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Crack front morphology near the free edges in double and single cantilever beam fracture experiments

Alex Møberg, Michal K. Budzik *, Henrik M. Jensen

Aarhus University, Department of Engineering, Inge Lehmanns Gade 10, 8000 Aarhus C, Denmark

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We analyse edge effects in two common adhesive joint fracture configurations, namely the single and the double cantilever beam tests. Several experiments were performed studying the crack front vicinity for deflection and crack front morphology using light scanning and microscopy techniques. To understand the findings a finite element model is used to determine the energy release rate at the crack front, particularly in the vicinity of free edges. Two approaches - an inverse procedure and a direct method - are compared. Using the inverse procedure, the local values of energy release rate along the experimentally obtained crack front are investigated. With this approach, the fracture criterion is however not necessarily fulfilled at each node along the crack front. In the direct method, a mixed-mode fracture criterion is used to determine the shape of the crack front at steady-state propagation. Qualitatively, the direct method stays in good agreement with experimental findings, showing that the free edges are likely to affect crack front morphology. A full match between the experimental results and numerical simulations can be achieved by using the Poisson's ratio as a fitting parameter.

1. Introduction

Multi-layered materials are used in many advanced structural applications: automotive, aerospace, wind energy, and microelectronics. Basic understanding of interface fracture is of fundamental importance. Single [1], and double cantilever beam tests [2], referred to as SCB and DCB respectively, are the most common experimental procedures used to assess the interfacial fracture toughness of such materials. While the SCB tests are used to study the crack onset and propagation between two dissimilar materials, the DCB tests are standardized for balanced joints, in which the material and geometrical parameters of the adherents are the same. A considerable amount of work has been published to investigate these configurations, their advantages, drawbacks, and flaws [3–6]. While in the SCB tests, due to the material and geometrical mismatch, mixed-mode conditions are produced at the crack tip, in the DCB tests, thanks to symmetry, pure mode I fracture occurs [7–9]. Importantly, the standard way of treating both configurations makes use of a one-dimensional beam model which, although efficient and providing phenomenological insights, does not allow to fully understand and investigate the crack front shape. In reality, bonded plates or shells are not simple one-dimensional beams and thus a more complex stress state can be expected once a refined analysis is employed, most of the time using numerical methods [10,11].

* Corresponding author.
E-mail address: mibu@eng.au.dk (M.K. Budzik).

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Nomenclature

a	crack length
A, B	constants
C	Searle's parameter
E_{adh}	Young's modulus of the adhesive
E_n	Young's modulus, $n = 1, 2$ refers to material 1 or 2
F_{ext}	applied external force
G_c	fracture energy
G_e	calculation error of the energy release rate, $G_e = \|G - G_c\|$
G_m	Energy Release Rate, $m = I, II$ or III depending on the fracture mode
G_{tot}	ΣG_m
h	thickness of the layer/specimen
I	second moment of the area
K_m	stress intensity factor
M, M_i	bending moment along $i = x, y, z$
N, N_i	membrane force normal to the crack front
n_i	unit normal vector
m_i	unit tangent vector
p	free edge singularity exponent
P	out-of-plane nodal force at the crack front
r	distance from the crack tip
R	radius of longitudinal curvature
R_t	radius of transverse curvature
T, T_i	shear forces tangent to the crack front
w	deflection
W	width of the specimen
x, y, z	coordinates of the Cartesian system
α, β	Dundurs' parameters
δ	deflection at the free tip of the beam [= $w(y = 0)$]
ΔN	residual stress
ϵ	bi-material constant
κ_n	3-4ν_n for plane strain
κ_n	3-$\nu_n/1 + \nu_n$ for plane stress
λ_i	mixed mode fracture fitting parameters, $i = 1, 2, 3$
μ_n	shear modulus
ν_n	Poisson's ratio
σ_{ij}	stress tensor, i,j=x, y or z for $i = j$
τ_{ij}	stress tensor, i,j=x, y or z for $i \neq j$
φ	mode III phase angle
ψ	mode I/II phase angle
ω	phase factor

Therefore the crack front morphologies differ from the expected straight-sided shapes [11,12] with the vicinity of the free edge of the specimen being somehow overlooked. Once the crack propagates all along the front, the energy release rate, possibly adjusted for mixed mode effects, should become constant and steady-state propagation would be expected. Edge effects could affect the initial crack onset and steady-state crack propagation stages, where the entire crack front is propagating in a self-similar fashion [13]. Insight into effects caused by intersection of the crack front with a free edge could be achieved by studying the stress state at interface corners [14]. The practical implications of these studies include relations between the crack length observed from the side of the specimen and the crack shape inside the specimen. Since the pioneering work by Mostovoy, Ripling et al. [15,16], the presence of a curved crack front in the fracture of adhesively bonded joints have be recognized and is now well-known. During the last decades, this topic has been investigated by a number of authors by using analytical and numerical models, as well as experimental testing [17–24]. However these approaches were focusing mainly on the main parabolic shape of the crack as expected in middle part of the specimen.

Studies of crack front morphology in the DCB specimens are still rare, and the crack front shape and the free edge effects seem overlooked in such geometries. It has been argued that the general, curved shape of the crack front should be associated to the anticlastic bending, however the behaviour close to the edges was not investigated [24,25]. Transitions between