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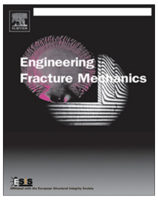

Micromechanical model for preferentially-oriented short-fibre-reinforced materials under cyclic loading

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ABSTRACT

The safety assessment of short-fibre-reinforced (SFR) composites, commonly used in structural applications involving repeated loads, requires to evaluate the degrading phenomena taking place in the matrix and at the fibre–matrix interface. The mechanical behaviour under both static and cyclic loading can be simulated applying damage degradation to the matrix mechanical characteristics, and employing fracture mechanics concepts to examine the fibre–matrix detachment as a 3D growing crack with degrading interface properties. In the present paper, a micromechanical model for unidirectional or random SFR materials under fatigue is developed. Some applications related to SFR polymeric composites found in the literature are presented.

1. Introduction

During last decades, Short-Fibre-Reinforced (SFR) composites have been used more and more for structural components due to the significant advantages provided by such a technology in terms of cost, weight and easy manufacturing with high production rate, aspects of fundamental importance for the industrial applications. Since most of such components are subjected to in-service cyclic loads, they have to be properly designed by taking into account the evolution of the material properties as well as the structural shaping (also at the microscopic level), and the effects related to both the loading conditions and the in-service environment effects. Consequently, a comprehensive knowledge of such materials is essential for an appropriate and economical design.

Many approaches have been formulated to analyse fatigue behaviour of traditional materials: empirical models based on the experimental Wöhler curves [1], power laws for propagating crack [2], approaches based on the critical plane theory [3], energy approaches [4], damage mechanics approaches [5], and so on.

Such fatigue aspects become more complex when SFR composites are involved, since the damaging phenomena are different from those related to traditional materials. Matrix fracture, crazing, fibre debonding and pull-out are commonly observed fatigue degrading mechanisms. Which failure mechanism is dominant depends on a variety of factors including the stress amplitude level, the strength of the fibre–matrix interface, the fibre orientation with respect to the load direction, and the glass transition temperature [6,7]. Moreover, the cyclic loads are responsible for both the decrease of the matrix mechanical properties and the reduction of the fibre–matrix bond stress-transfer efficiency. As a consequence of that, the criteria for the assessment of the SFR composite fatigue resistance have to be different from the classical ones applied to metallic materials.

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Nomenclature

$-B$	constant (negative) slope of the S–N Wöhler curve
$\mathbf{C}'_{eq}$, $\mathbf{C}'_m$, $\mathbf{C}'_f$	equivalent tangent elastic tensor of composite, tangent elastic tensor of matrix, tangent elastic tensor of fibre
C_i, m_i	Paris constants of the fibre–matrix interface
$D_m(\sigma_{0,ref}, N)$	uniaxial matrix damage parameter after N loading cycles with stress amplitude $\sigma_{0,ref}$
$D_{f,n}(N)$	multiaxial fatigue damage parameter
E_f, E_m, E_i	Young modulus of fibre, matrix and fibre–matrix interface, respectively
E'_f	tangent Young modulus of fibre
$E_{i0}, E_i(N)$	Young modulus for the undamaged fibre–matrix interface material and reduced value after N cycles, respectively
$E_{m0}, E_m(N)$	Young modulus for the undamaged matrix material and reduced value after N cycles, respectively
$\mathcal{G}_{ic}$	fibre–matrix interface fracture energy
K_i	equivalent Stress Intensity Factor (SIF) for a partially debonded fibre
K_{ic}	fibre–matrix interface fracture toughness
$K_I(\sigma_r^\infty), K_{II}(\sigma_r^\infty), K_{II}(\sigma_z^\infty), K^*_{Mw}$	Mode I and Mode II SIFs due to the remote stresses σ_r^∞ and σ_z^∞; dimensionless SIF due to the remote stress σ_w^∞ $(w = r, z)$
L_f, l	semi-length and debonded length of the fibre, respectively
N, N_f	actual number of loading cycles and number of loading cycles to failure for uniaxial load, respectively
R	stress ratio
$s(\overline{\varepsilon_f^m})$	sliding function
v_{cg}	crack growth velocity measured with respect to the number of loading cycles
ΔK_i, ΔK_{th}, ΔK_{ic}	equivalent stress intensity factor range, threshold SIF range, and critical SIF range, for cyclic remote stresses
$\overline{\varepsilon_f^m}$	average strain of the matrix along the fibre direction
μ_m, μ_f	matrix volume fraction and fibre volume fraction
$\upsilon_f, \upsilon_m, \upsilon_i$	Poisson's ratios of fibre, matrix, and fibre–matrix interface, respectively
σ_a, τ_a	normal and shear stress amplitudes, respectively
$\sigma_{af,-1}$, $\tau_{af,-1}$	normal and shear fatigue limits for fully reversed normal and shear stresses, respectively
$\sigma_{r,a}$, $\sigma_{z,a}$	radial and axial normal stress amplitudes, respectively
σ_r^∞, σ_z^∞	remote radial and axial stresses, acting on a fibre
$\sigma'_{r,a}$, $\sigma'_{z,a}$	dimensionless radial and axial normal stress amplitudes, respectively
$\sigma_{0,ref}$	reference remote applied stress amplitude
φ, ϑ	Euler angles defining the fibre spatial orientation
ϕ_f	diameter of the fibre

The fatigue behaviour of SFR materials has been discussed in several studies [8,9]. Due to the complexity of the problem, such a behaviour has traditionally been evaluated providing simple laws based on experimental data fitting. Empirical relationships have been developed only in few works [8,10,11].

In a recent literature review, Mortazavian and Fatemi [8] have presented various aspects influencing the fatigue behaviour of SFR polymer composites. Further, several experimental studies regarding SFR concrete under cyclic loading have been performed [9,12].

From experimental evidences, it can be noticed that the mechanical performance of SFR composites strongly depends on the fibre length and their orientation, and, in particular, the fatigue strength increases with the number of fibres aligned with the load direction [13–16]. In the case of short-fibre composites, the applied load transfers from the matrix to the fibres through the fibre ends and at the fibre–matrix interface. Such a load transferability is strongly affected by the fibre length [17,18]. Also the fibre aspect ratio is an important parameter and, in the case of SFR polymers, fatigue strength has experimentally been observed to increase with the fibre aspect ratio, until it reaches a plateau for fibre aspect ratio values greater than a particular value [8]. Another significant factor is the efficiency of the fibre–matrix interface [19,20], whereas the influence of the mean stress has also been examined by many authors [21–23].

Moreover, several studies have analysed multiaxial fatigue of SFR composites, including the effects of normal to shear ratio and phase shift at different temperatures and stress ratios [24]. It is worth mentioning that a multiaxial stress state can even be present under a remote uniaxial loading due to the anisotropy induced by the reinforcement on the matrix material, which can further be affected by high stress gradient due to notch or stress concentration such as that occurring in presence of short fibres [8].

Various mechanical parameters based on dissipative response of SFR composites have been used to characterise the damage accumulation and the fatigue life estimation under cyclic loadings [8]. Progressions of the hysteresis loop [25], strain energy [11], non-linear viscoelasticity [26], and hysteretic energy dissipation [27] are typical mechanical parameters used

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