Simulation of Isothermal RTM Filling Using SPH Method

S. Comas-Cardona[1], P.H.L. Groenenboom[2], C. Binetruy[1] and P. Krawczak[1]

[1] *Ecole des Mines de Douai, Technology of Polymers and Composites Department*
941 rue C. Bourseul, BP 838, 59508 Douai, France
[2] *ESI-BV, Gebouw Kortland, Nieuwe Tiendweg 11a,*
2922 EN Krimpen aan den IJssel, The Netherlands
Corresponding Author's e-mail: binetruy@ensm-douai.fr

SUMMARY: Resin Transfer Molding (RTM) can be a very attractive single-step process for sandwich structure manufacturing. During an RTM injection, the pressure field developing while saturating the fiber-reinforced skins can lead to large shifting or deformation of the foam core material. Such effects induce poor dimensional accuracy of skins and core thickness. Moreover, filling time and injected resin amount can be significantly increased as a result of foam core crushing. In order to model this type of hydro-mechanical coupling, the use of mixed Finite Element and Smoothed Particle Hydrodynamics (FE-SPH) method is presented in this study. This method combines Lagrangian particles and finite elements, modeling respectively the resin and the sandwich core. Computed pressure responses during the filling stage are compared to sandwich manufacturing test results. The potential of this original numerical method is discussed.

KEYWORDS: Smoothed Particle Hydrodynamics method, resin transfer molding, hydro-mechanical coupling, sandwich manufacturing

INTRODUCTION

Resin Transfer Molding (RTM) can be a very attractive single-step process for sandwich structures manufacturing. The two fiber-reinforced skins and the core are laid up in a mold cavity. Both skins are saturated and bonded to the core while resin is injected. During sandwich manufacturing using RTM, the pressure field developing while saturating the fiber-reinforced skins can experimentally lead to large shifting[1,2] or compression[2,3] of the core. Such effects are damaging to the part because they induce poor dimensional accuracy of both skin and core thickness. Also, filling time and injected resin amount can be significantly increased due to the core crushing.

Previous works focused on addressing similar manufacturing issues and this hydro-mechanical coupling using finite element methods (FEM)[2,4], mixed control volume / finite difference methods (CVM/FDM)[5] or even a one-dimensional Lagrangian formulation[6]. However, when the geometry of the flow domain changes, due to a free surface or interfaces with moving structures, special solutions are required within these numerical schemes. In this paper, it will be shown how the Smoothed Particle Hydrodynamics (SPH) method provides an attractive alternative solution to simulate such cases.

This method has previously been used to simulate isothermal RTM filling [7] and gave fairly good qualitative results in terms of resin flow front profiles.

This study particularly focuses on flow-induced foam core compression during sandwich manufacturing. In order to model this hydro-mechanical coupling, a mixed FE-SPH method has been chosen. An SPH package is available within the commercial simulation tool PAM-CRASH (ESI, France) and has been further developed to solve for viscous flow in porous media. The following section presents a brief review of flow within porous media and the SPH method. Then, pressure responses computed from the filling simulations will be compared to sandwich manufacturing test results where hydro-mechanical coupling is present. Finally, the potential of this alternative and generic numerical method is discussed.

FUNDAMENTALS

Fluid flow dynamics within porous media

It is possible to derive the conservation of mass and momentum equations for flow in porous media from the conservation equations for a two-phase medium in which one of the materials is fixed in space[8]. Considering constant fluid viscosity and laminar flow, and a proper scaling analysis for RTM, the equations to be solved (conservation of mass and momentum) are respectively:

$$\frac{\partial \eta}{\partial t} + \nabla(\eta \vec{u}) = 0 \qquad (1)$$

$$\eta \left\{ \frac{\partial \vec{u}}{\partial t} + \vec{u}(\nabla \cdot \vec{u}) \right\} = -\phi \nabla P + \eta \vec{g} - \phi^2 \mu K^{-1} \cdot \vec{u} \qquad (2)$$

where ϕ is the fluid volume fraction or porosity, $\vec{u}$ the fluid velocity, μ the viscosity, P the pressure, g the gravitational acceleration, K the permeability and η the apparent density defined as: $\eta = \phi\rho$, where ρ is the fluid density. In this study, in order to simulate the flow for all regions of the computational domain, whether porous or not, Eqn. 2 provides the basis of the solution with the viscous drag term only being used within the porous regions.

Smoothed Particle Hydrodynamics

The SPH method is a Lagrangian and mesh-less method which was originally developed to solve astrophysical problems [9,10] and has later been applied also to the flow of compressible fluids[11]. However when pressure wave propagation is not of prime interest, as in this study, the use of an artificial equation of state for nearly incompressible liquids is quite suitable[11]. In SPH, the fluid is represented by a population of particles that interact with each other. Properties are averaged within a sphere of influence. Fundamentals and details of the method are widely available in the literature [9-11].

The interaction of the particles with the finite elements, representing respectively the resin and the foam in this study, is modeled by the sliding interface algorithms available within PAM-CRASH. The use of such interaction between the SPH and finite elements has already been validated for a wide range of applications.

EXPERIMENTAL

Material characterization

An exhaustive materials characterization has been performed at room temperature in order to feed the code with material input data. A non-reactive Newtonian fluid (Di-Octyl Phtalate, DOP) is used. Its viscosity, measured using a Brookfield viscometer, is 0.07 Pa.s. The permeability of the woven fabric (1500S3, Chomarat Composites) was measured for fiber volume fractions varying from 0.43 to 0.57. The variation can be fitted to a second order polynomial as:

$$K = 1.08\times10^{-8} V_f^2 - 1.42\times10^{-8} V_f + 4.6\times10^{-9} \qquad (3)$$

where V_f is the fiber volume fraction and the permeability K is in m^2. The areal weight of the fabrics is 1500 g.m^{-2}. The foam core (NA1100, Alvéo) has also been characterized in compression. For the pressure levels used in this study, the foam can be considered as a linear elastic material and its bulk modulus is 1.2 MPa. Finally the unsaturated fabrics have been tested in compression using a tensile test machine with a cross-head speed of 0.5 mm.min^{-1}. Previous work showed that such mechanical behavior can be fitted to a power law relationship[12]:

$$\sigma = 19.30\, V_f^{9.32} \qquad (4)$$

where σ is the compressive stress in MPa.

Sandwich manufacturing

Sandwich panels are manufactured at room temperature using a mold whose cavity dimensions are 500 x 200 x 16 mm^3 (Fig. 1). The mold cavity is filled up with a 10 mm-thick soft closed-cell polyethylene foam core and two skins each consisting of 3 plies of glass woven fabric. The fiber volume fraction reached in both skins is close to 53%. Once the mold is closed, a fluid (DOP) is injected at constant flow rate (15 cl.min^{-1}).

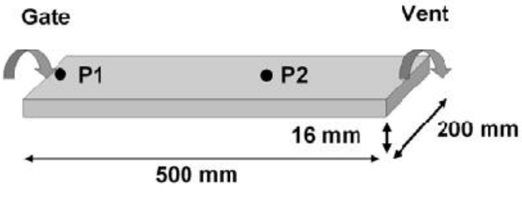

Fig. 1 Experimental setup.

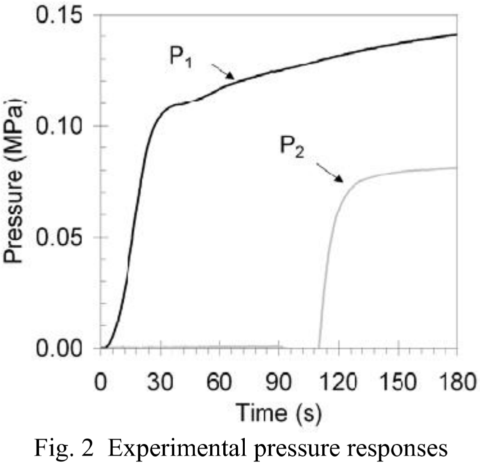

Fig. 2 Experimental pressure responses (P_1: at the gate. P_2: 29 cm from the gate).

Pressure at the injection gate (P1) and 29 cm away from the gate (P2) are monitored and recorded throughout the injection (Fig. 2). The pressure response at the gate location (P1 curve) can be separated into two regions. In the first one (until 25 s), the linearity between pressure and time verifies Darcy's law while the foam core is not deformed. After 25 s of injection, foam core compression occurs due to a local pressure built-up in the mold cavity. In the neighborhood of the gate, both porosity and permeability of the porous media increase, creating a discontinuity in slope of the pressure response – the resistance of the fluid to flow through the porous media decreases [3].

SIMULATION

Before using the mixed FE/SPH method to solve for hydro-mechanical coupling during sandwich manufacturing, the method has been quantitatively validated for isothermal RTM filling of monolithic composite parts. Comparisons of flow front positions and pressure distributions were made with the FEM-based commercial simulation tool PAM-RTM (ESI, France) and gave excellent agreements.

Lagrangian particles and finite elements are combined to model resin and sandwich core respectively (Fig. 3). The fluid response is transferred to the foam core using contact algorithms. The skins are modeled as porous regions in which Lagrangian particles are evolving. The foam is modeled as an elastic material which is initially loaded under compressive stress. This initial compressive load is calculated from the equilibrium between the fiber reinforcement and the foam compression at the closing of the mold [3]. When the foam is being compressed, more volume becomes available to the flow of resin, either by expansion of the porous material, or by the creation of a thin layer of free volume between the foam core and the porous material. Practical limitations do not allow to include this effect directly in the geometry of the computational model, but it is possible to derive simple mathematical expressions for the porosity and permeability as a function of the local core displacement. User-defined subroutines allow to include this effect in the simulations.

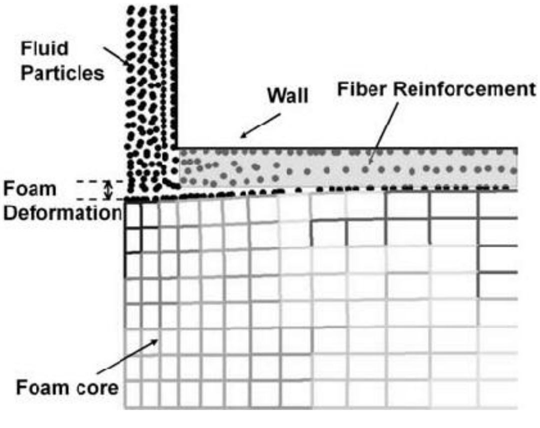

Fig. 3 Close-up of the foam deformation at the gate. Grayscale of the FE mesh represents the stress levels in the foam.

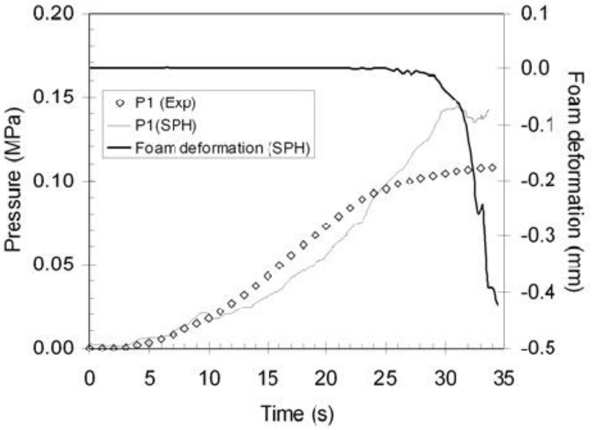

Fig. 4 Injection pressure and foam deformation

Figure 4 shows the simulation results compared to experimental data. Injection pressure responses match very well. After an initial pressure built-up, the increase slows down once the foam starts to deform. The experimental and numerical pressure responses are in excellent agreement. The foam deformation at the gate is also given from the simulation. Figure 3 is a close-up look at the foam deformation in the neighborhood of the injection gate after 35 s of injection. Because of technical issues it was not possible to measure it experimentally, using a contact-less displacement sensor for instance, since the experiments were carried out in an industrial mold. However, the foam core deformation (few tenths of millimeters) and the pressure response effects obtained in this study from the simulation, are in the same range as those obtained by Binetruy et al.[3] and Wirth et al.[2] for RTM using similar experimental conditions. Finally, the results of the study show that the simulation tool should be very sensitive. As a matter of fact, few tenths of millimeters of foam core crushing have a tremendous effect on the pressure response at the injection gate.

CONCLUSION

The mixed FE-SPH method has been successfully validated to solve for hydro-mechanical coupling in RTM. The accuracy of the method allows to properly predict the pressure and core crushing response during the injection. The mixed FE-SPH method is very generic and versatile, and should have the potential to solve for non-isothermal fluid flows.

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