8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao
www.ndt.net/app.EWSHM2016

Life Cycle Monitoring and Quality Control of Aerospace Composite Structures

Nobuo TAKEDA, Shu MINAKUCHI

[1] TJCC (UTokyo-JAXA Center for Composites), Graduate School of Frontier Sciences, The University of Tokyo, Mail Box 302, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8561, JAPAN
takeda@smart.k.u-tokyo.ac.jp, minakuchi@smart.k.u-tokyo.ac.jp

Key words: CFRP, Optical fiber sensor, Life cycle monitoring, Quality control.

Abstract

Optical fiber sensors are very useful to monitor the internal strain and temperature in composites during manufacturing and assembly as well as in practical operations. The authors have been using both multi-point and distributed strain monitoring techniques to characterize the internal state of composite structures. This paper reports some recent developments of life cycle monitoring and quality control of aerospace composite structures. Specifically, distributed sensing for large-scaled parts, through-thickness strain monitoring for complex-shaped parts, and direction-dependent cure shrinkage monitoring are described, highlighting wide applicability of embedded optical fiber sensors for intelligent process monitoring and quality assessment of composite parts. In addition, process control of composite bonded joints is demonstrated, which is one of the key technologies to realize bonded joints in composite aircraft primary structures (i.e., realization of boltless structures). Thus, embedded optical fiber sensors continuously monitor the composite manufacturing process itself, in-service usage, and damage throughout its life, which enables us to establish the life cycle monitoring and modeling methodology of CFRP structures.

1 INTRODUCTION

Even though carbon fiber reinforced plastic (CFRP) is being used in almost all modern aerospace structures as a primary structural material, it is still difficult to precisely manufacture large-scale CFRP structures and ensure their structural integrity during operation. Manufacturing CFRP structures often tends to rely on many process trials and errors mainly due to the lack of in-process material data available. Hence, there is an urgent need to develop innovative sensing techniques to monitor the internal states of composite structures and utilize the obtained data to improve safety, structural design, processing technologies and maintenance methods. Within the systems developed so far, optical fiber sensors have attracted considerable attention [1], since they are small, lightweight, immune to electromagnetic interference, and environmentally stable. Furthermore, they possess sufficient flexibility, strength, and heat resistance to be embedded relatively easily into composite laminates during the fabrication. Embedded sensors continuously monitor the composite manufacturing process itself, in-service usage, and damage (Fig. 1, [2]). By combining all the information obtained by the sensing network, we can accurately evaluate the internal state of the structure throughout its life. We call this technology "Life Cycle Monitoring" of composite structures. This paper reports some recent developments of our work, highlighting wide applicability of embedded optical fiber sensors for intelligent process monitoring and quality assessment of composite parts.

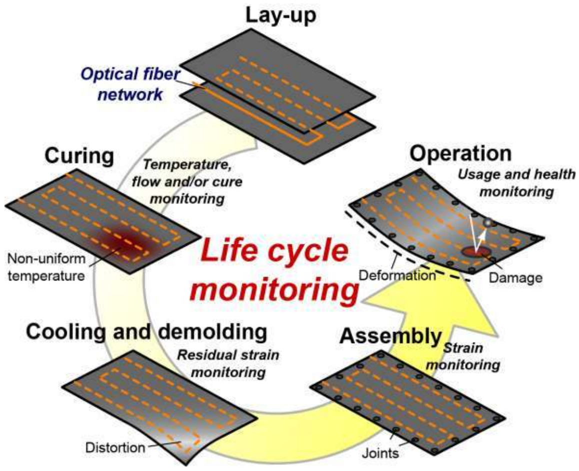


Figure 1: Life cycle monitoring of composite structures [2].

2 DISTRIBUTED STRAIN MONITORING OF LARGE-SCALE CFRP PARTS

Reference [2] demonstrated fiber-optic-based life cycle monitoring of a representative CFRP stiffened panel (Fig. 2) manufactured by vacuum assisted resin transfer molding (VARTM). A single optical fiber was embedded between the stiffeners and the skin during the laminate lay-up process and the formed fiber-optic network was then utilized to monitor the manufacturing process and subsequent impact tests. A Brillouin-based system with a spatial resolution of 10 cm was utilized for distributed strain measurement. The internal state of the panel was successfully monitored throughout its life (Fig. 3), confirming the effectiveness of life cycle monitoring by fiber-optic-based distributed sensing for developing highly-reliable composite structures.

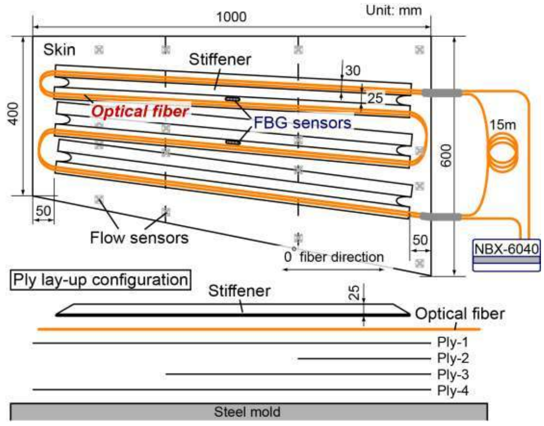


Figure 2: CFRP panel for demonstration fabricated through VaRTM process [2].

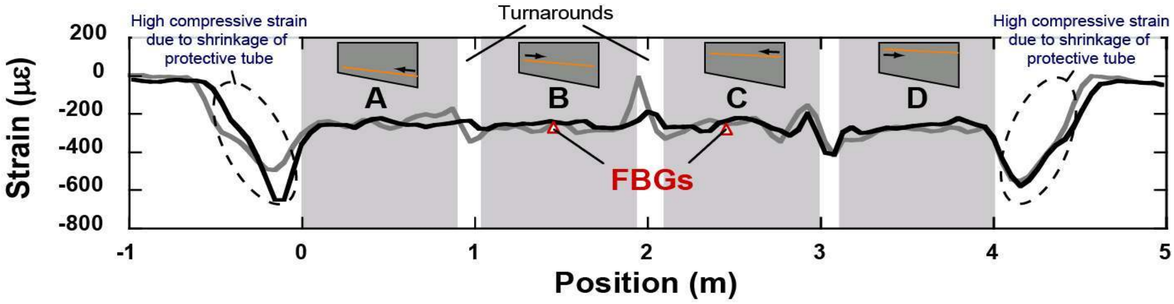


Figure 3: Thermal residual strain obtained from two lines embedded in the same position. Result agreed well with FBG measurement, validating measurement accuracy [2].

Following this demonstration, a hybrid Brillouin-Rayleigh system was developed, which can measure strain and temperature distribution simultaneously [3]. The system could identify a non-uniform thermal residual strain field induced by a non-uniform cure temperature. The distributed monitoring approach was further utilized to clarify the mechanism of strain development in a thick composite panel curing under a non-uniform temperature in the thickness direction [4]. It was confirmed that viscoelasticity is the key of the strain development.

3 THROUGH-THE-THICKNESS STRAIN MONITORING OF CFRP STRUCTURES WITH BIREFRINGENT EFFECT OF FBG SENSOR

A fiber Bragg grating (FBG) sensor has a periodic variation in the refractive index along the length of a single mode optical fiber. When broadband light is launched into the FBG sensor, a narrow spectral component is reflected back, and the reflection spectrum gives the measure of strain and/or temperature. When a non-axisymmetric strain state arises at the core of the FBG sensor (i.e., cross-sectional shape of the sensor is flattened), the reflection spectrum from the sensor splits into two peaks due to the birefringence effect. The authors have utilized this spectral response to measure through-thickness strain in complex-shaped composite parts.

3.1 L-shaped CFRP corner parts

One example is an L-shaped composite part [5]. L-shaped parts are structural key elements in complex-shaped aerospace composite structures, and life cycle cross-sectional strain change is their key. An FBG sensor was embedded in the through-thickness center of a corner part and the cross-sectional strain change was continuously evaluated by using a birefringence effect of the FBG. The embedded sensor could capture key strain changes throughout the structural life cycle with assistance of a new optical fiber reconnection method. It was confirmed that ‘‘non-axisymmetric strain’’ of the FBG sensor is a good indicator for spring-in distortion in manufacturing and through-thickness tensile failure in operation (Fig. 4). The developed system was further utilized for advanced quality assurance of assembled L-shaped parts, and a new strength prediction method was proposed based on the FBG response (Fig. 5).

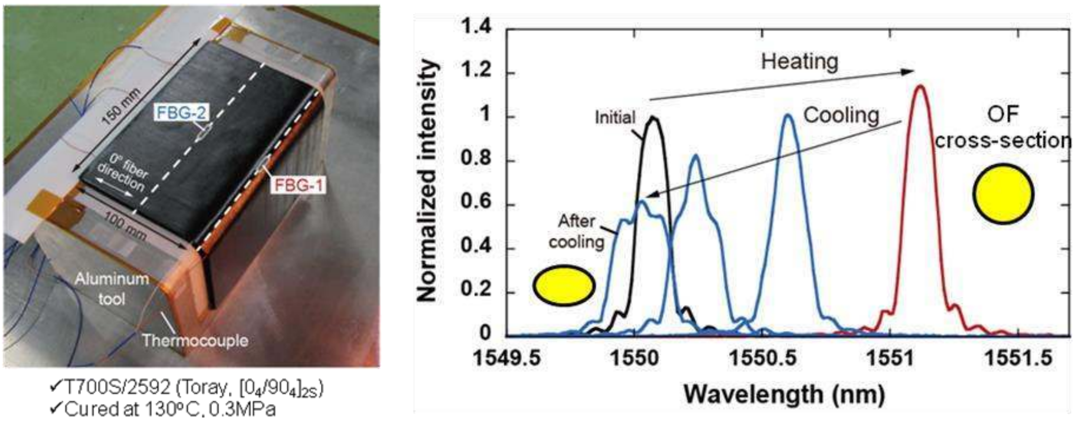


Figure 4: Process monitoring of L-shaped corner part. Through-thickness strain was continuously monitored using birefringence effect of FBG sensor [5].

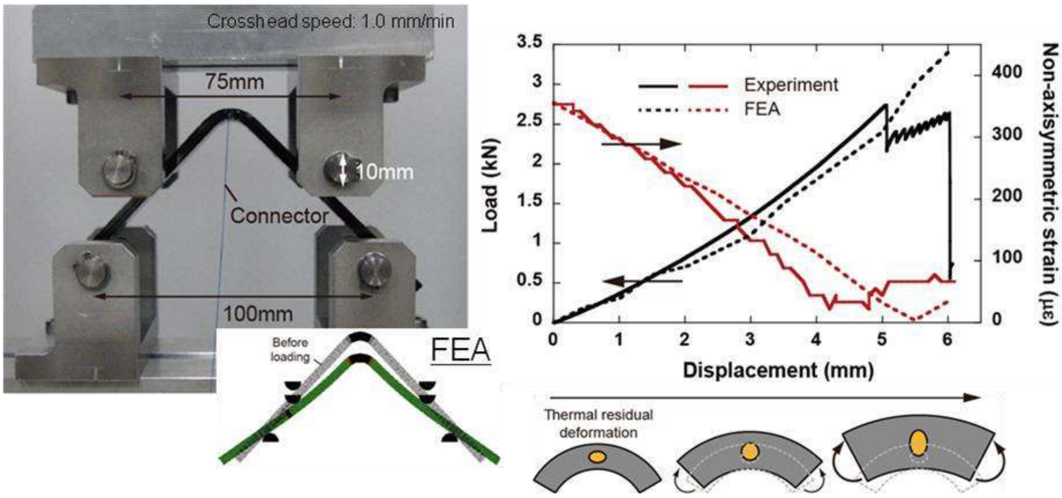


Figure 5: Through-thickness strain monitoring during four-point bending test of L-shaped corner part [5].

3.2 Thick-walled CFRP pipes

A similar technique was then applied to CFRP pipes [6]. In thick-walled composite pipes, significant radial tensile stress is induced during curing, leading to premature delamination failure and performance degradation. The fiber-optic-based system could sensitively capture through-thickness stress development and detect delamination failure in pipes. Following the establishment of the monitoring technique, a residual stress reduction method was proposed to develop thick-walled crack-free CFRP pipes [7]. The authors began by addressing the effect of stacking sequence on residual stress using theoretical and numerical analyses. The result led us to a novel stress-reduction method where circumferentially stiff layers are gathered close to the inner surface. Two pipes were then manufactured: asymmetric and symmetric lay-ups. The radial strain development was evaluated using the fiber-optic-based monitoring system to confirm the effectiveness of the method. Finally, a thick-walled pipe was fabricated. No failure was observed during curing, successfully demonstrating a thick-walled, crack-free CFRP pipe (Fig. 6).

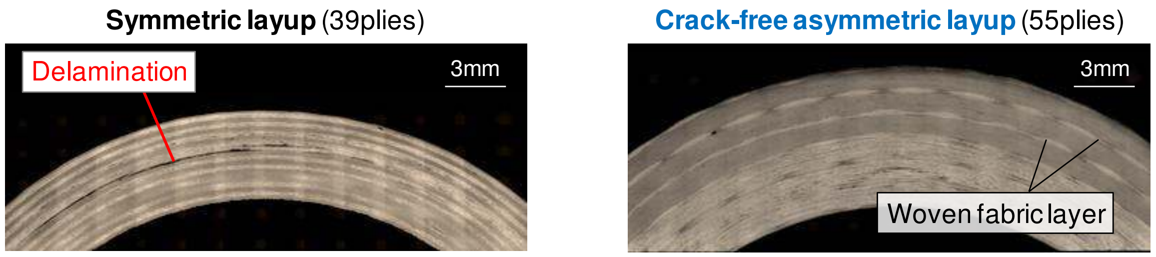


Figure 6: Cross-section of thick-walled CFRP pipes. No delamination failure was observed in proposed asymmetric lay-up. Stress reduction effect was validated using fiber-optic-based monitoring system [7].

3.3 CFRP bonded structures

The FBG-based approach was further extended to process control of composite bonded joints [8]. Stringent process control of bonding is one of the keys to realization of bonded joints in composite aircraft primary structures (i.e., realization of boltless structures) (Fig. 7). The authors developed the first fiber-optic-based quality control technique. Bonding pressure and residual strain in the adhesive were monitored, which enables manufacturing workers to identify areas with lack of bonding pressure before curing and to assure the quality of the bonded joint after curing. The proposed technique will be a key technology to improve the reliability of bonded joints and to reduce the manufacturing cost.

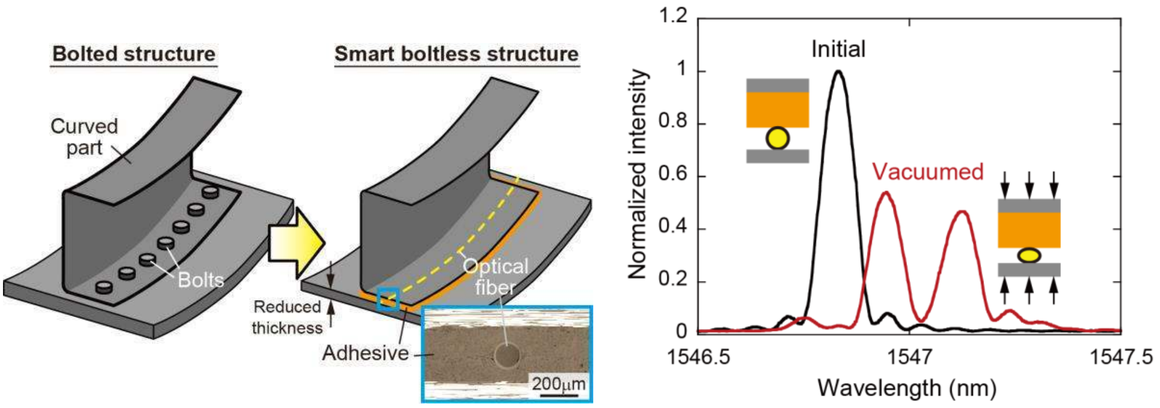
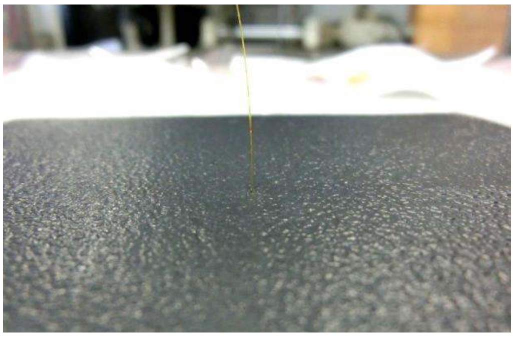


Figure 7: (Left) Smart boltless structure with embedded optical fiber sensor. Without bolts, component thickness can be reduced and more efficient load path is possible. (Right) FBG spectrum just after vacuuming. Using this response, manufacturing workers can immediately identify areas with lack of bonding pressure [8].

4 EMBEDDING SENSORS IN THROGTH-THE-THICKNESS DIRECTION

Reference [9] developed a fiber-optic-based technique for in situ characterization of direction-dependent cure-induced shrinkage in thermoset fiber-reinforced composites. A procedure was established to embed fiber Bragg grating (FBG) sensors in composite out-of-plane directions and to measure key through-thickness chemical cure shrinkage directly under practical curing conditions (Fig. 8). FBG sensors embedded in through-thickness and in-plane directions clarified direction-dependent cure-induced shrinkage in autoclaved unidirectional carbon/epoxy. The developed technique will also be a powerful tool for evaluating cure shrinkage in complex-shaped parts and for validating process-simulation tools based on internal strain.



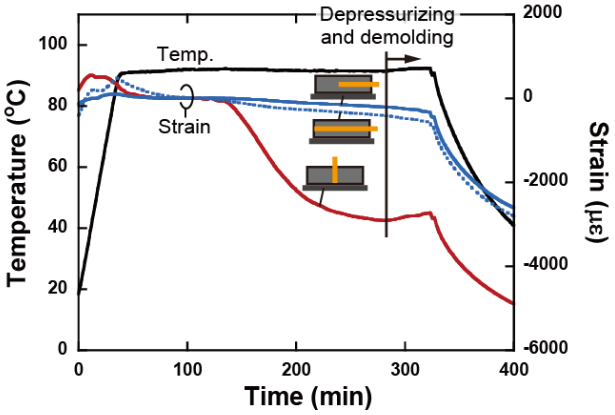


Figure 8: (Left) Surface of specimen with through-thickness sensor. Optical fiber is extending perpendicularly from surface. (Right) Transversely anisotropic shrinkage of unidirectional carbon/epoxy induced due to tool-part interaction. Measurement under practical curing condition is possible with this approach [9].

5 HIGH ACCURACY CURE PROCESS SIMULATION OF CFRP BASED ON IN-SITU INTERNAL STRAIN MESUREMENT

Following the above internal strain measurement system developed, we proposed a composite cure simulation scheme fully integrating the fiber-optic-based measurement [10]. Two FBG sensors with different tail length were embedded in a CFRP laminate and the two key parameters for simulation, i.e., composite shrinkage strain and stiffness change during curing, were determined simultaneously from in-situ strain measurement by considering the shear-lag effects (Fig. 9). Off-axis stiffness change during curing could only be obtained through the current method. Furthermore, the simulation was successfully validated based on the internal strain change during curing.

6 CONCLUSIONS

This paper reported some recent developments of our work. Specifically, distributed sensing for large-scaled parts, through-thickness strain monitoring for complex-shaped parts, and direction-dependent cure shrinkage monitoring were described, highlighting wide applicability of embedded optical fiber sensors for intelligent process monitoring and quality assessment of composite parts. An extention of our current work to new types of CFRP such as thermoplastic CFRP and OoA (Out-of-Autoclave) CFRP is also bing investigated and reported shortly.

We believe the quality control is one of the most important issues for low-cost and high-rate production manufaturing of CFRP structures in next-gerersation aircraft. We also believe in-situ process strain/temperature measurement and accurate process modeling and simulation can be important tools to realize such aircraft CFRP structures. A novel CFRP aircraft design might be generated only with such tools to avoid many trials and errors in manufaturing.

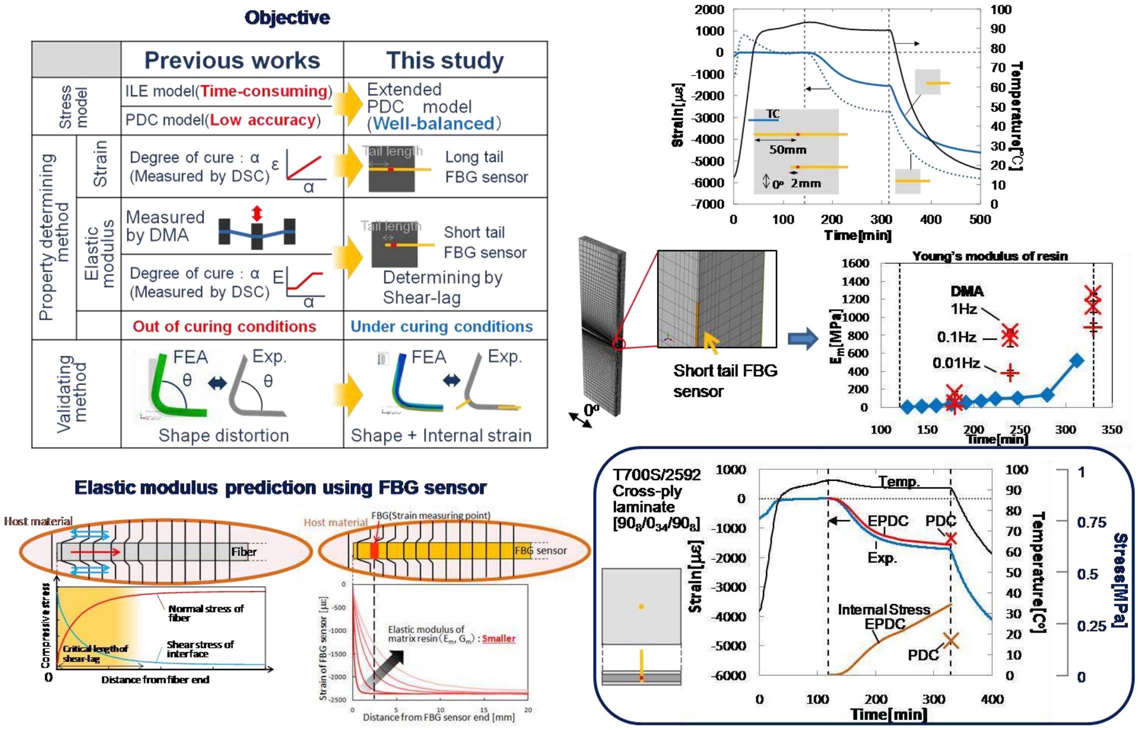


Figure 9: Composite cure simulation scheme fully integrating the fiber-optic-based measurement [10].

7 ACKNOWLEDGEMENTS

This work was partially supported by JSPS KAKENHI, Grant Number 26220912.

REFERENCES

[1] S. Minakuchi, and N. Takeda "Recent advancement in optical fiber sensing for aerospace composite structures," Photonic Sensors, **3** (4), 345-354 , 2013.

[2] S. Minakuchi, N. Takeda, S. Takeda, Y. Nagao, A. Franceschettic, and X. Liu, "Life cycle monitoring of large-scale CFRP VARTM structure by fiber-optic-based distributed sensing," Composites Part A: Applied Science and Manufacturing, **42**(6),669-676 , 2011.

[3] Y. Ito, S. Minakuchi, T. Mizutani, and N. Takeda "Cure monitoring of carbon-epoxy composites by optical-fiber-based distributed strain-temperature sensing system," Advanced Composite Materials, **21**(3), 259-271, 2012.

[4] Y. Ito, T. Obo, S. Minakuchi, N. Takeda, "Cure strain in thick CFRP laminate: optical-fiber-based distributed measurement and numerical simulation," Advanced Composite Materials, **24**(4), 325-342, 2015.

[5] S. Minakuchi, T. Umehara, K. Takagaki, Y. Ito, N. Takeda "Life cycle monitoring and advanced quality assurance of L-shaped composite corner part using embedded fiber-optic sensor," Composites Part A: Applied Science and Manufacturing, **48**, 153–161, 2013.

[6] K. Takagaki, S. Minakuchi, N. Takeda, "Fiber-optic-based life cycle monitoring of through-thickness strain in thick CFRP pipes," Advanced Composite Materials, **23**(3), 195–209, 2014.

[7] K. Takagaki, S. Minakuchi, N. Takeda, “Thick-walled crack-free CFRP pipes: stress reduction using atypical lay-up,” Composite Structures, **126**, 337–346, 2015.
[8] S. Minakuchi, K. Uhira, Y. Terada, N. Takeda, N. Saito, T. Shimizu, "Quality control of composite bonded joints using fiber-optic-based process monitoring," SAMPE Journal, **51**(1), 44-51, 2015.
[9] S. Minakuchi, “In-situ characterization of direction-dependent cure-induced shrinkage in thermoset composite laminates with fiber-optic sensors embedded in through-thickness and in-plane directions,” Journal of Composite Materials, **49**(9), 1021-1034, 2015.
[10] S. Minakuchi, S. Niwa, K. Takagaki and N. Takeda, "Composites Cure Simulatin Scheme Fully Integrating Internal Strain Measurement", Composites Part A: Applied Science and Manufacturing, **84**, 53–63, 2016.