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## EFFICIENT SIMULATION OF DUAL-SCALE FLOW IN RTM PROCESSES BY DOMAIN SKELETONIZATION

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**Abstract:** *In this work we present a novel Dual-Scale Skeleton model (DSS) to simulate the mesoscopic dual-scale flow inside a fibrous layout at an affordable computational cost. Instead of using a traditional Stokes-Brinkman model to govern the flow inside and around the tows, the flow domain is separated into three interconnected subdomains. For each subdomain, the three-dimensional mesoscale geometry of yarns and channels is replaced by their medial axis representation, on which the flow is simulated by FE method. The generation of a Hybrid Skeleton mesh (2D and 1D elements) allows to reduce the computational cost of the problem while still accounting for three-dimensional effects in the flow. This allows one to carry out mesoscale simulations on relatively large domains. Although further refinements are desirable, the DSS model shows potential for application in composites process modeling.*

**Keywords:** dual-scale flow; RTM process modeling; skeletonization; efficient simulation

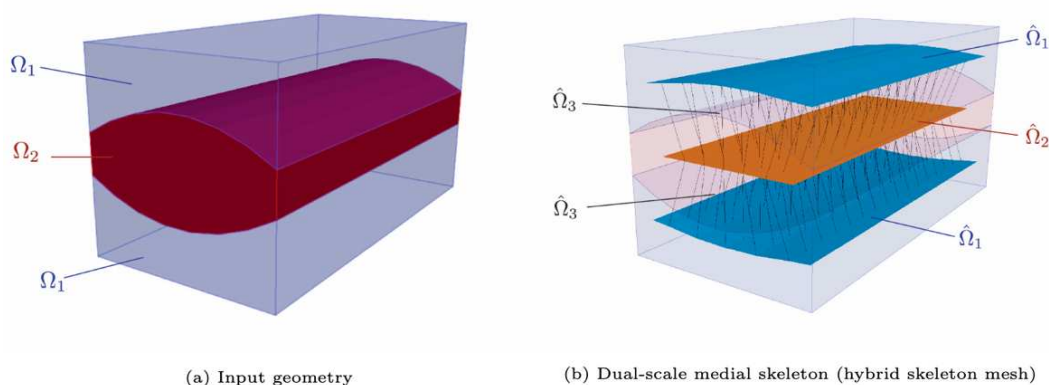
### 1. Introduction

In Resin Transfer Moulding (RTM) processes, a fibrous preform is compacted inside a mould and impregnated with a polymeric resin, which is later cured to obtain a structural composite part. Simulating the flow of resin as it impregnates the empty spaces within the porous preform is of great interest to process engineers, as it allows one to predict defects that may arise and/or optimize the location of the gates and vents. The flow of a resin infiltrating a dry preform is traditionally modeled at the macroscale using Darcy's law. This model, which relies on the permeability tensor of the material to compute the volume averaged velocity of the resin, is suitable for the numerical simulation of the filling of industrial scale parts. However, there are cases when this macroscale model falls short: for instance, when the upscaled permeability tensor of a certain stack cannot be characterized a priori, or when the effect of local features such as defects is to be studied. In such cases, one possibility is to model the dual-scale flow of the resin at the scale of the tows (mesoscale) to account for any local feature which is present in the input geometry. Provided that the mesoscale geometry of the preform is modeled with enough accuracy, the dual-scale flow of resin inside and around the tows can be directly simulated using the Stokes-Brinkman model [1], effectively bypassing the need for permeability characterization. However, the high computational cost of this detailed approach strongly limits the size of the domain that can be computed numerically. Consequently, the simulation of a 3D dual-scale flow is not suitable for application to entire parts, leaving the macroscale simulation the only option available to the process engineer [2]. In this work we introduce a new method to model the dual-scale filling of an RTM process at the mesoscale, at a reduced computational

cost when compared to a full 3D solution. To reduce the computational cost of the problem a series of assumptions are adopted, notably the lubrication approximation and topological skeletonization of 3D geometries. Such model, referred to as Dual Scale Skeleton (DSS) model, is introduced and validated over a simple test case before demonstrating an example application.

## 2. Methodology

The Dual Scale Skeleton (DSS) model is based on a series of assumptions that allow one to simplify both the governing equations and the geometrical dimension of the problem. Typically, the dual-scale flow of a resin in porous media such as dry textiles is modeled by combining Stokes and Darcy-Brinkman flow models, each describing the flow in a specific domain [1]. Stokes flow is generally accepted to model the flow of resin in the clear-fluid domain (the spaces in-between tows) under the assumption of creeping flow. Darcy's law models are conveniently applied to the flow inside the yarns [2] which are seen as porous domains and the velocity of the resin is phase averaged. Adding an additional term yields the Brinkmann's equation, which allows one to have stress continuity at the interface between the channels and the tows. Instead of solving the classical Stokes-Brinkman dual-scale problem, the DSS model is formulated through a series of assumptions: i) Lubrication approximation is adopted in the channels subdomain. ii) Darcy's law is valid in the tows subdomain. iii) A special "interface" domain ensures the interaction between channels and tows in the computation of the pressure solution. A key element in the DSS model is the topological skeletonization of the domains. Reynolds and Darcy equations adopt a gap-averaged or phase-averaged velocity definition, allowing one to reduce the geometrical representation of the channel and tow volumes from a three-dimensional volume to a two-dimensional surface, neglecting the dimension transverse to the characteristic direction of flow. Such surface is referred to as medial surface skeleton, or in its discrete representation as medial skeleton mesh.



*Figure 1. Yarn immersed in a channel: original three-dimensional geometry and corresponding hybrid skeleton mesh*

## 2.1 Skeletonization

Flow models in porous media based on medial skeletons have been developed before. The permeability of rock fractures was estimated using Reynolds equation and the medial skeleton in [4, 5], for 2D and 3D skeletons. Wong et al. in [6] solved lubricated flow on a 1D medial axis mesh to compute the upscaled permeability of textiles. In the DSS model, the 3D geometries of channel and tow subdomains are replaced by a 2D medial skeleton mesh which is assigned the gap height ( $h(x)$ ) at every node from the original boundaries. The interaction between the channel and tow domains is obtained by introducing a third “interface” subdomain composed by one-dimensional elements which connects them. Such mixed element skeleton mesh is named Hybrid Skeleton mesh. In Fig.1a an example of input domain is shown. The channel and tow subdomains are labeled as  $\Omega_1$  and  $\Omega_2$  respectively. In Fig.1b the corresponding Hybrid Skeleton mesh is shown. The physical subdomains  $\Omega_1$  and  $\Omega_2$  are reduced to their 2D skeleton versions  $\widehat{\Omega}_1$  (channels),  $\widehat{\Omega}_2$  (tows) and linked through the 1D elements  $\widehat{\Omega}_3$  (interface).

## 2.2 DSS model

The DSS model is formulated as an assembly of three different subdomains under the principle of mass conservation (continuity equation). For each one, different modeling assumptions are adopted.

**Channels domain ( $\widehat{\Omega}_1$ )** Flow in the channel domain is modeled using Reynolds equation, under the assumption of lubricated flow. Continuity equation can be expressed for the gap-averaged Reynolds velocity  $\langle \mathbf{u} \rangle$  by applying the volume averaging theorem of the divergence operator [7].

$$\nabla \cdot \left\langle -\frac{1}{\mu} \frac{h^2}{12} \nabla p \right\rangle + \frac{1}{V} \int_{\Gamma} q \, dx = 0 \quad (1)$$

where  $h$  denotes the channel gap height. The second term in Eq.1 is used to account for the transverse flow at the interface with the tows.

**Tows domain ( $\widehat{\Omega}_2$ )** Flow in the tow domain is modeled using Darcy’s law. As in Eq. 1, the interface extra term is present:

$$\nabla \cdot \left\langle -\frac{k}{\mu} \nabla p \right\rangle + \frac{1}{V} \int_{\Gamma} q \, dx = 0 \quad (2)$$

where  $k$  denotes the longitudinal permeability of the tow.

**Interface domain ( $\widehat{\Omega}_3$ )** The interface element couples the flow of resin between the mesh of the channel domain  $\widehat{\Omega}_1$  and the mesh of the tow domain  $\widehat{\Omega}_2$ . The lubrication approximation is adopted in the channels, therefore the pressure gradient in the direction of the interface element is null in the region  $\widehat{\Omega}_1$ . On the other hand, the pressure gradient in the direction of the interface element is not null in the region  $\widehat{\Omega}_2$ . Therefore, the flow velocity in the interface element is defined using Darcy’s law, but the pressure gradient is not null only in the portion of the element inside  $\widehat{\Omega}_2$ .

$$q = \mathbf{u} \cdot \mathbf{n} = -\frac{K_t}{\mu} \frac{\partial p}{\partial s} \quad (3)$$

where  $K_t$  is the yarn transverse permeability,  $\mathbf{n}$  is the interface normal and  $s$  denotes the curvilinear coordinate of the 1D element.

The pressure derivative is defined as a linear pressure gradient so that only the tow region is considered:

$$\frac{\partial p}{\partial s} = \frac{p_i - p_j}{L_e \delta_e} \quad (4)$$

where  $L_e$  is the total length of the element, and  $\delta_e$  is a scalar coefficient corresponding to the fraction of the element length which is immersed in the tow domain. Finally, Eqs. 1-3 expressed in FE weak form are combined into a global linear system that can be solved given appropriate boundary conditions.

### 2.3 Validation

The traditional Stokes-Brinkman model is adopted as a reference solution to compare against the result yielded by the DSS model. A test case used for validation consists of a two-layer domain, representing a channel ( $\Omega_1$ ) and a tow ( $\Omega_2$ ). The test case is shown in Fig. 2. Resin flow is introduced with inlet/outlet pressure boundary conditions and Stokes-Brinkman model is solved numerically by finite elements method. Conversely, the same flow scenario is solved using the DSS model after extracting the hybrid skeleton mesh from the input geometry. The error for velocities computed for this simple test case is  $\approx 12\%$ . The large gain in CPU time for solution on the same machine shows the potential of the model.

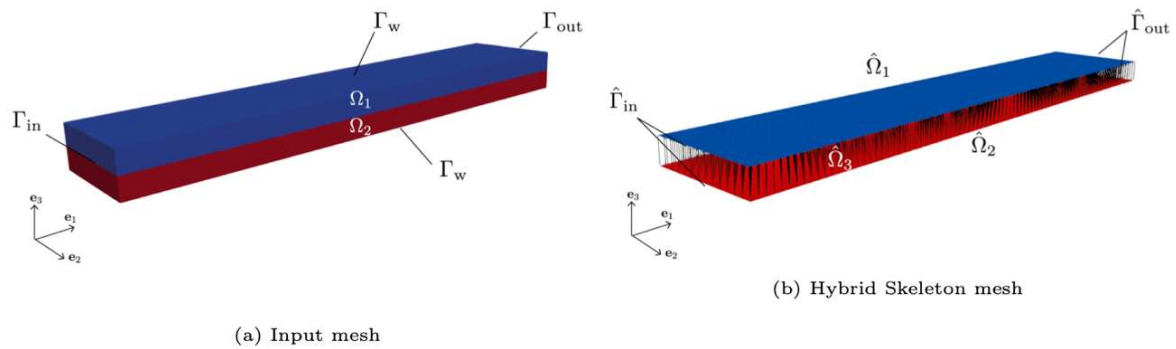


Figure 2. The geometry used for DSS model validation

Table 1: Results from DSS model validation test case

| Case            | $N_{\text{elem}}$ | CPU t [s] | $\langle u \rangle_{\Omega_1}$ [m/s] | $\langle u \rangle_{\Omega_2}$ [m/s] |
|-----------------|-------------------|-----------|--------------------------------------|--------------------------------------|
| Stokes-Brinkman | 63316             | 97        | 7.72E-04                             | 2.00E-05                             |
| DSS model       | 9354 (2D + 1D)    | 0.04      | 6.75E-04                             | 2.02E-05                             |

## 2.4 Filling simulation

By extracting the hybrid skeleton mesh from the input geometry of a multi-layer stack of fabrics, it is possible to simulate the unsaturated filling of the preform using the DSS model. For the purpose, the DSS model was implemented in the commercial filling simulation software LIMS [8, 9]. As an example, the dual-scale filling of an array of tows is simulated in Fig. 3. One can see the plug flow in the channel region as well as the partially saturated flow front in the tows because of the transverse flow from the channels. Although no full-3D validation is available in this case, the pattern observed in the flow front advancement qualitatively agrees with expected behavior.

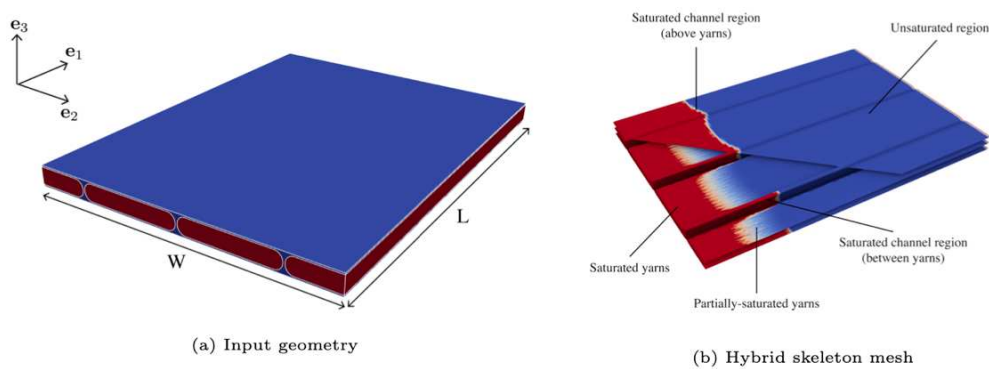


Figure 3. Input geometry and sliced view of the dual-scale flow front

## 3. Discussion and Conclusions

We have presented a new Dual-Scale Skeleton (DSS) model which can handle the dual-scale flow of a resin onto a novel Hybrid Skeleton mesh. The model can be used to compute both saturated and unsaturated RTM filling simulations at a reduced computational cost when compared to 3D solutions. The accuracy of the DSS model was assessed by comparison against a full-dimensional Stokes-Brinkman solution. The results show large gains in computational cost, while the tradeoff error is below 15%. This value cannot be assumed as representative of more complex scenarios: at the current level of development the model requires further validation, which could be achieved only by either experimental measurement or by solving the same scenarios numerically using a high-computing Stokes-Brinkman transient flow solver. It is worth to note that experimental validation is still very challenging. The dual scale flow in fabrics is very difficult to monitor and is subjected to experimental errors. However, several different test cases were solved using the DSS model and all the results show good qualitative agreement with how the flow is expected to behave in presence of some distinctive features (racetracks, low/high transverse yarn permeability...). Although still far from the possibility to simulate full-scale parts, the current state of work can be considered a first successful attempt at applying the novel Dual-Scale Skeleton model to the direct meso-scale simulation of RTM processes.

## 4. Acknowledgements

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