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The effects of shear and near tip deformations on interface fracture of symmetric sandwich beams

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ABSTRACT

The effects of shear on energy release rate and mode mixity in a symmetric sandwich beam with isotropic layers and a debond crack at the face-sheet/core interface are investigated through a semi-analytic approach based on two-dimensional elasticity and linear elastic fracture mechanics. The semi-analytic expressions for the shear components of energy release rate and mode mixity phase angle which have been derived in Li et al. (2004) for bi-material beams are extended to sandwich beams and the necessary numerical coefficients derived through accurate finite element analyses. The expressions are combined with earlier results for sandwich beams subjected to bending moments and axial forces in order to obtain solutions for general loading conditions and for an extensive range of geometrical and material properties. The physical and mechanical significance of the terms of the energy release rate which depend on the shear forces are explained using structural mechanics concepts and introducing crack tip root rotations to account for the main effects of the near tip deformations. The results are applicable to laboratory specimens used for the characterization of the fracture properties of sandwich composites for civil, marine, energy and aeronautical applications, provided the lengths of the crack and the ligament ahead of the crack tip are above minimum lengths which are defined in the paper.

1. Introduction

Composite sandwich structures are widely used in marine, energy, aeronautical and civil engineering applications. Their main advantages over traditional metallic materials or monolithic composites are the high stiffness to weight and strength to weight ratios, which make them key enablers for present and future lightweight structures.

Sandwich structures, however, are highly susceptible to manufacturing flaws as well as in-service damage. For instance, debonds may arise at the face/core interfaces. Such debonds will degrade the load carrying capacity and integrity of the sandwich structure, and may even grow catastrophically during both quasi-static and fatigue loading, depending on their location and loading conditions. In order to assess the criticality of debond flaws, the fracture properties of the face/core interface have to be measured and used as input properties in fracture mechanical analysis models. Several mixed mode interface fracture tests have been proposed in the literature for the characterization of sandwich face/core interfaces (see review in [1]). The analysis of most of the proposed test specimens relies on approximate structural theories and/or numerical finite element analyses to define energy release rate and mode mixity phase angle. Knowing energy release rate and mode mixity angle allows the reduction of the fracture toughness and crack propagation rate vs. energy release rate from measured data for different crack tip mixed mode loading conditions.

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Nomenclature

a	crack length
a_i^M, a_i^P, a_i^{VS}, a_i^{VD}	root rotation compliance coefficients for layer arm i ($i = 1, 2$ or d, s)
A_i, D_i, A_{Vi}	axial, bending and shear stiffnesses of layer arm i ($i = 1, 2, 3$ or d, s, b)
$\widetilde{A}_i$, $\widetilde{D}_i$, $\widetilde{A}_{Vi}$	non-dimensional stiffnesses, $(\widetilde{A}_i, \widetilde{A}_{Vi}) = (A_i, A_{Vi})/(\overline{E}_1 h_1)$, $\widetilde{D}_i = D_i/(\overline{E}_1 h_1^3)$
c	length of intact ligament
E_i	Young's modulus of material i ($i = 1$ upper and lower face sheets, $i =$ c core)
$\overline{E}_i$	reduced Young's modulus: $\overline{E}_i = E_i$ (plane-stress), $\overline{E}_i = E_i/(1-\nu_i^2)$ (plane-strain)
E_*	$E_*^{-1} = (1/\overline{E}_1 + 1/\overline{E}_c)/2$
e_i	position of neutral axis of layer arm i (i = b, d, s) relative to core mid-thickness
f_M, f_P, f_{VD}, f_{VS}	coefficients defining dimensionless energy release rate for elementary load systems
M, P, V_D, V_S	
G_i	shear modulus of material i ($i = 1$ upper and lower face sheets, $i =$ c core)
$\mathcal{G}$	energy release rate
h_i	thickness of the layer arm i ($i = 1$ upper and lower face sheets, $i =$ c core)
$K = K_1 + iK_2$	complex crack tip stress intensity factor
K_I, K_{II}	mode I and mode II stress intensity factors in beam with $\beta = 0$
M, $P + M_*$, V_S, V_D	self-equilibrated systems of crack tip bending moments, axial forces and single and double shear forces per unit width
M_i, N_i, V_i	crack tip bending moment, axial force and shear force per unit width in layer arm i ($i = 1, 2, 3$ or d, s, b)
M_i^e, N_i^e, V_i^e	bending moment, axial and shear forces acting per unit width on end sections of layer arm i ($i = 1, 2, 3$ or d, s, b)
S_i	shear area of layer arm i ($i = b, d, s$)
α, β	Dundurs' parameters of interface between core an upper layer
γ_M, γ_{VD}, γ_{VS}	modified phase angles for elementary load systems, e.g. $\gamma_M = \psi_M - \omega + \pi/2$
γ_i	global shear strain in the layer i (i = b, d, s)
$\Delta\varphi_{i,j} = \varphi_i - \varphi_j$	crack tip root rotation between layer arms i and j
Δu_x, Δu_y	relative crack sliding and opening displacements
ε	oscillatory index, $\varepsilon = 1/2\pi \ln[(1-\beta)(1+\beta)^{-1}]$
ε_{ij}	strain component i, j
η	relative face/core thickness, $\eta = h_1/h_c$
κ_i	shear correction factor of layer i ($i = 1, 2, 3$ or b, d, s)
ν_i	Poisson's ratio of material i ($i = 1$ upper and lower layers, $i = c$ core)
φ_i	bending rotation of layer arm i at crack tip cross section ($i = 1, 2, 3$ or d, s, b)
φ_i^e	bending rotation of layer arm i at end cross section ($i = 1, 2, 3$ or d, s, b)
σ_{ij}	stress component i, j
$\Sigma = \overline{E}_1/\overline{E}_c$	non-dimensional ratio of face/core Young's moduli
$\psi = \psi_{h1}$	phase angle of complex stress intensity factor giving ratio of shear and normal stresses at distance $r = h_1$ from crack tip
ψ_M, ψ_P, ψ_{VD}, ψ_{VS}	phase angles for elementary loading systems M, P, V_D, V_S
$\omega = \psi_P$	phase angle for pure axial loading

Subscript and superscripts

d, s, b	indices for delaminated, substrate and base arms (1, 2, 3 also used)
VD, VS	indices associated to elementary load systems of double and single shear
1, c	indices used for upper face sheet and core layer

Semi-analytic solutions based on 2D elasticity for sandwich beams subjected to generalized end forces are already available in the literature [2,3]. These solution, however, are limited to loading by pure bending and axial forces and are therefore applicable only to a limited number of fracture mechanics specimens, such as the Double Cantilever Beam specimen with Unequal Bending Moments, DCB-UBM [2,4]. However, most of the fracture specimens for sandwich composite systems are also subjected to shear, e.g. the Single Cantilever Beam (SCB), Double Cantilever Beam (DCB), Cracked Sandwich Beam (CSB), and Mixed Mode Bending (MMB) sandwich specimens. In all such cases shear is expected to modify crack tip fields and fracture parameters, as shown for the SCB sandwich specimen in [5] and for bi-material beams with interface cracks and edge-cracked homogeneous beams in [6,7].

The semi-analytic expressions derived in [2,3] for energy release rate and mode mixity phase angle in symmetric and asymmetric sandwich specimens subjected to axial forces and bending moments were obtained following and extending the method originally formulated by Suo and Hutchinson for isotropic, orthotropic and bi-material elastic layers [8,10,11,9]. The energy release rate is derived in closed form and coincides with predictions based on classical structural theories which assume the delaminated beam arms to be rigidly clamped at the crack tip cross section. In this problem the energy release rate is not affected by the near tip deformations or by the work done in the process zones ahead of the crack tip and depends only on the applied forces and the material and geometrical properties of the arms. The semi-analytic expressions of the mode mixity angle, on the other hand, require the numerical derivation of a single, load independent, dimensionless coefficient, which is typically chosen as the mode mixity angle associated to loading by pure axial forces.

The presence of shear forces substantially modify the response. Shear deformations along beam arms, near tip deformations and nonlinear mechanisms at the crack tip affect both the energy release rate and the mode mixity angle and must be accounted for in the derivations. The effects of shear on the fracture parameters has been studied using Linear Elastic Fracture Mechanics (LEFM) concepts in [6] for isotropic bi-material layers and in [7] for edge-cracked orthotropic layers. Using two different approaches, which will be reviewed and applied later in the paper, semi-analytic expressions were derived in [6,7] for energy release rate and mode mixity phase angle. The expressions depend on four numerically derived coefficients which add to that required for axial/bending loading.

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