Composite Structures 192 (2018) 82–92

Contents lists available at ScienceDirect

Composite Structures

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

Constitutive model for imperfectly bonded fibre-reinforced composites

Simon P.H. Skovsgaard*, Henrik Myhre Jensen

Department of Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000 Aarhus C, Denmark

ARTICLE INFO

Keywords:
Imperfect bonding
Strain localisation
Bifurcation
Constitutive model
Kink band

ABSTRACT

A constitutive model for fibre-reinforced composites has been developed that takes imperfect fibre/matrix interfacial bonding into account. The model can predict the nonlinear material response of a composite in the large strain regime. Independent constitutive laws can be used for the constituents behaving elastic or elastic-plastic. A constitutive equation is derived for the composite moduli relating stresses to strains. The model is used to predict the development of the compressive failure; fibre kinking that is either formed by bifurcation or due to an initial fibre imperfection. A three-dimensional finite element model for kink band formation is used to validate the results obtained using the constitutive model with varying levels of interfacial bonding.

1. Introduction

Fibre-reinforced composites (FRC) are used in many applications where high stiffness and low weight is desirable. These materials are composed of fibres bonded together using a resin material also known as the matrix material. In many of the frequently used FRCs as for example glass- and carbon fibre-reinforced composites, the fibres have high stiffness and strength and the matrix is more ductile and has high toughness but with a lower stiffness. These fibre composites have high strength in the direction of the fibres but when loaded in compression the critical stress can be considerable lower due to instabilities caused by imperfections coupled with matrix yielding. The compressive failure of multidirectional laminates is composed of several competing failure mechanisms including: fibre kinking, fibre splitting, matrix cracking, delamination, fibre/matrix interfacial debonding. In an experimental study conducted by Bishara et al. (2017) [1], together with finite element analyses, they showed that the compressive failure of a laminate with 16 layers initiated due to kink band formation in the 0° ply near an imperfection. The fibre kinking was triggered by matrix yielding. Several of the other mentioned failure mechanisms was seen to occur close to the kink band after the initiation.

The kink band failure has been observed experimentally by several authors including: Kyriakides et al. (1995) [2] who made a thorough investigation of the compressive failure of unidirectional AS4/PEEK composites. Kink band formation were seen both experimentally and in their two-dimensional micromechanical finite element model (FEM). Wadee et al. (2004) [3] conducted a compression test on a FRC and fibre kinking was observed and compared with a simple mechanical model taking bending, friction, membrane and foundation energy into account. Zhou et al. (2013) [4] investigated the compressive strength of unidirectional glass fibre reinforced-polymers (GFRP) from different angles and fibre kinking was the dominant failure for small angles. Nizolek et al. (2017) [5] observed kink band initiation and stable band broadening in a Cu-Nb nanolaminate exposed to compressive loading. It was observed by Nair et al. (2017) [6] that a 75 % reduction in compressive strength could be achieved by introducing a severe fibre waviness into the unidirectional GFRP and failed by kink band formation.

Several attempts have been done towards developing analytical expressions predicting the kink band initiation. In the early work of Rosen (1965) [7] an analytical expression was derived based on the compressive bifurcation load of beams surrounded by an elastic matrix. Argon (1972) [8] treated the kink band failure as a plastic event, with a composite behaving rigid perfectly plastic with an initial imperfection. Budiansky (1983) [9] extended the expression by assuming rigid fibres and elastic perfectly plastic shear response of the composite. Fleck and Budiansky (1991) [10] included shear stresses and later Slaughter et al. (1993) [11] introduced transverse stresses in an analytical expression. Christoffersen and Jensen (1996) [12] developed a method to find the kink band bifurcation load for a composite including fibre and matrix material nonlinearities and with multiaxial loading. In the case of rigid fibres an analytical equation was developed where the effect of residual stresses could be included. Later Jensen (1999) [13] developed an analytical expression for the kink band bifurcation in the extreme case of no bonding between fibre and matrix. The expression developed in Christoffersen and Jensen (1996) [12] assumed perfect bonding.

The kink band initiation can be investigated numerically either by setting up a simplified kink band analysis as done by Jensen and Christoffersen (1997) [14] and Wadee et al. (2004) [3] or by creating a

* Corresponding author.
E-mail addresses: sphs@eng.au.dk (S.P.H. Skovsgaard), hmj@eng.au.dk (H.M. Jensen).

https://doi.org/10.1016/j.compstruct.2018.02.053
Received 28 September 2017; Accepted 19 February 2018
Available online 26 February 2018
0263-8223/ © 2018 Elsevier Ltd. All rights reserved.

finite element model. The FEMs used to study kink bands can roughly be divided into two categories: discretized FEMs also known as micromechanical models or FEMs using homogenised constitutive models. The fibre and matrix constituents are modelled discretely in the micromechanical models. Examples of authors who have used this approach are Hsu et al. (1999) [15] who used a three-dimensional FEM with a hexagonal fibre distribution, and Wind et al. (2014) [16] who compared results obtained using a discretized model and a constitutive model. When advanced fibre layups or complex geometries are considered then discretized models become inexpedient compared to homogenized constitutive models. Fleck and Shu (1995) [17] developed a constitutive model using finite strain continuum theory combined with Cosserat couple theory. The constitutive model gives the smeared out properties of a composite including fibre bending effects. The constitutive model developed by Christoffersen and Jensen (1996) [12] is based on independent constitutive equations for the constituents instead of smeared out properties of the composite. Poulios and Niordson (2016) [18] developed a two-dimensional constitutive model based on independent constituent behaviour and included intrinsic size effects using higher order strain gradients. Skovsgaard and Jensen (2018) [19] developed a three-dimensional constitutive model for a FRC with independent elastic-plastic behaviour of the constituents similar to the two-dimensional model developed in Christoffersen and Jensen (1996) [12].

Dève (1997) [20] observed in a compression experiment on an aluminium matrix composite reinforced by Al_2O_3 fibres that the interfacial bonding between matrix and fibre has a severe influence on the compressive strength. In the experiment the fibres were coated so the interface was ”weak” and lower critical stresses were observed. To the authors' knowledge, this is the only compression experiment of kink band formation done where composites with strong and weak bonding are compared. The longitudinal and transverse response of an aluminium composite was investigated by Zhang et al. (2008) [21] and they concluded that the transverse properties depends strongly on interfacial bonding between matrix and fibre. It is commonly accepted that the kink band instability is sensitive to the composite shear response, and since the shear response is altered by the interfacial bonding then so are the critical kink band stress. Jiang et al. (2014) [22] investigated the composite properties using a finite element representative volume element with different levels of bonding between matrix and fibre and made the same conclusions as Zhang et al. (2008) [21]. The interface was modelled with cohesive contact surfaces. A comprehensive micromechanical kink band analysis with cohesive-frictional interfaces were conducted by Naya et al. (2017) [23].

The interface bonding between fibre and matrix has a severe influence on the critical compressive stress, and the need to have constitutive models to investigate complex geometries and fibre layouts leads to the main focus of this paper. The current paper focuses on the development of a novel constitutive model for imperfectly bonded fibre-reinforced composites. The constitutive model is validated using a kink band analysis and is compared with results obtained using a three-dimensional FE micromechanical kink band model. The paper is organised in 7 sections. The constitutive model and a novel analytical kink band expression is derived in Section 2. A semi-analytical kink band analysis with the constitutive model implemented is introduced in Section 3. The constituent behaviour used in the FE and semi-analytical analysis is presented in Section 4. The FEM together with the boundary conditions are shown in Section 5. Finally the results from the analyses are shown, compared and discussed in Section 6 and Section 7 concludes the paper.

2. Constitutive model

In the following section a constitutive model is derived that can take imperfect cohesion between fibre and matrix into account. The model is inspired by the two constitutive models derived by Christoffersen and Jensen (1996) [12] and Jensen (1999) [13]. The latter constitutive models are extrema where the model derived in Christoffersen and Jensen (1996) [12] assumes perfect bonding between the constituents and the model in Jensen (1999) [13] assumes complete decohesion. The present constitutive model can display the transition between the two previous mentioned extrema using a factor μ going from zero to unity. The constitutive model is implemented in a kink band analysis and is compared with a three-dimensional micromechanical finite element model for verification.

Simple representations of perfect and imperfect bonding are illustrated in Figs. 1 and 2 to enhance the understanding behind the assumptions used in the constitutive models. The model with perfect bonding is based on the assumptions.

1. Material lines parallel with the fibres are subject to a common stretching and rotation.
2. Planes parallel with the fibres transmit identical tractions.
3. The material of the constituents is elastic or elastic–plastic.

As outlined in Christoffersen and Jensen (1996) these assumptions leads to the restriction on the velocity gradients

$$v^m_{1,1} = v^f_{1,1} = v_{1,1}, \qquad v^m_{2,1} = v^f_{2,1} = v_{2,1},$$
$$c^f v^f_{1,2} + c^m v^m_{1,2} = v_{1,2}, \qquad c^f v^f_{2,2} + c^m v^m_{2,2} = v_{2,2}, \tag{1}$$

where c^m and c^f are volume fractions of matrix and fibre fulfilling $c^f + c^m = 1$. A comma $(\bullet)$, denotes partial derivative. Superscripts $(\bullet)^m$ and $(\bullet)^f$ will refer to quantities associated with the matrix and fibre constituent and omission of superscript refers to overall composite properties. This convention will be adopted in the current article. The second assumption together with overall equilibrium entails

$$\dot{t}^m_{21} = \dot{t}^f_{21} = \dot{t}_{21}, \qquad \dot{t}^m_{22} = \dot{t}^f_{22} = \dot{t}_{22},$$
$$c^f \dot{t}^f_{11} + c^m \dot{t}^m_{11} = \dot{t}_{11}, \qquad c^f \dot{t}^f_{12} + c^m \dot{t}^m_{12} = \dot{t}_{12}, \tag{2}$$

where $\dot{t}_{ij}$ is the nominal stress rates.

In Fig. 2 shear and transverse deformation of a fibre composite with imperfect bonding is shown. The constitutive model suggested by Jensen (1999) [13] also assumes that material lines parallel with the fibres are subject to a common stretching and rotation. Furthermore it is assumed that the matrix as a whole is subject to the overall strains

$$v^m_{1,1} = v^f_{1,1} = v_{1,1}, \quad v^m_{2,1} = v^f_{2,1} = v_{2,1},$$
$$v^m_{1,2} = v_{1,2} \quad v^m_{2,2} = v_{2,2}. \tag{3}$$

Further, the rate of nominal stress was given by

$$c^f \dot{t}^f_{11} + c^m \dot{t}^m_{11} = \dot{t}_{11}, \quad c^f \dot{t}^f_{12} + c^m \dot{t}^m_{12} = \dot{t}_{12},$$
$$c^m \dot{t}^m_{21} = \dot{t}_{21}, \quad \dot{t}^f_{21} = 0, \quad c^m \dot{t}^m_{22} = \dot{t}_{22}, \quad \dot{t}^f_{22} = 0. \tag{4}$$

The suggestion $\dot{t}_{1\alpha} = c^f \dot{t}^f_{1\alpha} + c^m \dot{t}^m_{1\alpha}$ is an average of the tractions where both the fibre and matrix transmit traction. The assumption $c^m \dot{t}^m_{2\alpha} = \dot{t}_{2\alpha}$ is an average where only the matrix constituent contributes.

2.1. General relations

The index notation and the summation convention is adopted. Latin indices i.e. i,j,k take values 1,2,3, and Greek indices i.e. α,β,γ take values 1,2. The relation between nominal stress rates and velocity gradients is given by

$$\dot{t}_{ij} = C_{ijkl} v_{l,k}, \tag{5}$$

where $\dot{t}_{ij}$are components of the nominal stress rate, $v_{l,k}$ are the velocity gradients and C_{ijkl} are components of nominal moduli. The moduli C_{ijkl} can be calculated using

$$C_{ijkl} = L_{ijkl} - \frac{1}{2}\tau_{kj}\delta_{il} - \frac{1}{2}\tau_{lj}\delta_{ik} - \frac{1}{2}\tau_{il}\delta_{kj} + \frac{1}{2}\tau_{ik}\delta_{lj}, \tag{6}$$

Download English Version:

https://daneshyari.com/en/article/6703582

Download Persian Version:

https://daneshyari.com/article/6703582

Daneshyari.com