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Boundary Element Method for the dynamic evolution of intra-tow voids in dual-scale fibrous reinforcements using a Stokes–Darcy formulation

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ABSTRACT

The Boundary Element Method (BEM) is implemented in the simulation of compression, displacement, migration and splitting of intra-tow voids in dual-scale fibrous reinforcements. The last three processes have not been simulated at mesoscopic scale in previous works due to the consideration of a constant pressure in the channels of the Representative Unitary Cell. In this work, both the channels and tows are modeled using the Stokes and Darcy equations, respectively, a pressure gradient is prescribed along the fluid motion, and full air compressibility is deemed, thereby allowing to consider these three processes. The void migration process from the weft towards the channel is analyzed in terms of the ratio between the average air migration velocity and the average liquid velocity, and of the normalized air rate from the weft towards the channel. According to BEM results, the bubble can migrate at both lower and higher velocities with respect to the liquid velocity, and the void removal out of the tows can occur after several stages of compression–displacement–migration–splitting; additionally, the bubble breaks up after several cycles of expansion and compression. BEM results also show that the liquid surface tension, pressure gradient and average channel pressure have important influence in the void migration process.

1. Introduction

Most of fibrous reinforcements used in the processing of composites materials can be considered as dual-scale porous media, in which two domains with very dissimilar permeabilities are present in the Representative Unitary Cell (RUC); in this particular case, these domains are the high-permeable channels and the low-permeable tows. Accordingly, this kind of reinforcements are commonly known as dual-scale fibrous reinforcements, in which the imbalances between the capillary flow in the tows and the viscous flow in the channels cause the formation of voids by mechanical entrapment of air [1–7]. Once the voids are formed, several processes can take place in them, like compression, displacement, migration and splitting. The physical assumptions and governing equations of each process depend on the zone where the void is located. For channel voids (macrovoids or inter-tow voids), a spherical bubble that experiences a compression governed by the ideal gas law was reported by Lundström [8], where the capillary pressure was taken into account and the bubble shape did not change when compressed. On the other hand, the displacement of macrovoids along the channels has been studied in both numerical [3,9–12] and experimental works [11,13–15], where it has been mentioned that this process is mainly governed by drag and adhesion forces. The former forces make reference to the pressure gradient between both extremes of the bubble, while the latter ones refer to the interfacial adhesion between the bubbles and the walls of the domain that represent the contour of the tows. If the bubble is smaller than the inter-tow space (channel) it tends to be spherical to minimize the free surface energy [15] and it moves easily until it reaches a constriction where a minimum pressure gradient is required to preserve the motion [16,17]. On the contrary, if the frontal section of the bubble is equal to the inter-tow space, the bubble tends to be cylindrical when its volume increases [15]. The bubble length has a double effect in its mobility [8,15,17]: the larger the bubble, the higher the pressure gradient, promoting the bubble's motion; however, the contact surfaces bubble-tows, and consequently the interfacial forces, increase with the bubble length, which make more difficult the bubble's motion. Strictly speaking, the motion of macrovoids along the channels depends mainly on the pressure gradient, bubble geometry (frontal area, perimeter and length), surface tractions at the liquid–air interface, liquid viscosity, advancing and receding contact angles and architecture of the channels [16,17]. Since some of these parameters are difficult to determine experimentally, some phenomenological [3,11,18] and analytical models [19] have been proposed to relate the average liquid velocity, $\langle u_g \rangle^g$,

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which can be experimentally measured, with the void velocity along the channel, $\langle u^v \rangle$.

The bubbles formed inside the tows (microvoids or intra-tow voids), which are the principal focus of the present work, can also undergo several processes. The microvoid compression takes place inside the tow by the overall effect of the pressure of the liquid surrounding the tow, the air pressure at the fluid front, which in turns depends on the initial air pressure, bubble volume and air dissolution, and the capillary pressure. In dual-scale fibrous reinforcements, the process of microvoids compression is considerably slower than the corresponding macrovoids compression due to the dissimilar permeabilities of the tows and channels [3]. As it was mentioned in other works [3,20], and confirmed here, the compression of the bubble inside the tow takes place provided that the air pressure at the fluid front is lower than the maximum liquid pressure surrounding the tow plus the capillary pressure, otherwise, the bubble moves inside the tow without changing its volume and could migrate towards the channels. This is consistent with the dynamic condition at the bubble interface.

The conditions that lead to the void migration from the tows towards the channels have been studied in different numerical and experimental works. According to Lundström et al. [21], the bubble compresses until a critical volume is reached, in which the pressure is high enough to originate the void migration towards the channels. This concept was brought up later in an experimental work to explain the reduction of the microvoid content with the modified capillary number, C_a^*, in constant flow rate injections, after reaching certain value of the inlet pressure, which was identified as the critical pressure for the onset of the void migration, P_c [22]. The critical pressure, P_c, was then used in the development of a numerical model to predict the dynamic void content in macroscopic simulations [23,24]. In that model, P_c was taken as an input parameter that modifies the equivalent fiber volume fraction appearing in the calculation of the fill factor of the Control Volumes (CV's), in such a way that when the pressure is greater than P_c, the equivalent fiber volume fraction is set to its initial value in order to consider the void removal out of the tow. According to Yamaleev and Mohan [25], the increase of the liquid pressure not only causes the reduction of the void content because of the void compression, but also because it promotes the air dissolution into the liquid by molecular diffusion. The mathematical model developed by Park et al. [3] shows that the void migration process is encouraged by the liquid pressure gradient, $\Delta P/\Delta x$, and, consequently, by the average liquid velocity, $\langle u_g \rangle^g$. On the other hand, according to Lunström et al. [10], the wettability of the fibers favors the motion of the microvoids from the tows towards the channels, being the molecular diffusion the principal mechanism of microvoids removal at points far upstream of the fluid front.

In the present work, the Boundary Element Method (BEM) is implemented in the problem of the dynamic evolution of intra-voids formed in dual-scale fibrous reinforcements, considering a coupled Stokes–Darcy formulation. The processes of compression, displacement, migration and splitting of intra-tow voids are analyzed at the mesoscopic level, i.e, considering the filling in a RUC, on the basis of the BEM results. It is assumed that the channel is fully filled with liquid before any infiltration occurs inside the tows, as previously considered in other works [26–31]. This is valid provided that the fluid front velocity in the channel is considerably larger than the fluid front velocity in the tows, which is more realistic when the channel is significantly more permeable than the tows and the injection pressure or flow rate are high enough to neglect the capillary effects at the macroscopic fluid front. The principal contributions of the present work can be summarized as follows:

- The simulation of void motion in both macroscopic and mesoscopic scales has been tackled by several numerical techniques: FEM/CV conforming [3,20,23,24], Monte Carlo Method [10], FEM/CV non-conforming [32], among others. The works using FEM/CV techniques require the domain discretization, whereas our BEM approach only requires the use of a contour mesh and not the use of internal elements. This is convenient when dealing with moving boundary problems where the domain changes with the time as the process evolves, since the remeshing operation are considerably simpler. On the other hand, the tracking of the fluid front in FEM/CV techniques is carried out by assigning a fill factor to each control volume (CV) and using an interface capturing scheme, like the Flow Analysis Network (FAN) [33,34], to approximate the shape of the fluid front. In our numerical scheme, a direct integration of the interface kinematic condition is used to advance the fluid front (Euler method), which assures a higher order accuracy of the fluid front shape with respect to the FEM/CV techniques. On the other hand, the numerical technique used by Lunström et al. [10] to track the fluid front is the Level Set Method, where specific solvers for hyperbolic equations are required to find a signed distance function, which sets to zero at the fluid front. In the Level Set method, an auxiliary domain mesh is required to compute the extended velocities and the accuracy of the fluid front position depends on the refinement of such auxiliary mesh [35]. In the tracking technique used here, which is much simpler and computationally more efficient, the fluid front position is directly obtained from the velocity field of the moving interface, not requiring the use of auxiliary meshes.
- To the best of our knowledge, the migration of the bubbles from the tows towards the channels at the mesoscopic scale has not been directly simulated before; this process has been considered in macroscopic simulations by stochastic approaches [10], phenomenological models involving experimental tests [3,11,18], analytical model for the source term in terms of supposed migration frequencies [20], or experimental parameters, like the critical pressure, P_c, that are introduced as input parameters in the numerical codes [23,24]. In the present work, the migration and splitting of intra-tow bubbles are directly simulated by BEM and the influence of the average channel pressure ($\langle P_g \rangle^g$), pressure gradient ($\Delta P/\Delta x$) and surface tension (λ) on these two processes is studied. Additionally, the time evolution of the source term associated to the void migration is also analyzed, as well as the time evolution of the ratio between the average void migration velocity, $\langle u_{air} \rangle$, and the average liquid velocity in the channel, $\langle u_g \rangle^g$. This ratio is important because it relates a variable that is difficult to measure, namely, the void migration velocity, with a experimentally measurable variable, namely, the liquid velocity in the channel.
- In the composites literature, when it is assumed that the channels are totally filled with liquid before the infiltration of the tows occurs, most authors suppose a constant liquid pressure in the channels of the RUC during the mesoscopic simulations [26–31]. This assumption is not physically consistent with the fact that the fluid in the channels is actually moving. Additionally, the processes of displacement at constant volume, migration and subsequent splitting of the intra-tow bubbles are not possible under this assumption since the fluid front moves towards the center of the tows, no matter the direction of the fluid velocity in the channels, causing that the bubbles remain trapped or disappear depending on the air entrapment parameter considered [36]. Some experimental and numerical works have confirmed that the bubbles are not necessarily located at the center of the tows and can migrate towards the channel depending on the liquid pressure gradient and the internal pressure of the void [14,18,22,37–39]. In the present work, the channel and tows are modeled using the Stokes and Darcy equations, respectively, a pressure gradient is considered along the RUC length and the matching conditions between the tows and the channel determine the filling of the former ones. In this way, decentered bubbles are formed inside the tows and the displacement, migration and splitting of these bubbles are possible, which is more consistent with previous experimental results.

In the processing of composites materials, different sorts of RUC architectures can be examined for dual-scale fibrous reinforcements. In