MODELLING MULTIPLE SCALES IN COMPOSITES MANUFACTURING

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ABSTRACT: In this contribution, we develop a generic two-phase porous media continuum and the associated FE implementation aimed for modelling simultaneous sub-processes accruing at different spatial and temporal scales. The development is based on our previous work [1], where focus has been on coupling the preform deformation on different scales to the process of micro infiltration. In this work, we extend the previous developments with respect to the Darcian interaction on the macro scale. The background idea is to identify a set of relevant phases, i.e. solid and fluid, and assign a separate continuous medium to each phase. The result is a set of overlapping continuous media, each having its own density-, velocity- and stress field on the macroscopic scale. In addition, we allow for phase compressibility and introduce internal variables to describe irreversible micro-processes in the system, such as microscopic infiltration. A coupled displacement-pressure, fully non-linear, finite element model is presented. The approach is applied to a representative numerical example, displaying the relevance of the involved sub-processes.

KEYWORDS: two-phase continuum, finite strains, hyperelasticity, wetting, Darcian interaction, poromechanics.

INTRODUCTION

One of the current trends in composites manufacturing is to cut down on the number of operations required to produce a component. For example, all of the steps of impregnation, consolidation, forming into shape and curing (or solidification) may be combined in a single processing operation, such as is the case of commingled yarn based composites [1] and Engineered Vacuum Channel (EVaC) prepregs [2], cf. Fig. 1. This leads to increasingly complex operations, with many sub-processes occurring simultaneously on different spatial and temporal scales. Today, all the individual sub-processes are reasonably well understood. However, the modelling of the complex problems that occur in a real operation, involving several coupled processes on different length and time scales, received only very limited attention [3-5].

The purpose of the present work is to extend the developments in [1] towards a more general formulation by accounting for macroscopic level Darcian flow. Consistently with the previous formulation, of particular interest is the modelling of solid compressibility due to void exclusion by the wetting process. In this context, we formulate the phase compressibility via mass balance in terms of logarithmic strain measures, cf. [6]. This formulation is paralleled by the proper formulation of Darcian resin flow and development of the governing equations of a biphasic compressible continuum. The paper is concluded by a couple of numerical examples of the coupled deformation-pressure response of a partially saturated fibre composite specimen.

THEORETICAL DEVELOPMENT

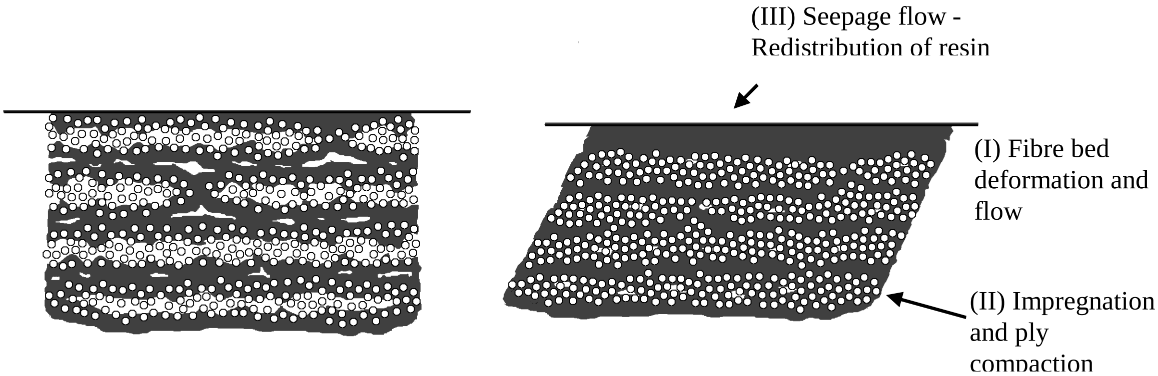


Fig. 1 The assumed manufacturing operation

Consider a representative volume of the composites mixture, as depicted in Fig. 1, consisting of three different constituents at the micro scale: incompressible particles *p* representing the fibres, an incompressible liquid *l* representing the resin and a void space *v* associated with the fibres. Of course, the constituent volume fractions must obey the saturation constraint, i.e.

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

We relate the micro constituents to the continuum phases by assigning the particles and the associated voids to the solid phase $n^s = \phi^p + \phi^v$ and the resin to the fluid phase $n^f = \phi^l$. Also, we distinguish the average particle (fibre) volume ϕ^p and the local particle (fibre) volume within a bundle or a ply and designate it ϕ. Finally, we define a ratio between dry particles and all of the particles ξ to describe the degree of wetting and observe that void exclusion by the wetting process will result in intrinsic compressibility of the solid phase.

Motivated by the above observation, we thereby focus to the formulation of a binary continuum, consisting of a *compressible* solid phase *s* and an *incompressible* fluid phase *f*. It is also assumed that each spatial point of the current configuration is simultaneously occupied by the solid and fluid material particles from different reference configurations, i.e. during deformation the particles move via individual deformation maps and associated velocity fields. Hence, the relative velocity between the phases is introduced as $v^r = v^f - v^s$. Moreover, in accordance with standard continuum jargon we introduce the deformation gradient **F** and its Jacobian *J* associated with the solid deformation map as

$$\mathbf{F} = \varphi\left(\mathbf{x}^s\right) \otimes \boldsymbol{\nabla} \text{ and } J = \det\left(\mathbf{F}\right), \tag{2}$$

where φ is the solid deformation map.

In the following paragraph, we give a brief review of the governing equations for the binary continuum in terms conservation of mass and entropy inequality, for further details and the development of momentum and energy balances see e.g. [6]. Following development in [6] the total mass balance of the binary mixture with compressible solid phase is obtained as

$$\boldsymbol{\nabla} \cdot \mathbf{v}^s - n^s \dot{\varepsilon} = -\boldsymbol{\nabla} \cdot \mathbf{v}^d , \tag{3}$$

where ε is the intrinsic compaction of the solid phase defined as

$$\varepsilon = \log\left(\frac{\rho_0^s}{\rho^s}\right), \tag{4}$$

and $v^d = n^f v^r$ is the Darcian velocity. Similarly, the entropy inequality for the mixture pertinent to isothermal behavior is obtained as

$$\mathscr{D} = \dot{\hat{e}} - \dot{\hat{\psi}} + \rho^f \mathbf{v}^d \cdot \boldsymbol{\nabla} e^f \geq 0 , \tag{5}$$

where e is the internal energy, ψ is the free energy, and the “hat” designates mixture. Upon introduction of momentum and energy balances into (5), the entropy inequality is finally obtained as

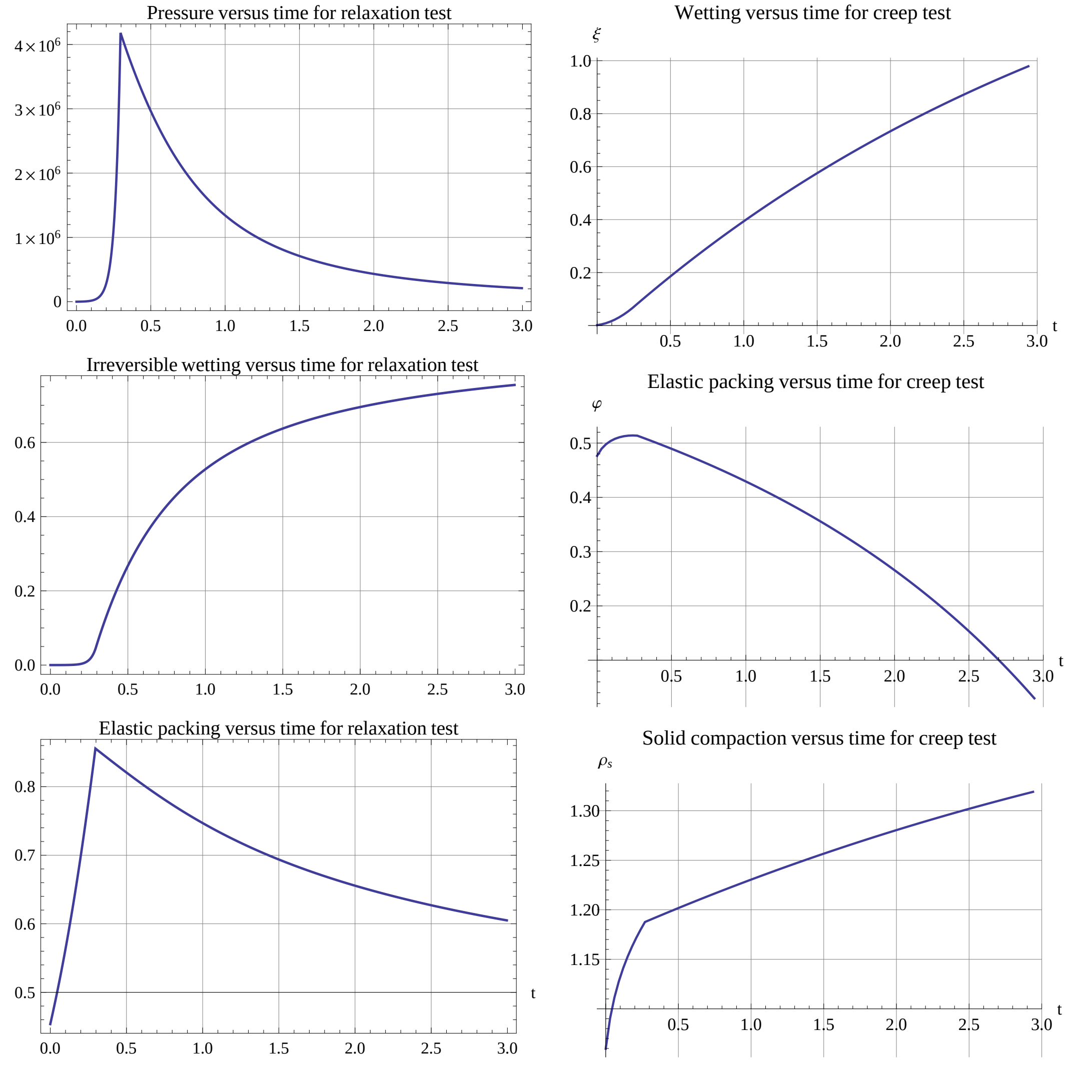
$$\mathscr{D} = \boldsymbol{\sigma}^s : \mathbf{l}^s - n^s p^f \dot{\varepsilon}^s - \hat{\rho}\dot{\psi} + \mathbf{v}^d \cdot \left(\rho^f \mathbf{g} - \boldsymbol{\nabla} p\right) \geq 0 , \tag{6}$$

where $\mathbf{l}$ is the spatial velocity gradient. The total mechanical dissipation may be interpreted in terms of a few independent mechanisms. In particular, the three first terms are due to the dissipation produced by the solid phase considered as independent from the dissipation induced by drag interaction between the phases (the fourth and last term).

The constitutive equations are established by distinguishing the different types of dissipative mechanism of the total dissipation, Eq. (6). Those however follow the development in [7] and will not be reiterated here. In the FE solution the weak form of the momentum balance for the mixture of solid and fluid phases and mass balance are considered. In order to solve the non-linear governing equations, the weak form of the internal virtual work and mass balance are linearised and discretised using standard finite element procedures. The route is similar to the one outlined in [6], where the problem is solve monolithically using total Lagrangian finite strain approach.

NUMERICAL EXAMPLE

In the following example the developed methodology is used for studying constitutive response at a material point. Since, for the material point response the phase interaction is difficult to evaluate and assess, the present discussion is specialised to the undrained conditions. A more exhaustive evaluation of the model including phase interaction will be discussed at the conference.



a) relaxation test b) creep test

Fig. 2 Numerical example.

Table 1 Material parameters used in the example

Parameter	ϕ_0	p_0	μ	α
Value	0.45	1 kPa	5.5 MPa·s	12

Consider the relaxation and creep tests displaying the intriguing mechanics of the micro-infiltration process for the parameters in Table 1, where ϕ_0 the fibre volume fraction in undeformed configuration, p_0 is the configurational fluid pressure in the initially non-saturated representative preform, $\mu = \eta / K$ is viscous resistance where K is the permeability and η is the resin viscosity and α is a power law exponent, for further details on the models and parameters see e.g. [1, 7]. The results from the relaxation test are shown in Fig. 2a, for a prescribed compaction step $\varepsilon = -0.65$ (corresponding to $\rho^s = 1.9\rho_0^s$) with the rate $\dot{\varepsilon} = -2.16\,s^{-1}$. We note the initial elastic packing in Fig. 2 yielding an increase of the fibre content ϕ up to approximately 90%. Associated with the initial elastic packing, the fluid pressure builds is up to a level of 4MPa. Thereafter the compaction is held fixed and relaxation occurs due to wetting of the fibres as shown in Fig. 2a. Similar results are displayed in Fig. 2b for a creep test, carried out using the same material parameters as in the relaxation test. In this case the loading consists of a prescribed pressure $p = 1.5\,MPa$ applied with the loading rate $\dot{p} = 1.62\,MPa/s$. Initially, the main response is elastic, corresponding to a slight build-up of fibre content. During the process, wetting continue until almost complete wet-out is obtained after t = 3s. The corresponding solid phase compaction is also shown in Fig. 2b.

CONCLUSIONS

The main contribution of the present work is a framework for modelling interactions between different physical processes at different temporal and spatial scales. Using this framework, the existing constitutive model has been adapted, implemented into a finite element code and demonstrated using simple example.

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REFERENCES

1. R. Larsson, M. Wysocki and S. Toll, Process-modelling of composites using two-phase porous media theory, *European Journal of Mechanics part A/Solids*, Vol. 23, pages 15-36 (2004)
2. S. Thomas, C. Bongiovanni and S.R. Nutt, In situ estimation of through-thickness resin flow using ultrasound, *Composites Science and Technology*, Vol. 68 pages 3093–3098 (2008)
3. K.M. Pillai, C.L. Tucker and F.N. Phelan, Numerical Simulation of Injection/Compression Liquid Composite Moulding. Part 2: Preform Compression. *Composites: Part A*, Vol. 32 pages 207-220 (2001)
4. M Li and C.L. Tucker, Modelling and Simulation of Two-Dimensional Consolidation for Thermoset Matrix Composites. *Composites Part A*, Vol. 33 pages 877-892 (2002)
5. P. Hubert, R. Vaziri and A. Poursartip, A two-dimensional flow model for the process simulation of complex shape composite laminates, *International Journal of Numerical Methods in Engineering*, Vol. 44 pages 1–26 (1999)
6. J. Larsson, and R. Larsson, Non-linear analysis of nearly saturated porous media - Theoretical and numerical formulation, *Computational Methods in Applied Mechanical Engineering*, Vol. 191 pages 3885-3907 (2002)
7. M. Wysocki, Continuum modelling of composites consolidation, *PhD thesis ISBN/ISSN 91-7291-874-8 at Chalmers University of Technology*, Department of Applied Mechanics (2006)