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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report of Investigation

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Development of a Novel Fiber-Optic Strain Sensor System for Long-Term Monitoring of Highway Structures

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PREFACE

This Final Report describes the work conducted under the National Cooperative Highway Research Program (NCHRP) entitled "Development of a Novel Fiber-optic Strain Sensor System for Long-term Monitoring of Highway Structures." Funding for this program was supplied by the Transportation Research Board (TRB)/National Research Council (NRC) under Contract NCHRP-94-ID024. This contract was administered by the TRB/NRC in Washington, D.C., under the technical direction of Dr. K. Thirumalai, Dr. Inam Jawed, and Dr. Selwyn Berg. The contract was performed by Simula Government Products, Inc., of Tempe, Arizona, and Arizona State University, of Tempe, Arizona. Dr. Ken-An Lou served as Principal Investigator, and Mr. Bernd Zimmermann and Dr. Apostolos Fafitis served as Co-Principal Investigators.

DEVELOPMENT OF A NOVEL FIBER-OPTIC STRAIN SENSOR SYSTEM FOR LONG-TERM MONITORING OF HIGHWAY STRUCTURES

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EXECUTIVE SUMMARY

The project investigated the feasibility of a fiber-optic (FO) strain sensor system for long-term monitoring of highway structures.

The principle of operation relies upon measuring the time-offlight of an optical signal's propagation through an optical fiber and then converting it to mechanical strain. By segmenting an optical fiber string with optical reflectors, the strain of in-line segments can be determined separately. This method enables strain mapping of an entire structure with a finite-element sensor grid and is capable of deleting localized damage such as cracking and stress corrosion. The monitoring system includes a custom-built high-resolution optical time domain reflectometer (OTDR), dedicated FO data acquisition (FODAC) software, and novel FO strain gauge patches (FOSGPs), which allow monitoring of integral strain in large structures (Figure 1). The FOSGPs are flexible sensor patches that can be embedded in or attached to the structure to be monitored.

The FOSGP are inherently resistant to corrosion, can measure integral strain over discrete segments of a structure, may only be accessed at one end, and can be multiplexed in-line to interrogate multiple sections of the structure. The FO sensor approach is immune to electromagnetic interference (EMI), allows remote monitoring without requiring on-site personnel, and can be implemented as both an embedded and a surface-attached device.

The novel FOSGP includes an optical fiber with two reflective markers at a predetermined distance along its length and two thin layers of carrier material. The optical fiber, with its reflective markers, is formed into several loops and sandwiched between the two carrier layers. The multiple loops increase the sensitivity and accuracy over those of single-path sensors. The carrier layers can either be cured in situ within the structure (e.g., when used with composite materials) or can be precured and then embedded into or attached to the structure to be monitored.

The FOSGPs were developed and design parameters were optimized. Data acquisition software was also developed. Steel and composite coupons with attached or embedded FOSGP's were tested for strain. Results showed that using latest optical time domain reflectometer (OTDR), the FOSGP sensors achieved a resolution of 0.01 percent strain and could resolve tensile strain in reinforced concrete just before the failure due to fracture. The data also suggests that FOSGP sensors will be most successful at detecting strain in concrete structures if placed in compression locations.

The sensitivity of the FOSGP sensor appears to be limited by the OTDR system. Also, the potential to multiplex patches in-line (to interrogate multiple locations) was limited because of increased attenuation the FO sensors by the glass-reinforced epoxy carrier material. The fiber-optic leads were found to be too delicate to be embedded in concrete. For the time delay strain measurements to be practical for structural monitoring, OTDR accuracy must be improved to at least better than 3.0 ps. This time resolution is needed to give a strain resolution of 5 with a 10-m patch. The smaller 3-m patches may be multiplexed, but would require OTDR with a resolution of better than 1.0 ps. The sensors appear to be most successful at detecting strain if placed at compression locations on concrete structures. The final task involved long-term monitoring under field conditions. A 10-foot fiberglass composite I-beam and a 12-ft. full-scale concrete beam were instrumented with FOSGP and conventional sensor systems and set up outdoors under natural environmental conditions for long-term monitoring. Because of the limitations of the current OTDR system in achieving accurate measurements and the limitations of the type of optical fiber used in the concrete environment, no field demonstrations were conducted.

INTRODUCTION

BACKGROUND

The civil engineering community has recently been expressing the need for a novel approach to monitor strain within large structures such as bridges, dams, buildings, and pipelines. A large number of these structures are in imminent danger of failure due to aging, or they may show signs of potentially dangerous fatigue in the near future. Many U.S. bridges, for example, have been identified as structurally deficient. The Civil Engineering Research Foundation (CERF), which recently evaluated the status of infrastructure in the United States, set the number of deficient bridges in the United States at more than 75,000. The cost of repair and/or replacement of these bridges was estimated at over $70 billion. The immediate development and commercialization of high-performance materials, processes, and instrumentation to replace, restore, and monitor infrastructure was recommended to minimize or avoid any additional accidents involving civil structures. Furthermore, advanced sensor systems that can provide on-line information on the integrity of civil structures are required.

Conventional sensors, i.e., electro-resistive strain gauges, have been used to measure strain, but they are limited by their susceptibility to corrosion, their capability of providing "point" measurements only, and the necessity of running several wires for each strain gauge site. Nonetheless, electro-resistive strain gauges are being used in laboratory experiments to measure the mechanical behavior of highway structures such as steel-reinforced concrete beams and struts. Experience from this type of work has shown that hundreds of strain gauges using cumbersome wiring are required to instrument these structures and allow an understanding of their static and dynamic responses. Furthermore, experience has also shown that the implementation of conventional strain gauges in real-life highway applications is not very practical.

The development of an advanced strain sensor system which is highly resistant to corrosion and is capable of performing "integral" strain measurements, i.e., capturing damage such as cracking over a wide area. Simula Government Products, Inc., has developed a novel fiber optic (FO) strain sensor system for long-term monitoring of highway structures. The system utilizes novel FO strain gauge "patches," is inherently resistant to corrosion, measures integral strain over discrete segments of a structure, only needs to be accessed at one end, and is multiplexed in-line to interrogate multiple sections of the structure. Furthermore, the FO sensor approach is immune to electromagnetic interference (EMI), allows remote monitoring without requiring on-site personnel, and can be implemented as both an embedded and/or a surface-attached device. The system's principle of operation relies upon measuring the time-of-flight of an optical signal propagating though an optical fiber, and converting it to a mechanical strain value. By segmenting a FO string with optical reflectors, the strain of in-line segments can be determined separately. This method enables the strain-mapping of an entire structure with a finite-element sensor grid.

The ultimate goal of this program is to develop a FO strain sensor system which utilizes novel FO strain gage patches for long-term health monitoring of highway structures. This report documents the development efforts to demonstrate concept feasibility and validate the methodology of the FO strain gauge system.

PROGRAM OBJECTIVES AND APPROACH

Five main objectives were established for the program. They were:

- Develop prototype ruggedized FO strain gage patches for embedded and surface-attached applications
- Characterize prototype FO strain gage patches for composite and steel specimens
- Fabricate and instrument representative bridge components with FO strain gage patches
- Conduct preliminary proof-of-concept tests to evaluate the performance of the FO strain gage patches
- Conduct a field demonstration of the FO strain gage patches.

To accomplish the objectives, the program was conducted in five main tasks:

- Task I - Design and Fabricate Prototype FO Strain Gage Patch Sensors
- Task II - Test and Calibrate Prototype FO Strain Gage Patch Sensors
- Task III - Fabricate Beams with Embedded and Surface-attached FO Strain Gage Patch Sensors
- Task IV - Conduct Preliminary Proof-of-Concept Tests to Evaluate the Performance of the FO Strain Gage Patch Sensors
- Task V - Conduct a Field Demonstration of the FO Strain Gage Patch Sensors.

IDEA PROJECT INVESTIGATIONS AND PROGRESS

TASK I - DESIGN AND FABRICATE PROTOTYPE FO STRAIN GAGE PATCH SENSORS

FO Strain Gage Patch Design

A graded-index multi-mode 100/140-μm core/cladding diameter silica fiber manufactured by Spectran Corporation with a 170-μm-diameter polyimide coating was chosen as the sensor fiber. Each FO strain gage patch fabricated during this program contained two reflective optical markers. Each marker contained of a physical interruption of the optical fiber achieved by cleaving and re-aligning the fiber. The dimensions of the marker were 1.3 cm in length and 0.75 mm in diameter (see Figure 1). These two markers were spaced 3 m, 5 m, or 10 m from each other, defining the length over which strain would be measured. The FO strain gage patch involved multiple fiber paths through each sensing region. A typical configuration of a 3-m FO strain gage patch is shown in Figure 2. In addition to the length between two markers, the design parameters for the FO strain gage patch also included the length and width of the patch, the minimum radius of the optical fiber, the number of optical fiber loops, and the gap between two adjacent optical fiber loops.

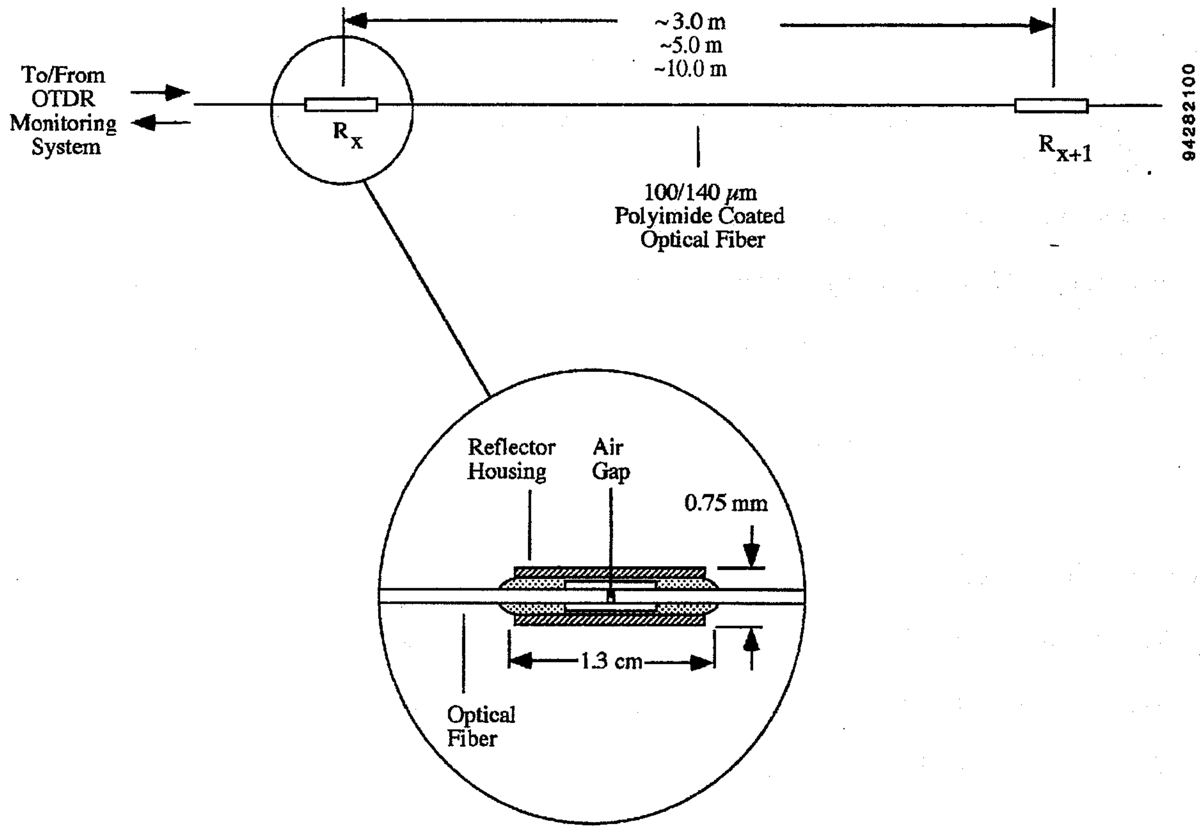

FIGURE 1 Schematic of FO sensor to be wound within FO strain gage patch.

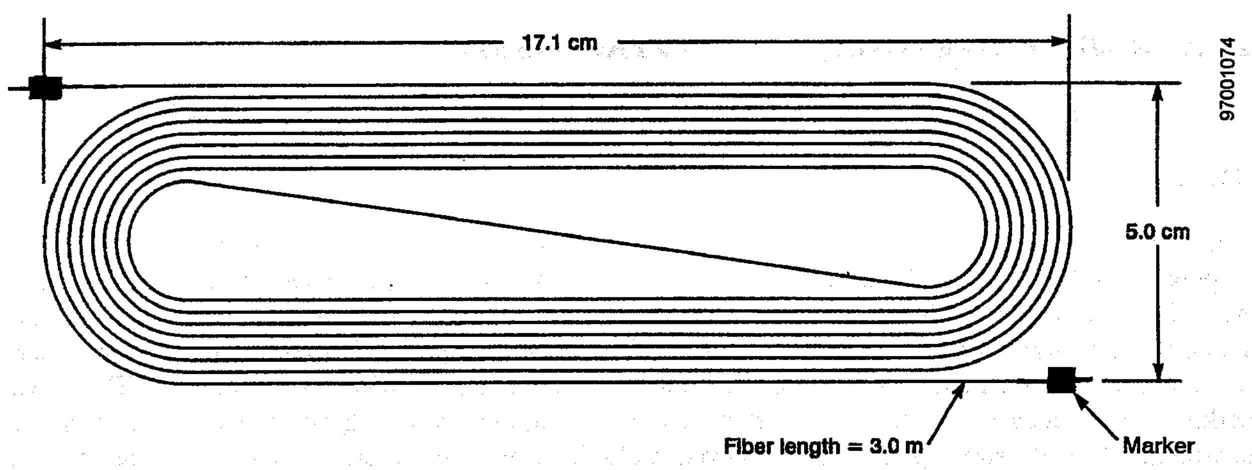

FIGURE 2 FO strain gage patch.

FO Strain Gage Patch Fabrication

The optical fibers are placed between two flexible layers of glass-reinforced epoxy carrier material. Fabrication of a patch involves laying the optical fiber strain sensor in a precise pattern on a thin sheet of glass-reinforced epoxy. The adhesion of the epoxy holds the sensor in place until the arrangement is complete. Then a second epoxy sheet is placed on top of the first, encasing the optical fiber in composite material. The FO lead that exits the patch is covered with furcation tubing to provide strain relief at the exit point and protect the lead fiber from damage. A bayonet-type connector can be added to the end of the lead fiber to provide a quick connection to monitoring equipment. The completed patch can be cured alone for surface-attachment applications or embedded in a composite part and cured simultaneously with the embedding structure.

TASK 11- TEST AND CALIBRATE PROTOTYPE FO STRAIN GAGE PATCH SENSORS

Theory and FO Monitoring System

Optical time domain reflectometry (OTDR) is a versatile method of measuring FO characteristics as a function of distance. In an OTDR system, light pulses are sent down an optical fiber and the signals returning from the fiber are observed. The laser diode produces light pulses which are sent into the test FO strain gage patch. The reflected signals from the markers travel back to a photodetector. This system enables the measurement of the time delay of the reflected signals; thus, the optical fiber length between two markers can be measured.

The OTDR system used in this program is an Opto-Electronics, Inc. MF20/TDR30 millimeter resolution (10 ps) system. The system consists of a signal processor, a power supply, a signal delay generator, a sampling unit, a photodetector, and a laser (see Figure 3). This system is ideal for measuring absolute or relative distances in single-mode or multi-mode optical fibers from 1 mm to 30 km based on the company's published data. The actual performance of the system will be discussed later in this report.

The structural strain (ε) can be calculated from a measurement of the time delay change (Δt) in the time that the optical signal travels between markers according to:

$$\varepsilon = A \frac{\Delta t}{t}$$

where t is the time delay between markers (Note: Because the pulse is reflected, it travels the distance between the two markers twice.), typically measured in a zero loading condition, and A is a geometric factor which takes into consideration the curved section of fiber which also contributes to the change in time delay under strain. As a point of fact, the optical fiber in the patch experiences a total elongation along the principal major loading axis. However, the length of the fiber along the curved section is being partially strained only. Factor A can be determined from calibration tests. The time delay for a 3-m, 5-m, and 10-m patch is approximately 30, 50, and 100 ns, respectively.

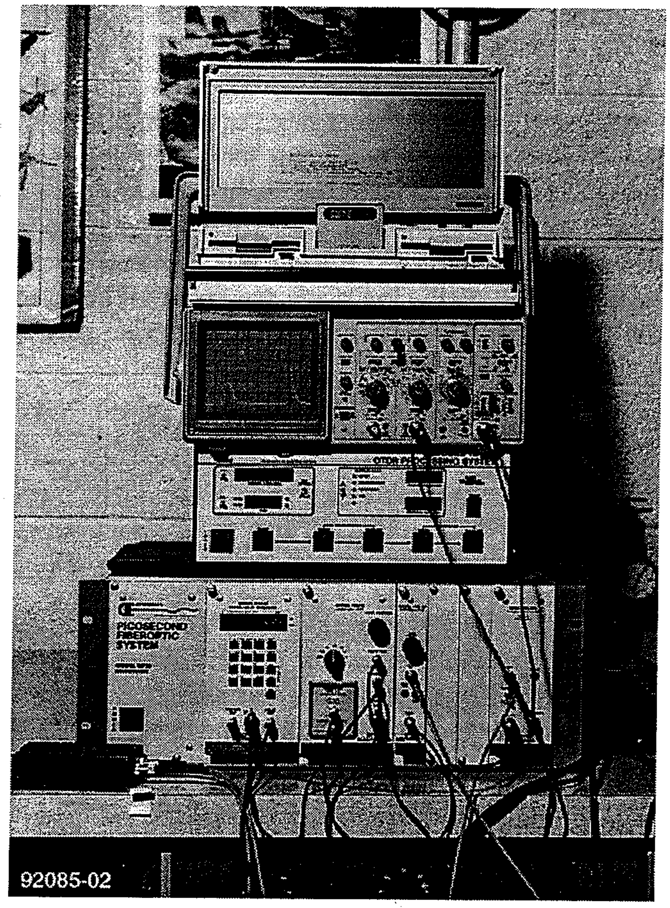

FIGURE 3 FO sensor data acquisition system.

The FO data acquisition software has been developed. The software's output is a Windows-based program that controls the OTDR from a personal computer (PC) using a general purpose interface bus (GPIB). The software is designed to continuously interrogate the FO strain gage patches and store the measured time delay data on a hard disk drive.

Characterization of the FO Strain Gage Patch Sensors

A characterization test matrix for the FO strain gage patch sensors has been designed (Table 1). The test samples consisted of E-glass/epoxy composite and steel coupons. The FO strain gage patch sensors were placed on the surface of the steel and composite coupons, and were also embedded in the composite coupons, (see Figure 4). An adhesive was used to bond the patches to the test coupons. The coupons were tested in both axial tension and four-point bending (see Figure 5).

TABLE 1 Characterization Test Matrix for the FO Strain Gage Patch Sensors

FO Length (m)	Sensor Location	Coupon Material	Loading	Coupon Number
3	Surface	Steel	Tension	S1
5	Surface	Steel	Tension	S2
10	Surface	Steel	Tension	S3
3	Surface	Steel	Four-point Bending	S4
5	Surface	Steel	Four-point Bending	S5
10	Surface	Steel	Four-point Bending	S6
3	Surface	Composite	Tension	C1
5	Surface	Composite	Tension	C2
10	Surface	Composite	Tension	C3
3	Surface	Composite	Four-point Bending	C4
5	Surface	Composite	Four-point Bending	C5
10	Surface	Composite	Four-point Bending	C6
3	Embedded	Composite	Tension	C7
5	Embedded	Composite	Tension	C8
10	Embedded	Composite	Tension	C9
3	Embedded	Composite	Four-point Bending	C10
5	Embedded	Composite	Four-point Bending	C11
10	Embedded	Composite	Four-point Bending	C12

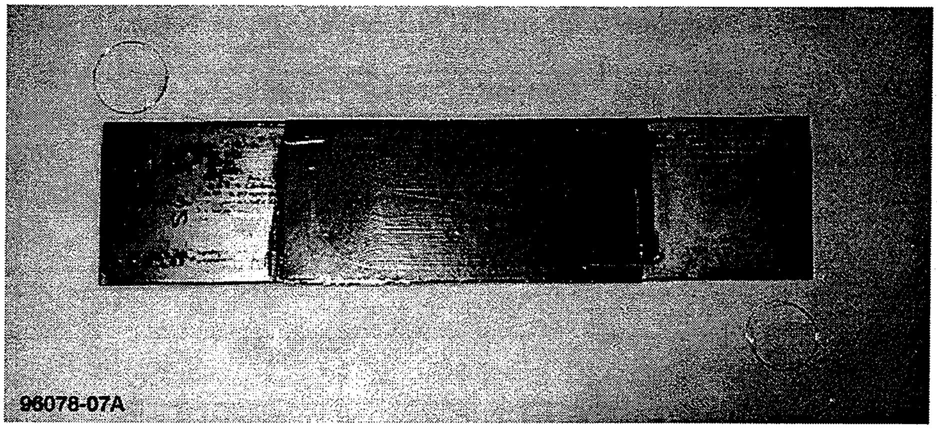

FIGURE 4 FO strain gage patch attached to a steel plate.

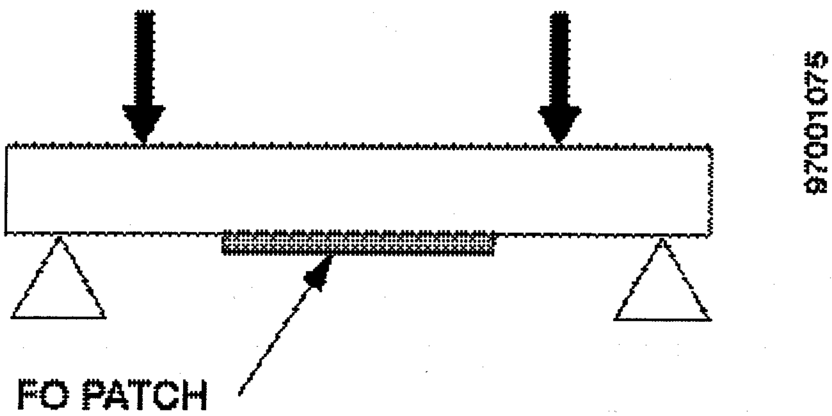

FIGURE 5 Test coupons showing FO patch placement.

The lay-up sequence for these composite coupons with embedded FO strain gage patch sensors were (0_4/patch/0_4) for the tension test coupon, and (0/90/patch/+45/-45/0/90/+45/-45/-45/+45/90/0/-45/+45/90/0) for the 4-point bending test coupon, respectively. A conventional strain gage was attached to the surface of each coupon at the center location of the FO strain gage patch for sensor calibration.

A total of 18 coupons were fabricated, but 3 coupons were damaged during the fabrication process. In these three coupons no reflected pulse was found from the far end marker because the optical fiber was damaged within the patch between the two markers. The remaining 15 coupons were tested to failure. The failure strain for both the FO strain gage patch and the composite coupon was between 0.25 to 0.30 percent. Plastic strain had been observed on the steel coupon under this strain level. There were 3 to 5 readings taken at each loading level during each test. An average time delay was calculated and converted to engineering strain.

Finally, the FO strain gage patch data was compared with readings from conventional strain gages. Since the conventional strain gage was reading the strain on the surface of the composite coupon instead of reading the strain inside the composite coupon at the point where the FO strain gage was placed during the four-point bending test, a linear strain distribution across the thickness of the composite coupon was assumed, and the strain gage readings were modified accordingly. Unfortunately, an instability in the FO strain measurement was found for eight of the test coupons. This instability appeared to be directly attributable to an instability in the 850-nm laser light source in the OTDR unit. After the tests, the laser was sent to Opto-Electronics for repair. However, these eight coupons could not be re-tested, since permanent deformation and delamination had occurred for the steel and the composite coupon, respectively.

Test results for coupons S1, S4, C1, C8, C9, C10, and C11 are shown in Figures 6 through 12. A linear curve fitting was conducted to calculate the factor A as defined in Section 3.1 equation (1). .A typical raw FO strain gage patch data is shown in Figure 13. A decision was made not to take the four "bad" data points into account due to the instability of the laser light source.

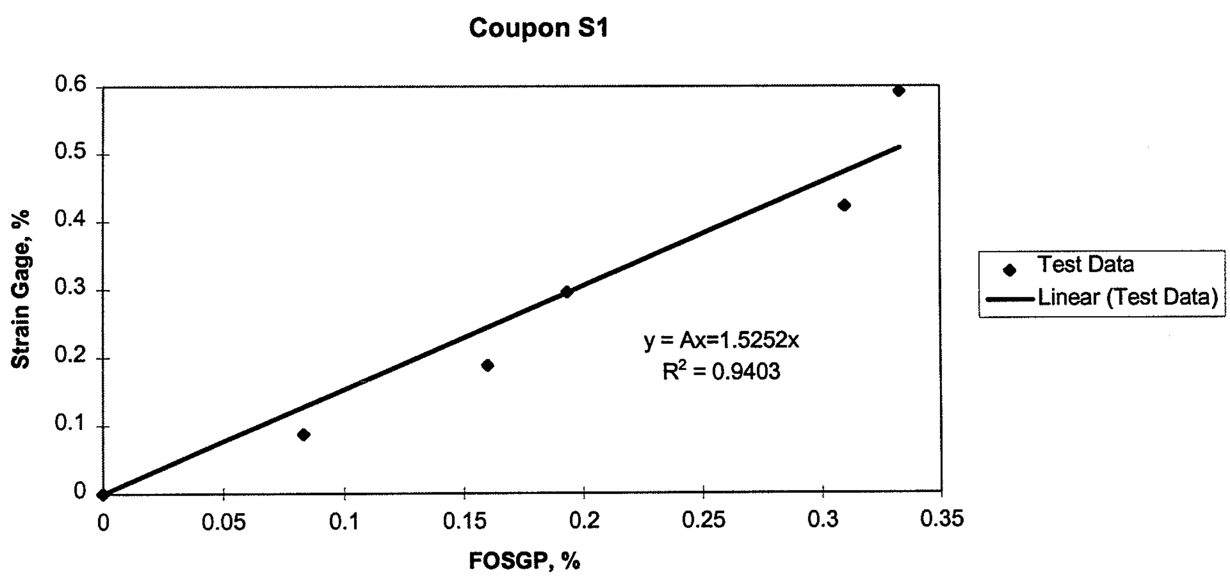

FIGURE 6 3-m patch (steel coupon - tension test)

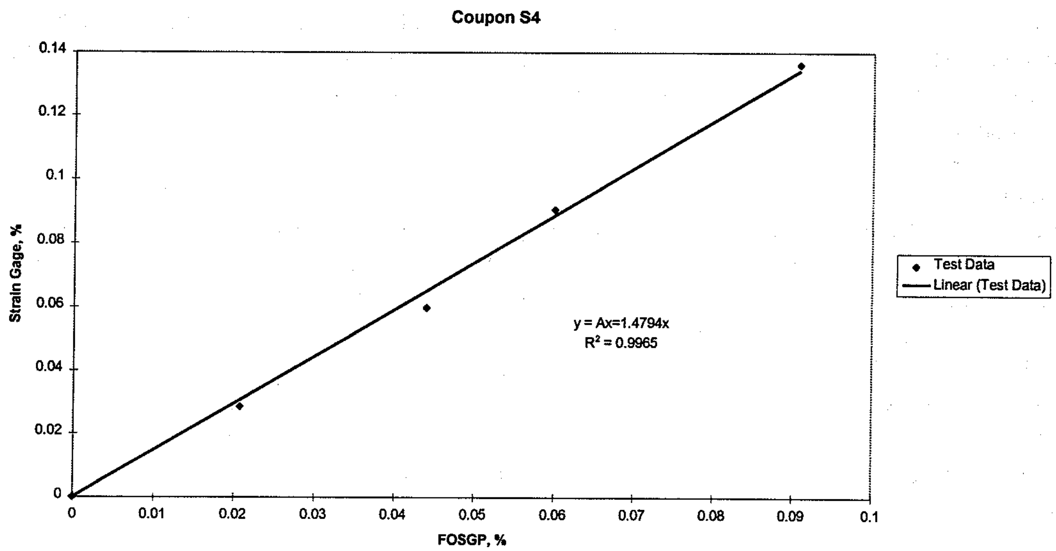

FIGURE 7 3-m patch (steel coupon - 4-point bending test).

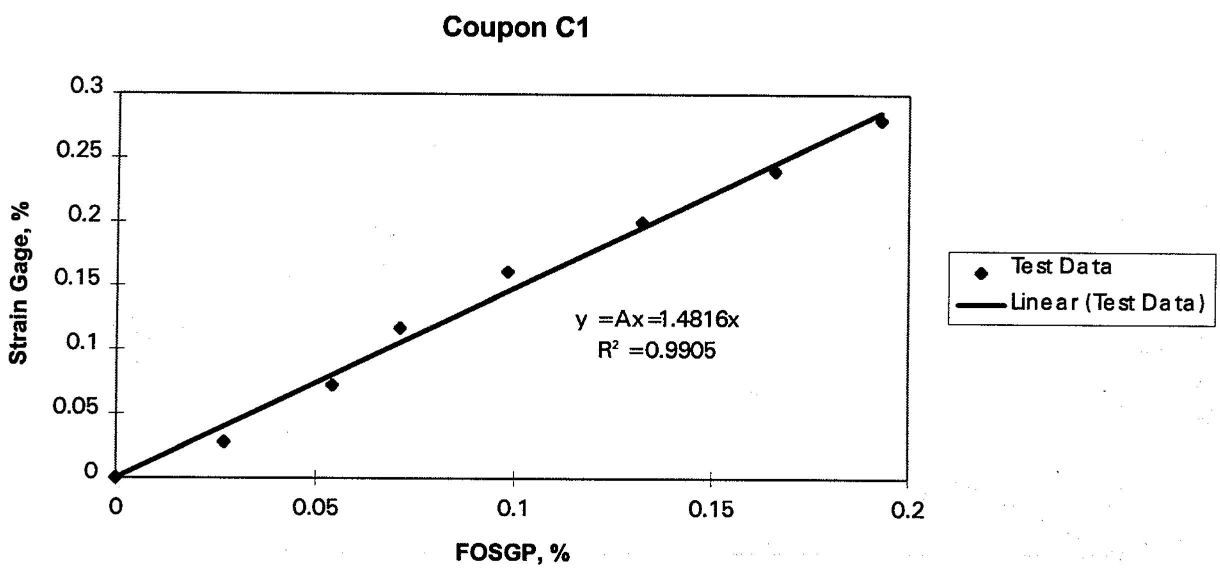

FIGURE 8 3-m patch (composite - tension test).

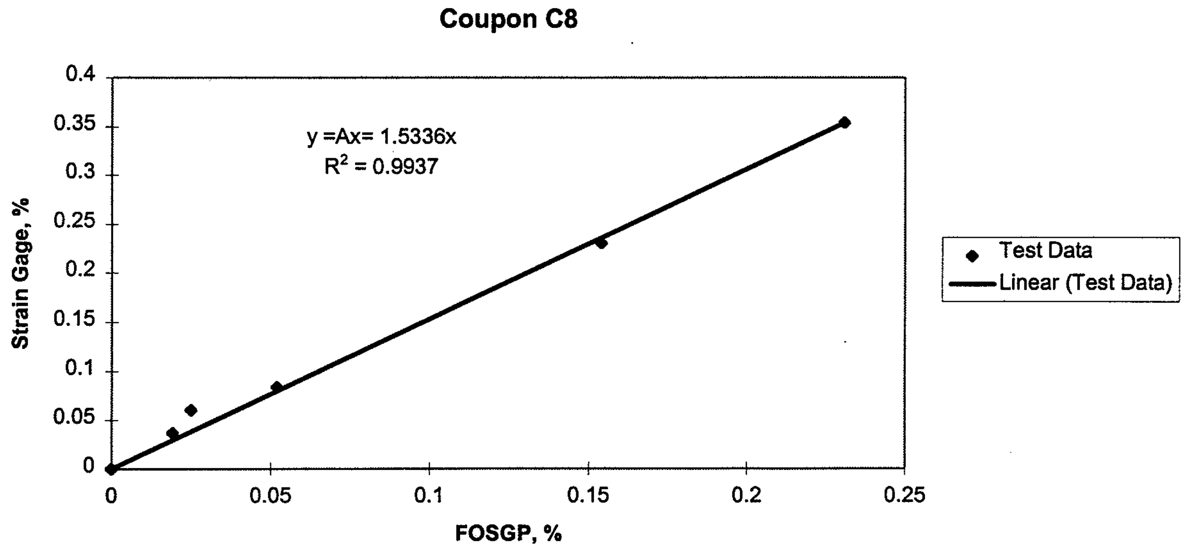

FIGURE 9 3-m patch (composite - tension test).

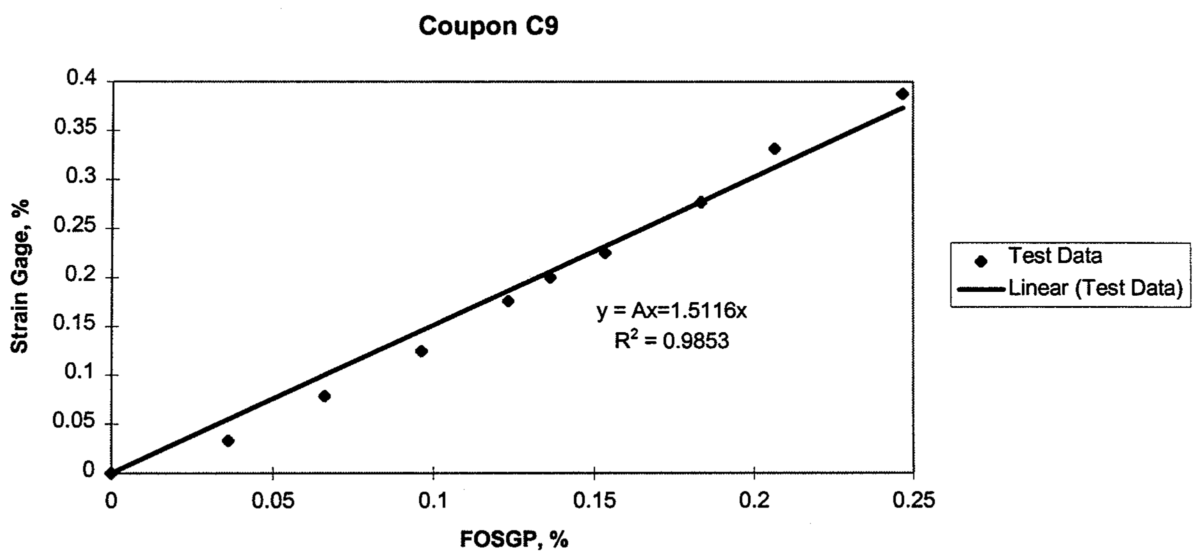

FIGURE 10 10-m patch (composite - tension test).

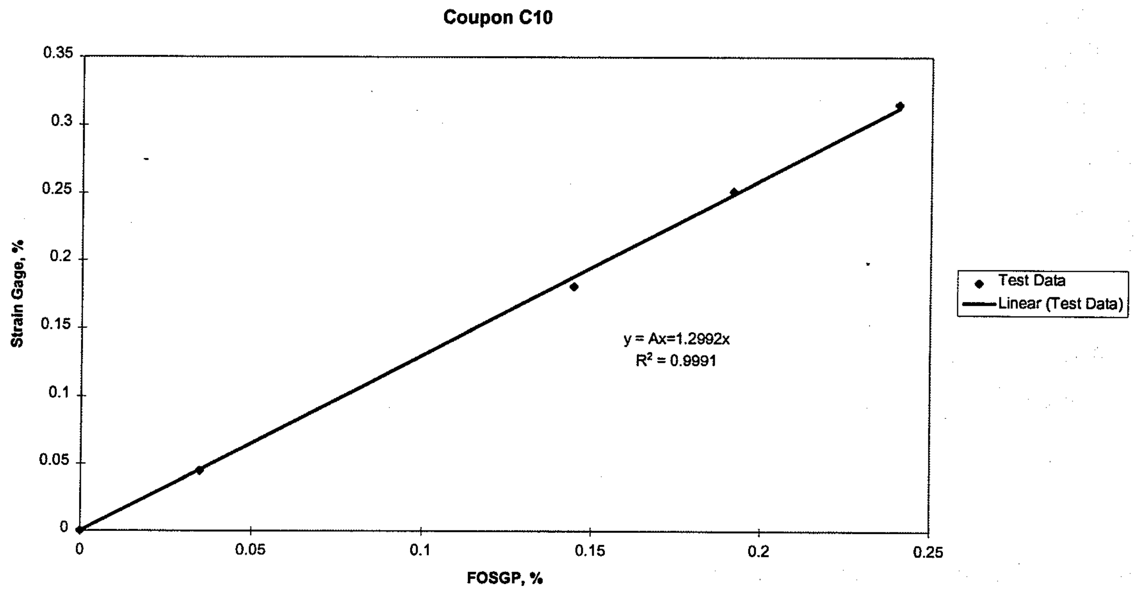

FIGURE 11 3-m patch (composite - 4-point bending test).

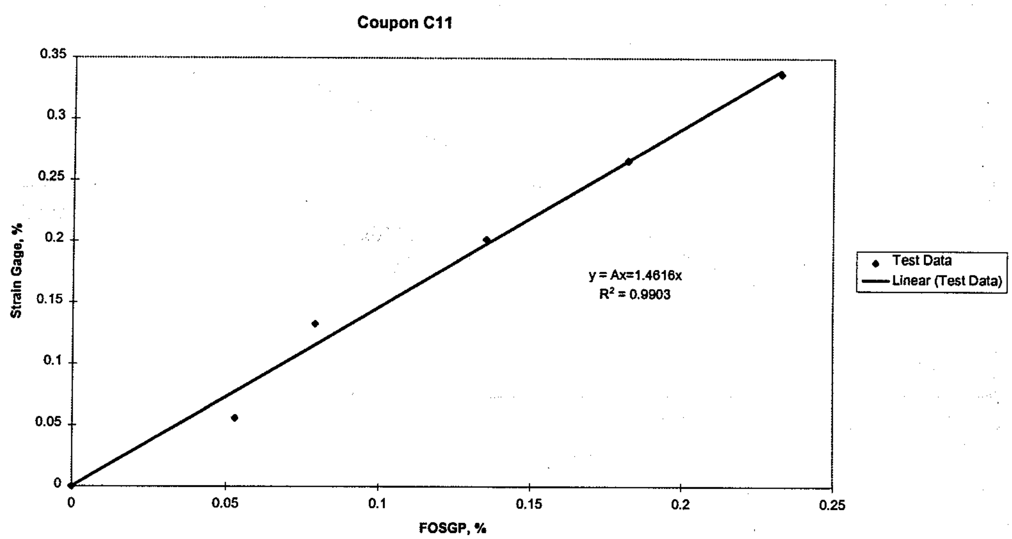

FIGURE 12 5-m patch (composite - 4-point bending test).

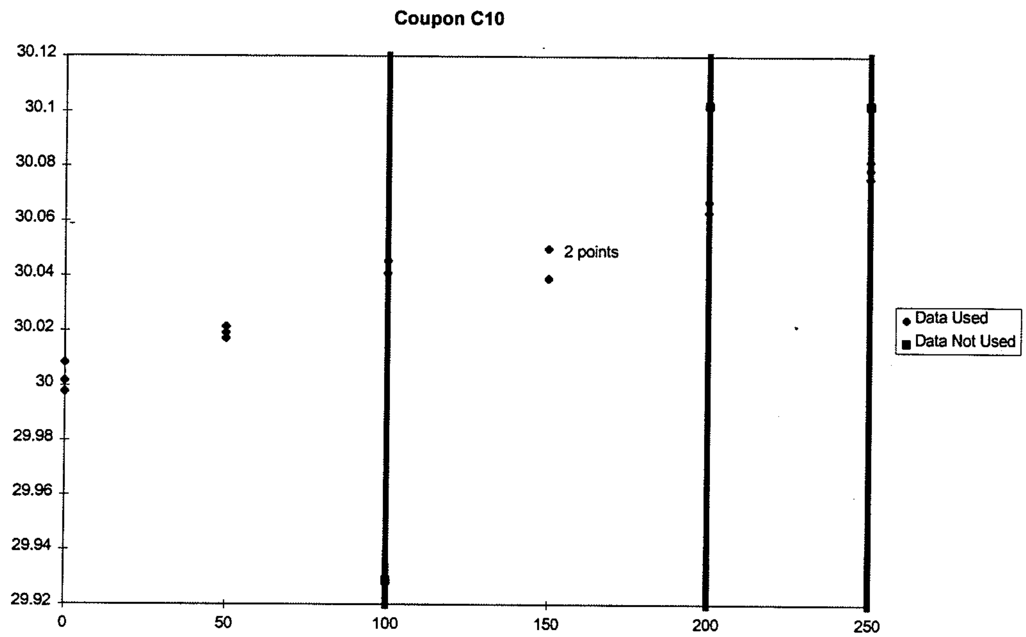

FIGURE 13 Typical raw FO strain gage patch data.

Finally, all of the 3-m patch data were plotted on the same figure (see Figure 14), and a linear curve fitting was conducted again, and the factor A was found to be 1.4634. Similarly, the factor A for 5-m patch and 10-m patch were found to be 1.4913 and 1.5116, respectively. (See Figures 15 and 16). Table 2 shows what the strain would be by using 3-m, 5-m, and 10-m FO strain gage patch sensors. These numbers were calculated based on the factor A, as obtained from the coupon calibration tests. It should be noted that 10 ps is the best resolution claimed by the OTDR manufacturer. During this study; however, 40 ps was the best resolution that could be achieved.

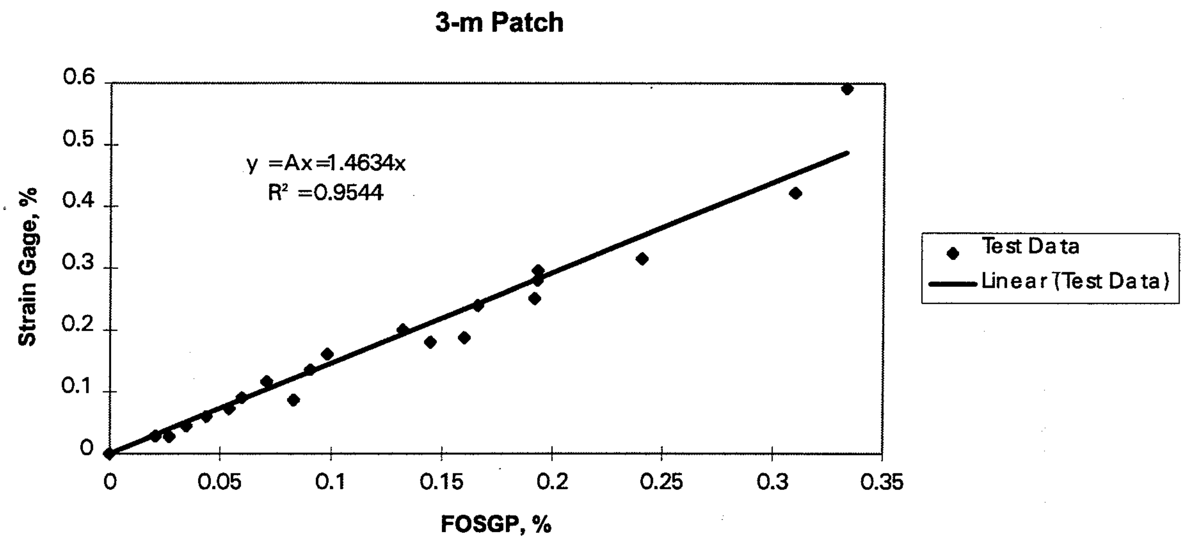

FIGURE 14 Calibration curve for 3-m patches.

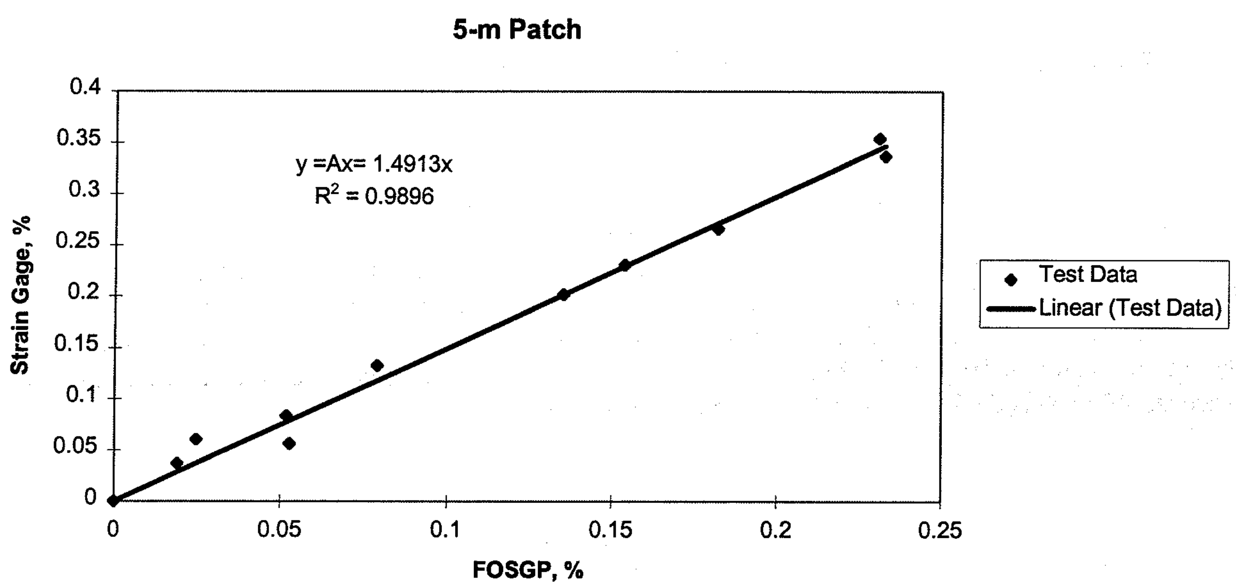

FIGURE 15 Calibration curve for 5-m patches.

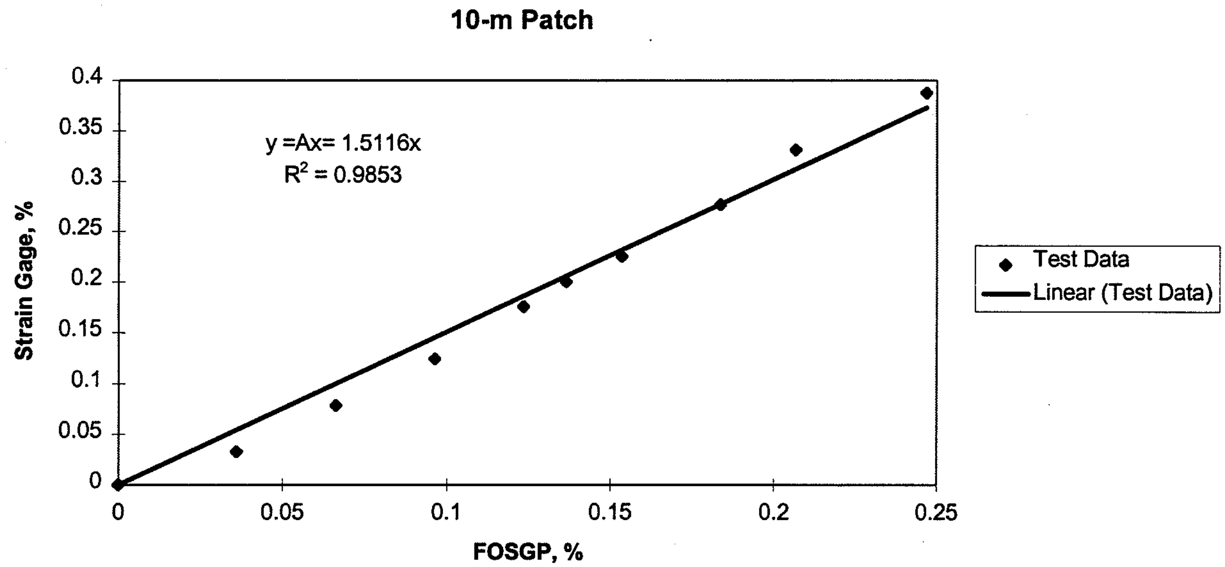

FIGURE 16 Calibration curve for 10-m patches.

TABLE 2 Strain in Percentage Using FO Strain Gage Patch Sensors

Delay (ps)	3-m Patch	5-m Patch	10-m Patch
10	0.04878	0.02983	0.01512
20	0.09756	0.05965	0.03023
30	0.14634	0.08948	0.04535
40	0.19512	0.11930	0.06046
50	0.24390	0.14913	0.07558
100	0.48780	0.29826	0.15116
150	0.73170	0.44739	0.22674
200	0.97560	0.59652	0.30232
300	1.46340	0.89478	0.45348

TASK III - FABRICATE BEAMS WITH SURFACE-ATTACHED AND EMBEDDED FO STRAIN GAGE PATCH SENSORS

The objective of this task was to fabricate a composite I-beam and a rectangular steel reinforced concrete beam with surface-attached and embedded FO strain gage patch sensors for preliminary proof-of-concept tests. The following sections describe the fabrication procedure used for each beam and the instrumentation setup.

Composite I-Beam

A 20.32-cm x 0.9525-cm x 3-m long wide-flange fiberglass beam was purchased from the Morrison Molded Fiber Glass (MMFG) Company. Two sensor strings were attached to the top and bottom flange surfaces, respectively. Each sensor string consisted of three in-line, 10-m and 3-m FO strain gage patches (see Figure 17).

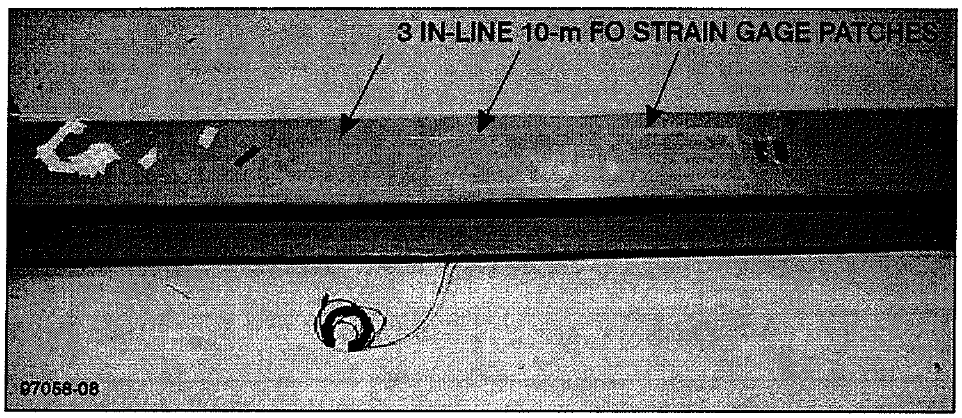

FIGURE 17 Composite beam with surface-attached FO sensor string.

Due to high FO attenuation caused by the patch cure process, only one single 10-m patch could be monitored in-line by the OTDR system. All three of the 3-m patches could be monitored in-line by the OTDR system; however, the pulses from the third patch down the line were very weak and were not worth monitoring. Figures 18 and 19 show the scatter of time-delay data under a zero loading condition for the first and second 3-m patches in-line. It appears that the accuracy of the OTDR for the first and second 3-m patch is 20 ps (0.09 pct) and 50 ps (0.24 pct), respectively, despite the 10 ps accuracy claimed by the manufacturer, while operating the OTDR under ideal conditions.

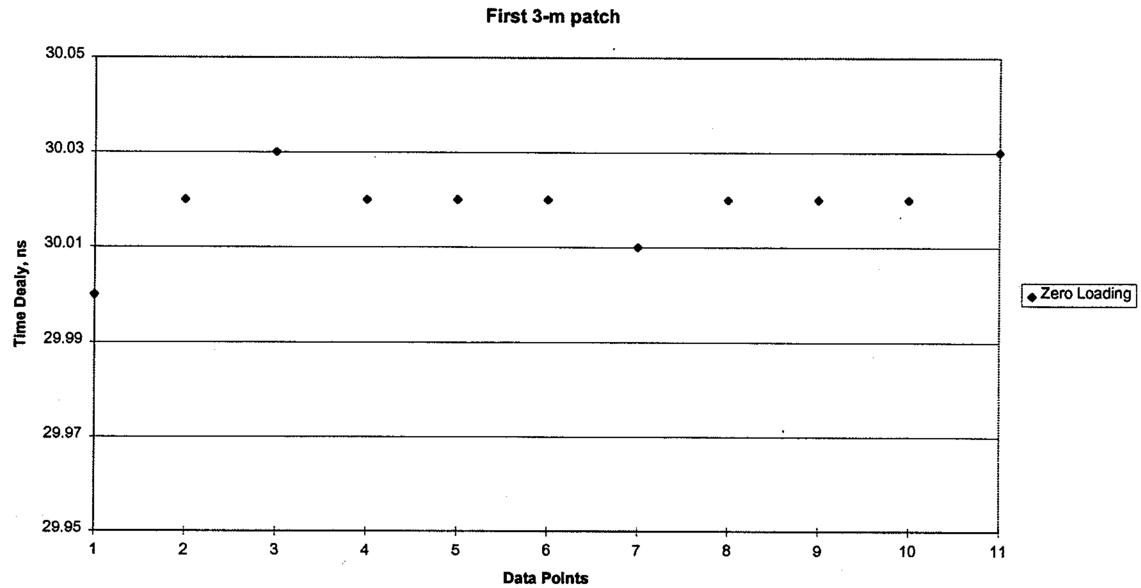

FIGURE 18 Noise with 20 ps resolution for the first 3-m patch in-line.

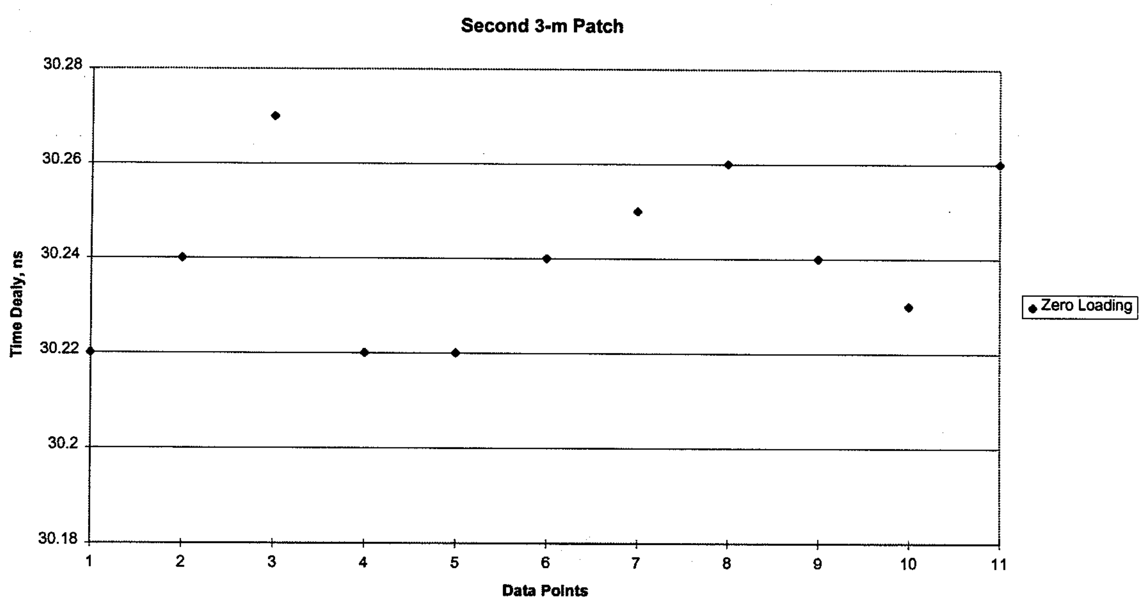

FIGURE 19 Noise with 50 ps resolution for the second 3-m patch in-line.

As mentioned in the proposal, Sedona Scientific, Inc., Simula Government Product's corporate affiliate, is also developing a low-cost FO sensor monitoring system under its own IR&D funding. It was decided to compare the performance of both sensors, so one of Sedona Scientific's proprietary FO sensors was attached to the composite beam for evaluation, as well. The configuration of the low-cost FO sensor and the monitoring system are totally different than the FO strain gage patch and the OTDR system. The test results of the low-cost FO sensor are discussed in Section 5.1.2.

Concrete Beam

A 2-m concrete beam was designed and fabricated with embedded FO sensors. The concrete beam with the embedded FO strain gage patch and low-cost FO sensor locations is shown in Figure 20. Figure 21 is a photo of the form taken before concrete was poured into it to make the beam.

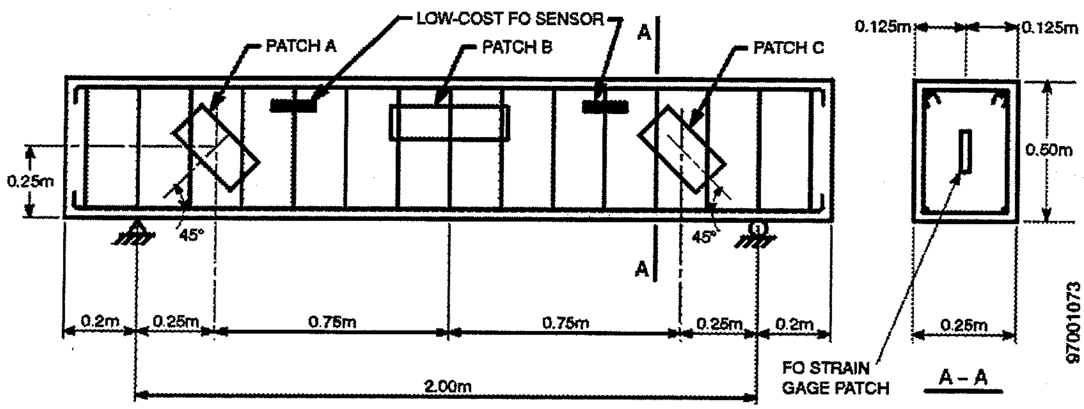

FIGURE 20 Concrete beam with embedded FO strain gage patches.

FIGURE 21 Concrete beam ready for casting

Based on the OTDR resolution readings found during the preparation of the composite beam, as described in Section 4.1, it was decided three individual 10-m FO strain gage patches would be embedded in the beam, instead of three patches in-line. These three 10-m FO strain gage patches were cast within a rugged epoxy to prevent potential mechanical damage during the pouring of the concrete (see Figure 22). The size of the concrete FO strain gage patch is about 20 x 45 x 1.0 cm. Two of Sedona Scientific's low-cost FO sensors would also be embedded in the concrete beam for evaluation. Five electro-resistive strain gages that could be embedded in concrete were purchased from Micro-Measurements Division, Measurements Group, Inc. These strain gages were attached to the surface of the FO strain gage patches and the low-cost FO sensors for comparison.

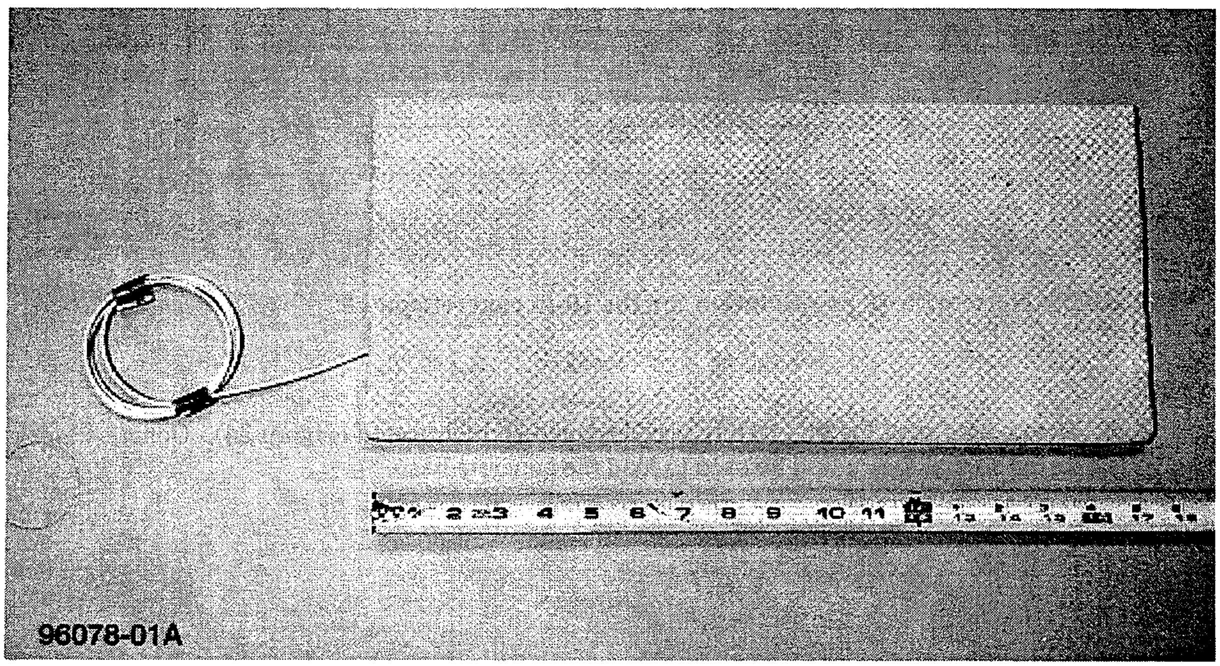

FIGURE 22 10-m patch ready for embedding in the concrete beam.

After the beam was cast and cured in the field for 28 days, the FO strain gage patches were connected to the OTDR to make sure that they all survived during the fabrication process. Figure 23 shows the 10-m patch pulse delay under a zero loading condition. The accuracy of the OTDR for the 10-m patch is approximately 40 ps (0.06 pct). However, the lead fiber to one of the low-cost FO sensors was broken; therefore, only one low-cost FO sensor was available for evaluation.

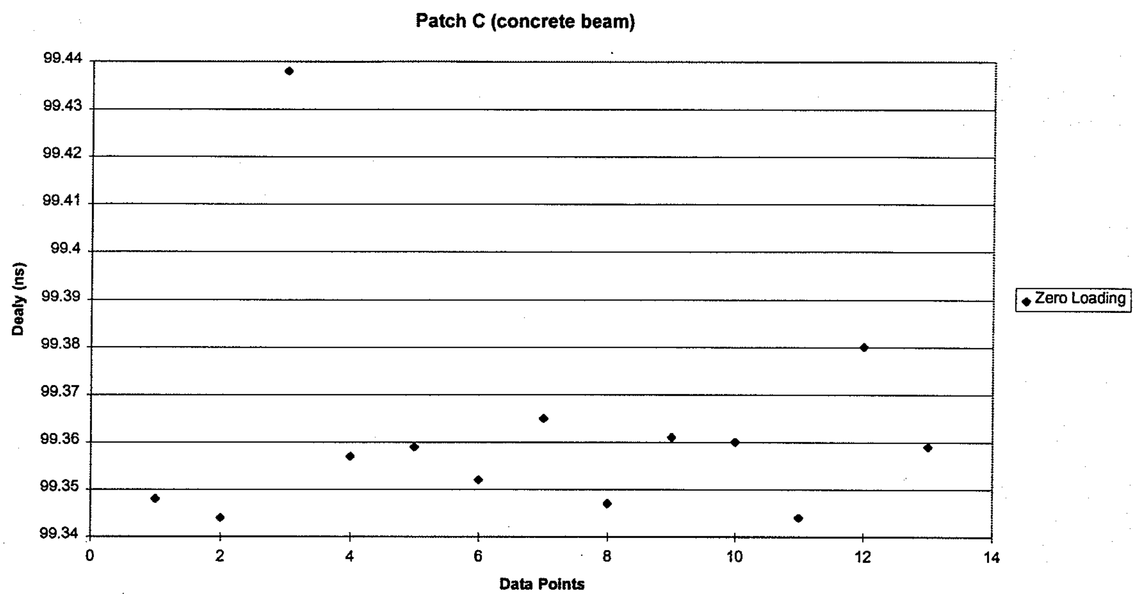

FIGURE 23 Noise with 40 ps resolution for the 10-m concrete patch.

A cantilever-type steel loading fixture was designed and fabricated (Figure 24). Concrete blocks were also fabricated so that they could be used to load the concrete beam.

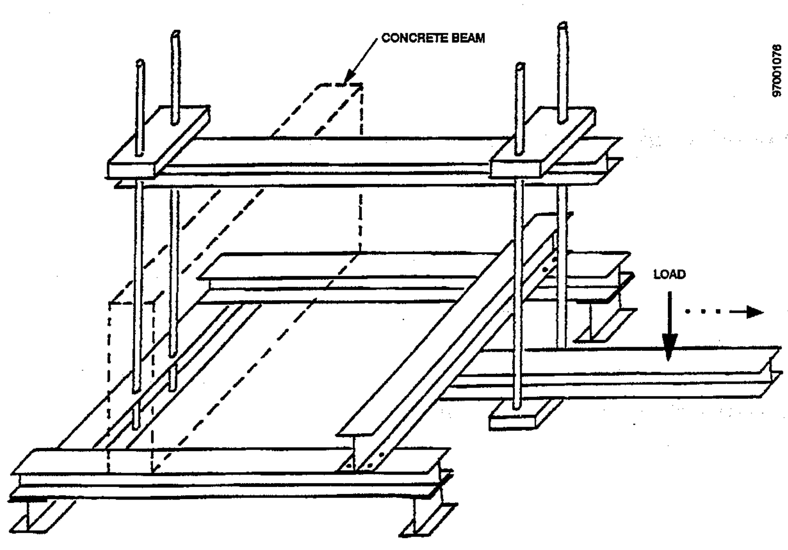

FIGURE 24 Steel loading frame.

TASK IV - PRELIMINARY PROOF-OF-CONCEPT TESTING

Mechanical Testing of the Composite Beam

The composite beam was subjected to three-point bending loads. The beam was loaded to a maximum of 8,000 lb at the maximum strain level of approximately 0.27 pct. The load was applied to the beam in 1,000-lb load increments through a load cell. (See Figure 25.) Two readings were taken at each loading level. One 10-m patch in the compression side, and two 3-m patches in-line in the tension side, were monitored. (See Figure 26). During the test, the FO cables connected to the 10-m patch and the other two 3-m patches were manually switched to make a connection to the OTDR.

FIGURE 25 Mechanical testing of composite beam.

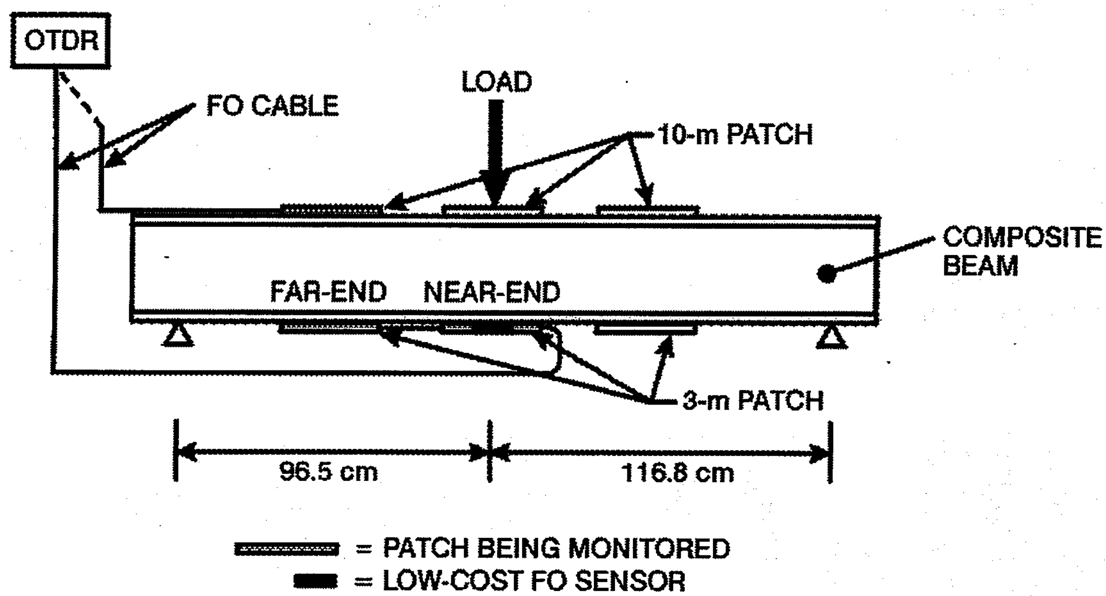

FIGURE 26 FO patches being monitored during test.

FO Strain Gage Patch Test Results

The measurements from the 10-m patch and the far end 3-m patch were not acceptable and were unusable. Figure 27 shows the results from the near end 3-m patch. A constant error bar of 0.09 pct (see Section 4.1) also added to the FO sensor data. It is noted that the sensor reading failed after the load exceeded 6,000 lb. The calculated strain was the peak strain at the loading point.

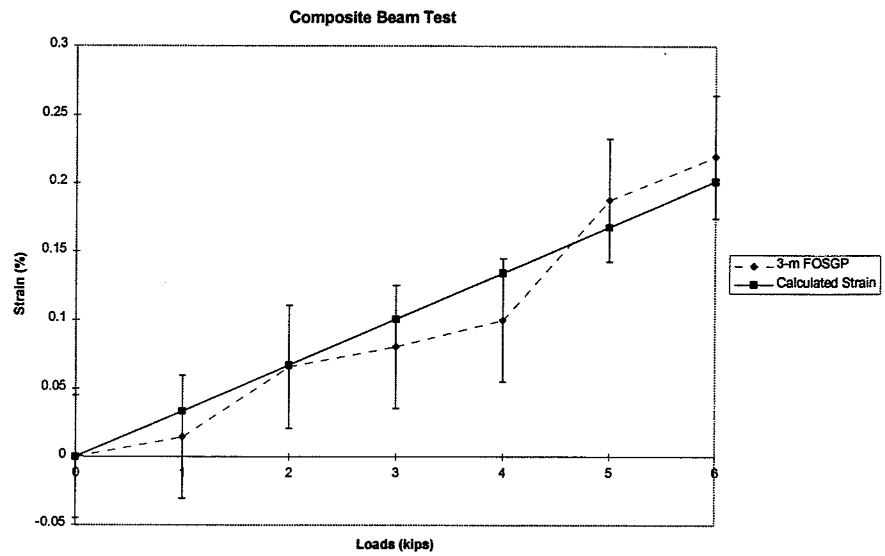

FIGURE 27 Sensor results from the first 3-m patch in-line.

However, it should be noted that the FO strain gage patch measures integral strain over the entire patch area, and it is not designed as a point sensor. Therefore, the FO strain gage patch measures lower strain than the calculated maximum strain. When the maximum strain exceeds 0.15 pct, the FO strain gage patch predicts a higher strain. This event could be attributed to the instability of the OTDR system.

Low-Cost FO Sensor Test Results

Figure 28 shows the results from the low-cost FO sensor system. Good correlation was found between the low-cost FO sensor and the calculated strain in both loading and unloading conditions.

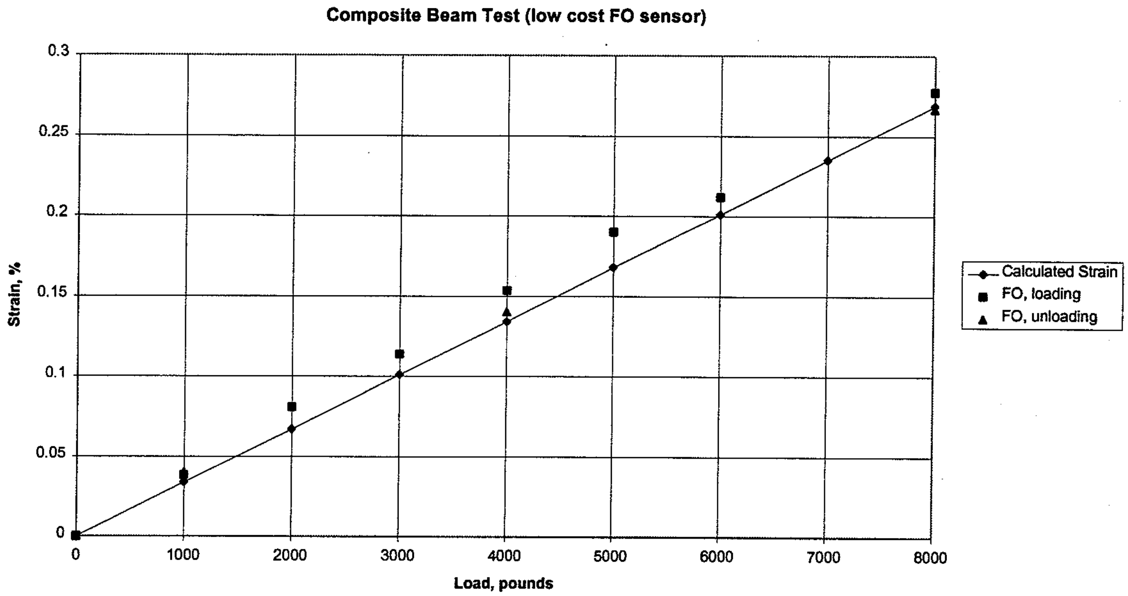

FIGURE 28 Sensor results from the low-cost system (Sedona Scientific).

Mechanical Testing of the Concrete Beam

The 2-m full-scale concrete beam and loading fixture were set up in the field in a natural environment. (See Figure 29). A security fence was placed around them to avoid any man or animal interference with the test beam.

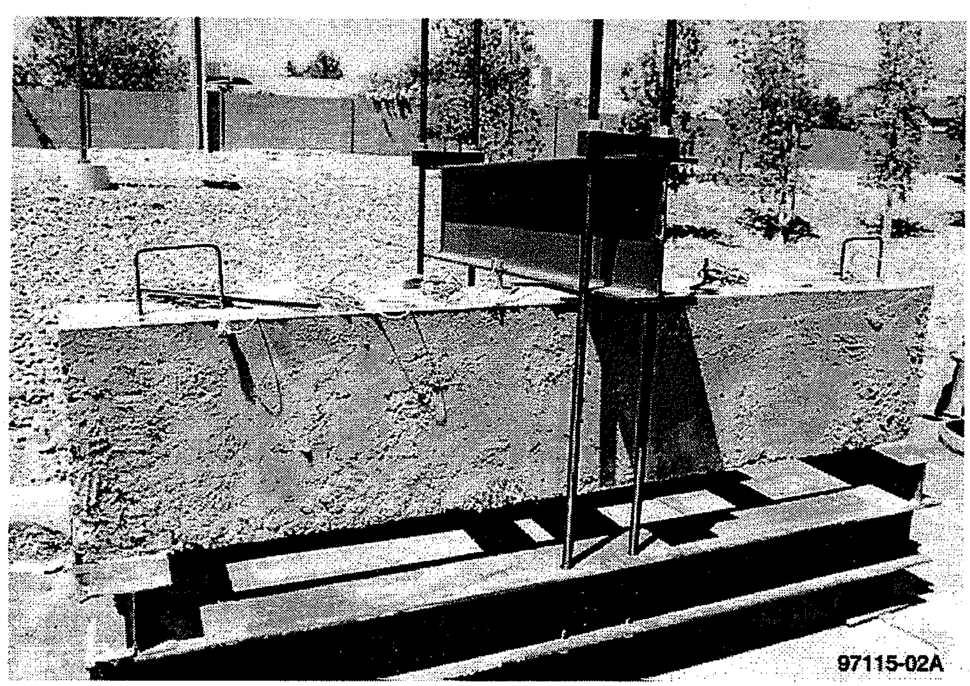

FIGURE 29 Concrete beam test set up in the field.

The calculated maximum load applied to the concrete beam was 40,000 lb, which was based on a 28-day concrete strength of 4,000 lb/in^2. Under the maximum loading, the calculated strains in each of the FO strain gage patches and the low cost FO sensor are listed in Table 3.

Table 3. Calculated Maximum Strain in Each FO Sensor

Sensor I.D.	Patch A	Patch B	Patch C	Low-cost Sensor
$\mu\varepsilon$	-29	-206	29	-257

Data from the FO strain gage patches, the low-cost FO sensor, and the conventional strain gages were taken before and after a load of approximately 12,600 lb was first applied to the concrete beam. The anticipated strains in the FO strain gage patches and the low-cost FO sensor are listed in Table 4.

Table 4. Calculated Strain Under 12,600 lb Load

Sensor I.D.	Patch A	Patch B	Patch C	Low-cost Sensor
$\mu\varepsilon$	-9	-65	9	-81

Unfortunately, all of the systems failed to predict the strains, as shown in Table 4.

Wires which were approximately 40-m long were used to connect the conventional strain gages to the data acquisition system, which was inside a laboratory. Due to electromagnetic interference, the data was extremely noisy and unacceptable.

The load was kept constant and the FO strain gage patch data was continuously taken twice a day for five days. At each time measurement, seven to ten data points were measured and the average time delay was calculated. Again, the accuracy of the OTDR for the 10-m patch was approximately 40 ps (600 $\mu\varepsilon$) during each time measurements. However, it was found that these measurements could not be repeated each time although the accuracy of the OTDR still remained at 40 ps. Also, the strain level in the FO strain gage patches was too low to be detectable.

On the other hand, the strain level in the low-cost FO sensor was within its detectable range. Since no signal change was observed during several loading and unloading trials, it was decided to use three dial gages to monitor the deflection of the concrete beam. As a result, it was discovered that the concrete beam deflected until half of the load was applied, and then the whole concrete beam and the test fixture were lifted-up. To prevent this from occurring, the test fixture is being modified so that it will remain stable during continuous tests.

A decision has been made that only the low-cost FO sensor will be used to monitor the concrete beam. It is believed that only the low-cost FO sensor is suitable to monitor such a low strain level in the concrete.

SUMMARY AND CONCLUSIONS

Several conclusions can be drawn from this IDEA project.

1. A novel FO strain gage patch was developed. The patch was intended to be embedded in composite and concrete materials or attached to the surface of structures. The sensors were intended to measure integral strain over discrete sections of the structure and needed to be accessed from only one end. The work performed for this program revealed that more effort remains to be done in order to make this type of sensor robust enough to be embedded in concrete. The fiber optic leads are currently too delicate to be embedded.

2. When the FO sensors are positioned between glass-reinforced epoxy carrier material, micro-bending on the FO sensors during the carrier material cure process increases the FO attenuation; thus, it limits the potential to multiplex patches in-line in order to interrogate multiple locations. With the monitor used in this program, no multiplexing was achieved. Only single patches could be monitored.

3. The sensitivity of the FO strain gage patch sensor was limited by the OTDR system. The accuracy of the OTDR for 3-m and 10-m patches is 20 ps (0.09 pct), and 40 ps (0.06 pct), respectively. This accuracy is suitable for materials such as steel and some composites, but it is not suitable for concrete.

4. The low-cost FO sensor performed much better than the OTDR FO strain gage patch sensor. This low-cost FO sensor would normally be attached to the surface of a structure, but conceivably could also be embedded and multiplexed in-line. This type of sensor is appropriate for monitoring dynamic and impact loads as well. However, it is not suitable for long-term monitoring.

RECOMMENDATIONS

In order for the time delay strain measurements to be practical for structural monitoring of concrete structures, the accuracy of OTDR instruments must be improved to better than ± 3 ps. This time resolution would give a strain resolution of 50 $\mu\varepsilon$ with a 10-m patch. The 3-m patches are smaller in area. These shorter patches are more likely to be able to be multiplexed. However, these patches would require that the OTDR have a resolution of better than 1.0 ps.