論文の内容の要旨

論文題目　：Fiber-Optic Process/Health Monitoring　for Composite Structures Manufactured by VaRTM
-An Application of Embedded FBG　Sensors with Multiplexing Techniques-
（光ファイバセンサを用いたVaRTM成形複合材料構造のヘルスモニタリング
－埋込型FBGセンサによる多点測定技術の応用－）

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Recently, liquid composite molding (LCM) processes have been accepted to manufacture fiber reinforced composite structures. VaRTM is one of LCM processes and employed widely as the fabrication method for large composite structures, such as a wind turbine blade and a ship hull, to achieve good quality and save costs. VaRTM has simpler equipments than traditional resin transfer molding (RTM). While RTM needs fully enclosing two-side rigid mold, VaRTM uses one-side mold with relatively lower stiffness because high temperature and pressure are not required for curing process.

In VaRTM process, vacuum acts as driving forces to draw resin into the preform, compact the preform and remove air from resin and mold cavity. A mold is sealed by a vacuum bag film and tacky sealant tapes. Resin is infused to the preform through a spiral tube from the inlet port by vacuum pressure and distributed into the whole preform smoothly by a porous resin flow distribution media. An extracted resin is flowed out to vacuum port through another spiral tube. A peel ply is inserted on the preform in order to peel off a porous resin flow distribution media and the vacuum film after curing.

In VaRTM, resin flow should be well controlled to prevent manufacturing defects. For example, a dry spot is a region where resin isn’t filled sufficiently and it may be occurred during resin filling process. Their formation depends on the resin flow condition which is affected by viscosity of resin, permeability of the preform, pressure, temperature, staking pattern and infusion strategy. The prediction and prevention of the dry spot are the problems to be solved because it can degrade mechanical properties of the product and they can be carried out based on the real-time information on resin flow. In addition, shrinkage of resin matrix causes residual stress, buckling and delamination in composite structures, and reduces dimensional stability of the final product. Therefore, it is essential to monitor the manufacturing process in VaRTM for the quality assurance of the product.

Several researches have been reported about resin flow monitoring and/or cure monitoring during VaRTM process or other LCM processes with optical fiber sensors, electrical sensors or an ultrasonic technique in recent years. Resin flow and cure condition can be monitored by the change of the transmission spectrum or the optical power output due to the refractive index changes of surrounding resin. Direct current resistance measurement using the SMARTweave system has been employed to monitor resin position and cure state as the sensing gap between two crossing conductive filaments is filled with resin. By using ultrasonic transmission, the resin propagation can be detected. However the sensing systems in these researches were used for only process monitoring. It is more effective and reasonable to apply the same sensing system to both process monitoring and in-service inspection.

In order to obtain desired quality of the product and to access the integrity of composite structures fabricated by VaRTM effectively, the resin flow condition, the shrinkage of resin and the strain variation have to be detected and located over whole product. Accordingly, the distributed sensing technique is required to map the temperature and strain profile. In this study, optical fiber sensor was employed because it can be embedded easily into composites with its flexibility and thin diameter, and can apply to carbon fiber reinforced plastics (CFRP) because of withstand voltage characteristic and anti-electromagnetic induction. Fiber Bragg grating (FBG) which responds to temperature and strain was employed as optical fiber sensor.

Especially, at the particular part, for example, the stress concentration part and the low permeable part, the distributed sensing method with the high spatial resolution is required to acquire detail information. Therefore, the long gauge FBGs which are 10 times longer than an ordinary FBG whose length is about 10 mm were employed for distributed sensing. In order to measure distributions of temperature or strain along FBG with a high spatial resolution, optical frequency domain reflectometry (OFDR) was chosen for the measurement system. Its spatial resolution is less than 1 mm.

In the case of the fabrication of the large scale composite structure, the quasi-distributed sensing method is required to monitor the entire resin flow front. Wavelength division multiplexing (WDM) method was employed for the quasi-distributed sensing. The ordinary FBG sensors were interrogated with WDM technique.

The aim of this research is to verify the applicability of using the distributed sensing system based on long gauge FBGs based on OFDR and short gauge FBGs based on WDM technique for detecting resin flow condition, shrinkage of resin during VaRTM process and conducting in-service inspection of the product manufactured by VaRTM. The preform with embedded FBGs sensors were subjected to VaRTM process, and resin flow condition and shrinkage of resin were detected by the long gauge FBGs. To evaluate the capability of in-service inspection with the laminate made by VaRTM, the three point bending test and the tensile test were conducted.

Finally, the confirmed monitoring method was applied to the real composite structure, wind turbine blade successfully. In the wind turbine blade manufacturing process, the resin flow front, the resin cure conditions were monitored by using the monitoring methods mentioned above. In order to investigate the structural health monitoring for the wind turbine blade, the static blade and dynamic blade tests were implemented.

The feasibility study for process and structural health monitoring for VaRTM by using one kind of optical fiber sensing system was implemented. The long gauge FBG was employed as optical fiber sensor, and OFDR system was adopted for the distributed sensing system. Resin flow front was detected as measuring resin temperature within the gauge length of FBG sensor. Cure monitoring was carried out by detecting the shrinkage of resin. Thee point bending test, tensile test and tensile test with notched specimen were performed to conduct the structure health monitoring. The measured strain distributions show good agreement with theoretical values.

The ability of FBG sensors with interrogating systems based on WDM technique and OFDR for resin flow front monitoring during VARTM process was investigated. The resin flow front monitoring with the strain change was investigated based on the results from chapter 4. Under the vacuum pressure, the embedded FBG sensor measured the compressive strain. When the resin closed FBG sensor, the strain was more developed. Then the FBG sensor was merged by the resin and detected the strain release. Resin flow front monitoring based on the quasi-distributed sensing and the distributed sensing was investigated successfully.

The model for strain development, which is media for resin flow front monitoring, was suggested. The experiment and the microstructure analysis were carried out to confirm the modeling. Also, it was clarified experimentally that the strain change was caused by the movement of the yarn of fabric when the resin was close to the FBG sensors. The experimental results reflected well the suggested conceptual model.

Process/health monitoring for the wind turbine blade manufactured by VaRTM was implemented with the monitoring method and sensing system which were investigated in chapter 4 ~ chapter 6. The wind turbine blade whose length is 1 m was designed and manufactured. The 8 FBG sensors array on a single optical fiber and the long gauge FBG sensor were employed for the quasi-distributed and distributed sensing respectively. The applicability of the monitoring method to the real composite structure, which is proposed in this study, was proved successfully.

Finally, it is hope that the novel process/health monitoring method presented in this thesis can contribute to upgrading the quality and reliability of the composite structures manufactured by VaRTM.