AN INVESTIGATION ON SPRING-IN BEHAVIOR OF Va-RTM COMPOSITE WING STRUCTURE

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Keywords: *Va-RTM, Graphite/Epoxy Composite, Cure Monitoring, Spring-In, FBG*

Abstract

This paper examines the spring-in behavior of the graphite/epoxy composite structures manufactured by using Va-RTM (Vacuum-assisted Resin Transfer Molding) manufacturing technique. Since Va-RTM Composite does not require expensive manufacturing facilities and have potential of integrated manufacturing of component structure that have complicated shapes, large reduction of required manufacturing cost is counted on. As a result of manufacturing of the full-scale wing demonstrator, the harmful process induced deformation called spring-in was observed. In order to prevent this deformation, some of the process parameters such as the cure cycle and resin temperature during impregnation process are modified and 3 stage cure cycle is newly proposed. Furthermore, in order to examine the effect of residual stress distribution and temperature gradient through the thickness direction, multi-point cure monitoring was performed with thermo couples and conventional FBG strain sensors.

1 Introduction

At the moment, because of their potential for reducing the weight, the maintenance cost and the running cost, high performance composite such as graphite/epoxy laminated composites are planning to be widely adopted for new generation commercial aircraft structures. However, manufacturing cost for composite structure is currently much higher than that of conventional aluminum alloy structures. In order to reduce the manufacturing cost for composite structures, developing new manufacturing process of low cost composite is now strongly desired.

Aiming to the large reduction of the manufacturing cost of composite aircraft structures, several projects have been conducted.[1-4] Though it have been successfully manufactured the full scale composite wing box by means of RFI (resin film infusion) process in those project, the process require high pressure curing with autoclave.

In our research group: JAXA (Japan Aerospace Exploration Agency), the low cost manufacturing technique called Va-RTM (Vacuum-assisted Resin Transfer Molding) is now focused on. Since the manufacturing method does not require expensive instrument such as autoclave, the method have a potential of reduction of manufacturing cost rather than other method. Our research group has been involved in the research and development of the integrally manufactured full-scale Va-RTM graphite/epoxy composite wing structure [5]. In order to reduce the manufacturing cost and weight, the skin panels, blade-type stiffeners, and the front and rear spars are designed as fabricated integrally, minimizing the number of mechanical fasteners needed to assemble the wing box. However, process-induced deformation such as spring-in at the bend section is often occurs even in the simple L-shape channels [6]. This phenomena becomes a major issue for the large sized complex structure such as integrated manufactured wing box when the final assembly.

Therefore, the objective of this paper is to examine the spring-in behavior of the Va-RTM composite wing structure. Some of the process parameters such as the cure cycle and resin temperature during resin impregnating and curing process are modified to reduce the spring-in at skin-spar joint section. Furthermore, in order to examine the effect of residual stress distribution and temperature gradient through the thickness direction, multi-point cure monitoring was performed with thermo couples and conventional FBG strain sensors.

2 Development of VaRTM Wing Box

2.1 Manufacturing Process of VaRTM

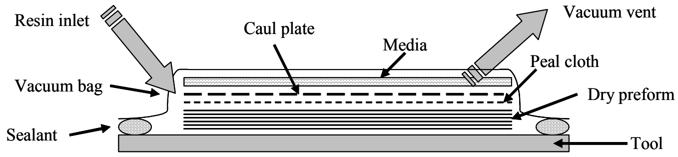
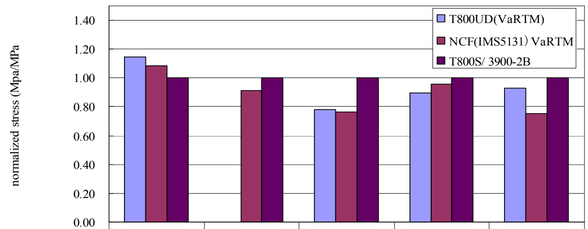


Fig. 1 Schematics of Va-RTM process

In Vacuum-assisted Resin Transfer Molding (Va-RTM), dry fibers or fabrics are lay-upped (preform) on a one-sided mold (tool) and covered by a flexible bag film where the cavity is sealed with vacuum tape. Then, the resin is drawn into the preform under vacuum. In order to assure the surface smoothness of the bag side, a thin steel plate called caul plate is mounted on the peel ply. For the smooth resin impregnation, a large meshed net called flow medium is inserted between the caul plate and the vacuum bag film.

The most different point when compared to the conventional graphite/epoxy composite manufacture by prepreg is the curing condition: though prepreg composite requires high pressure provided by using auto crave, Va-RTM composite cured under atmospheric ambient pressure.

It is usually difficult to achieve a high fiber volume fraction and good mechanical properties by Va-RTM manufacturing processes due to their low pressure condition during resin impregnating and curing process. In order to achieve a high mechanical properties and fiber volume fraction, a uni-directional (UD) type non-crimp fiber of T800SC produced by Toray Co. LTD., and modified low viscosity epoxy resin XNR6809/XNH6809 for conventional RTM process produced by Nagase Elecs., Co. LTD., is selected as fiber and resin respectively, in this study. As a result, high fiber volume fraction of 56% on average and high mechanical properties is achieved. The developed Va-RTM composite are comparable to conventional prepreg graphite epoxy composite for aircraft primary structures. (See Fig. 2) The details are described in [7].



	NHT	OHT	NHC	OHC	CAI
T800UD(VaRTM)	1.15	0.00	0.78	0.90	0.93
NCF(IMS5131) VaRTM	1.08	0.91	0.76	0.96	0.75
T800S/ 3900-2B	1.00	1.00	1.00	1.00	1.00

Fig. 2 Mechanical properties of Va-RTM composite (normalized by conventional prepreg composite properties)

2.2 Manufacturing of Integrated Wing Box

Principal structures made of composite are usually complies of several components such as skin panel, stringer, and spar. In the conventional manufacturing method with prepreg composite, each component are manufactured separately, and finally assembled by secondary bonding, co-curing or fastening.

As mentioned above, Va-RTM composites have a possibility of integrated manufacturing of complicated shape structure. The integrated fabrication can reduce the man-hour for assembly and the number of fasteners, thus, the required manufacturing cost can be reduced. Therefore, in this program, the curved skin panel, the blade type stringers, and spars are attempted to manufacture integrally; and possibility of manufacturing cost reduction with reducing the man-hour for assembly is examined. The final target of this programs are developing the full scale wing box by Va-RTM process which simulate the mid-size commercial aircraft of 30 passengers and conducting the full-scale test to assess the applicability of the demonstrator. For the first step, in order to fined out the technical issues, two demonstrators of 2.1 m long (Fig. 3) and 6.0m long integral structures (Fig. 4) were manufactured.

2.3 Prevention of Spring-in Deformation by Modifying Cure Cycle

As a result of the manufacturing of 2.1m long demonstrator, spring-in deformation was observed. (See Fig. 5) The definition of the spring-in deformation and the measured deformations are shown in Fig. 6 and 7, respectively.

In order to reduce this deformation, cure-cycle and resin temperature during impregnation process

Fig. 3. 2.1m long wing-Box demonstrators

Fig. 4. 6.0m long wing-box demonstrators

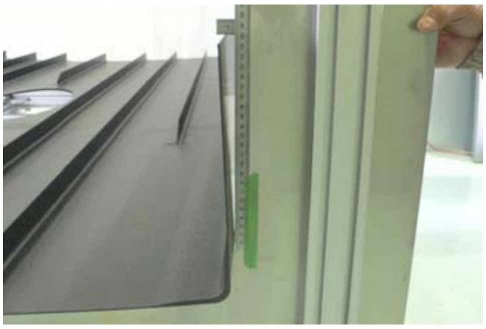


Fig. 5. Spring-in deformation of 2.1m long demonstrator

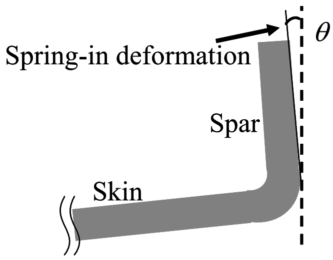


Fig. 6. Definition of spring-in deformation

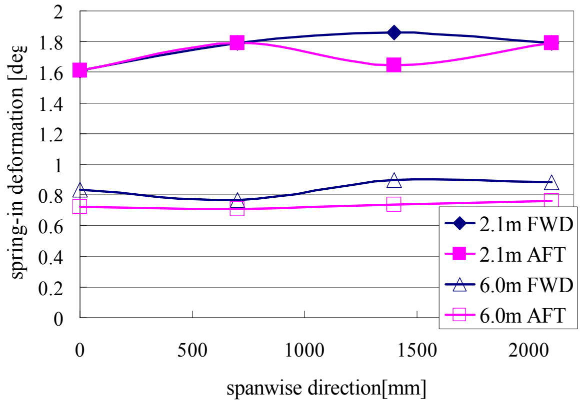


Fig. 7 Measured spring-in deformation

was carefully modified. The relationship between the cure-cycle and Tg of the resin were examined for several types of cure-cycles. As a result, three stage step-up cure cycle of pre-cure and subsequent post-cure was determined as: 24h at 60ºC + 1h at 70ºC + 2h at 80ºC and 2h at 120ºC. Since the modified step-up cure-cycle changes gradually the resin Tg, residual stresses due to the thermal shrinkage of resin can be reduced. Several researches that focus on the relationship between the cure cycle and residual stress of prepreg composite have been reported. [8] It is generally known that the residual stress due to thermal shrinkage is reduced with decreasing of the temperature climb rate during cure.

Using the improved step-up cure-cycle, the 6.0m long demonstrator was manufactured. The measured spring-in deformation is also shown in Fig. 7. Though the spring-in deformation remains about 0.8 degrees on average, the improved cure-cycle can reduce the spring-in deformation by approximately 50% at the skin-spar joint section. It is confirmed that the multi-stage cure cycle that reduce the temperature climbing rate is effective for reducing the spring-in deformation of Va-RTM composite.

3 Cure Monitoring of Va-RTM Process

3.1 Specimen

In order to examine the effect of temperature gradient and residual stress distribution inside of the Va-RTM composite structure, scale model of skin-spar integrated structure was investigated. The stacking sequence and thickness are defined as same as the root section of the 6.0m long wing-box demonstrator: The thickness is approximate 13.9mm and the stacking sequence is $[45_2/0_2/90_2/\text{-}45_2]_{16}$s.

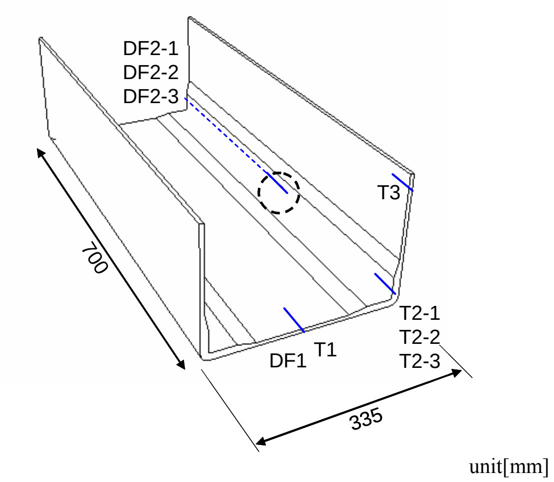


Fig. 8 Configuration of Specimen

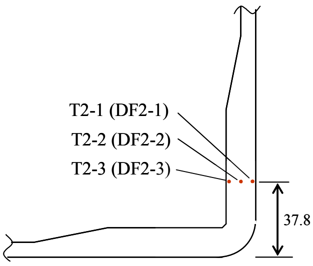


Fig. 9 Thickness location of the embedded sensors

The fibers and the resin is the same as used in the wing demonstrator. The schematic of the specimen is shown in Fig. 8.

The multi-point cure monitoring was performed with embedded fiber Bragg grating (FBG) strain sensors and thermo couples. T1 - T4 in the Fig. 8 represent the location of embedded thermo couples and DF1 – DF2 represent the location of embedded fiber optic sensors. The embedded location of T2-1, T2-2, and T2-3 are embedded in the same location but the thickness position is only different. Similarly, DF2-1, DF2-2 and DF-3 are embedded different thickness position in the same location. The sensors are embedded at the corner pad-up part of skin-spar joining: embedded into the inter-lamina of 3rd–4th layer (outer mold side), 37th-38th layer (middle of the laminate), and 61th-62th layer (bag-side), respectively as shown in Fig. 9.

3.2 Sensors and Monitoring System

In this experiment, FBG sensors produced by FiberLabs Inc. are adopted to monitor the internal strain distribution and temperature distribution. The diameter of the FBG sensor applied in this study is 125µm. The length of the grating is 10mm. In order to identify the reflected light of each FBG, the center wavelength is gradually changed from 1535nm to 1553nm for each FBG sensors. As previously described, the FBG sensors are used for not only strain monitoring bat temperature monitoring. Both the strain and temperature is calculated by the reflection spectrum shifts. Since the reflection spectrum shifts are caused by the grating deformation of the FBG sensor itself, it is usually difficult to directly discriminate the reflection spectrum shift due to strain and that of due to temperature change. To solve this problem, encapsulated FBG sensor for temperature monitoring is adopted in this study. (See Fig. 10) The grating is protected by a polyimide capillary tube whose internal diameter is 180µm.

The monitoring system is schematically shown in Fig. 11. Light generated by ASE light source AQ4310 (Yokogawa Electric Co.) is launched into an optical fiber which connects to the circulator. The circulator is connected with the optical switch OSW8108 (THORLABS) which control switching of the multiple embedded optical fibers. Each embedded optical fiber has the two Bragg gratings: one is the bare FBG and another is encapsulated FBG. The center wave length of obtained reflected light is measured by the FBG sensor monitor FB200 produced by Yokogawa Electric Co. Exact measurement of the strain and temperature change at the same point during cure process can be performed by applying the embedded optical fiber which has two different FBG: bare FBG and encapsulated FBG.

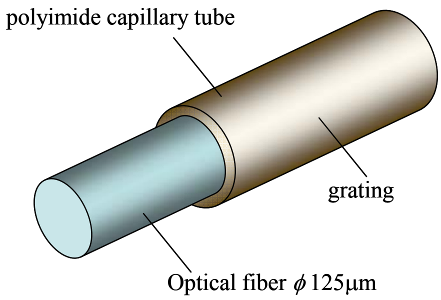


Fig. 10 Encapsulated FBG sensor

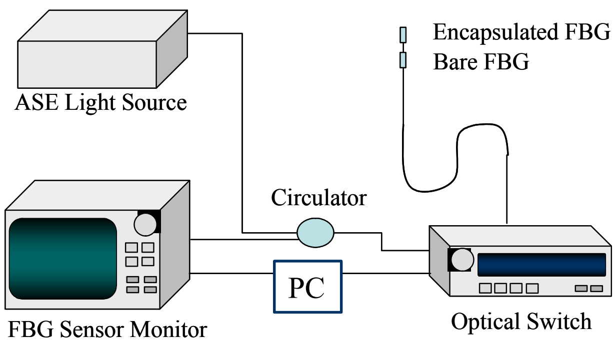
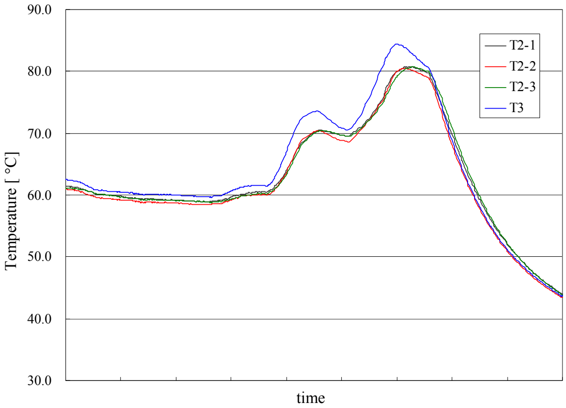


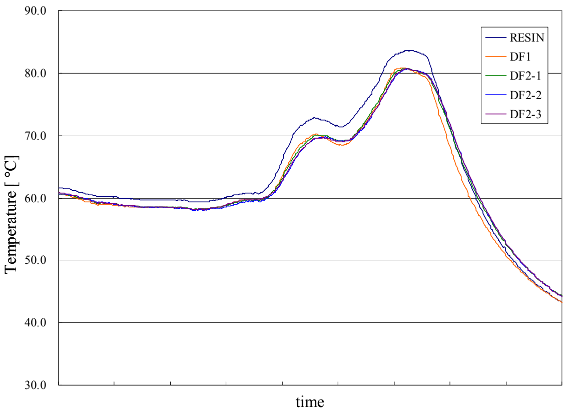
Fig. 11 FBG monitoring system

3.2 Results and Discussion

The measured temperature variations during the cure process are shown in Fig. 12. In the Fig .12 a) and b) show the results of embedded thermo couples and those of embedded FBG sensors, respectively. Unfortunately, the results of thermocouple T1 could not be measured due to breaking of wire during vacuum bagging process. In Fig. 12 b), the temperature variation of the resin measured by means of the FBG sensor is also shown. The resin temperature was measured in the resin storage pot.



a) Measured with thermo couples



b) Measured with FBG

Fig. 12 Measured results of temperature variation

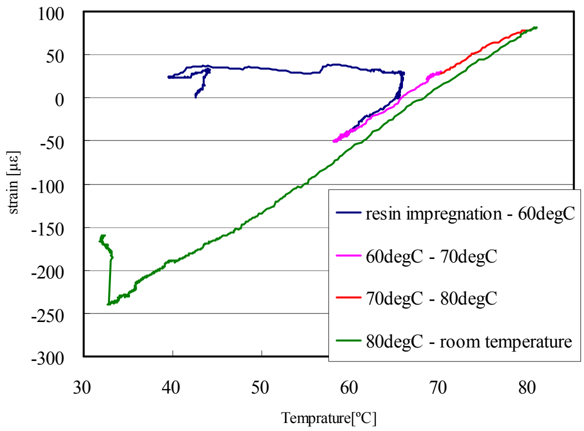
The obtained tendency of the thermo couples results and that of the FBG results are quite similar. The difference between the temperature variations measured with the embedded sensors (T2-1, T2-2, T2-3, DF1, DF2-1, DF2-2, and DF2-3) is very small: It can be negligible. Since this fact indicates that the temperature gradient through the thickness directions is very small during the cure process, it can be concluded that the spring-in deformation is not affected from the temperature gradient through the thickness direction. However, the measured result of T3 shows the gap between the others results. This is because that the thermo couple T3 is located on the bag side surface near the resin inlet point. The tendency of the T3 variation is similar to that of the resin in Fig. 12 b). Therefore, it can be considered that the difference between T3 result and the others are due to self-heating effect of excess-supply resin near the resin inlet.

The results of the measured strain variances with the embedded FBG sensors are shown in Fig. 13: a) shows the result of DF1, b) DF2-1 (Outer mold side), c) DF2-2 (Middle of the laminate), and d) DF2-3 (Bag side). As shown in Fig. 9, the result of DF2-1, DF2-2, and DF2-3 show the strain history distribution through the thickness direction at the same point. (See Fig. 9)

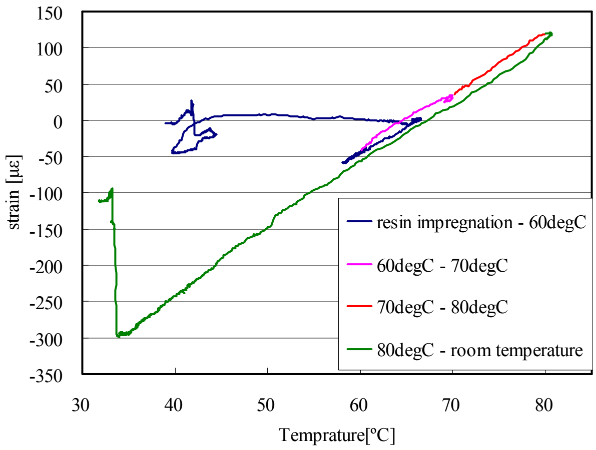
After starting the cure process, all of the measured strain variations show the linear relationship with the temperature change. In the final stage of the cooling phase, the rapid variation of the residual strain can be observed in the all results. This rapid change due to the mismatch of the coefficient of thermal expansion between Va-RTM composite and outer mold made of grass/epoxy laminate; the interface between cured Va-RTM composite and outer mold fails when the interface shear strength was exceeded. Similar behavior of the graphite/epoxy laminate during an infusion process has been reported. [9]

The measured strain after this rapid change is the true residual strength that we want to measure. The obtained residual strength at the room temperature is -112με at the outer mold side (DF2-1), -175με at the middle of the laminate (DF2-2), and -207με at the bag side (DF2-3), respectively. It can be confirmed that the residual strain of the outer mold side (DF2-1) is approximately 100με below that of the bag-side (DF2-3), and the residual strain distribution has a linear gradient toward the thickness direction of the laminate.

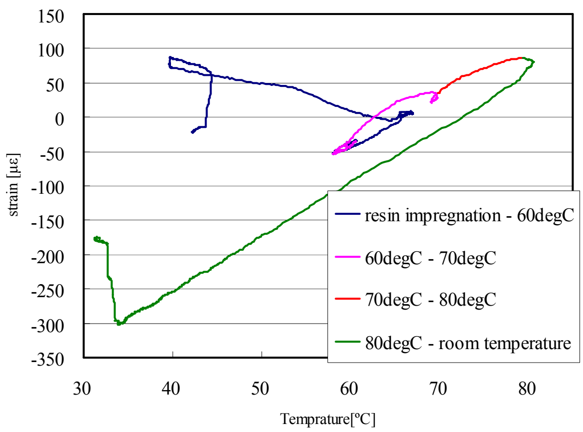
From the results of the cure monitoring, it can be clarified that the spring-in deformation of the VaRTM composite is more affected from the residual strain gradient due to the cure shrinkage than the temperature distribution though thickness direction. Additionally, the mismatch of the coefficient of thermal expansion between the material and outer mold will have a large effect on the spring-in deformation.



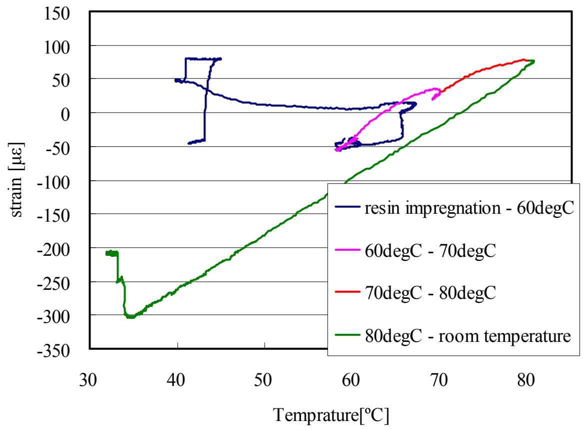
a) Strain history of DF1



b) Strain history of DF2-1
(Outer mold side)



c) Strain history of DF2-2
(Middle of laminate)



d) Strain history of DF2-3
(bag side)

Fig. 13 Relationship between measured internal residual strain and temperature with FBGs

4 Concluding remarks

In this study, spring-in behavior of the Va-RTM graphite/epoxy composite wing structure is investigated. Though the Va-RTM process have a possibility to reduce the manufacturing cost by applying the integral molding of several parts, process-induced deformation such as spring-in might be a major issue for assembling.

In order to prevent a spring-in deformation of the full-scale Va-RTM wing demonstrator, three-stage step up cure cycle is newly proposed. As a result, the proposed cure cycle successfully reduce the spring-in deformation of the wing demonstrator.

Furthermore, in order to examine the effect of temperature gradient and residual stress distribution inside of the Va-RTM composite structure, scale model of skin-spar integrated structure was investigated. The real time cure monitoring of the temperature and strain histories inside of the test peace were successfully performed by using multiple FBG sensors and thermo couples. Though there is no temperature gradient through the thickness direction, it can be observed that the residual stress distribution has a linear gradient toward the thickness direction. As a result, it is clarified that the spring-in deformation is more affected from the residual strain gradient than the temperature gradient though thickness direction.

Acknowledgments

The authors take the opportunity to thank the KADO Corporation for supporting this research.

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