Composite Structures 111 (2014) 122–129

Contents lists available at ScienceDirect

Composite Structures

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

A continuum constitutive model for the simulation of fabric-reinforced composites

E. Martín-Santos [a,*], P. Maimí [a], E.V. González [a], P. Cruz [b]

[a] AMADE, Dept. of Mechanical Engineering and Industrial Construction, Universitat de Girona, Campus Montilivi s/n, E-17071 Girona, Spain
[b] Applus IDIADA, Principal centro técnico, Santa Oliva, E-43710 Tarragona, Spain

ARTICLE INFO

Article history:
Available online 27 December 2013

Keywords:
Woven composite
Constitutive model
Continuum Damage Mechanics
Open hole

ABSTRACT

Fibre-reinforced polymer-based composite materials fail due to a wide variety of interacting damage mechanisms, which require complex constitutive models in order to develop Finite Element (FE) predictive analysis. In this paper, a constitutive behaviour model based on Continuum Damage Mechanics (CDM) is proposed for the simulation of fabric-reinforced composites. The model uses simplified loading functions in order to minimise the computational time required to obtain the numerical solution. To reduce the influence of mesh refinement on the numerical solutions, the Crack Band Model (CBM) algorithm is implemented. In this way, the energy dissipated at each point in the material is regularized for the different damage mechanisms. This newly-formulated constitutive model is implemented by means of a user-defined material subroutine in Abaqus/Explicit FE code. The model is validated by comparing the results of FE predictions with experimental data from open hole specimens, under quasi-static tensile loading conditions. A good correlation between the numerical and experimental results is achieved when using a bilinear cohesive law, for different combinations of hole diameter and specimen width.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Composite materials that are reinforced with continuum fibres can be classified into two main categories: Unidirectional (UD) reinforced composites – in which the fibres are aligned in one direction within each ply (or lamina) and fabric-reinforced composites – in which fibres form a woven layer within each ply (and this woven layer may consist of one of a number of different patterns). Generally, when compared to UD composites with an equivalent fibre volume in the load direction, fabric-reinforced composites present lower in-plane stiffness as well as lower ultimate strength, due to the effect of fibre waviness. However, fabric-reinforced composites do have better through-the-thickness properties and damage tolerance than UD composites [1]. These properties allow them to dissipate higher levels of energy under impact and crashworthiness events. The good drapability of fabric-reinforced composites enables difficult shapes to be manufactured. This property, combined with their capacity to dissipate energy, and their good specific strength and stiffness, makes these materials a suitable option for car manufacturers in mass produced vehicles, compared with conventional metallic alloys, e.g., in the BMW i3 [2].

The development of virtual tools to predict structure behaviour is a topic of interest in industry, since such tools can reduce the number of specimens required for testing, with consequent reductions in time and design costs. For this reason, constitutive models based on Continuum Damage Mechanics (CDM) are widely implemented in Finite Element (FE) software for a large variety of materials. This methodology provides predictions of the degrading process of a material at meso- or macro-scale levels and is compatible with elastic formulations in the FE methodology (FEM), as well as with other possible inelastic mechanisms (such as the isotropic hardening). CDM is based on the concept that the presence of cracks or defects due to degradation in a material implies a reduction in its capacity to withstand stresses. Therefore, damage variables are related to each failure mechanism and these variables can quantify the loss of stiffness caused by the presence of microcracks and voids created during a damaging event.

In commercial FE software, there are several CDM-based constitutive models for simulating composite materials. Ladevèze [3,4] produced a constitutive model for UD composites and this has been adapted by various authors to simulate the behaviour of fabric-reinforced composites: Hochard et al. [5] adapted Ladevèze's model to simulate the first ply failure and then extended that model to simulate the behaviour of the material under fatigue conditions [6]. Johnson et al. [7] also adapted Ladevèze's model, in this case to textile composites for explicit FE analysis, in order

---

[*] Corresponding author. Tel.: +34 972 418 817.
E-mail address: eduardo.martin@udg.edu (E. Martín-Santos).

0263-8223/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.12.024

to focus on impact simulations. This adaptation was subsequently improved and incorporated into the material libraries of PAM-CRASH FEM software by Fouinneteau [8].

Matzenmiller et al. developed an in-plane, anisotropic damage model for UD composites [9] which was later extended to 2D and 3D fabric-reinforced composites by Böhm et al. [10]. Iannucci et al. formulated another adaptation of Matzenmiller's model for fabric-reinforced composites, which was implemented in LS-DYNA [11] and in which a linear stress/strain relationship is assumed for fibre-related damage mechanisms. This adaptation was later improved by means of the Crack Band methodology [12], used to ensure a certain dissipation of energy regardless of the refinement of the mesh [13,14].

In this paper, a finite element constitutive model for simulating fabric-reinforced composite structures is presented. The model uses an explicit integration scheme, considers only the principal damage mechanisms (fibre failure and shear plasticity) and is implemented with simplified loading functions, as is the case with other constitutive models described in the literature; in this way, large structures can be simulated within reasonable computational times (compared to other damage models using FEM). The Crack Band Model algorithm is incorporated, in order to reduce the loss of accuracy in the computation of the energy dissipated by the different damage mechanisms, otherwise influenced by the size of the elements used in the numerical models.

The constitutive model is performed in a user-defined, material subroutine of Abaqus/Explicit, which can be used with conventional shell elements. These features allow us to model different plies, or even an entire laminate stacked in the thickness of a single element. In this way, the FE models can be simplified, in parts where delamination is either not expected, or negligible.

The validity of our model was verified using experimental data from open hole specimens in tensile tests under quasi-static conditions carried out by Kim et al. [15]. Numerical simulations were performed to test whether our model was capable of reproducing some of the experimental results provided by Kim et al. [15]. When applying a cohesive bilinear law to take into account the damage progression on the composite material, a good correlation between the experimental and the numerical results was achieved for predicting the notched strength in specimens with different total width/hole diameter ratios.

2. Model description

The constitutive model proposed is formulated within the framework of Continuum Damage Mechanics, where the behaviour of the fabric-reinforced composite plies can be simulated at the mesoscale level from an undamaged state until their complete degradation. A plane-stress state is taken into consideration in order to make the model compatible with shell elements and classical laminate theory.

The configuration of the fibres and the matrix in composite plies provides these materials with orthotropic symmetry. In order to reproduce this behaviour, the constitutive model is defined using an orthotropic formulation, where the principal directions are aligned with the fibres of the ply: direction 1 is aligned with the weft tows (which normally have the strongest properties in the composite ply) and direction 2 is aligned with warp tows.

It is well known that metallic structures tend to dissipate energy via plastic deformation, whereas in composite materials, the energy is dissipated in a more complex way, since there is a simultaneous combination of different failure mechanisms (i.e. matrix cracking, fibre breakage and delamination [8]). Thus, fibre-related damaging mechanisms usually present a quasi-brittle behaviour, while matrix-related damaging mechanisms can present a hardening behaviour, before the degradation of their properties (e.g., matrix hardening under a shear stress).

Under a stress aligned with the principal directions of the composite ply, the fibres withstand the largest portion of the load. Damage onset and propagation are influenced by the mechanical properties and the fibre volume fraction in the load direction, and by their misalignment in the lattice configuration. Tensile failure starts with isolated fractures in weak zones [16]. These fractures increase the stress concentration in the surrounding material, leading to fibre–matrix debonding and matrix cracking. If the applied load increases, additional fibre fractures appear, leading to the final collapse of the material [16]. On the other hand, compressive failure is caused by a combination of shear effects that leads to the formation of a kink band [16,17]. In this case, four damage mechanisms are considered in the constitutive model, in order to describe the tensile behaviour and the compressive behaviour of the composite ply in both of the principal directions (1 and 2), in which the weft and warp tows of the woven distribution are aligned.

A cohesive law-based formulation has been adopted to describe the degradation of the mechanical properties for the implemented damage mechanisms (see Section 2.2.4). In a specimen without stress concentrations, the response is almost linear until the onset of damage, with no hardening behaviour. Under these conditions, the degradation mechanisms are located in a failure plane. A cohesive law-based formulation is an appropriate approach to model the behaviour of a material that presents a localised damage process. Thus, a bilinear cohesive law is considered for each one of the four damaging mechanisms present in the constitutive model. The Crack Band Model is included in their formulation, in order to minimise the dependency of the numerical solution on the refinement of the mesh.

In-plane shear behaviour of fabric-reinforced composites is governed by their matrix properties. Damage to a fabric-reinforced composite ply under shear stresses occurs in several stages: when the yielding stress is reached, matrix cracking begins to occur; then, the crack density grows until a saturation level is reached. From this point on, a non-linear response appears, caused by the tendency of the fibres to be aligned in the loading direction (behaviour known as trellising effect). This stage continues until the total collapse of the structure [18].

The influence of the trellising effect is variable and depends on the fibre–matrix configuration. Trellising is more significant in composite materials in which the matrix has a low elastic modulus and low ultimate strength, such as in thermoplastic matrices or applications at high temperatures [18–21]. In the case of other matrices, such as epoxy, shear behaviour can be adjusted to a hardening law in plasticity [1,22], without the need to model the trellising effect.

The model we propose here takes into account an isotropic hardening plasticity for the shear stress–strain relationship. Degradation of the properties under shear stresses is not incorporated into the constitutive model, since matrix damage is not considered a catastrophic mode of failure, especially when the ply is embedded within a laminated composite. The coupling between the shear and the principal stresses caused by the strengthening behaviour is, however, taken into account.

2.1. Constitutive model

2.1.1. Complementary energy and elastic response

To describe the constitutive behaviour of the material, the scalar function of the complementary free energy density ($\mathcal{G}$) is defined which, for the model proposed here, is as follows:

$$\mathcal{G} = \frac{\sigma_{11}^2}{2(1-d_1)E_{11}} + \frac{\sigma_{22}^2}{2(1-d_2)E_{22}} + \frac{\sigma_{12}^2}{2G_{12}} - \frac{\nu_{12}}{E_{11}}\sigma_{11}\sigma_{22} + \sigma_{12}\varepsilon_{12}^p \qquad (1)$$

Download English Version:

https://daneshyari.com/en/article/6707811

Download Persian Version:

https://daneshyari.com/article/6707811

Daneshyari.com