Modeling Consolidation and Void Dynamics During Automated Tape Placement Process

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Introduction

Initial incoming thermoplastic tapes that are used in the Automated Tape Placement (ATP) process to fabricate composite structures usually contain 2 to 5 percent voids. The goal of the ATP process is to form a good bond between the current tape layer and previously consolidated layer below it using a roller and a local heating source. It is expected that the roller pressure will also eliminate the voids in the incoming tape. However, experimentally, such statement is not unconditionally true. In this work, a squeeze flow model is developed that relates the incoming voids within the initial tape to the roller pressure, tape speed and heat flow. We further refine this squeeze flow model by using the PGD method to model the movement of the voids in the tape width and the thickness direction. The general PGD approach has been reported in [1]. A study is conducted to quantify the void dynamics and relate the final quality of the tape to the process parameters and the in-coming tape quality.

Modelling the void dynamics

The voids in the incoming tape are modelled as air bubbles inside a porous media consisting of the fibres and a fluid matrix. The material behaviour due to the roller movement in the negative y direction as shown in Figure 1 is modelled using squeeze flow in the width direction [2]. Resin is driven through the fibrous porous media due to the pressure gradient created by the roller movement in the tape is modelled using Darcy's law. In this work, we approximate the transient model by a quasi-static approach, assuming the equilibrium is reached at each time step. Thus, a steady state squeeze flow problem is solved at each given time step. The solution domain consists of a tape's cross section, as illustrated in Figure 1.

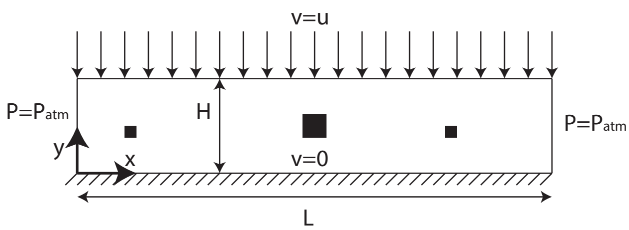

Figure 1: *Schematic of the simulated domain with the corresponding boundary conditions*

Figure 1 depicts the solution domain as well as the boundary conditions. The black squares are voids present in the incoming tape. An imposed "constant pressure" region in the void area models the presence of the voids in the incoming tape. This imposed pressure is initialized to a value slightly larger than the atmospheric pressure.

The height of the domain H changes with time. Therefore two approaches are possible using the PGD method: to include the height of the domain as an extra parameter in the formulation [3], or remesh the domain at each time step in an incremental algorithm [4]. Because of the voids displacement and shape changes, the second approach is adopted since an incremental solution is necessary in this case.

After solving the flow problem, the obtained pressure field is derived with respect to x and y directions to obtain the pressure gradients and then the velocity field using Darcy's law. Later on, we can integrate the velocity fields over the surface of the void to obtain the fluid flux going inside the voids, which leads to the volume change inside the voids using:

$$V_{i+1} = V_i - \int_{\Gamma} \vec{v_i} . \overrightarrow{dA} \tag{1}$$

Where V_i and V_{i+1} are the void volume at time steps i and i+1. The fluid flow inside the void is computed by integrating the velocity field at iteration i over the outer boundary of the void Γ.

The pressure inside the voids changes due to the change in voids' volume which is modelled by using the ideal gas law.

Numerical results

The PGD is used to solve the model after decomposing the cross section domain illustrated in Figure 1 using a 1D x 1D decomposition of the physical domain to alleviate the calculation time [4]. Later on, a transient incremental simulation changing H, the voids' positions and the voids' pressure is performed. A snapshot of the pressure field is illustrated in Figure 2 for an imposed compression velocity of the roller equal to u=0.1 mm/s on top (see Figure 1), a fluid viscosity of 1 Pa.s, and a domain permeability of 8×10^{-11}Pa.m, at t=40 ms from the beginning of the compression.

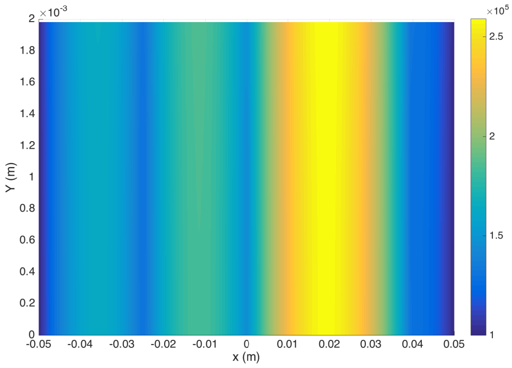

Figure 2: *Pressure field in the simulated domain including the voids at*

Figure 2 shows that the pressure field satisfies the lubrication assumptions due to the limited initial thickness of the domain H. The void motion can be modelled by considering the difference in the void velocities on the left and right edges of the void for horizontal displacement, top and bottom for vertical displacement. The results show a horizontal and vertical displacement of the voids, as well as a faster void size reduction for the ones in the middle of the domain, whereas the size of ones on the left and right sides reduce at a slower pace.

Conclusions

The illustrated model in this work represents an innovative void dynamics calculation algorithm. Voids dynamics, to the best knowledge of the authors, are not mastered yet and no modelling attempt at the meso scale level exists in the literature. Moreover, the PGD is used to reduce the calculation time using a 1D x 1D decomposition to obtain the full 2D solution at each time step.

References

[1] F. Chinesta, A. Ammar, E. Cueto. Recent Advances in the Use of the Proper Generalized Decomposition for Solving Multidimensional Models. *Archives of Computational Methods in Engineering*, 17: 327-350, 2010.

[2] Simacek, P , Advani, SG , Gruber, M , Jensen, B, "A non-local void filling model to describe its dynamics during processing thermoplastic composites", *Composites Part A-Applied Science And Manufacturing*, 46: 154-165, 2013.

[3] C. Ghnatios, G. Xu, A. Leygue, M. Visonneau, F. Chinesta, A. Cimetiere. On the space separated representation when addressing the solution of PDE in complex domains. *Discrete & Continuous Dynamical Systems-S*, 9: 475–500, 2016.

[4] C. Ghnatios, C.H. Mathis, R. Simic, N. D Spencer, F. Chinesta, Modeling soft, permeable matter with the Proper Generalized Decomposition (PGD) approach, and verification by means of nanoindentation. *Soft Matter*, 13: 4482-4493, 2017.