Evaluation of the VARTM composite skin/stringer structure using fiber-optic sensors

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ABSTRACT:

VARTM (Vacuum-Assisted Resin Transfer Molding) is one of the promising molding methods for large-scale composite structures. This technique is very effective for the cost saving of the molding because the autoclave system is not required and also effective for the molding of complex shaped composites because resin is impregnated into the combined dry preform. Therefore, the VARTM composite structures will be used for the future airplanes. Fiber-optic sensors are laying on some infrastructures to replace the point-to-point sensor system with the new sensing network because of their lightweight and multiplexed capability. Since the fiber-optic sensors can be applied for the strain and temperature measurements, they are suitable for evaluation of the composite structures. Therefore, the monitoring of curing process and the structural integrity was carried out for a CFRP skin/stringer panel manufactured by VARTM.

FBG (Fiber Bragg Grating) sensors and optical fibers were embedded into the interface between the skin part and the stringer part before the resin impregnation. The reflection spectra of the FBG sensors monitored the strain and temperature changes during all the molding processes. The internal residual strains of the CFRP panel could be evaluated during both the curing time and the post-curing time. The temperature changes indicated the differences between the dry preform and outside of the vacuum bagging. After the molding, four-point bending was applied to the panel for verification of its structural integrity and the sensor capabilities. Then, the optical fibers were used for the newly-developed PPP-BOTDA (Pulse-PrePump Brillouin Optical Time Domain Analysis) system. The long-range distributed strain and temperature can be measured by this system, whose spatial resolution is 100 mm. The strain changes from the FBGs and the PPP-BOTDA agreed well with those from the conventional strain gages and/or the FE analysis of the CFRP panel. Thus, the applications of the fiber-optic sensors and its system were very effective for the VARTM composite structures.

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INTRODUCTION

VaRTM (Vacuum-assisted Resin Transfer Molding) is one of the promising molding methods for large-scale composite structures. This technique is very effective for the cost-saving of the molding because the autoclave system is not required and is also effective for the molding of complex shaped composites because the resin is impregnated into the combined dry preforms. Therefore, the VaRTM composite structures will be used for future aircrafts. Fiber-optic sensors are being used for some infrastructures to replace the point-to-point sensor system with the new sensing network because of their light weight and multiplexed capability. Since the fiber-optic sensors can be applied for the strain and temperature measurements, they are suitable for evaluation of the composite structures. Therefore, the monitoring of the curing process and the structural integrity was carried out for a CFRP skin/stringer panel manufactured by VaRTM.

COMPOSITE SKIN/STRINGER STRUCTURE

A stiffened panel was fabricated by VaRTM on the assumption that this is a partial structure of the outer skin of small-size civil aircrafts. As shown in Figure 1, the panel combined the T-shaped stringer with a skin of 900 mm × 100 mm × 4.8 mm. The materials were dry preforms of UD carbon fabric (T800SC-24k, SAERTEX Co. KG) and epoxy resin (XNR6809/XNH6809, NagaseEleX.CO.,LTD). The stacking sequences were $[45/0/\text{-}45/90]_{S3}$ for the skin and $[45/0/\text{-}45/90]_{S2}$ for the stringer. Since fiber-optic sensors were used for both the process monitoring and the structural health monitoring, small-diameter optical fibers were embedded into the interface between the skin part and the stringer part. The resin was impregnated into the vacuum bag including the combined dry preforms and molding equipments at 40 °C. After the confirmation of the impregnation, the resin was stored at 80 °C in 6 hours for the curing process. The post-curing was carried out at 120 °C in 3 hours.

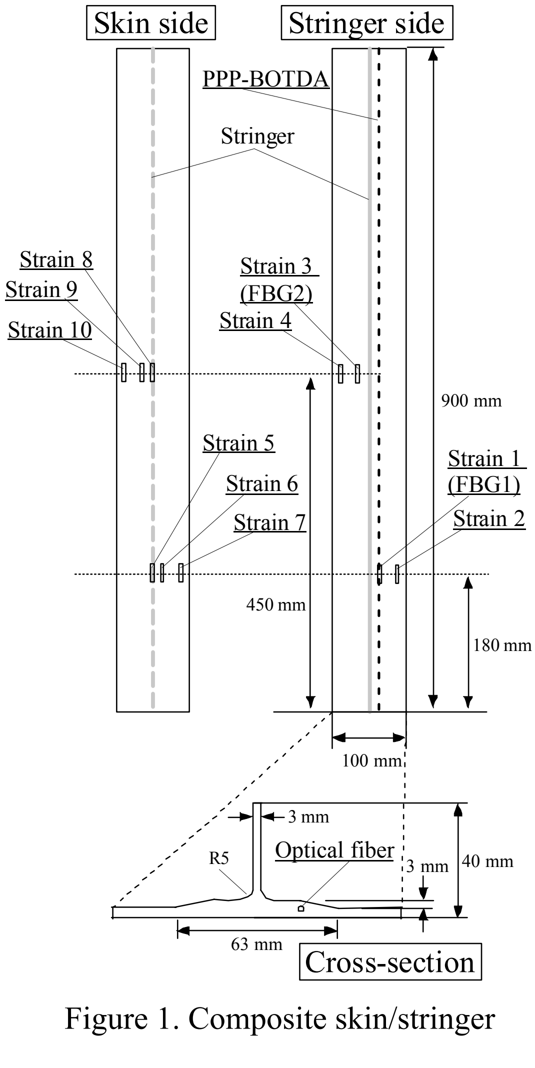


Figure 1. Composite skin/stringer

Small-diameter FBG sensors (Hitachi Cable, Ltd) were applied to both the process monitoring and the structural health monitoring. Sensor locations were 180 mm away from the edge (FBG1) and the center (FBG2). The two FBG sensors were arranged on each location; one was a normal

FBG for strain measurement and the other was a strain-free state FBG in the hollow tube for temperature measurement [1]. The single FBG sensor was fabricated in single optical fiber as a localized sensor, and its gauge length was 10 mm. After the process monitoring, the distributed sensing technique was applied to the structural health monitoring using PPP-BOTDA system (NBX-6000, Neubrex Co., Ltd.) for comparison of the results of the FBG sensors. The usually used small-diameter optical fiber was 7.8 μm of core diameter and 0.65 % of relative index difference. The power of Brillouin scattered light is quite small in such a long-range application because the optical power loss occurs along the entire length of the optical fiber. The practical power of the light source will be limited by the appearances of some nonlinear phenomena [2]. Thus the optical power loss of the small-diameter optical fibers was improved by the changes in the core diameter and the relative index difference. This kind of improvement becomes considerably important for the embedded fiber-optic sensors into composites in the future. Electrical-resistance strain gauges were attached to the stringer side (from Strain1 to Strain4) and the skin side (from Strain5 to Strain10) as shown in Figure 1. The strains were also measured by the strain gauges during the four-point bending as the structural health monitoring. The strain values were used for comparison with the strain values calculated by the FE analysis of the panel, and for reference values under the four-point bending.

PROCESS MONITORING OF VARTM

Strain and temperature are important physical values for VaRTM process because they represent the cure state of the epoxy resin. An FBG sensor produces the reflected light measured as a reflection spectrum. Relationships between the center wavelength of the reflection spectrum and strain and/or temperature are known to be almost linear. These relationships are used for the strain and temperature measurements in this study. The reflection spectrum was measured by an optical spectrum analyzer at sampling speeds of 6/min, and the period of the process monitoring was all three days. The strain measurement accuracy and temperature measurement accuracy are 1 με and 0.1 °C, respectively. Figure 2 shows the strain and temperature changes obtained by the

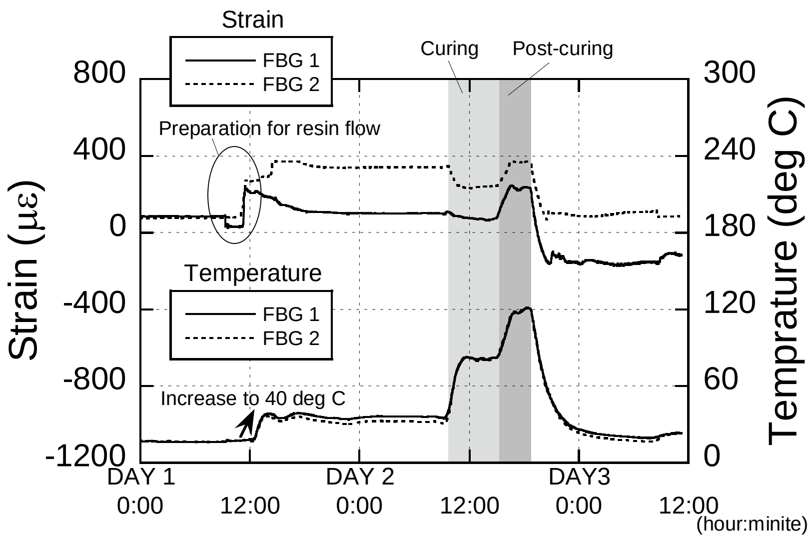


Figure 2. Strains and temperatures measured by FBG sensors.

measured reflection spectra. The strain was compensated by the FBG for temperature measurement because the temperature transition is relatively large compared with the strain change in the fabrication process. When the dry preform of the stringer/r was put on the dry preform of the skin before 12:00 of DAY1, the FBG sensors can detected the strain changes sensitively. Since the slight loading was applied to the FBG sensors due to the positioning of the dry preforms, the strains changed into about 250 με for both the FBG1 and the FBG2. At the increasing process from room temperature (22 °C) to 40 °C, the temperature compensating will be effective because the strain changes was small. During the constant temperature process of the 40 °C, the strain values were different such as 350 με and 100 με. This is because applied slight bending or twist differ among the two FBG sensors, and this will influence the strain values. At the increasing process from 40 °C to 80 °C, the strains decreased due to cure shrinkage. The strain change of the FBG1 is valid compared with that of the FBG2 because the cure shrinkage of epoxy was very small. Moreover, at the increasing process from 80 °C to 120 °C, the strains were expected to increase due to expansion of the epoxy resin. The strain difference between the FBG1 and FBG2 before the curing process remained till after the post-curing process or final stage of the fabrication process

Comparison between temperature measured by the FBG sensors and temperature measured by thermocouples is shown in Figure 3. TC1, TC2, and TC3 express the temperatures measured by the thermocouples. The locations of temperature measurement were outside of the vacuum bagging (TC1) and inside of the vacuum bagging (TC2 and TC3). At the curing process from 9:30 to 15:00 of DAY2, the temperatures of TC1 and TC3 indicated an overshoot of the set value, 80 °C. At the post-curing process from 15:00 to 19:00 of DAY2, the temperature of TC3 also indicated an overshoot of the set value, 120 °C. Nevertheless, the temperatures measured by the FBG sensors were in good agreement with those measured by the thermocouples. On the other hand, the temperature changes measured by the FBG slow down compared with those measured by the thermocouples. This time-lag was caused by the embedding of the FBG sensors into the dry preform because the speed of heat transfer was relatively small. Since internal temperature directly affects the resin curing, the temperature measured by FBG sensors is

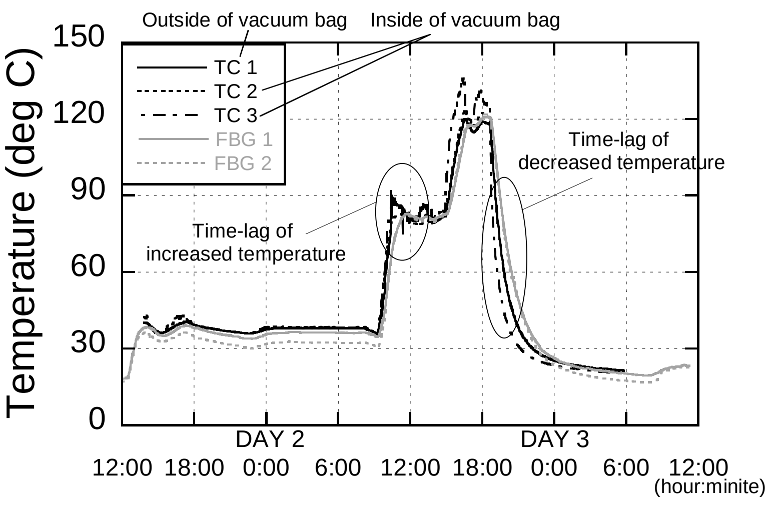


Figure 3. Temperatures measured by thermocouples and FBG sensors.

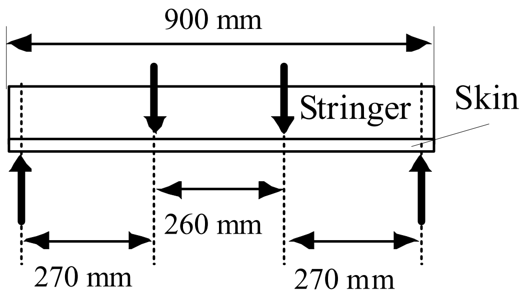
useful for the fabrication process including temperature control. The composite panel of this study was a small substructure, however, so the monitoring is more useful for large-scale composite structures that are easily affected by temperature distribution depending on the location.

STRUCTURAL HEALTH MONITORING UNDER FOUR-POINT BENDING

After the fabrication, the CFRP skin/stringer panel was cut out to test the four-point bending as shown in Figure 4. The quasi-static loading was applied to the panel at a displacement control of 0.5 mm/min. The test appearance and the boundary conditions are shown in Figure 4. The strain changes were monitored by the embedded FBG sensors and the distributed sensing technique, PPP-BOTDA. The loading value, the displacement at the center of the panel, and the strain values measured by conventional strain gages were obtained simultaneously. In the PPP-BOTDA system, strain measurement accuracy and spatial resolution are ±25 με and 0.1 m, respectively. Since it takes one or two minutes to measure the distributed strain like other distributed sensing techniques, the loading was maintained at the strain measurement. The baselines of the hold are the strain values of 500 με and 1000με in Strain10 of Figure 1. Figure 5 shows the distributed strains along the optical fiber direction. The results of the measured strains contain some external noises because not only the embedded part into the panel but also the entire optical fiber serve as the distributed sensing network. Thus, three results of the strain measurements at the strain-free state were used for the averaging procedure as shown in Ref.1, Ref.2, and Ref.3 of Figure 5. Though the strain values fluctuated around 0 με before the loading, the embedding can be monitored due to the loading till Strain10 reaches 500 με. When the additional loading was applied to the panel, the value of Strain10 was confirmed to reach 1000 με.

For verification of the validities of measured strains, the skin/stringer panel was modeled by using an 8-node continuum shell element. A full FE such a shell element is suited to the laminated composites for saving of the calculation cost [3]. The FE model consisted of three different plates, skin part, flange part, and web part as shown in Figure 6. The total number of elements and nodes were 3620 and 7826, respectively. The calculated strain were obtained under the conditions of 500 με and 1000 με in

(b) Test appearance.



(a) Boundary conditions.

Figure 4. Four-point bending test.

Strain10 of Figure 1. The FE analysis was performed by using ABAQUS code. All the strain values are summarized in Table 1. The measured strains are small compared with the calculated strains for the results of Strain1 and Strain3. That is because the gradient of the thickness in the flange part could not introduced into the FE model, and attached location of the strain gauges was on borderline of the thickness change. Using the calculated results, the measured strains were verified for the strain gauges and the embedded FBG sensors. The corresponding strain to the embedded FBG sensor was assumed to be same as average of the stain in the upper 45° layer of the skin part and the stain in the lower 45° layer of the flange part. The strains measured by the fiber-optic sensors were good agreement with those of calculated strains. The embedded FBG sensors and optical fibers for the PPP-BOTDA were verified to be useful for the structural health monitoring as well as the process monitoring of VaRTM.

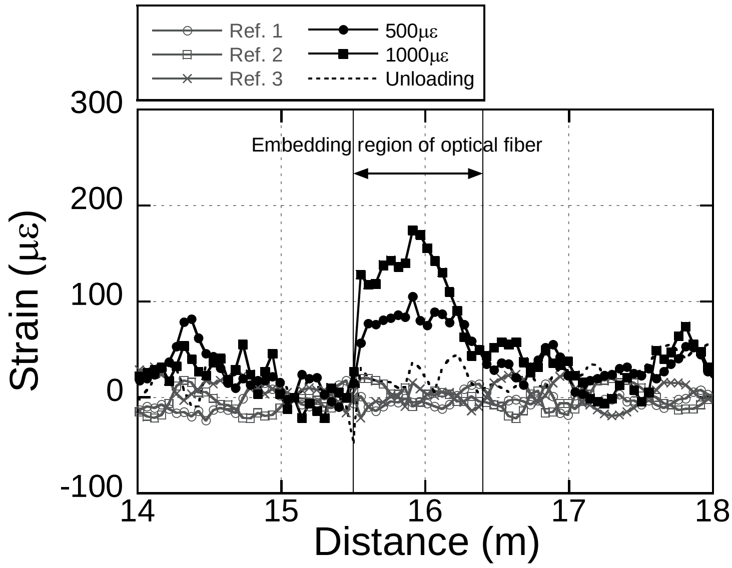


Figure 5. Strain measured by PPP-BOTDA.

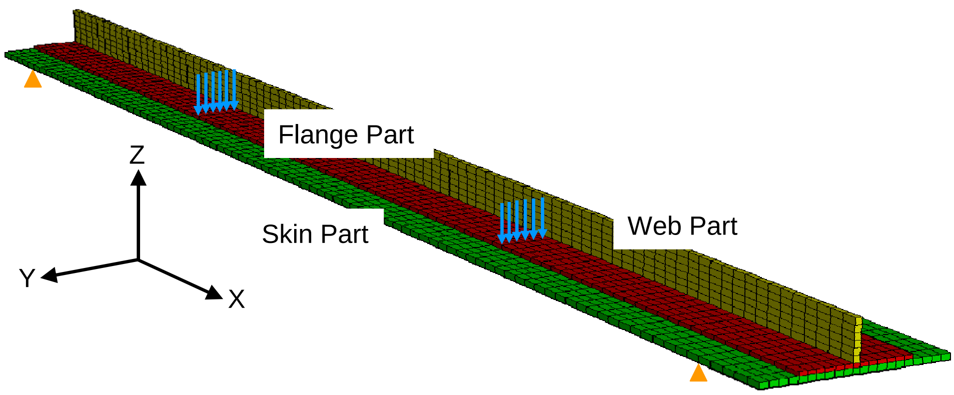


Figure 6. FE model of skin/stringer structure.

Table 1

	Measured strain (με)	Calculated strain (με)
FBG1 (PPP-BOTDA)	89 (119)	114
FBG2 (PPP-BOTDA)	201 (174)	236
FBG1	-82	-130
FBG2	104	121
FBG3	-160	-268
FBG4	293	253
FBG5	464	483
FBG6	443	483
FBG7	458	482
FBG8	1010	1001
FBG9	1000	1000
FBG10	1036	1000

CONCLUSIONS

The CFRP stiffened panel was fabricated by VaRTM for the monitoring of the molding process including measurements of strain and temperature using the FBG sensors. Moreover, four-point bending was applied to the panel for verification of its structural integrity and the sensor capabilities using the FBG sensors and the PPP-BOTDA system. Though the economic efficiency has to be considered for practical use, the monitoring with fiber-optic sensors was found to be effective for increasing VaRTM composite structures. The following are issues in the future of health monitoring using fiber-optic sensors.
FBG sensors: cost of multiplexing, reproducibility of embedding condition
PPP-BOTDA: strain accuracy and spatial distance, processing time of measurement

ACKNOWLEDGEMENTS

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