Engineering Fracture Mechanics 98 (2013) 296–314

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Modelling the static response of unaged adhesively bonded structures

S. Sugiman [a], A.D. Crocombe [b,*], I.A. Aschroft [c]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Mataram, Mataram, West Nusa Tenggara 83125, Indonesia
[b] Division of Mechanical, Medical and Aerospace Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, UK
[c] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, UK

ARTICLE INFO

Article history:
Received 27 January 2012
Received in revised form 31 August 2012
Accepted 14 October 2012

Keywords:
Aluminium alloys
Cohesive zone modelling
Damage

ABSTRACT

A cohesive zone model has been used to model the progressive damage in adhesively bonded aluminium monolithic single lap joints and laminated doublers. The backface strain technique was used to monitor the damage process in the adhesive layer and was also key in the calibration of a unique set of cohesive zone properties in the single lap joint. Further, this backface strain technique has been successfully used to assess the effect of substrate plasticity, position of cohesive elements, traction and fracture energy, and adhesive fillet in a monolithic single joint. The calibrated cohesive properties have then been successfully used to predict the static strength and backface strain response of the doublers in bending.

1. Introduction

First introduced by Barenblatt [1,2] for metals, the cohesive zone model (CZM) has been extensively used to simulate the progressive damage (initiation and propagation) in adhesively bonded joints. When predicting the failure load and failure process of adhesively bonded joints, the CZM properties should be determined properly. The main parameters of a CZM are the traction and the fracture energy. Some researchers [3–5] determined the normal and shear fracture energy from wedge double cantilever beam (DCB) and end notch flexure (ENF) specimens respectively, while the normal and shear tractions were obtained from the tensile bulk adhesive and the torsion butt joint, respectively. They reported good agreement between the numerical and the experiment results. However, the damage process in the adhesive layer was not investigated. Other methods to determine the CZM parameters as reported by da Silva and Campilho [6] are direct and inverse methods and both approaches are able to give an accurate predicted response of the material system studied.

Another aspect of the cohesive zone model is the shape of the unloading response. Many shapes of CZM have been proposed and used in modelling of fracture including exponential, polynomial, trapezoidal, and bilinear. A comparison of these models has been made and reported in literature. Chandra et al. [8] studied the effect of the bilinear and exponential shape of the CZM on the prediction of silicon carbide fibre push out in a metal matrix and found that the shape of CZM has a significant effect on the load–displacement response. Here, although the geometry is small, the bulk stiffness is very high. Volokh [7] studied the effect of the CZM shape (bilinear, parabolic, sinusoidal, and exponential) on the predicted load–displacement response of a rigid block peel specimen and also found that CZM shape has a significant effect on the load–displacement response. Alfano [9] studied the effect of a bilinear, an exponential, a trapezoidal, and a parabolic shape of CZM on the predicted response of an aluminium DCB and a steel compact tension specimen and reported that for a typical DCB (i.e. made of aluminium with thickness of 3 mm, with a modulus of 70 GPa), the shape of CZM does not have a significant effect on the predicted load–displacement response. However, with the increase of specimen geometry (thickness of 60 mm), a variation

* Corresponding author. Tel.: +44 1483 689194.
E-mail address: a.crocombe@surrey.ac.uk (A.D. Crocombe).

0013-7944/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfracmech.2012.10.014

Nomenclature

D	scalar damage variable
E	Young's modulus, GPa
G	shear modulus, GPa
G_C	fracture energy, kJ/m^2
G_T	total strain energy release rate (sum of SERR of mode I, mode II, and mode III), kJ/m^2
G_I, G_{IC}	strain energy release rate (SERR) and its critical value under mode I loading respectively, kJ/m^2
G_{II}, G_{IIC}	strain energy release rate (SERR) and its critical value under mode II loading respectively, kJ/m^2
G_{III}, G_{IIIC}	strain energy release rate (SERR) and its critical value under mode III loading respectively, kJ/m^2
G_{mC}	mixed mode fracture energy, kJ/m^2
$K_{n,s,t}$	elastic stiffness for normal, first and second shear direction of cohesive zone, N/mm^3
P	applied load, kN
T_n, $T_{n,max}$	normal traction and its maximum value respectively, MPa
T_s, $T_{s,max}$	first shear traction and its maximum value respectively, MPa
T_t, $T_{t,max}$	second shear traction and its maximum value respectively, MPa
$\overline{T}_n$	normal traction component without damage, MPa
$\overline{T}_s$	first shear traction component without damage, MPa
$\overline{T}_t$	second shear traction component without damage, MPa
t_{CZM}	cohesive element thickness, mm
v	Poisson's ratio
δ_n^f	normal separation at failure, mm
δ_s^f	first shear separation at failure, mm
δ_m^f	mixed mode separation at failure, mm
δ_o, δ_f	separation at maximum traction and at failure respectively, mm
η	a material parameter
CAE	chromic acid etching
C3D8	8-node linear bricks
COH3D	three dimensional cohesive element
CPE4	4-node quadrilateral plane strain elements
CPS4	4-node quadrilateral plane stress elements
CZ	cohesive zone
CZM	cohesive zone model
DCB	double cantilever beam
ENF	end notch flexure
FE	finite element
LDB	laminated doublers in bending
MSLJ	monolithic single lap joint
PAA	phosphoric acid anodising
SG	strain gauge
XFEM	extended finite element method
2D	two-dimensions
3D	three-dimensions

of predicted load–displacement response occurred at the vicinity of peak load (bilinear and exponential were close but trapezoidal and linear parabolic were higher than both bilinear and exponential). When the thickness of specimen was 100 mm and the substrate modulus increased from 70 GPa (aluminium) to 210 GPa (steel), a variation of predicted peak load between bilinear and exponential, and trapezoidal and linear parabolic of up to 15% was observed. Further, this variation was also observed in the mode II pull out test made of aluminium where extensional stiffness is involved rather than flexural stiffness. The length of cohesive zone increased with the increase of specimen size and stiffness (from approximately 1.5 mm for aluminium DCB with thickness of 3 mm to approximately 12 mm for thickness of 60 mm, while for a steel compact tension specimen, the cohesive zone length was approximately 23 mm). Thus, the shape of CZM has a more significant effect when the geometry and bulk stiffness is relatively large resulting in a large cohesive zone length as well.

A useful method for monitoring the damage process in the adhesive layer of a bonded joint is the backface strain technique. This technique was initially introduced by Abe and Satoh [10] to monitor the crack initiation and propagation in welded structures. Then that technique was employed in adhesively bonded joints by Zhang et al. [11] to monitor damage propagation by placing the strain gauges (SGs) on the substrate in the overlap region. Further, Crocombe et al. [12] studied the backface strain technique in adhesively bonded joints numerically. It was found that when there was no crack in the adhesive layer, the backface strain reached a maximum just outside the overlap and when a crack was introduced at one