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Damage of short-fibre reinforced materials with anisotropy induced by complex fibres orientations

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ABSTRACT

In this paper, a behaviour model for damageable elastoplastic materials reinforced with short fibres that have complex orientations is proposed. The composite material is seen as the assembly of the matrix medium and several linear elastic fibre media. Its macroscopic behaviour is computed thanks to an additive decomposition of the state potential, with no need to implement complex methods of homogenisation. A 4th-order tensor that depends on the characteristics of each fibre medium is introduced to model the anisotropic damage of the matrix material induced by the reinforcement, as well as the progressive degradation of the fibre–matrix interface. The division of short fibres into several families means that complex distributions of orientation or random orientation can be easily modelled. The model is tested for the case of a polyamide reinforced with different contents of short-glass fibres with distributed orientations and subjected to uniaxial tensile tests in different loading directions. The comparison of the results with experimental data (extracted from the literature) demonstrates the efficiency of the model.

1. Introduction

The use of short-fibre reinforced composites (SFRC) is appealing because of the high rigidities of the fibres (e.g. about 70–80 GPa for glass fibres, more than 200 GPa for carbon fibres). The macroscopic behaviour of SFRC can be fully anisotropic depending on the content and the orientation of the short fibres diluted in the matrix material. Fibres orientation is not easy to control in the formation of SFRC, for instance when they are injection moulded. Micro-tomography analyses (Bernasconi et al., 2008) reveal that fibres are actually oriented following a distribution of orientations that depends on the production process and the fibre content. Some models of fibres orientation in injection moulded SFRC are available (Doghri and Tinel, 2006; Vincent et al., 1997).

In the framework of linear elasticity, simple macroscopic rules of mixture can be relevant to predict the tensile/flexural apparent rigidity of composites reinforced with aligned fibres. Furthermore, they can be enriched with corrective parameters to take into account the distributions of fibres length and orientation (Bowyer and Bader, 1972; Fu et al., 2000; Mouhmid et al., 2006, e.g.) and accurate descriptions can generally hold for arbitrarily complex load cases. However, understanding and modelling the behaviour of SFRC beyond the limits of linear elasticity is essential for industrial applications. Numerous interdependent phenomena influence the behaviour of SFRC until failure, starting with the development of a plastic flow in the matrix material. This can be responsible for ductile damage of the matrix material (void growth and coalescence), which is strongly influenced by the characteristics of the reinforcement. Phenomena such as fibre breakage, fibre debonding and pull-out may also occur. If the fibres length is lower than a critical value, which depends on the rigidity and the aspect ratio of the fibres in particular, fibre

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pull-out is generally predominant compared to fibre breakage during tensile loadings of SFRC (Bowyer and Bader, 1972; Fu et al., 2000, e.g.).

All these phenomena can obviously not be modelled by simple rules of mixture. More elaborate models consider the composite material as an assembly of representative elementary volumes (REV, or meso-regions) containing several phases. Generally, two phases are defined which represent the matrix material and the fibres. In an original way, Zaïri et al. (2008) introduce a third phase that represents the voids that develop at the interface because of fibre debonding. Finite element computations can be used to solve the mechanical behaviour over each REV. The macroscopic behaviour is then obtained by the integration in the total material volume of the mechanical quantities computed for each REV (Böhm et al., 2002). This method can however be costly because finite element models may require very fine meshes. An increasingly widespread approach, which does not need finite element simulation, consists in treating the multi-phase material as an inclusion-type problem, based on the theory originally developed by Eshelby (1957) and progressively improved. In particular, works of Mori and Tanaka (1973) deal with multi-inclusion materials by working on the basis of a type of collective interaction. The non-linear behaviour of the individual components can be linearised so that an approximate solution based on the original Eshelby solution (exact only when dealing with linear elasticity) can be found. An important point to consider is that only average data within phases are obtained. Fluctuations of mechanical fields within homogeneous phases can be analysed with second-order moment approaches (Ponte-Castañeda, 2002, e.g.). Approximate solutions can however be improved using self-consistent or Mori–Tanaka schemes (Mercier and Molinari, 2009; Schjødt-Thomsen and Pyrz, 2011). The inclusion-type problems can become very difficult to state in the case of reinforcements with non-aligned short fibres (i.e. when fibres are not all aligned in the same direction). To overcome this difficulty, Doghri and Tinel (2005) developed a procedure of homogenisation in two steps. The first one is the homogenisation of a two-phase "pseudo-grain", constituted of the matrix material reinforced with identical and aligned fibres; the second one consists in the homogenisation of all pseudo-grains to compute the mechanical properties at the RVE scale. All these contributions show the difficulty of implementing such procedures of homogenisation, and even multi-homogenisation, when dealing with complex behaviours and/or complex fibres orientation distributions. On the contrary, the present model aims at predicting the macroscopic behaviour of SFRC without any procedure of homogenisation (Notta-Cuvier et al., 2013). The composite material is simply seen as the assembly of a matrix medium and several fibre media, linked by an additive decomposition of the state potential (Section 2.3). In particular, complex fibres orientations (distributed or random orientations, e.g.) can be modelled in a simple way (Section 2.2).

Moreover, it is evident that the modelling of damage phenomena in SFRC deserves more thorough study. Recently, Kammoun et al. (2011) improved the two-step procedure of homogenisation by taking damage phenomena into account in the second step. However, damage is in this case evaluated in terms of "pseudo-grains failure", i.e. in a purely deterministic approach that does not integrate the physics of the damage mechanisms. Zaïri et al. (2008) model the damage of SFRC by a progressive degradation of the interface resulting in the development of a third phase of voids, as already mentioned, but they neglect matrix cracking, fibre pull-out and breakage. Other interesting approaches combine micromechanical and continuum damage mechanics (CDM) descriptions. For instance, Nguyen and Khaleel (2004) evaluate the effective and damaged stiffness tensors of composites reinforced with randomly aligned fibres using self-consistent and Mori–Tanaka schemes, applied to a reference aligned fibre composite and a distribution over all possible orientations. The evolution of the cracks in the elastic matrix material is then modelled using the CDM framework. Lee and Simunovic (2000) use the same type of approach but for elastoplastic matrix materials. Matrix cracking is not modelled but the composite damages because of progressive fibre debonding whose evolution is governed by a Weibull's probability distribution function.

In this paper, a strongly anisotropic ductile damage of the matrix material is modelled. The damage laws are developed in the framework of continuum damage mechanics. A 4th-order damage tensor is built based on the characteristics of the reinforcement (Section 2.1). All kinds of elastoplastic behaviour can be considered for the matrix material, including compressible plastic flow. Fibres have an elastic linear behaviour. The load transmission at the fibre–matrix interfaces is determined thanks to an adaptation of the theory of Bowyer and Bader (1972) to 3D cases and complex fibres orientations. Fibres debonding or pull-out are not strictly speaking modelled. However, the damaged parts of the matrix are seen as unable to transmit load, which can be interpreted as a progressive degradation of the interfaces. Computed macroscopic behaviours are compared to experimental data (extracted from the literature) for the case of a polyamide reinforced with different contents of misaligned short glass fibres and subjected to tensile loading in different directions (Section 3). The influence of the matrix damage is discussed in Section 4, as well as that of the fibres orientation and fibre content on the evolution of the damage variables.

2. Elastoplastic damage matrix material reinforced with short fibres with all kinds of orientations

The reinforced composite material is made of short fibres assumed to be uniformly dispersed in a damageable elastoplastic matrix. A fundamental assumption is that the fibres carry loads only in their direction of orientation. Their linear elastic behaviour is therefore assumed unidimensional. Each fibre is characterised by an orientation vector expressed in the global system of coordinates (i.e. linked to the composite or equivalently to the matrix). Fibres that have the same Young modulus, E_F^α, and the same orientation vector, $\vec{a}^\alpha$, are grouped into family number α; n_{fam} families of fibres are thus defined. Each of them is characterised by a volume fraction, v_F^α, so that