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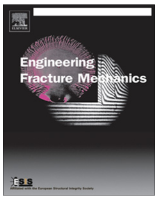

Fracture resistance enhancement of layered structures by multiple cracks

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ABSTRACT

A theoretical model is developed to test if the fracture resistance of a layered structure can be increased by introducing weak layers changing the cracking mechanism. An analytical model, based on the *J* integral, predicts a linear dependency between the number of cracks and the steady state fracture resistance. A finite element cohesive zone model, containing two cracking planes for simplicity, is used to check the theoretical model and its predictions. It is shown that for a wide range of cohesive law parameters, the numerical predictions agree well quantitatively with the theoretical model. Thus, it is possible to enhance considerably the fracture resistance of a structure by adding weak layers.

1. Introduction

Layered structures/materials often exhibit low interlaminar fracture resistance and are therefore susceptible to delamination when loaded. Through-thickness stresses, arising for example from manufacturing defects or geometric discontinuities, can result in propagation of interlaminar cracks which may lead to a substantial decrease in the structural integrity of a component [1,2].

As a result, many techniques have been developed to improve the through-thickness fracture resistance of layered structures and materials *e.g.* fibre reinforced polymer composites. However, at the same time, the in-plane properties are usually adversely affected [3]. In the field of composite materials, the research in developing damage tolerant composites can be categorised into two directions: (a) material improvements and (b) modifications of the fibre architecture.

Material improvements include modified/tougher matrices [4–7], effect of fibre/matrix interface [8–11] and interleaving concepts [12–16]. The alternative approach of modification of the fibre architecture includes stitching [17], knitting [18,19], weaving and braiding [20,21] of textiles laminates or z-pinning [3] usually for prepreg laminates [22,23].

All the above techniques aim, in general, to increase the fracture resistance of damage prone areas by making the damage prone areas stronger or tougher. In the present paper, an alternative approach is proposed, motivated by recent experimental work of Rask and Sørensen [24]. Testing Double Cantilever Beam (DCB) specimens, they observed that by changing the ply thicknesses of glass fibre/polyester composite beams bonded together with a thermoset adhesive, more delamination cracks could develop next to the adhesive/laminate crack. The overall steady-state fracture resistance was found to increase proportionally to the number of secondary cracks. These results suggest that a linear relationship may exist between the number of crack tips/fracture process zones and the overall steady state fracture resistance values.

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Nomenclature

Symbol	
h	ligament thickness
ℓ	crack length
n_i	unit vector oriented normal to the integration path
u_i	displacement vector
x_i	Cartesian coordinate system
B	width of DCB specimen
E	Young's modulus
F_{cr}	fracture criterion
H	height of DCB specimen
J	J integral
J_{ext}	J integral evaluated around the external boundaries of the specimen
J_h^+	J integral evaluated across the ligament in the positive x_2 direction
J_h^-	J integral evaluated across the ligament in the negative x_2 direction
J_{loc}	J integral evaluated locally around the active cohesive zone
J_{loc}^1	J integral evaluated locally around the primary crack
J_{loc}^{2-}	J integral evaluation of a left hand side of the secondary crack
J_{loc}^{2+}	J integral evaluation of a right hand side of the secondary crack
$J_{n,ss}^i$	total work per unit area of the normal traction (steady state fracture resistance) of crack number i
J_R	overall fracture resistance
$J_{R,ss}$	overall steady-state fracture resistance
$J_{t,ss}^i$	total work per unit area of the shear traction (steady state fracture resistance) of crack number i
K_n^i	stiffness of normal traction of cohesive law number i
K_t^i	stiffness of shear traction of cohesive law number i
L	length of DCB specimen
M_1	moment applied to the upper cantilever beam (taken positive in the anti-clockwise direction)
M_2	moment applied to the lower cantilever beam (taken positive in the anti-clockwise direction)
N	number of secondary cracks
W_n^i	work per unit area of normal traction for cohesive law number i
W_t^i	work per unit area of shear traction for cohesive law number i
δ_n^i	normal opening of cohesive law number i
$\delta_n^{c,1}$	critical normal separation of cohesive law of primary crack
$\delta_n^{c,2}$	critical normal separation of cohesive law of secondary crack
$\delta_n^{o,i}$	normal opening of cohesive law number i corresponding to $\hat{\sigma}_n^i$
$\delta_n^{*,1}$	end-opening of primary crack
$\delta_n^{*,2-}$	end-opening of left hand end of secondary crack
$\delta_n^{*,2+}$	end-opening of right hand end of secondary crack
δ_t^i	tangential opening of cohesive law number i
$\delta_t^{c,1}$	critical tangential separation of cohesive law of primary crack
$\delta_t^{c,2}$	critical tangential separation of cohesive law of secondary crack
$\delta_t^{o,i}$	tangential opening of cohesive law number i corresponding to $\hat{\sigma}_t^i$
θ	applied rotation angle
v	Poisson's ratio
σ_{ij}	stress tensor
σ_n^i	normal traction, i is the crack number
$\hat{\sigma}_n^1$	peak normal traction of primary crack
$\hat{\sigma}_n^2$	peak normal traction of secondary crack
σ_t^i	shear traction, i is the crack number
$\hat{\sigma}_t^1$	peak shear traction of primary crack
$\hat{\sigma}_t^2$	peak shear traction of secondary crack
σ_{22}	normal stress in the x_2-direction