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Application of the direct method for cohesive law estimation applied to the strength prediction of double-lap joints

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ABSTRACT

Currently, significant efforts are being made in the design of aircraft and aeronautical applications to reduce weight and improve reliability. Thus, adhesive bonding techniques have been largely employed, which also enables the combined use of steel with lighter materials such as aluminium or high strength composites. Cohesive Zone Models (CZM) are a powerful tool for the design of bonded structures, but they require careful estimation of the cohesive laws for reliable results. This work experimentally evaluates by the *J*-integral/direct method the tensile and shear CZM laws of three adhesives with distinct ductility. The Double-Cantilever Beam (DCB) and End-Notched Flexure (ENF) specimens were considered to obtain the tensile and shear CZM laws of the adhesives, respectively. After obtaining the tensile and shear CZM laws, triangular, exponential and trapezoidal CZM laws were built to reproduce their behaviour. Validation of these CZM laws was undertaken with a mixed-mode geometry (double-lap joint) considering the same three adhesives and varying overlap lengths (L_O). The strength prediction by this technique revealed accurate predictions for a given CZM law shape, depending on the adhesive ductility, although all CZM law shapes were moderately accurate.

1. Introduction

Currently, significant efforts are being made in the design of aircraft and aeronautical applications to reduce weight and improve reliability. Thus, adhesive bonding techniques have been largely employed, which also enables the combined use of steel with lighter materials such as aluminium or high strength composites. This, in turn, promotes less fuel consumption and reduction in the CO_2 emissions to the atmosphere, consequently bringing a major environment-related advantage [1]. It was shown that replacing rivet connections by adhesive bonding in aircrafts could reduce weight of the body mass up to 25% and decrease costs by 20% [2]. Moreover, it is foreseen that in the near future several other fields of industry may benefit from design optimization by combining different materials [3], further emphasizing the advantages of using bonded connections, since these are particularly suited to prevent galvanic corrosion between different metals, have some freedom to absorb different thermal expansions and are more effective than conventional mechanical joints to join composite adherends, by not cancelling the fibres' continuity and typically providing stronger bonds. Other advantages over mechanical joints are the increase in productivity regarding costs and fabrication times, excellent insulation, superior damping, noise reduction and improved aesthetics [4]. Pethrick [5] recently presented a comprehensive review regarding the adhesives' selection for structural applications. Limitations of bonded joints include the requirement and correct choice of surface treatment to the bonding surfaces, and sensitivity to temperature and humidity [6].

There is a countless number of joint configurations addressed in the literature, although the most common are single-lap, double-lap and scarf joints [7]. The availability of accurate and straightforward predictive methods is thus mandatory for the safe design of bonded joints. Although several techniques have been proposed for many decades, beginning with the theoretical analysis of Volkersen [8], some difficulties still exist originating from the known stress variations typically appearing at the bond edges and damage growth under mixed-mode conditions [9]. This makes difficult the application of analytical methods coupled with continuum mechanics criteria for strength prediction, since analytical techniques are usually based on a single stress or strain component, thus not accounting for mixed-mode conditions, and typically

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suffer from a large number of simplifying assumptions [10]. Apart from this issue, modern adhesives are ductile, and these criteria do not work well under these conditions [11]. Continuum mechanics criteria coupled to a Finite Element Analysis (FEA) to estimate stresses or strains result in mesh-dependent predictions, although it is easy to accommodate issues such as the adherends and adhesives' plasticity. However, damage growth prediction is not allowed, which is a serious limitation, as modern adhesives have at least some degree of ductility, making the fracture toughness in tension (G_{IC}) and shear (G_{IIC}) of the adhesives preponderant in the outcome of the joints' behaviour. Linear Elastic Fracture Mechanics (LEFM) methods account for these effects and are recommended over continuum mechanics approaches (either coupled to analytical techniques or FEA) [12], yet having limitations such as incorrect assumption of the stress fields at the crack tip under a ductile behaviour and inability to analyse un-cracked structures [13]. CZM were initially proposed some decades ago, and have been refined ever since to become nowadays a very powerful technique for damage growth and strength prediction of structures, including the analysis of wood failure [14], composite delaminations [15] and bonded joint analysis [16], for which this technique is particularly suited [17]. CZM assume the existence of a damage or Fracture Process Zone (FPZ) at the crack tip, which can be modelled by including, in the expected failure paths, a cohesive law that correlates the cohesive tractions (t_n for tension and t_s for shear) with the crack-tip relative displacements (δ_n for tension and δ_s for shear). The main parameters of the cohesive laws are t_n^0 and t_s^0 (cohesive strengths in tension and shear, respectively, giving the peak tractions), and the values of G_{IC} and G_{IIC}. With this technique, damage initiation is usually inferred by a stress-based criterion and crack growth by energetic criteria. Thus, the Fracture Mechanics limitation of requiring an initial crack to apply the criteria do infer failure is surpassed [18]. In practice, structural joints are under combined loadings, rather than pure tensile or shear loads [19]. It is possible to model mode-mixity in CZM simulations by applying different criteria, enabling the analysis of structures under arbitrary loadings, and also modelling bonded structures, in which an adhesive layer undergoes damage between stiffer and stronger adherends, which results in mixed-mode crack propagation [17].

While CZM is a powerful technique to predict the strength of bonded joints, some premises must be accounted for to ensure reliable results: the adhesive should be characterized under identical geometrical conditions in which the resulting laws will be used in the simulations, and the stipulated CZM law shape should be consistent with the adhesive's behaviour [20]. Different techniques are nowadays available for the definition of the cohesive parameters (G_{IC}, G_{IIC}, t_n^0 and t_s^0), such as the property identification technique, the direct method and the inverse method. These methods usually rely on DCB, ENF or single-lap specimens [21]. The property identification technique consists of the separated calculation of each one of the cohesive law parameters by suitable tests, while in the inverse method the CZM parameters are estimated by iterative fitting the FEA prediction with experimentally measured data (typically the load-displacement, P-δ, curve) up to an accurate representation. Both of these approaches begin with the assumption of a CZM shape to simulate a specific material, which approximately replicates it in terms of post-elastic behaviour [20]. On the other hand, the direct method gives the precise shape of the CZM laws of a specific material or interface, since these are estimated from the experimental data of fracture tests such as the DCB or ENF [22]. This is done by differentiation of the tensile strain energy release rate, G_I, for tension, or the shear strain energy release rate, G_{II}, for shear, with respect to the relative opening of the crack (δ_n for tension or δ_s for shear). Nonetheless, it is usual to convert the obtained shape to an approximated parameterized shape for introduction in the FEA software. For an accurate measurement of the required parameters such as δ_n or δ_s, physical sensors [23] or image correlation methods [24] can be used. The validity of the direct approach can be checked by numerically replicating the tensile or shear fracture tests with identical dimensions and with the experimentally obtained CZM laws as input for the adhesive layer's behaviour, followed by comparing the obtained P-δ curves with the original ones from the experiments [24]. However, complete validation of the CZM laws should include testing the pure mode CZM laws in a mixed-mode geometry, although to the authors' knowledge such works are not available in the literature, being these works limited to pure-mode verifications. Ji et al. [23] used the direct method to DCB specimen data to estimate the tensile CZM laws of a brittle epoxy adhesive (Loctite® Hysol 9460) as a function of the adhesive thickness (t_A). Initially, G_{IC} was measured by an analytical J–integral expression that required as input the adherends rotation at the specimen's loading point (θ_p). The t_n-δ_n laws (or CZM laws) were obtained by differentiation of the G_I–δ_n curves. It was shown that G_{IC} increases with t_A up to 1 mm. On the other hand, t_n^0 was highest for t_A = 0.09 mm, by ≈3 times the bulk adhesive's strength, reducing for higher t_A values. Campilho et al. [25] proposed a technique to obtain G_{IC} and tensile CZM law by a J-integral/direct method methodology and applied it to DCB specimens between natural fibre composite adherends. The procedure consisted of an automated image processing technique that estimated the required parameters during the test. The G_{IC} measurements of the adhesive Sikaforce® 7888 were consistent with the literature data and the CZM law confirmed the ductile characteristics of the adhesive. Leffler et al. [26] estimated G_{IIC} and shear CZM law of an epoxy adhesive (DOW Betamate XW1044-3) using the J-integral applied to the ENF specimen. The value of δ_s during the test measured by a digital camera attached to a microscope. Shear CZM laws obtained at a constant displacement rate and constant shear deformation rate were compared, showing virtually no differences in the estimated values of t_s^0, whilst G_{IIC} was higher by the tests at a constant displacement rate because in this case the shear deformation rate accelerates during the test.

This work experimentally evaluates by the J-integral/direct method the tensile and shear CZM laws of three adhesives with distinct ductility. The DCB and ENF specimens were considered to obtain the tensile and shear CZM laws of the adhesives, respectively. After obtaining the tensile and shear CZM laws, triangular, exponential and trapezoidal CZM laws were built to reproduce their behaviour. Validation of these CZM laws was undertaken with a mixed-mode geometry (double-lap joint) considering the same three adhesives and varying L_O values.

2. Experimental work

2.1. Materials

For the DCB, ENF and double-lap specimens, the ductile aluminium alloy AA6082 T651 was chosen for the adherends. Regarding the DCB and ENF specimens, the mechanical characteristics were high enough to guarantee measurement of the CZM laws without adherend plasticization, which otherwise would introduce errors in the results. The tensile mechanical properties of this material were obtained in the work of Campilho et al. [16]: 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 experimental testing programme included three structural adhesives: the brittle epoxy Araldite® AV138, the ductile epoxy Araldite® 2015 and the ductile polyurethane Sikaforce® 7752. In this manner, different

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