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Unidirectional compression of fibre reinforcements. Part 1: A non-linear elastic-plastic behaviour

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Abstract

Liquid composite moulding processes are increasingly used to manufacture composite structures. Such processes combine compression of the fibre reinforcements (in dry and/or lubricated states) and resin flow. A better modelling of the compression of fibre reinforcements would improve the accuracy of hydro-mechanical coupling modelling involved in these processes. Several models are available in the literature, but none of them consider permanent deformations (such as plasticity). This article presents a methodology to measure plasticity of fibre reinforcements in dry and impregnated states. Also a non-linear elastic-plastic model, including large deformations, is proposed for unidirectional compression. Results on glass fibre reinforcements are presented and discussed.

Keywords: Unidirectional compression; Finite strains; A. fabrics/textiles; Elastoplasticity

1. Introduction

Structural composite materials are increasingly produced using liquid composite moulding (LCM) manufacturing techniques. During such processes, dry fibre reinforcements are placed into a rigid half mould, which is closed either with another half mould for resin transfer moulding (RTM) or with a flexible bag tooling for vacuum assisted resin transfer moulding (VARTM) for instance. The common feature between such processes is that the fibre reinforcement will be compacted. Then a flow is created to force the liquid resin through the fibre reinforcement. Positive pressure is used for RTM whereas vacuum is used during VARTM. Once the resin has impregnated the fibre reinforcements and has cured, the part can be demolded.

Two types of fibre reinforcement compressive deformations can occur and be observed during processing: controlled and induced deformations. The deformation is qualified of “controlled” during RTM, for example, when the top half of the mould comes into close contact with the reinforcement and compresses it until reaching the desired thickness.

Induced deformations happen for most of LCM processes. During monolithic composite RTM manufacturing, the use of pressure-driven flows on dry fibre reinforcements can generate a force on the fabric surface that may deform [1]. In the case of sandwich structures manufacturing using RTM, besides the initial compression during mould closing of both core and skin reinforcements, the core can also be further compressed (e.g., deformable cores such as polymeric foams) [2,3] and even shifted away during the filling stage [3,4]. During those processes, involving hydro-mechanical coupling, once the reinforcement is impregnated, it will continue to deform and eventually, when the injection is completed, it may not fully recover [3,4]. Induced deformations can also be present during processes such as VARTM. Recent studies have shown that the part thickness evolves during the resin filling. Moreover the final part thickness is not necessarily uniform and is always

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Nomenclature

A	sample planar area in the deformed configuration
A_0	sample planar area in the reference configuration
C	elastoplastic compression tangent modulus of the fibre reinforcement in the z-direction
C^e	elastic compression tangent modulus of the fibre reinforcement in the z-direction
$\mathbf{E}$	Green strain tensor
$\mathbf{E}^e$	elastic strain tensor
$\mathbf{E}^p$	plastic strain tensor
$\mathrm{d}\boldsymbol{f}$	force acting on a deformed area element
$\mathrm{d}\boldsymbol{f}_0$	transformed force acting on the corresponding reference area element
F	resultant force applied to the sample in the z-direction
$\mathbf{F}$	deformation gradient tensor
h	sample height in the current configuration
h_0	initial sample height
H	hardening compression modulus of the fibre reinforcement in the z-direction
$\mathbf{I}$	identity tensor
M	material point
$\mathbf{n}$	normal vector on the deformed configuration
$\mathbf{n}_0$	normal vector on the reference configuration
S	surface in the deformed configuration
S_0	surface in the reference configuration
$\mathbf{u}$	displacement
x, y, z	cartesian coordinates
α	relative shortening in the z-direction
λ	nominal stress applied to the fibre reinforcement in the z-direction
$\mathbf{\Pi}$	first Piola–Kirchhoff stress tensor
$\mathbf{\Sigma}$	second Piola–Kirchhoff stress tensor

larger at the gate than at the vent because of the mechanical equilibrium between the reinforcement stress, liquid pressure, vacuum and atmospheric pressure [5,6].

A proper modelling of the processes previously cited, especially estimating the final thicknesses of the manufactured parts, for instance, requires constitutive laws for compression of fibre reinforcements in dry and lubricated states. Such models should also take into account the different loading and unloading behaviours of the reinforcement. Numerous experimental studies have been performed for transverse compression of fibre reinforcements [7–12]. It is well known that the compression curves (pressure vs. fibre volume fraction or thickness) display a non-linear behaviour. Also, depending on the compression speed, the compression curves can be shifted revealing viscoelastic behaviour. However, Saunders et al. mentioned that, for a dry plain-woven fabric, the compression exhibits no changes with compression speeds ranging from 0.05 to 1 mm/min [11]. Also Rudd et al., working on dry glass fibre reinforcements (continuous filament random mat and quasi-unidirectional), observed that there was no significant change of compaction behaviour for compression speeds between 2 and 10 mm/min even with the presence of binder [9].

Researchers attempted to model fibre reinforcement submitted to transverse compression using power laws [8]. Other studies proposed non-linear elastic models usually based on micromechanics, where fibre bundles or fibres are assumed to behave such as elastic beams [12–14]. Those models lead to a relationship between applied pressure and fibre volume fraction and have several empirical parameters to fit to the experimental data. Other studies focused on the viscoelastic and relaxation behaviours displayed by the fibre reinforcement using a Maxwell–Wiechert viscoelastic model [15] or a non-linear viscoelastic model [16].

During VARTM, when the vacuum is initially applied to the fabrics, the latter are submitted to compression. Then, when the resin infuses the part, the fibre reinforcement is gradually unloaded. Some recent studies focused on those loading and unloading behaviours. Rudd et al. applied another compression to a sample that had already been compacted. They noted that the reinforcement did not return to its initial thickness before recompaction. They concluded that the reinforcements displayed a pseudoplastic behaviour [9]. Another study showed that elastic and permanent deformations are very significant for continuous filament random mat and plain weave fabric compressions, while viscoelasticity remains less important [17]. Also because of the limited compression speeds, involved in VARTM for instance, viscoelastic effects can be considered limited. Even though numerous previous studies focused on fibre reinforcement compression modelling, none of them seemed to include permanent deformations.

Finally, during composites manufacturing, in order to obtain the desired fibre volume fraction, the fibre reinforcements are highly compressed. A 50% reduction of the fabric thickness (between the natural thickness and the final thickness) is quite usual. Therefore, the modelling of fibre reinforcements behaviour in compression does not comply with the small strains assumption and requires the use of a large deformation formulation.

Usually during composites manufacturing, the fibre reinforcements can be compressed and sheared in the three directions of space. However, in this study we focus on the unidirectional compression behaviour in order to discard shearing effects. Therefore, a non-linear elastic-plastic constitutive law for fibre reinforcement in compressive loading and unloading including finite strains is proposed. An experimental methodology is given in order to accurately measure the model's parameters. Results of the modelling