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A non-local void filling model to describe its dynamics during processing thermoplastic composites

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ABSTRACT

A model is developed to describe the void dynamics within thermoplastic composite tape during the tape placement process. The model relates the volatile pressure in voids, the applied compaction load, fiber bed response and the resin pressure due to squeeze-flow of resin from resin-rich regions to fill void regions. This model relies on some geometric simplifications, but incorporates the relevant physical phenomena.

This void consolidation model was implemented in a numerical code which predicts the void development during the process. The initial void geometry can be introduced either manually, using a random generation algorithm or from actual processed tape micrographs.

The model predicts that the final void content depends on the original void content but also on the initial void distribution. Presented results analyze the influence of void distribution on tape consolidation. Limitations of the consolidation process rate by the resin squeeze flow pressures are clearly demonstrated.

1. Introduction

1.1. The tape placement process

Out-of autoclave placement of thermoplastic composites builds the composite structure gradually by depositing thermoplastic fiber reinforced tape or prepreg over the previously deposited layers. To ensure adhesion, the thermoplastic matrix is locally softened by introducing energy from a variety of sources such as infrared heaters, blow torch or lasers to provide heating. The incoming tape is brought in contact with the previous layer (or the substrate if it is the first layer) by the application of force with a rigid or flexible head or roller (Fig. 1).

The incoming tape usually contains voids in the form of "bubbles" within the thermoplastic matrix. These may be present in the tape or be created by condensation of dissolved volatiles on reheating. Additionally, volatiles may get entrapped during processing between the two layers of the tape or the tape and the substrate because of surface roughness, or they may be created by the vaporizing liquid or presence of solid contaminants during the heating phase. The applied force is expected to collapse and consolidate these voids to keep the resulting material porosity within acceptable levels for the functionality of the final product.

1.2. Previous models

Most void consolidation models take into consideration the applied temperature and force and material parameters including the initial porosity and predict the final porosity values. The existing approach [1–3] to modeling the void consolidation in deposited tape is principally "local". It relates the void volume, pressure and temperature within the void ("bubble") using the equation of state for ideal gases. The thermoplastic material rheology enters the model only as the circular shell surrounding the void which provides some viscous damping to void diameter change. The viscosity and radius of this shell are both "effective" values and allow some manipulation of the rate of void growth/compaction, and for reasonable values the response is found to be very fast [1–3], making both void compaction and rebound virtually an instantaneous process. No resin transport or void motion is considered, though the deformation of fiber bed around the void is accommodated by the "effective" values selected for the shell. There is some work available [4] that accommodates longer range transport via gas dissolution/re-condensation, but the range of both pressures and times involved is at least order of magnitude larger than what can be considered practical in our process.

There are important questions that arise here. First, if a void is present in the dry fiber bed, this fiber bed will not lend itself to the kinematic model described in [1–3]. How does one address void filling for such a case? Second, even if the void volume is devoid of any material, if the void with its polymer shell increases or

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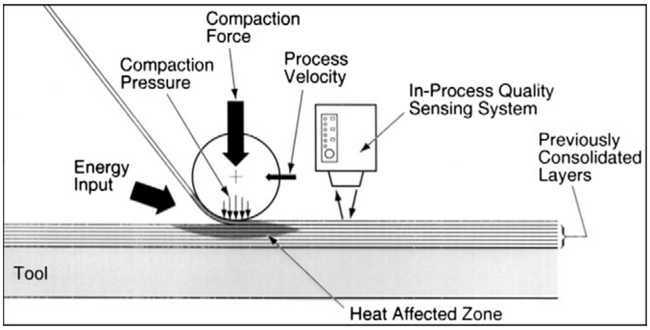

Fig. 1. Schematics of tape laying process [1].

shrinks its size, how does one account for the volume destroyed or created at that location? The continuity relation between the uniformly deformed tape and locally collapsing/rebounding voids will require some material transfer from far away distances (larger than tape thickness – order of millimeters) as the usual tape compaction mechanism does not provide for localized changes in thickness. Obviously, if the tape voids are distributed uniformly and are very small compared to the tape thickness, the tape could be represented as a continuum of bubbles but these conditions are rarely found during the manufacturing process. Similarly, if the compacting head consisted of very small segments the localized compaction and non-uniform thickness could result, but that is unlikely scenario as well.

1.3. Flow in deformable porous media

To address these shortcomings, we formulated a non-local void filling model. It is based on application of a uniform tape compaction by a prescribed load that could vary with time, resulting in resin squeeze flow providing resin to fill the void regions. The compacting pressure in this model is thus responsible for two effects, void consolidation and fiber bed compaction. The former is accomplished mostly by the resin redistribution: squeeze flow driven by a non-uniform pressure field within the resin. The displaced resin flows across the fiber bed to fill the voids. The volatile pressure in the voids opposes the resin pressure gradient and consequently reduces the void filling rate until the pressure outside the void is equal to the pressure inside and no additional resin flow and void filling is possible.

Resin is driven through the fibrous porous media by the pressure gradient. Any capillary action is neglected as, for our cases of interest, the applied pressure gradients are large and process times are short. The volume averaged resin velocity $\langle v \rangle$ is related to the resin pressure gradient by the Darcy's law:

$$\langle v \rangle = -\frac{\mathbf{K}}{\eta}\nabla p \tag{1}$$

where $\mathbf{K}$ is the fiber bed permeability (dependent on fiber volume fraction), η is the resin viscosity (dependent on the temperature) and ∇p is the porous volume averaged pressure gradient within the resin. This is caused by the applied pressure by the head or roller during the tape laying process as shown in Fig. 1. If the porous volume is subjected to volumetric strain rate of $\dot{\varepsilon}$, Eq. (1) can be combined with the volume conservation equation [5] which results in

$$-\dot{\varepsilon} = \nabla \cdot \left(\frac{\mathbf{K}}{\eta}\nabla p\right) \tag{2}$$

The stress field within the porous media is a combination of stress in fiber bed $\boldsymbol{\sigma}_F$ and the averaged pressure in the resin p [6]:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}_F - \boldsymbol{I} \cdot p \tag{3}$$

Here $\boldsymbol{I}$ is the diagonal tensor. This stress has to be in integral equilibrium with the applied compaction load on the upper surface. This equilibrium will determine the rate at which the consolidation progresses.

The resin pressure can be determined by solving Eq. (2) with boundary conditions of pressure present inside the void which is the pressure equal to the volatiles' pressure. Finally, the elastic stress in fiber bed, $\boldsymbol{\sigma}_F$, is related to the volumetric strain by a constitutive equation of the form:

$$\varepsilon = \varepsilon(\boldsymbol{\sigma}_F) \tag{4}$$

Note that in composite processing, the "strain" based Eqs. (2) and (4) may not be the most desirable form, as much of the fiber bed, fabric, or prepreg characterization is based on material compaction described by fiber volume fraction v_f, rather than by the somewhat elusive dimensional change. The two can be easily related as follows

$$\varepsilon = \frac{dV}{V} \tag{5}$$

And

$$V \cdot v_f = Const. \tag{6}$$

Differentiating (6) we obtain

$$\varepsilon = \frac{dV}{V} = -\frac{dv_f}{v_f} \tag{7}$$

And we can write the governing Eq. (2) as

$$\frac{\dot{v}_f}{v_f} = \nabla \cdot \left(\frac{\mathbf{K}}{\eta}\nabla p\right) \tag{8}$$

Then, the constitutive equation for compaction (4) can be written in the usual form [5] as

$$v_f = v_f(\boldsymbol{\sigma}_F) \tag{9}$$

The system of Eqs. (8) and (9) and the pressure boundary conditions have to be written for the assumed simplified tape and void geometry and solved to determine the pressure distribution, compaction rate and void consolidation (or rebound) rate.

Essentially, the initial geometry can be characterized from micrographs of the tape which can serve as input to the model to solve for the pressure and final void content and distribution numerically in its entirety in two dimensions. This would, however, require significant resources both for describing the problem and to obtain the solution. Consequently, making any sizeable parametric study would be time intensive and embedding the consolidation model in process design and optimization would be overwhelming. On the other hand, the problem may be simplified by judicious assumptions to obtain reasonable predictive capability in real time, well suitable for optimization and parametric studies. We will, therefore, adopt the latter approach and generate model(s) for simplified geometry. Later, we will show how to relate the simplified geometry to the actual void layup.

1.4. Temperature effects

The resin viscosity depends on temperature which changes during the consolidation process. The temperature distribution can be independently evaluated by solving the energy equation. Although, heat transfer depends on the resin flow, but as the domain of interest is very small (mm) and the flow is slow and localized, we assume that while the region of interest experiences transient temperature changes, the temperature does not significantly vary with location. In addition, heat dissipation is neglected. For the