Performance of miniaturized optical fiber interconnects between sensor-embedded composite panels

R. Claus, R. Crotts, and K. Murphy
Fiber & Electro-Optics Research Center, Virginia Tech
Blacksburg, VA 24061-0111, (703)231-7203

R. Dahlgren, Fujikura Technology America Corp.

T. Tran and S. Poland, Fiber and Sensor Technologies
P.O. Box 11704
Blacksburg, VA 24061-1704, (703) 231-4224

ABSTRACT

This paper reports the performance of low-profile multi-fiber connectors between sensor-embedded composite panels. The interconnection of such composite panels has been cited as a major limitation to optical fiber sensor-embedded "smart materials and structures" during the past fourteen years. Typically the leads of optical fiber sensors embedded in composites have been brought out of the material either at the sides through protective tubing or through the surface via standard connectors in recessed depressions in the material surface. The first of these options suffers from a lack of mechanical robustness, while the second serves to locally weaken the material and to expose the fiber sensor channel to the external environment. We report successful connector embedment at the panel edge with singlemode connector losses of less than 1.1 dB, and connectorized fiber sensors accessed through the fiber connector.

2. INTRODUCTION

Optical fibers embedded into composite materials for proposed smart structures have been a major research area since 1979 [1]. Optical fiber sensors, proposed for integration with smart structures, promise many advantages, such as small size, light weight, corrosion resistant, immunity from electromagnetic interference, large bandwidth and they can be configured to respond to many physical observables. A major obstacle for the realization of these smart materials has been the ingress/egress issues associated with embedding fiber sensors into composite materials. To overcome these problems, a low-profile precision silica-filled plastic connector has been inserted into the sides of composite panel, and used both to provide local connection of embedded sensor leads and to align the parts. The US Conec Ltd., Conec™ Multifiber Ferrule allows the interconnection of up to 12 optical fibers of standard outer diameter and may be used to access optical fiber sensors embedded into the composite material [2]. The interconnect may be fitted into the side of the panel and recessed during fabrication, then uncovered during the trip operation. The connector allows fiber-to-fiber connection with losses typically as low as 0.35 dB for singlemode fibers. A diagram of the multifiber connector can be seen in Figure 1.

The composite panel connectorization demonstrations have included fabricating the panels with embedded plain (no sensors, strictly for connector insertion loss measurements) singlemode fiber and interferometric sensor elements. Subsequent tests included measuring insertion losses on the plain fiber and demonstrating the sensors elements after the embedment process.

0-8194-1337-2/94/$6.00

3. EXPERIMENTAL DESCRIPTION

Basically two experiments were preformed with the low-profile connectors 1) simple throughput loss measurements for singlemode optical fiber and 2) a demonstration of the extrinsic Fabry-Perot interferometer (EFPI) [3]. The multifiber connectors used were capable of handling four fibers. Four polyimide coated singlemode optical fibers were first inserted into the connectors and were prepared in the normal prescribed fashion by the manufacturer [2]. Two connector sets were fabricated for testing. Three of the fibers in each connector were plain singlemode fibers, while the fourth fiber served as the lead in/lead out fiber for the EFPI sensor. The two connector sets were prepared and first characterized for throughput loss before embedding them into the composite panel for comparison purposes after the embedment procedure was complete.

The test composite panel was fabricated with 20 plys with the connector between the 9th and 10th plys. Figure 2 shows the layout of the individual fibers and sensors. The connectors were embedded into a composite panel with notched layers to accommodate the connector housing and to prevent fiber breakage at the fiber/connector interface. As shown in Figure 3, connection 1 was fully notched to fit the connector design, while connection 2 was partially notched to minimize composite material removal. No experiments were preformed to quantify the composite strength degradation as a result of connector embedment.

4. SENSOR DESCRIPTION

The extrinsic Fabry-Perot interferometer (EFPI) fiber sensor have been used in the past to measure strain, displacement, temperature, pressure and ultrasonic waves [3]. A schematic of the sensor construction is shown in Figure 4. Light from a 1300 nm pigtailed laser diode is coupled into the sensor head via a 3 dB 2x2 directional coupler. The sensor head consists of a hollow core silica fiber capped over the end of a single-mode input/output fiber. Another single mode fiber placed through the other end of the hollow core acts as the second interface of a low-finesse Fabry-Perot cavity. The gage length of the sensor is measured by determining the distance between the locations where the input fiber and reflector fiber are epoxied to the hollow core fiber.

The observed EFPI interference occurs between the light reflected from the planar surfaces of the air-gap sensing element. Since the reflection coefficient from a planar silica surface is low (4%), the EFPI can be considered to be essentially a two-beam interferometer. The observed intensity, I, at the germanium photo detector can be modeled by [1]:

$$I = A_1^2 + A_2^2 + 2A_1A_2 \cos \phi_o \qquad (1)$$

$$\phi_o = \frac{4\pi n d}{\lambda} \qquad (2)$$

where ϕ_o is the round trip optical path length difference (OPD), A_1 and A_2 represent the electric field amplitudes of the interfering light from the two interfaces of the air-gap cavity, λ is the wavelength of the source, n is the refractive index of the air-gap, and d is the spacing of cavity which changes due to the host material undergoing strain. For large strain measurements the output intensity can be accurately monitored and it is calculated from the relation:

$$\varepsilon = \frac{\Delta d}{L} \qquad (3)$$

where Δd is the change in resonant cavity length, and L is the sensor gage length. The change in cavity length can be measured by counting the optical fringes which occur at the output of the sensor, when used in the differential mode. For a 1300 nm laser source, one complete cycle of intensity oscillation (optical fringe) corresponds to cavity length change of 650 nm. For a 10 mm gage length, the resolution of the EFPI is typically 0.1 $\mu\varepsilon$.

5. RESULTS

A photograph of the connectorized panel is shown in Figure 5. The results for the insertion losses are listed in table form Figure 6. For each four-fiber connector, insertion losses were measured before and after embedment for three of the four singlemode fibers, while the fourth fiber connected to an EFPI sensor. The maximum insertion loss was 1.1 dB for connector 2, which used the partial notch described in Section 3. The fully notched panel reduces the optical fiber bend at the insertion point on the back of the connector, which resulted in an average insertion loss of 0.5 dB. The increased insertion losses for the partially notched connection, above the fully notched connection is due to increased bending losses at the fiber/connector interface.

Figure 7 shows the EFPI strain sensor output as a result of panel bending. Insertion losses were estimated to be less than 1.0 dB, but are difficult to verify with the single ended extrinsic Fabry-Perot interferometer. The embedded EFPI strain sensors survived, demonstrating connectorized fiber sensors for smart structure applications.

6. CONCLUSIONS

We have successfully embedded multifiber optical fiber connectors with an average insertion loss of 0.5 db, and accessed embedded fiber sensors using the embedded connector. Efforts are under way to use these connectorized sensors to monitor strain and long-term degradation in the composite material and incorporate connectorized actuators for the ultimate realization of smart materials.

REFERENCES

1. NASA Research Contract No. 78-04379 to Virginia Tech, R. O. Claus and J. Heyman, 1979.

2. US Conec Ltd., Conec™ Multifiber Ferrule data sheet.

3. "Quadrature phase-shifted, extrinsic Fabry-Perot optical fiber sensors," K. Murphy, M. Gunther, A. Vengsarkar and R. O. Claus, *Optics Letters*, Vol. 16, No. 4, February 1991, pp. 173-275 .

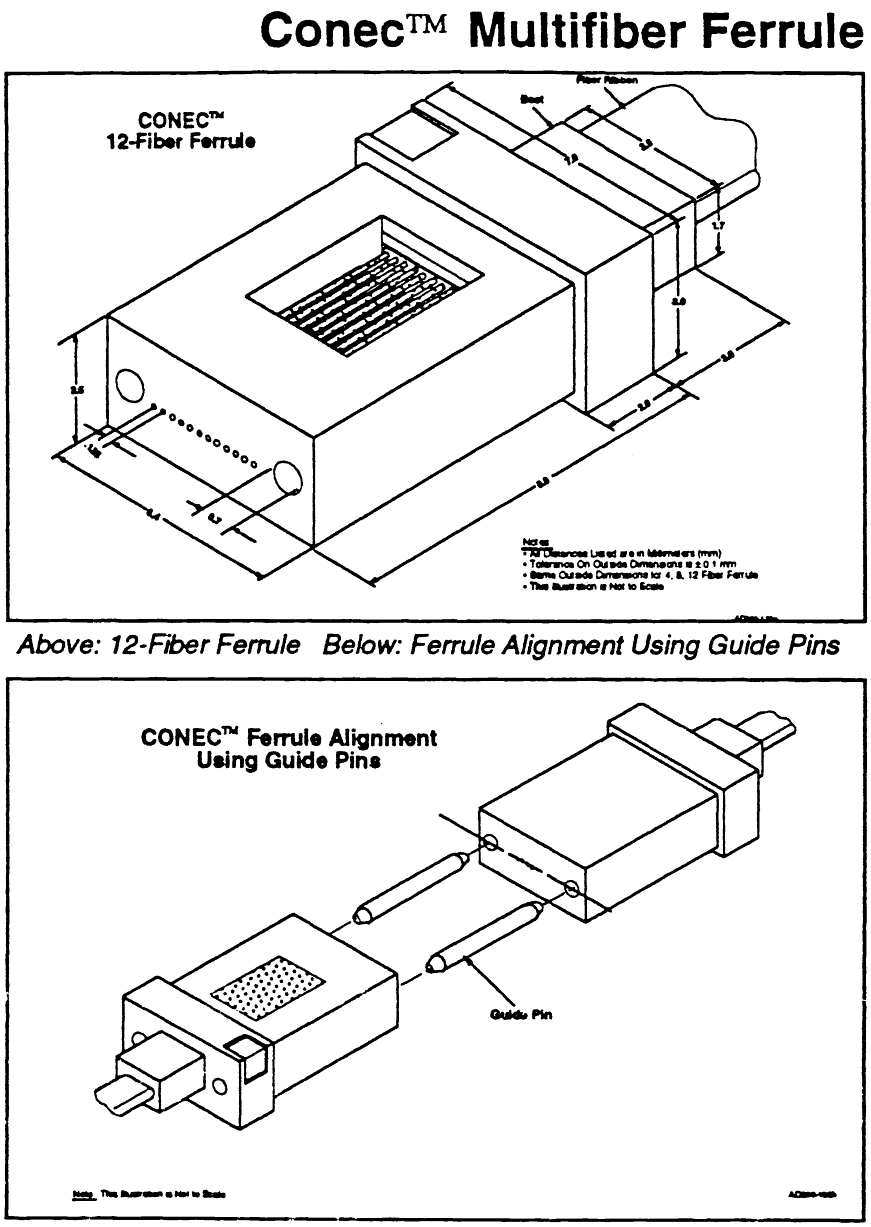


Figure 1. Connector diagram.

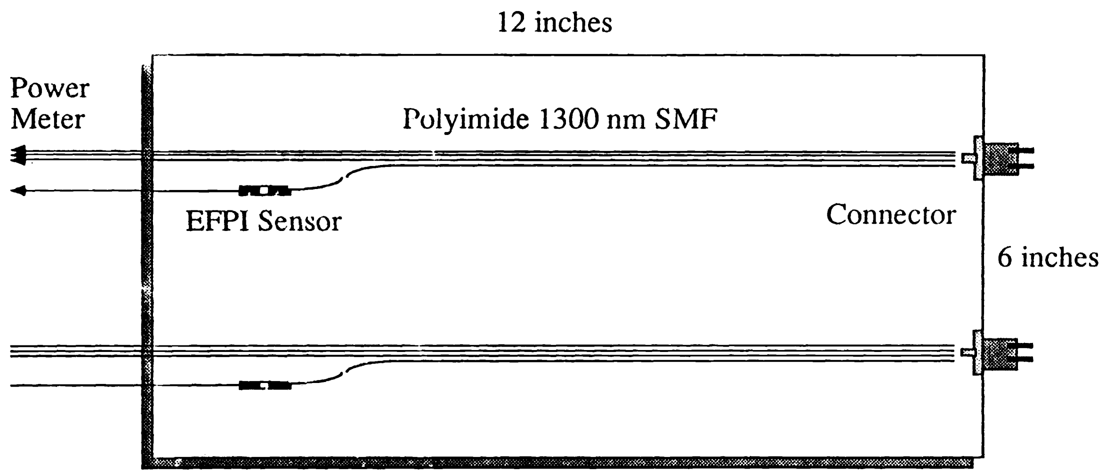


Figure 2. Optical fiber and fiber sensor layout configuration.

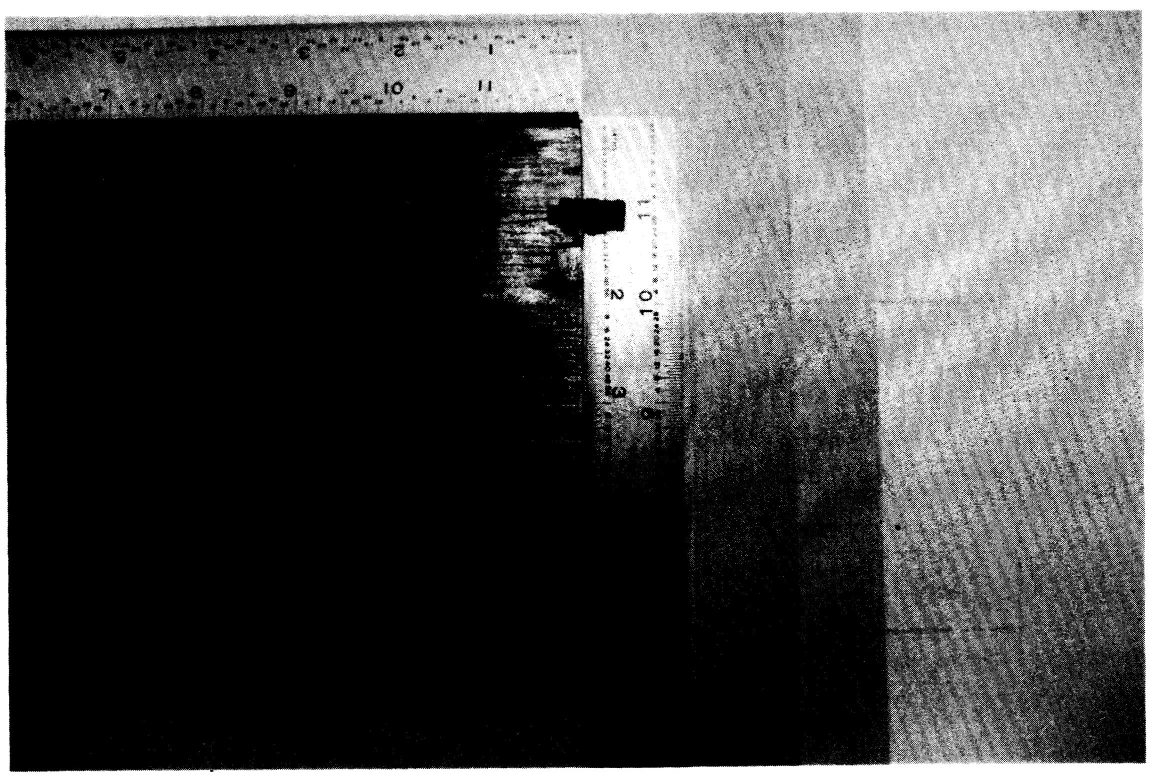


Figure 3. Photograph of the notched composite panel and fiber connectors.

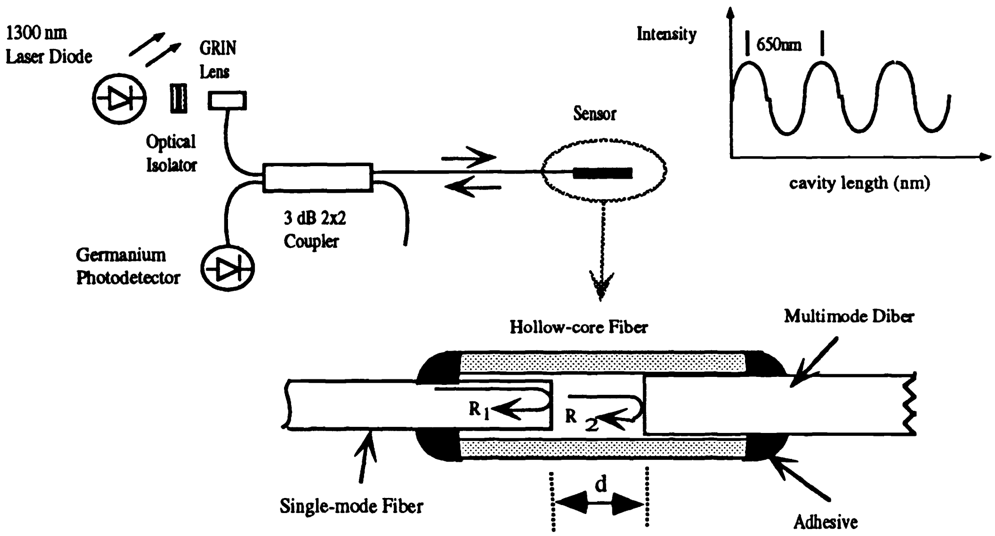


Figure 4. Extrinsic Fabry-Perot interferometric fiber sensor.

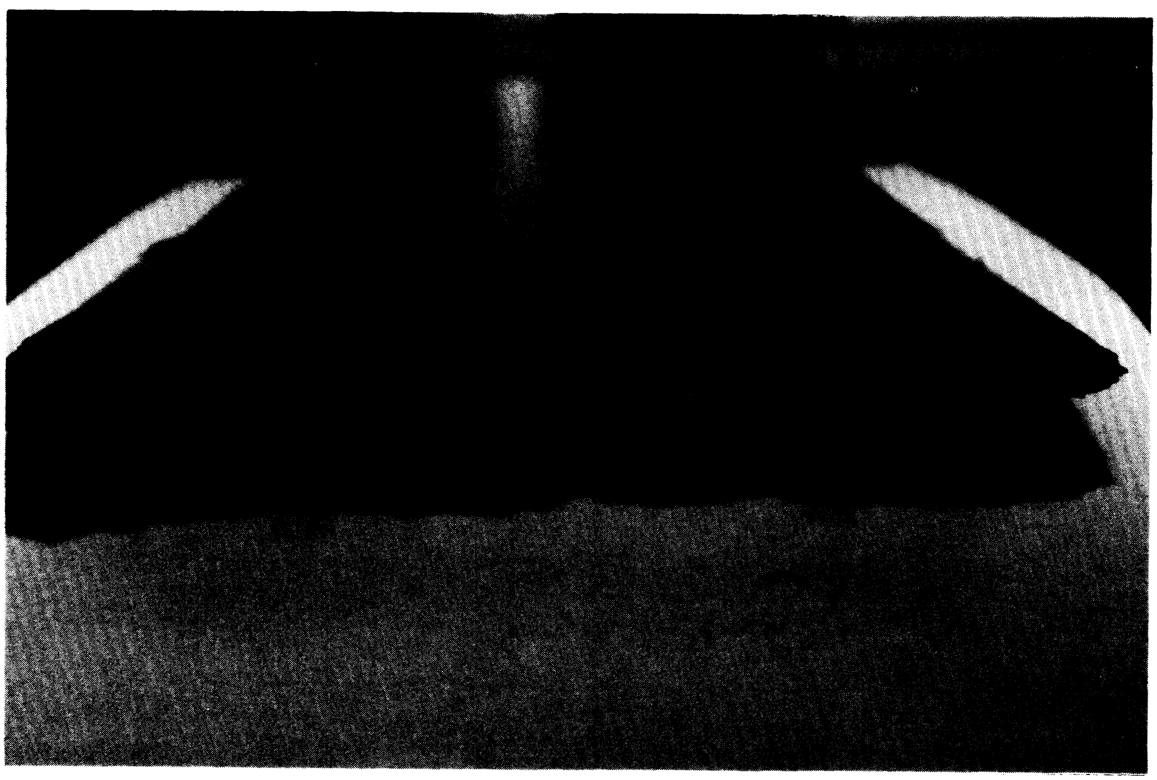


Figure 5. Photograph of the connectorized panel.

Cable Assembly 1 Connector Loss (dB)			
Channel	Bench Connector	Embedded Connector	Deviation
1	.55	EFPI	–
2	.45	.65	45%
3	.32	.49	53%
4	.35	.44	26%

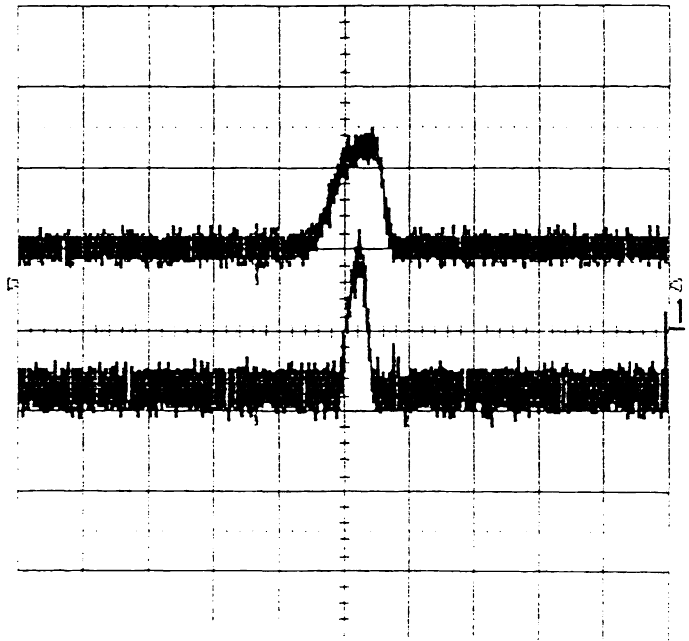
Fully Notched Composite Panel

Cable Assembly 2 Connector Loss (dB)			
Channel	Bench Connector	Embedded Connector	Deviation
1	.35	EFPI	–
2	.50	1.1	120%
3	.55	.9	64%
4	.45	1.1	144%

Partially Notched Composite Panel

Figure 6. Table of insertion losses before and after embedding.

Sensor 1



Sensor 2

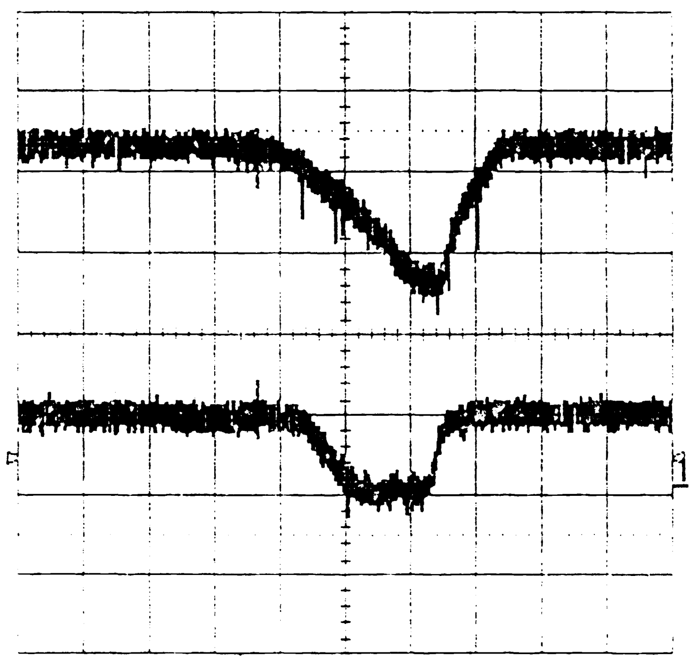


Figure 7. EFPI output under loading conditions, showing successful connectorization of embedded fiber sensors, a) EFPI output during bending through connector 1 and b) EFPI output from connector 2. Both oscilloscope traces are 1 volt/div vertical scale and 1 sec/div horizontal scale.