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Validation of an H_{cr}-based fracture initiation criterion for adhesively bonded joints

Angelos Mintzas *, David Nowell

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

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ABSTRACT

The singular stress fields that develop around wedges found in adhesively bonded scarf and double lap joint configurations are fully determined by employing Williams' eigenfunction expansion method in combination with a path independent contour integral method. The intensities of the near-tip stress fields (H) are then used as fracture initiation parameters in order to predict the strengths of these joints. The predicted strengths are compared to experimental results found in literature and the conditions for the validity of the proposed H_{cr}-based fracture initiation criterion are examined.

1. Introduction

Adhesive bonding has gained the attention of various industries such as automotive, marine and aerospace over the last decades. The development of higher performance adhesives as well as the necessity to join efficiently a large variety of material combinations such as metal to composites, ceramics to composites, etc. has led to a partial shift from mechanical fastening techniques to adhesive bonding ones [1]. Although one of the main advantages of adhesively bonded joints is the more uniform distribution of stresses over the whole joined area, when compared for example to bolted or riveted ones, stress concentrations or even singularities at the interface corner, where the two dissimilar materials meet cannot be avoided. Given the singular nature of the stresses and strains, conventional failure criteria can be applied only when the values of stresses/strains are evaluated at a distance from the singular corner [2] or by averaging them over an area. Unfortunately, this area or distance is found to be a function of the joint geometry and the material properties of the constituent parts and experiments are needed for its determination [3]. A fracture mechanics approach therefore seems more appealing when dealing with such problems.

Williams [4] first developed an asymptotic method for the determination of the elastic singular stress field that develops around re-entrant corners in isotropic materials. Since then, a number of researchers have applied the method to bimaterial wedges in isotropic [5–8] and anisotropic materials [9–12] as well as to multi-material wedges [13–15]. A general summary of the main formulae involved is provided by [16]. However, all of the studies reported above focused on the determination of the order of the stress singularity ($\lambda - 1$) and its dependence on the wedge geometry and material combinations. It was only after the 1970s that scientists [17–24] became interested in fully characterising the near-tip stress and displacement fields and thus attempted to calculate their intensities, i.e. the generalised stress intensity factors (H). Over the last years there have been a number of studies that have successfully correlated fracture of specimens containing monolithic [25–27] and bimaterial wedges [28,29] to a critical value of the generalised stress intensity factor (H_{cr}). Therefore, the idea of using H as a fracture initiation parameter in an analogous way to the use of the crack tip stress intensity factor (K) in

* Corresponding author. Tel.: +44 1865 283475; fax: +44 1865 273906.
E-mail address: angelos.mintzas@eng.ox.ac.uk (A. Mintzas).

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Nomenclature

A_{jm} $j = 1,\ldots,8$ arbitrary constants of the asymptotic stress/displacement fields
b joint thickness along dimension perpendicular to X–Y plane
$B(\lambda)$ 8×8 matrix obtained from the boundary conditions of a bimaterial wedge
c double lap joint overlap length
C outer contour integral path
C_{an} analytical contour integral path in Eq. (12)
C_1, C_2, C_3 rectangular contour integral paths
C_r circular contour integral path
d double lap joint adherend length
$E_m m = 1, 2$ Young modulus for isotropic materials
E_{11}, E_{22}, E_{33} Young moduli for orthotropic material
$f_{ijk,}$ $k = 1,\ldots,\infty$ angular variations of the actual stress field
f'_{ijk}, $k = 1,\ldots,\infty$ angular variations of the auxiliary stress field
F_u joint failure load
g_{ik}, $k = 1,\ldots,\infty$ angular variations of the actual displacement field
g'_{ik}, $k = 1,\ldots,\infty$ angular variations of the auxiliary displacement field
G_{12}, G_{13}, G_{23} shear moduli for orthotropic material
h adhesive thickness
H_{cr} critical value of the generalised stress intensity factor
H_k, $k = 1,\ldots,\infty$ generalised stress intensity factors of the actual fields
H'_k, $k = 1,\ldots,\infty$ generalised stress intensity factors of the auxiliary fields
$I_{\theta 1 \theta 2}$ integral depending on f_{ijk}, g_{ik}, f'_{ijk}, g'_{ik}
L scarf joint adherend length
$m = 1, 2$ material index
M_o double lap joint internal bending moment
P multiplication factor for the plastic yield zone size
r radial wedge tip coordinate
r_s radial extent of the singular stress field
r_{ym}, $m = 1, 2$ radial extent of the yield zone size
t actual traction field
t' auxiliary traction field
t_a double lap joint adherend thickness
u actual displacement field
u_i^{FE} displacement components evaluated from finite elements
u' auxiliary displacement field
w scarf joint adherend width
X, Y Cartesian coordinates
$Y(h/w)$ correction factor for H
θ polar wedge tip coordinate
θ_m $m = 1, 2$ angles shown in Fig. 1
λ_k, λ'_k $k = 1,\ldots,\infty$ eigenvalues of the elasticity wedge problem
$\lambda_k - 1$ order of the stress singularity
v_m, $m = 1, 2$ Poisson's ratio for isotropic materials
v_{12}, v_{13}, v_{23} Poisson's ratios for orthotropic material
σ_o far field load
σ_{ij} stress components
σ_{ij}^{FE} stress components evaluated from finite elements
σ_u joint strength

classical linear elastic fracture mechanics is becoming more mature. The most extensively studied adhesively bonded joint configuration is the scarf joint [30–36] for which H_{cr} values have been calculated for various material combinations, geometries, mechanical and thermal loadings. Single lap and double lap joints are amongst the most widely used joint configurations for structural joining applications as well as for testing joints and adhesives. Penado presented a comprehensive analysis of all the possible singular regions that can be found within adhesively bonded single lap joints with isotropic [37] and anisotropic adherends [38]. However, to the best of the writer's knowledge, only Groth [39] has attempted to predict the failure loads of adhesively bonded single lap joints by using an H_{cr}-based criterion. This was only achieved with moderate success since the conditions for the validity of the criterion were not examined. As with classical linear elastic fracture mechanics, an H_{cr}-based criterion will only be strictly valid when the region affected by material non-linearities and deviations from the perfectly sharp geometry is significantly smaller than the region dominated by the singular field.