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Composite materials non-linear modelling for long fibre-reinforced laminates
Continuum basis, computational aspects and validations

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Abstract

An innovative computational methodology is proposed for modelling the material non-linear mechanical behaviour of FRP structures. To model a single unidirectional composite lamina, a serial–parallel (SP) continuum approach has been developed assuming that components behave as parallel materials in the fibres alignment direction and as serial materials in orthogonal directions. The model is based on the appropriate management of the constitutive models of the component materials, by making use of suitable 'closure equations' that characterize the composite micro-mechanics [Rastellini F. Modelización numérica de la no-linealidad constitutiva de laminados compuestos. PhD thesis. ETSECCPB, Politechnical University of Catalonia, Barcelona, March, 2006. [in Spanish]]. Classical lamination theory is combined with the SP model to describe multidirectional laminates. The methodology is validated through several numerical analyses, which are contrasted against benchmark tests and experimental data taken from the world-wide failure exercise [Hinton MJ, Soden PD. Predicting failure in composite laminates: The background to the exercise. Comp Sci Technol 1998; 58:1001–10].

Keywords: FRP; Long fibre laminates; Composite failure; Non-linear modelling; FEM

1. Introduction

The use of long fibre composites (LFC) has been extensively developed in the automotive and aeronautical industries during the last 40 years, mainly due to the excellent mechanical properties of this type of materials. During the same period, a great theoretical effort has been made in the analysis of LFC and in the construction of a mathematical basis for the description of their complex micro- and macro-mechanics; consequently, a large amount of literature devising constitutive models for LFC has been produced. Nevertheless, it is remarkable that reliance upon the effectiveness of the failure prediction theories and upon the constitutive models devised in the design of composite structures has not gone hand in hand with the reliance upon the structural properties of this class of materials.

In the last decade, this perspective has begun to change, since the industry demands for improved design methods to reduce the time and cost of bringing new components to the market. Industrial design requires constitutive models that allow realistic structural analysis with degradation of mechanical properties and failure predictions, but at the same time, easy to implement efficiently in an FEM code (finite elements method). An ideal composite model would be the one that could combine already-developed constitutive models (for simple materials) and, at the same time, consider the heterogeneous microstructure. Such a model would make it possible to transfer the large amount of FE

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technology that is currently employed for homogeneous materials. These needs constitute the main motivation of this work, which is to obtain a fast and accurate model to allow reliable numerical simulations of composites. This model would help to predict the ultimate strength of structures and to reduce the expensive experimental testing currently employed in the design practice of components.

The development of a constitutive model for composite laminates is not a simple task since it requires a proper account of the non-linear stress–strain relationships. The lamination sequence obliges us to consider the behaviour of each lamina separately [3], and even the modelling of a single lamina appears to be a complex task since phenomena like fracture, fibre–matrix debonding, micro-buckling and large deformations have to be considered together with their mutual interactions. Puck [4,5] have also remarked that, in the analysis of fibre-reinforced laminates, it is essential to distinguish between fibre failure and matrix failure as well as between fibre degradation and matrix degradation. This observation constitutes a big limitation for those models that consider the composite as an equivalent continuum and accordingly employs exclusively state variables and governing equations which refer to the whole homogenized material. Moreover, as shown by Oller et al. [6,7], the computational cost of a complete double scale approach for a large scale non-linear structural analysis is still not affordable with ordinary computers, even with parallel computations.

The mean-field methods assume that averaged values of the stress and strain states are representative of the behaviour of each phase, and that they are related to the composite stress and strain by mechanical influence functions called concentration tensors. Voigt [8] and Reuss [9] assumed that the strain and stress fields were, respectively, constant in all phases. They proposed simple formulas nowadays-called the rule of mixtures (ROM) and inverse ROM, respectively, to compute the elastic constants of composite.

Classical mixing theory (CMT), whose simpler expression is the ROM, was first studied in 1960 [10] establishing the basis for subsequent developments [11–14]. CMT takes into account the volume fraction of components but not its morphological distribution, since it assumes all component materials experiment the same strain state in all directions (pure parallel behaviour). This feature is a strong limitation for the use of CMT to predict the behaviour of most composites, and consequently modifications to this theory were developed [15,16]. The experience gained in this field with previous research by the authors [17,18] helped to achieve the methodology presented here.

In this paper, within the mean-field approach, a formulation is developed to specifically model the non-linear material behaviour of unidirectional long fibre-reinforced laminas. The aim of the model is to make the composite behaviour dependent on the constitutive laws of component materials according to their volume fractions and to their morphological distribution inside the composite.

The proposed model (for a single lamina) is combined with classical lamination theory to describe laminates consisting of unidirectional continuously reinforced layers.

For validation purposes, the results of several numerical analyses are contrasted with experimental results found in the literature and with the experimental benchmark data [29] provided in the context of the "world-wide failure exercise". Recently, the authors employed this model to asses fatigue behaviour of composite fibre-reinforced laminates [20].

2. Numerical model development

The proposed composite model is based on the appropriate management of the constitutive models of component phases within a continuum framework. This model was first sketched by Rastellini and Oller [19] to account for components with additive plasticity and/or damage in elastic stiffness. The generalization presented here allows the compounding of materials with any non-linear constitutive model.

To this end, a preliminary formalization of the multi-material approach denominated 'compounding of material models' is proposed. This may be the basis for future enhancements to take into account different morphological arrangement of the reinforcement by means of proper close equations. Within this framework, two versions of the model are formulated, which basically differ in the closure equations taken into account. Specifically, the former, referred to as the basic serial parallel (BSP) model, inherits closure equations that consider isostrain hypothesis in fibre direction and isostress hypothesis in transversal directions; while the latter, denominated the enriched serial parallel (ESP) model, is devised to improve the transverse and shear stiffness underestimated by the BSP model.

The aim of serial–parallel (SP) models is to help quickly and accurately in the assessment of the non-linear behaviour of composite structures due to material degradation. The consistency of the results is assured by the appropriate election of component material models.

2.1. Basic notations and definitions

It is considered a biphasic fibrous composite material and is postulated the existence, in a statistical sense, of a periodic representative volume element (RVE) with transversely isotropic symmetry. From now on, the two constituent phases will be addressed as 'matrix' and 'fibre', and all the quantities related to them will be denoted by the superscripts m and f.

The reference placement of the composite material body will be denoted by the symbol $\Omega \subset \mathbb{R}^3$. The RVE is classically decomposed as the union of the two non-overlapping subdomains of component materials: $\Omega = {}^m\Omega \cup {}^f\Omega$. We will denote the volumetric fraction by ${}^fk, {}^mk$; evidently ${}^fk + {}^mk = 1$. Average quantities will be used in the subsequent sections. The standard definition of the volumetric