

IN SITU CURE MONITORING OF 3D-SHAPED FRP USING HIGHLY FLEXIBLE OPTICAL FIBER SENSORS

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Abstract

Recently, cure monitoring of FRP by embedded optical fiber sensors have been paid attention to as a promising in situ method for FRP molding. In order to apply the method to large-scale and complex shape FRP products, the effect of optical loss by local bending on the measurement accuracy when the optical fiber was embedded should be taken account to. In the present paper, the effect of optical loss by local bending to measurement accuracy of degree-of-cure by the Fresnel-based optical fiber sensors was investigated. Two kinds of optical fibers, one is a standard communication fiber and another is a highly-flexible fiber, were used for the experiments. First, optical loss by bending was measured as a function of bending length and radius. The results showed that the bending loss of the highly-flexible fiber was much less than the standard fiber. Second, measurement of degree-of-cure of epoxy resin was conducted with 20, 50 and 80% optical loss. From the experimental results, it appeared that the influence of optical loss less than 80% on the degree-of-cure measurement was very low. Finally, the optical fiber was embedded in the curved plate and cure monitoring was carried on. From the results, it appeared the sensor with large bending loss by embedding in FRP could measure degree-of-cure precisely.

1. Introduction

Up to the present, many methods for measuring the degree-of-cure of FRP have been developed. Among these methods, monitoring degree-of-cure of FRP by embedded optical fiber sensors have been paid attention to as a method to obtain internal information of FRP during cure. In this method, the end face of the optical fiber is cut and embedded in the resin. And, the resin refractive index is estimated from the intensity of the reflected light at the interface between the optical fiber and the resin [1], [2]. Process monitoring technologies as use an embeddable optical fiber sensor obtain the degree-of-cure in a local region inside the resin at high speed and in real time. It expected that the technology is used for cure monitoring and control of molding process of FRP [3]. In recent years, the size and complexity of the FRP products are growing, however the applications of the previous studies are resin or simple-shaped FRP. Therefore, applications of the optical fiber sensors to large-scale and three-dimensional products have been expected. High optical loss may occur when the optical fiber sensor is embedded in large and complex-shaped FRP parts due to severe bending and long length of embedment. Therefore, quantitative evaluation of influence of optical loss on the measurement accuracy of optical fiber sensors should be investigated. In the present paper, the effect of optical loss by local bending to the measurement accuracy of Fresnel-based optical fiber sensors was investigated.

2. Experimental methods

2.1 Measurement method of bending optical loss

Figure 1 shows schematic view of experimental system for measuring optical loss by applying bend to an optical fiber. In this study, a light source (THORLABS's PM Benchtop SLD Source, S5FC1018P, 1310 nm, 30 mW, and 45 nm) and an optical power meter (THORLABS's Dual-Channel Benchtop Power and Energy Meter Console, PM320E) were used. Light emitted from a SLD flights in a fiber and arrives at the distal end of fiber. The light reflects at the boundary between air/glass and the reflected light travels to an optical power meter via an optical circulator. Light intensity loss was applied to the optical fiber sensor by winding it around bar-type jig whose radius were 4, 5 and 6 mm as illustrated in Fig.1. Then, the optical loss in dB caused by the bending jig are doubled due to the round-trip path. The measurement was carried out using a standard optical fiber and a highly flexible optical fiber as a sensor. The optical fiber sensor was wound around bar with the angles which were from 45° to 360° with every 45° increment. Then, light intensity loss was calculated and the average value was obtained. Here, the light intensity loss is defined as a ratio of the initial and measured power.

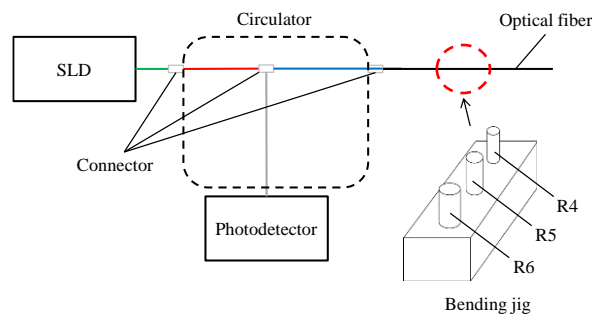


Figure 1. Schematic of experimental method for measuring optical loss by bending

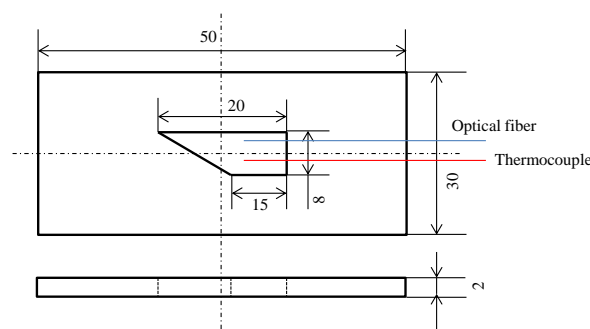


Figure 2. Silicon mold for cure monitoring of epoxy resin

2.2 Measurement method of Degree-of-cure

In this study, epoxy resin (base compound is ARALDITE LY5052, and curing agent is ARADUR 5052CH, mixing ratio is 100:38) were used. The epoxy resin was poured into a mold made of silicon illustrated in Fig.2, and degree-of-cure measurement was carried out to investigate the influence of loss. The reason for using a trapezoidal shape of mold is to reduce the influence of reflected light from the inner wall of mold. The silicon mold can decrease restraint of resin by the mold. Thickness of the mold is set so to prevent overheating due to cure reaction. The optical system used for measurement of degree-of-cure is the same as that illustrated in Fig.1. The end tip of the optical fiber and a thin thermocouple were embedded in the mold. The heating condition of cure process was heating from

room temperature to 140° in one hour and holding temperature for one hour. The optical loss of 20%, 50% and 80% with bending radius of 5mm were applied. Degree-of-cure curves were calculated from the measured refractive-index curves in real time.

2.3 Measurement method of Degree-of-cure of the 3D-shaped GFRP plate

The degree-of-cure measurement of curved GFRP plate was conducted using embedded the Fresnel-based standard optical fiber sensor during VaRTM. As shown in Fig.3, the base mold plate had corners with radiuses of 5 mm. Then the bending angle applied to the embedded optical fiber was (180°×2) through the round trip of light. Ten glass cloths cut to length 120 mm and width 80 mm were stacked on the lower plate. The standard optical fiber and a thermocouple were placed between the fifth and sixth glass cloth. Then, the material was covered with a vacuum sheet and vacuum-drawing was carried out so that a pressure of 0.1 MPa was constantly applied during molding. The heating cycle was heating with 2 °C/min. up to 104 °C.

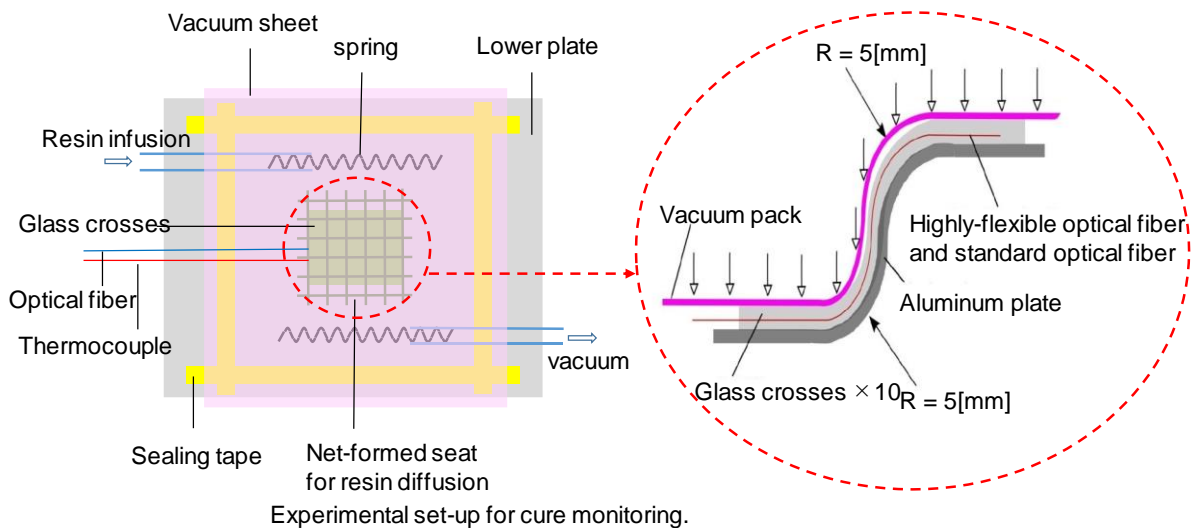


Figure 3. Set-up for cure monitoring of curved GFRP plate during VaRTM molding

3. Experimental Results and Discussion

3.1 Measurement of optical bending loss

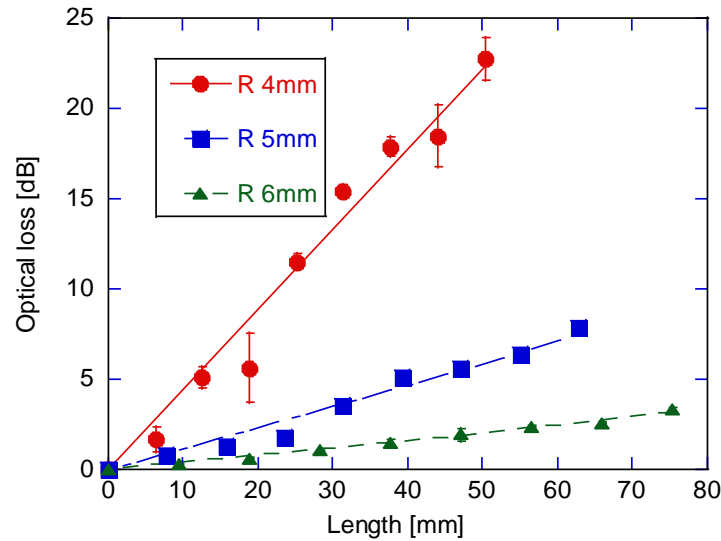
Figures 4 show the results of measurement of light intensity loss by winding the optical fibers around the bars of R4, R5, and R6 for the standard and highly-flexible optical fiber sensors. As seen from both figures, it appeared that optical bending loss increased proportionally to bending length. In addition, it is shown that the light intensity loss of the highly-flexible optical fiber is much smaller than that of the standard optical fiber. From these results, it was concluded that the highly-flexible optical fiber was much better for cure monitoring of complex-shaped FRP.

The optical loss rate dL/dx , which is the sensitivity of optical loss L to the bending length x is important parameter to predict optical loss by embedding the fiber into complex-shaped FRP. The total optical loss can be represented by the following formula.

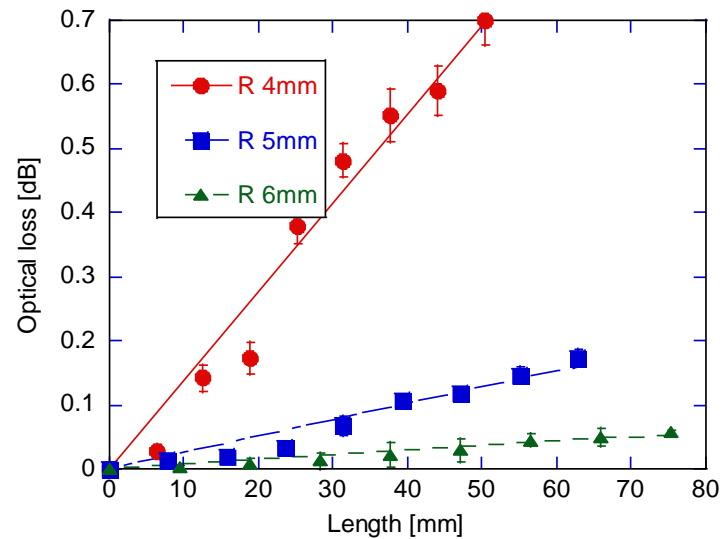
$$L = \int \left(\frac{dL_{bend}(R)}{dx} + \frac{dL_{press}(P)}{dx} \right) dx \quad (1)$$

Where, L_{bend} and L_{press} are the bending loss and pressured loss, and P is molding pressure. The L_{press} is considered to be too small to be negligible for VaRTM molding.

Figure 5 shows relationship between optical loss rate and bending radiuses for the both types of fibers. From the figure, it was found that optical loss rate had not linear relationship to the bending radius. When the radius becomes smaller than 5 mm, the loss increase rapidly. The bending radius of an optical fiber embedded in preform during VaRTM may be vary slightly by pressure of resin flow. Therefore, the sensitivity of loss is desired to be so low that the change in bending radius is almost insensitive to the loss. The effective bending radius can be glown by placing the fiber along the direction of low curvature when the embedding corner surface is sharp.



Standard fiber



highly-flexible fibers

Figure 4. Relationship between optical loss by bending and bending length for standard and highly-flexible optical fibers .

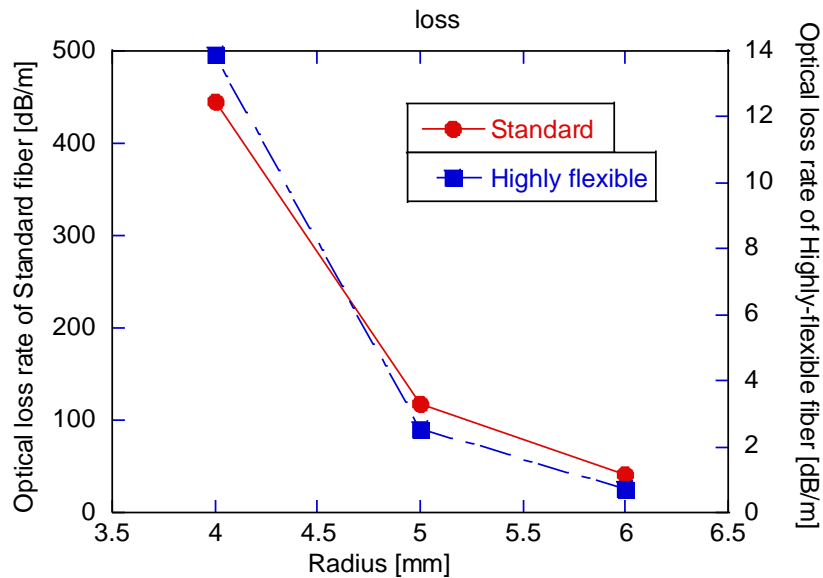


Figure 5. Optical loss rate vs bending radius for standard (left axis) and highly-flexible (right axis) optical fibers.

3.2 Measurement of degree-of-cure with local bending

Figure 6 shows the measurement results of the degree-of-cure curves of the epoxy resin using the standard optical fiber with the optical loss of 20, 50 and 80% by bending with radius of 5 mm. From the figure, it was found that the measurement accuracy of degree-of-cure was hardly affected by the optical loss when the loss was less than 80%. On the other hand, the experimental results for the highly-flexible fiber by bending with radius of 5 mm are shown in Fig.7. From the results, it appeared that the effect of optical loss on the measurement accuracy of the degree-of-cure was very weak. Because the optical loss of the highly-flexible fiber was much less than that of the standard fiber, this results indicate that multiple bending with small radius, that is, embedment in a complex-shaped composites is applicable in the cure monitoring using the highly-flexible fibers. From the above results, it was concluded that the optical loss less than 80% hardly affected the measurement accuracy of degree-of-cure for both the standard and high-flexible fibers.

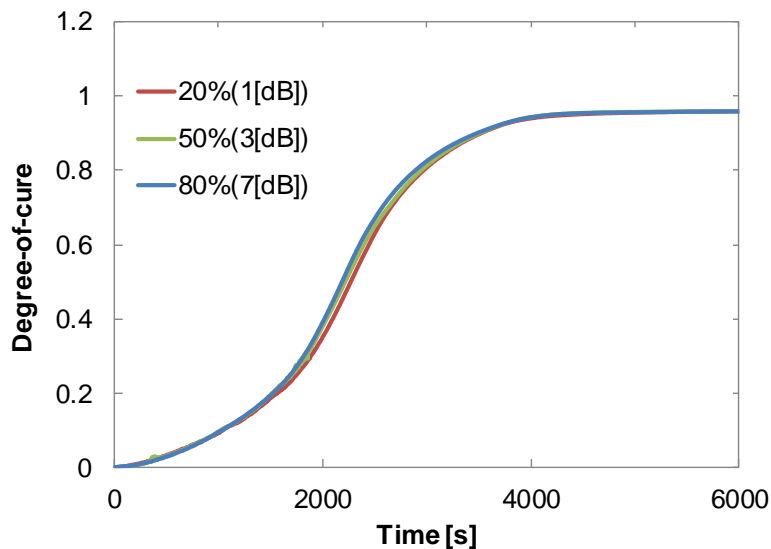


Figure 6. Degree-of-cure curves against process time for standard optical fibers with optical loss of 20, 50 and 80%.

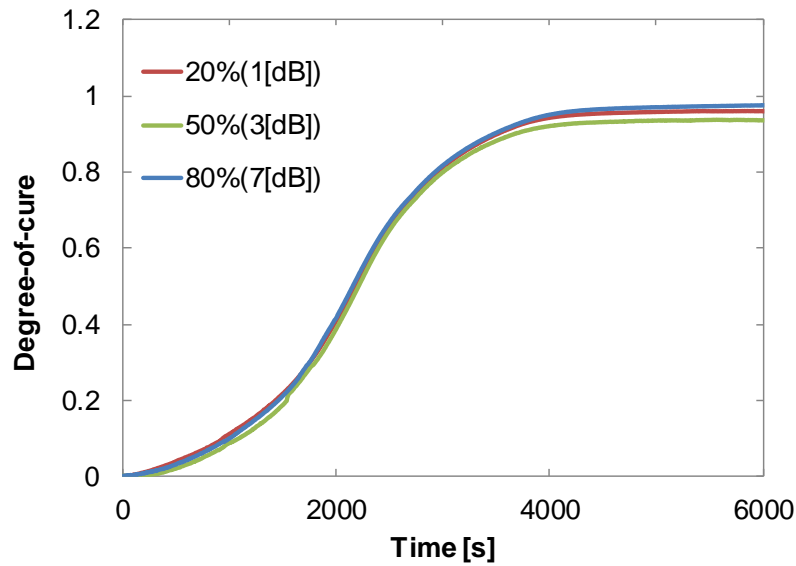


Figure 7. Degree-of-cure curves against process time for highly-flexible optical fibers with optical loss of 20, 50 and 80%.

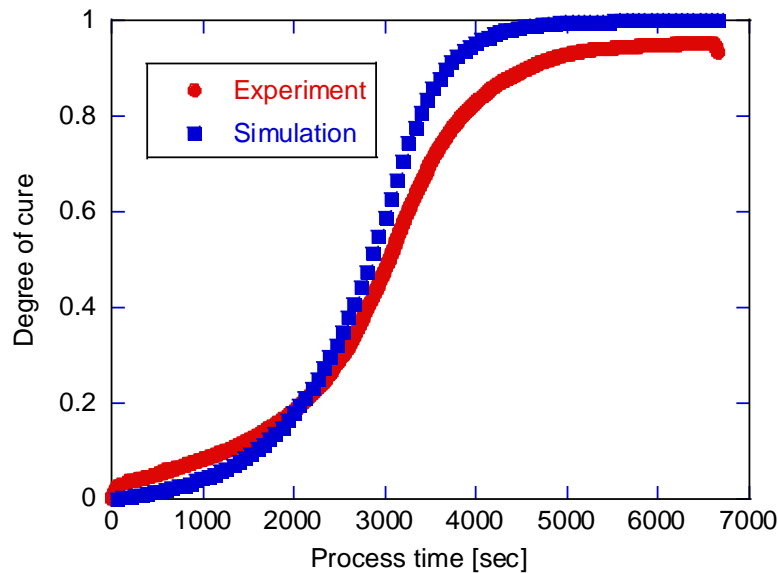


Figure 8. Measured and simulated degree-of-cure curves against process time for standard optical fiber embedded in the curved GFRP plate (Loss was 53%)

3.4 Measurement of degree-of-cure of curved GFRP plate

The optical loss by embedding the standard optical fiber in the curved GFRP plate was 53%. On the other hand, the optical loss predicted by the equation (1) was 42.6%. The difference of the optical loss was caused by that the embedding path of optical fiber varied slightly during impregnation process. Figure 8 shows the degree-of-cure curve against process time for standard optical fiber embedded in the curved GFRP plate. The degree-of-cure curve simulated using kinetic model of cure reaction was plotted in the same graph. From the figure, it appeared that the experimental results agreed almostly with simulated results. However there was difference between behaviors of the both curves when the degree-of-cure was larger than 0.6. It was shown that the degree-of-cure became 0.95 at the end of cure process although the simulated results show that the cure reaction completed. Since the maximum molding temperature was 104 °C and the value is though to be insufficient for completion of cure

reaction, it is considered that the kinetic model should be improved. From these results, it was concluded that the degree-of-cure of the curved FRP plate could be measured precisely by Fresnel-based optical fibers.

4. Conclusions

In this study, the influences of optical bending loss on measurement of degree-of-cure by Fresnel-based optical fiber sensors were examined. Two kinds of sensors, one is the standard fiber and another is the highly-flexible fiber, were used in the experiments. From the results, it can be concluded as follows;

- (1) From the results of experiments of measurement of bending loss, it was found that the optical loss was proportional to the bending length and loss of the highly-flexible fiber was much lower than that of the standard fiber.
- (2) From the experimental results of measurement of degree-of-cure by the fiber where bending loss was applied, it appeared that the effect of optical bending loss less than 80% on the measurement accuracy of degree-of-cure of resin was low.
- (3) From the result of measurement of cure monitoring of a curved GFRP where the fibers were embedded with two corners of 5 mm radiuses and 90° angles, it was found that degree-of-cure could be measured accurately. The optical loss by embedding was 53% although the prediction was 42.6%. It can be considered that the difference caused by change of the optical fiber path during impregnation of resin, but the difference did not affect the measurement accuracy.

Acknowledgments

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