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Simulating the progressive crushing of fabric reinforced composite structures

E.V. Morozov *, V.A. Thomson

School of Mechanical Engineering, University of KwaZulu-Natal, Howard College, Durban 4041, South Africa

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Abstract

Simulating the crush response of a glass fabric reinforced thin-walled laminated structural component has been undertaken using the finite element modelling method. The finite element model was developed and analyzed using the PAM-CRASH analysis tool, employing a modified bi-phase material model to describe the behaviour of the elementary ply. The material model treats the orthotropic ply as a quasi-homogeneous layer that includes progressive damage to model material fracture. Description of the material behaviour is accomplished based upon experimentally recorded stress–strain data for both tensile and compressive cases of loading. Simulation results for the demonstrator's crush response are compared to experimentally recorded data and the predicted deformation states and failure patterns show good resemblance to the experimental data. The initial load response is also well predicted by the simulation and refinement of the material characterisation process is proposed to improve the models accuracy over the full range of crushing.

Keywords: Progressive damage; Material characterisation; Finite element modelling

1. Introduction

Finite element modelling of a glass fabric reinforced laminated demonstrator component has been undertaken employing multi-layered shell elements for discretisation of the demonstrator's structure. Description of the elementary fabric ply behaviour is accomplished using a modified bi-phase material model [1,2] which treats the composite ply as a quasi-homogeneous orthotropic layer that includes progressive damage. Characterisation of the material ply is completed through uniaxial tensile and compressive testing of material specimens. The non-linear explicit finite element dynamic analysis code, PAM-CRASH, is used for simulation of the demonstrator's response to a crushing load with a constant velocity of 150 mm/s. The simulated load–displacement response is compared to the experimentally recorded curve and a comparison of the predicted deformation modes is also made with deformation states recorded during experiment.

Modelling the crush response of composite components requires prediction of the material's response right up to the point of ultimate failure. To this end, composite materials under load generally experience internal material failure before any change in the material macroscopic appearance (and response) is observed. Different modes of internal failure have been identified and accepted for fibre composite materials (e.g., [3]) with the prevalence of any failure mode under a given loading being dependant upon the direction and nature of loading at the infinitesimal material level. The four accepted modes of failure are: (i) matrix microcracking, (ii) fibre/matrix debonding, (iii) fibre breaking and (iv) delamination.

The progressive nature of composite failure leads to the progressive damage modelling for composite materials in order to predict the material and structural response over large displacements. Progressive damage modelling of fibre composite materials is integrated into mathematical models using continuum damage mechanics (CDM) as a basis and

* Corresponding author. Fax: +27 31 260 3217.
E-mail address: morozov@ukzn.ac.za (E.V. Morozov).

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various approaches have been developed (and implemented) in order to capture the effect of the progressive internal material failures on the overall material macroscopic response. In order to model the behaviour of a laminate (made up of a number of plies) damage law must be applied at the material ply level since stresses vary from one ply to the next. The ply may then either be considered as a whole [4] or the fibre and matrix behaviours can be considered separately and then combined to describe the ply behaviour [1].

The bi-phase model treats fibre and matrix phases separately, using the measured elastic properties of a unidirectional ply, together with the known fibre properties and fibre volume fraction, to deduce the elastic properties of the matrix phase [5]. Damage law is implemented according to:

$$E = E_0(1 - d) \tag{1}$$

where E_0 is the initial modulus, E the instantaneous modulus and d the damage parameter lying in the range $0 \leqslant d \leqslant 1$. Damage parameter is defined separately for the separate material phases and at any given time is the sum of volumetric damage, due to a volumetric equivalent strain, and shear damage, due to a shear equivalent strain. The model also allows for separate definition of tensile and compressive behaviour in the principal material directions.

A significant amount of research effort has been dedicated to studying the energy absorption for the axial crushing of composite structures, typically with tubular cross-section, e.g., [6,7]. The work of Mamalis et al. [8] provides a comprehensive overview of the axial crushing and bending collapse of composite tubes of varied cross-sectional shape. The attention to this area of research is driven by the ability of the composites to absorb a greater amount of energy per unit mass under controlled progressive axial crushing, an advantage for application as crash energy absorbers. The collapse of a thin-walled structural component under crushing type loads, on the other hand, occurs due to a combination of bending and tearing of the structural shell as crushing progresses and may include cases of local and global buckling. For the general crushing of a mixed structure, a complex combination of axial and bending collapse will occur depending upon the nature of the loading and the orientation of the various sub-structures to the crushing loads. The present work aims to predict the composite structural component's response to crushing type loads, dominated by the combined bending and membrane modes of response of the thin-walled structure.

2. Progressive damage modelling

The bi-phase model is a heterogeneous material model adapted to unidirectional continuous fibre reinforced composites or composite fabrics. The material stiffness is calculated by superimposing the effects of an orthotropic material phase (matrix) and a one dimensional material phase (fibres). Each phase (fibre, matrix) has its own rheological law, e.g., an elastic/brittle orthotropic or microfracturing brittle damage law for the matrix phase and a unidirectional elastic-brittle damage law for the fibres.

For this model the orthotropic character of the cloth and of the unidirectional composite layers of a stackup can be modelled in two principal ways: either using two material phases, namely fibres plus matrix ('classical' model), or using one material phase, namely an orthotropic layer only ('modified' model) [5]. Using the 'modified' approach, the material is modelled as a single orthotropic layer and separate fibre and matrix properties need not be specified. In this case the measured composite properties are used to describe the quasi-homogeneous layer.

Damage law for the bi-phase model is implemented by a reduction in stiffness, as given by:

$$\boldsymbol{C}(d) = \boldsymbol{C}_0 \times (1 - d) \tag{2}$$

where $\boldsymbol{C}$ is the instantaneous stiffness matrix, $\boldsymbol{C}_0$ is the initial undamaged stiffness matrix and d is a unitless scalar damage parameter that is a function of strain. As for the material elastic constants, damage function for the bi-phase model is defined separately for cases of tension and compression, and may propagate independently for matrix and fibres when both material phases are employed.

Damage function is separated into volumetric and shear components as given by

$$d(\varepsilon) = d_{\mathrm{v}}(\varepsilon_{\mathrm{v}}) + d_{\mathrm{s}}(\varepsilon_{\mathrm{s}}) \tag{3}$$

where d_{v} is the volumetric damage as a function of volumetric strain

$$\varepsilon_{\mathrm{v}} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \tag{4}$$

and d_{s} is a shear induced damage as a function of equivalent shear strain

$$\varepsilon_{\mathrm{s}} = \sqrt{\frac{1}{3}[(\varepsilon_{11}^2 + \varepsilon_{22}^2 + \varepsilon_{33}^2 - \varepsilon_{11}\varepsilon_{22} - \varepsilon_{22}\varepsilon_{33} - \varepsilon_{11}\varepsilon_{33}) + 3\varepsilon_{12}^2 + 3\varepsilon_{23}^2 + 3\varepsilon_{13}^2]} \tag{5}$$

where ε_{ij} $(i, j = 1, 2, 3)$ are the components of the strain tensor.

Description of the damage functions, $d_{\mathrm{v}}(\varepsilon_{\mathrm{v}})$ and $d_{\mathrm{s}}(\varepsilon_{\mathrm{s}})$, is accomplished by choosing three critical damage points from the relevant stress–strain diagram (Fig. 1). They are the initial damage point (i), the intermediate damage point (1) and the ultimate damage point (u). The damage function is then assumed to be piecewise linear between the critical damage points and is subject to the limits $0 \leqslant d \leqslant 1$. Evolution of damage begins when the initial damage point is passed (measured in terms of strain), since $d = 0$ for $0 \leqslant \varepsilon \leqslant \varepsilon_i$. The damage value then increases linearly over the range $\varepsilon_i \leqslant \varepsilon \leqslant \varepsilon_1$, where damage equals d_1 when strain equals ε_1. Damage continues linearly over the range $\varepsilon_1 \leqslant \varepsilon \leqslant \varepsilon_u$, until the ultimate damage point is reached ($d = d_u$ when $\varepsilon = \varepsilon_u$). For $\varepsilon > \varepsilon_u$, the damage value grows asymptotically from d_u to a value of one.

Description of the fabric reinforced orthotropic material requires nine independent elastic constants. These are the