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Effect of interphase on fibre-bridging toughness of a unidirectional FRP composite thin plate

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Abstract

A parametric analysis of the toughening mechanisms in a uniaxially fibre reinforced polymer (FRP) thin plate with a power-law hardening shear interphase is presented. An interfacial shear-lag model is used to analyse the relationship between the crack surface traction exerted by the intact fibres and the crack opening displacement (COD). Numerical solutions of the equations governing bridge-toughening are given. Two special kinds of interphase, i.e. linearly elastic and perfect plastic, are discussed. The results demonstrate that the toughening ratio of the composite thin plate is sensitive to several parameters, e.g. the thickness of the interphase between fibre and matrix, the hardening parameter of the interphase, the interfacial shear properties (stiffness and strength), the fibre radius and the far-field load. The results of this investigation will be beneficial to the selection of constitutive materials, the improvement of mechanical behaviour and the fabrication process of FRP composites.

Keywords: FRP composites; Toughness; Fibre-bridging; Interphase

1. Introduction

The advantages of utilizing fibre reinforced polymer (FRP) in structural engineering over conventional materials are well known, i.e. higher strength and stiffness to weight ratio, good resistance to corrosion and fatigue performance. As a new kind of structural material, its strength and toughness are topics of particular concern to the designers of structures made of such a material. Experimental research has confirmed that there are various energy dissipation mechanisms when an FRP is stressed to failure. From a fracture mechanics point of view, if an FRP specimen (e.g. a thin plate) is stressed by an increasing load, the presence of alternative energy dissipation phenomena (debonding, pull-out, fibre-bridging and friction) will result in an increase of the toughness [1]. The various energy dissipation mechanisms will generally occur at loads corresponding to a defined stress level. In these mechanisms, fibre-bridging behind a crack tip is one of the most important factors resulting in an increase of toughness during crack growth. This phenomenon is generally taken into account by considered the bridging zone as shielding the crack tip [2,3] thus reducing the net stress intensity factor (SIF).

In a number of publications [4–7] which discuss the bridge-toughening of various composites, a key issue is to find an appropriate relationship between the fracture surface traction $\sigma(x)$ supplied by the intact bridging fibres and the crack opening displacement (COD) $\delta(x)$, where x is the coordinate of an arbitrary point along the crack surface in the bridging zone (Fig. 1). The traction is influenced by both the sliding resistance of the fibre–matrix interphase and the mechanical behaviour of the bridging fibres. However, very little research has been carried out on the coupling effect of fibre-bridging and interphase. The present investigation provides a

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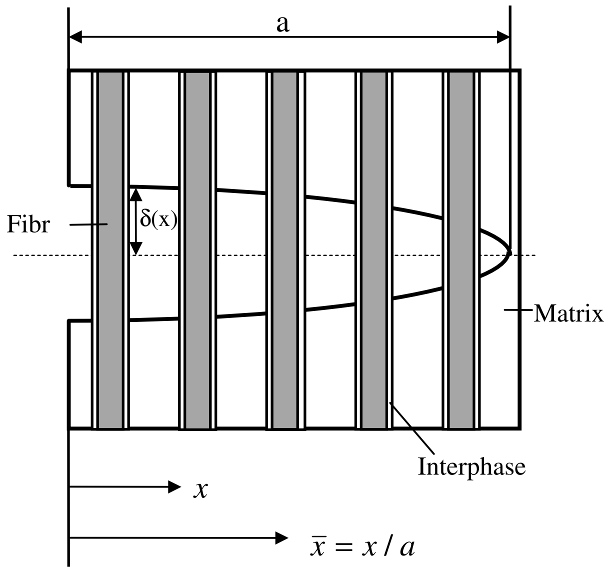

Fig. 1. Half of a central fully bridge crack in an FRP thin plate.

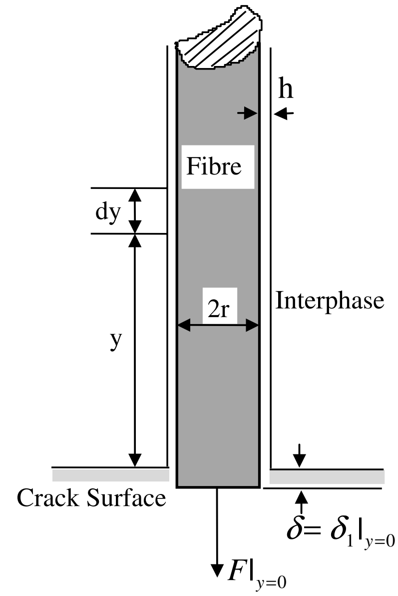

Fig. 2. Single fibre bridge model.

parametric analysis of the toughening mechanisms in uniaxially fibre reinforced polymer (FRP) with consideration of the coupling effect of interphase and fibre-bridging.

2. Analytical model

The model considered here is a central fully-bridged crack in an infinite uniaxially aligned FRP composite thin plate, with the fibres oriented perpendicular to the matrix crack. If the plate is sufficiently thin, a plane stress state is guaranteed. Due to the sizing and curing treatment of the fibres and polymer matrix a complicated chemical and physical reaction occurs, and it is this which leads to the formulation of the interphase (Fig. 2) between the fibres and matrix. An interphase with a certain thickness could have different behavioural properties such as elastic, elastic–plastic, perfect plastic, viscous, etc., depending on the sizing, the types of fibre and matrix and the curing process. If an external load is applied to the thin composite plate, crack propagation and stress transfer within the interphase will take place. As pointed out above, in this process, fibre-bridging behind a crack tip is one of the most important factors which influences the toughness increase during crack growth. The main topic of bridge-toughening analysis is therefore to determine an appropriate relationship between the bridging force and the COD. Without loss of generality, a power-law hardening interfacial layer (interphase) enveloping the fibres is assumed. The non-dimensional distance parameter $\bar{x} = x/a$ is introduced for simplicity, where x defines the location along the length of the crack from the crack midpoint, and a is the half length of the crack (Fig. 1). If the composite plate has a longitudinal modulus E_c and Poisson's ratio v, the governing equations for the dimensionless COD $\bar{\delta}$ and SIF $\overline{K}$ are respectively [8]:

$$\bar{\delta}(\bar{x}) = \int_{\bar{x}}^{1} \frac{\xi}{(\xi^2 - x^2)^{1/2}} \int_0^{\xi} \frac{1 - \bar{p}(\eta)}{(\xi^2 - \eta^2)^{1/2}} \, d\eta \, d\xi \tag{1}$$

$$\overline{K} = \int_0^1 \frac{1 - \bar{p}(\bar{x})}{(1 - \bar{x}^2)^{1/2}} \, d\bar{x} \tag{2}$$

$$\text{where} \quad \begin{cases} \bar{\delta} = \delta/\delta_0, \ \ \overline{K} = K/K_0, \ \ \bar{p} = p/\sigma_\infty \\ K_0 = 2\sigma_\infty \sqrt{a/\pi} \\ \delta_0 = 4(1 - v^2)a \cdot \sigma_\infty/(g\pi E_c) \end{cases}$$

and σ_∞ is the far-field stress normal to the crack plane and g is a constant which is slightly greater than unity [9] for a given composite thin plate. The bridging force $p(\bar{x})$ exerted by the fibres on the crack faces depends on the COD, $2\delta(\bar{x})$.

3. Shear-lag analysis

The solution of Eqs. (1) and (2) requires another independent relationship between $p(\bar{x})$ and $\delta(\bar{x})$. For the thin FRP plate with interfacial effect, it is difficult to obtain an exact description of the interfacial transfer stresses as well as the fibre stress and displacement [10,11]. Here a simple shear-lag approach is employed to analyse the interface stress transfer. Considering an embedded fibre at an arbitrary location, $\bar{x}$ (Fig. 2), the fibre is assumed to have a radius, r, and a constant