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In Situ Formation of Strain Sensors by Breaking Optical Fibers in Structural Materials

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ABSTRACT: This article describes the formation of strain sensors embedded in a matrix material by breaking a notched optical fiber in the matrix. When a specimen with an embedded optical fiber with a notch is tensile tested, fracture of the fiber at the notch occurs, producing an optical interference type strain sensor. During the formation process optical transmission loss is recorded. The case of multiply notched optical fibers is also considered and it is shown that the optical loss of the embedded optical fiber during tensile test increases with the number of breaks. Using bending, instead of tension, to form the sensor, allows a reduction of break pitch and consequently improves the local nature of the sensor. The multiple fractured type optical fiber sensor has also been used on an active laminate to monitor its curvature change during actuation.

KEY WORDS: smart material, optical fiber, composite, strain sensor, active material.

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Figures 1–6 appear in color online: <http://jtc.sagepub.com>

INTRODUCTION

ADVANCED STRUCTURAL MATERIALS with embedded sensors are attracting worldwide interest because of their innovative functions such as health monitoring [1–4] as well as shape monitoring and control [5,6]. Fiber optic sensors in particular offer several advantages over the conventional ones: they are immune from electromagnetic interferences, they are small, and made of glass which is an insulating material. This last aspect is very convenient when the embedding is performed in metallic materials. Furthermore, the specific weight is much lower than copper. Various types of sophisticated fiber optic sensors have been developed such as the Fiber Fabry Perot Interferometer (FFPI) and the Fiber Bragg Gratings (FBGs) [7–9]. Also embedding procedures for those sensors have been tested in high performance structural materials such as composites. Embedding in metals, ceramics, and concrete have been performed successfully as shown in [10–12].

A simple and effective optical interference or loss type sensor is tested in this work. The concept, proposed by Asanuma [13,14] is shown in Figure 1. The sensor can be obtained by breaking a notched optical fiber embedded in a material. The sensing part is formed inside the material without the need of alignment of the fiber optical axis, a tube for the alignment, and an adhesive for fixing the tube. A simple, compact, robust, and low cost fiber optic sensor can be easily obtained. The purpose of this study is to demonstrate the concept and examine the performances of this new sensor. The active laminate, already proposed in [15] is also used to show a possible application of this new type of sensor.

EXPERIMENTAL

Formation of Sensors in Epoxy Matrix

A quartz type and single mode optical fiber (produced by Fujikura Co., Ltd.) was used. Fiber diameter was 250 μm , including the acrylate coating (125 μm without coating). Notches were made on the optical fiber with an optical fiber cutter. Epoxy resin (Araldite CY230) was used for the material. The curing temperature and period were 393 K and 3.6 ks, respectively.

Number of notches and their distances on the optical fiber are expressed as n and s , respectively, as shown in Figure 1. The n and s were varied from 1 to 15 and 0.5 to 10 mm, respectively. Optical fibers with the notches were embedded in the epoxy resin. A tensile sample, shown in Figure 2(a), and a bending sample, shown in Figure 2(b), were made. For the higher number of n and s the gage length needed to be increased (for instance in

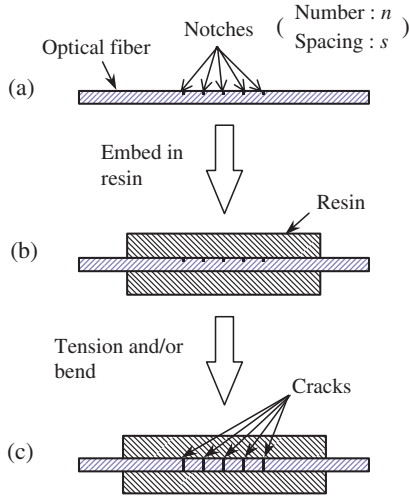


Figure 1. Concept for in situ formation of fiber-optic strain sensors.

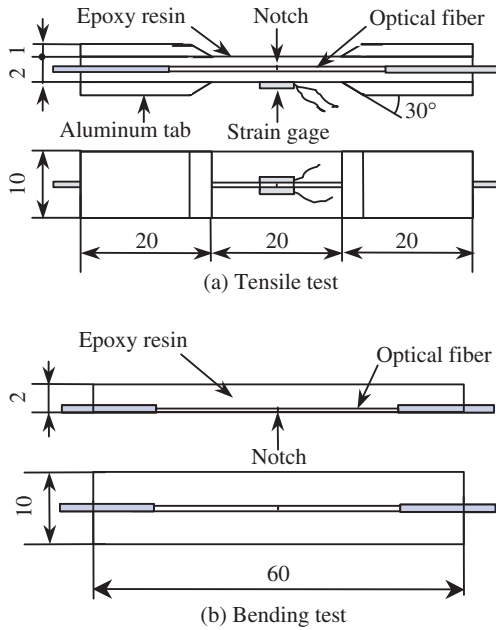


Figure 2. Shapes and dimensions of the test pieces (in mm).

the case of $n = 10$ and 15 at $s = 4$ mm the gage length was increased to 40 and 60 mm, respectively).

Tensile test was undertaken by using an Instron type machine at room temperature under the crosshead speed of 0.1 mm/min. Bending test was undertaken by using the same testing machine, a 90° V block, and an R type punch with a radius of 5 mm. The test piece was put on the block so that the embedded optical fiber was above the neutral axis.

In both the tensile and bending tests, one end of the embedded optical fiber was connected to an LD light source of $0.67 \mu\text{m}$ wavelength and the other end was connected to a light power meter.

Formation of Sensors in Active Laminate

The materials used to fabricate the active laminate are shown in Table 1. The aluminum plate was used as the high coefficient of thermal expansion (CTE) material while the carbon fiber reinforced plastics (CFRP) prepreg was used as the low CTE material and the heater. An epoxy adhesive film was used as the insulator between them, while the copper foils were used, in two opposite edges of the laminate, as the electrodes to apply a voltage on the CFRP laminate. When current flows in the carbon fiber of the CFRP laminate, heat is produced by the Joule effect. Heat propagates on the aluminum plate as well causing its expansion. On the other hand, CFRP due to the negative CTE of carbon fibers has a negligible deformation. As a consequence the active laminate bends.

To manufacture the sensor, 15 notches with $s = 3$ mm were made on an optical fiber. Then the notched optical fiber was placed between the plies of the CFRP prepregs to form the laminate. Copper foils were also included, as shown in Figure 3(a), to provide the electrical contact required during operation. This pile was hot-pressed at 453 K, 0.1 MPa for 7.2 ks.

Table 1. Materials used to manufacture the active laminate.

Material	CTE α (10^{-6} K^{-1})	Thickness, t (mm)	Type
Aluminum plate	23.6	0.2	A1050P-H24
CFRP prepreg	0.7	0.125	P3060B-12 (Fiber: Torayca T300 ($V_f = 0.6$), Resin: 453K cure type epoxy resin (#3601)) produced by Toray Co., Ltd.
Epoxy adhesive film	60	0.25	Redux 319 produced by Hexcel Composites Ltd.
Copper foil	16.5	0.02	C1100

Next, this consolidated layer was bent with a rod as shown in Figure 3(b) to break the embedded optical fiber at the notches while monitoring optical loss through the LD light source of $0.67\ \mu\text{m}$ wavelength and the power meter. Finally, this laminate was completed with the adhesive film, which is known to be important also for providing electrical insulation, and the aluminum plate (Figure 4(a)). This hybrid laminate is then hot-pressed at 448 K, under 0.1 MPa for 3.6 ks. The result is the active laminate with the embedded optical fiber sensor (Figure 4(b)).

In Figure 5, a schematic diagram of the curvature and optical loss measurement system is shown. The active laminate was put on a 90° V block having supporting edges of 50 mm span and its embedded optical fiber was connected to the LD light source and the power meter. Subsequently, the laminate was heated by connecting the electric power source to

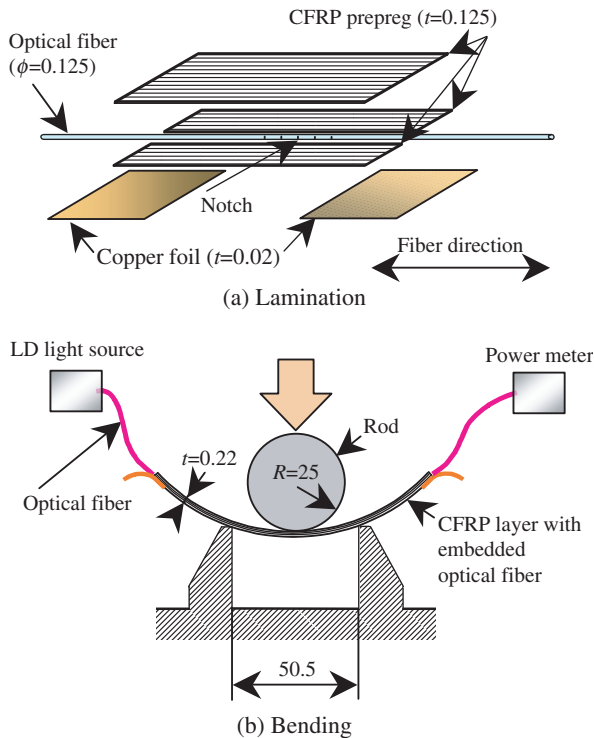


Figure 3. Method to introduce the optical loss type sensor in the CFRP layer: (a) lamination of the materials to form a CFRP layer embedded with a notched optical fiber and (b) bending of the CFRP layer to cause fractures of its embedded optical fiber at the notches. (Dimensions indicated are in mm.)

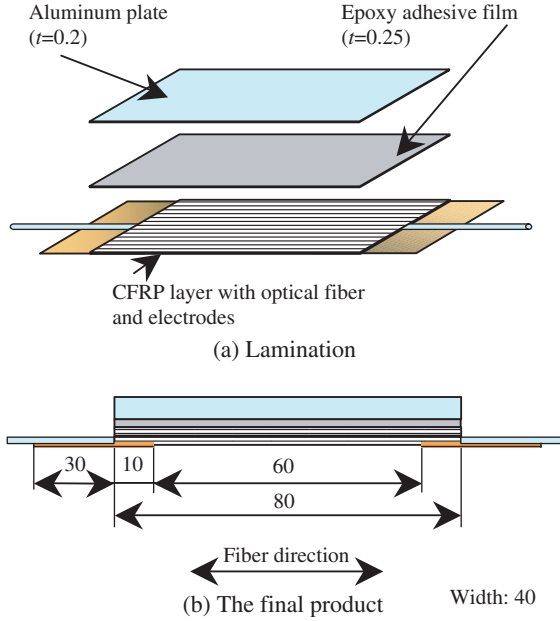


Figure 4. Lamination of the CFRP layer with the other materials to form the active laminate with the embedded optical fiber sensor. (Dimensions are in mm.)

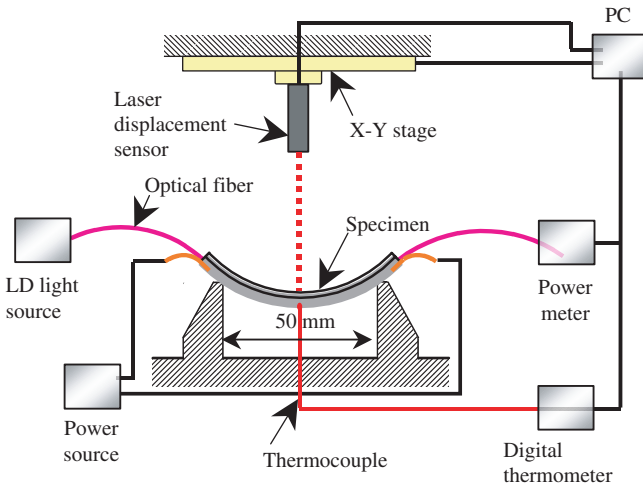


Figure 5. Schematic diagram of the curvature and optical loss measurement system for the active laminate.

the CFRP layer through the copper foils. The change in curvature is independently measured by monitoring the central point and the other two points near the supporting edges on the specimen surface. Coordinates of these three points were measured with the laser displacement sensor attached to the X–Y stage. Average curvature of the specimen was calculated taking the inverse of the radius of the circle passing through those three points. Variation of the optical loss during the curvature change was monitored.

RESULTS AND DISCUSSION

Tensile Test on Optical Fiber

A notch made with the optical fiber cutter is shown in Figure 6. As shown in this figure, length of the notch is about $50\ \mu\text{m}$, so, knowing the fiber diameter, it is easy to calculate the depth of the notch as $5.2\ \mu\text{m}$. Tensile strengths of the undamaged optical fiber and with a notch are compared in Figure 7. From the figure, it is clear that the average tensile strength is drastically decreased from 1.52 GPa to 1.25 MPa due to the introduction of the notch. To avoid fiber breakage at the jaws of the tensile machine, the fiber was fully accommodated on a groove manufactured on the tabs. Resin was used to block the fiber on the tabs.

Forming the Optical Interference Type Strain Sensor

An epoxy resin specimen with an embedded notched optical fiber was tensile tested while monitoring optical transmission loss. In Figure 8, the optical transmission loss and tensile strain versus time in the case of $n = 1$ is shown. According to the figure, the optical loss remains constant up to around 100 s, that is, at the strain of 0.55%, and then it starts to fluctuate sinusoidally. This result means that the optical fiber breaks at the strain of 0.55% and that the fracture surfaces are parallel to each other and normal to the optical axis. The two surfaces work as mirrors to cause optical interference that changes output light intensity while changing spacing between them. The optical fiber breaks at the location of the notch and the subsequent variation of optical power is also visually observed because the epoxy resin test piece is transparent and the leaked laser light is visible. Therefore, the fractured part is available as an optical interference type strain sensor, and the result clarified the effectiveness of the concept shown in Figure 1. The main difference between the proposed sensor and an FFPI is in the manufacturing process that is more complex for the FFPI and in the fact that usually only one FFPI is used in the fiber. In the proposed

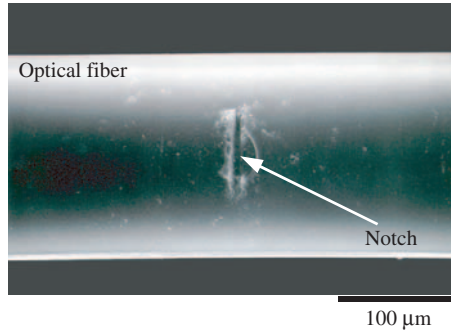


Figure 6. Optical fiber with a notch.

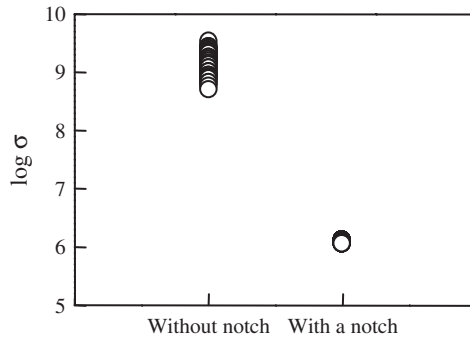


Figure 7. Tensile strengths of the optical fibers with and without a notch.

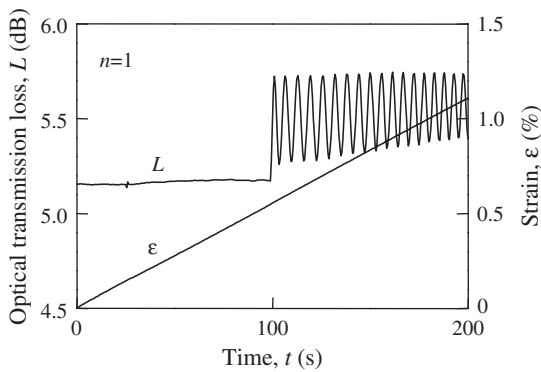


Figure 8. Optical transmission loss and tensile strain of a test piece with one notch ($n = 1$) as a function of time.

sensor there is a series of FFPI in cascade along the same fiber. The power transmitted by a single FFPI is, under certain simplified assumption:

$$I_t = I_0 \frac{(1 - r^2)^2}{\left[(1 - r^2)^2 + 4r^2 \sin^2(ka) \right]}$$

where I_0 is the light intensity before entering the FFPI, I_t is the light intensity after entering the FFPI, r is the reflection coefficient of the surface at the FFPI, $k = 2\pi/\lambda$ the wavenumber, and a is the distance between the two faces of the FFPI.

Tensile Test

In order to obtain a multiply fractured optical fiber in a material, spacing between the notches, s has to be equal to or larger than a critical length. Tensile test pieces were made to investigate the effect of s on the number of fractures, that is, 1 or 2. So, the spacing s between the two notches was varied between 1 and 10 mm. If the optical fiber breaks at both notches, the spacing s is large enough to cause its multiple fractures.

An example of results of the tensile test in the case of $n = 2$ and $s = 10$ mm is shown in Figure 9. According to the result, the optical fiber is broken at both notches in succession, and the light transmission loss caused by interference shows a jump at about 140 s.

In Table 2, the number of specimens in which 1 or 2 breaks occurred is reported as a function of the spacing s between the two notches. According to the results, the embedded optical fiber having two notches ($n = 2$) always breaks at both notches when s is equal to or larger than 4 mm. So the spacing s was selected at 4 mm to obtain multiple fractures.

In Figure 10, the optical loss and the strain versus time is shown for different number of notches n with constant spacing of $s = 4$ mm. In the case of $n = 5$, shown in Figure 10(a), the behavior is more complicated due to multiple fractures inside the same optical fiber. The oscillations are due to the interference occurring in the gap, analytically expressed by the $\sin^2(ka)$ reported in the previous formula. When n increases from 5 to 10 and 15, the optical interference becomes more complicated, but the average value of the optical loss with increasing n becomes closer to the behavior of the strain as shown in Figure 10(b) and (c). So the multiply fractured optical fiber in a material has a possibility to work as an optical loss type strain sensor.

The tensile test pieces, embedded with the multiply notched optical fiber, were loaded and unloaded for 4 cycles while monitoring the optical

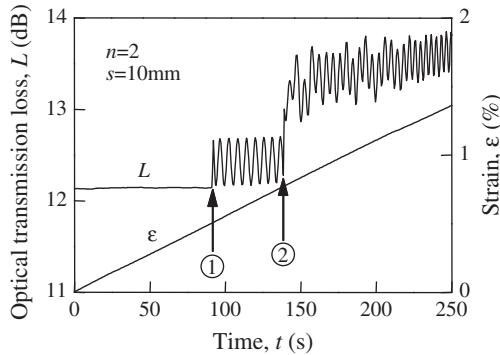


Figure 9. Optical transmission loss and tensile strain of a specimen with two notches ($n=2$) and $s=10\text{ mm}$ as a function of time.

Table 2. Effect of spacing of notches s on number of tensile test results in which optical fiber broke at 1 or 2 of the notches.

Spacing of notches s (mm)	Number of results	
	1 fracture	2 fracture
1	2	0
2	1	3
3	2	3
4	0	4
5	0	3
10	0	3

transmission losses. The results in the cases of $n=5$, 10, and 15 are shown in Figure 11. The optical loss in the case of $n=5$ roughly follows the behavior of strain during testing as shown in Figure 11(a). An improvement is obtained by increasing n to 10 and 15 as shown in Figure 11(b) and (c).

Bending Test

In order to decrease the critical fiber length and consequently notch distances, bending test was also performed. A bending test piece with an embedded optical fiber with $n=3$ and $s=0.5\text{ mm}$ was tested. The result is shown in Figure 12. According to the result, it is clear that the embedded optical fiber can be fractured into fragments as short as 0.5 mm. So bending is more effective with respect to the density of breaks.

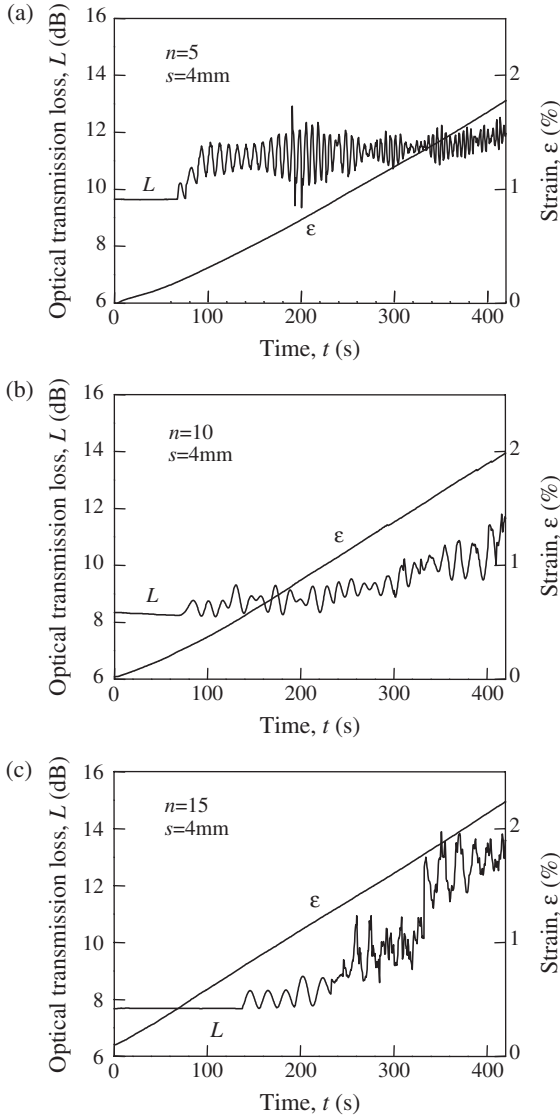


Figure 10. Optical transmission loss and tensile strain of test pieces with 5, 10, and 15 notches ($n = 5, 10, 15$) and $s = 4\text{ mm}$ as a function of time.

Optical Fiber Embedded in Active Laminate

Notched optical fibers of $n = 1$, and of $n = 15$ and $s = 3\text{ mm}$ were embedded in the CFRP layers as shown in Figure 3(a). The bending test

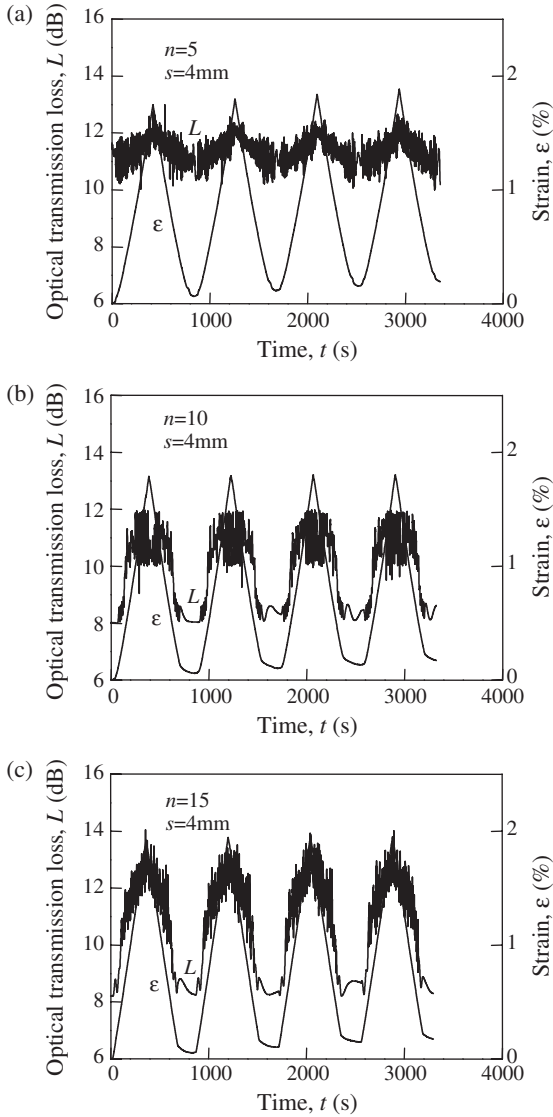


Figure 11. Optical transmission loss and tensile strain of test pieces with 5, 10, and 15 notches and $s = 4\text{ mm}$ as a function of time.

was performed with a punch of 25 mm radius as shown in Figure 3(b). The embedded optical fibers, as a consequence of the test, could break at each of the notches. These CFRP layers were then bonded with aluminum plates to obtain the active laminate as described in the section

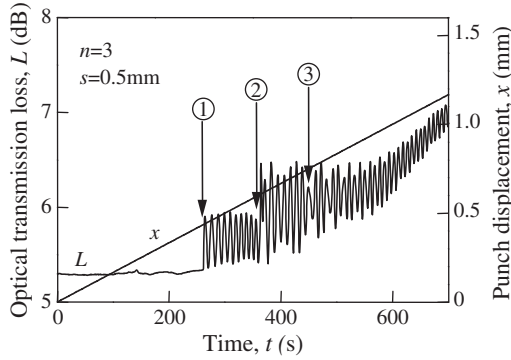


Figure 12. Bending test. Optical transmission loss of a test piece with 3 notches and $s=0.5\text{ mm}$. Punch displacement in mm as a function of time.

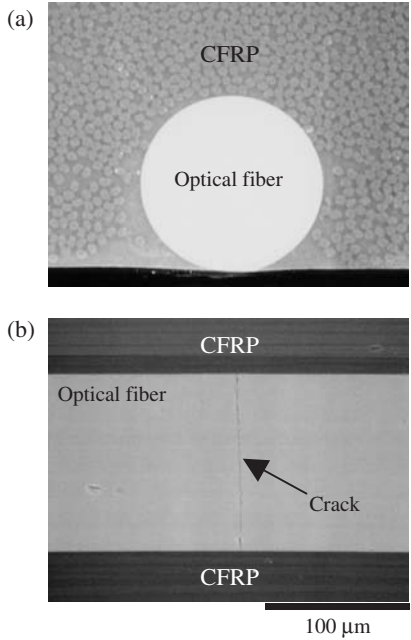


Figure 13. SEM images of: (a) a cross section and (b) a longitudinal section near the surface of the active laminate with the optical fiber.

titled ‘Formation of Sensors in Active Laminate’ and as shown in Figure 4. In Figure 13, a scanning electron micrograph of a cross section and of a longitudinal section of the active laminate are given. It can be seen that the optical fiber is placed adjacent to the free surface of

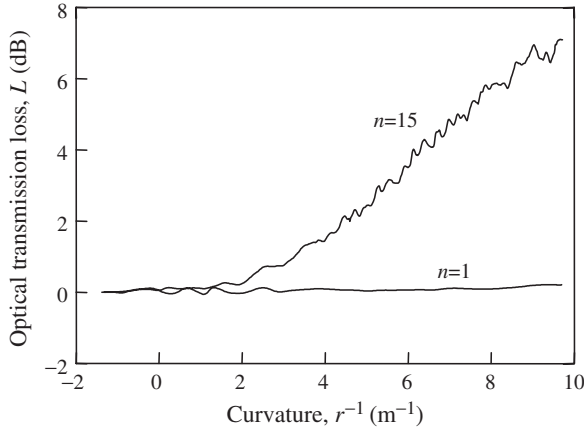


Figure 14. Effect of fracture number n of embedded optical fiber on the relation between curvature and optical transmission loss of the active laminate.

the CFRP laminate. That means the fiber will be subjected to the largest tensile strain during subsequent bending tests. Figure 13 also shows a crack in the optical fiber.

In Figure 14, the effect of the number of notches n of the embedded optical fiber on the relation between the curvature changed by heating of the CFRP layer and the optical transmission loss of the active laminate is shown. In agreement with what has already been shown in previous sections and in Figure 11 for the resin test samples, the higher number of notches, and ultimately of cracks, improves the sensing capability of the sensor. In fact according to Figure 14, the optical loss as a function of the curvature is clearly increased by the increase of the number n from 1 to 15. So the multiple breaks of the embedded optical fiber at its notches is effective to form a sensor for curvature monitoring of the active laminate and ultimately for its shape control.

CONCLUSIONS

1. An optical interference type strain sensor was successfully made in an epoxy resin test piece by breaking an embedded notched optical fiber by tensile test.
2. In the case of a multiply notched optical fiber, spacing of the notches was experimentally obtained as 4 mm in the case of tensile test.
3. Optical loss in the embedded optical fiber increases by increasing the number of fiber breaks from 5 to 15.

4. In the case of cyclic tests, performed on the specimens with embedded multiply fractured optical fibers, the optical losses follows the strain behavior better by increasing the number of the fiber fractures.
5. The pitch of the fiber breaks could be made as small as 0.5 mm by changing from tensile to bending tests.
6. The sensor, was successfully formed in the CFRP layer of the active laminate to monitor its curvature change during actuation.

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