carbon/vinyl-ester and glass/vinyl-ester. An extensive experimental study was carried out to obtain and compare properties (stiffness, strength, and failure modes) for a quarter portion of the full-sized bridge. The bridge response was measured for design loading, two-million-cycle fatigue loading, and ultimate load capacity. In addition to meeting H20 load criteria, the test article showed almost no reduction in stiffness or strength under fatigue loading and excellent linear elastic behavior up to failure. Fiber optic strain sensors were evaluated on the test article during testing. Sensor characteristics are determined as preparation for permanent field installation.

## I. INTRODUCTION

**M**AINTENANCE of transportation infrastructure, especially bridges, is a growing concern worldwide. The deteriorating condition of bridges and other structures

Manuscript received May 10, 2004. This work was partially supported by the National Science Foundation through Combined Research-Curriculum Development Grant # EEC-9872546 with Mary Poats as technical contact. Additional support from Composite Products, Inc. (John F. Unser, President), the Missouri Department of Transportation, the Missouri Department of Economic Development, Lemay Center for Composites Technology, and University Transportation Center of University of Missouri - Rolla is acknowledged. Other partners and supporting companies for the smart composite bridge development and additional project documentation are available on the web at <http://campu.UMR.edu/smarteng/bridge>.

K. Chandrashekhara is with the Department of Mechanical and Aerospace Engineering and Engineering Mechanics, University of Missouri-Rolla, Rolla, MO 65409 USA (e-mail: [chandra@umr.edu](mailto:chandra@umr.edu)).

S. E. Watkins is with the Department of Electrical and Computer Engineering, University of Missouri-Rolla, Rolla, MO 65409 USA (e-mail: [steve.e.watkins@ieee.org](mailto:steve.e.watkins@ieee.org)). (corresponding author: 573-341-6321; fax: 573-341-4532; e-mail: [steve.e.watkins@ieee.org](mailto:steve.e.watkins@ieee.org)).

A. Nanni is with the Department of Civil Engineering, University of Missouri-Rolla, Rolla, MO 65409 USA (e-mail: [nanni@umr.edu](mailto:nanni@umr.edu)).

P. Kumar is with the Department of Mechanical and Aerospace Engineering and Engineering Mechanics, University of Missouri-Rolla, Rolla, MO 65409 USA.

has been widely documented [1-4] as one of the most complex problems in transportation infrastructure. Finding innovative, cost-effective solutions for the replacement and repair of concrete and steel in bridges and for the long-term health monitoring of field infrastructure is a necessity. Fiber-reinforced polymers (FRP) are an alternative to conventional infrastructure materials. Besides having high stiffness and strength-to-weight ratios, excellent fatigue and corrosion properties, faster installation time, and reduced maintenance costs, composites offer superior resistance to environmental degradation as compared to traditional building materials. Fiber optic sensor systems are being developed due to advantages of environmental ruggedness, low profile, high sensitivity, and multiplexing capability. In particular, fiber optic sensors and data lines are compatible with FRP composite materials and structures.

Short-span bridges and bridge decks represent a large investment across the nation and their maintenance is an ongoing expense. Due to significant corrosion problems and environmental deterioration, these applications are promising candidates for high-performance, long-life FRP composites. Field experience with bridge systems and decks made predominantly with FRP composite materials has grown with the successful installation of several composite bridges around the United States by various private companies in collaboration with federal, state, and county agencies [5-10]. However, the cost of high-strength FRP composite materials is high [11] and the practical acceptance of non-traditional technologies is often tied to health monitoring systems.

A smart structure has integral sensors that provide control or interpretation functions [12]. The development of smart bridge instrumentation addresses management concerns including such as design expectations, damage characterizations, and health monitoring [13]. In structural applications, strain is a key parameter. Optical-fiber-based Fabry-Perot interferometers are among the most successful strain sensors [14]. These sensors correlate well with conventional strain gauges [cf. 15] and perform well when embedded in composites [16-17].

However, many interdisciplinary challenges exist in the development of field instrumentation, multiplexing, data acquisition, intelligent processing, and installation protocols [18].

This work describes technologies and associated laboratory tests for a smart composite bridge. The design is for a short-span application with bridge dimensions of 9.14-m (30-ft.) long and 2.74-m (9-ft.) wide and has a requirement of American Association of State Highway and Transportation Officials (AASHTO) H20 highway load ratings [19]. The approach is an alternative to other bridge designs [5-10]. The modular construction is based on assemblies of pultruded hollow square tubes. The tubes have side dimensions of 76 mm (3 in.) and are made of carbon/vinyl-ester and glass/vinyl-ester. An experimental study of structural properties (stiffness, strength, and failure modes) was performed for a quarter portion of the full-sized bridge. The bridge response was measured for design loading, two-million-cycle fatigue loading, and ultimate load capacity. Fiber-optic extrinsic Fabry-Perot interferometric (EFPI) strain sensors were evaluated on the test article during the testing. Sensor characteristics are determined as preparation for permanent field installation.

## II. BRIDGE DESIGN

### A. Structural Details

The cross section of the bridge design is shown in Figure 1. Four identical I-beam structures are formed from eight layers of tubes. The bottom two layers and the top three layers are continuous. Alternate layers of tubes are bonded transversely and longitudinally to the direction of traffic. The load-bearing layers are the bottom and next-to-top longitudinal layers and are made of carbon tubes.

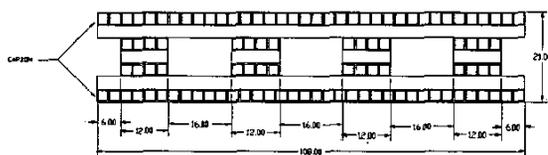


Figure 1: Schematic cross section of the full-size bridge. The four I-beam structures and the carbon load-bearing layers are shown (the test article has an additional glass layer on the top). All dimensions are in inches.

The tubes are made in a resin matrix of Derakane 411-350 vinyl ester from DOW Chemical with reinforcement from longitudinal fibers of Zoltek Panex 33 carbon and stitched mat on the inside and outside surfaces. The other

tubes form the web of the I-beams and transverse load-distributing layers. These tubes are obtained from Bedford Reinforced Plastic with glass roving and CoRezyn vinyl ester resin. All tubes have side dimensions of 76 mm (3 in.) and wall thickness of 6.4 mm (0.25 in.). The layers are bonded with Hysol 9460 epoxy adhesive and they are mechanically fastened using screws during cure.

The bridge was designed to AASHTO ratings for a 9.14-m (30-ft.) span for traffic using the H20 truck configuration shown in Figure 2 [19]. This live load distribution was based on an H20 truck with two back axles positioned equi-distant on either side of the center of the span. The service load was calculated as 142.4 kN (32,000 lbs) with 71.2 kN (16,000 lbs.) on each back axle. AASHTO bridge specifications limit the mid-span deflection to 1/800 of the span length. Hence, the allowable deflection for the design span at H20 loading is 11.4 mm.

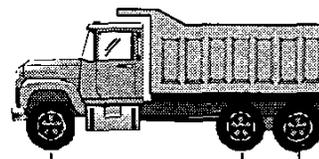


Figure 2: AASHTO H20 Truck

### B. Sensing Objective

The smart sensing objective for the bridge project is to measure flexure strain at point locations throughout the structure. Key monitoring locations are mid-span in the load-bearing carbon-tube layers. The sensing system must be permanent and rugged for long-term monitoring and must be capable of internal installation. The sensor measurements are compared to conventional measurements of strain from electrical resistance gauges and displacement from linear variable differential transformers.

A sensing system using EFPI strain sensors is used. Research issues include the sensor performance under extreme loading conditions and installation protocols for sensor protection and effective bonding. Internal strain measurements by each embedded sensor must be associated with only one tube and not complicated by interface effects.

The installation of the fiber optic sensors is done by the following procedure. Small grooves at the point locations provide protection from accidental impacts and, when

internal to the tube assemblies, minimize the influence of the adjacent tube. The sensors were bonded using the adhesive for the tube assemblies after the grooves were cleaned with acetone. The fiber optic leads were routed and bonded along the interface between tubes, again providing physical protection. For a permanent installation, additional lead protection, a connection patch box, and optical fiber strain relief would be needed as well [20].

### C. Test Article

The primary structural element is the I-beam. Assuming even distribution of the load, each I-beam in Figure 1 must carry one quarter of the load and meet the deflection criteria. A full-scale eight-layer test article was fabricated with dimensions of 9.14 m (30 ft.) long by 610 mm (2 ft.) wide by 610 mm (2 ft.) high. The web has a thickness of 305 mm (1 ft.). It was equivalent to a quarter of the bridge deck and had the cross-section of a single I-beam. The tubes and manufacture were as specified in Section II.A.

## III. TESTING PROGRAM

The testing program consisted of experimental loading on the test article, i.e. the quarter portion of the full-size bridge, and evaluation of the sensing system. Preliminary tests using glass/vinyl-ester tubes were performed on individual tubes, double-tube assembly, and a four-layer alternating-tube assembly [21]. These tests were used to identify the specified tube types, the tube/adhesive bonding characteristics, and embedded EFPI sensor behavior. The best adhesive gave uniform bonding in which failure occurred in the tubes rather than at the bonding surface. Mechanical fasteners were not used in the preliminary tests.

A key test was of the four-layer beam. This glass assembly had dimensions of 2.44-m x 30.5-cm x 30.5-cm (8-ft. x 1-ft. x 1-ft.). Several EFPI sensors were embedded in the assembly during fabrication. They were bonded on the surfaces of interest between the tubes. A three-point loading test resulted in audible popping at a load of 89 kN (20,000 lbs.), deformation of transverse tubes at a load of 111 kN (25,000 lbs.), and significant cracking of tube corners at a load of 134 kN (30,000 lbs.). The embedded EFPI sensors gave measurements that closely matched the measurements from the external electrical resistance gauges and linear variable differential transformers. The embedded optical sensors survived the failure events.

### A. Experimental Overview

The I-beam test article was subjected to an experimental study of stiffness, strength, durability, and failure modes. AASHTO H20 deflection standards were the criteria. As a

quarter portion of the proposed bridge, the desired design load is 35.5 kN (8,000 lbs.), i.e. 142.4/4 kN (32,000/4 lbs.). Four-point loading was used. The test article was simply supported by two rollers spaced 8.54 m (28 ft.) apart so that the beam extended 305 mm (1 ft.) beyond these end supports.

The following tests were performed: (1) design load test (quasi-static loading in excess of the design load at the mid-span of the deck); (2) fatigue or cyclic load test (fatigue loading under service loads to 2 million cycles with quasi-static load tests at periodic intervals to assess degradation); (3) ultimate load test (static loading to failure with load at mid-span of the deck). Loading for tests 1 and 3 was applied using an 889.6 kN (200,000 lbs.) manual hydraulic jack. Loading for test 2 was applied using an MTS electro-hydraulic actuator with MTS 436 controller. The actuator had a 97.9 kN (22,000 lbs.) loading capacity and a 152.4 mm (6 in.) stroke. Rectangular loading patches of 203 mm (8 in.) x 508 mm (20 in.), with the larger dimension transverse to the direction of traffic, were used to simulate the action of wheel loads of an H-20 truck. The loading patches were at a distance of 1.22 m (4 ft.), or 610 mm (2 ft.) off-center, representative of the distance between the two back axles of an H-20 truck. The static test is shown in Figure 3.

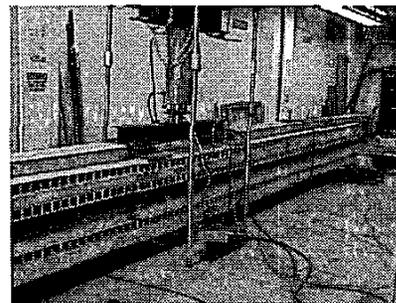


Figure 3: Test Article in the Loading Apparatus.

### B. Laboratory Instrumentation

Strain, displacement, and load were recorded using a high-speed automated data acquisition system. Ten 120-ohm electrical resistance gauges of gauge length 6 mm measured longitudinal and transverse strain on the top and bottom surfaces at mid-span and other selected locations. Linear variable differential transformers measured the mid-span deflection. Load cells on the hydraulic jack and actuator monitored vertical applied load.

### C. Smart Fiber-Optic Instrumentation

An AFSS-PC fiber-optic sensor system made by Luna Innovations was used for the experimental work. The

system uses EFPI fiber-optic sensors to measure absolute strain [14,22,23]. A sensor schematic is shown in Figure 4(a). Operation is based on multiple-beam interference in a cavity formed between two polished, coated end-faces of optical fiber. A capillary tube is bonded to the fibers and maintains the alignment of their end-faces. Strain on the capillary tube produces changes in cavity length which modulate the irradiance of returned light in the fiber. The sensor has little transverse coupling and effectively evaluates the axial component of strain [15,16]. The gauge length is determined by the length of this capillary tube. EFPI strain sensors can measure strain given the gauge length. Two high-finesse strain sensors with gauge lengths of about 8 cm were used on the I-beam test article.

The AFSS data-acquisition and processing system is shown in Figure 4(b). A broadband LED source is used that is centered about a wavelength of 830 nm. The input light is directed to the sensor by a fiber coupler and the returned light is sent to a wavelength demodulator and detector. The interference response at several wavelengths can determine the absolute cavity displacement and hence the absolute strain can be demodulated.

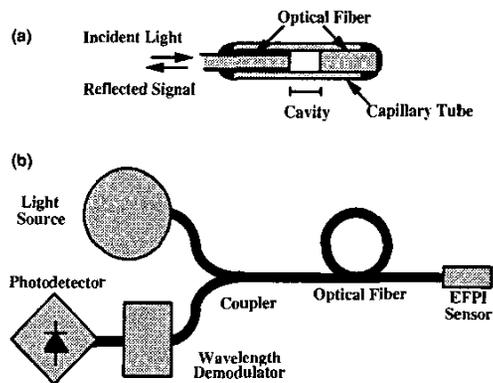


Figure 4: Sensor System (a) High-finesse EFPI sensor and (b) Instrumentation for absolute strain measurement.

#### IV. EXPERIMENTAL PROCEDURE AND RESULTS

##### A. Design Load Test

The design test assessed serviceability and performance of the composite approach up to 111 kN (25,000 lbs.). Note that this level was more than three times the AASHTO H20 load. As the load was increased beyond 80 kN (18,000 lbs.), a minor sounds were heard which appeared to be cracking of the adhesive layer between a

few of the tubes. However, the test article maintained elastic behavior. Mid-span deflection was 22 mm (0.86 in.) at the largest loading. Mid-span deflection was only 6.6 mm (0.26 in) upon application of the design load of 35.5 kN (8,000 lb). The deflection was fifty-eight percent of the target 11.4-mm limit. No premature deterioration or damage was observed for this test.

##### B. Fatigue Load Test

The fatigue test simulated the typical transient loading of a bridge and consequently addressed durability. Normally, fatigue tests are run for no more than 2 to 3 million cycles, even though, for bridge applications, this limit may represent only a few years of actual service. (Sometimes, researchers attempt to "accelerate" the fatigue damage by testing at loads much higher than the service load. However, this approach is inadequate as different damage mechanisms may dominate under different load levels.) In this work, the test article was subjected to fatigue loading for 2 million cycles at a frequency of 4 Hertz. The load-control test had a 0.045 minimum/maximum load ratio. The maximum load was 48.93 kN (11,000 lbs.) and the minimum load was 2.2 kN (500 lbs.). The loading cycles simulate the repeated passage of the back axles of an H20 truck over the points of application.

Quasi-static flexure tests were periodically performed to check for degradation. The flexure load level was 88.96 kN (20,000 lbs.). Measurements were performed before the fatigue test and after every 400,000 cycles, i.e. at 0, 0.4, 0.8, 1.2, 1.6, and 2.0 million cycles. Also, the mid-span height of the test article from the floor was recorded before each set of quasi-static measurements as a check for permanent deformation or bending.

Figure 5 shows the mid-span strain measurements against the applied load during the periodic quasi-static tests. No apparent loss in stiffness was demonstrated up to the maximum applied load of 88.96 kN (20,000 lbs.) and the mid-span deflection was unchanged throughout the test. A thorough visual inspection was done during each quasi-static load test and no sign of fracture or debonding between the FRP tubes in any of the eight layers was observed. The assembly fasteners were also inspected and were found to be in perfect condition. No other form of damage was observed either during or after the conclusion of the fatigue load test.

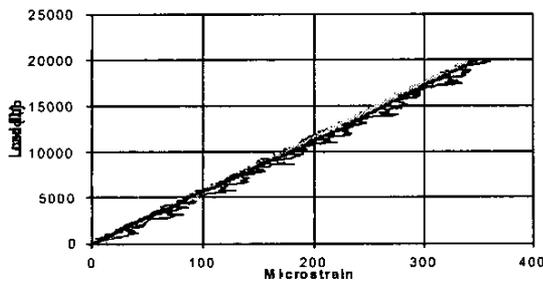


Figure 5: Load-strain curves for periodic flexure tests.

### C. Ultimate Load Test

The ultimate load capacity of the test article was measured to evaluate the overall margin of safety and the failure modes. Concentrated static load was applied in cycles under the four point bending configuration to the mid-span of the test article. No indication of damage occurred during the first loading cycle from 0 to 88.96 kN (20,000 lbs.). Inelastic behavior and loud popping noises occurred at the end of the second cycle from 88.96 kN (20,000 lbs.) to 133.5 kN (30,000 lbs.). Deflection increased without any increase in the load occurred at the end of the third cycle from 111 kN (25,000 lbs.) to 169 kN (38,000 lbs.). Significant failure, i.e. cracking of the tube corners, occurred at a load of 155.7 kN (35,000 lbs.).

The load on top of the sample was again reduced to about 111 kN (25,000 lbs.). Upon reloading to 155.7 kN (35,000 lbs.), the deflection and strain on the sample increased with no increase in load, i.e. the reduction in the load carrying capacity of the whole structure was permanently reduced. Despite the reduction in stiffness and the tube cracks, the mid-span point of the test article returned to almost its initial height after load removal. No other permanent distortion or visual defects were observed.

### D. Fiber-Optic Sensor Performance

Both EFPI sensors survived three tests including the final failure event. Also, the signals from these fiber-optic sensors clearly identified strain variations during minor and major damage events. The measurements from these sensors correlated with and had lower noise than electrical resistance gauges that were closely located on the structure.

## V. CONCLUSIONS

Bridge technologies are presented that incorporate FRP composite construction and smart EFPI instrumentation. A quarter portion of the full-scale bridge was tested under

design loading, fatigue loading, and failure loading. EFPI sensors were evaluated as an integral part of the bridge.

The work has shown that a short-span all-composite bridge construction of off-the-shelf pultruded carbon and glass tubes can meet the strength and deflection design criteria for AASHTO H20 highway loads. The net central deflection ranged within the limits of length/800 and no fatigue problems were identified in the long-term durability test. The following results are noted from the experiments.

- The deflection and strain histories of the test article show linear elastic bending and shear behavior with a slightly non-linear envelope close to the failure load. The deflections and strains are closely symmetric up to the point of failure.
- The test article showed almost no reduction in stiffness or strength after 2 million cycles of fatigue loading in excess of the design wheel load.
- The failure onset of 133.5 kN (30,000 lb.) was almost four times the design wheel load of 35.5 kN (8,000 lb.) for the quarter portion of the bridge deck.
- Ultimate failure was non-catastrophic which has a safety benefit for civil engineering application.
- The EFPI sensor performance matched that of the conventional instrumentation and the embedded sensors provided reliable data past failure.

A smart composite bridge based on this approach was constructed on the University of Missouri-Rolla campus [11,24]. The final design differed only in the elimination of the upper transverse layer of tubes as a cost and weight-saving change. This prototype bridge, the first all-composite bridge in Missouri with a highway rating, is a long-term demonstration of FRP composite and sensor technologies and a field laboratory for smart structures courses and research. Field loading and associated finite element analysis will be reported in future papers.

## REFERENCES

- [1] American Society of Civil Engineers, "The 2001 Report Card for America's Infrastructure," ASCE, (2001). Available online WWW <http://www.asce.org/reportcard>.
- [2] A. J. Aref, and I. D. Parsons, "Design and Analysis Procedures for a Novel Fiber Reinforced Plastic Bridge Deck," *Advanced Composite Materials in Bridges and Structures*, CSCE, Montreal, Quebec, Canada, pp. 743-750, 1996.
- [3] V. M. Karbhari, F. Seible, G. A. Heigemier, and L. Zhao, "Fiber Reinforced Composite Decks for Infrastructure Renewal - Results and Issues," *Proceedings of International Composites Exposition*, Session 3-C, pp. 1-6, 1997.
- [4] A. H. Zureick, B. Shih, and E. Munley, "Fiber-Reinforced Polymeric Bridge Decks," *Structural Engineering Review*, vol.7, no.3, pp. 257-266, 1995.

- [5] J. D. Plunkett, "Fiber-Reinforced Polymer Honeycomb Short Span Bridge for Rapid Installation," *IDEA Project Final Report*, Contract NCHRP-96-ID030, National Research Council, 1997.
- [6] F. Seible, "US Perspective of Advanced Composites Bridge Technology in Europe and Japan," *Proceedings of Second International Conference on Composites in Infrastructure*, vol.2, pp. 605-636, 1998.
- [7] R. Lopez-Anido, P. A. Howdyshell, L. D. Stephenson, and H. V. S. Gangarao, "Fatigue and Failure Evaluation of Modular FRP Composite Bridge Deck," *Proceedings of International Composites Exposition*, Session 4-B, pp. 1-6, 1998.
- [8] D. C. Foster, G. C. Goble, J. L. Schulz, B. C. Commander, and D. L. Thomson, "Structural Testing of a Composite Material Highway Bridge," *Proceedings of International Composites Exposition*, Session 4-C, pp. 1-9, 1998.
- [9] M. Chajes, J. Gillespie, D. Mertz, and H. Shenton, "Advanced Composite Bridges in Delaware," *Proceedings of Second International Conference on Composites in Infrastructure*, Tucson, Arizona, vol.1, January 5-7, pp. 645-650, 1998.
- [10] D. Stone, A. Nanni, J. Myers, and S. E. Watkins, "Field and Laboratory Performance of FRP Bridge Decks," *CCC 2001 – International Conference on Composites in Constructions*, Porto, Portugal, 10-12 October 2001.
- [11] H. E. Nystrom, S. E. Watkins, A. Nanni, and S. Murray, "Financial Viability of Fiber Reinforced Polymer (FRP) Bridges," *Journal of Management in Engineering*, vol. 19, no. 1, pp. 2-8, 2003.
- [12] W. B. Spillman, Jr., "Sensing and Processing for Smart Structures," *Proc. IEEE*, vol. 84, no. 1, pp. 68-77, Jan. 1996.
- [13] S. E. Watkins, "Smart Bridges with Fiber Optic Sensors," *IEEE Instrumentation and Measurement Magazine*, vol. 6, no. 2, pp. 25-30, June 2003.
- [14] E. Udd, "Fiber Optic Smart Structures," *Proc. IEEE*, vol. 84, no. 6, pp. 884-894, June 1996.
- [15] F. Akhavan, S. E. Watkins, and K. Chandrashekhara, "Measurement and Analysis of Impact-induced strain using Extrinsic Fabry-Perot Fiber Optic Sensors," *Smart Materials and Structures*, vol. 7, no. 6, pp. 745-751, 1998.
- [16] J. S. Sirkis, "Phase-Strain-Temperature Model for Structurally Embedded Interferometric Optical Fiber Sensors with Applications," *SPIE Proc.*, 1588, pp. 26-43, 1991.
- [17] D. G. Lee, M. Mitrovic, A. Friedman, G. P. Carman, and L. Richards, "Characterization of Fiber Optic Sensors for Structural Monitoring," *Journal of Composite Materials*, vol. 36, no. 11, pp. 1349-1366, 2002.
- [18] A. E. Aktan, A. J. Helmicki, and V. J. Hunt, "Issues in Health Monitoring for Intelligent Infrastructure," *Smart Structures and Materials*, vol. 7, no. 5, pp. 674-692, 1998.
- [19] American Association of State Highway and Transportation Officials, "Standard Specifications for Highway Bridges", AASHTO, Washington D.C., Sixteenth Edition (1996).
- [20] J. W. Fonda and S. E. Watkins, "Embedded Fiber Optic Sensing for Bridge Rehabilitation," *16<sup>th</sup> World Conference on Nondestructive Testing*, Montreal, Canada, 30 Aug. – 3 Sept. 2004.
- [21] P. Kumar, K. Chandrashekhara, and A. Nanni, "Testing and Evaluation of Components for a Composite Bridge Deck," *Journal of Reinforced Plastics and Composites*, vol. 20, no. 5, 2002.
- [22] T. Yoshino, K. Kurasawa, and I. Katsuji, "Fiber-optic Fabry-Perot Interferometer and its Sensor Applications," *IEEE Journal of Quantum Electronics*, vol. 10, pp. 1624-1633, 1982.
- [23] K. A. Murphy, M. F. Gunther, A. M. Vengsarkar, and R. O. Claus, "Quadrature Phase-Shifted, Extrinsic Fabry-Perot Optical Fiber Sensors," *Optics Letters*, vol 16, no. 4, pp. 273-275, 1991.
- [24] S. E. Watkins, J. F. Unser, A. Nanni, K. Chandrashekhara, and A. Belarbi, "Instrumentation and Manufacture of a Smart Composite Bridge for Short-span Applications," *Smart Structures and Materials 2001*, *SPIE Proc.* 4330, pp. 147-157, 2001.