DETECTION OF CRACKS IN FRP BY USING EMBEDDED PLASTIC OPTICAL FIBER

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Abstract: Plastic optical fiber is a multi-mode optical fiber and used for short distance communication, illumination, etc. Plastic optical fibers can be also used as a damage sensor by measuring optical power loss. Plastic optical fibers are much cheaper and easier to connect than silica fibers, and suitable to be embedded in FRP because of the similarity of its elasticity and coefficients of thermal expansion. In this work, plastic optical fibers were embedded in three types of GFRP specimens including unidirectional and cross-ply laminates. The relations among the optical power, the strain and the number of cracks were studied. Cracks in GFRP laminates were observed by a video microscope under tensile load. As the strain increased, the optical power decreased linearly before the initiation of cracks and nonlinearly after that. The optical power loss by a single crack was simulated by using a three-dimensional ray tracing model and the results were compared with the experimental results. Then, it was concluded that the nonlinearity of curve of the optical power loss was affected by the cracks and the plastic optical fiber has much potential to be used as a crack-detecting sensor for smart composites.

Key words: Plastic optical fiber, Smart composite, Crack detection

1. INTRODUCTION

An optical fiber has been developed for a sensor of smart structures and materials because of the small size, low weight, geometrical flexibility and so on. Smart structures and materials where optical fibers are embedded have capabilities of health-monitoring by detecting cracks and/or a change in strain or stress.

The cracks in materials can be detected when embedded optical fibers are cut by the cracks. For long fiber reinforced composite materials, transverse cracks are serious damages. To detect transverse cracks in long fiber reinforced composite materials, optical fibers should be embedded in 90° plies (Fig.1(a)). However, in this configuration, matrix rich area around optical fibers may enhance initiation of transverse cracks and the material strength may decrease. Then it is preferable to detect transverse cracks in cross-ply FRP laminates by optical fibers embedded in 0° plies adjacent to 90° plies (Fig.1(b)).

We selected a plastic optical fiber as an embedded optical fiber sensor. A plastic optical fiber can be used as the sensor which detects change in optical power. A plastic optical fiber has some advantages. The first is that the cost is lower than silica optical fibers. The second is that the connectivity between fibers are better because of the radius of the core is larger than that of silica optical fibers. The third is that a plastic fiber is easier to be embedded into FRP because of the thermal expansion coefficient is almost the same as the matrix.

A plastic optical fiber has low elasticity and high failure strain. Then, a plastic optical fiber will not break near cracks at large strain. When the cracks initiate, the field of strain near the cracks is changed. Then, it is considered that the optical power propagating through the plastic optical fiber embedded near the cracks decreases because the core of

Transverse crack

90° plies

0° plies

(a) Embedded in 90° plies

Optical fiber

Transverse crack

90° plies

0° plies

(b) Embedded in 0° plies

Optical fiber

Fig.1. Transverse crack detection by embedded optical fibers.
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In this paper, tensile tests of GFRP where plastic optical fibers were embedded were conducted. The relations among the optical power, strain and cracks were obtained experimentally. The experimental results were compared with numerical simulations based on an optical fiber theory.

2. EXPERIMENT

2.1. Specimen

Parameters of plastic optical fibers (ESCA CK10, Mitsubishi Rayon Co., Ltd.) used in this paper are shown in Table 1. The size of the specimens where optical fibers were embedded are shown in Fig.2. Optical fibers were embedded in the center of the GFRP laminates. The material properties of the GFRP lamina is shown in Table 2, where direction 1 is along reinforced fibers. Dimension of specimen is shown in Fig. 2. The tapered aluminium tabs were attached on the specimen out of the region where fiber were embedded to avoid the effects of cramping pressure to the power loss. The strain gage was attached on the center of the specimen.

Three types of specimens were tested. The stacking sequence of the Type A specimen was [90°/0°3/90°] and an optical fiber was embedded in the 0° ply along the direction of glass fibers of GFRP (Fig.3 (a)). The thickness of 0° plies was approximately the same as the diameter of the plastic optical fiber. Type A specimens were provided to study the effect of multiple cracks in 90° plies on the optical power loss. The stacking sequence of the Type B and C specimens was [0°], (Fig.3 (b)). Type B specimens were tested to study an optical power loss only by tension. Type C specimens have an initial crack at the center in the top ply (Fig.3 (c)). Type C specimens were used to study the effect of a single crack in 90° plies to the optical power loss.

2.2. Experimental Setup

The schematic view of the experimental setup is shown in Fig.4. The light from a LED (Light Emitting Diode, λ= 660 nm) was focused through a lens and incident into an optical fiber. Specimens were loaded under load control, and the load and the strain of the specimen were measured by a load cell and a strain gage, respectively. The light through the optical fiber was incident into a PD (Photo Detector) and the optical power was measured by an optical power meter. The surface of type A specimen was observed to count the number of cracks in 90° plies by a video microscope under loading.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Type A and B Specimens

The optical power and the crack density of the specimen are plotted against the strain in Fig.5 for the type A specimen. The relation between the optical power and the strain is shown in Fig.6 for the type B specimen. Figure 6
shows that the optical power decreased linearly with the strain when no crack appeared. On the other hand, Fig. 5 shows that the optical power decreased linearly until the strain reached $1.0 \times 10^4 \mu e$, and then decreased nonlinearly up to $2.5 \times 10^4 \mu e$ after cracks initiated at $1.0 \times 10^4 \mu e$. At approximately $2.5 \times 10^4 \mu e$, the specimen was broken. Some leakage of the light was observed at the cracks, but no break of the optical fiber was detected. Therefore, it is considered that the nonlinearity of the optical power loss in Fig. 5 resulted from the cracks in the $90^\circ$ plies.

3.2. Type C Specimen
3.2.1 Simulation
Before discussion of experimental results of the type C specimen, a simulation method of the optical power loss by a crack is presented. The model of rays propagating in the deformed fiber embedded in the GFRP near the crack is shown in Fig. 7. The deformation of a fiber near a crack was calculated by using three-dimensional finite element method (FEM). Calculated results showed that the shape of cross section of a deformed optical fiber was assumed to be an ellipse. Then, to simplify calculation, optical fiber was assumed to be a bending cylindroid and the curves of major axis $a(z)$, minor axis $b(z)$ and center coordinate $(x_0(z), y_0(z))$ were obtained from FEM result as polynomial curves.

The behavior of a light propagating through the fiber is simulated by three dimensional ray tracing method. One ray through a small element at $z = 0$ is traced in Fig. 8. The ray is identified by a center coordinate of the element and the propagating directions $\theta_0$ and $\phi_0$. It is noted that the $(r, \phi)$ coordinate is not a cylindrical system and defined by

$$ x = r a_0 \cos \theta, \quad y = r b_0 \sin \theta $$

(1)

where, $a_0 = a(0)$ and $b_0 = b(0)$. The critical angle $\theta_c$ is defined by

$$ \sin \alpha_c = n_c / n_0 = \cos \theta_c $$

(2)
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Fig. 8. Ray through the small element.

where \( n_c \) and \( n_{\infty} \) are refractive indexes of a clad and a core of a fiber, respectively. The reflection at the boundary between core and clad of a fiber is considered at local coordinates \( \tilde{x}\tilde{y}\tilde{z} \) defined in Fig. 9[1]. The \( \theta_i, \theta_j \) and \( \alpha \) are obtained by tracing ray and are functions of \( r \), \( \theta \), \( \theta_0 \) and \( \theta_\alpha \). The power reflection rate \( T_i \) at reflecting position \( P_i \) \((i = 1, 2,...)\) is defined as follows.

\[
T_i = \begin{cases} 
1 & 0 \leq \theta_i < \theta_c \\
T_i(<1) & 0 \leq \alpha < \alpha_c \\
T_i(>1) & \theta_c \leq \theta_i < \pi/2 \text{ and } \alpha_c \leq \alpha < \pi/2 
\end{cases}
\]

where, \( T_i \) is a power reflection rate of refracting rays and \( T_i \) is a power reflection rate of tunneling rays [2]. When \( 0 \leq \theta_i < \theta_c \), rays are reflected perfectly and called bound rays. The power of refracting and tunneling rays are leaked.

The total optical power of light through a fiber are calculated by the following equation.

\[
I_{\text{total}} = 2a_0b_0 \int_0^{2\pi} d\theta_0 \int_0^{\pi} d\theta \int_{-\pi/2}^{\pi/2} \left[ \prod_i T_i(rdr) \right] \]

3.2.2 Experimental results

The relation between the optical power and the strain by a single crack is shown in Fig. 10 with simulated results. The optical power decreases nonlinearly because the specimen has an initial crack. The simulated results are less than the experimental results. That is because index of optical fiber and shape of crack used in simulation are different from actual value. However, the results shows that the deformation of the plastic optical fiber by a single crack has strong effects on the optical power loss. From the above experimental results, it is considered that the number of transverse cracks can be detected by an embedded plastic optical fiber in 0° plies near 90° plies of cross-ply laminates.

4. CONCLUSION

It is experimentally confirmed that the optical power of light propagating through a plastic fiber embedded in GFRP laminates decrease nonlinearly after the initiation of transverse cracks when the specimen is loaded in tension. From the experimental result and the simulation of the specimen which has an initial crack, it is considered that the nonlinearly change of the optical power loss is strongly affected by the deformation of the optical fiber embedded near a crack. An embedded plastic optical fiber can be used to detect the number of transverse cracks in cross-ply laminates.

REFERENCES