Composite Structures 182 (2017) 223–236

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Hybrid micromechanical-phenomenological modelling of anisotropic damage and anelasticity induced by micro-cracks in unidirectional composites

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ARTICLE INFO

Keywords:
Non-linear behaviour
Anisotropic damage
Micromechanics
Implicit implementation
Unidirectional composites

ABSTRACT

In this paper, a new damage modelling approach is presented to describe the mechanical response of unidirectional composites under the small strain assumption. The proposed constitutive equations inherits from the phenomenological theories of Continuum Damage Mechanics (CDM) but brings out a micromechanical description of the damaged Representative Volume Element (RVE) while being formulated in a proper thermodynamical framework. The model is provided with an implicit numerical scheme based on the so-called "return mapping algorithm" as well as the formulation of the tangent operator. The identification and the prediction capabilities of the model are validated using experimental data including off-axis tensile tests. Finally, to provide a better understanding of the model, a multi-axial non-proportional simulation is performed and analysed.

1. Introduction

The development of unidirectional composites has been driven by the necessity to develop lightweight new structures with enhanced mechanical properties, especially for automotive and transportation industries. The design of such structural components requires the deep understanding of their mechanical behaviour and failure mechanisms. In composite materials, the damage mechanisms are governed by the specific arrangement of the reinforcement, leading to an anisotropic evolution of their mechanical response. For the case of unidirectional composites reinforced with stiff fibres (e.g., glass or carbon), the longitudinal behaviour exhibits a linear elastic response until the material brittle failure due to fibres breakage. The presence of continuous fibrous reinforcements actually prevents the appearance of others damage mechanisms in the fibre direction. The transverse tension and the in-plane shear responses generally exhibit progressive stiffness degradation prior to failure. Indeed, transverse damage is induced by the appearance of a diffuse micro-crack network that initiates by debonding at the fibre/matrix interfaces (Fig. 1a) and propagates by coalescence (Fig. 1b).

Most of the modelling efforts have therefore focused on the definition of damage variables related to the previously described behaviour. Continuum Damage Mechanics (CDM) along with the concept of effective stress formulated within the framework of thermodynamics [31,32] is particularly adapted for such description. Initially developed in the context of isotropic material response, the CDM was adapted to the anisotropic case of unidirectional composites [29,26,25,1,4,5,33]. The effects of micro-cracks are usually accounted through the introduction of several damage state variables that directly define the reduction of the material stiffness. In addition, the anelastic mechanisms are generally described by a plastic-like strain tensor whose evolution is governed by a yield function written in the effective stress space in order to account for the coupling with the damage. Nevertheless, if the use of CDM is convenient and straightforward in the isotropic case, its extension to anisotropy may lead to the following issues:

- Several damage state variables are assumed to capture properly the anisotropic evolution of the material response. Each variable is associated with an evolution equation that potentially depends on several field variables (temperature, stress) where multi-axial couplings may be included. Such a modelling strategy leads to an important number of material parameters with additional difficulties regarding their identification.
- The definition of the effective stress tensor is required to account for coupling effects with the anelastic mechanisms. In the case of anisotropic materials the physical meaning of the effective stress is not obvious [32].

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http://dx.doi.org/10.1016/j.compstruct.2017.09.013
Received 16 May 2017; Received in revised form 9 September 2017; Accepted 14 September 2017
Available online 18 September 2017
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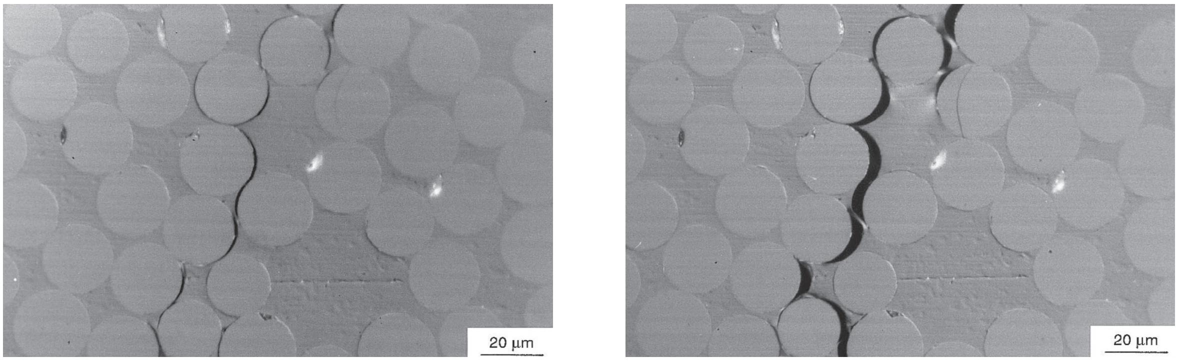

(a) Initiation of the micro-cracks by debonding of the fibre/matrix interfaces

(b) Coalescence into micro-cracks

Fig. 1. Transverse damage mechanism in unidirectional composites [13].

To overcome those issues, the evolution of the mechanical response of such composites can be rather based on the evolution of the micro-cracks network itself through micromechanics [28,27,45].

The main objective of this work is to propose a computationally efficient, hybrid micromechanical-phenomenological model that has a reduced number of internal variables. The evolution of these variables is controlled by criteria that depend on local stress estimations, providing hence a physically based description of the damage mechanisms. Such constitutive model is intended to be utilized for representing the response of bundles or yarns towards multi-scale analyses of woven fabric or SMC composites.

The new model accounts for anisotropic damage and anelasticity induced by micro-cracks in unidirectional composites. The damage is introduced through a micromechanical description of a Representative Volume Element (RVE) containing micro-cracks. Those defects are quantified by a unique internal state variable whose evolution is governed by a local stress criterion. The anisotropic evolution of the stiffness as well as the connection between overall and local stress-strain fields are therefore determined using micromechanical relationships that are directly incorporated within the constitutive equations. In that sense, the proposed model is based on a hybrid micromechanical-phenomenological formulation [8,60,49]. A novelty of the proposed model consists in accounting for anelastic deformation mechanisms by introducing the concept of damage induced anelasticity, where permanent strains are assumed to be caused by the non-closure effect of the micro-cracks. The constitutive equations are then expressed within the framework of thermodynamics of irreversible processes applied to the overall medium, describing its mechanical response under the small strain assumption and isothermal conditions.

Compared to classical CDM models for unidirectional composites [29,26,25,1,4,5,33], the present modelling strategy leads to a reduced number of parameters with a certain ease regarding their identification. Moreover, the hybrid micromechanical-phenomenological formulation brings a physical basis to the model, while its practical use remains as computationally efficient as any purely phenomenological approach.

This paper is structured as follows: In the second section, the constitutive equations, the thermodynamical framework and the micromechanical aspects of the proposed model are presented. The third section is devoted to the numerical time implicit implementation scheme in which a user material algorithm is formulated alongside the definition of the tangent operator. The latter is essential for the finite element framework. The fourth section focuses on the identification strategy of the model parameters. The fifth section presents an example of simulation where the material is subjected to a non-proportional multi-axial loading. The last section summarizes the main conclusions and discuses the perspective related to this work.

The following notation is adopted in this work: bold and blackboard symbols respectively denote second and fourth order tensors while other symbols are scalar quantities. The twice contracted and dyadic products are given by:

$$\boldsymbol{A}:\boldsymbol{B} = A_{ij}B_{ij}, \quad (\mathbb{A}:\boldsymbol{B})_{ij} = A_{ijkl}B_{kl}, \quad (\boldsymbol{A}\otimes\boldsymbol{B})_{ijkl} = A_{ij}B_{kl}.$$

Moreover, all the second order tensors are symmetric ($A_{ij} = A_{ji}$) and all the fourth order tensors have at least the minor symmetries ($A_{ijkl} = A_{jikl} = A_{ijlk}$). Consequently, they can be respectively reduced to 6 × 1 and 6 × 6 matrices according to the Voigt notation. $\boldsymbol{I}$ and $\mathbb{I}$ are the second and the fourth order identity tensors, respectively, defined as:

$$(\boldsymbol{I})_{ij} = \delta_{ij}, \quad (\mathbb{I})_{ijkl} = \frac{1}{2}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}),$$

where δ_{ij} is the Kronecker symbol. The inverse of a fourth order tensor $\mathbb{A}$, that has the minor symmetries, is the fourth order tensor $\mathbb{A}^{-1}$ for which $\mathbb{A}:\mathbb{A}^{-1} = \mathbb{A}^{-1}:\mathbb{A} = \mathbb{I}$.

2. Constitutive model and thermodynamical framework

The idea of the proposed model is to link, through micromechanical concepts, the overall stiffness reduction of a unidirectional composite with the evolution of a single scalar state variable γ_c that quantifies the state of the involved damage mechanism, the oriented micro-cracking in the present case. This stiffness reduction is represented under the form of a fourth order tensor $\mathbb{D}(\gamma_c)$ that gradually decreases the initial stiffness tensor $\mathbb{C}_0$ of the material, the latter having transversely isotropic properties as it represents the elastic behaviour of the undamaged unidirectional composite (initial material). The tensor $\mathbb{D}(\gamma_c)$ is assessed by homogenization of the initial material in which a micro-crack density γ_c is introduced (Fig. 2). The latter is defined as a void volume fraction created when the material is being damaged. Due to the micro-structure arrangement the micro-crack are forced to propagate in a plane parallel to the fibre direction $\vec{x_1}$. Moreover, if the material is mainly loaded in plane stress (plane $\vec{x_1}, \vec{x_2}$) as it is often the case, then the propagation plane of the micro-cracks can be considered as being perpendicular to the second direction $\vec{x_2}$ and consequently always oriented in the same plane (Fig. 2).

Damage in such type of materials generally brings about permanent strains due to the micro-cracks non-closure and the resultant sliding with friction [29,26,4,5,33]. In the present model, these damage induced permanent strains are phenomenologically described by an anelastic strain tensor denoted by $\boldsymbol{\varepsilon_s}$. The total overall strain is then expressed by summation of the elastic strain $\boldsymbol{\varepsilon_e}$ with the anelastic strain $\boldsymbol{\varepsilon_s}$:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon_e} + \boldsymbol{\varepsilon_s}. \tag{1}$$

The observable state variable of the model is the total strain $\boldsymbol{\varepsilon}$ while

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