Modeling resin infusion of composite sandwich structures by the VARTM process

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Abstract

A computer model based on the finite element/control volume (FE/CV) method was developed to study the resin flow during the vacuum assisted resin transfer molding (VARTM) process of a new type of composite sandwich structure containing through-the-thickness stitches. The effects of the stitch density are investigated by studying the resin infusion of three structures with different stitch row spacing of 6.25 mm, 12.7 mm, and 25.4 mm. It is found that increasing the stitch row spacing shortens the total infiltration time, but makes the flow pattern more nonuniform. Extreme non-uniformity of the flow front shape could result in dry spots in the composite and should be avoided. The computer model is validated by experiments.

Keywords: Vacuum assisted resin transfer molding (VARTM); Resin flow; Porous medium; Composite manufacturing; Finite element/control volume (FE/CV) method

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1. Introduction

In the last decade, vacuum assisted resin transfer molding (VARTM) processes have been successfully developed to manufacture different large and complex composite structures with significantly reduced cost [1,2,3,4]. In this study, we explored the application of the VARTM process in the fabrication of one new type of composite sandwich structures that contain through-the-thickness reinforcement. Previous studies have shown that the transverse stitching can improve damage tolerance of these structures, making them better suited for service in aircraft structure applications [5].

In the VARTM process of this new composite sandwich structure, Derakane 510A–40 vinyl ester resin was infused into the preform consisting of two 3 mm thick carbon face sheets and a 12.7 mm thick polymethacrylimide (PMI) foam core. The face sheets are attached to the non-porous foam core by stitching through the thickness of the preform with a 1600 denier Kevlar/PVA thread. The length and width of the foam core sandwich structures studied here are 64.5 cm and 30.5 cm, respectively. A high-permeable nylon distribution medium is used to facilitate the resin flow in the preform and reduce the processing time. Complete filling of the sandwich preform with adequate wetting of the carbon face sheets is the primary objective in the VARTM process. Thus, it is very important to investigate the detail of the resin flow through the stitched foam core preforms. Here we developed a computer simulation model based on the finite element/control volume (FE/CV) method [6] to track the resin flow front and evaluate the total infiltration time. In order to investigate the effect of stitch density on the filling time and infiltration pattern, we studied three preforms with different stitch row spacings of 6.25 mm, 12.7 mm, and 25.4 mm, respectively. For all the three preforms, the stitch pitch was held constant at four stitches per 25.4 mm. The simulation results were verified by the flow visualization experiments [7].

2. Numerical formulation

The resin flow through the distribution medium and sandwich preform can be modeled as incompressible flow through anisotropic porous media. The resin fluid

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is assumed to be Newtonian with the viscosity independent of shear rate. Assuming that the flow is quasi-steady state, the governing equations for the flow problem are the continuity equation for an incompressible fluid, and Darcy's law of flow through a porous medium [8,9,10,11]:

$$\nabla \cdot \vec{\nu} = 0 \tag{1}$$

$$\vec{\nu} = \frac{\vec{q}}{\phi} = -\frac{S}{\phi\mu}\nabla P \tag{2}$$

where $\vec{\nu}$ is the interstitial velocity vector of the resin, $\vec{q}$ the superficial velocity vector, ϕ the porosity of the porous preform, μ the viscosity of the fluid, S the permeability tensor of the preform, and P the resin pressure. Substituting Eq. (2) into (1) gives the governing differential equation of the flow:

$$\nabla \cdot \left(\frac{S}{\phi\mu}\nabla P \right) = 0 \tag{3}$$

The boundary conditions required to solve Eq. (3) are:

- A flow front pressure condition: $P_{flowfront} = 0$.
- A constant pressure condition at the inlet: $P_{inlet} = 1$ atm.
- The velocity normal to the mold wall is zero: $\vec{\nu} \cdot \vec{n} = 0$, where $\vec{n}$ is the vector normal to the boundary wall.

Note that this is a moving boundary problem. The finite element/control volume (FE/CV) method [6] is utilized to track the progression of the flow front using a fixed mesh. A computer code based on the FE/CV technique was developed to simulate the resin flow in the distribution medium and sandwich structures. An important feature of the code is the ability of simultaneous integration of 1-D, 2-D, and 3-D element types in a single simulation, which enables efficient modeling of the flow in complex mold geometries such as the sandwich structures.

3. Simulation model

During the VARTM process, the resin enters the distribution medium through a single line source along one short edge of the upper face sheets. The resin first moves across the high-permeable distribution medium, infiltrates the top face sheet, then flows through the non-porous foam by 'leaking' through the holes created by the needle penetrations of the stitching, and finally infiltrates the bottom face sheet. Therefore, in order to simulate resin infiltration of stitched foam core sandwich structures, a finite element model should include a high-permeable distribution medium, and two porous carbon face sheets connected by the transverse stitches. The closed-cell nature of the PMI foam core makes it impervious to fluid, thus the foam core is excluded from the resin model.

The resin flow along each transverse stitch can be regarded as one-dimensional flow and 1-D rod elements can be used to model the stitches. This type of finite element model was named 'the channel model', where the needle penetrations in the foam core were described by a series of channels that permit 1-D resin flow from the upper to the lower face sheet. The channel model requires a huge number of nodes to model the structure since it makes the constraints that the mesh density along the length of the face sheets must be larger than one element per 6.25 mm. Due to the use of the distribution medium, the pressure gradient changes drastically in the thickness direction while the pressure gradient does not vary much along the length direction. Therefore, the channel model causes an unnecessary waste of the computational resource. Instead of modeling the single stitches, a more efficient model is constructed using a two-dimensional strip to represent one row of stitching. By setting the permeability normal to the transverse stitching threads to be zero, these strips allow resin flow in the direction along the stitches only.

The finite element models were constructed for the three sandwich panels. Three-dimensional hexahedral elements were used to discretize the distribution medium and carbon face sheets, and 2-D quadrilateral elements were used for the strips, which represent the porous region in the foam core.

4. Permeability of the strips

Another challenge in the modeling resides in the evaluation of the transverse permeability of the porous regions (i.e. strips) in the foam core. It is difficult to measure the permeability directly by experiments. Here a theoretical model was proposed to calculate it by modifying the classical straight capillary model [12]. In the model, the porous stitches are represented by a bundle of straight parallel 'capillary units'. The capillary unit is a circular hole holding a concentric cylinder in it. The radius of the cylinder, r_1, is less than the radius of the hole, r_2. The circular hole represents the hole created by the needle penetration of the stitching and the cylinder represents the thread through the hole. The flow Q through a capillary unit can be calculated by solving the Navier-Stokes equations:

$$Q = -\bar{S}\frac{1}{\mu}\frac{dP}{dy} \tag{4}$$

where

$$\bar{S} = 2\pi \int_{r_1}^{r_2} \left(\frac{1}{4} r^3 + C_1 r \ln r + C_2 r \right) dr \tag{5}$$

C_1 and C_2 are defined as

$$C_1 = \frac{r_1^2 - r_2^2}{4(\ln r_2 - \ln r_1)} \tag{6}$$

$$C_2 = \frac{r_1^2 \ln r_2 - r_2^2 \ln r_1}{4(\ln r_2 - \ln r_1)} \tag{7}$$

where μ is the viscosity and dP/dy is the pressure gradient along the capillary unit.

If there are n such capillary units in the strip, the flow per unit area of cross-section of the strip, q, will be

$$q = -\frac{n\bar{S}}{A_{strip}} \frac{1}{\mu} \frac{dP}{dy} \tag{8}$$

where A_{strip} is the cross sectional area of the strip.

As the flow can also be expressed by Darcy's law

$$q = -\frac{S}{\mu} \frac{dP}{dy} \tag{9}$$

the permeability of the strip in the transverse direction can be calculated by combining Eqs. (8) and (9):

$$S = \frac{n\bar{S}}{A_{strip}} \tag{10}$$

5. Results

Figures 1–3 show the model predicted infiltration patterns in both the upper and lower face sheets of the three sandwich preforms with different row spacing of 6.35 mm, 12.7 mm, and 25.4 mm, respectively. They agree with the flow patterns observed in the experiments [7] very well. The flow fronts on the top surface are fairly uniform. However, since resin enters the lower face sheets through the vertical stitches and then permeates normal to the stitching direction to fill the areas between the stitches, it results in the resin flow along the stitching leading the flow in the region between the stitches. When the row spacing is small, the lag length is small and the flow front appears to be uniform. However, when the row spacing increases, the lag length becomes larger and the infiltration pattern illustrates obvious non-uniformity, which could result in the formation of dry spots and should be avoided.

The measured and predicted total infiltration time for the three preforms were compared in Table 1. Both the experiment and simulation show that the filling time increases with the increasing stitch density. The predictions for the infiltration time agree with the measured values within an error of 4 to 14%.

Table 1
Measured and predicted infiltration time

Stitch row spacing (mm)	Infiltration time (min) Experiment measurements [7]	Model prediction	% error
6.35	29.77	25.59	14
12.7	26.40	22.67	14
25.4	23.47	22.52	4

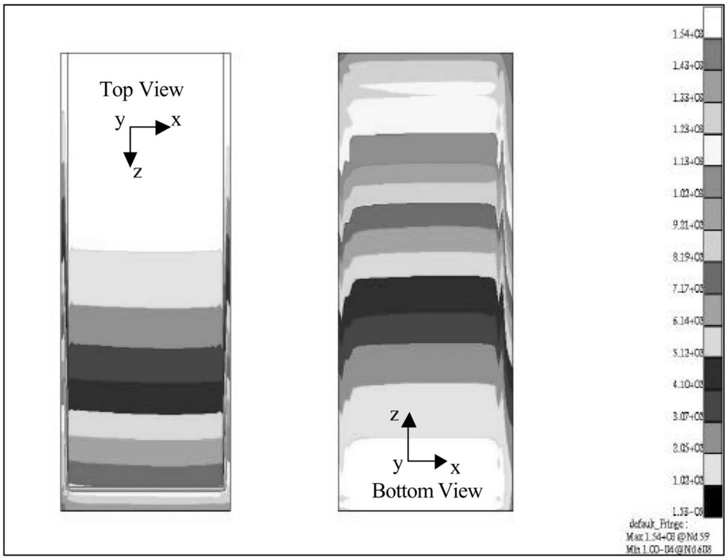

Fig. 1. Resin flow pattern along the top (left) and bottom (right) surfaces of the preform with 6.35 mm stitch row spacing.

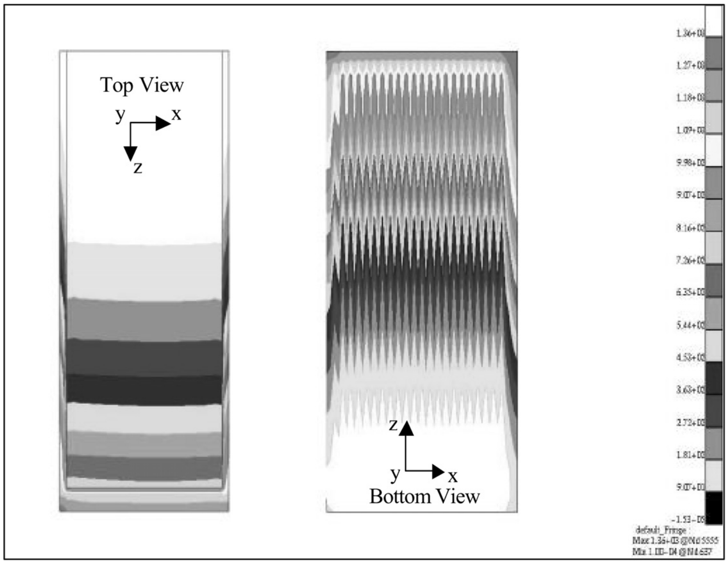

Fig. 2. Resin flow pattern along the top (left) and bottom (right) surfaces of the preform with 12.7 mm stitch row spacing.

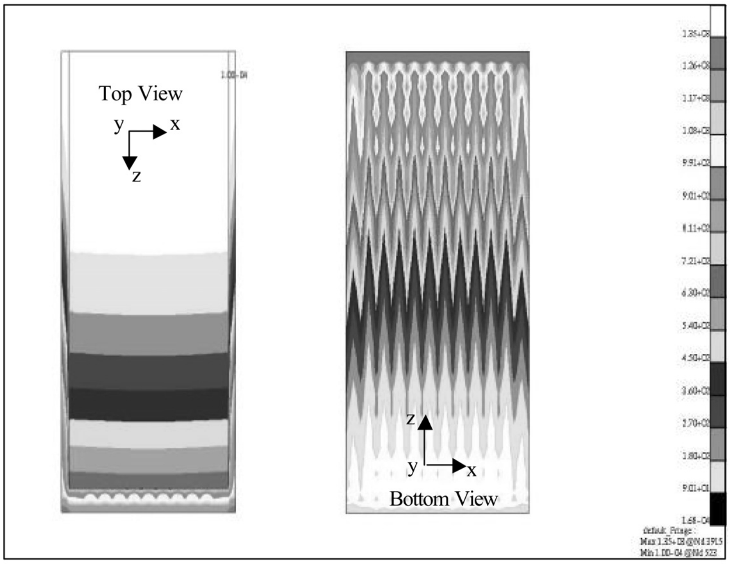

Fig. 3. Resin flow pattern along the top (left) and bottom (right) surfaces of the preform with 25.4 mm stitch row spacing.

6. Conclusions

The resin flow during the VARTM process of a new type of composite sandwich structure containing through-the-thickness stitches was successfully modeled using the finite element / control volume (FE/CV) technique. In the model, each row of stitches was described as a porous strip, in which the resin is only allowed to flow in through-the-thickness direction. The permeability of the strip was calculated analytically using a modified straight capillary model. Simulation results are verified by the flow visualization experiments. It is found that the stitch density affects both the resin infiltration patterns and the total infiltration time. When the stitch row spacing increases, the infiltration time decreases, but the flow pattern on the bottom face sheet becomes more nonuniform. Extreme nonuniformity of the flow front shape could result in the formation of dry spots and should be avoided.

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