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Investigation into property control of VaRTM composites by resin infusion process

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This paper proposes a property control method in vacuum-assisted resin transfer molding (VaRTM) using porous mold process (PMP) to fabricate carbon fiber-reinforced plastics (CFRP) composites. Low-cost VaRTM process generally induces the variation in quality and properties of fabricated composites, depending on infusion and curing process, dimension and configuration of stacked fabrics, etc. and involves difficulty in control of the properties of fabricated composites. As resin content in the composites can be easily controlled in VaRTM process combined with PMP, this paper investigates the effect of infused resin content on the final mechanical properties of CFRP. It is demonstrated that volume fraction of carbon fibers and the resultant mechanical properties of CFRP can be controlled by the infusion process control. Finally, application of the present control method to the manufacturing of a complex CFRP panel with thickness variation is demonstrated. It is concluded that the measured mechanical properties fit well with the designated properties.

Keywords: composite manufacturing; VaRTM; porous mold; mechanical properties

1. Introduction

Carbon fiber-reinforced plastics (CFRP) are widely used as primary structures in aerospace, maritime, and civil industries. Traditionally, autoclave process using CFRP prepregs has been widely applied, specifically in aerospace industry, in order to make CFRP structures with high quality and reliable properties. Recently, Out-of-Autoclave (OoA) processes have been widely investigated to develop low-cost manufacturing processes.[1–5] One of the representative low-cost processes of CFRP structures is vacuum-assisted resin transfer molding (VaRTM),[6–12] in which dry preforms are placed on the mold followed by the resin infusion using the vacuum-induced pressure difference. In this method, integral production of complex structures with little components is possible using affordable molds and facilities.

In the production of in-plane large-scale structures using VaRTM process, however, incomplete resin impregnation and void formation inevitably happen.[13–23] In addition, quality of the fabricated composites strongly depends on the used materials and sub-materials, the positions of inlets and outlets, the resin providing time, etc.[24–28] Numerous trials are generally required to develop a stable process depending on the products. The authors proposed porous mold process (PMP),[29] in which a porous mold with functions of shape holding and vacuum application is used for composite

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fabrication, in order to provide a simple knowhow-less manufacturing process of CFRP with stable and reliable quality. The previous study [29] demonstrated the experimental application of PMP to VaRTM process. Figure 1 gives the concept of PMP-based VaRTM process.

In VaRTM process combined with PMP, resin is supplied from the inlet, and no resin flows out. This means that infused resin content is same as the resin content supplied from the inlet, which is easily controlled. The present study aims to apply the control of infused resin content to regulate the volume fraction of carbon fibers, and thus, the properties of the final CFRP products. In the previous study,[29] there was no close operation of the inlet after infusion, resulting in full resin infusion in the composites. The final volume fraction was limited to around 50% in the previous experiment. If the volume fraction of carbon fiber could be increased and controlled, the mechanical properties are expected to increase and be controlled. As the previous study just demonstrated the PMP-based VaRTM process and included no control process, the purpose of this study is to propose the infusion process control method (i.e. resin content control) in PMP-based VaRTM process to obtain increased and controlled mechanical properties of CFRP.

This paper presents a method to control the resin content of CFRP in PMP-based VaRTM process followed by explanation of experimental procedures. CFRP panels are fabricated by changing the number of stacked dry fabrics and the resin contents, and volume fractions and mechanical properties are evaluated to investigate the controllability of properties by the proposed control method. Finally, application of the present control method to the manufacturing of a complex CFRP panel with thickness variation is presented, and the obtained mechanical properties are discussed.

2. Experimental

2.1. Resin infusion

In this study, porous aluminum, METAPOR® (average pore diameter: 12 μm, density: 1.9 g/cm^3, pore volume fraction: 16%, binder included), was used as the porous mold with machinability and enough stiffness. The details of the porous mold and related vacuum procedures are referred to Ref. [29].

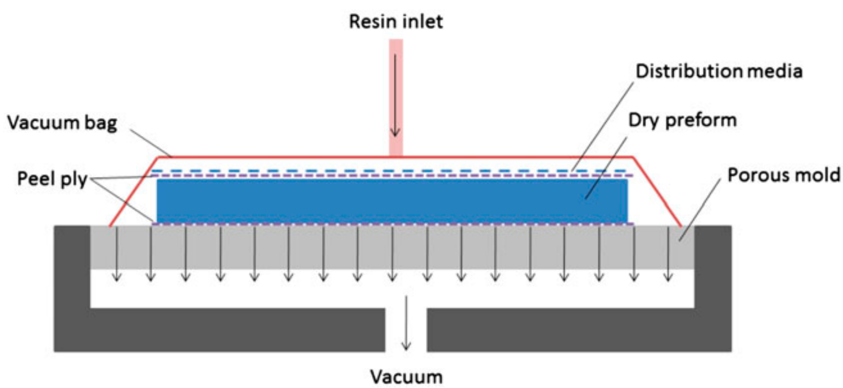

Figure 1. VaRTM process using porous mold.[29]

Plain-woven carbon fabrics, T700SC-12K (areal weight of 480 g/cm^2), were used as the dry preforms, and epoxy, XNR6815 with XNH6815 hardener (Nagase ChemteX Corporation), was used as the infused resin. Dry preforms with 300 mm × 300 mm dimension were placed with peel plies and distribution media, and they were covered by the vacuum bag film. Resin inlet was connected in the central portion of the preforms. The experimental apparatus of resin infusion during the PMP-based VaRTM process is presented in Figure 2. As already discussed in Ref. [29], resin infusion behavior exhibits in-plane anisotropy. This results from the weft and warp directions of distribution media on carbon fabrics.

After starting the resin infusion, no close operation of the resin inlet was applied in the previous study.[29] This means that resin was fully infused in the dry preforms. In this study, this state is called as 100% (complete) infusion. The thickness variation during the resin infusion was measured at specific locations using laser displacement meters in the previous study.[29] It was demonstrated that when the resin approached the measurement points of thickness change (thickness difference between stacked layers without resin under vacuum condition and those with infused resin), thickness of the dry fabrics including peel plies and distribution media decreased slightly followed by the monotonic increase of thickness, and then, the thickness approached steady-state value. The example of thickness change history is shown in Figure 3. Thickness decrease is induced by the compaction of fabrics due to lubrication effect by the resin, and the subsequent thickness increase results from the inner pressure increase due to the resin infusion. The steady-state thickness change is summarized as a function of number of dry fabrics layers in Figure 4 including the previous data and the recent preliminary results. This figure (Figure 4) shows the thickness variation when 100% infusion is applied in the PMP-based VaRTM process using the above-mentioned materials

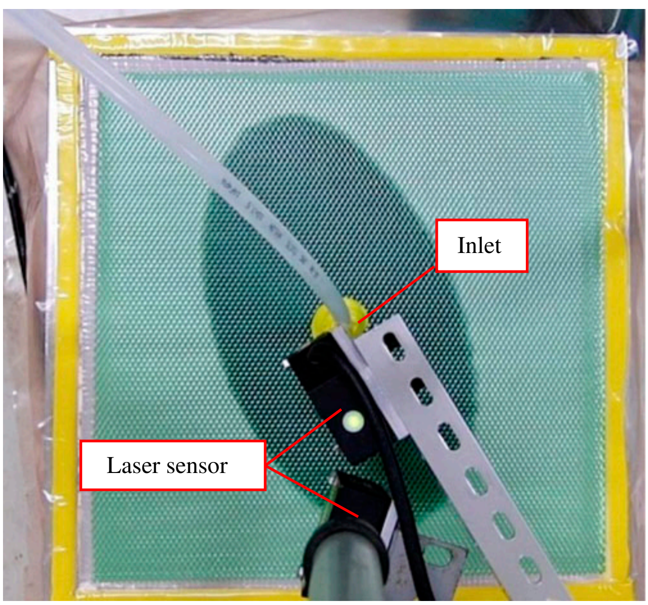

Figure 2. Top view of resin infusion behavior.

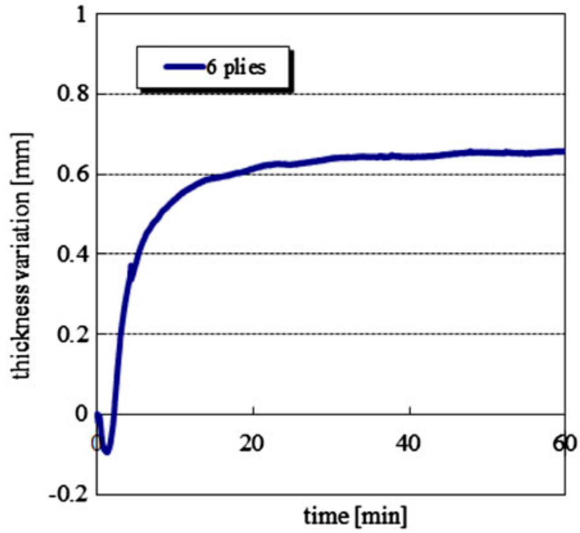

Figure 3. Thickness change history during resin infusion in six fabric layers.

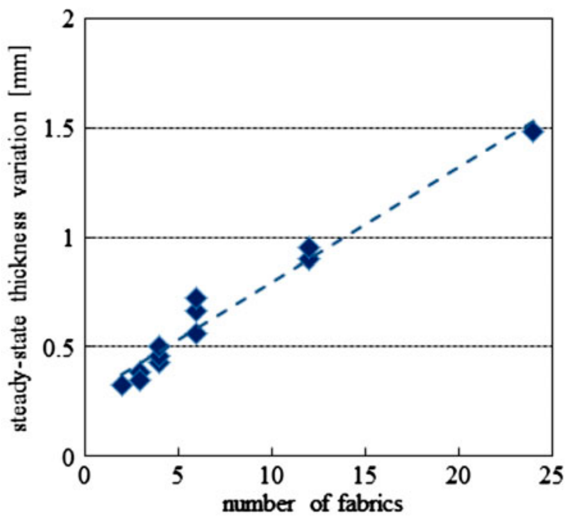

Figure 4. Steady-state thickness change as a function of number of dry fabrics.

and sub-materials. Figure 4 can be used as the references for the infusion control method described below.

As explained in the introduction, supplied resin content can be easily controlled in PMP-based VaRTM process. If close operation of the resin inlet is conducted, overall infused resin content can be regulated, resulting in the control of volume fraction of carbon fibers and properties of composites. One can propose that overall weight change of supplied resin is a measure to accomplish this control. However, the weight change of resin includes the effect of specimen dimension as well as the effect of resin in the distribution media, in the inlet tube, and in the edge regions of the specimens. Thus, this study utilizes the thickness change data during infusion, and proposes the close operation in a specific timing to control the resin content. When the dimension of composite panel varies, the proposed method using thickness change is considered to be independently applicable, as the thickness change is a measure to control the resin content. This is valid as the through-the-thickness resin flow dominates in the PMP-based VaRTM process.

Steady-state thickness change (corresponding to 100% infusion) was already obtained as the dashed line in Figure 4 depending on number of dry fabrics. This study investigates the effect of timing of close operation on the resulting volume fraction of carbon fibers and mechanical properties of composites. In the present experiments, thickness change at the locations with 50 and 100 mm distance from the inlet position was measured using laser displacement meters. Note that thickness change at the location of 100 mm was utilized for the present infusion control, although both laser sensors exhibited almost same history.[29] When the measured thickness change approached x% of the thickness change corresponding to 100% infusion, the inlet was closed. This is called as x% infusion in this study. Note that x% does not mean the real resin content, but denotes the ratio of thickness variation compared to the case of full resin infusion, and larger x means more resin content. Numbers of dry fabrics were 4, 6, and 12 in the present experiment, while x varied as 50, 75, and 100. The CFRP specimens were cured at room temperature for more than one day.

2.2. Evaluation method

As mentioned above, thickness change ratio (x%) is not meant as the resin content. To obtain the relationship between the thickness change and the real properties (e.g. fiber volume fraction, mechanical properties), the following measurements were performed.

- Measurement of thickness distribution of CFRP panels;
- Measurement of volume fraction of carbon fibers in CFRP; and
- Measurement of bending modulus and strength of CFRP.

For the thickness measurement, the fabricated CFRP panels were cut to specimens with 15 mm width, and the thickness was measured using a micrometer at the intervals of 15 mm for all cut specimens. The averages and standard deviations of thickness were evaluated. Volume fractions of carbon fibers were evaluated using the cut small specimens in reference to the combustion method prescribed in JIS K7075. Three-point bending tests were also conducted in reference to JIS K7074 standard in order to evaluate the bending properties. Specimen dimensions and loading conditions (e.g. span length and cross-head speed) were determined based on the standard. Displacement-controlled bending loads were applied to the specimens using Instron 5582 testing machine.

3. Results

The average thickness of cured CFRP panels is summarized in Figure 5 as a function of thickness variation ratio, x, with varied number of stacked dry fabrics. Almost linear increase in thickness of cured CFRP is observed by the increase of x. Thickness deviation in the same CFRP panel was relatively small, and the coefficient of variance was

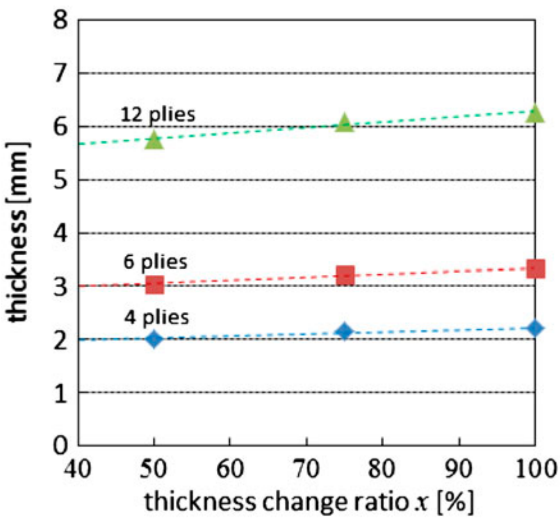

Figure 5. Average thickness of fabricated CFRP panel.

less than 2% for all the fabricated panels. Figure 5 suggests that thickness of cured CFRP panels can be controlled by the thickness variation ratio, *x*, during infusion process. Thickness is generally related to volume fraction of carbon fibers in CFRP, and thus, it is expected that properties of final CFRP products can be controlled by the infusion process in PMP-based VaRTM process.

Figure 6 gives the measured volume fractions of carbon fibers depending on thickness change ratio, *x*. Fiber volume fractions increase as the decrease of thickness variation ratio, *x*, as expected. In the case of full resin infusion process (i.e. without close operation), the fiber volume fractions were limited to about 50%. The present resin infusion control (control of *x*) enables us to increase the fiber volume fractions up to 60% within the cases in this study. The void contents were also evaluated and were less than 1.5% for all the samples. This means that fiber volume fraction can be enhanced without any increase of void content.

The measured bending modulus and strength are presented in Figure 7. Mild increase of bending modulus is observed as the decrease of thickness variation ratio, *x*. This was expected, however, the increasing ratio is small considering the increase ratio of fiber volume fraction as shown in Figure 6. For example, in the case of 4-ply specimens, the fiber volume fraction exhibited 9% increase, when *x* decreases to 50, compared to the case of 100% thickness change, while the bending modulus only increased about 4%. In the present study, bending properties of woven composites (not properties of unidirectional composites) were evaluated. Straight-forward relationship between fiber volume fraction and bending modulus might not be obtained as the decrease of undulation in woven composites may happen due to increase of fiber contents. Nevertheless, increase of bending modulus by resin infusion control was demonstrated as shown in Figure 7(a). It should be noted that thinner panels exhibited lower modulus. In the present experimental program, thinner panels tended to have lower fiber volume fractions as seen in Figure 6. The difference of bending modulus among three panels (4-ply, 6-ply, and 12-ply panels) is, however, unexpectedly large compared to the difference of fiber volume fractions. This trend was also observed in the previous

Table 1. Evaluated properties of CFRP panels with thickness variation in comparison to specimens with constant thickness ($x = 75\%$).

	6 plies		12 plies		18 plies	
	Complex panel	Constant specimen	Complex panel	Constant specimen	Complex panel	Constant specimen
Fiber volume fraction (%)	54.5 (1.6%)	54.0 (3.0%)	56.2 (1.7%)	55.3 (1.3%)	56.7 (1.6%)	N/A
Bending modulus (GPa)	44.6 (1.9%)	46.1 (1.7%)	51.2 (1.1%)	49.2 (0.7%)	53.3 (1.0%)	N/A
Bending strength (MPa)	602 (5.5%)	652 (7.1%)	592 (6.9%)	595 (4.5%)	593 (6.0%)	N/A

Note: Parentheses indicate coefficient of variance.

study.[29] It is further necessary to investigate this reason. In the case of bending strength, there was almost no change independently of thickness change ratio, x (or slight decrease in strength was observed when x decreased). In the present three-point bending test, failure (out-of-plane compressive failure or interlaminar failure) occurred underneath the upper loading point. This means that failure load was influenced by local out-of-plane properties. Therefore, the obtained strength was not improved by the resin content control.

The above-mentioned measured thicknesses, volume fractions, and bending properties seemed to be independent of specimen locations or distance from the inlet location in the fabricated panels (There was no relationship between the property variation and the specimen location in the panels). In the present VaRTM process, the resin was infused in the distribution media, followed by the through-the-thickness resin infusion into the carbon fabrics. The former infusion (resin infusion in the distribution media) takes negligible time compared to the latter infusion (through-the-thickness infusion). This suggests that the inlet location and the direction of distribution media (directions of the weft and warp of distribution media) have no significant effect on the resulting properties.

Overall, it is demonstrated that resin content control method during resin infusion in PMP-based VaRTM process can regulate the fiber volume fraction, affecting the final mechanical properties of fabricated CFRPs. In the following section, this control method is applied to a complex CFRP panel with thickness variation.

4. Application to CFRP panel with thickness variation

A CFRP panel with 480 mm × 480 mm in-plane dimension was fabricated using the same material systems by the PMP-based VaRTM process. This panel contained thickness variation in a stepwise manner. The schematic of the fabricated panel is shown in Figure 8. Three uniform regions with 6, 12, and 18 plies of dry fabrics constituted the

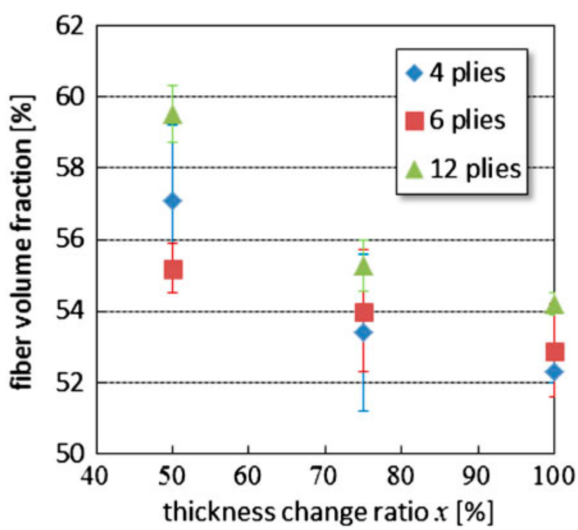

Figure 6. Fiber volume fraction of fabricated CFRP panel.

CFRP panel. The resin infusion behavior is presented in Figure 9. Considering the gravity and the infusion time, the inlet location was set as the central position of 18-ply region. Laser sensors were placed in the region of 12 and 18 plies to measure the thickness change during resin infusion.

In this example, the target of the resin infusion was set to 75% (i.e. $x = 75$) using the laser sensor in the 12-ply region. From Figure 4, 100% infusion condition corresponds to about 0.9 mm thickness change in the case of 12 plies. Therefore, the target thickness increase was 0.67 mm. The thickness change history during resin infusion is summarized in Figure 10. When the thickness change measured by laser sensor in the

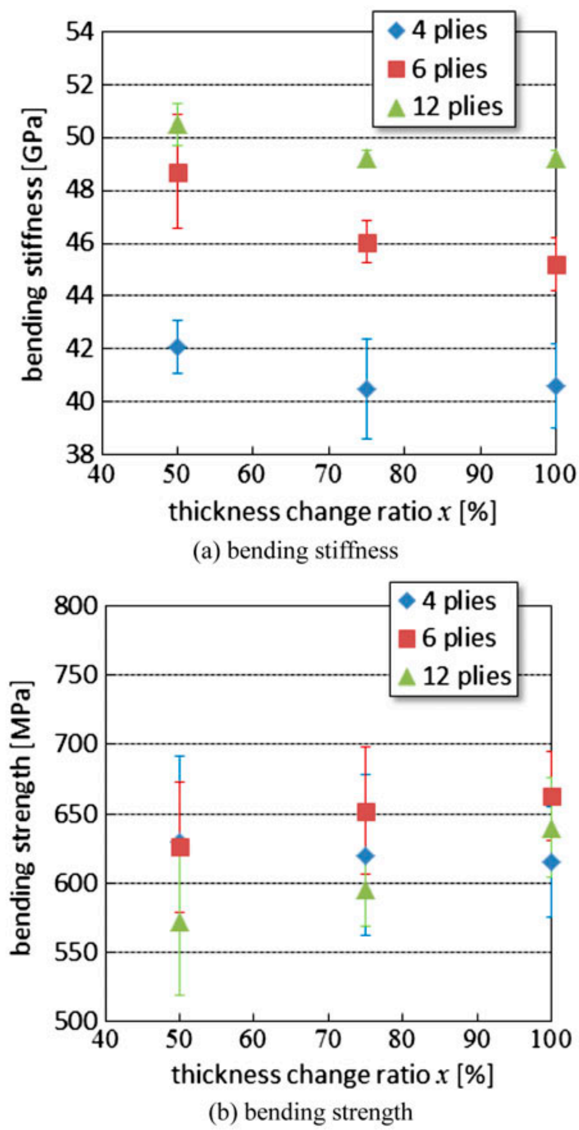

Figure 7. Bending properties of fabricated CFRP.

12-ply region approached 0.67 mm, the resin inlet was closed. At this time, the thickness change measured by the laser in the 18-ply region was 1.0 mm, which corresponded to 79% infusion (i.e. $x = 79$) in the case of 18 plies (see the dashed line in Figure 4; thickness change is about 1.26 mm for 100% infusion in the case of 18 plies). This result suggests that resin content was controlled in the overall CFRP panel with thickness variation.

Figure 11 shows apparatus of the cured CFRP panel. The panel was cut to prepare the specimens for measurement of fiber volume fractions and bending properties. Thickness distribution was also measured in the uniform 6-ply, 12-ply, and 18-ply regions. The thickness was 3.15 mm (1.8%), 5.93 mm (1.1%), and 8.84 mm (1.2%) for 6-ply, 12-ply, and 18-ply regions, respectively. The parentheses indicate the coefficient of variance. These measured thickness in 6-ply and 12-ply regions agrees well (within 2% error) with the results at $x = 75$ in Figure 5. It is confirmed that the present infusion control method enables us to control the panel thickness of the final product.

Finally, fiber volume fractions and mechanical properties based on the three-point bending test were evaluated in a similar manner described in Section 2.2. The results are summarized in Table 1 in comparison to the data in Section 3 (see Figures 6 and 7 for the latter, when $x = 75$ of specimens with constant thickness). Note that data of 18-ply specimen with constant thickness were not available. The CFRP panel with thickness variation had similar properties relative to the panels with constant thickness. Note that void contents were less than 1.5% all over the panel. Thicker regions exhibited higher fiber volume fractions and bending modulus, which is the same trend

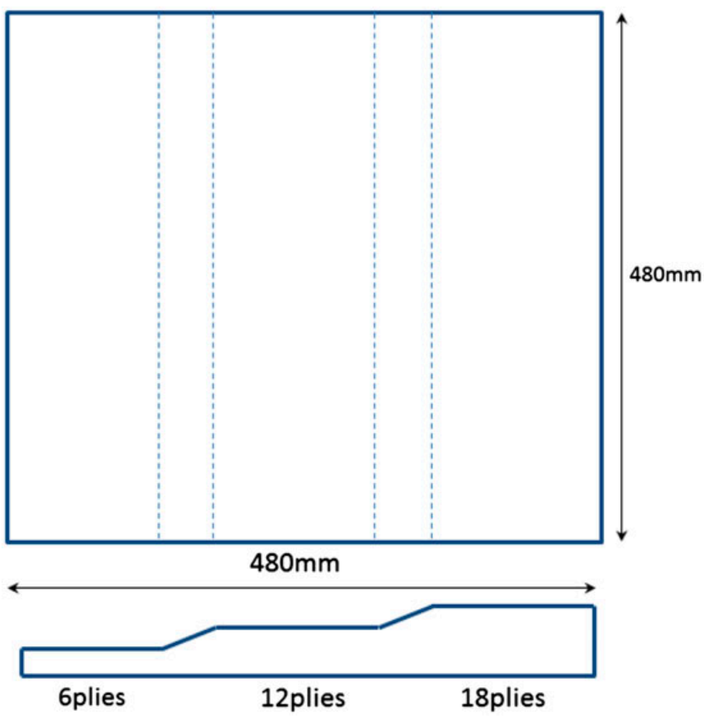

Figure 8. Schematic of CFRP panel with thickness variation.

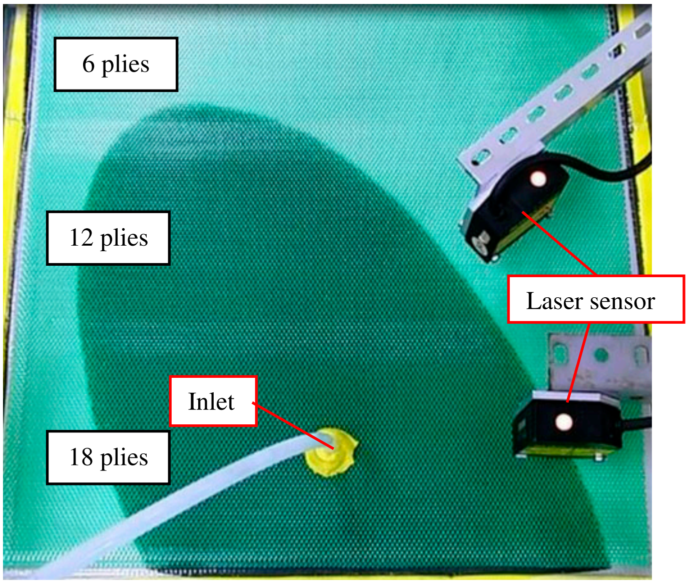

Figure 9. Resin infusion behavior in CFRP panel with thickness variation.

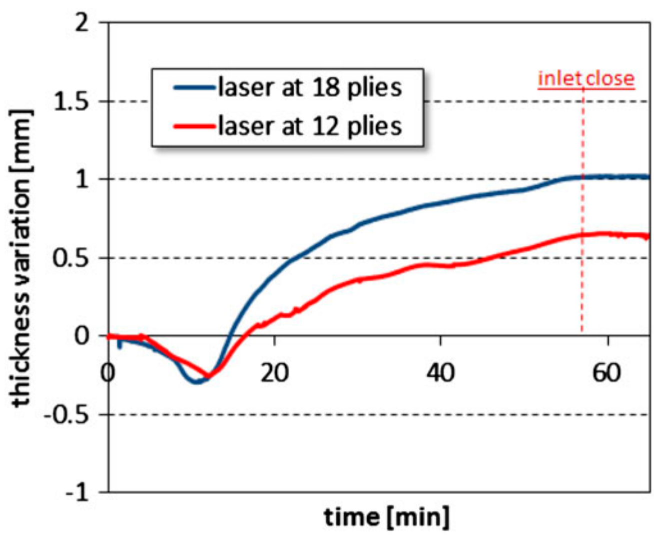

Figure 10. Thickness change history during resin infusion of CFRP panel with thickness variation.

as described in Section 3. Successful fabrication of a complex CFRP panel with designated properties (corresponding to 75% infusion) was presented in this study. It is demonstrated that properties can be controlled a priori by the resin infusion control method.

Figure 11. Apparatus of cured CFRP panel with thickness variation.

5. Concluding remarks

The present study proposed and investigated a method to control the resin content in PMP-based VaRTM process for the property control of the final products. Thickness change during resin infusion was used as a measure to control the resin content, and as a result, to control the properties of cured composites. Experimental results of fiber volume fractions and flexural mechanical properties were obtained by changing the infusion ratio (i.e. thickness change ratio, x). It was experimentally shown that properties of CFRP panel depend on the thickness change ratio.

Using the proposed control method, a CFRP panel with thickness variation in a stepwise manner was fabricated. The target of thickness change ratio was designated at 75%, and the properties of the final products were evaluated. Successful fabrication of a complex CFRP panel with designated properties (corresponding to the prescribed thickness change ratio) was presented in this study. It was demonstrated that properties can be controlled a priori by the resin infusion control method.

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