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HYPERELASTIC CONSTITUTIVE MODELS FOR CONSOLIDATION OF COMMINGLED YARN BASED COMPOSITES

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SUMMARY: Pressure driven consolidation of a component made from a commingled yarn composite is modelled and simulated. A finite-element code is developed based on a novel two-phase continuum framework. Constitutive equations governing the forming process are developed. These are the effective stress response of the preform, compaction of the solid phase, and Darcian interaction between the phases. Particular attention in this paper is paid to the tension-compression asymmetric response of the fibre skeleton. The applicability of the code to complex geometries is demonstrated by analysis of the consolidation, i.e. resin infiltration and preform deformation, of an axisymmetric filament wound GF/PP pressure vessel. In conclusion, the consolidation of the vessel is prevented by the loading mode where the pressure is applied on the interior. To succeed in manufacturing of this type of pressure vessel, a use of a loosely wound preform that allows extension in the fibre direction is suggested.

KEYWORDS: thermoplastics, consolidation, forming, hyperelasticity, finite deformation, two-phase continuum, micro-mechanics, Finite Elements (FE)

INTRODUCTION

Thermoplastic matrix composites are considered the composites of the future. However, their use has been hampered by the difficulty encountered in their fabrication, i.e., thermoplastic polymers exhibit significantly higher viscosity than thermoset resins. This may be illustrated by an analogy with the difference between the flow properties of honey and water.

Composite manufacture involves wetting a very large fibre area. Consequently, the difficulty experienced in the manufacture of thermoplastic matrix composites is related to the polymer flow and impregnation of the reinforcing fibres. Manufacturing processes to mitigate this problem have been developed by Gibson and Månson [1], where processing of the composite is carried out in two steps: pre-impregnation and moulding. The pre-impregnation yields a semi-product, in which the thermoplastic has been dispersed in the fibre network, minimising the distance the polymer must flow to wet the fibres, yet no wetting has taken place, which keeps the semi-product flexible. Commingling of thermoplastic fibres with the reinforcing fibres is a promising route for pre-impregnation, see Fig. 1, featuring relatively high and uniform pre-impregnation quality at low cost.

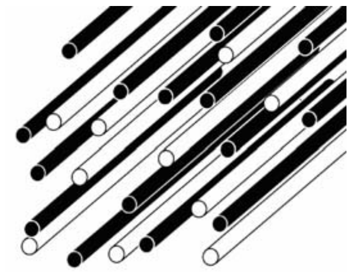


Fig. 1 Pre-impregnation by commingling thermoplastic (black) and reinforcing (white) fibres.

The consolidation of commingled yarn composites, in all its complexity, is a multi-process problem. To tackle this challenge, a continuum thermodynamic framework has recently been developed in Larsson et al. [2]. In Wysocki et al. [3], the framework was extended by establishing constitutive equations governing the wetting of commingled yarn based composites. In Wysocki et al. [4] we introduced an experimental method to study the overall preform deformation separately from the wetting and compaction of individual bundles. Finally, in Wysocki [5] a constitutive equation for the tension-compression asymmetric response of a fibrous preform was proposed.

The objective of this work is to present constitutive equations for anisotropic fibre preform, introduce them into the two-phase continuum framework developed earlier in [2], solve an arbitrary boundary value problem using finite element method and, finally, demonstrated it by simulating the consolidation of an axisymmetric commingled-yarn filament wound pressure vessel.

CONSTITUTIVE MODELS

In Larsson et al. [3] we identified four primary deformation processes, as illustrated in Fig. 2. These are (I) elastic interactions within the preform, (IIa) compression and (IIb) wetting of individual fibre bundles, and (III) resin flow between bundles, i.e., macroscopic drainage. A constitutive assumption was made that the hydrostatic fluid pressure governs the bundle level processes, while the macroscopic tractions govern the preform level processes. Therefore, we assume that (1) there is no coupling on the constitutive level between the preform (fibre network) deformation in terms of the right Cauchy-Green deformation tensor **C** and the intrinsic compaction ε, (2) the anisotropy may be represented using a structure tensor denoted **M**, and (3) the intrinsic compaction due to matrix infiltration may be represented as an internal variable denoted ε^v. As a consequence, the Helmholtz free energy ψ possesses the following additive structure:

$$\psi = \psi\left(\mathbf{C}, \mathbf{M}, \varepsilon, \varepsilon^{v}\right) = \psi^{1}\left(\mathbf{C}, \mathbf{M}\right) + \psi^{2}\left(\varepsilon, \varepsilon^{v}\right). \tag{1}$$

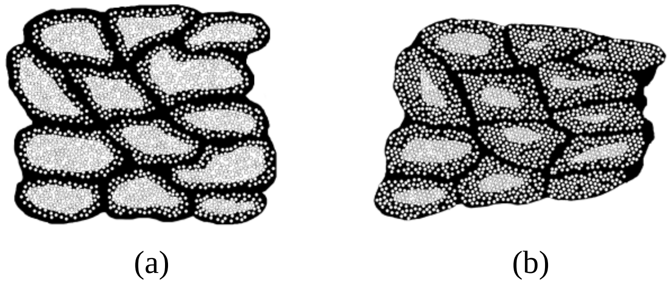


Fig. 2 Elastic deformation and viscous flow between and within the bundles:
(a) undeformed and (b) deformed configuration.

The anisotropic part of the free energy is assumed to be caused by longitudinal fibre stretch. We choose to use the square of fibre stretch in each fibre family, i.e., the first mixed invariant of the tensors $\mathbf{C}$ and $\mathbf{M}_i$:

$$I_{4i} = \mathbf{C} : \mathbf{M}_i , \tag{2}$$

where $\mathbf{M}_i = \mathbf{A}_i \otimes \mathbf{A}_i$ is the structure tensor (no summation over *i*) and $\mathbf{A}_i$ is a set of directors in the reference configuration, one for each family of parallel fibres *i*. We also assume that a contribution from one fibre family does not influence the contribution from other fibre families, i.e., that the total anisotropic response is simply a sum of individual fibre family responses. This leads to a free-energy of the following form:

$$\psi^{1}\left(\mathbf{C}, \mathbf{M}\right) = \psi^{vol}\left(\mathbf{C}\right) + \sum_{i=1}^{N} \psi_i^{\|}\left(I_{4i}\right) \cdot \tag{3}$$

i.e., the anisotropy arises through the invariant I_{4i} only

Fig. 3 Axial deformation of aligned fibres: (a) tension and (b) compression.

In [5] a constitutive model for the axial fibre contribution based on the phenomenological observation that the fibre exhibits two distinct response regimes, one due to tensile loading and one due to compressive loadings, cf. Fig. 3, was developed. It was assumed that the response in the tensile regime is governed by the tensile stiffness of the fibres while the compressive regime is governed by fibre buckling. There may also be a transition from the compliant compressive behaviour to the stiff tensile behaviour.

The free energy for the axial fibre contribution proposed in [5] has the following form:

$$\psi_i^{\parallel} = \phi_{0i}^p \Upsilon_i W\left(I_{4i}, \upsilon_i, \vartheta_i\right), \tag{4}$$

where Υ_i is a stiffness parameter of the i^{th} fibre family, ϕ_{0i}^p is the particle volume fraction in reference configuration of the i^{th} fibre family, subject to the condition $\phi_0^p = \sum_{i=1}^{N} \phi_{0i}^p$, N is the number of fibre families and $W\left(I_{4i}, \upsilon_i, \vartheta_i\right)$ is a tension-compression asymmetric function defined as

$$\begin{aligned} W\left(I_{4i}, \upsilon_i, \vartheta_i\right) &= \frac{1}{2\pi}\left(\left(I_{4i} - \vartheta_i\right)^2 - \upsilon_i^2\right)\arctan\left(\frac{I_{4i} - \vartheta_i}{\upsilon_i}\right) \\ &+ \frac{\left(I_{4i} - \vartheta_i\right)}{4\pi}\left(\pi\left(I_{4i} - \vartheta_i\right) + 2\upsilon_i\left(1 - \ln\left(1 + \frac{\left(I_{4i} - \vartheta_i\right)^2}{\upsilon_i^2}\right)\right)\right), \end{aligned} \tag{5}$$

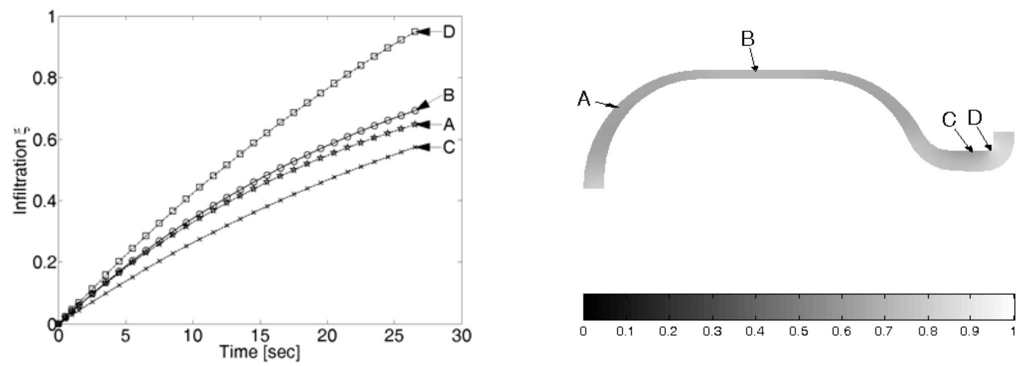
where the parameter υ_i determines the width of the tension-compression transition and $I_{4i} = \vartheta_i$ is the stress free state.

Considering the other contributions, we simply refer to Larsson et al. [2], where they have been through described. As for the constitutive equations for the fibre bundle response due to the wetting process, they were established in Wysocki et al. [3], assuming a compressible solid phase consisting of fibres plus intra-fibre void. The compaction of the solid phase was caused by a combination of matrix infiltration and elastic compression of the fibre bundles. Complete derivations can be found in [3].

NUMERICAL EXAMPLE

In the present example, the finite-element analysis of undrained consolidation of the axisymmetric Twintex ® based pressure vessel, is considered. The computational finite element model consists of 334 CST-elements. The preform is assumed to be filament wound layered structure consisting of two fibre families in each layer at an angle of ±55° (the optimal winding pattern of an ideal pressure vessel [5]) on a liner made from cross-linked PE. We also investigate the effect of oversizing the preform (by loosely winding) to allow stress free infiltration. The pressure vessel is assumed to be consolidated at 8 bars using autoclave type process. The consolidation pressure is applied on the inner surface of the preform in order to avoid fibre wrinkling. The outer boundary, representing a rigid tool, is constrained in all degrees of freedom. The material parameters are from a series of tests performed on the GF/PP Twintex R PP 75 AF commingled yarns in [3-5] at a temperature of 190°C.

RESULTS



(a) (b)

Fig. 4 Evolution of infiltration and snapshot taken at t = 28 sec for the loosely wound preform.

The results for the tightly wound preform (not shown in this report) indicates that, due to the fibre tensioin unloading the fluid pressure, the pressure vessel is exceptionally difficult to consolidate. Therefore, only the results for the oversized, loosely wound, preform will be presented, see Fig. 4. The degree of infiltration in the loosely wound vessel is on average between $0.65 \le \xi \le 0.85$, except in the vicinity of C, where $0.62 \le \xi \le 0.65$, and D, where $0.85 \le \xi \le 0.95$. The absence of fibre response in the oversized preform is modelled by setting the parameter $\Upsilon = 0$. The stretch in the fibre direction, however, can still be calculated as shown in Fig. 5, and may be interpreted as the spatial distribution of the required minimum fibre excess length that is needed for consolidation without fibre tension.

CONCLUDING REMARKS

The preform is wound using a constant winding angle of ±55°, the optimal angle for carrying a pure internal pressure load. Therefore, it is expected that the tightly wound preform should be difficult to consolidate. Indeed, the consolidation of the whole vessel, except at the opening, is prevented by the loading mode where the pressure is applied on the interior. To succeed in manufacturing of this type of pressure vessel we suggest using a loosely wound preform that allows extension in the fibre direction. The proposed model provides the spatial distribution of the fibre excess, needed for consolidation without fibre tension, cf. Fig. 5. On average, a 2 % oversize should be sufficient for consolidation without fibres constraining the process.

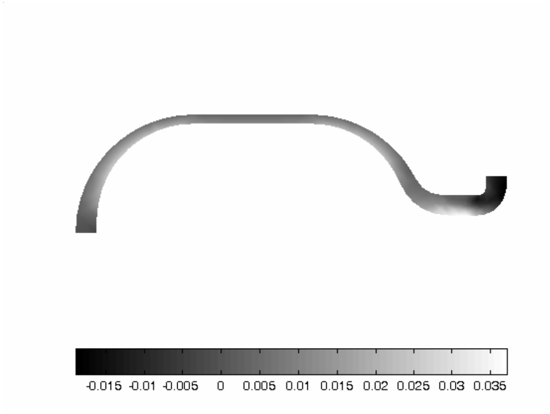


Fig. 5 Snapshot of the stretch in the fibre direction calculated for the loosely wound preform.

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