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Modeling of coupled dual-scale flow–deformation processes in composites manufacturing

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ABSTRACT

The present contribution is a part of the work towards a framework for holistic modeling of composites manufacturing. Here we focus our attention onto the particular problem of coupled dual-scale deformation–flow process such as the one arising in RTM, Vacuum Assisted Resin Infusion (VARI) and Vacuum Bag Only (VBO) prepregs. The formulation considers coupling effects between macro-scale preform processes and meso-scale ply processes as well as coupling effects between the solid and fluid phases. The framework comprises a nonlinear compressible fiber network saturated with incompressible fluid phase. Internal variables are introduced in terms of solid compressibility to describe the irreversible mesoscopic infiltration and reversible preform compaction processes. As a main result a coupled displacement–pressure, geometrically nonlinear, finite element simulation tool is developed. The paper is concluded with a numerical example, where a relaxation–compression test of a planar fluid filled VBO preform at globally un-drained and partly drained conditions is considered.

1. Introduction

Traditional processing of high quality composite materials requires autoclave consolidation and curing at elevated pressure and temperature. Composite parts cured inside an autoclave have excellent quality; however, this quality comes with a high price tag. Recent developments in prepreg technology have led to the development of an Out-Of-Autoclave (OOA) prepreg that can be cured with only vacuum pressure and lower temperatures [1]. Vacuum Bag Only (VBO) prepregs are a member of the family of OOA techniques for composite manufacturing in which composite laminates are produced from prepregs by vacuum-bag consolidation followed by curing in an oven [2]. The advantages of VBO over autoclave processing are lower capital investment, elimination of the need for costly nitrogen gas, greater energy efficiency and reduction of size constraints (larger parts) [3].

As the resin flow through fiber bed is often the single most important processing step in composites manufacturing, it has been investigated by many researchers [4]. Many efforts in modeling flow and infiltration have been carried out by assuming that the different scales are treated in an uncoupled fashion and the fiber bed often assumed stationary, cf. e.g. [5–9]. Moreover, it is well established [10] that a true processing operation will result in dual-scale flow, resulting in a number of successful attempts to predict the study of the dual scale flow [11–19]. Unfortunately, only a few of these have focused on the fiber bed saturation coupled to the motion of the fiber bed and resin flow [10,20–24]. In this context, we note that both VARI as well as consolidation of VBO prepregs is due to external pressure at elevated temperature resulting in coupled resin flow and fiber bed deformations. In addition, during this process two coupled flows may be present: inter- and intra-ply (bundle) flows [25,26]. The inter-ply flow is the flow through the wide channels between the plies, whereas the flow between the fibers inside the plies is the intra-ply flow. Presently there are only few publications that can handle resin flow and fiber bed deformations and also limited number of publications onto the modeling of two-scale processes. Unfortunately, to the authors' knowledge, there are no published models capable of simultaneous modeling of the coupled deformations–flow at two different scales in the finite strain regime.

Larsson et al. [27] proposed a method to predict the consolidation involving coupled micro- and macro-resin flow based on a two-phase porous media theory formulation. The considered processes involve deformation of a fiber bed network at completely un-drained conditions, wetting by penetration of resin into fiber plies, and resin flow (affine with the preform velocity) through the fiber bed network. In the present work we extend the developments in [24,27] to allow for more general (anisotropic) resin flow at drained conditions. Similarly to [27] the emphasis is placed on

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the modeling of solid compressibility, due to micro-level wetting and volumetric change of the fiber network, and the modeling of macroscopic resin flow in the deforming preform.

The paper is outlined as follows: (1) the involved micro-constituents are identified and expressed using the relevant variables at the micro-level; (2) the governing equations of a biphasic compressible theory of porous media are reiterated; (3) the associated entropy inequality is considered in terms of three independent dissipative mechanisms: (i) deformation of the solid phase, (ii) intrinsic compressibility in the solid phase and (iii) Darcian interaction between the phases; (4) the dissipations in the solid phase are derived at a micro-mechanical level, and a model for the irreversible wetting process is established in terms of a logarithmic intrinsic compaction strain in the solid phase. In this development, an exponential packing law, cf. [28], is proposed to link the fluid pressure to the intrinsic compression of the solid phase. Moreover, to describe the wetting process, a linear visco-elastic evolution law is proposed for the evolution of wetting, whereby positive dissipation can be ensured; (5) the boundary value problem is formulated with respect to nonlinear kinematics and drained conditions; (6) the paper is concluded by a numerical example of the volumetric deformation–pressure response of a fluid saturated fiber composite specimen. To simplify the analysis in the example the preform is considered isotropic in terms of a linear shear stiffness and power law type of response for the volumetric deformations.

2. Micro-constituents and solid phase compaction

To begin with, let us establish the link between micro- and macro constituents in terms of a representative mixture (having volume V) consisting of three different micro-scale constituents, as depicted in Fig. 1. The micro-constituents of the mixture are the following:

- Incompressible solid particles, p with the volume fraction $\phi^p = V^p/V$, representing the fibers.
- Incompressible liquid constituent, l with the volume fraction $\phi^l = V^l/V$, representing the resin.
- Voids, v with volume fraction $\phi^v = V^v/V$, embedded in the fiber plies.

In order to ensure that each representative control volume of the solid is occupied with the fluid and solid/void mixture where we have the saturation constraint

$$\phi^p + \phi^l + \phi^v = 1. \tag{1}$$

We also relate to the two-phase porous media theory, where the micro-constituents are considered homogenized. In particular, the macroscopic volume fractions for the solid and the fluid phases, n^s and n^f, are defined as

$$n^s = \frac{V^s}{V} = \frac{V^p + V^v}{V}, \quad n^f = \frac{V^f}{V} = \frac{V^l}{V}. \tag{2}$$

In view of Eq. (1), we also have the saturation constraint

$$n^s + n^f = 1 \quad \text{with} \quad n^s = \phi^p + \phi^v \quad \& \quad n^f = \phi^l. \tag{3}$$

As to the modeling of fluid infiltration of fiber plies, the partially saturated fibers (named particles) are subdivided into a wet portion (already penetrated by resin fluid) and a dry portion ϕ^{pd}, as shown in Fig. 2. Hence, the fiber content ϕ in the dry region of the fiber bed is obtained as

$$\phi = \frac{\phi^{pd}}{\phi^{pd} + \phi^v}, \tag{4}$$

where the particle portion is defined by wet particles and dry particles, in terms of a saturation ratio ξ defining the degree of wet out within a representative fiber ply, defined by

$$\xi = \frac{\phi^p - \phi^{pd}}{\phi^p}, \tag{5}$$

whereby the fiber content ϕ in the dry region can be resolved as

$$\phi = \frac{\phi^p - \xi\phi^p}{n^s + \xi\phi^p}. \tag{6}$$

Observing that in the typical vacuum assisted process the influence of pore gas contribution in the mass balance can be neglected, leads to the relation $n^s\rho^s = \phi^p\rho^p$ whereby Eq. (6) becomes

$$\phi = (1-\xi)\left(\frac{\rho^p}{\rho^s} - \xi\right)^{-1}. \tag{7}$$

where ρ's are the densities. It may be noted that we have the initial condition at $\xi \to 0$ leading to $\phi_0 = \rho^s_0/\rho^p$. We thereby also have $\rho^s \to \rho^s_0/\phi_0$, which in combination with Eq. (7) gives the compaction of the solid phase as a function of irreversible wetting factor ξ and the reversible packing volume fraction ϕ in terms of

$$\frac{\rho^s_0}{\rho^s} = \frac{\phi_0}{\phi}\,\frac{1-\xi(1-\phi)}{1-\xi(1-\phi_0)}(1-\xi(1-\phi)). \tag{8}$$

Taking the logarithm of Eq. (8) yields the additive decomposition of the total compaction strain ε as

$$\begin{aligned}\varepsilon &= \log\left[\frac{\rho^s_0}{\rho^s}\right] = \log\left[\frac{\phi_0}{\phi}\,\frac{1-\xi(1-\phi)}{1-\xi(1-\phi_0)}\right] + \log[1-\xi(1-\phi_0)] \\ &= \varepsilon^e + \varepsilon^p,\end{aligned} \tag{9}$$

where the reversible compaction strain ε^e (related to the packing ϕ and the saturation degree ξ) and the irreversible wetting compaction ε^p (related only to the saturation degree ξ) are defined.

3. A homogenized theory of porous media

Assuming that the void motion is affine with the particle motion, the micro problem of three actual constituents in the mixture

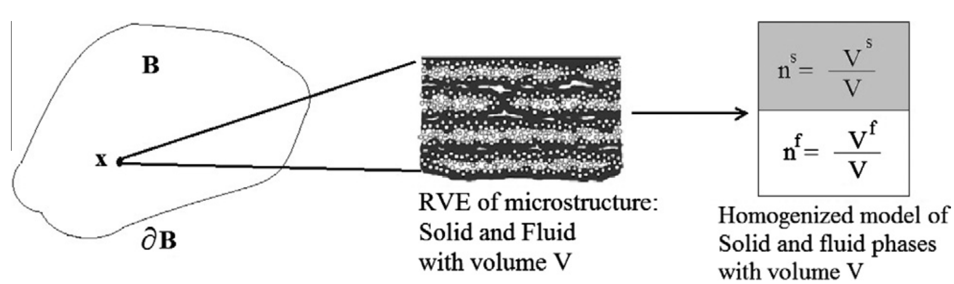

Fig. 1. Homogenized theory of porous media.