# Using Fiber-Optic Sensing Techniques To Monitor Behavior of Transportation Materials

JAMES M. SIGNORE AND JEFFERY R. ROESLER

Although not new to the communications or manufacturing area, fiber-optic sensors are only recently being applied to civil engineering structural evaluation. These sensors offer enormous potential within the transportation field to examine and characterize strain behavior in commonly used materials. Fiber-optic sensing research efforts conducted during the past 2 years on three materials relevant to the transportation industry are documented: portland cement concrete, steel, and asphalt concrete. Portland cement mortar beams were tested to determine the rate and magnitude of shrinkage. Impending fractures in steel structures may be avoided by real-time sensing, thereby minimizing potential safety problems. Steel beams were loaded to measure bending strains, as a precursor to beam crack detection. Finally the lateral strain behavior of axially loaded asphalt emulsion aggregate mixture (EAM) cylinders was studied. The EAM Poisson ratio was determined. Findings comparable with those calculated from theory, found in the literature, and obtained with traditional sensing techniques are presented. Whereas this fiber-optic sensing methodology offers great potential, the reliability and viability of this new measurement technique must be further assessed. This research advances the development and use of this innovative technology.

Although traditionally used for communications purposes, fiber optics show considerable promise as strain sensors. These sensors have been used primarily to evaluate composite materials (*1,2*). Progress is beginning to be made in the use of fiber-optic sensors in civil engineering. The evaluation of crack formation and propagation in concrete beams has also been researched (*3,4*). Stresses and strains present in concrete specimens under load were also investigated (*5–7*).

In this research, fiber-optic sensing techniques were used to test and characterize the behavioral properties of three transportation materials: portland cement concrete (mortar), steel, and asphalt emulsion aggregate mixtures (EAMs). The shrinkage strains associated with mortar beams, the bending strains of a loaded steel beam, and the lateral deformation of EAM cylinders subjected to compressive loads were studied. An additional intent of this research was to verify the viability of fiber-optic sensors in civil engineering.

## RESEARCH OBJECTIVE

The objective of this research was to use innovative fiber-optic sensing methods to evaluate nondestructively three transportation materials and to assess the practicality of using fiber-optic sensing techniques in this domain. Specifically the study objectives were to

- Determine the total amount (and rate) of internal shrinkage strain that a mortar beam undergoes at certain critical points in its cross section during the curing process.
- Determine bending strains within a steel beam subjected to load.
- Determine the lateral strain associated with rutting and fatigue evaluation that EAM cylinders undergo when subjected to static compressive loads.

## EXPERIMENTAL PROGRAM

This research involved blending several engineering disciplines. To ensure that the sensors were accurately evaluating the material characteristics, knowledge of optical fibers and the host materials is necessary. Brief descriptions of pertinent background information and the procedures followed in this study are presented to help the reader understand fiber-optic sensing methodologies.

### Optical Fibers as Strain Sensors

#### *Basics*

Optical fibers consist of a central core and cladding surrounded by a protective jacket (Figure 1). The core and cladding are typically silica glass, and the jacket is usually a polymeric material. In manufacture of the fiber, the core and cladding are drawn together as a filament from a single piece of molten glass called the preform. This preform is an enlarged version of the fiber that exhibits the same general physical properties as those desired in the final product. The cladding is doped with trace elements or impurities to give it a higher index of refraction than the core, which allows for light transmission through the core via total internal reflection as shown in Figure 1. The polymeric (or other material, such as metal or ceramic) jacket is applied to the fiber after it is drawn from the preform and provides protection to the core and cladding.

The light that propagates through the fiber is sent by a laser or light emitting diode and detected by a photodetector. Associated peripheral electronics adjust the laser output and process the signals produced by the photodetector. By analyzing the signal outputs, fiber strains and host material changes can be determined.

---

Civil Engineering Department, University of Illinois at Urbana-Champaign, 1208 NCEL, MC–250, Urbana, Ill. 61801.

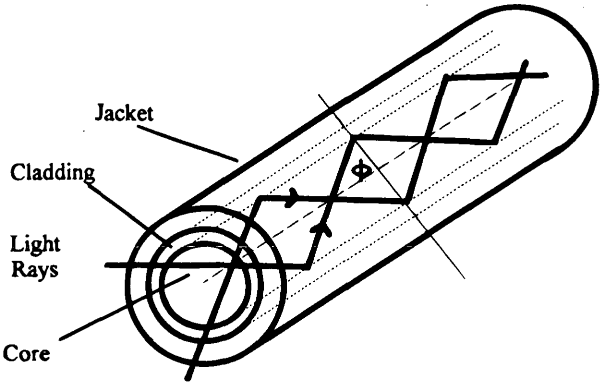

**FIGURE 1 Optical fiber and light transmission.**

### *Issues and Concerns*

Three issues dealing with the use of fiber optics as sensors need to be addressed. These issues are often ignored or assumptions are made to minimize their influence in previous literature. The first issue is the potential for slippage or loss of bond at the core or cladding and jacket interface. The core or cladding is the active sensing region of the fiber, and any slippage with the jacket will result in erroneous test data because the jacket is bonded to the host material. Tests performed in this study confirmed that there is adequate bond present to assume a full bond. This assumption implies that any strain transferred to the jacket along the fiber length must also be transferred to the glass core. Concerns have arisen in the literature about the capabilities of given jacket materials to transfer stresses and strains adequately; hence the proper choice of jacket material is important (*8*).

The second issue is the bond between the fiber jacket and the host material. For this research, adequate bond between the fiber and concrete matrix, fiber and steel, and fiber and asphalt must be present. One approach taken to ensure that adequate bond exists is to use a cement paste coating on the fiber before embedding it into the concrete (*4*). Most of the remaining literature on the subject does not address this issue. In early attempts it was difficult to obtain consistent and reliable bond between the optical fiber and the mortar, thereby yielding errant results. A novel technique was developed to ensure bond between the fiber and the mortar, resulting in a dramatically increased repeatability and consistency of results. Beads of epoxy were formed along the length of the fiber to protrude into the mortar matrix similar to deformed rebars (Figure 2). This ensured a strong bond between the mortar and the fiber so that strain could be transferred to the fiber jacket without slip between the mortar and the fiber jacket. Fortunately, the loss of bond in localized areas is not critical to measuring the total strain.

For bonding to the steel beams and EAM specimens, a combination of surface roughness and selected epoxies were used to ensure ample bonding. Previous experimentation with various epoxies and host material surface conditions provided the knowledge of which epoxies and surface conditions result in the most accurate and consistent measurement values.

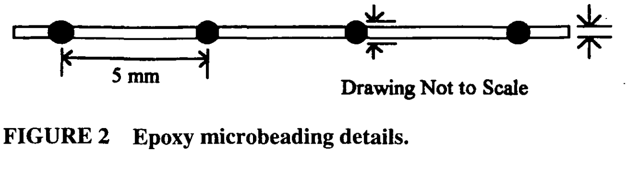

**FIGURE 2 Epoxy microbeading details.**

The third issue deals with fiber-optic survivability under demanding conditions. Although this study consisted of laboratory experiments, appropriate fiber materials that can withstand harsh environments such as temperature extremes, moisture, and dynamic or static fatigue as well as ways to best protect the fibers from impact damage were investigated. Some existing literature deals with these concerns because fiber failure is a major concern in the telecommunications industry as well as in sensor development (*9,10*).

### *Sensing Techniques*

Several different methods of fiber-optic sensing are now in use. One method is monitoring light polarization, which deals with examining the character of the light as it progresses through a fiber (*11*). As a fiber is stressed transversely, the fiber deforms and the relative polarization of the light changes locally. These changes can then be correlated to the applied pressures. Another technique measures the relative phase of light waves exiting a fiber (*11*). The phase change experienced by the light, as a result of fiber perturbation, is indicative of the strain experienced by the fiber. In addition, changes in the intensity of light propagating through a fiber indicate the degree of stress, strain, or bending within a fiber (*5*). Light intensity diminishes as fibers are bent into curves or are stressed transversely. This decrease in light output can then be correlated to material deformations. In optical time domain reflectometry (OTDR), the relative transit times for light sent through a fiber are monitored, and time changes are indicative of fiber strain (*12*). An OTDR may also be used to measure light intensity.

Because the primary concern in this study was to determine length changes, OTDR was the most applicable and practical technique to use. The instrument used was a very high-speed, high-resolution OTDR that could measure fiber length changes or locate fiber breaks to within 0.1 mm. The OTDR injects a laser pulse into a fiber and detects changes in laser pulse transit time through a fiber that has experienced strain or refractive index change, whether by applied load or temperature change (*12*). These changes in light transit time are converted into length changes by accounting for the speed of light, temperature variation, and material density changes. Note that the density of the core increases during shrinkage and decreases during elongation. This density change affects the speed of light within the fiber, which can then be related to shrinkage or bending strain. Light travels at a speed of $c/n$ through the fiber, where $n$ is the index of refraction of the fiber, typically around 1.5, and $c$ is the speed of light (3E8 m/sec). This research graded index used multimode fibers with a 100-micron core diameter and 140-micron cladding diameter. The graded index of refraction profile of the fiber core minimizes light pulse dispersion by progressively slowing down the light as it nears the fiber core axis. This enables the light, which travels along many reflected paths within the fiber, to arrive at the fiber end more coherently.

Two OTDR sensing techniques were used in this research. The first sensing technique used in this research was far-end reflection time measurement, as illustrated in Figure 3. Light was sent through the fiber under test, and the time it took to traverse the fiber and return to the detector was noted. Subsequent readings were taken, and changes in this "transit time" due to perturbations of the material under test reflected changes in fiber/beam length. An increase

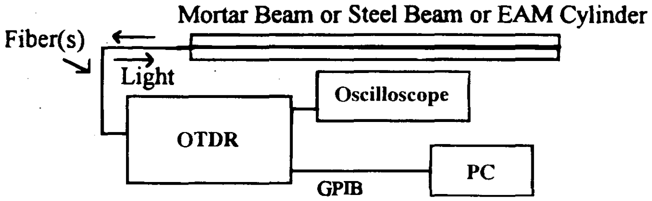

**FIGURE 3** **Original test setup.**

in transit time would reflect a corresponding increase in fiber length and therefore material strain.

The second sensing technique used was a more elaborate technique known as "fiber re-entrant loops" (*12*) (Figure 4). As in previous experiments, the fiber was inserted longitudinally through or around the specimen, but this time the laser sensing pulse was circulated through the fiber many times via a fiber coupler. An important benefit of this technique was that, because the accuracy of the sensing equipment was limited for a given gauge length, increasing the gauge length increased the strain resolution. In the re-entrant loop technique, each circulation effectively increased the sensing length by an additional beam length or EAM specimen circumference. For example, five circulations afforded a fivefold increase in strain resolution over the far end reflection technique.

## Fiber-Optic Sensing Studies and Discussion

### *Concrete Shrinkage*

Concrete shrinkage typically presents an unpredictable and undesirable problem during the design and construction of concrete structures such as buildings and pavements. Concrete maturity and overall shrinkage vary widely depending on the curing conditions and type of mixture. Although the shrinkage characteristics of concrete measured at the surface have been extensively reported in the literature (*13–19*), the measurement of the internal shrinkage of concrete has been limited (*20*) and lacks conclusive results. Having the capability to know a priori the internal shrinkage for a given mixture and curing conditions would be an extremely valuable tool for the design engineer. This information could be used to better understand crack formation in concrete and how to control this problem.

Sixteen concrete beams were produced for this experimental study. The specimens were made of mortar paste consisting of Type I cement, sand, and water at a weight ratio of 1:1:0.4. The fineness modulus of the sand was 2.55. The beams were 760 mm (30 in.) long with 50 mm (2 in.) by 50 mm (2 in.) square cross sections. Precision forms were made to ensure that the fibers were placed exactly along the axis of each beam at three locations in the beam cross section. The outside fibers (A and C) were 12 mm (0.5 in.) from the edge and centered in the vertical direction, and the third fiber (B) was placed exactly in the center of the beam (Figure 5). The specimens were removed from the forms 24 hr after casting. Baseline readings were then taken, and the specimens were placed in a controlled environment at 55°C (130°F) and less than 10 percent relative humidity to facilitate shrinkage.

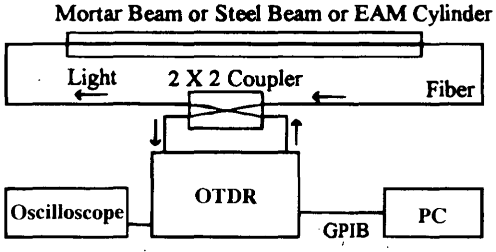

**FIGURE 4** **Re-entrant loop setup.**

Two different methods were investigated to ensure correct fiber placement within the beams. The first method was to feed the fiber through a long hypodermic steel tube placed within the mortar (*21*). Once the fiber is fed through the tube, the tube is carefully pulled out. The second method developed as part of this research was to place the mortar around pretensioned fibers and then thoroughly vibrate the form to promote bond between the mortar and the fibers (Figure 6).

Pull-out tests performed on the beams indicated that the tensioning method was preferred over the hypodermic steel tube. The bleeding effect seen around the void left by the steel tube resulted in weak, unbonded spots along the fiber. The second method, although more difficult and fiber-breakage prone, yielded solid and continuous bonds in this experiment. It was realized that in situations with larger aggregate concrete the tensioning method was preferable if good bond could somehow be ensured. These tests were performed before developing the epoxy microbead procedure, so either of the procedures could have been implemented in this study.

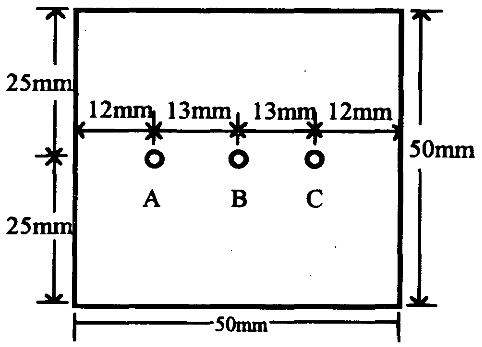

**FIGURE 5** **Mortar beam cross section.**

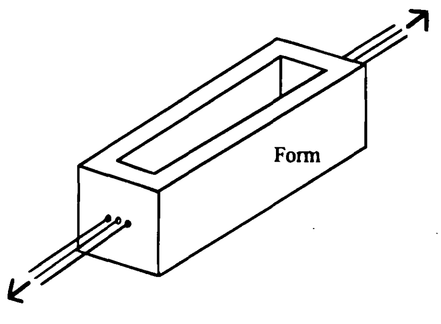

**FIGURE 6** **Fiber placement and tensioning.**

With these fibers placed longitudinally along the entire length of the beam, the total strain in the beam could be determined. A major advantage of this technique was that the entire beam length was the gauge length. Attempts have been made to evaluate internal shrinkage by using embedded strain transducers. However, the intrusive wires and gauges only give values of local shrinkage over a minimal gauge length, not of regional or total deformations (*20*). Concrete surface shrinkage can be determined relatively easily using commonly available gauges; however, correlation of internal shrinkage from surface shrinkage is not an accurate approach. To date, this approach has met with limited success because the free surface boundary conditions cause moisture loss associated with plastic shrinkage, whereas internal shrinkage (drying shrinkage) is attributed to loss of interlayer water in the cement paste (*15*).

The magnitude of the ultimate shrinkage for each of the 16 beams tested is presented in Table 1. The values shown are the average readings from the three fibers embedded in each beam. As was typical in dealing with mortar, there was variation in the ultimate shrinkage. This variation typically was no more than 15 percent from the mean and followed no particular trends. Figure 7 shows a representative plot of shrinkage versus time. Fibers A and C are those fibers located 12 mm (0.5 in.) from the edge of the beam, and fiber B is the center fiber. The internal shrinkage strains shown are similar to results obtained in other experiments (*14*). The shrinkage results also appear realistic as a function of time. Mortar shrinkage was found to be 0.2 to 0.3 percent at a relative humidity of less than 20 percent and determined an ultimate shrinkage at 0 percent relative humidity of 0.32 percent (*14*). In this study, a mean shrinkage of 0.25 percent (2,517 microstrain) was determined (Table 1). Discrepancies can be attributed to the use of a lower water-to-cement ratio in this experiment and that surface shrinkage was measured with a dial gauge comparator (*14*).

The shrinkage at the center of the beam can be compared with that nearer the edge. As expected, the internal shrinkage at the center was less than that at the edges. The outside two fibers (A and C) showed similar results throughout the experimental program. It is well-known that the specimen size and shape affect the measured ultimate shrinkage of concrete, especially when the dimensions are less than 100 mm (4 in.) (*16,17*). Although the specimen cross section used in this study was only 50 mm (2 in.) by 50 mm (2 in.), the results shown in Figure 7 show that there is a difference between internal and near-surface shrinkage in the mortar beams. These preliminary results indicate the possibility of a moisture gradient present in the mortar.

**TABLE 1** **Mortar Beam Shrinkage Results Summary**

| Beam # | Ultimate Shrinkage Average of 3 Fibers (Microstrain) |
|---|---|
| 1 | 2300 |
| 2 | 3100 |
| 3 | * |
| 4 | * |
| 5 | 2000 |
| 6 | 1900 |
| 7 | 2800 |
| 8 | 2900 |
| 9 | 2700 |
| 10 | 2700 |
| 11 | 2300 |
| 12 | 2000 |
| 13 | 2800 |
| 14 | 2800 |
| 15 | 2200 |
| 16 | 2000 |
| **Mean** | **2517** |
| Standard Dev. | 405 |

### *Steel Bending Strain*

Structural members weakened through deterioration pose a safety problem for state and federal highway agencies. As the design lives of bridges are reached or exceeded, early detection of structural weaknesses that result in increased failure potential become more critical. Detection of strained or cracked members before their structural usefulness diminishes to the point of bridge collapse could be an enormous benefit in terms of lives and dollars saved. Research is underway to evaluate procedures for sensing strains and crack formation in reinforced concrete structures (*22,23*) and bridges (*24*). The goal of this research is to measure bending strains in loaded steel beams.

Optical fibers were affixed to a steel beam, which was then loaded for the purpose of measuring bending strains. For initial assessment of the sensing capability, a simply supported beam configuration was used (Figure 8). The beam was 9.5 mm (0.375 in.) thick by 51 mm (2 in.) wide, with a span of 2.2 m (88 in.). The fibers were epoxied onto the tensile side of the beam. Three strain gauges were added at the L/4 points of the beam for additional verification of the bending strains.

For various loads, bending strains were measured. The fiber-optic sensing system was able to detect the integrated or total strain along the entire beam. This measured strain was compared with beam theory predictions and the readings from the strain gauges on the beam. Typical test results are shown in Figure 9. Predictions within 5 percent of theoretical predictions were common for small strains with slight decreases in accuracy at much higher strains. However, both the optical-fiber system and resistive strain gauges produced comparable results throughout the study. Of note is that the test results show linear strain behavior similar to that theoretically predicted and shown by the strain gauges. Additional refinement of the measurement and bonding techniques are underway to further increase accuracy. A significant outcome of this study was that fiber-optic sensing techniques were extremely repeatable, with minimal variation between readings.

To fully use these sensors in a field environment, suitable epoxies or fiber bonding methods, or both, that can withstand harsh weather conditions are necessary. Methods of isolating or protecting the fibers from impact damage are also needed. The fibers must be capable of functioning under severe conditions, such as fatigue and temperature cycling. To implement a real-time sensing system on a field structure, there must be a monitoring system that includes a signal to indicate whether a structural problem exists. Each of these system concerns is under investigation.

### *Asphalt EAM Deformation*

Much of the knowledge about EAM behavior is based on simple mechanical measurements. Knowledge of the lateral straining char-

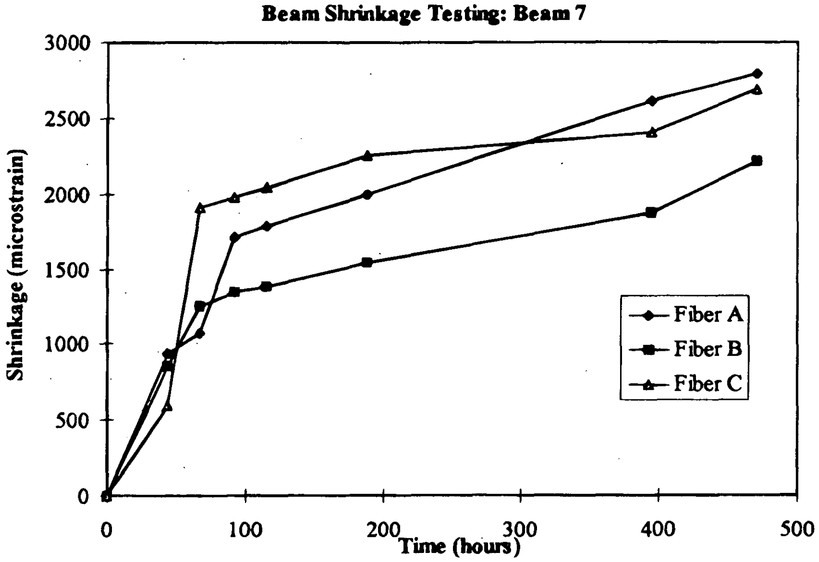

**FIGURE 7 Representative shrinkage plot.**

acteristics of EAM under load is an important feature in assessing the rutting and fatigue performance of the material. In this research, fiber-optic methods were used to determine the Poisson ratio (horizontal strain/vertical strain) for EAM samples.

The testing of EAM specimens with fiber-optic sensors is a completely new concept, and this study is the first such application the authors have found on this subject. Fibers were affixed about the perimeter of the cylindrical samples, and the subsequent circumferential deformation of the sample under load was measured. Figure 10 illustrates the setup for this test. The samples under test were 305 mm (12 in.) long with a diameter of 152 mm (6 in.). Only static loading of the sample was evaluated. It is hoped that the behavior under dynamic loading can be addressed as the fiber-sensing technique develops.

The Poisson ratio was determined by relating the horizontal and vertical strain in the material. Unlike current methods used to measure horizontal deformation, which only assess the deformation in one plane, the fiber sensor allows for a complete assessment of horizontal deformation entirely around the sample. For these tests, vertical deformations were incremented in 1.25 mm (0.05 in.) steps and were limited to 6mm (0.25 in.) to maintain linear elastic behavior in the specimen. Vertical and horizontal strains were recorded at each increment. The experimentally determined Poisson ratios were 0.44 for the first sample and 0.35 for the second sample. Although these measured Poisson ratios are not exact, they are close to the accepted values of 0.40 ± for EAM specimens. The test procedure was simple to conduct.

## FIBER OPTICS VERSUS TRADITIONAL SENSORS

This paper has shown that fiber-optic sensors can give comparable results to existing measurement techniques, such as strain gauges. The use of fibers to directly measure total internal strains and strains in large structures has promise because global estimates are not extrapolated from local measurements. Fiber optics have proved their viability in the laboratory as a research tool. However, fiber-optic sensing is delicate, and there is only limited structural application, much of which has inconclusive results. This sensing technique is presently impractical for widespread field use because of the cost of the equipment and peripheral items. As technology progresses, along with the use of other less expensive techniques, fiber-optic sensing should become competitive.

## SUMMARY AND CONCLUSIONS

Research efforts using fiber-optic sensing procedures in the civil engineering field are just beginning. These sensors offer great potential for evaluating commonly used transportation materials and structures in a nondestructive manner. In this study, the strain characteristics of cement mortar beams, steel beams, and emulsion aggregate mixtures were examined with success. This research has shown that fiber-optic sensors produce repeatable and accurate measurements under a variety of conditions. The test results compare favorably with existing techniques. Fiber-optic sensors also

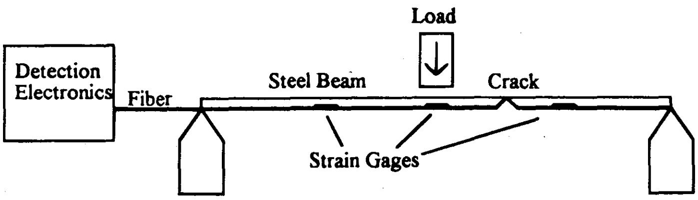

**FIGURE 8 Typical steel beam testing configuration.**

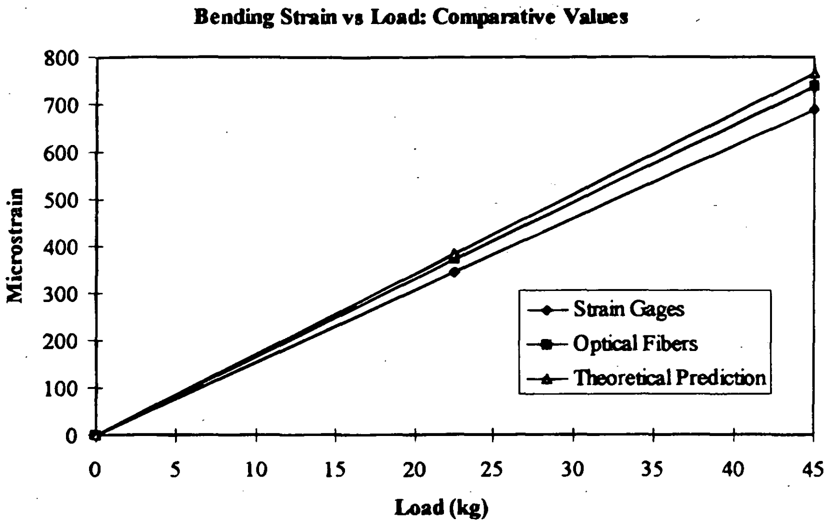

FIGURE 9 Steel beam bending strain.

offer the advantages of being immune to electromagnetic interference and can measure total or integrated strain as well as point strain. To fully use the capability of these sensors, however, further work must be performed relating to long-term sensor reliability and survivability.

The internal shrinkage of mortar beams was monitored. Methods were developed to ensure that the measured internal shrinkage strains were accurate through a full bond between the mortar and the optical fiber, and the fiber core and the jacket. The shrinkage strains measured for the mortar specimens of 0.25 percent were similar to results reported in the literature. It was shown that the use of fiber-optic sensors may be used internally in a cement-based material to provide excellent real-time results.

Fiber-optic sensors were applied to steel beams to sense bending strains due to static loads. The results were both accurate and consistent. Research efforts on larger-scale projects that would include crack detection would be an important next step. Eventually with refinement, this technique should allow for real-time monitoring of high-risk field structures, statically and dynamically.

The first use of fiber-optic sensors on EAM samples resulted in the measurement of Poisson's ratio. This technique may be used to further corroborate mechanically derived Poisson values. The results of these initial tests indicate that further research toward additional applications is promising.

These positive research findings suggest that fiber-optic sensors have many applications in civil engineering. Examples of possible

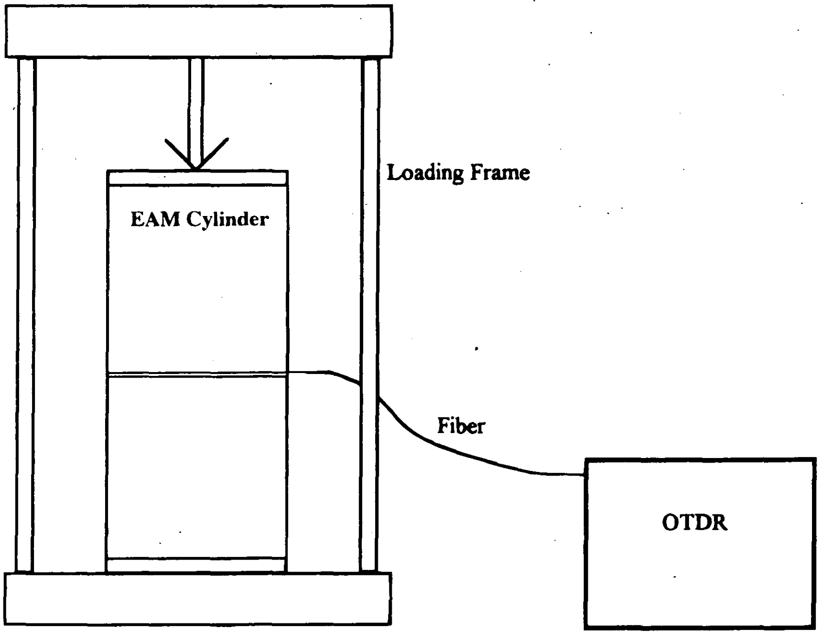

FIGURE 10 EAM deformation testing.

applications include long-term concrete shrinkage and creep monitoring, concrete and steel crack initiation and propagation, and monitoring the growth of the fracture process zone. In addition, real-time information on static and dynamic loading and displacements of in situ structures, such as buildings and pavements, may be obtained.

## ACKNOWLEDGMENTS

This project was funded through a research grant from the Association of American Railroads. The authors would like to thank Basors Barry Dempsey, Ernest Barenberg, and David Lange of the Civil Engineering Department of the University of Illinois for their consultations during this research.

## REFERENCES

1. Claus, R. O., K. D. Bennett, A. M. Vengsarkar, and K. A. Murphy. Embedded Optical Fiber Sensors for Materials Evaluation. *Journal of Nondestructive Evaluation*, Vol. 8, No. 2, 1989, pp. 135–145.
2. Meisseler, H. J., and R. Wolff. Experience with Fiber Composite Materials and Monitoring with Optical Fiber Sensors. *Proc., Advanced Composite Materials in Civil Engineering Structures*, ASCE, 1991, pp. 167–181.
3. Rossi, P., and F. LeMaou. New Method for Detecting Cracks in Concrete Using Fiber Optics. *Materials and Structures (RILEM)*, Vol. 22, No. 122, Nov. 1989, pp. 437–442.
4. Ansari, F., and R.K. Navalurkar. Kinematics of Crack Formation in Cementitious Composites by Fiber Optics. *Journal of Engineering Mechanics, ASCE*, Vol. 119, No. 5, May 1993, pp. 1048–1061.
5. Nanni, A., C. C. Yang, K. Pan, J. Wang, and R. Michael. Fiber-Optic Sensors for Concrete Strain/Stress Measurement. *ACI Materials Journal*, May-June 1991, pp. 257-264.
6. de Vries, M., M. Nasta, and R. Claus. Fatigue Loaded Fiber Optic Strain Gages Performance in Reinforced Concrete Structures, prepublication from authors, 1993.
7. Huston, D., P. Fuhr, P. Kajenski, and D. Snyder. Concrete Beam Testing with Optical Fiber Sensors. *Nondestructive Testing of Concrete*, pp. 61–69.
8. Dasgupta, A., and J. S. Sirkis. Importance of Coatings to Optical Fiber Sensors Embedded in 'Smart' Structures. *AIAA Journal*, Vol. 30, No. 5, May 1992, pp. 1337–1343.
9. Saifi, M. A. Long-Term Fiber Reliability. *Fiber Optic Reliability: Benign and Adverse Environments IV*, SPIE Vol. 1366, 1990, pp. 58–70.
10. Biswas, D. R. Strength and Fatigue of Optical Fibers at Different Temperatures. *Fiber Optic Reliability: Benign and Adverse Environments IV*, SPIE Vol. 1366, 1990, pp. 71–76.
11. Grossman, B., T. Alavie, F. Ham, J. Franke, and M. Thursby. Fiber-Optic Sensor and Smart Structures Research at Florida Institute of Technology. *Fiber Optic Smart Structures and Skins II*, SPIE Vol. 1170, 1989, pp. 123–135.
12. Zimmermann, B. D., R. O. Claus, D. A. Kapp, and K. A. Murphy. Fiber-Optic Sensors Using High-Resolution Optical Time Domain Instrumentation Systems. *Journal of Lightwave Technology*, Vol. 8, No. 9, Sept. 1990, pp. 1273–1277.
13. Bryant, A. H., and C. Vadhanavikkrt. Creep, Shrinkage-Sized, and Age at Loading Effects. *ACI Materials Journal*, Vol. 84, No. 2, March-April 1987, pp. 117–123.
14. Hansen, W., and J. A. Almudaiheem. Ultimate Drying Shrinkage of Concrete-Influence of Major Parameters. *ACI Materials Journal*, Vol. 84, No. 3, May-June 1987, pp. 217–223.
15. Mindness, S., and J. F. Young. *Concrete*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1981.
16. Almudaiheem, J. A., and W. Hansen. Effect of Specimen Size and Shape on Drying Shrinkage of Concrete. *ACI Materials Journal*, Vol. 84, No. 2, March-April 1987, pp. 130–135.
17. Kraai, P. P. Proposed Field Test for Drying Shrinkage of Concrete. *Concrete Construction*, Vol. 29, July 1984, pp. 663–665.
18. Smadi, M. M., F. O. Slate, and A. H. Nilson. Shrinkage and Creep of High, Medium, and Low Strength Concretes, Including Overloads. *ACI Materials Journal*, Vol. 84, No. 3, May-June 1987, pp. 224–234.
19. Bazant, Z. P., F. H. Wittmann, and J. K. Kim. Statistical Extrapolation of Shrinkage Data. *ACI Materials Journal*, Vol. 84, No. 1, Jan.-Feb. 1987, pp. 20–34.
20. Chaallal, O., B. Benmokrane, and G. Balling. Drying Shrinkage Strains: Experimental Versus Codes. *ACI Materials Journal*, Vol. 89, No. 3, May-June 1992, pp. 263–266.
21. Mendez, A., and T. F. Morse. Overview of Optical Fiber Sensors Embedded in Concrete. *Fiber Optic Smart Structures and Skins V*, SPIE Vol. 1198, 1992, pp. 123–136.
22. Ansari, F. Nondestructive Testing of Concrete: Real-Time Condition Monitoring of Concrete Structures by Embedded Optical Fibers. In *Nondestructive Testing of Concrete Elements and Structures*, 1992, pp. 49–59.
23. Wolff, R. Applications with Optical Fiber Sensor Systems for Monitoring Prestressed Concrete Structures. *Structures Congress Abstracts*, American Society of Civil Engineers, 1990, pp. 94–95.
24. Miesseler, H., and R. Lessing. Monitoring of Load Bearing Structures with Optical Fiber Sensors. *Proc., IABSF Symposium*, 1989, pp. 853–858.

---

*Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.*