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An original approach for mechanical modelling of short-fibre reinforced composites with complex distributions of fibre orientation

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ABSTRACT

In this paper, an original and effective model of behaviour for short-fibre reinforced composites is presented. In particular, complex fibre distributions of orientation can be dealt with in a very easy way, without orientation averaging or additional homogenisation steps. The matrix material has elastoplastic damage behaviour with non-isochoric plastic flow. Ductile damage can be fully anisotropic depending on the reinforcement characteristics. The model is validated for the case of a polypropylene reinforced with short flax fibres. In addition, simulations are performed to investigate the influence of key parameters like fibre length and interfacial shear strength, as well as the impact of progressive debonding at the fibre tips.

1. Introduction

Short fibre reinforced composites (SFRC) are now widely employed for the production of load bearing pieces in many industrial sectors. It is therefore essential to define efficient models of behaviour in order to predict the mechanical response of SFRC. The fibre behaviour is generally assumed elastic, since the composite is quite likely to fail before the fibre stress reaches the yield stress. On the contrary, the matrix material can have complex elastoplastic behaviour and possibly compressible plastic flow (especially for polymers), viscous effects (viscoelasticity and/or viscoplasticity), ductile damage, etc. The modelling of the fibre/matrix interface is undoubtedly a key point when dealing with SFRC. Indeed, the interface properties govern the load transmission from the matrix to the fibres and fibre/matrix debonding is one of major damage phenomena of SFRC, together with matrix cracking and fibre breaking. Another challenge is to take complex fibre orientations into account [1].

Among approaches going beyond the framework of elasticity, the most appealing are unit-cell (UC) based methods and homogenisation procedures. A UC is made of a single fibre embedded in the matrix material, with volume proportions equal to those of the composite. A finite element (FE) model is built using two different kinds of material properties for the fibre and matrix media. FE simulations using different kinds of loading must be performed to characterise the behaviour of the UC. It is worth noting that any modification of the matrix and/or fibre behaviour therefore requires re-characterising the UC. The composite behaviour is finally computed by direction averaging over all existing fibre orientations. UC based methods are generally used to model SFRC with randomly oriented fibres [2,3]. Homogenisation procedures are originally based on inclusion-type problems; important improvements have been done by considering non-aligned fibres with two-step homogenisation procedures [4]. In a principle very close to UC based techniques, the first step consists in the homogenisation of a two-phase "pseudo-grain" with aligned fibres followed by the homogenisation of all pseudo-grains according to the fibre orientation properties. More recently, Kammoun et al. have taken damage phenomena into account in the two-step homogenisation procedure [5]. However, they adopt a purely deterministic approach that does not integrate the physics of damage mechanisms (evolution of damage is based on probability law of pseudo-grain failure). Brighenti et al. have developed a model that takes several damage mechanisms (matrix cracking, fibre orientation effect and debonding, etc.) into account for brittle matrix material [6,7]. To the authors' knowledge, a coupled elastoplastic-damage model of the matrix behaviour has never been considered for SFRC in association with other composite damage mechanisms.

The model presented in this paper aims to be an original and effective alternative to UC based techniques and homogenisation procedures to predict the behaviour of SFRC with complex fibres orientations. The matrix material has elastoplastic behaviour with non-isochoric plastic flow. Matrix ductile damage is also modelled in the framework of Continuum Damage Mechanics. Damage can be fully anisotropic depending on the reinforcement characteris-

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Nomenclature

List of symbols

A^α	fibre matrix of orientation
$\vec{a}^\alpha$	fibre vector of orientation
a	parameter of Ramberg–Osgood law (matrix)
$\mathbf{D}$	4th-order damage tensor (matrix)
$C - C_F^\alpha$	right Cauchy–Green tensors (composite material and fibre medium)
E_F–E_M	Young moduli (fibre and matrix)
$F - F_F^\alpha$	tensors of deformation gradient (composite and fibre medium)
g	law of evolution of fibre/matrix debonding
H–h	hardening law and variable
$\tilde{J}_2$	matrix effective von Mises equivalent stress
L^α – L_c	fibre length – critical length for fibre breakage
N	number of fibre media
n	parameter of Ramberg–Osgood law (matrix)
p	cumulative plastic strain
p_D	damage threshold
r^α	fibre radius
$\tilde{S}_M$	deviatoric part of matrix effective Cauchy stress tensor
S_n – S_s	damage parameters
T^α	transition matrix from fibre medium coordinate system to the global one
V	volume of the composite material
v_M	matrix volume fraction
v'_M	matrix volume fraction where damage remains isotropic
$v_F - v_F^\alpha$	total fibre volume fraction – fibre medium α volume fraction
Y_n – Y_s	strain energy release rates
δ	Kronecker's symbol
γ	parameter field governing pressure sensitivity of matrix plastic potential of dissipation
ε – ε^e – ε^p	total, elastic and plastic strain tensors (composite and matrix materials)
$\varepsilon_F^{\alpha 0} - E_F^{\alpha 0} - \varepsilon_F^\alpha$	one-dimensional Hencky and Green strains of fibre medium α – 3D Hencky strain tensor of fibre medium α
$\hat{\varepsilon}_F^{\alpha 0}$	one-dimensional Hencky strain of fibre medium α in case of partial debonding
ε_1–ε_2	material parameters governing the evolution of fibre/matrix debonding
ζ^α	non-null eigenvalue of tensor C_F^α
η	Drucker–Prager parameter governing pressure sensitivity of plasticity criterion (matrix)
θ	elevation angle of fibre orientation
Λ	plastic multiplier
v_M, v_p	matrix Poisson ratio and plastic Poisson ratio
ξ	parameter governing the asymmetry of the yield surface
ρ, ρ_M, ρ_F^α	densities of the composite, matrix material and fibre medium α
σ_M – $\tilde{\sigma}_M - \tilde{\sigma}_H - \tilde{\sigma}_y - \tilde{\sigma}_{eq}$	matrix actual and effective Cauchy stress tensors, hydrostatic and yield stress and effective Drucker–Prager equivalent stress
$\sigma_F^{\alpha 0}$	one-dimensional axial stress of fibre medium α
σ_0	parameter of Ramberg–Osgood law
τ^α	interfacial shear strength (IFSS)
Φ, Φ_M, Φ_F^α	Helmhotlz free energies of the composite, matrix and fibre medium
φ	azimuthal angle of fibre orientation
ψ^P – ψ^D	plastic and damage parts of the dissipation potential (matrix).

Exponent α refers to fibre medium α

tics. The SFRC is seen as the assembly of a matrix medium and as many fibre media as there are different fibre orientations, in which all media are linked by an additive decomposition of the state potential. Complex orientations can therefore be dealt with in a very easy way, with no need to perform orientation averaging or second homogenisation step. Different types of material behaviour (hardening law, compressibility, e.g.) and/or material parameters can be easily considered (no re-characterisation of the UC). In addition, FE simulations of complex specimens can be greatly simplified, with no need to define periodic boundary conditions.

The following section presents the constitutive equation of the SFRC behaviour model. It is validated in Section 3 for the case of tensile tests of a polypropylene reinforced with short flax fibres. The influence of key parameters like fibre length and interfacial shear strength as well as the impact of a progressive debonding at the fibre tips are discussed in Section 4.

2. Behaviour of elastoplastic damage matrix reinforced with misaligned short fibre

The composite material is seen as the assembly of a damageable elastoplastic matrix material (volume fraction v_M) and of N one-dimensional linear elastic fibre media (Young modulus E_F, total volume fraction $v_F = 1 - v_M$). Each fibre medium is characterised by a unit vector of orientation, $\vec{a}^\alpha$, that gives the fibre axis direction in the global system of coordinates, and by a volume fraction, v_F^α. The behaviour of each medium is solved successively before the composite behaviour is computed thanks to an additive decomposition of the state potential (cf Section 2.3).

2.1. Elastoplastic damage behaviour of the matrix material

The elastoplastic behaviour of the matrix material is described using the Drucker–Prager criterion for plasticity in the framework of non-associative plasticity. This way, different material response in tension and in compression, as well as non-isochoric plastic flow can be dealt with [8]. An isotropic ductile damage, which evolves with the plastic strain, is assumed for the neat matrix material. In the composite, the matrix damage can become fully anisotropic depending on the characteristics of the reinforcement. A 4th-order damage tensor, $\mathbf{D}$, is therefore introduced to link the actual (σ_M) and effective ($\tilde{\sigma}_M$) Cauchy stress tensors of the matrix material, with $\sigma_M = \mathbf{D}\ \tilde{\sigma}_M$, i.e. $\sigma_{Mij} = D_{ijkl}\tilde{\sigma}_{M\,kl}\ \forall ij$ (summation over k and l). It is assumed that each fibre medium governs the damage characteristics over the volume $v_F^\alpha V$ of the matrix material, V being whole volume of the composite material. Fibres' influence on matrix damage is modelled by intermediate damage tensors $\mathbf{D}^\alpha$, expressed in fibre medium coordinates system. The fibres are assumed to prevent the matrix damage in their direction of orientation (i.e. $\mathbf{D}^\alpha{}_{1111} = 1$). Moreover, the presence of the fibres can result in different mechanisms of damage in tension and shear [9]. Two independent scalar variables are therefore introduced: D_s acts on the deviatoric stress components and D_n acts on the hydrostatic stress. Based on these hypotheses, intermediate damage tensors, $\mathbf{D}^\alpha$, are expressed by $\mathbf{D}_{ijkl}^\alpha = \delta_{ik}\delta_{jl}\lfloor 1 - D_n\delta_{ij}(1-\delta_{i1}) - D_s(1-\delta_{ij})\rfloor$ [10]. Finally, the global damage tensor is expressed by assembling the