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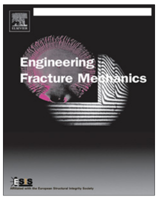

Characterizing cohesive zone model using a mixed-mode direct method

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ABSTRACT

In this paper, a direct method was proposed for determining the traction–separation laws (TSL) of cohesive zone model in modes I, II and mixed-mode using a mixed mode bending (MMB) specimen tested in different mixed-mode ratios and a compliance based beam method. The method was applied on adhesively bonded joints. TSLs obtained using the proposed method were in good agreement with TSLs obtained independently from double cantilever beam (DCB) and end notch flexure (ENF) tests representing pure mode stress states. Moreover, the mechanical behaviors of the MMB, DCB and ENF specimens were reasonably well predicted using the obtained TSLs.

1. Introduction

Adhesive bonding has attracted considerable attentions in various industries. Adhesively bonded joints are being rapidly replacing other conventional joints due to their superior advantages such as higher strength to weight ratio, cheaper fabrication process, lower stress concentration and better fatigue properties.

Various factors such as geometrical, material and environmental factors can considerably affect the mechanical behavior of adhesively bonded joints. To improve the applicability of adhesive bonding even more widespread, the effects of various factors need to be fully known. The effects of the mentioned factors can be studied experimentally and numerically. However, experimental testing is usually costly and time consuming. Therefore, numerical modeling can effectively assist engineers to minimize the experimental efforts. Damage modeling is of vital importance in adhesively bonded joints. The cohesive zone model (CZM) has received significant attention in damage modeling for a wide variety of problems and materials (e.g. FRP-concrete [1,2] and FRP-steel materials [3]). This method combines continuum damage and fracture mechanics concepts to model material damage behavior [4]. The CZM was introduced by Barenblatt [5,6] based on the Griffith's theory. He assumed that finite molecular cohesion forces exist near the crack fronts and expressed the crack propagation in brittle materials using this model. Later, Dugdale [7] took the process zone at the crack tip into account and managed to extend the model for plastic materials. Hillerborg et al. [8] for the first time brought CZM in finite element computational framework. They suggested a fictitious crack model for studying the crack growth in cementitious materials. Their work was of crucial importance as they defined traction versus crack opening displacement and therefore the current description of CZM in the form of traction–separation law was formed. This was in contrast with the previous works (e.g. [5–7]) where the cohesive zone traction had been defined as a function of the crack tip distance. Other researchers improved the model by proposing

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Nomenclature

COD	crack opening displacement
CZM	cohesive zone model
DCB	double cantilever beam
DIC	digital image correlation
ENF	end notch flexure
MMB	mixed mode bending
SERR	strain energy release rate
TSL	traction–separation law
a	crack length (mm)
a_0	initial crack length (mm)
a_e	equivalent crack length (mm)
B	substrate width (mm)
c	lever arm distance (mm)
C	mixed-mode compliance (mm/N)
C_0	initial compliance (mm/N)
C_I	mode-I compliance (mm/N)
C_{II}	mode-II compliance (mm/N)
E	elastic modulus (MPa)
E_{eq}	equivalent elastic modulus (MPa)
G	shear modulus (MPa)
G_I	mode-I strain energy release rate (N/mm)
G_{II}	mode-II strain energy release rate (N/mm)
G_T	total strain energy release rate of modes I and II (N/mm)
G_{IC}	mode-I fracture energy (N/mm)
G_{IIC}	mode-II fracture energy (N/mm)
h	substrate height (mm)
L	specimen half-length (mm)
m	mixed-mode ratio
P	load (N)
P_I	mode-I portion of MMB load (N)
P_{II}	mode-II portion of MMB load (N)
t_n	traction in normal direction (MPa)
t_s	traction in shear direction (MPa)
t_n^0	tripping traction in normal direction (MPa)
t_s^0	tripping traction in shear direction (MPa)
u	mode-I crack opening displacement (mm)
v	mode-II crack opening displacement (mm)
w	mixed-mode crack opening displacement (mm)
α	ratio of modes I and II fracture energies
β	parameter in lever arm relation
χ	crack length correcting factor
Γ	elastic modulus correction parameter
δ	displacement (mm)
δ_I	mode-I portion of MMB displacement (mm)
δ_{II}	mode-II portion of MMB displacement (mm)
η	material parameter

various traction–separation functions and applying the model to different problems and different materials, such as the fracture of metals, polymers, ceramics, composites and their compositions. For example, Needleman [9,10] suggested a number of different functions for traction–separation relationship including polynomial [9] and exponential [10]. More details about the different functions can be found in Ref. [11]. Using the framework developed by Hillerborg et al. [8], opening/sliding constitutive models for zero-thickness interface elements were employed by several researchers [12–15] in modeling the fracture behavior of cohesive-frictional materials in a meso-scale level. An important point in employing cohesive zone model is determining the traction–separation law. For this purpose, several methods are available which can be categorized into two main groups; namely inverse and direct methods. In the inverse methods, by considering some assumptions such as the shape of traction–separation curve, the cohesive zone model parameters are tuned so the experimental macroscopic damage