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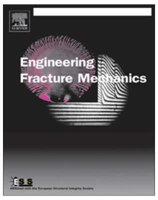

Constitutive law of adhesive layer measured with mixed mode bending test

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ABSTRACT

New analytical theory is presented in this paper to measure the mixed mode constitutive law of adhesive bonding. The theory is on the basis of the J-integral theory and the mixed mode bending test. The fracture energy and the mode I/II constitutive law components were obtained at different mode mixity ratios. A comprehensive discussion is carried out with focus on the plastic yielding and initiation of localized damage. In situ SEM was used to analyse the tension/shear deformation mechanisms. The mixed mode fracture energy is found to increase significantly as the mode mixity ratio increased. The tension stress started to decrease after plastic yielding, while the shear stress kept increasing until the emergence of localized damage. This difference was attributed to the anisotropy of the adhesive material, caused by shear banding. The plastic deformation consisted of cavitation caused by tension and shear banding caused by shear. The present method is verified with numerical simulations. The constitutive law measured with the present method can be used to develop new cohesive zone models, and may produce a more accurate analysis of adhesive bonded structures than existing methods do.

1. Introduction

Adhesive bonding is now used in a variety of fields including aerospace and marine industries. Accurate and reliable analysis of the mechanical properties of adhesive bonding is essential for its successful application in load bearing structures.

Many analysis methods have been developed which are mainly on the basis of one of the following two mechanical properties: strength (critical stress or strain) and fracture toughness (G_C, K_C). Some strain or stress based damage criteria have been proposed to determine the critical failure load of bonded structures [1,13,29]. Corresponding test methods have been developed to measure the adhesive strength; the most commonly used ones are the single lap joint test [22], butt joint test [28] and Arcan test [14]. However, strength based models are only able to analyse the load at first failure, while the crack propagation process and final failure load cannot be predicted. Their application is further hindered by difficulties in obtaining the true strength value caused by the non-uniform stress distribution across the bondline in the above mentioned tests [9,11,33]. Damage criteria based on fracture toughness have been used to analyze the failure of adhesive bonded structures. Linear elastic fracture mechanics (LEFM) [15] and the J-integral [26] were used to calculate the strain intensity factor and energy release rate. Double cantilever beam (DCB) tests [7], end notched flexure (ENF) tests [12] and mixed mode bending (MMB) tests [25] were used to get the critical strain energy release rate G_C at different phase angles. The application of LEFM

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Nomenclature

a	initial crack length (mm)
b	specimen width (mm)
c_g	distance between the center of mass and the middle nose (mm)
c	lever beam length (mm)
d	displacement of load head (mm)
E_f	longitudinal Young's modulus of laminates (MPa)
G_{13}	transverse shear modulus of laminates (MPa)
h	thickness of adherend laminates (mm)
L	half span of beam (mm)
J_I	mode I fracture energy (N/mm)
J_{II}	mode II fracture energy (N/mm)
J_M	mixed mode fracture energy (N/mm)
k	shear stiffness of adhesive layer (MPa)
m	weight of lever beam (N)
P	load (N)
P_I	mode I load component (N)
P_{II}	mode II load component (N)
r	nominal mode mix ratio, nominal mode mixity (1)
ϕ	true mode mix ratio, true mode mixity (1)
v	relative shear deformation at initial crack tip (mm)
w	relative tension deformation at initial crack tip (mm)
τ	shear stress (MPa)
σ	tensile stress (MPa)
CZM	cohesive zone model
DCB	double cantilever beam
DIC	digital image correlation
ENF	end notched flexure
MMB	mixed mode bending
FEM	finite element model
FPZ	failure process zone

is questionable for modern toughened adhesives as the size of the nonlinear fracture process zone (FPZ) may be comparable with the dimension of the macro crack, so the basic assumption of LEFM is thus challenged. Besides, the single parameter G_C is not able to consider the increase of critical fracture energy with crack growth [4], which also leads to the puzzle that, whether the G when the crack has just initiated or the steady G when a saturated FPZ has been formed, should be regarded as the fracture toughness in DCB, ENF and MMB tests. The initiation G value is only capable of predicting the onset of damage, while the steady G value is only able to aid the analysis of the crack propagation provided that the crack length is longer than the size of failure process zone.

Cohesive zone modeling (CZM) (Tvergaard and Hutchinson [35]) has been increasingly used to analyse the adhesive debonding process as it is able to predict both crack initiation and propagation, and can account for large FPZ. The constitutive relation of the CZM is defined by the interfacial traction stresses as a function of the separation and sliding between adjacent surfaces. There are mainly four factors to define a traction separation law: stiffness, strength, fracture energy and its shape [2]. Among these factors, the fracture energy is traditionally considered as the most critical for obtaining a reliable prediction. Different shapes have been used for traction–separation laws, in which the bilinear law [19], trapezoidal law [12] and exponential law [36] were mainly employed. In practice, the stiffness and strength of traction–separation laws are difficult to be measured experimentally, and the values of these parameters are usually selected empirically [34], or estimated by matching simulation with experiments [19]. However, the stress distribution within the FPZ may influence the overall structure response in large scale yielding fracture, such as the failure of ductile adhesive bonding. Recent research indicates that the shape of the traction–separation law plays a critical role in the analysis of ductile materials [21,27]. Direct measurement of the traction–separation (*T–S*) law is therefore necessary for the accurate analysis of ductile adhesive bonded structures. The *T–S* law of adhesive bonding depends on several parameters such as the thickness of adhesive layer [23]. In this paper, the constitutive law of adhesive layer is considered to be independent of the adherend [20], and it is equal to the mechanical properties of adhesive bonding with constant adhesive thickness.

Some pioneering studies have been carried out to measure the local constitutive response of adhesive layers. On the base of the path independence of the J-integral method [20,32], the differentiation of the energy release rate J with respect to the deformation at the initial crack tip δ gives the local constitutive law. The theory was recently used to experimentally measure the *T–S* law with standard fracture test configurations. The mode I *T–S* law was measured by Sørensen [30] and Andersson and Stigh [5]. The mode II *T–S* law of adhesive bonding was also experimentally obtained [20]. Limited work