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SIMULATION OF CO-CURED MULTI-CELL COMPOSITE BOX BEAM MANUFACTURING VIA VARTM

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Abstract: Sub-structures of aircraft structures mainly consist of stiffened shells such as fuselage frames, ribs and multi-cell box beams. Conventionally, these stiffened shells are manufactured through a process wherein shells and stiffeners are fabricated separately and then are integrated either through mechanical fastening and adhesive bonding. Co-curing is an integral molding technique that can greatly reduce the part count and the final assembly costs for composite materials. This article presents a simulation of integral manufacturing of a three-cell composite box beam by vacuum assisted resin infusion process. To validate the model, the characterization tests of both resin and reinforcement materials were carried out. Porosity and permeability testing of the reinforcement materials were conducted. Moreover, the effect of stacking sequence and vacuum level on the preform porosity were investigated. Additionally, the resin viscosity measurements were performed and the influence of temperature and curing on resin viscosity were examined. Having obtained the characterization data, vacuum infusion model was validated using RTMWorx software and then simulation of a three-cell composite box beam was conducted.

Keywords: vacuum-assisted infusion process, model validation, vacuum infusion model.

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INTRODUCTION

Sub-structures of aircraft structures are mainly consisted of stiffened shells such as fuselage frames, ribs and multi-cell box beams. Conventionally, these stiffened shells are manufactured through a process where shells and stiffeners are fabricated separately and then are integrated either through mechanical fastening or adhesive bonding. This conventional process is so-called Secondary Bonding.

Co-curing is an integral molding technique that can greatly reduce the part count and the final assembly costs for composite materials. Co-curing and its tooling technology proprietary in nature and details are mostly not open publicly. The very first application of this technology in literature is Japanese XF-2 fighter aircraft wing in late 1990s [Kageyama & Yoshida, 2000]. In the XF-2 fighter aircraft wing, spars and ribs were co-cured with the bottom skin. [Mahruz et al., 2004] developed a new process to manufacture composite skin-stringer assembly in one-step using VARTM.

VARTM is highly labor intensive and difficult process so that if injection and venting strategy is not properly configured, dry spots that regions with only dry fibers or racetracking problem can easily occur. Simulation of the resin flow will allow one to investigate the resin impregnation process and strategically design gates and vents and injection schemes to optimally fill the composite part without any dry spots. In this paper, simulation of a co-cured multi-cell composite box beam is investigated by using RTM-Worx resin flow simulation software. The manufacturing method of the multi-cell box beam is based on the procedure of [Mahruz et al., 2004] with slight modification.

EXPERIMENTS

Both preform and resin characterization tests are carried out. For preform characterization, two sets of experiments are performed: (1) porosity experiments, and (2) permeability tests; whereas rheological experiments are made for the resin characterization.

Materials

Materials used in characterization tests are given in Table 1.

Table 1: Resin and fabric materials used in characterization tests.

Reinforcement	Carbon Fiber, 1x1 Plain, 200g/m^2
Resin	Huntsman XB3585-Aradur 3486
Peel Ply	Metyx PA80R1
Distribution Media	Metyx PE Flow Mesh

Fabric Characterization Experiments

Porosity Experiments

The term porosity of dry reinforcement material refers the amount of space in reinforcement that can be filled with resin. Porosity is often calculated as

$$\emptyset = 1 - V_f \qquad \text{(Eq. 1)}$$

Basically, the fiber volume fraction is a fraction of amount of fiber to the total volume and can be calculated as, (Bird, Stewart, & Lightfoot, 1960),

$$V_f = \frac{W}{hA_f \rho} \qquad \text{(Eq. 2)}$$

where, W is the sample mass in kg, h is the sample thickness in m, and A_f is the area of sample in m^2, ρ is the density of fabric in kg/m^3. The setup of porosity experiment is shown in Figure 1 and the results are given in Table 2.

Effect of Stacking Sequence on Porosity

The effect of the number of preforms on preform porosity is investigated using two, five, seven and ten layers of 1x1 plain, 200gr/cm^2 carbon fiber preforms.

In order to calculate the porosity, first physical measurement of fabric is made. All fabrics are cut in 300mm x 400mm dimensions and each is weighted as 24 grams. The thickness of fabric is 0.3mm.

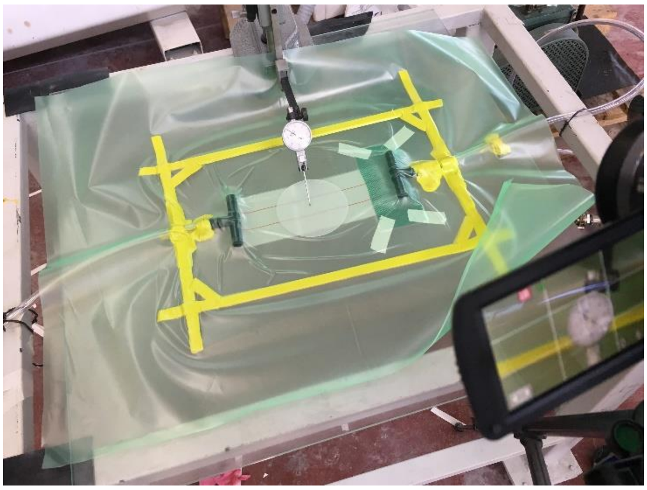

Figure 1: Porosity Experiment Set-up.

Table 2: Porosity experiment results.

Material Name	Superficial Density ($g/cm^{2)}$)	Porosity	Layer Thickness (mm)
Distribution Media	-	0.85	1.35
Peel Ply	80	0.35	0.2
Carbon Fiber Preform	200	0.52	0.3

Having obtained the physical properties, change in preform thickness is measured precisely using a dial gauge, shown in Figure 1. Vacuum is continued after the preform compaction for 10 minutes in order to reduce the nestling effect. Two sets of measurements are collected: (1) immediately after the vacuum is applied (2) after the 10minutes hold time. The results show a quasi-linear relation between the porosity and the number of layers, see Figure 2.

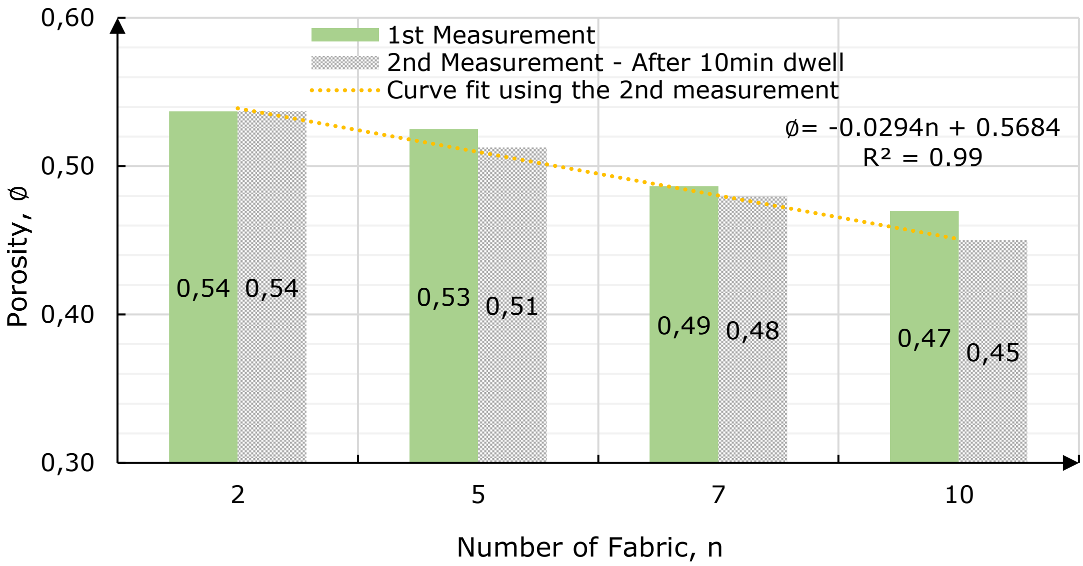

Figure 2: Porosity of carbon fiber fabric with respect to the number of layer count.

Effect of Vacuum Level on Porosity

Having analyzed the effect of the preform count, the effect of the vacuum level on preform porosity is investigated by changing the vacuum level from 13000Pa (100mmHg) to 93325Pa (700mmHg). Both peel ply, distribution media and carbon fiber preform are tested and the results are presented in Figure 3.

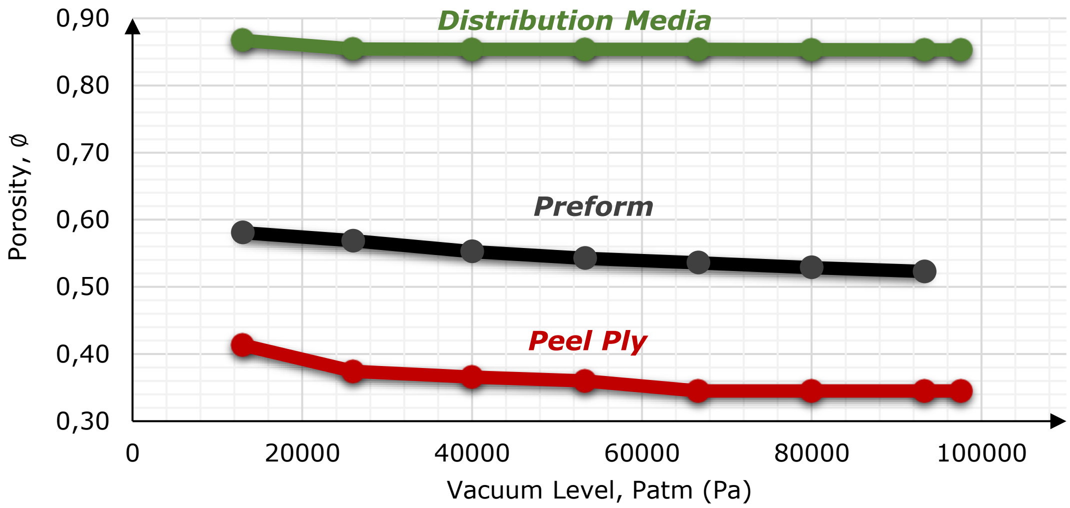

Figure 3: Porosity of layers with respect to vacuum level.

Permeability Tests

Permeability characterizes the ease with which a fluid can flow through a porous medium. In this paper, 1D channel flow method was used to determine permeability, which utilizes the following formulation (Rudd, Long, Kendall, & Mangin, 1997).

$$K = \frac{\mu \emptyset}{2\Delta p}\frac{x_f^2}{t_f} \qquad \text{(Eq. 3)}$$

where μ is the resin viscosity in Pa.s, $\emptyset$ is the fabric porosity, Δp is the pressure difference in Pa, x_f is the flow front in m and t_f is the time elapsed for flow front in s. The permeability test set-up is shown in Figure 4.

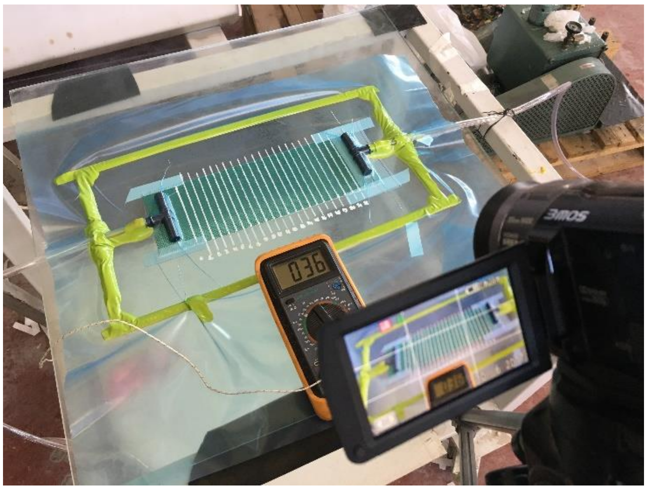

Figure 4: Permeability Test Set-up.

The porosity and resin viscosity data is taken from the experiments and the test results are tabulated in Table 3.

Table 3: Permeability Test Results.

Test Properties and Results	**Distribution Media**	**Peel Ply**	**Carbon Fiber**
Resin Temperature (°C)	36-37	54-55	35-40
Resin Viscosity (Pa.s)	0.3085	0.115	0.29
Porosity	0.85	0.35	0.54
Vacuum Pressure (Pa)	99325	97325	97325
K_{11} (m^2)	5.24E-09	2.06E-12	2.85E-12

Resin Characterization Experiments

Rheological measurements for resin are conducted by using TA, AR2000 rheometer. Parallel circular plates having a diameter of 25mm with the maximum gap of 1mm under the flow mode are chosen in this study.

Effect of Temperature on Viscosity

To investigate the temperature effect on viscosity, temperature ramp test is carried out, whose results are seen in Figure 4. Equation (4) is the exponential curve fit acquired by the experiment.

$$\mu = 488235T^{-3.641}, R^2 = 0.998 \quad \text{(Eq. 4)}$$

Effect of Curing on Viscosity

Since chemical reaction sets in, the resin starts the cross-binding process whereby its viscosity is increasing. In order to understand the curing effect on viscosity, resin with catalyst is tested additionally. The curve fit equation is given in Equation (5).

$$\mu = 819.34T^{-2.191}, R^2 = 0.976 \quad \text{(Eq. 5)}$$

As shown in Figure 5, resin has lower viscosity when mixed with catalyst.

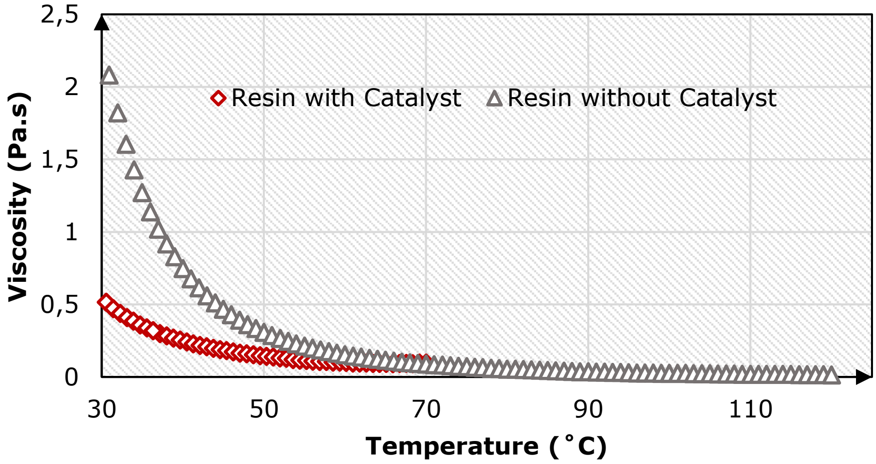

Figure 5: Resin with and without catalyst viscosities as a function of temperature.

Time hold test is furthermore conducted at 40°C, which is the process temperature, to better understand the time dependent characteristic of viscosity. Figure 6 presents the exponential characteristic of the viscosity and the curve fit equation is given in Equation (6).

$$\mu = 0.1669e^{(1.6102\frac{t_{gel}}{t})}, R^2 = 0.999 \quad \text{(Eq. 6)}$$

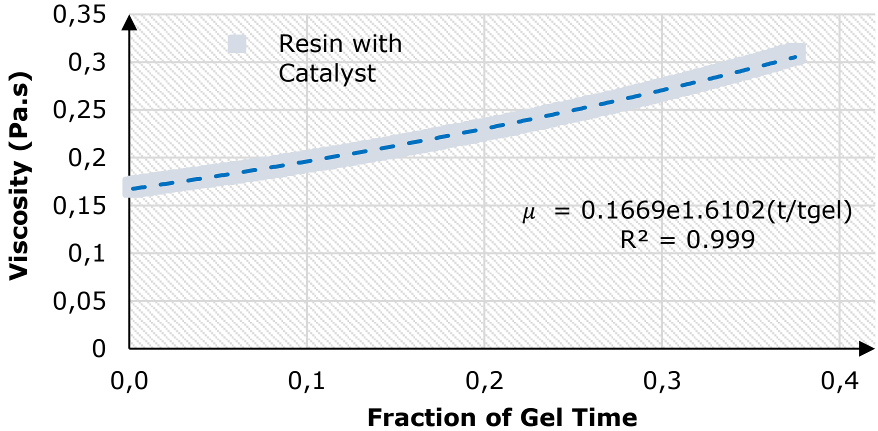

Figure 6: Resin with catalyst viscosity as a function of the normalized curing time.

SIMULATION RESULTS AND DISCUSSION

The resin flow simulation of a co-cured multi-cell box beam is made by using RTMWorx software, which solves the governing Darcy's flow equation using Finite Element/Control Volume (FE/CV) technique. In this study, so-called $2\frac{1}{2}\mathrm{D}$ model, wherein resin flow in 3D space is considered as 2D, since resin flow through thickness is negligible, is constructed. Hereby, permeability averaging technique (Equation (7), that is simply based on rule of mixture is used to average the permeability of fiber preform having the stacking sequence presenting in Figure 7.

$$\bar{K}_{uv} = \frac{1}{H}\sum_{j=1}^{n} h^{(j)}K_{uv}^{(j)} \qquad \text{(Eq. 7)}$$

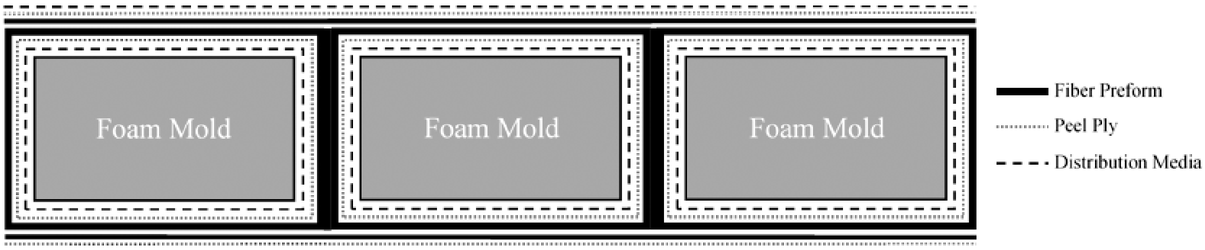

Figure 7: Schematic diagram of the stacking sequences of box beam.

The size of box beam is selected to be consistent with [Mahruz et. al., 2004] so that the webs are 50 mm high and 90 mm wide. The assembly is 288.3 mm wide, 500 mm long.

Table 4: Simulation Inputs.

Skin Thickness	2.1mm
Web Thickness	3.0mm
Side Web Thickness	1.5mm
Resin Viscosity	0.24 Pa.s
Pressure Difference	97325 Pa
Injection Line Diameter	14mm
Suction Line Diameter	14mm
Number of Elements	15292

In practice, a space needs to secure the injection line thereby the feed line is placed 30mm away from the edge, while the suction line is positioned along the opposite edge. The additional simulation parameters are stated in Table 4.

Figure 8 presents the results of flow simulation. The total fill time is calculated as 761s and no dry spot is observed; nevertheless, the lead-lag between the top and bottom skins is present.

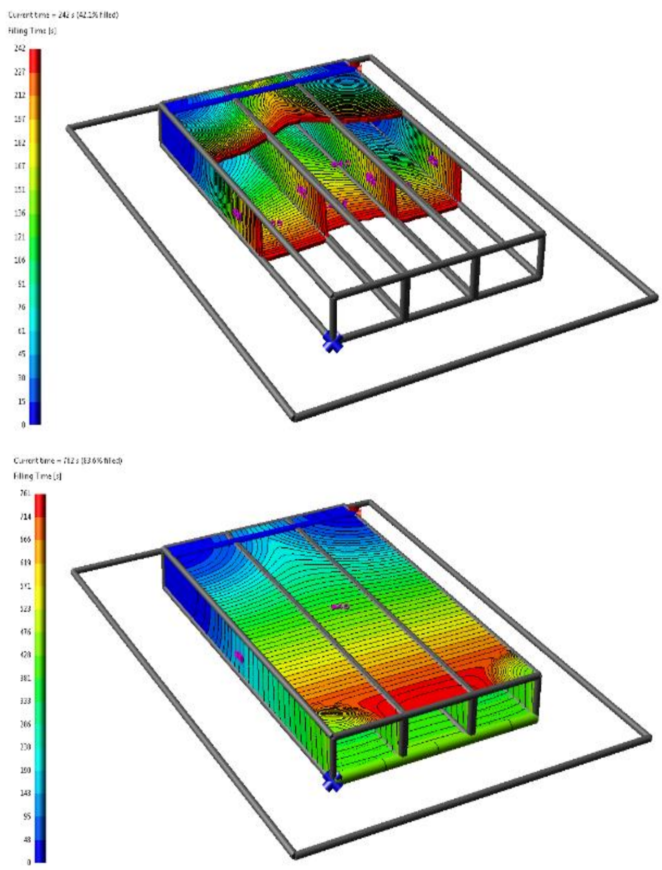

Figure 8: Resin flow propagation at a) t=242s b) t=761s.

Considering the injection strategy, there can be two possible reasons for the lead-lag: (1) Suction is applied from the lower surface. (2) As the resin feed line on the top skin, resin is forced to travel around the three molds, which are wrapped with preform.

CONCLUSIONS

In this study, the simulation of co-cured three-cell box beam is presented. Both resin and preform characterization tests are carried out. One of the important results we have achieved from the characterization tests is that porosity of preform declines as the number of layer increases. The effect of vacuum level is additionally investigated for the layers and the results are presented in Figure 3. For the resin viscosity both the temperature and curing effects are investigated. The simulation results show that dry is not the case for the selected injection strategy; nonetheless the lead-lag between the top and bottom skins is observed. The reasons for the lead-lag are presented.

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