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Shear cohesive law estimation of adhesive layers by digital image correlation

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Abstract

Modern and competitive structures are sought to be strong, reliable and lightweight, which increased the industrial and research interest in adhesive bonding. With this joining technique, design can be oriented towards lighter structures. The large-scale application of a given joint technique supposes that reliable tools for design and failure prediction are available. Cohesive Zone Models (CZM) are a powerful tool, although the CZM laws of the adhesive bond in tension and shear are required as input in the models. This work evaluated the value of shear fracture toughness (G_{IIC}) and CZM laws of bonded joints. The experimental work consisted on the shear fracture characterization of the bond by a conventional and the *J*-integral techniques. Additionally, by the *J*-integral technique, the precise shape of the cohesive law is defined. For the *J*-integral, a digital image correlation method is used for the evaluation of the adhesive layer shear displacement at the crack tip (δ_s) during the test, coupled to a Matlab® sub-routine for extraction of this parameter automatically. As output of this work, fracture data is provided in shear for the selected adhesive, allowing the subsequent strength prediction of bonded joints.

Keywords: Adhesive joints; finite element method; cohesive zone models; direct method.

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1. Introduction

Modern and competitive structures are sought to be strong, reliable and lightweight. With adhesive bonding, design can be oriented towards lighter structures, not only regarding the direct weight saving advantages of the joint over fastened or welded joints, but also because of flexibility to joint different materials. Other advantages include the smaller surface geometry disruption, more uniform stresses along the joint, ease of fabrication, design flexibility and corrosion prevention when bonding different materials [1]. Klarbring [2] showed by an asymptotic analysis that the behaviour of thin adhesive layers between stiff adherends is ruled by elongation, w, and shear, v (whose derivative variables are the normal stress, σ, and shear stress, τ, respectively). Many previous studies showed that this simplification is accurate for reproducing the macro-behaviour of adhesive layers. One justification for this, for ductile adhesives in particular, is that the damaged or Fracture Process Zone (FPZ) develops by a significant length beyond the crack tip, which makes the fracture toughness of adhesives not particularly dependent of stresses at the crack tip [3].

The large-scale application of a given joint technique supposes that reliable tools for design and failure prediction are available. Analytical models are limited for damage growth analysis. The concepts of Linear Elastic Fracture Mechanics (LEFM) can be used to analyse fracture of adhesive bonds [4], although involving few limitations: (1) the assumed stress fields are not correctly captured when large-scale plasticity

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is present and (2) in most cases the purpose is to analyse undamaged joints. Thus, these conventional techniques are not the most applicable for bonded joints, unlike CZM, which assume that the FPZ can be described by a law relating the tractions and the physical separations at the crack tip. The cohesive laws are independently characterized for each loading mode and each transition in the global (mixed-mode) law is assessed by different criteria. This technique has been applied to adhesively-bonded structures, in conjunction with development and testing of refined damage onset and failure criteria, different cohesive law shapes and improved cohesive law estimation techniques [5]. The most important step in applying this technique is the estimation of the CZM law, although this is still not standardized [6]. A few data reduction techniques are currently available (the property determination technique, the direct method and the inverse method) that vary in complexity and expected accuracy. In all cases, pure fracture tests, such as the Double-Cantilever Beam (DCB) for mode I and the End-Notched Flexure (ENF), are employed.

The property identification method is based on building a parameterized CZM law by isolated materials properties. The main limitation is that the surrounding adherends lead to deviations between the bulk and thin adhesive bond cohesive properties, which are not accounted for [3]. The inverse method relies on a trial and error fitting analysis to experimental data, such as the load-displacement (P-δ) curve of fracture tests, allowing tuning of simplified shape CZM laws for particular conditions [7]. Direct methods output the cohesive law directly from experimental data. Under this scope, the cohesive law is obtained by measuring the J-integral and crack tip displacements [8] by differentiation of the tensile fracture toughness–tensile displacement (G_I–δ_n) or shear fracture toughness (G_{II})–δ_s curves. Zhu *et al.* [9] characterized the tensile (DCB) and shear (ENF) cohesive laws of steel/polyurea/steel specimens by the J-integral/differentiation approach to obtain the rate dependency of these laws considering nominal strain rates between 0.003 and 3 s^{-1}. The shear CZM laws were highly nonlinear and strain rate-dependent, which was explained by the interfacial behaviour.

This work evaluated the value of G_{IIC} of bonded joints. The experimental work consisted on the shear fracture characterization of the bond by a conventional and the J-integral techniques. By the J-integral technique, the precise shape of the cohesive law is defined. For the J-integral, a digital image correlation method is used for the evaluation of δ_s, coupled to a Matlab® sub-routine for extraction of this parameter automatically.

2. Experimental Part

2.1. Materials

The aluminium alloy AA6082 T651 was selected for the adherends. The mechanical properties were previously obtained [10]: Young's modulus (E) of 70.07±0.83 GPa, tensile yield stress (σ_y) of 261.67±7.65 MPa, tensile failure strength (σ_f) of 324±0.16 MPa and tensile failure strain (ε_f) of 21.70±4.24%. The ductile epoxy Araldite® 2015 was selected as the adhesive. A comprehensive mechanical and fracture characterization of this adhesive was recently undertaken [5]. Table 1 presents the relevant mechanical and fracture data of the adhesive.

Table 1. Properties of the adhesive Araldite® 2015 [5].

Property	
Young's modulus, E (GPa)	1.85±0.21
Poisson's ratio, ν	0.33 [a]
Tensile yield strength, σ_y (MPa)	12.63±0.61
Tensile failure strength, σ_f (MPa)	21.63±1.61
Tensile failure strain, ε_f (%)	4.77±0.15
Shear modulus, G (GPa)	0.56±0.21
Shear yield strength, τ_y (MPa)	14.6±1.3
Shear failure strength, τ_f (MPa)	17.9±1.8
Shear failure strain, γ_f (%)	43.9±3.4
Toughness in tension, G_{IC} (N/mm)	0.43±0.02 [b]
Toughness in shear, G_{IIC} (N/mm)	4.70±0.34 [b]

[a] manufacturer's data

[b] estimated in reference [10]

2.2. Joint dimensions, fabrication and testing

Fig. 1 shows the geometry and dimensions of the ENF joints: mid-span L_H=100 mm, initial crack length a_0≈60 mm, adherend thickness t_P=3 mm, width b=25 mm and adhesive thickness t_A=0.2 mm.

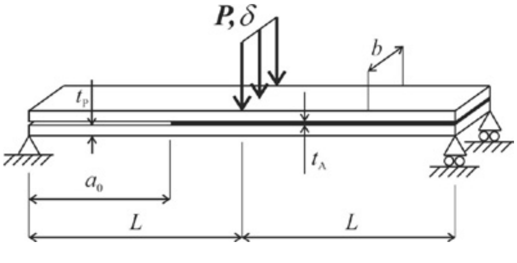

Fig. 1. Geometry of the ENF specimens.