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A progressive damage model for unidirectional fibre-reinforced composites based on fibre fragmentation. Part II: Stiffness reduction in environment sensitive fibres under fatigue

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Abstract

The mechanical behaviour of glass–fibre composites under fatigue or under long term stress is strongly influenced by the stress corrosion cracking of the fibres. In this paper, a stress corrosion model for composite materials reinforced with environment sensitive fibres has been developed and incorporated into a progressive damage model. The model is based on the definition of an effective stress, $\sigma^*(t)$, which depends on the stress story, that permits the initial failure probability, given by a Weibull distribution, to be used at any later time. This methodology has been incorporated to a thermodynamically consistent constitutive model valid for early fragmentation stages. The model may be used to account for the fibre's behaviour in numerical models based on the rule of mixtures. The ability of the extended progressive damage model to reproduce the stiffness loss of the composite under static or cyclic fatigue loads is demonstrated.

Keywords: A: Glass fibres; B: Corrosion; Fatigue; Fragmentation; Environmental degradation; C: Damage mechanics

1. Introduction

A progressive damage model for unidirectional fibre-reinforced composites based on fibre fragmentation is described in Part I of this work [1]. The aim of the present article is to extend the capabilities of the model to the fatigue behaviour of glass–fibre-reinforced polymer (GFRP) unidirectional laminates or to any fibre-reinforced laminate in general in which the fibres suffer a stress–corrosion–cracking degradation.

Glass fibres are known to weaken when they are stressed in tension in the presence of water molecules on their surface [2]. Glass fibres' sensitivity to stress and moisture has been shown to be responsible for the dependence of the S–N curves in fatigue experiments on the frequency of the cyclic load, which is not found in carbon composites [3–5]. The influence of hygrothermal ageing on the fatigue behaviour and durability of unidirectional GFRP has been reported in a limited number of investigations [3–9]. Moreover, glass–fibre composites in chemical plants and pipelines undergo chemical degradation. In experiments on flexural fatigue it has been shown that the stiffness loss in relation to the number of cycles exhibits some of the main characteristic of the delayed failure of a statistical population of glass fibres in a stress–corrosion–cracking mechanism [10]. Moreover, creep behaviour of GFRP in humid environments is also highly influenced by the strength loss of glass fibres.

In summary, this experimental evidence clearly points to the need to include this phenomenon in a damage

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model aimed at being an efficient tool for predicting long term behaviour of GFRP. In addition, it should be noted that GFRP are often applied in structural elements that operate in moisture rich environments (boats, wind turbine blades in offshore applications, etc.) or chemically aggressive environments (pipelines). Optimising the design of such parts requires the development of numerical tools with constitutive models that take into account the environmental degradation of the material.

Few models of fatigue-related degradation of mechanical properties account for this phenomenon. Most of the researchers and designers that deal with fatigue of composite materials use phenomenological approaches formerly developed for metals. However, because the fatigue behaviour depends on ply configuration it is convenient to use mechanistic models, which are based on the understanding of local damage mechanisms, their occurrence, their interaction and their effect on the degraded mechanical properties (reduced stiffness and strength). This mechanistic approach, although ideally being the most powerful approach, is still far from completion. Existing studies concerning a particular damage model can be considered as fragmentary ingredients of such a model. Successful mechanistic models for damage modelling in composite materials would require extensive partial investigations as well as large computation facilities.

Even though fibre fragmentation has been thoroughly studied to predict the strength of fibre-reinforced composites (see [11] for more references), few studies have related this phenomenon to the loss of stiffness during fatigue or to the whole fatigue behaviour ([10–14] and references therein).

In this paper, a mechanistic damage model for the stiffness loss during the first stages of fatigue degradation is presented. The model reproduces the stiffness evolution of the composite when the density of the fibre breaks is relatively small, that is, when global sharing of the load of the broken fibre may be assumed. The model does not aim to predict composite failure, which is governed by local load sharing and fibre failure coalescence. In the present investigation, the strength degradation of the fibres is easily incorporated into the progressive damage model introduced in Part I [1]. This thermodynamically consistent constitutive equation can account for the fibre behaviour in numerical models that are based on the rule of mixtures. These models require a constitutive model for each constituent. The present model gives the opportunity to introduce the environment motivated strength degradation of glass fibres, which is normally not taken into account. Moreover, in mesoscale models, where each ply of a laminate is taken as a homogeneous material, the present model in combination with the properties of the matrix may determine the lamina behaviour under on-axis stresses.

2. Stress–corrosion–cracking

Glass fibres have been known to be moisture sensitive since the early studies by Charles in the middle 50's [2]. When the fibre is stressed in opening mode (mode I) a surface flaw grows subcritically at a velocity $\mathrm{d}a/\mathrm{d}t$ given by

$$\frac{\mathrm{d}a}{\mathrm{d}t} = A\left(\frac{K_\mathrm{I}}{K_\mathrm{IC}}\right)^n, \tag{1}$$

where a is the flaw size, K_I is the stress intensity factor for mode I and K_IC is the mode I fracture toughness; n and A are experimental factors that depend mainly on the chemical environment and temperature. In the previous expression the growth rate dependency with the applied stress and crack size is implicitly contained in the stress intensity factor, K_I

$$K_\mathrm{I} = \sigma \cdot Y \cdot \sqrt{a} \tag{2}$$

being Y a geometric factor close to 1. Substituting Eq. (2) into Eq. (1) and by integrating along time, the flaw size evolution over time results as follows:

$$a(t)^{1-n/2} = a_0^{1-n/2} + \left(1-\frac{n}{2}\right)\cdot A \cdot \left(\frac{Y}{K_\mathrm{IC}}\right)^n \cdot \int_t \sigma(\tau)^n \,\mathrm{d}\tau, \tag{3}$$

where a_0 is the flaw size at $t = 0$. The ultimate strength of the fibre associated to the initial flaw of size a_0 is given by

$$\sigma^u(0) = \frac{K_\mathrm{IC}}{Y\cdot\sqrt{a_0}}, \tag{4}$$

whereas the same flaw, once it has grown to size $a(t)$ during time t, has a reduced ultimate strength given by $\sigma^u(t)$. The relationship between the ultimate strength at time t and the initial ultimate strength can be obtained by substituting Eq. (4) into Eq. (3) resulting in

$$(\sigma^u(t))^{n-2} = B \cdot \int_t \sigma(\tau)^n \,\mathrm{d}\tau + (\sigma^u(0))^{n-2}, \tag{5}$$

where B is a material constant (under isothermal conditions) given by

$$B = \left(1-\frac{n}{2}\right)\cdot A \cdot \left(\frac{Y}{K_\mathrm{IC}}\right)^2. \tag{6}$$

Eq. (5) provides the degradation of the ultimate strength related to the flaw (of initial size a_0) due to the stress corrosion phenomenon when the glass fibre has followed the stress story given by $\sigma(t)$. Therefore, fibre failure at time t associated to that flaw will occur if the applied stress at that instant overcomes the residual strength

$$\sigma(t) \geqslant \sigma^u(t). \tag{7}$$