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Shear fracture toughness and cohesive laws of adhesively-bonded joints

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Abstract

Adhesive bonding is a viable technique to reduce weight and complexity in structures. Additionally, this joining technique is also a common repair method for metal and composite structures. However, a generalized lack of confidence in the fatigue and long-term behaviour of bonded joints hinder their wider application. Suitable strength prediction techniques must be available for the application of adhesive bonding, and these can be based on mechanics of materials, conventional fracture mechanics or damage mechanics. These two last methodologies require the knowledge of the fracture toughness (G_C) of materials. Being damage mechanics-based, Cohesive Zone Modelling (CZM) analyses coupled with Finite Elements (FE) are under investigation. In this work, CZM laws were estimated in shear for a brittle adhesive (Araldite® AV138) and high-strength aluminium adherends, considering the End-Notched Flexure (ENF) test geometry. The CZM laws were obtained by an inverse methodology based on curve fitting, which made possible the precise estimation of the adhesive joints' behaviour. It was concluded that a unique set of shear fracture toughness (G_{IIC}) and shear cohesive strength (t_s^0) exists for each specimen that accurately reproduces the adhesive layer behaviour. With this information, the accurate strength prediction of adhesive joints in shear is made possible by CZM.

Keywords: Crack growth; finite element analysis; fracture mechanics; structural integrity.

1. Introduction

The adhesive bonding technique enables a weight and complexity reduction in structures that require some joining technique to be used on account of fabrication/component shape issues. This compares to the large weight penalty of bolted or fastened joints, which adds to the requirement of dealing with the large stress concentrations around the structure' holes. However, some uncertainties regarding the fatigue and long-term behaviour of bonded joints still prevent adhesive bonding to be applied at a larger scale [1]. The availability of strength prediction techniques for adhesive joints is thus essential for their generalized application and it can rely on mechanics of materials, conventional fracture mechanics or damage mechanics. These two last techniques require the measurement of the value of G_C of materials.

When dealing with real joints, mixed-mode behaviours are present, and the typical modelling approach is to define tensile and shear laws that can be combined by suitable criteria. Under shear, the ENF test is the most popular because of the specimen simplicity, easy test set-up and availability of accurate and straight-forward data reduction methods for estimation of G_{IIC} [2]. Since the introduction of this method by Barrett and Foschi [3], many works dealt with G_{IIC} determination for wood, composites and bonded joints, addressing effects such as test set-up and geometric parameters [4]. Data reduction techniques that account for large plasticization of modern toughened adhesives are available by advanced techniques and also the *J*-integral [5], this

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last method additionally enabling the cohesive law estimation.

Within the framework of damage mechanics, a valid option is the use of CZM coupled with FE analyses. CZM applied to bonded joint prediction takes advantage of damage laws to simulate the behaviour of the adhesive, and eventually internal failures in the composite adherends (if applicable). CZM is based on the definition of the cohesive strength in tension and shear, t_n^0 and t_s^0, respectively (relating to the end of the elastic regime and beginning of damage), and tensile fracture toughness (G_{IC}) and G_{IIC} (accounting for the amount of allowable plasticization prior to failure) [6]. Mainly three techniques can be used to estimate these properties: the property identification, inverse and direct methods. All of these depend on Double-Cantilever Beam (DCB), ENF or single-lap tests [7]. The property identification method lies on the separated calculation of the CZM parameters by proper tests, whilst inverse methods rely on estimating the CZM parameters by iterative fitting FE with experimental data (typically the load-displacement or P-δ curve) until reaching a good agreement between both. The direct method estimates the CZM law of a specific material or interface from the experimental data of fracture tests such as the DCB or ENF [8,9]. With this purpose, the test protocol usually requires measurement of additional parameters, such as the normal or shear opening at the crack tip. Carlberger and Stigh [10] studied, by the direct method, the mode I and mode II cohesive behaviour of adhesive layers of the epoxy Dow Betamate® XW1044-3 as a function of the adhesive thickness (t_A). The ENF testing protocol for mode II characterization relied on using a Linear Variable Differential Transformer (LVDT) mounted between rigid supports, one fixed to each adherend, to provide the real-time measurement of the shear relative displacement (δ_s). G_{IIC} showed to be more influent than t_s^0 by varying the value of t_A. However, the G_{IIC} dependency with t_A was much smaller than G_{IC}, although revealing an increasing trend with t_A. Alfredsson *et al.* [11] recently adapted the direct method in shear mode for thick adhesive layers, by considering a novel mathematical expression to estimate G_{IIC}. FE results showed that the pre-fracture behaviour is accurately captured.

Other works addressed the inverse technique. In a previous work [12], the shear CZM law of a ductile adhesive layer was estimated by the ENF test. The procedure involved the definition of G_{IIC} by suitable data reduction methods. The values of G_{IIC} were input in numerical models involving a trapezoidal CZM law that accounted for the adhesive ductility. An inverse method, by fitting between the numerical and experimental P-δ curves, enabled finding t_s^0 and building the complete CZM law that reproduced the adhesive layer in shear. In the work of Chen *et al.* [13], an inverse technique was applied to determine the shear cohesive law of 2024-T3 aluminium alloy, considering the Arcan test geometry and different mode ratios, ranging from tensile to shear. A triangular CZM law was employed in the simulations. The inverse technique was based on minimizing the difference between experimental measurements on the load-extension curve and the respective numerical predictions.

In this work, CZM laws for adhesive joints considering a brittle adhesive were estimated. The ENF test geometry was selected based on overall test simplicity and results accuracy. The adhesive Araldite® AV138 was studied between high-strength aluminium adherends. Estimation of the CZM laws was carried out by an inverse methodology based on a curve fitting procedure.

2. Experimental Part

2.1. Adherend and adhesive materials

The adherends are made of a high-strength aluminium alloy (AA6082 T651). The mechanical properties of this material are available in the literature [14]. The adhesive Araldite® AV138 was previously characterized regarding the mechanical and toughness properties [14,15]. The collected data of the adhesive are summarized in Table 1.

Table 1. Properties of the adhesive Araldite® AV138 [14,15].

Property	AV138
Young's modulus, E (GPa)	4.89±0.81
Poisson's ratio, ν	0.35 [a]
Tensile yield strength, σ_y (MPa)	36.49±2.47
Tensile failure strength, σ_f (MPa)	39.45±3.18
Tensile failure strain, ε_f (%)	1.21±0.10
Shear modulus, G (GPa)	1.56±0.01
Shear yield strength, τ_y (MPa)	25.1±0.33
Shear failure strength, τ_f (MPa)	30.2±0.40
Shear failure strain, γ_f (%)	7.8±0.7
Toughness in tension, G_{IC} (N/mm)	0.20 [b]
Toughness in shear, G_{IIC} (N/mm)	0.38 [b]

[a] manufacturer's data
[b] estimated in reference [14]