MODELLING OF COMPOSITES PROCESSING USING A TWO-PHASE POROUS MEDIA THEORY

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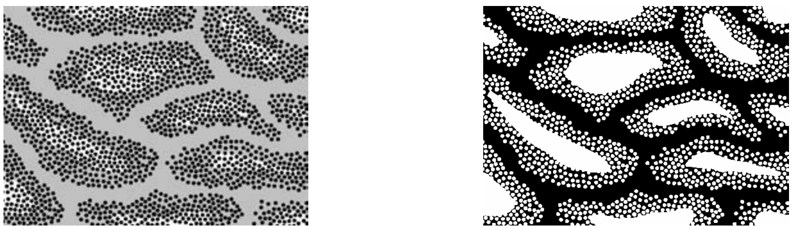
Summary In the present contribution we propose a framework for the modelling of various forming processes for biphasic fiber composites. The class of processes considered involves deformation of a fiber bundle network, wetting by penetration of resin into fiber bundles, and resin flow through the fiber bundle network. The wetting process is considered as an irreversible dissipative mechanism that leads to the compaction of solid phase due to the exclusion of voids and "elastic" packing of the fibers. In the present contribution, we use a micro-mechanically motivated viscous flow rule for the evolution of the wetting. In addition, anisotropic macroscopic Darcian flow of the resin is accounted for. In the numerical example, a finite element analysis creep test representing the press-forming processing of a polymeric composite material is demonstrated.

INTRODUCTION

In the processing of fibre composite materials, three basic tasks must be performed: wetting of fibres by the resin, forming into shape and, when applicable, macroscopic drainage of resin. There is a variety of new, high speed manufacturing processes for fibre composites, which perform all these tasks in a single operation. Simulation of such process will require a series of sub-models describing the various mechanisms. But it will also require an appropriate continuum mechanical formulation to handle all the sub-models simultaneously while ensuring positive energy dissipation and balance of mass, momentum and energy.

In parallel with the increasing computer capacity, the porous media theory has been extensively developed and exploited. As an example, we may mention the development of the continuum theory of porous media formulated by Bowen [1]. In recent years the thermodynamic basis and the constitutive equations in the finite strain regime, along with the description of the various dissipative mechanisms have been further exploited, cf. Ehlers and Diebels [2], Armero [3] and Larsson and Larsson [4]. A few researchers, e.g. Pillai et al. [5], have proposed formulations to model the processing of fibre composites using porous media theory, a concept that is further developed in the present contribution.

CONSTITUENTS AND DEFORMATION PROCESSES



a) b)

Figure 1. Schematic of a) the considered microstructure consisting of matrix (grey), intra-bundle voids (white) and particles i.e. fibres (black) and b) the assumed phases, consisting of a solid phase (white) and a fluid phase (black)

Consider the coupling between the micro- and macro-scales in terms of a mixture consisting of three different micro-scale constituents, as depicted in Fig. 1a. To address the wetting process, the fiber bundles are subdivided into a wet portion (already penetrated by fluid) and a dry portion. It is emphasized that the void constituent is considered to be embedded within the fiber bundles. Consequently, the fibres and the voids are assumed to move in a synchronous fashion. A two-phase continuum model thus describes the three-constituent system, as depicted in Fig. 1b.

During processing of such a material system, four primary mechanisms can be identified: The two first mechanisms concern the deformation of the fiber-network and the "macroscopic" Darcian flow, i.e. drainage of matrix between the bundles. The other two mechanisms relate to wetting of individual fiber bundles, i.e. micro-scale infiltration with matrix, and the densification of the bundles.

A TWO-PHASE CONTINUUM MODEL AND CONSTITUTIVE EQUATIONS

As alluded to in the previous section, the problem of three constituents is reduced to a two-phase problem, which is resolved using the two-phase theory of porous media. We therefore assume that each spatial point $\mathbf{x}$ of the mixture is simultaneously occupied by the material particles $\mathbf{X}^s$ and $\mathbf{X}^f$, as shown in Fig. 2. Note that the two phases relate to different reference configurations.

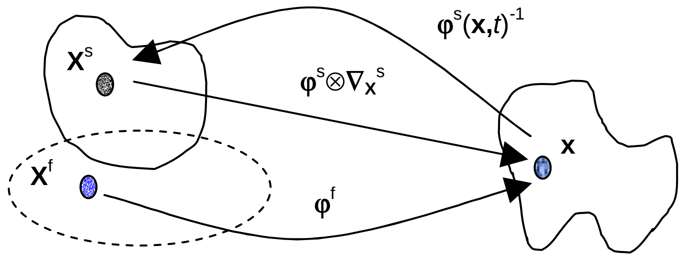


Figure 1. Deformation of a two-phase continuum body

Following the developments in [5], the momentum balance, the conservation of mass, the energy balance are combined in the entropy inequality. The constitutive equations can now be established, by distinguishing three different types of dissipative mechanism, from the total dissipation $\mathcal{D}$ defined as

$$\mathcal{D} = \underbrace{\boldsymbol{\sigma} : \mathbf{l} - n^s \rho^s \dot{\psi}^1}_{\mathcal{D}_1} - \underbrace{n^s p \dot{\varepsilon} - n^s \rho^s \dot{\psi}^2}_{\mathcal{D}_2} - \underbrace{\mathbf{h} \cdot \mathbf{v}^d}_{\mathcal{D}_3} \geq 0 \tag{1}$$

where $\boldsymbol{\sigma}$ is the effective Terzaghi stress, $\mathbf{l}$ is the spatial velocity gradient, n^s is the solid volume fraction, ρ^s is intrinsic solid density, ψ^1 and ψ^2 are the Helmholtz free energies relating to the macro- and micro-scale processes, respectively, p is the fluid pressure, ε is a logarithmic compaction strain relating the initial and current solid densities, $\mathbf{h}$ is the effective drag force acting on the fluid phase and $\mathbf{v}^d$ is the Darcian velocity. The three dissipative mechanisms are: $\mathcal{D}_1$, the response due to effective stress, $\mathcal{D}_2$, the response due to fluid pressure, and $\mathcal{D}_3$, the response due to fluid-solid interaction owing to macroscopic Darcy flow. Note that these mechanisms correspond to the material responses of 1) elastic interaction between bundles, 2) wetting and compressing of fibre bundles by the liquid resin and 3) matrix flow between bundles, i.e. macroscopic drainage.

RESULTS AND CONCLUSIONS

In the presented examples, for the effective stress response, a hyper-elastic model based on isochoric-volumetric split is proposed. The isochoric response is described using a Neo-Hooke model, whereas the volumetric response is derived on the basis of a fibre packing law originally proposed by Toll [6]. As to the compaction of the bundles, the same fiber packing law was used in combination with specific infiltration model. The macroscopic drainage, is modeled based on anisotropic Darcian flow.

We emphasize in the present contribution, a developed framework for the modelling of a family of manufacturing processes of fiber composites using two-phase porous media theory. We have shown that a system involving three constituents may be described as a two-phase continuum, where the solid phase includes the voids as well as the fibers in the reinforcing fiber bundles. In this development, elimination of voids by penetration of liquid into a fiber bundle accompanied by an elastic compression of the bundle is manifested as an intrinsic compaction of the solid phase. The intrinsic compressibility of a fiber bundle was described by an established packing law. The same type of packing law was used at the fiber network level as well as at the fiber bundle level.

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