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Comparative evaluation of the Double-Cantilever Beam and Tapered Double-Cantilever Beam tests for estimation of the tensile fracture toughness of adhesive joints

R.M. Lopes, R.D.S.G. Campilho*, F.J.G. da Silva, T.M.S. Faneco

Departamento de Engenharia Mecânica, Instituto Superior de Engenharia do Porto, Instituto Politécnico do Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal

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A B S T R A C T

The continuous development observed in bonded joints, along with the improvements of the adhesives' properties, are resulting in an increase of the bonded joint applications, as well as the variety of applications. Regarding the strength prediction of adhesive joints, two highly relevant methods are Fracture Mechanics and Cohesive Zone Models (CZM). By Fracture Mechanics, this is usually carried out by an energetic analysis. CZM enable the simulation of damage initiation and propagation. The tensile critical strain energy release rate (G_{Ic}) of adhesives is one of the most important parameters for predicting the joint strength. Two of the most commonly used tests are the Double-Cantilever Beam (DCB) and the Tapered Double-Cantilever Beam (TDCB). This work aims to assess the capability of the DCB and TDCB test to estimate the value of G_{Ic} of adhesive joints. Three types of adhesives with different levels of ductility are used, to study the accuracy of the typical data reduction methods under conditions that are not always consistent with Linear Elastic Fracture Mechanics (LEFM) principles. For both test protocols, methods that do not require measurement of the crack length (a) during the test are evaluated. In the DCB test, these are the Compliance Calibration Method (CCM), Corrected Beam Theory (CBT) and Compliance-Based Beam Method (CBBM). The methods used in the TDCB test are the Simple Beam Theory (SBT), CCM and CBT. With few exceptions, the results were consistent between the different methods considered for each test. The discrepancy of results is higher when comparing the two types of tests, except for the brittle adhesive. It was concluded that the data reduction methods for the TDCB test are too conservative to measure G_{Ic} of ductile adhesives.

1. Introduction

The continuous development observed in bonded joints, along with the improvements of the adhesives' properties, are resulting on an increase of the bonded joint applications, as well as the variety of applications. Adhesives are nowadays used in industries such as aerospace, aeronautical, automotive, packaging and construction. The weight reduction, easy way to join different materials and improved load transfer over traditional joining methods are the main advantages when bonded assemblies are used [1]. The drawbacks are associated with the stress concentrations at the ends of the overlap, the service life of adhesives and lack of standardized procedures for the strength prediction of bonded joints. A careful surface preparation is also required to remove contaminants such as oils, dust or lubricants. The type of surface preparation is highly dependent on the adherend material. With a proper surface preparation, failure is expected to occur cohesively in the adhesive layer or even as a tensile net failure of the adherends.

With accurate predictive tools for bonded joints it is possible to reduce costs, decrease the design time and improve the performance. Within this scope, two of the most relevant techniques for strength prediction are classic Fracture Mechanics and CZM. By Fracture Mechanics, the strength prediction is usually carried out by an energetic analysis. CZM, supported by the Finite Element Method, enable the simulation of damage initiation and propagation. For both of these two techniques, G_{Ic} and the shear critical strain energy release rate (G_{IIc}) are the main material parameters for predicting the joint strength. Mixed-mode loadings are typically found in real bonded structures, which further requires the existence of fracture envelopes and mixed-mode criteria for damage initiation and growth that couple the pure-mode data for crack growth prediction. The recent review of Chaves et al. [2] describes the main test methods and respective data reduction techniques for fracture toughness estimation in tension, shear and mixed-mode. Tests that enable varying the

* Corresponding author. Tel.: +351939526892; fax: +351228321159.
E-mail address: raulcampilho@gmail.com (R.D.S.G. Campilho).

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mode-mixity are also described, which are valuable in obtaining the fracture envelope, useful for design purposes.

Two of the most commonly used tests to estimate G_{Ic} are the DCB and TDCB. Both of these tests are standardized. The ASTM D3433-99 [3] provides strict dimensions to both specimens and, thus, it is recommended for unexperienced users [4]. However, it is known that some variations can be expected on the G_{Ic} value of adhesive joints depending on the adhesive thickness (t_A), adherend thickness (t_P) or adherend material, since these vary the constraining effects of the adherends that influence the Fracture Process Zone (FPZ) dimensions [5,6]. The ISO 25217 standard [7] is more flexible in the specimen dimensions, and it also benefits from more accurate data reduction techniques and the possibility to estimate the full resistance (or *R*-) curves. These two standards accommodate unstable crack propagation or stick-slip crack growth, which can occur for brittle adhesives, especially at low temperatures. Between the two test methods, the DCB is the most widespread. Actually, the specimens are easy to manufacture and test, and a large variety of data reduction methods is available, either within the scope of LEFM or with corrections to account for the adhesives' plasticity or other effects [8]. The main drawback of the DCB test is the requirement to measure *a* during the test, which can be particularly critical in dynamic fracture toughness testing. Some developed methods permit the estimation of G_{Ic} purely from the load–displacement (P–δ) data by using an equivalent crack length (a_{eq}) derived from the experimental compliance [9]. The TDCB test has the advantage of not requiring the measurement of *a* even for classical (standardized) formulations. This is possible due to the use of tapered adherends, providing a t_P variation as the crack progresses such that the compliance ($C=\delta/P$) during the tests varies linearly with *a*. Under this assumption, it is possible to derive an expression from the Irwin–Kies equation that is independent of *a* [10]. Different authors evaluated the DCB and TDCB tests for G_{Ic} estimation of adhesive joints, although only very few works are available for the TDCB test. de Moura et al. [9] used the DCB test geometry for fracture characterisation of bonded joints under pure mode I loading. The used data reduction techniques were the CCM, the direct beam theory (DBT), the CBT and the CBBM. The adherend material was unidirectional carbon-epoxy composite, and the adhesive a ductile epoxy (Araldite® 2015). The CBBM had the advantage of not requiring the measurement of *a* and taking into account the energy dissipation in the FPZ. The experiments revealed similar results between the CBT and CBBM, some inconsistencies in the CCM due to polynomial fitting difficulties, and under prediction by the DBT, due to absence of corrections to account for root rotations and shear effects. A numerical analysis was performed, by CZM, to assess each of the data reduction methods. This was carried out by running numerical models with specific G_{Ic} values input in the tensile cohesive law, and applying all data reduction methods to the respective P–δ curve, in an attempt to replicate the input value of G_{Ic}. The CBT and CBBM error was under 1.0%, whilst the CCM and DBT showed errors of 5.6% and 14.9%, respectively. The CBBM was considered the most reliable on account of its accuracy and non-requirement to measure the value of *a*. Karac et al. [11] analytically evaluated G_{Ic} of adhesive joints at different test rates by the TDCB test. The aluminium-alloy EN-AW2014A was used as adherend material, and the adhesive was a structural epoxy (Betamate XD4600). The test rates ranged between 3.33×10^{-6} m/s and 13.5 m/s, including a total of four different test rates. The CBT method was considered to determine G_{Ic}. The experiments were numerically replicated using an implicit finite-volume method together with a CZM. The numerical predictions were accurate in predicting the joints' behaviour for all tested loading rates, although the experimentally observed unstable crack propagation could only be replicated by a rate-dependent CZM. Cooper et al. [12] performed TDCB tests in joints bonded with a structural epoxy adhesive to determine G_{Ic}, considering t_A values between 0.25 and 2.5 mm. The ASTM D3433-99 [3] and BS 7991 [13] test protocols were compared. Both joint configurations showed equivalent results, reporting a G_{Ic} improvement by increasing t_A up to 1.3 mm and keeping a constant G_{Ic} for higher t_A values. A detailed numerical analysis allowed concluding that the dependence of G_{Ic} with t_A was induced by the change of the intrinsic fracture energy, instead of the variation in the far-field plastic zone size that is typically assumed. Blackman et al. [14] compared the values of G_{Ic} of a brittle adhesive obtained by DCB and TDCB tests. Several materials were used as adherends. In the DCB tests, the adherend materials were unidirectional carbon-fibre composite and mild steel. In the TDCB tests, the adherend materials were mild steel and aluminum alloy. The comparison of the resulting values of G_{Ic} by the SBT, CCM and CBT (for both DCB and TDCB tests) showed that the results were identical between the test geometry, although dependent on the adherend material. Moreover, the SBT under predicted the G_{Ic} values.

This work aims at evaluating the capability of the DCB and TDCB tests in estimating the value of G_{Ic} of adhesive joints. Three types of adhesives with different levels of ductility are used, to study the accuracy of the typical data reduction methods under conditions that are not always consistent with LEFM principles. For both test protocols, methods that do not require measurement of *a* during the test are addressed. For the DCB test, the methods used to obtain G_{Ic} are the CCM, the CBT and the CBBM. The methods used in the TDCB test are the SBT, the CBT and the CCM.

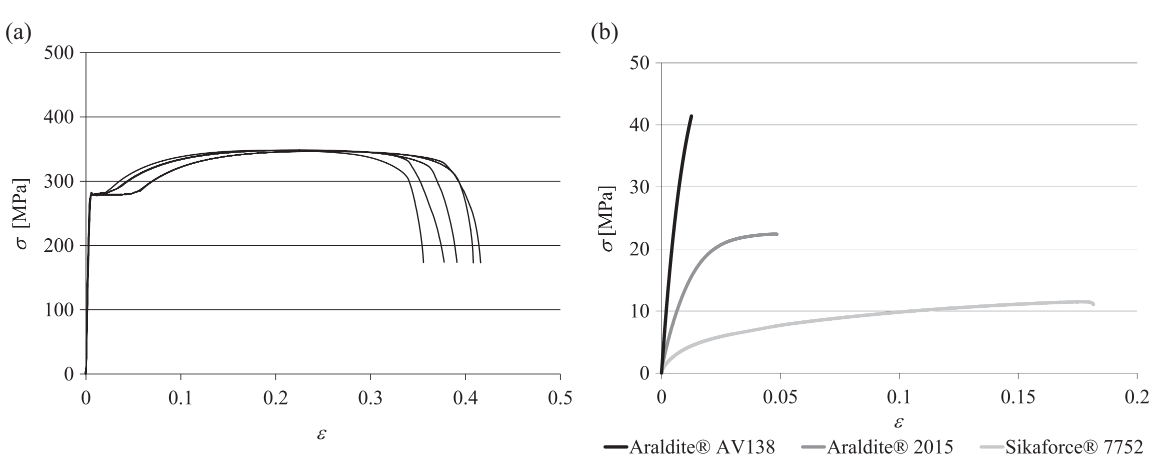

Fig. 1. Experimental σ–ε curves of the steel adherends and FEM approximation (a) and representative σ–ε curves of the three adhesives considered (b).