INFLUENCDE OF ABSORBED WATER IN CFRP LAMINATES ON EMBEDDED FBG SENSORS

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Abstract
FBG sensors were embedded into the CFRP laminates to evaluate the strain changes caused by water absorption. The water absorptions were also evaluated by the weight changes in the UD and cross-ply CFRP coupons. The increasing rates in the weight were good agreement with those in the strain. The spectral change, especially the decrease in the width due to depression of birefringence effect in the FBG, showed the progress of water absorption in the CFRP laminates.

1 Introduction
CFRP laminates are routinely used to airframe structures, and it makes recent aircrafts lighter in weight and more efficient. Furthermore, health monitoring technology that can diagnose the structural integrity in real-time, is expected to apply to realize much more efficient aircrafts. The sensing capability of fiber-optic sensors had been proved useful for detection of damages in CFRPs. However, some concerns remain before the application to the real structure. The signals from the sensors have the possibilities to change at the times not just damage occurrence but long-term operation. Specifically, the shrinkage of resin due to physical aging and/or the swelling of resin due to moisture/water absorption influence on the strain changes in the sensors. The relationship between the signal changes and the factors should be verified for making clear distinction on damage occurrence, as it were avoiding erroneous decision. In this study, FBG sensors were applied to the CFRP laminates immersed in distilled water. Though the water absorption is a different from the moisture absorption, the swelling of resin would occur in both conditions. If the present evaluation approach is available to CFRP immersed in water, may be applied to the moisture absorption as well.

2 Evaluation of absorbed water
2.1 Specimens and measuring conditions
All the specimens were manufactured from epoxy-based CFRP UD prepregs (IMS60/#133, Toho Tenax Co. Ltd). The stacked prepregs of 60 mm length and 60 mm width were cured at 180 °C, 2.5 hours using an autoclave machine. The thickness in the range of 50 mm square was almost uniform by flat pressure plate. The specimen configurations were $[0]_x$ (x=4, 8, 24) and $[0_8/90_8/0_8]$. These specimens are used for measurement in weight changes caused by water absorption. The specimens were immersed in distilled water of 71 °C (HWT: hot water temperature). After the specimen is taken from the water bath on appropriate timing, the

weight of the specimen was measured quickly by an electric precision balance. An optical fiber was embedded into some of the specimens in order to investigate the influence of the embedding of optical fiber on the weight gain. Embedding location was just middle of the layer in thickness direction. The optical fiber is made of silica glass coated with polyimide, and their outside diameter is 150 μm.

2.3 Results

Figure 1 shows the relationship between weight gain and immersion time for the specimens with and without the optical fiber. The each result indicates the average value of 3 specimens and an error bar of standard deviation. In this figure OF(0) and OF(90) represent the directions of the optical fiber, parallel to carbon fibers and orthogonal to them, respectively. The increasing in weight gain and influence of the embedding directions were unobservable because the error bars were overlapped each other. The water absorption via polyimide coating of the optical fiber is considered good for practical application or its impact is very small.

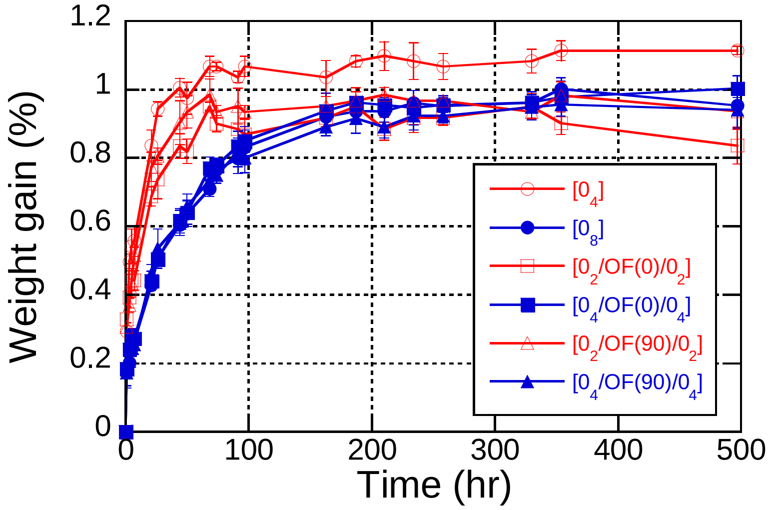

Figure 1. Weight gains of CFRP specimens for the specimens with and without the optical fiber.

Figure 2 shows relationship between weight gain and immersion time for 8 plies and 24 plies specimens. The increasing rate of the weight gain depended on the specimen thickness at early stage. These results agreed with the results in many previous studies. The cutoff specimens is 50 mm square from the normal specimen. These specimens have 6 flat surfaces that water can enter. The weight gains of cutoff specimens were larger than those of the uncut specimens for all specimen configurations. That is because the diffusivity along the carbon fiber direction is largest as is well known [1-3]. The weight gain of the 8 plies specimens increased rapidly by 200 hours, and then increased slightly by 800 hours. In contrast, the weight gain of the 24 plies specimens increased gradually by 800 hours. The final stage of this measurement would not far away from saturation point. The weight gain of the cross-ply specimen was a little bit larger than that of the 24 plies UD specimen. This is suspected because the differences of resin content between them.

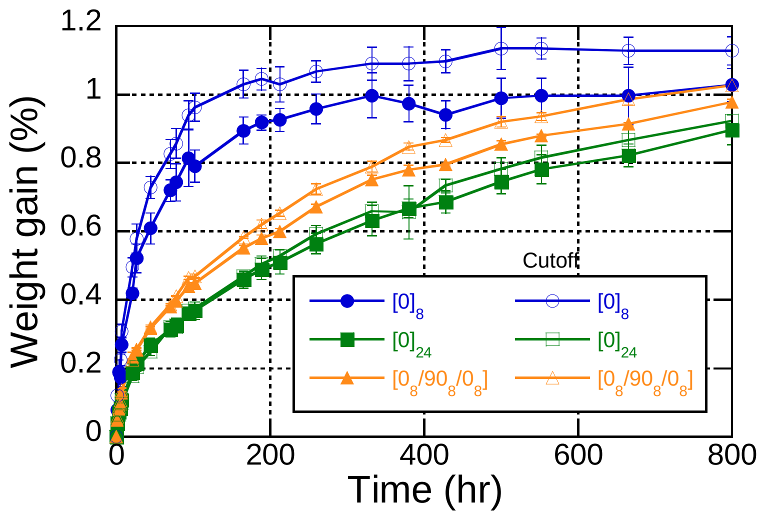

Figure 2. Weight gains of CFRP specimens for the specimens with and without the optical fiber.

3 Evaluation of strain changes

3.1 Specimens

The specimens were fabricated by same cure process using same materials. The FBG sensor was embedded into the center of the specimen as shown in Figure 3. The edge of the specimen didn't cut off for monitoring using FBG sensors. This handling was same as the specimens in the weight measurement. The specification of the optical fiber was same as that in the weight measurement. The FBGs was 10 mm length sensitive to strain and temperature. The configuration of the specimens and the specification of the FBG were summarized in Table 1. The sensitivity of FBGs to strain and temperature were obtained by the calibration.

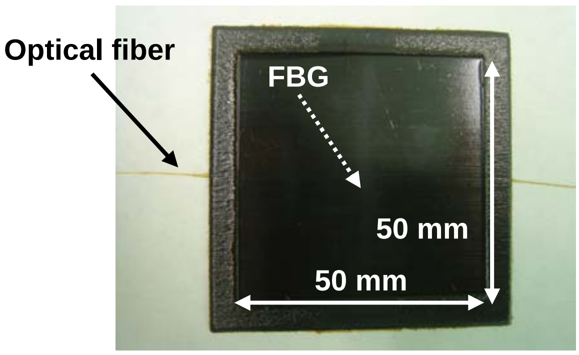

Figure 3. Photograph of specimen with an embedded optical fiber.

3.2 Measuring conditions

After the curing process, the spectra were measured once at room temperature (RT), 23.5°C. The specimens were stored in a desiccator for avoiding the moisture ingress into the specimens. After that, the specimens were immersed under the same condition as the weight measurement. Figure 4 shows the framework of strain measuring system using FBGs. When the broadband light was launched into the FBG thorough a circulator and an optical switch, the narrow band light is reflected. The spectra from the FBGs were measured every 1 hour. One FBG was also immersed for temperature compensation and confirmation of long-term reliability itself.

Total plies	Stacking sequence
4	$[0_2/FBG(0)/0_2]$ $[0_2/FBG(90)/0_2]$
8	$[0_4/ FBG(0)/0_4]$ $[0_4/ FBG(90)/0_4]$
24	$[0_{12}/ FBG(0)/0_{12}]$ $[0_{12}/FBG(90)/0_{12}]$ $[0_8/90_4/FBG(0)90_4/0_8]$ $[0_8/90_4/FBG(90)90_4/0_8]$

FBG	
Cladding dia.	125 με
Coating dia.	150 με
Gage length	15 mm
Sensitivities	1.198 pm/με 12.26 pm/°C

Table 1. Specimen configurations and specification of FBG

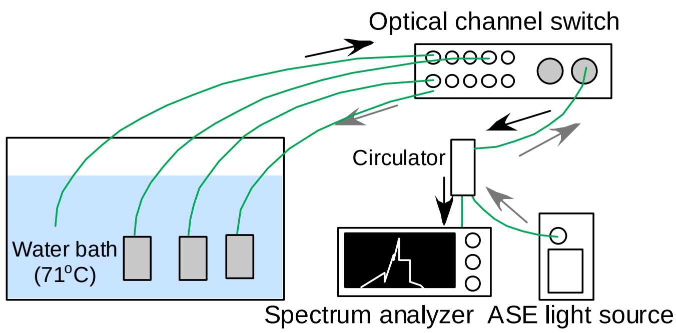

Figure 4. Schematic illustration of strain measuring system.

3.3 Experimental results

Figure 5 shows the spectral changes in the immersed FBG. The center wavelength of the spectrum shifted 0.5475 nm with an increase in temperature. The temperature change measured by the FBG, 44.66 °C is a little bit smaller than the temperature change from RT to HWT. The spectrum kept its shape during immersion and their center wavelength shift was 0.003 nm, 2.5 με in strain terms. These results proved that the FBGs have the potential to use for long-term operation in high humidity environment.

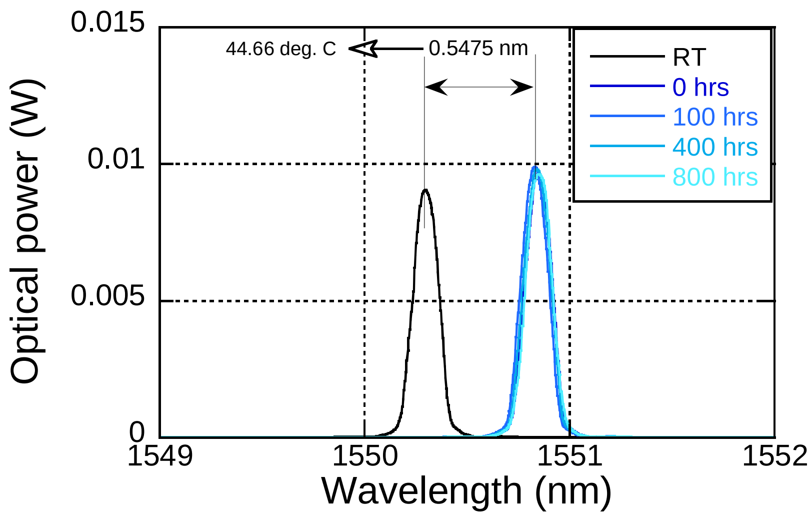

Figure 5. Spectral changes in the immersed FBG.

Figure 6 shows the spectral changes in the 24 plies specimens with the embedded FBG along the 0 deg. carbon fiber direction. The strain change after temperature compensation was calculated about -100 με that is caused by shrinkage of the specimen along 0 deg. direction. The spectrum kept its shape during immersion and their center wavelength shift was 0.005 nm, 4.2 με in strain terms. This strain change is quite small.

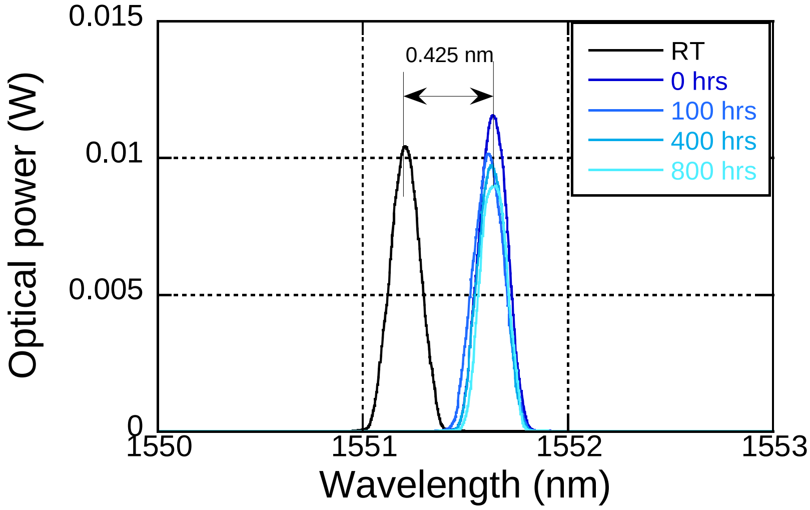

Figure 6. Spectral changes in the specimen, [0_{12}/ FBG(0)/0_{12}].

Figure 7 shows the spectral changes in the 24 plies specimens with the embedded FBG along the 90 deg. carbon fiber direction. The shape of the spectrum was two peaks before start of immersion. This change was known as birefringence effect in FBGs that was caused by embedding of the FBG into along the 90 deg. carbon fiber direction. The strain change after temperature compensation was calculated about 1407 με that was caused by mainly expansion of the specimen along 90 deg. direction. It is difficult to detect the center wavelength for the deformed spectra. The center wavelength was defined by threshold values, of optical power in the spectrum. The spectrum shifted during immersion and their center wavelength shift was 3.592 nm, about 3000 με in strain terms. This large strain change was concluded the swelling of resin along 90 deg. direction. The shape of the spectrum also changed to one peak gradually due to depression of birefringence effect in the FBG.

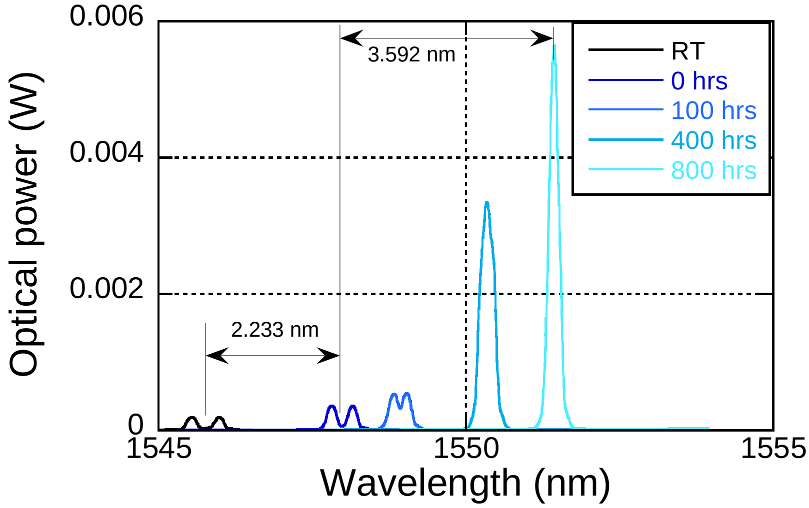

Figure 7. Spectral changes in the specimen, [0_{12}/ FBG(90)/0_{12}].

4 Discussions

4.1 Strain changes due to water absorption

Figure 8 shows the strain changes during immersion calculated by shift of the spectra. The strain change of $[0_4/$ FBG(90)/$0_4]$ specimen increased rapidly by 200 hours, and then increased slightly by 800 hours. Figure 9 shows the superposition the strain changes on the weight gains of the specimens. The increasing rate of the strain was good agreement with that of weight gain. The strain change of $[0_8/90_4/$ FBG(90)/$90_4/0_8]$ was small, and increasing rate was unstable compared with the UD specimens. This suggests the influences of viscoelastic properties and/or concentration gradient of absorbed water. It is now unclear about the behavior to be explained.

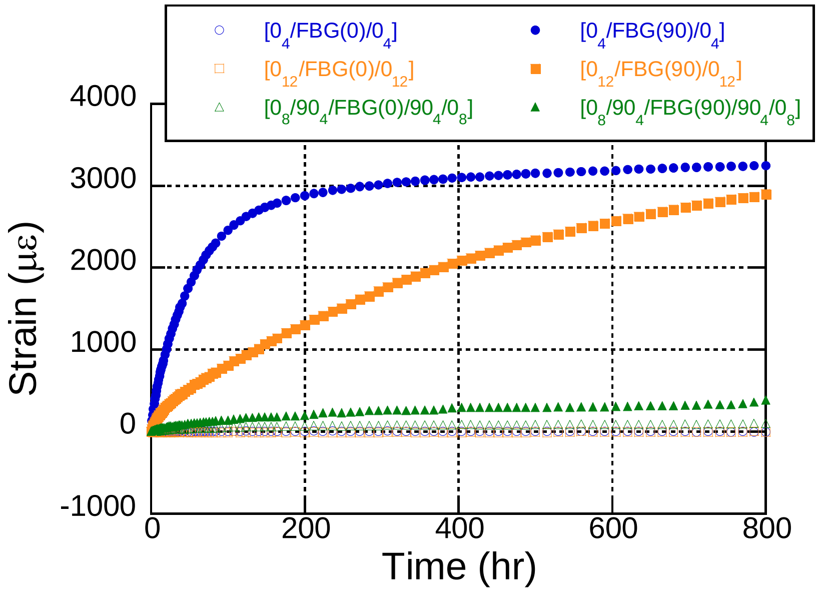

Figure 8. Strain changes during immersion.

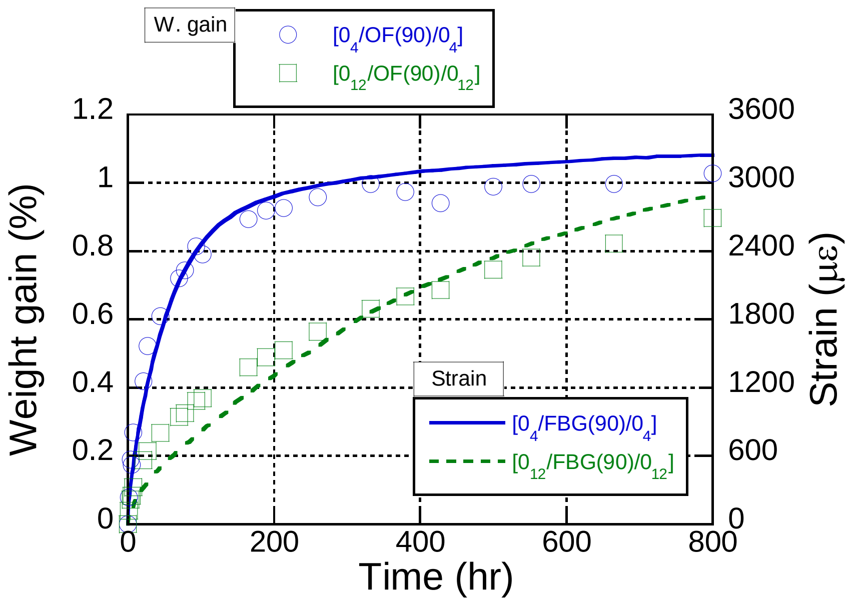

Figure 9. Strain changes during immersion.

5 Conclusions

This study has been reported the experimental results about influence of absorbed water in CFRP laminates on embedded FBG sensors. It was proved that the FBGs have the potential to use for long-term operation in high humidity environment. The strain change along the 90 deg. carbon fiber direction can be evaluated by the shift of spectra. The decrease in the width becomes a good indicator because depression of birefringence effect in the FBG was caused by swelling of resin. These are confirmed by FE analysis, and we hope to report after the more detail becomes clear.

Acknowledgment

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References

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