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Micromechanical crack growth-based fatigue damage in fibrous composites

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ABSTRACT

A partially debonded fibre can be analysed as a 3-D mixed Mode fracture case, for which the fibre–matrix detachment growth – leading to a progressive loss of the composite's bearing capacity – can be assessed through classical fatigue crack propagation laws. In the present research, the above mentioned case is firstly examined from the fracture mechanics theoretical point of view, and the effects of the stress field in the matrix material on the Stress Intensity Factors – SIFs – (associated to the crack representing the fibre–matrix detachment) are taken into account. Fatigue effects on the matrix material are accounted for by means of a mechanical damage, quantified through a Wöhler-based approach. A damage scalar parameter aimed at measuring the debonding severity during fatigue process is also introduced. Finally, some numerical simulations are performed, and the obtained results are compared with experimental data found in the literature.

1. Introduction

Composite structural materials typically consist of two or more constituents combined at a macroscopic level. Their classification is usually based on the kind of matrix material (polymers, metals, ceramics) and of reinforcing phase (fibres, particles, flakes). Due to their high-quality mechanical properties (such as improved tensile strength, fracture resistance, durability, corrosion resistance, enhanced wear and fatigue strength), composite materials – such as the fibre-reinforced ones – are commonly used in advanced engineering applications where traditional materials cannot conveniently be employed [1–3]. The mechanical properties of such multiphase materials depend on those of their constituents, i.e. the bulk material (matrix) and the reinforcing phase (such as fibres), as well as on their reciprocal interface bonding.

The strength and durability design of composite structural components must consider the typical damage phenomena occurring in such materials under in-service loading. Such degrading effects, typically responsible for a significant decrease of the mechanical performances of the structures, can mainly be related to the fibre–matrix delamination (also identified as debonding), fibre breaking, fibre buckling, matrix plastic deformation or cracking. These effects can be particularly relevant and dangerous for structural components under repeated loading [4–6].

The present research deals with a micromechanical-based approach for examining the fatigue behaviour of short-fibre-reinforced composites under uniaxial cyclic loading. The assessments of the damaging effects occurring in such non-homogeneous materials subjected to uniaxial cyclic loading (even under load levels much below the material strength) are very complex. Simple and reliable mechanics-based models for quantitative evaluation of such damaging effects are needed. In particular, the main degrading effects taking place in the matrix, in the fibres and affecting their reciprocal bonding are herein taken into account and quantified by analysing the mechanical damaging phenomena occurring at the micro-scale level.

The last Sections of the present paper show some comparisons with experimental data, and discuss some results of a parametric simulation aimed at underlying the mechanical effects of the involved parameters on the fatigue behaviour of fibre-reinforced multiphase materials.

2. Mechanics of fibre–matrix detachment

2.1. Shear lag model

At the beginning of the composite science development, the fibre–matrix debonding was studied through the classical shear lag model initially proposed by Cox [7]. Such a model examines a cylindrical portion of composite made by a fibre surrounded by a sufficiently large volume of matrix material, under remote tensile

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Nomenclature

$A, B > 0$ Wöhler's fatigue constants of the matrix material
c Fibre perimeter
C_i, m_i Paris constants of the fibre–matrix interface
$D_c(\sigma^*, R^*, N)$ Damage parameter after N loading cycles with stress amplitude σ^* and stress ratio R^*
$D_i = l/L_f$ Fibre debonding-related damage parameter
E_i Fibre–matrix interface Young modulus
$E_{m0}, E_m(N)$ Young modulus for the undamaged matrix material and reduced Young modulus after N loading cycles
E_f Elastic modulus of the fibre
$\mathcal{G}_{ic}$ Fibre–matrix interface fracture energy
$\bar{k}$ Shear stiffness of the fibre–matrix bonding
K_i Equivalent SIF for a partially debonded fibre
$K_{IC}, \Delta K_{th}$ Fibre–matrix interface fracture toughness and threshold SIF, respectively
$K_I(\sigma_r^\infty), K_{II}(\sigma_r^\infty) K_{II}(\sigma_z^\infty), K^*_{Mw}$ Mode I and Mode II SIFs due to the remote stresses σ_r^∞ and σ_z^∞ , respectively, and dimensionless SIFs due to the remote stress σ_w^∞ $(w = r, z)$
ΔK_i Stress-Intensity Factor range at the fibre–matrix interface
$L_{ad}, L_f, l = L_f - L_{ad}$ Adhesion length of a partially debonded fibre, fibre semi-length, and fibre debonded length, respectively
N^* Number of loading cycles to failure under stress amplitude $\sigma^* \leqslant \sigma_0$
$R = \sigma_{\min}/\sigma_{\max}$ Load ratio of the constant amplitude stress cycles
$v_{cg} = dl/dN$ Crack growth velocity measured with respect to the number of loading cycles
$\alpha = \frac{1}{(E_m \cdot A_m)} + \frac{1}{(E_f \cdot A_f)}$ $\beta = \sqrt{c \cdot \bar{k} \cdot \alpha}$ Parameters of the fibre–matrix composite material
$\varepsilon_f(z), \varepsilon_f^m, \overline{\varepsilon_f^m}$ Fibre strain and matrix strain measured along the fibre direction, and mean value of matrix strain
$[[\varepsilon_{f-m}(z)]], [[\overline{\varepsilon_{f-m}}]]$ Difference between the matrix and the fibre strain (strain jump) and corresponding averaged value along the fibre, respectively
ν_i, ϕ_f Fibre–matrix interface Poisson's ratio, and diameter of the fibre
μ, η Fibre volume fraction and matrix volume fraction
σ^*, σ_0^* Generic stress amplitude, and conventional fatigue limit of the matrix material
$\sigma_z^m(z), \sigma_z^f(z)$ Stress in the matrix material and in the fibre acting along the z-axis (coincident with the fibre direction)
$\sigma_r^\infty, \sigma_z^\infty$ Remote radial stress and remote axial stress (acting on a fibre)
$\tau_f(z)$ Fibre–matrix interface shear stress
$\tau_{f,f}, \tau_{f,u}$ Interface friction stress, and ultimate adhesion fibre–matrix interface shear stress

stress acting parallel to the fibre direction (Fig. 1a). The corresponding fibre–matrix interface shear stress $\tau_f(z)$ and the normal stress $\sigma_z^m(z)$ (acting parallel to the fibre axis) in the matrix can be expressed as follows (Fig. 1a) [8,9]:

$$\tau_f(z) = \frac{F \cdot \beta}{c} \cdot \left[\frac{\sinh(\beta \cdot z)}{\cosh(\beta \cdot L_f)}\right]$$

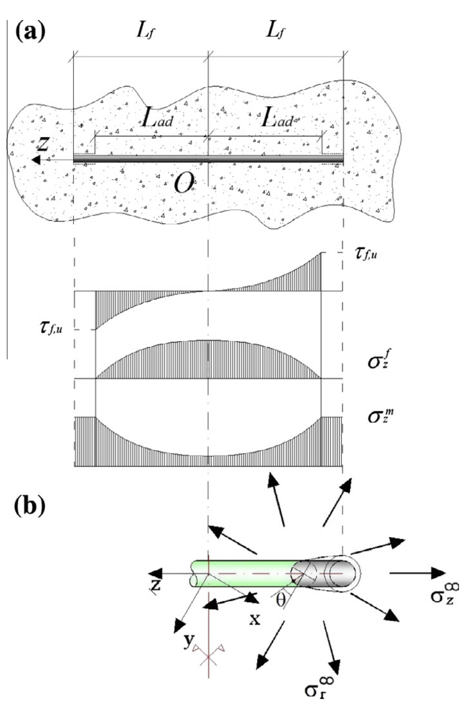

Fig. 1. (a) Stress distributions along the fibre in a partial debonding stage; (b) debonded extremity (3D cylindrical crack) of a fibre under remote radial (σ_r^∞) and axial (σ_z^∞) stresses.

$$\sigma_z^m(z) = \frac{P - f(z)}{A_m} = \frac{F}{A_m} \cdot \left\{\alpha \cdot E_m \cdot A_m - \left[1 - \frac{\cosh(\beta \cdot z)}{\cosh(\beta \cdot L_f)}\right]\right\} \quad (1)$$

with $\sigma_z^f(z) \cdot A_f + \sigma_z^m(z) \cdot A_m = P$

where P is the total force sustained by the composite cylindrical element, c is the fibre perimeter, A_f and A_m are the cross sections of the fibre and of the matrix that surrounds the single fibre, respectively, and $f(z) = \sigma_z^f(z) \cdot A_f$ is the axial force in the fibre.

Further:

$$\alpha = (E_m \cdot A_m)^{-1} + (E_f \cdot A_f)^{-1}, \ \beta = \sqrt{c \cdot \bar{k} \cdot \alpha}, \ F = P/(\alpha \cdot E_m \cdot A_m) \quad (1a)$$

where $\bar{k}$ is the stiffness of the fibre–matrix interface.

The strain jump, $[[\varepsilon_{f\text{-}m}(z)]]$, i.e. the difference between the matrix strain and the fibre strain, occurring in correspondence of the detached zones, can be written as follows [8,9]:

$$[[\varepsilon_{f-m}(z)]] = \varepsilon_f^m(z) - \varepsilon_f(z) \quad \text{with } \varepsilon_f(z) = s(\varepsilon_f^m(z)) \cdot \varepsilon_f^m(z) \quad (2)$$

where $s(z)$ is a scalar function which quantifies the local 'degree of sliding' between the fibre and the matrix. When $s(z) = 0$, the detachment is complete and $[[\varepsilon_{f-m}(z)]] = \varepsilon_f^m(z)$. When the bond is perfect – i.e. no strain jump occurs $[[\varepsilon_{f\text{-}m}(z)]] = 0$ – the sliding function tends to the unity, and the fibre strain coincides with the matrix strain in the fibre direction, $\varepsilon_f^m(z)$. Such a function can conveniently be written by using average quantities:

$$[[\overline{\varepsilon_{f-m}}]] = \overline{\varepsilon_f^m} - \varepsilon_f = \overline{\varepsilon_f^m} \cdot \left\lfloor 1 - s(\overline{\varepsilon_f^m}) \right\rfloor \quad (2a)$$

Consequently its mean value, $s(\overline{\varepsilon_f^m})$, can be evaluated based on the energy equivalence, i.e. by equating the actual elastic energy W stored in the fibre with the average energy $\bar{W}$ [4]:

$$s(\overline{\varepsilon_f^m}) = \frac{1}{\overline{\varepsilon_f^m} \cdot E_f} \cdot \sqrt{\frac{\int_{-L_f}^{L_f} \sigma_z^{f^2}(z) dz}{2L_f}} \quad (3)$$