JOURNAL OF MATERIALS SCIENCE **34** (1999) 5853–5860

The mechanical behavior of optical fiber sensor embedded within the composite laminate

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Mechanical behavior, such as tensile and fatigue strength, of the optical fiber sensor embedded within the composite laminate was investigated. Tensile and fatigue tests were performed to evaluate the static and fatigue characteristics of optical fibers embedded within three types of laminated composite specimens, $[0_6/\mathrm{OF}/0_6]_\mathrm{T}$, $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$ and $[0_3/90_3/\mathrm{OF}/90_3/0_3]_\mathrm{T}$. The initiation of damage and fracture of the optical fiber were detected by observation of the intensity drop-off of laser signal transmitted through the optical fiber during test. Experimental results showed that the fatigue strength of optical fiber embedded within the cross-ply laminate is much lower than the fatigue strength of optical fiber within the unidirectional ply laminate. It was also found that the optical fiber embedded within unidirectional ply laminate fractured due to the fatigue damage accumulation of internal defects of optical fiber itself. However the optical fiber embedded within the cross-ply laminate fractured due to the growth of transverse matrix crack of host composite laminate.

1. Introduction

The high specific modulus and strength of continuous fiber reinforced composites, combined with their excellent corrosion and fatigue resistance make them prime candidate materials for various engineering structural applications. However, one of the limiting features of laminated composite materials in service is their tendency for matrix cracking either within a ply (e.g. transverse ply cracking) or between plies (i.e. delamination or interlaminar cracking). This requires accurate characterization of damage initiation and process taking place within the composite structure during service. Various destructive and non-destructive evaluation techniques have been developed to detect and visualize the characteristic internal damage states [1–3].

Most of the conventional damage assessment techniques require the composite structures or components to be taken out of service. Therefore, the development of viable *in situ* damage monitoring techniques for the composite components involving network of embedded optical fiber sensors may offer significant benefits to the whole composite application industries. These fiber optic smart structures allow engineers to add nervous system to their designs, enabling capabilities to structures that would be very difficult to achieve by other means, including continuous assessment of damage processes [4–7]. The increasing use of optical fiber sensor as a sensing material has been found because they have several attractive features compared to other sensors [8], that is, optical fibers are small, light weight, flexible and are immune to electromagnetic interference and so on. Optical fiber sensors can offer following capabilities to composite structures, such as detection of damage and deformation, aiming to obtain continuous real time health monitoring for the integrity of structures.

One of such applications is the embedding of optical fibers into the laminated composite structures to establish nervous system. Jensen *et al.* [9, 10] and Measures *et al.* [11] reported that embedded optical fibers may degrade the uniaxial tensile and compressive properties of composite laminates. There have been a number of studies aiming at measuring the damage development and structural integrity of polymer matrix composite with embedded optical fibers [12–15].

However, for the successful application of optical fiber sensor to smart composite structures, in addition to the integrity of the host composite laminate with embedded optical fibers, it should be also investigated that whether or not the embedded optical fiber sensor can survive and perform their designed functions under the service loading condition of host structures which are usually subjected to various fatigue loading.

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A serious study on the fiber optic composite structures has started since the early of 1990s and considerable research papers, concerning effect of the embedded optical fiber on the mechanical behavior of host composite structures, have been reported. But few study on the mechanical behavior of optical fiber sensor itself embedded within the composite structures [16], which can be influenced by the loading condition of host structures, has been reported.

In this paper, based on the literature survey, the mechanical behavior of optical fiber sensor itself embedded within composite laminate was investigated. The observation of damage initiation and propagation, due to the external loading, of optical fiber embedded within the laminated composite specimens is performed by using drop-off of the intensity of laser light signal transmitted through the specimens. Comparison of the fatigue behavior of the optical fiber embedded within different ply laminates was performed by measuring fatigue life of optical fibers embedded within different specimens and obtaining the *S*-*N* curve. Fracture and damage mode of optical fiber embedded within different ply laminates were also observed.

2. Experimental procedure

2.1. Specimen fabrication

Test specimens consisted of three types of stacking sequence; a unidirectional ply laminate, $[0_6/\mathrm{OF}/0_6]_\mathrm{T}$, two cross-ply laminates, $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$ and $[0_3/90_3/\mathrm{OF}/90_3/0_3]_\mathrm{T}$. Fig. 1 shows the location and orientation of the optical fiber embedded within cross-ply laminate specimen, $[0_3/90_3/\mathrm{OF}/90_3/0_3]_\mathrm{T}$, as an example, among three types of laminated specimens.

All specimens were fabricated with UGN-150 glass/epoxy prepreg produced by SUNKYUNG INDUSTRY Co. Single mode optical fiber DSF (dispersion shifted fiber) produced by SAMSUNG ELECTRONICS Co. was embedded within laminated composite specimens. The transparent glass/epoxy laminates were used. Because the initiation and propagation of damage such as delamination, matrix cracking and the leakage of laser light signal due to the damage or fracture of optical fiber can be observed visually and directly. An optical fiber was embedded within the neutral plane of specimens along the loading direction. The coating, for 60 mm test section of specimen as shown in Fig. 1, of optical fiber was removed chemically by acetone to increase the sensitivity of optical fiber to damage of composite laminate.

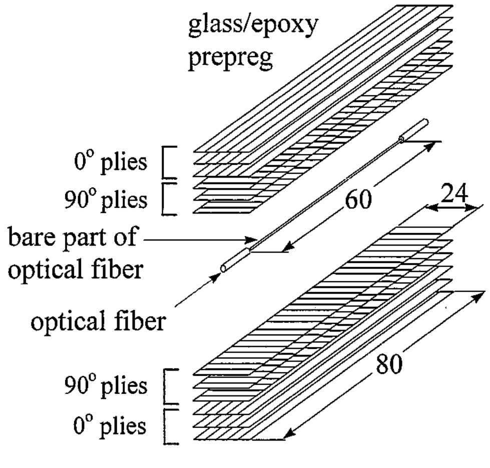


Figure 1 The position and the orientation of the embedded optical fiber for $[0_3/90_3/\mathrm{OF}/90_3/0_3]_\mathrm{T}$ specimen .

After curing of the laminated prepreg according to the manufacturer's instruction for the cure cycle, loading tabs were bonded using CYANAMID FM 73 film adhesive at both ends of specimens. The completed test specimens can be obtained from the cured laminate panel by cutting out using a water-cooled diamond wheel cutter. The completed specimen's dimension is shown in Fig. 2.

2.2. Test setup

Tensile and fatigue tests were performed for the composite laminate specimens using 25 ton MTS 810 servo-hydraulic test machine. Tensile tests were performed with constant loading rate, 0.6 mm/min. Fatigue tests were carried out under the load of sinusoidal wave with frequency of 5 Hz and stress ratio, *R* (minimum stress/maximum stress), of 0.1 to avoid the compressive stress during the cyclic loading. The overall experimental setup is shown schematically in Fig. 3.

He-Ne laser with the wavelength of 0.6328 μm was introduced into the optical fiber embedded within

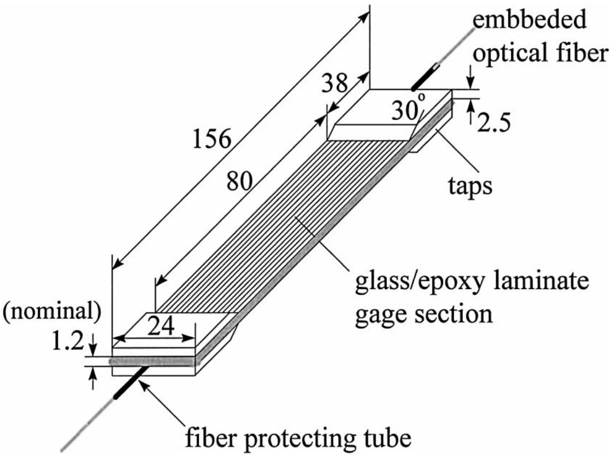


Figure 2 Dimension of a specimen (unit in mm).

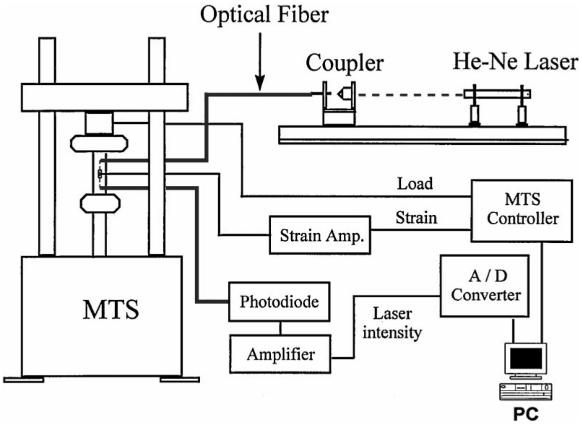


Figure 3 Schematic diagram of experimental setup.

composite laminate specimens by using coupler which consists of a set of lenses and an optical fiber positioning assembly. The intensity of laser signal transmitted through the embedded optical fiber was measured in terms of voltage by a photo-diode transducer. Static, cyclic load history and the intensity of laser signal were recorded automatically during the tests by a PC-based data acquisition system. The damage initiation and fracture of the optical fiber was detected by the observation of intensity drop-off of laser signal transmitted through optical fiber and also confirmed visually by the leakage of laser signal at the location of damaged optical fiber.

3. Results and discussion

3.1. Tensile behavior of optical fiber embedded within the composite laminates

3.1.1. Tensile behavior of optical fiber embedded within the unidirectional ply laminate

Before fatigue test, tension tests for the composite specimens were performed to determine the tensile strength of optical fiber sensors embedded within the laminated composite specimens, $[0_6/\mathrm{OF}/0_6]_T$. Fig. 4 shows the relationship between the intensity of laser signal and strain of composite specimens. As shown in Fig. 4, damage initiation occurs at around 1% strain and complete fracture of optical fiber embedded within the specimen occurs 1.2% strain. An abrupt drop-off of the intensity of laser signal at around 1.2% strain indicates that the complete fracture of optical fiber occurred. This behavior of damage initiation and fracture of optical fiber can be also observed visually because of the transparency of glass fiber/epoxy laminate specimens as shown in Fig. 5. As shown in this figure, if damage initiation occurs, the optical fiber leaks laser light resulting in the intensity drop-off of laser signal until complete fracture of optical fiber.

Fig. 6 shows the cumulative distribution of failure probability of optical fibers embedded within unidirectional specimens with the applied stress. Generally, fibrous materials, such as optical fibers, show that the tensile strength has large scatter band due to the inhomogeneous distribution of internal defects within the materials. Thus the expression of tensile strength of fibrous materials in terms of statistical cumulative distribution of failure probability is preferred [17, 18]. The failure probability of optical fiber embedded within the specimens under the tensile load can be express as Equation 1 from this experimental data.

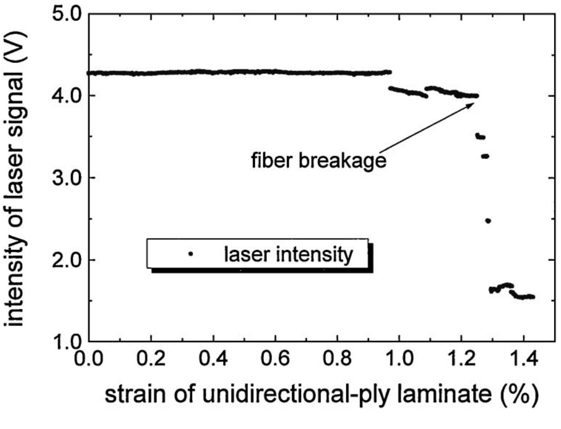


Figure 4 The intensity drop-off, due to the damage or fracture of optical fiber, of laser signal transmitted through the optical fiber sensor embedded within unidirectional ply laminate under static loading.

$$F(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{480}\right)\right)^{5.47}, \quad \text{for} \quad [0_6/\mathrm{OF}/0_6]_T \tag{1}$$

In Equation 1, $F(\sigma)$ is the cumulative failure probability and σ (MPa) is stress applied to specimen. The average tensile strength of embedded optical fiber, which is obtained from the distribution of failure probability as shown in Fig. 6, is 443 Mpa but the average tensile strength of composite laminate specimens itself, $[0_6/\mathrm{OF}/0_6]_T$, is 900 MPa.

Macroscopically, evidence for the initiation of any damage of specimen itself, such as matrix cracking, delamination and fiber breakage, was not observed up to 443 MPa during the tensile test.

3.1.2. Tensile behavior of optical fiber embedded within the cross-ply laminate

Tension tests for the cross-ply laminate with embedded optical fiber, $[0_2/90_4/\mathrm{OF}/90_4/0_2]_T$ and $[0_3/90_3/\mathrm{OF}/90_3/0_3]_T$, were performed with same manner as for the unidirectional ply. Fig. 7 shows the cumulative distribution of failure probability for the above two cross-ply specimens. The statistical Weibull distribution of above two cross-ply specimens was expressed by the following equations.

$$F(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{179}\right)\right)^{5.68}, \quad \text{for} \quad [0_2/90_4/\mathrm{OF}/90_4/0_2]_T \tag{2}$$

$$F(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{209}\right)\right)^{7.49}, \quad \text{for} \quad [0_3/90_3/\mathrm{OF}/90_3/0_3]_T \tag{3}$$

As expected, failure probability of optical fibers embedded within the cross-ply specimens is influenced by the number of 0° ply of the cross-ply specimens as shown in Fig. 7, that is, the optical fibers embedded within the specimens of $[0_3/90_3/\mathrm{OF}/90_3/0_3]_T$ have lower failure probability than that of specimen of $[0_2/90_4/\mathrm{OF}/90_4/0_2]_T$ at same stress level.

The average tensile strengths of optical fibers embedded within the $[0_2/90_4/\mathrm{OF}/90_4/0_2]_T$ and $[0_3/90_3/\mathrm{OF}/90_3/0_3]_T$ are 165 and 197 MPa respectively. During the tensile test of above two cross-ply specimens, about 10–20 transverse matrix cracks were observed within the 160 mm gauge length when the fracture of optical fiber was occurred.

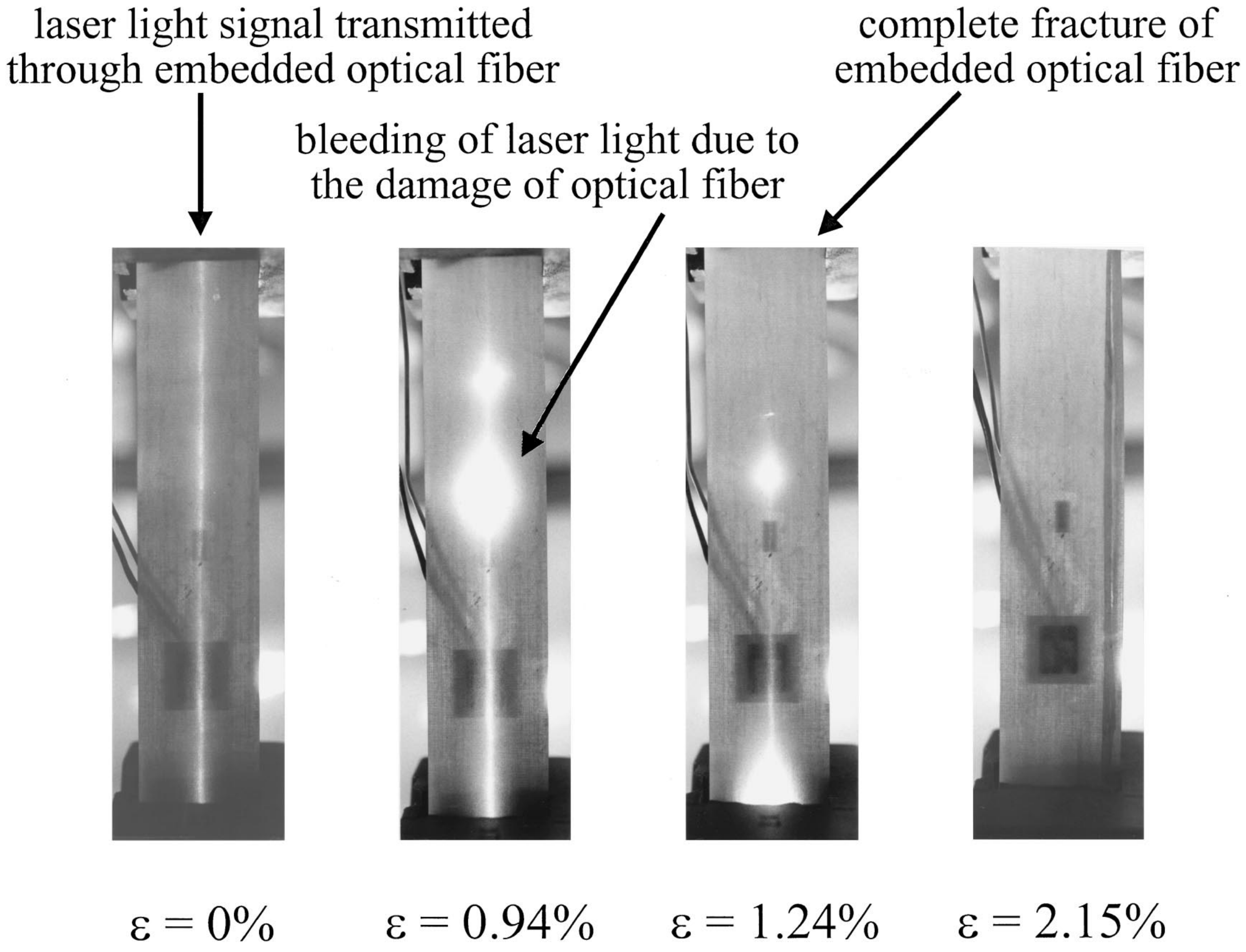


Figure 5 Photographs showing damage and fracture, resulting in leakage of laser light signal, of the optical fiber embedded within unidirectional ply specimen.

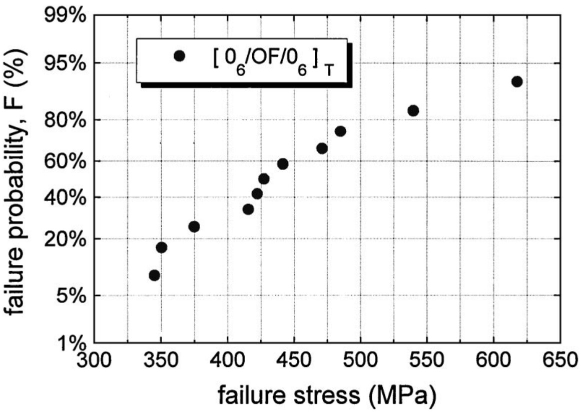


Figure 6 Cumulative distribution of failure probability of the embedded optical fiber sensor for the tensile stress applied to $[0_6/\mathrm{OF}/0_6]_\mathrm{T}$ specimen.

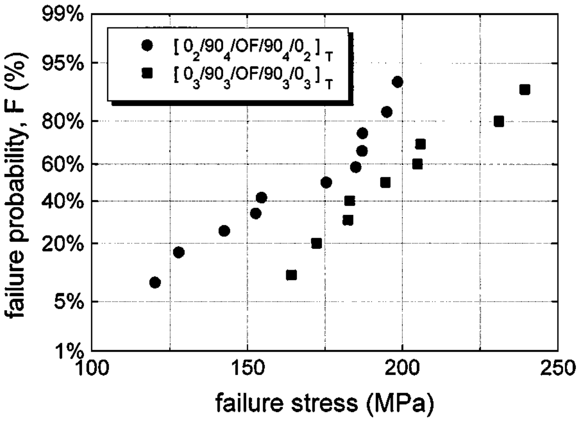


Figure 7 Cumulative distribution of failure probability of the embedded optical fiber sensors for the tensile stress applied to $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$ and $[0_3/90_3/\mathrm{OF}/90_3/0_3]_\mathrm{T}$ specimen.

3.2. Fatigue behavior of optical fiber embedded within the composite laminates

3.2.1. Fatigue behavior of optical fiber embedded within the unidirectional ply laminate

Fig. 8 shows the typical example for the drop-off of intensity of laser signal transmitted through the optical fiber embedded within the unidirectional ply specimen according to the increase of fatigue cycle. The intensity of laser signal is almost constant until the fiber fracture and then abrupt drop-off of the intensity of laser signal occurs due to the fracture of optical fiber. In this figure the intensity of laser signal is expressed in terms of voltage obtained from the photo-diode transducer. To observe the fractured optical fiber microscopically, the outer ply of specimen covering the fractured optical fiber was removed by using abrasive and schematic diagram of the specimen prepared for microscopic observation is shown in Fig. 9. Any visible significant

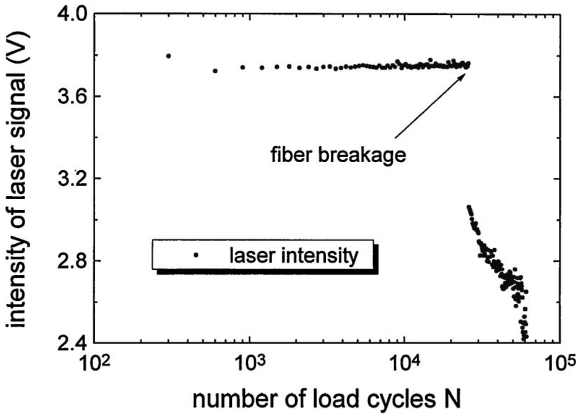


Figure 8 The intensity drop-off of laser signal transmitted through the optical fiber sensor embedded within the unidirectional-ply laminate under fatigue loading.

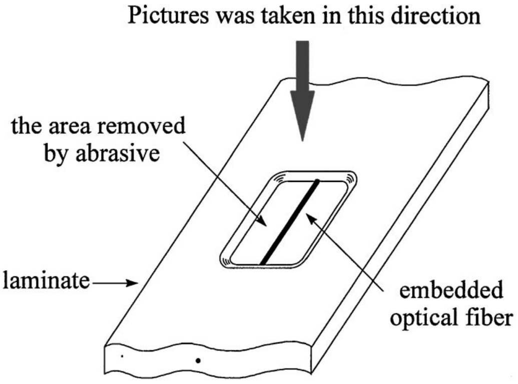


Figure 9 Schematic diagram of the specimen prepared for microscopic observation.

damage around the fractured optical fiber, such as glass fiber breakage, splitting of matrix resin and delamination, was not found by observation with optical microscope until the fracture of optical fiber embedded within the unidirectional specimen as shown in Fig. 10. Based on the above observation, it may be said that the fracture of optical fiber embedded within the unidirectional ply was not influenced by any damage of host composite specimen, such as fiber breakage and delamination which may cause additional stress in the optical fiber, and the fracture of optical fiber embedded within the unidirectional ply started from the damage accumulation of microstructural internal defect of optical fiber itself.

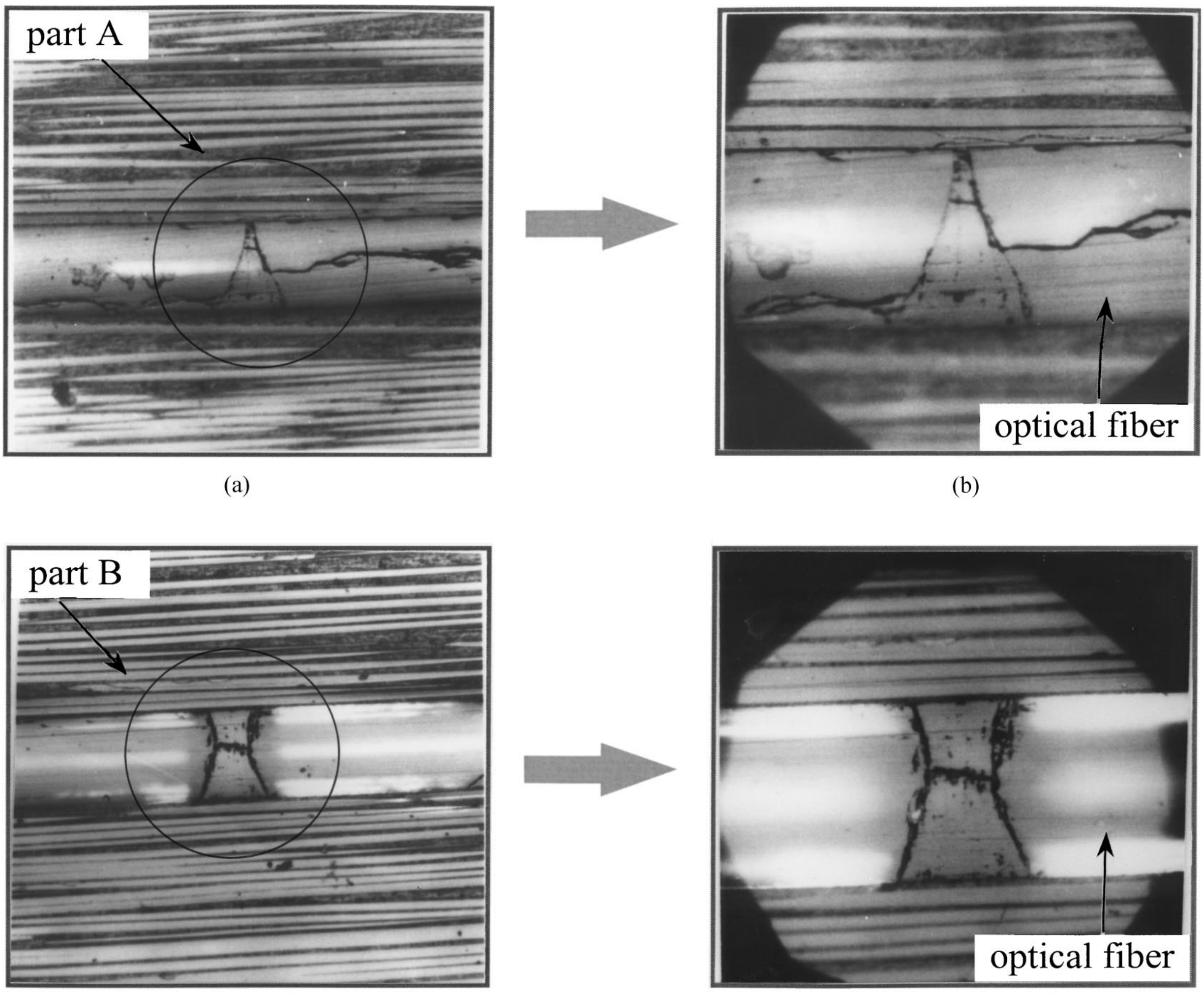
Fig. 11 shows the relationship between cyclic stress amplitudes, S, and number of failure cycles, N, which is S-N curve of optical fiber sensors embedded within the unidirectional ply specimens. This S-N curve shows the fatigue characteristics of optical fiber embedded within the composite laminates. Because of relatively wide scatter band of data, it is difficult to describe clearly fatigue behavior such as fatigue limit. However, from Fig. 11, about 40% of static tensile strength can be suggested as fatigue limit of optical fiber embedded within the unidirectional ply. The wide scatter band of fatigue data can be attributed to the inhomogeneous distribution of microstructural defect in an optical fiber itself. This means that the size and distribution of internal defect of optical fiber itself shows much differences between the optical fibers embedded within specimens. Therefore for the successful application of optical fiber sensors to composite structures, careful design considerations should be given to obtain the integrity of an optical fiber sensor of smart composite structures with optical safety factor.

3.2.2. Fatigue behavior of optical fiber embedded within the cross-ply laminate

Unlike unidirectional ply laminate in which any visible damage of specimens was not found until the fracture of optical fiber, during the fatigue test for the cross-ply specimens, $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$ and $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$, matrix cracks in transverse ply were found before the fracture of the embedded optical fiber. Matrix cracks of the cross-ply laminate, initiated from the both ends befoe the fracture of optical fiber, propagate to the optical fiber embedded within the center of width of specimens according to the increment of fatigue cycle. Among the matrix cracks within the transverse ply, if any matrix crack tip arrived at the optical fiber, the fracture of optical fiber was observed within a several fatigue cycles due to the strain concentration on the matrix crack. Thus, the fatigue life of optical fiber embedded within the cross-ply is almost same as the time of propagation of matrix crack from both ends of specimen width to the optical fiber. The optical micro photos of Fig. 12 show the close-up of fractured optical fiber within a cross-ply laminate. From this figure, it is clear that the propagating matrix crack causes directly the fracture of optical fiber. Based on the observation in Fig. 10, in which any damage of specimens was not found, it can be said that the major cause of the fracture of optical fiber within a cross-ply specimens is quite different from that of unidirectional specimen.

Another notable difference between the static and fatigue loading is that under the fatigue loading only a few matrix crack is enough to cause the fracture of optical fiber, while under the static loading about 10–20 matrix cracks were found before fracture of optical fiber within a cross-ply specimens. Under the fatigue loading the transverse matrix cracks show more serious effect on the fracture of optical fiber than the matrix cracks of the static loading.

S-N curves for two cross-ply specimens, $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$ and $[0_3/90_3/\mathrm{OF}/90_3/0_3]_\mathrm{T}$, were shown in Fig. 13. The fatigue limits of optical fibers embedded within these two cross-ply specimens are about 30% of the static strength and the relatively narrow scatter bands of fatigue life data are shown in Fig. 13 compared to the data of unidirectional ply specimens. This indicates that the major cause of the fracture of optical fiber within the cross-ply is not the internal defect of optical fiber itself but the transverse matrix crack. The comparison of fatigue life of optical fiber embedded within different ply is shown in Fig. 14. The fatigue life of optical fiber embedded within the cross-ply is much lower than that of unidirectional ply. This means that the transverse matrix cracks of cross-ply laminate have significant effect on the fatigue life of optical fiber embedded within the cross-ply laminates.



(a) (b)

(c) (d)

Figure 10 Microscopic photographs of fractured optical fiber sensor embedded within unidirectional ply laminate; (b), (d) are the close-up of part A and part B in (a), (c).

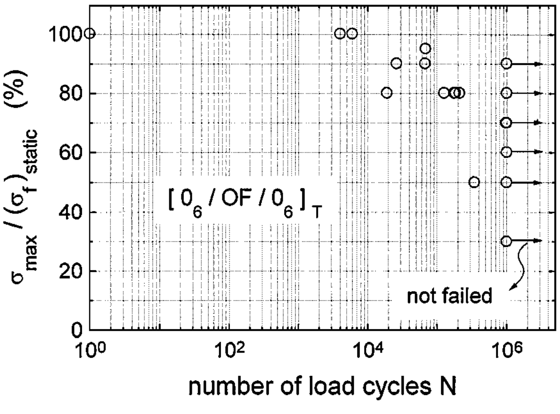
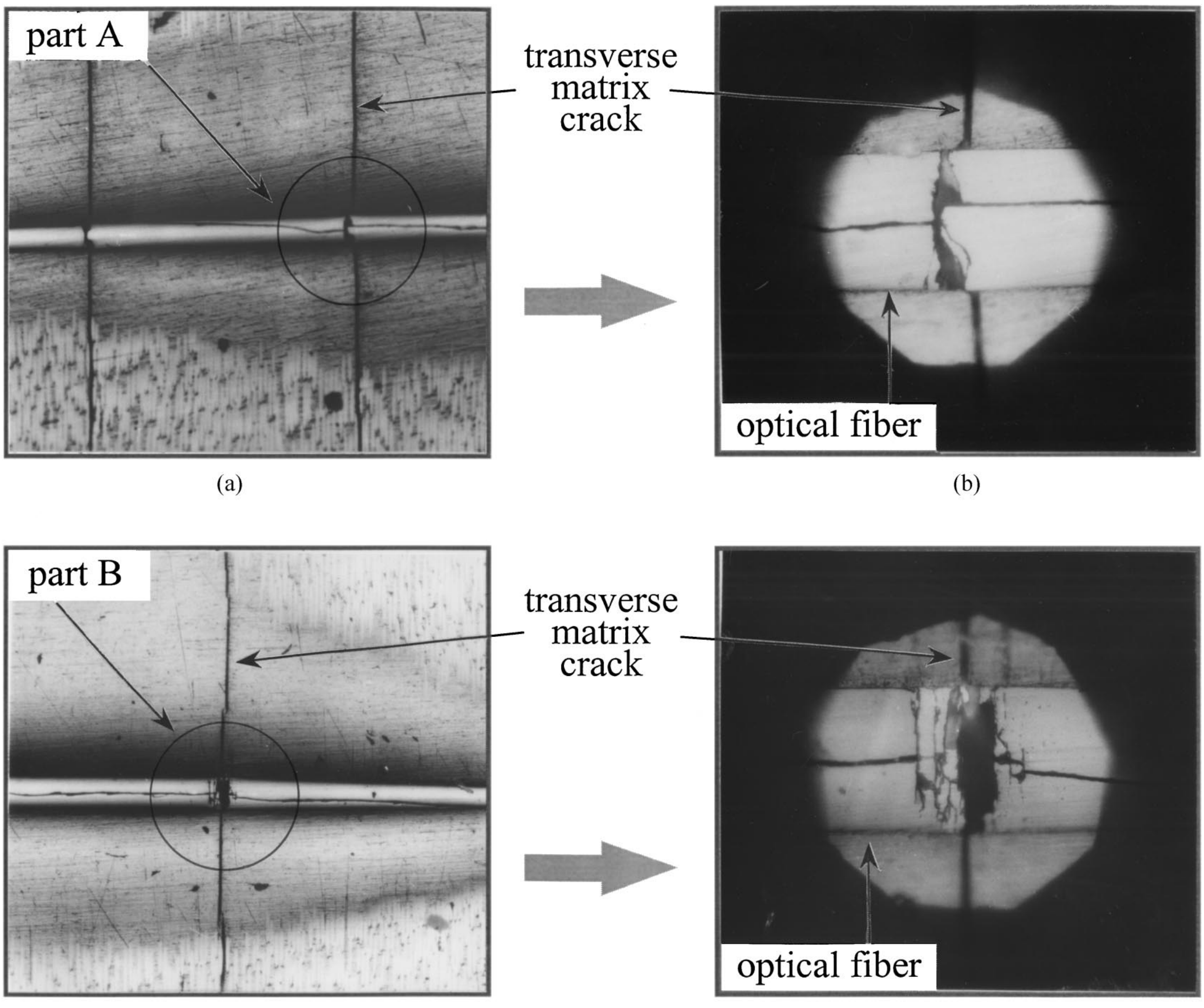


Figure 11 *S-N* curve of the optical fiber sensor embedded within $[0_6/OF/0_6]_T$ specimens.

3.2.3. The effect of gauge length of specimen on the fatigue life of optical fiber embedded within the composite laminates

All experimental data mentioned above were obtained from specimens which have 60 mm gauge length of specimen. Because generally the tensile strength of fibrous materials such as optical fiber is dependent on the gauge length [18, 19], the separate fatigue tests were performed with two different types of specimen, $[0_6/OF/0_6]_T$ and $[0_2/90_4/OF/90_4/0_2]_T$ which have 120 mm gauge length, to confirm the relationship between the fatigue life of optical fiber embedded within composite laminate and gauge length of specimens used for test.

The fatigue life data obtained from specimens which have 120 mm gauge length were compared with that of 60 mm gauge length. Fig. 15 shows the comparison of fatigue life of optical fiber within the unidirectional ply laminate which have different gauge length. The reduction of fatigue life of optical fiber embedded within the specimens which have longer gauge length was found in this figure, that is, the fatigue life of optical fiber within the specimen of 120 mm gauge length shows lower fatigue life compared to that of specimens which have 60 mm gauge length. This result can be explained by the size effect on the strength of fibrous materials which means that failure probability of materials increases with the increment of volume of materials. Thus it can be said that gauge length of optical fiber within the unidirectional ply laminate is major factor which influences the probability of fracture. However the situation is quite different for the optical fiber embedded within the cross-ply specimens as shown in Fig. 16. The fatigue life of optical fiber



(a) (b)

(c) (d)

Figure 12 Microscopic photographs of fractured optical fiber sensor embedded in cross-ply laminate; (b), (d) are the close-up of part A and part B in (a), (c).

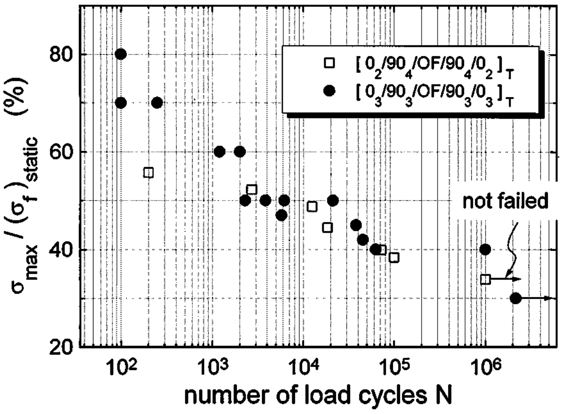


Figure 13 *S-N* curves of the optical fiber sensors embedded within cross-ply laminates.

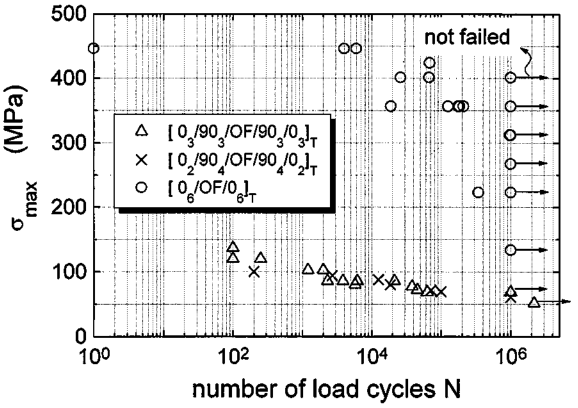


Figure 14 *S-N* curves of the optical fiber sensor embedded within different laminates.

within the cross-ply specimens does not show much differences between two different gauge lengths. As shown in Fig. 16, the fatigue life of optical fiber within the cross-ply specimens, $[0_2/90_4/OF/90_4/0_2]_T$, which have 120 mm gauge length is similar to that of 60 mm gauge length.

The difference of gauge length effect, between unidirectional and cross-ply laminate specimens, on the fatigue life of optical fiber within the laminate is due to the different fracture mechanism. The fatigue fracture of optical fiber within the unidirectional ply laminate is caused by the damage accumulation of the internal defect of optical fiber itself, while the fatigue fracture of optical fiber within the cross-ply takes place because of the matrix crack of transverse ply. Thus the fatigue life of optical fiber within the cross-ply is less sensitive

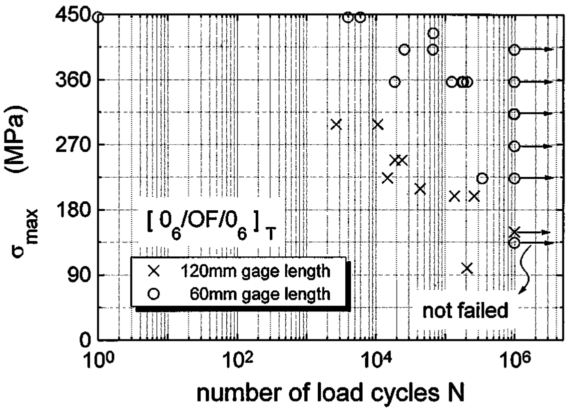


Figure 15 *S-N* curves of the optical fiber sensors embedded within $[0_6/\mathrm{OF}/0_6]_\mathrm{T}$ specimens with different gauge length.

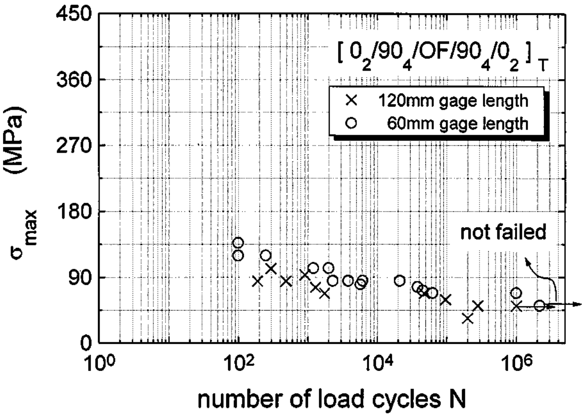


Figure 16 *S-N* curves of the optical fiber sensors embedded within $[0_2/90_4/\mathrm{OF}/90_4/0_2]_\mathrm{T}$ specimens with different gauge length.

to the gauge length of specimens compared to the unidirectional ply.

4. Conclusions

To evaluate the mechanical behavior, such as the tensile and fatigue characteristics, of optical fiber embedded within two different ply composite laminate specimens, fatigue tests were performed and *S-N* curves for these test were obtained. Optical microscopic observation was also performed to understand the fracture mechanism of optical fibers embedded within specimens. From these experiments the following conclusions were obtained.

1. The fatigue strength of optical fiber within the cross-ply laminate is much lower than that of unidirectional ply. This can be attributed to the different fracture mechanism. Thus for the successful application of optical fiber to smart composite structures, this factors should be considered at design process.

2. Under the fatigue loading the fatigue fracture of optical fiber within the unidirectional ply is initiated from the damage accumulation of internal defects of optical fiber itself, while the fatigue fracture of optical fiber within the cross-ply laminate takes place due to the matrix crack of transverse ply which causes the strain concentration.

3. The fatigue life of optical fiber within the unidirectional ply is dependent on the gauge length of specimens. However, the gauge length of cross-ply laminate do not affect much the fatigue life of optical fiber embedded within cross-ply laminate because the matrix crack is the dominant factor of fracture of optical fiber within the cross-ply laminate.

Acknowledgement

This study was supported by KOSEF research fund. We would like to thank KOSEF for this support.

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Received 30 July
and accepted 23 December 1998