Process and Health Monitoring Using Fiber Optic Distributed Sensors for Wind Turbine Blades

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ABSTRACT:
VaRTM has been applied to manufacture wind turbine blades recently. However, VaRTM has several problems to be solved to increase quality of wind turbine blades made of FRP. If the preform is very thick or the permeability of resin varies with location due to the resin flow medium or nonuniformity, an unimpregnated part may be generated during the resin infusion. A dry spot can be also occurred according to resin flow pattern. Additionally, residual stress after cure can be the cause of delamination or lower dimensional stability in the wind turbine blade. Therefore, it is useful for quality assurance of the blade to monitor the manufacturing process which includes resin infusion and cure in VaRTM. If one can monitor not only the manufacturing process but also the structural integrity of the in-service blade by the same system, the reliability of it will be more improved without the extra costs.

In this study, we tried to do process and health monitoring with the same optical fiber sensor. We fabricated a specimen by VaRTM to investigate the applicability of process and structural health monitoring of a wind turbine blade with fiber Bragg grating sensors (FBGs) based on optical frequency domain reflectometory (OFDR). Especially, the long gauge FBGs (about 100mm) which are 10 times longer than an ordinary FBG were employed for a distributed sensing. During VaRTM, the embedded FBGs measured how the preform affected the sensor by vacuum pressure and resin was flowed into the preform. Then, shrinkage of resin that was developed during cure was detected by the sensors. Distributed strain measurements in 3 point bending tests were conducted with the laminate to prove the applicability of structural health monitoring with the same optical fiber sensors used for process monitoring. We could measure the effect of vacuum pressure, resin flow edge, shrinkage of resin during VaRTM and strain change of the laminate, successfully.

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INTRODUCTION

Recently, liquid composite molding processes have been accepted due to can manufacture high quality composite structures. Among them, VaRTM (Vacuum assisted Resin Transfer Molding) is employed as the fabrication method for the wind turbine blades to achieve high strength and stiffness. VaRTM can fabricate large structure such as the wind turbine blades exceed 40 m because it needs only one side mold, and the mold is closed by vacuum bag film with sealant tape. VaRTM uses vacuum pressure as the driving force to impregnate the resin into the preform (Fig.1) [1]. VaRTM has various advantages such as saving tooling and process cost, high fiber volume content, mechanical properties, lower void content, fume free, etc. [2]. However, VaRTM has disadvantages like unimpregnated part, dry spot, shrinkage of resin, lower dimensional stability, etc. It is necessary to do process monitoring of VaRTM and health monitoring of structures made by VaRTM in order to apply VaRTM to the fabrication of the wind turbine blades more effectively.

When resin is impregnated into the prefrom, if preform is very thick or has large difference of permeability with resin flow medium, unimpregnated part is occurred. And dry spot can be generated according to resin flow pattern. In the case of thermosetting resin, shrinkage of matrix and residual stress are generated during cure. These will be causes of delamination [3] and lower dimensional stability in wind turbine blade that made of FRP. Accordingly, it is necessary to control the manufacturing processes through resin flow monitoring and cure monitoring.

Several research groups [4, 5] have been studied about resin flow monitoring and/or cure monitoring in VaRTM with optical fiber sensors or electrical sensors. However they did not structural health monitoring with the same sensor. If different types of sensor are used according to monitoring objects in VaRTM, sensing system will be expensive and complicated, and sensors can affect to the mechanical properties of composite structures.

In this study, we tried to process monitoring (flow monitoring and cure monitoring) and health monitoring with a strand of optical fiber sensor to simplify the monitoring system in order to apply this system for wind turbine blade as shown in Fig. 2. We adapted optical frequency domain refelectometry and the long gauge FBGs which are 10 times longer than an ordinary FBG for a distributed sensing. Three long gauge FBGs were embeded into the preform to measure the effect of vacuum pressure and resin flow edge. Then, shrinkage of resin that was developed during cure was detected by them. Distributed strain measurements in 3 point bending tests were conducted with the laminate which was fabricated by VaRTM to prove the applicability of structural health monitoring with the same optical fiber sensors used for process monitoring.

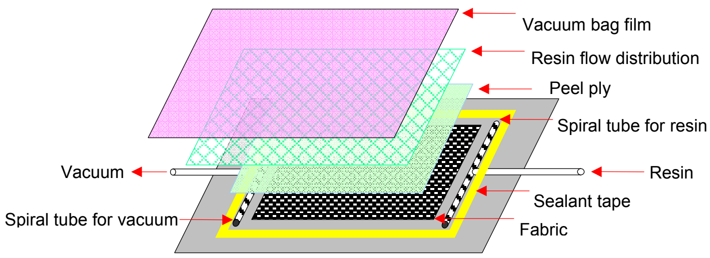


Figure 1: VaRTM set up

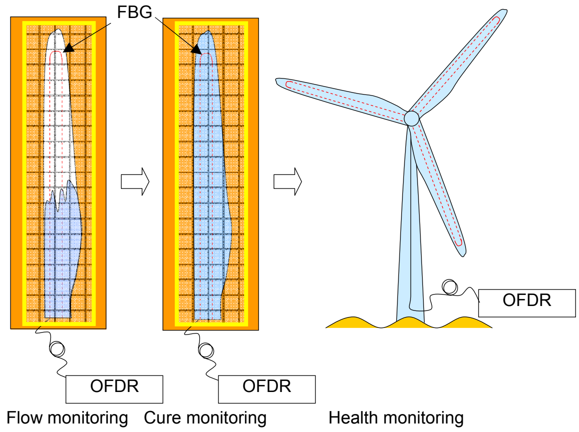


Figure 2: Concept of process and health monitoring with FBGs based on OFDR

OPTICAL FREQUENCY DOMAIN REFLECTOMETRY (OFDR)

OFDR is consisted on wavelength tunable laser, two photodiode detectors (D1, D2), three broadband reflectors (R1, R2 and R3), three 3dB couplers (C1 C2 and C3), a long gauge FBG, personal computer and A/D converter as shown Fig. 3. The wavelength tunable laser is controlled with personal computer through GPIB, and a measured data is acquired by A/D converter. The part including D1, C2, R1 and R2 is in-fiber interferometer. As light is turned, light is separated at C1 and travels to C2 and C3. Light is interfered within two reflectors, R1 and R2. The light intensity that depends on constant wave number change, Δk (eq. 1) was acquired at D1. This signal acts as trigger for measurement. We can sample the signal of D2 (eq. 2) with the constant wave number interval by using the signal of D1 as trigger. D2 acquires reflected light that includes frequency between R3 and each grating. The spectra along the long gauge FBG can be determined by Fourier analysis [6, 7].

$$\Delta k = \frac{\pi}{nL} \tag{1}$$

where n is the effective index and L is the path difference of the two paths through the interferometer.

$$D_2 = R_i \cos(k 2nL_i) \tag{2}$$

where R_i is the spectrum of the i'th grating and L_i is the path difference of the corresponding i'th interferometer. In the case of the long gauge FBG, the summation is not needed. The wavenumber, k is related to the wavelength and given by the following equation (eq. 3).

$$k = \frac{2\pi}{\lambda} \tag{3}$$

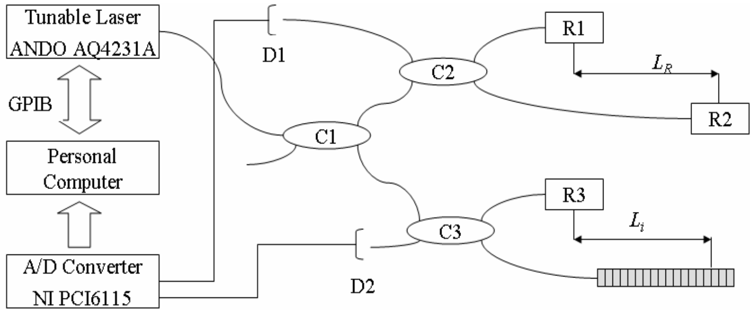


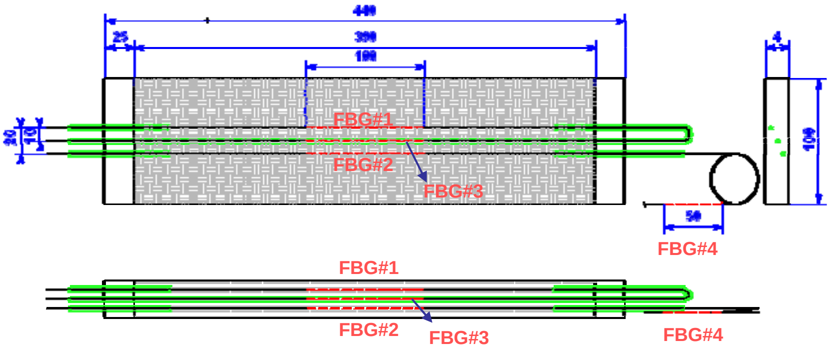
Figure 3: OFDR system

EXPERIMENTS

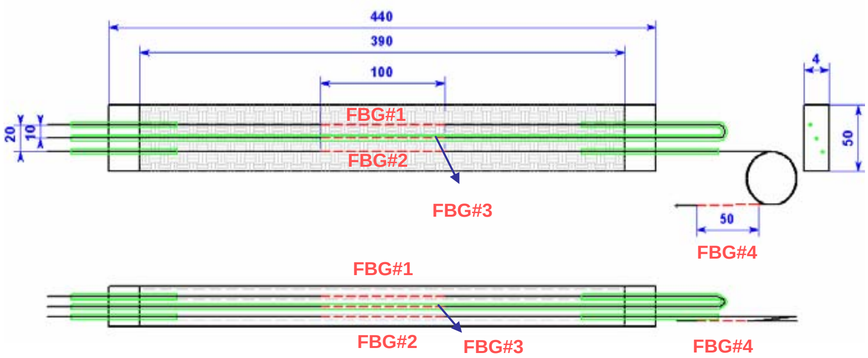
Figure 4 shows details of specimen. Fig. 4 (a) shows the specimen size to monitor resin flow edge and resin cure in VaRTM. The long gauge FBG 1, 2 and 3 were located at the center of specimen on its length direction. Each FBG was located by 10 mm interval. FBG 1, FBG 2, and FBG 3 were laid on 4 plies, 16 plies and 10 plies of glass fiber mats respectively. FBG 3 was protected by the tube. FBG 3 was strain free to compensate temperature for the data which acquired by FBG1 and 2. FBG 4 also installed to use as temperature compensation. To prevent break optical fiber by vaccum pressure, we installed two acryl plates in both edges of preform. Tubes passed through the acryl plates, and each optical fiber passed through each tube. Each edge of tube was sealed with the sealant tape to prevent leakage air into the vacuum bag. To monitor changes of temperature, thermocouples were inserted by 50 mm intervals on 4 plies and 16 plies of glass fiber mat. After cure, we trimmed both side of specimen for 3 point bending test as shown Fig. 4 (b).

Resin flow is very important parameter in VaRTM. It is good that viscosity of resin is as possible as low to increase manufacturing efficiency. So, sometimes resin is warmed to down viscosity. If the warm resin is infused into the preform, temperature gradient will be developed between impregnated preform and unimpregnated one. At that time, the point which temperature gradient will be started becomes resin flow edge from the data acquired from the long gauge FBG. We monitored that point as resin flow edge by the long gauge FBG with OFDR. If the volume of matrix shrinks during cure, FBG will be pressed by around matrix. At that time, compressive strain occurs in FBG. Then FBG can measure compressive strain. To prove ability of health monitoring, we conducted 3 point bending test. Top side of FBG detect compressive strain, Bottom side of FBG detect tensile strain.

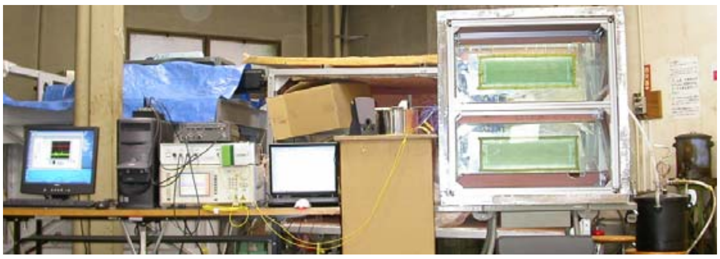
Figure 5 shows the experimental set up. Fig. 5(a) shows OFDR system and VaRTM jig. We made VaRTM jig to observe flow difference of top side and bottom side of laminate by installed each mirror with ±45°. Room temperature was 17 °C and resin temperature was about 60 °C. Resin was warmed by an oil bath that is able to control temperature. In the case of resin flow monitoring and cure monitoring, sampling rates were 1.7 sec./sampling and 10 min./sampling, respectively. Sampling was started before applying vacuum to vacuum bag with 1.7 sec./sampling for process and resin flow monitoring The sampling rate was changed to 10 min./sampling for cure monitoring, when the temperature of impregnated preform returned to room temperature during cure.



(a) for VaRTM



(b) for 3 point bending test
Figure 4: Specimen for this study (unit: mm)



(a) for resin flow and cure monitoring

(b) for 3 point bending test
Figure 5: Experimental set up

After curing, the laminate that includes three strands of 100 mm gauge length FBG was released from the glass plate, and tooled for 3 point bending test. Fig. 5 (b) shows 3 point bending test with OFDR for the laminate made by VaRTM. 3 point bending test was conducted to prove ability of health monitoring with same optical fiber which was used for resin flow and cure monitoring. At the 3 point bending test, FBG 1 toward top side and FBG 2 toward bottom side. Two strain gauges were attached each surface on FBG with 40 mm interval to compare with the results from FBGs. Loads were applied to the specimen with cross head speed 1 mm/min. Max. strain was 800 με. We measured strains with each FBG every 100 με. Support span was 280 mm.

RESULTS AND DISCUSSIONS

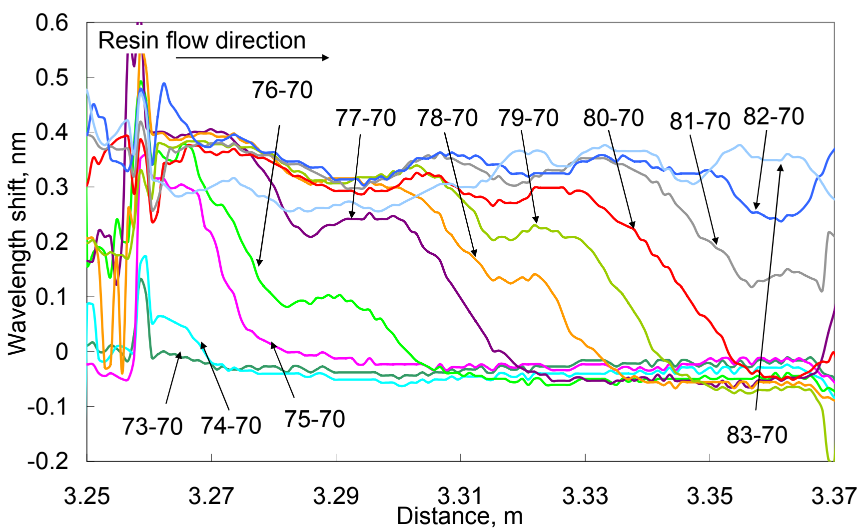
Figure 5 shows the results of resin flow monitoring. Fig. 5 (a) shows how to shift the wavelength of FBG 2 within 100 mm gauge length, when the resin arrived at FBG. Resin flow depending on time is appeared by wavelength shift. Before the resin arrived at FBG, the wavelength shifts were not observed. Wavelength shifts were toward corresponding with resin flow. Each number means the elapsed time (each number x 1.7 sec.). Number 70 was a primary stage that resin was not infused into preform, and only vacuum was applied.

Each graph shows the values that subtracted the results of No. 70 from each measured one to know how wavelength shifted by resin flow. Resin flow edge is the point that wavelength shifted rapidly.

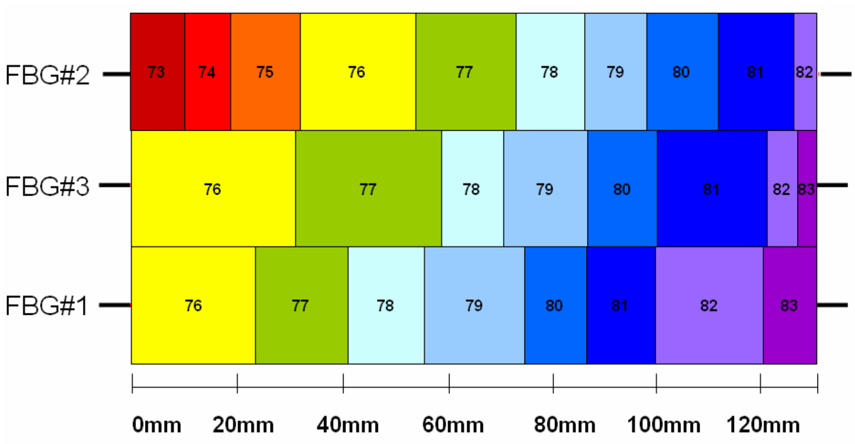
Colligating the results from each FBG 1, 2 and 3, we could know the difference of velocities of resin flow between top and bottom sides according to different permeabilities between resin flow medium and preform as shown Fig. 5 (b). Resin flow of upper side is faster than bottom side because of resin flow medium.

Figure 6 shows the results of cure monitoring. After vacuum applied into the vacuum bag, compressive strain developed. When resin filled on FBG, compressive strain is released by volume of resin. As resin filled to preform perfectly, compressive strain is more released. After resin cured perfectly, we could know that compressive strain was developed again by shrinkage or resin.

Results of 3 point bending test is as shown Fig. 7. According to apply load, increased strain was observed by FBGs that were embedded in composite structure manufactured by VaRTM. Wavelength shifts were conversed to strains. Results from FBGs were corresponding with theoretical strains. From in these results, we could also know how to distribute strains along to the long gauge FBG.



(a) FBG 2



(b) Difference of resin flow velocities on FBG 1, 2, and 3
Figure 5: Results of resin flow monitoring

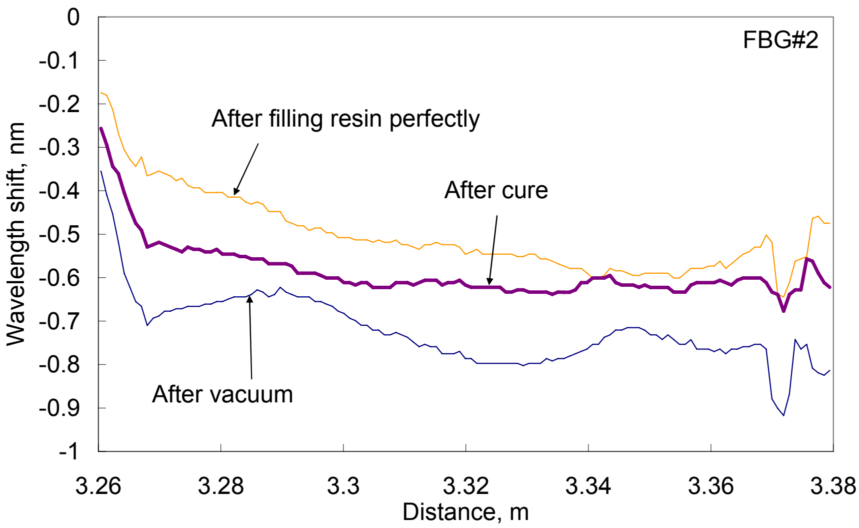


Figure 6: Results of cure monitoring

CONCLUSIONS

In this study, we tried to process and health monitoring of wind turbine blade manufactured by VaRTM which is one of the advanced liquid composites molding processes. Process and health monitoring were able to conduct resin flow monitoring, cure monitoring and 3 point bending test with one optical fiber sensor. We adapted the 100 mm long gauge FBG and OFDR system in order to be able to distributed sensing. We could measure resin flow edge and shape of resin flow with 100 mm gauge length. Shrinkage of resin was also detected by the long gauge FBG. The ability of health monitoring was proved as conducted 3 point bending test by same optical fiber sensors which were used for resin flow and cure monitoring in VaRTM. Accordingly, it is expected that quality and maintenance of wind turbine blade can control with the system that was suggested in this study with low cost.

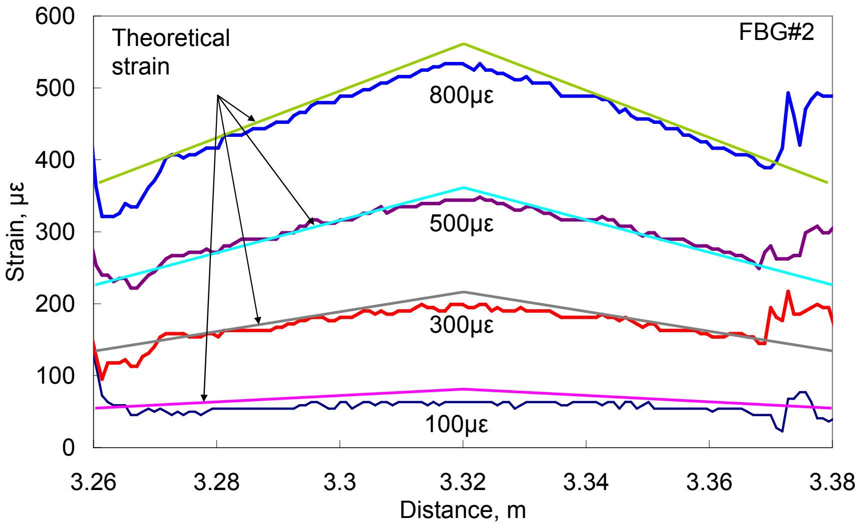


Figure 7: Results of 3 point bending test

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