Numerical Simulation of Free Boundary Viscous Flows at all Length Scales of LCM Process

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Summary

Numerical simulation aspects related to low Reynolds number free boundary viscous flows at micro, meso and macrolevel during the resin impregnation stage of the Liquid Composite Molding (LCM) Process are studied. Free boundary program (FBP), developed by the authors is used to track the movement of the resin front accurately by accounting for the surface tension effects at the boundary. FBP encompasses a set of subroutines that are linked to modules in ANSYS and has full capability of capturing the void formation dynamics. Issues related to the global and local mass conservation (GMC and LMC) are identified and discussed. Unsuitable conditions for LMC and consequently GMC are uncovered at low capillary number. Detailed discussion is devoted to the kinematic free boundary condition and progression of the free boundary according to the frontal velocities. Possible differences related to the free boundary patterns of such cases are shown.

Introduction

Liquid Composite Molding (LCM) is a class of processes in which the fiber preform is held stationary in the mold and a thermoset resin is injected into the mold to cover the empty spaces between the fibers. The main objectives of the related fluid flow analysis are free boundary pattern and pressure determination. From manufacturing viewpoint, injection should be slow enough to allow interface region formation between the resin and the fiber ensuring their adhesion; and quick enough to reduce manufacturing cost and to be finished before the resin starts curing. Residual void content must be minimized, and dry spots as well as resin rich areas are not allowed, because they significantly decrease the mechanical performance of the final part.

Fiber preforms composed by knitted layers from fiber tows, allow one to tailor better mechanical properties of final composites and facilitate arrangement

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of the reinforcement in the mold cavity. On the other hand, this type of fiber preform forms not single but dual porous medium and therefore can cause very high non-uniformity in the resin progression, not only across the thickness, but also in the plane of fabricated components [1-3]. Non-uniformity is originated by very different permeabilities in intra and inter-tow spaces and by wicking flows, which might dominate in intra-tow spaces when hydrodynamic pressure gradient is low. These facts result in transition region at the macrolevel and necessity of studying the resin flow at all length scales: at the microscale (scale of fibers), at the mesoscale (scale of fiber tows) and at the macroscale (scale of the mold).

Resin infiltration is modeled as a liquid flowing though a porous medium. Darcy's law, as an exact homogenization result for macrolevel analysis when incompressible Newtonian resin slowly flows at microlevel is usually used in numerical simulation codes. In order to account for the transition region at the macrolevel, liquid advance should be achieved by the continuity equation:

$$\phi\frac{\partial s}{\partial t} = -\nabla\cdot\mathbf{v}^{D}(s), \tag{1}$$

where ϕ, t and s are the porosity of the fiber preform, the time and the saturation, respectively. ∇ stands for spatial gradient and Darcy's velocity $\mathbf{v}^{D}=\langle\mathbf{v}\rangle$ is the phase average of the local velocity $\mathbf{v}$. Darcy's law for saturated flows must be therefore modified in the way to satisfy Eq. (1) exactly:

$$\mathbf{v}^{D}(s) = -\frac{k(s)}{\mu}\mathbf{K}\cdot\nabla\big(P(s)-P_c(s)\big). \tag{2}$$

Here μ is the viscosity, effective permeability $\mathbf{K}^{ef}(s)=k(s)\cdot\mathbf{K}$ (in anisotropic case $K_{ij}^{ef} = k_{ij}(s)\cdot K_{ij}$, $k_{ij}\in[0,1]$, $k_{ij}(0)=0$, $k_{ij}(1)=1$) and P is the intrinsic phase average of the local pressure $P=\langle p\rangle^{f}$. Homogenized capillary pressure $P_c(s)$ obeys $P_c(1)=0$ and unlike its microscopic analog, p_c, it acts in the full transition region without dependency on the actual "front curvature". Its definition can be set as $P_c = 2\gamma\langle H\rangle$, where H is the mean curvature and γ is the resin surface tension.

$P_c(s)$ and k(s) must enter macroscopic analysis as known data; therefore they must be determined elsewhere, experimentally or by exploiting homogenization techniques applied to resin progression results from micro and/or mesolevel; the latter manner is our objective and therefore FBP was developed. FBP is concerned with the moving flow front, which requires results extraction for a current time t_k, determination of new resin front position at t_{k+1}, stabilization of this new front, application and stabilization of boundary conditions and then the base analysis is solved by ANSYS CFD FLOTRAN module and the process is repeated. FBP results have been published for microlevel filling along with first methodologies for relative permeability and homogenized capillary pressure determination under some restrictions in [4]. For the time being FBP can handle micro and mesolevel filling. Exploiting analogy with thermal analysis macrolevel injection can also be modeled. FBP efficiency of calculation was improved by inclusion of several stabilization techniques, improving not only the speed of calculation but also the accuracy of solution. Discussion of numerical aspects related to these issues is the aim of this paper.

Micro and Mesolevel Analysis

In mesolevel analysis liquid flowing along two different levels have to be combined together at each discretized time t_k, which implies that Stokes problem in inter-tow spaces $\Omega_{t_k}^{S_r}$ and Darcy's problem in intra-tow region $\Omega_{t_k}^{B_r}$ have to be solved. In fact, Darcy's law must be modified to Brinkman equations, in order to account for viscous stress at the interface between these two regions:

in inter-tow spaces: $\nabla \cdot \mathbf{v} = 0$ and $\nabla p = \mu \Delta \mathbf{v}$ in $\Omega_{t_k}^{S_r}$ $\forall k$, (3a)

in intra-tow spaces:

$$\nabla \cdot \langle \mathbf{v} \rangle = 0 \text{ and } \nabla \langle p \rangle^f = \mu \Delta \langle \mathbf{v} \rangle - \mu \mathbf{K}^{-1} \langle \mathbf{v} \rangle \quad \Omega_{t_k}^{B_r} \quad \forall k . \tag{3b}$$

Surface tension influence cannot be omitted therefore:

$$\boldsymbol{\tau}^v \cdot \mathbf{n} = \mathbf{0} \text{ and } \boldsymbol{\sigma} \cdot \mathbf{n} = -p_c \mathbf{n} = -2\gamma H \mathbf{n} \quad \text{at } \Gamma_{t_k}^{S_r} , \tag{4a}$$

$$\langle \boldsymbol{\tau}^v \rangle^f \cdot \mathbf{n} = \mathbf{0} \text{ and } \langle \boldsymbol{\sigma} \rangle^f \cdot \mathbf{n} = -P_c \mathbf{n} = -2\gamma \langle H \rangle \mathbf{n} \quad \text{at } \Gamma_{t_k}^{B_r} , \tag{4b}$$

where $\boldsymbol{\tau}^v$ is viscous shear stress, $\boldsymbol{\sigma}$ is stress tensor and $\mathbf{n}$ is the outer unit normal to the free front; $\Gamma_{t_k}^{S_r}$ and $\Gamma_{t_k}^{B_r}$ are parts of the free boundary contained in the Stokes and Brinkman region.

Fiber tows in mesolevel analysis belong to single porous media with uniform pore size, therefore transition region can be omitted (i.e. quasi steady state assumption can be adopted) and the homogenized value P_c can be calculated as explained in [4]. Additional condition to move the resin front can be derived from the free surface equation:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = 0 \quad \text{at } \Gamma_{t_k}^{S_r}, \tag{5a}$$

$$\frac{\partial f}{\partial t} + \frac{1}{\phi_t}\langle \mathbf{v} \rangle \cdot \nabla f = 0 \quad \text{at } \Gamma_{t_k}^{B_r}, \tag{5b}$$

where implicit function f(**x**(t),t)=0 describes the moving front, **x** is spatial variable and ϕ_t stands for intra-tow porosity.

Modifications for microlevel analysis are obvious. In addition, if fibers are rigid, impermeable and stationary during injection, it must hold:

$$\text{at the fiber boundary: } v=0 \quad \text{at } \Gamma_{t_k}^{f}, \tag{6a}$$

$$\text{contact angle } \theta \text{ is formed at } \Gamma_{t_k}^{S_r} \cap \Gamma_{t_k}^{f}, \tag{6b}$$

Now first problems in the mesolevel analysis are clearly visible, they are related to the ambiguity of Eqs. (5-6) at the node at the intersection $\Gamma_{t_k}^{S_r} \cap \Gamma_{t_k}^{B_r}$, which we will name as the transition node. In order to eliminate this ambiguity, FE mesh around the transition node is refined, condition from Eq. (5) is not applied, it is imposed in the way as it should be only at proximal frontal nodes; and automatic correction of the free front to straight line using two adjacent new nodal positions, as it is shown in Fig. 1, is implemented.

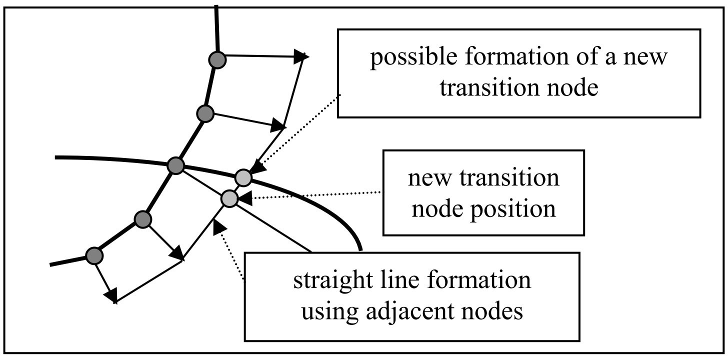

Fig. 1: Treatment of the free boundary advance at the transition node

Several stabilization techniques are included in FBP in order to decrease the danger of front oscillations, which can originate due to unphysical non-smoothness, as a result of LMC violation at low capillary numbers. The first one corrects normal extent in significantly curved front regions and it is based on estimation of the frontal medium velocity (Fig. 2).

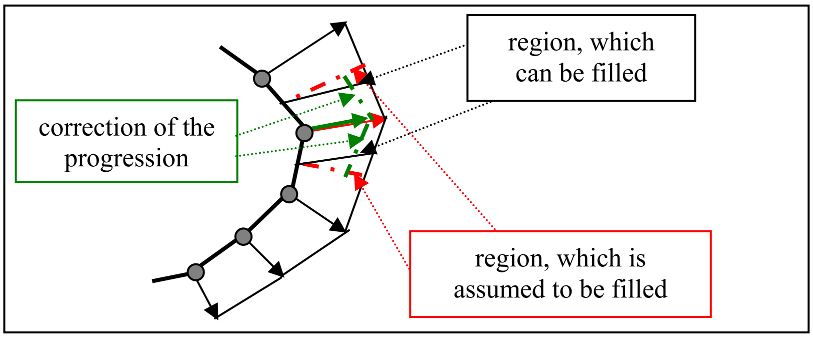

Fig. 2: Stabilization technique of LMC in significantly curved fronts

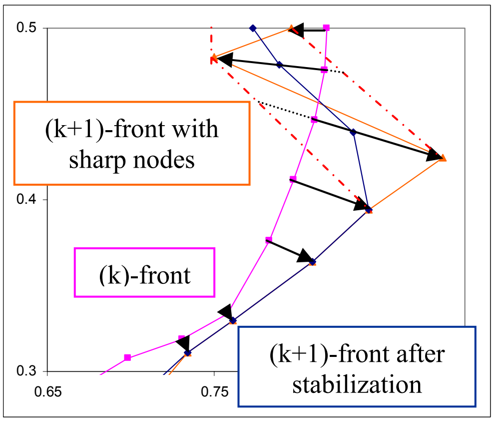

Fig. 3: Stabilization technique of unphysical non-smoothness

Last technique stabilizes capillary pressure before its application on $\Gamma_{t_k}^{S_r}$ by least square method in Maple module.

In mesoanalysis at low capillary number N_c=0.0025, with fine mesh and all stabilization techniques invoked, the total injected resin well fits the analytical value and represents a significant improvement of the original analysis, as shown in Fig.5.

In Fig. 3 treatment of "sharp" angles on the flow front is shown. Another technique corrects the fictitious time predicted by the free boundary condition in the way to preserve GMC as explained in Fig. 4.

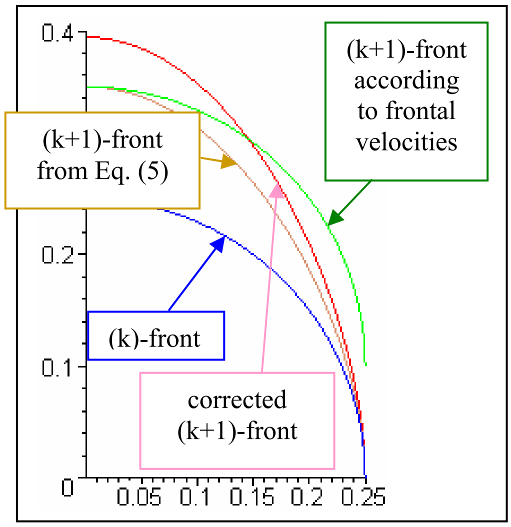

Fig.4: Correction of the fictitious time predicted by the free boundary condition

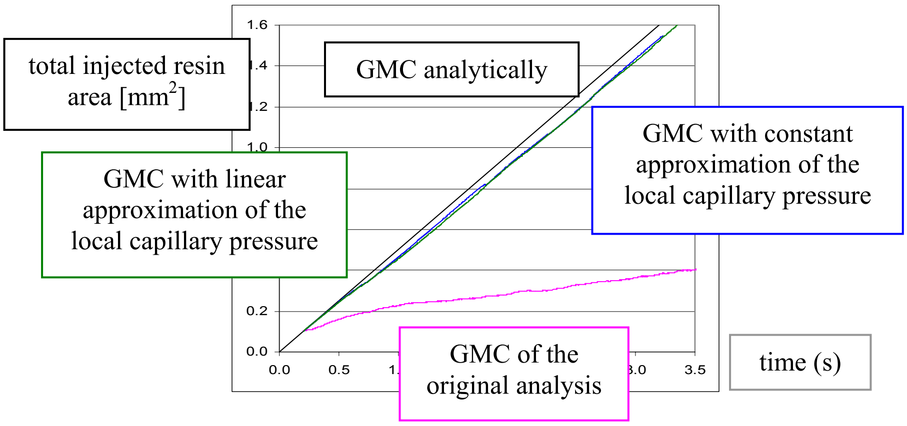

Fig. 5: Analytical GM compared to the stabilized and the original analysis

Conclusion

In this article free boundary progression pattern at micro and mesolevel infiltration of LCM manufacturing process determined by FBP was discussed. Currently only two dimensional problems can be treated; extension to three dimensions is a subject for further research. Stabilization techniques are only necessary for low capillary number impregnations. No problems were detected at the resin-fiber tow interface, although treated by FE and not by CV/FEM. FBP belongs to the group of moving mesh algorithms and has the potential to calculate several averages to be used in homogenization techniques.

References

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