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Adhesive thickness effects of a ductile adhesive by optical measurement techniques

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ABSTRACT

Adhesive bonding is an excellent alternative to traditional joining techniques such as welding, mechanical fastening or riveting. However, there are many factors that have to be accounted for during joint design to accurately predict the joint strength. One of these is the adhesive layer thickness (t_A). Most of the results are for epoxy structural adhesives, tailored to perform best with small values of t_A, and these show that the lap joint strength decreases with increase of t_A (the optimum joint strength is usually obtained with t_A values between 0.1 and 0.2 mm). Recently, polyurethane adhesives were made available in the market, designed to perform with larger t_A values, and whose fracture behaviour is still not studied. In this work, the effect of t_A on the tensile fracture toughness (G_n^c) of a bonded joint is studied, considering a novel high strength and ductile polyurethane adhesive for the automotive industry. This work consists on the fracture characterization of the bond by a conventional and the *J*-integral techniques, which accurately account for root rotation effects. An optical measurement method is used for the evaluation of crack tip opening (δ_n) and adherends rotation at the crack tip (θ_o) during the test, supported by a Matlab® sub-routine for the automated extraction of these parameters. As output of this work, fracture data is provided in traction for the selected adhesive, enabling the subsequent strength prediction of bonded joints.

1. Introduction

Adhesive bonding is an excellent alternative to traditional joining techniques such as welding, mechanical fastening or riveting. Actually, the developments in recent commercial structural adhesives enabled their use for adhesive bonding in many fields of engineering, such as automotive and aeronautical. Many of the industrial adhesives used nowadays, such as epoxies and polyurethanes, have high strength and ductility [1,2]. There are many other advantages such as more uniform stress fields, capability of fluid sealing, high fatigue resistance, and the possibility to join different materials. On the other hand, length-wise stress concentrations owing to the gradual transfer of load between the adherends and the adherends rotation in the presence of asymmetric loads act as disadvantages [3]. Many works, such as that of Campilho et al. [4], detail the critical factors affecting the integrity of adhesive joints, such as the value of adhesive layer thickness (t_A), bonding length and geometric modifications that reduce stress concentrations. These factors have to be accounted for in joint design and to accurately predict the joint strength.

The effect of t_A on single-lap joints is well documented in the literature. Most of the results are for typical structural adhesives and show that the lap joint strength decreases as t_A increases. For epoxy adhesives, as stated by Adams and Peppiatt [5], the optimum joint strength is obtained with a small value of t_A, in the range of 0.1–0.2 mm. However, analytical models like those of Volkersen [6] or Goland and Reissner [7] predict the opposite. There are many theories that attempt to explain this fact and this subject is still controversial. Adams and Peppiatt [5] claimed that an increase in t_A increases the odds of having internal imperfections in the joint (voids and micro-cracks), which will lead to premature failure of the joints. Crocombe [8] shows that thicker single-lap joints have a lower strength by considering the plasticity of the adhesive. Gleich et al. [9] showed with a finite element analysis on single-lap joints that the increase of interface stresses (peel and shear) as t_A increases causes the failure

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load of a bonded joint to decrease with increasing t_A. Grant et al. [10] found a reduction in joint strength with increasing t_A when testing single-lap joints for the automotive industry with an epoxy adhesive. The strength reduction was attributed to the higher bending moments for the lap joints with large t_A values due to the increase in the loading offset. When composites are used, a decrease in t_A increases the peel stress at the ends of the overlap and might trigger composite delamination. Therefore, the benefits of using a small value of t_A might be reduced. Other studies dealt with the influence of t_A on the cohesive strength (t_n^0 for tension and t_s^0 for shear) and fracture toughness (G_n^c for tensile and G_s^c for shear, or generically G^c). The consensus in this matter, as discussed in the work of Leffler et al. [11], is that adhesives in the form of thin bonds behave differently than as a bulk material, because of the strain constraining effects of the adherends and the respective typical mixed mode crack propagation. Different studies reported the dependence of G_n^c of adhesive bonds with t_A, e.g. the work of Lee et al. [12]. The value of G_n^c of epoxy adhesive bonds was previously studied mostly by the Double-Cantilever Beam (DCB) test. Typically, G_n^c increases with t_A up to a peak value, bigger than the bulk quantity. After, G_n^c decreases with t_A to a steady-state value, corresponding to G_n^c of the bulk adhesive (the work of Duan et al. [13] is a clear example of this effect). Biel [14] emphasized on the bigger values of G_n^c near the optimal value of t_A than as a bulk. This was due to the predominantly state of prescribed deformation at the region where the crack could propagate, which enlarged the damage zone. Actually, with tough engineering adhesives, near the optimal value of t_A, the damage zone typically extends several times larger than the value of t_A, and substantially longer than in bulk adhesives, resulting on bigger values of G_n^c. Kinloch and Shaw [15] argued that G_n^c is directly related to the plastic zone size that, in turn, is controlled by the surrounding constraints (i.e., adherends). Equivalent studies, such that of Carlberger and Stigh [16], are available for G_s^c, mainly by the End-Notched Flexure (ENF) test. Recently, polyurethane adhesives appeared in the market, designed to perform with larger t_A values, and whose fracture behaviour is still not studied.

Since the values of strength and toughness of adhesive layers vary as discussed, it is mandatory that they are estimated with accuracy. The DCB test is the most suitable to measure G_n^c due to the test simplicity and accuracy. The conventional and standardized G_n^c estimation methods are based on Linear-Elastic Fracture Mechanics (LEFM) and rely on the measurement of the crack length (a) during the test. However, it is known that G_n^c of ductile adhesives is not accurately characterized by LEFM methods [17]. In recent years, methods that do not need measurement of a have been developed, such that considered in the work of Campilho et al. [18], additionally including the plasticity effects around the crack tip. As an alternative, in the presence of large-scale plasticity, J-integral solutions are recommended. Carlberger and Stigh [16] computed the cohesive laws of adhesive layers in tension and shear by the J-integral using the DCB and ENF tests, respectively, considering $0.1 \leq t_A \leq 1.6$ mm. The rotation of the adherends was measured by an incremental shaft encoder and the crack tip opening (δ_n) by two Linear Variable Differential Transducers (LVDT). The analysis of Ji et al. [19] used a J-integral technique applied to the DCB specimen to study the influence of t_A on t_n^0 and G_n^c for a brittle epoxy adhesive (Loctite® Hysol 9460). The analysis methodology relied on the measurement of G_n^c by an analytical J-integral method, requiring the measurement of the adherends rotation at the specimen free ends. For the measurement of rotation, two digital inclinometers with a 0.01° precision were attached at the free end of each adherend. A charge-coupled device (CCD) camera with a resolution of 3.7×3.7 μm^2/pixel was also used during the experiments to measure δ_n, necessary for correlation with the load and rotation for the definition of the tensile strain energy (G_n).

In this work, the t_A effect on the value of G_n^c of a bonded joint is studied, considering a novel high strength and ductile polyurethane adhesive for the automotive industry. The experimental work consists on the fracture characterization of the bond by a conventional and the J-integral techniques. An optical measurement method is used for the evaluation of δ_n and adherends rotation at the crack tip (θ_o) during the test, supported by a Matlab® sub-routine for the automated extraction of these parameters.

2. Experimental work

2.1. Materials

The material selected for the adherends is a laminated high strength aluminium alloy sheet (AA6082 T651) cut by precision disc cutting into specimens of $140 \times 25 \times 3$ mm^3. The mechanical properties of this material are available in the literature in the reference of Campilho et al. [20], giving the following bulk values: 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 $21.70 \pm 4.24\%$. A novel polyurethane structural adhesive, SikaForce® 7752-L60, was selected for this work. This is a two-part adhesive, and it consists of a filled polyol based resin and an isocyanate based hardener. It is characterized by a room temperature cure, high impact resistance and flexibility at low temperatures. This adhesive was previously characterized in bulk tension in the work of Faneco [21], giving the following properties: $E = 493.81 \pm 89.60$ MPa, $\sigma_y = 3.24 \pm 0.48$ MPa, $\sigma_f = 11.49 \pm 0.25$ MPa and $\varepsilon_f = 19.18 \pm 1.40\%$. Fig. 1 shows the experimental σ–ε curves of the adhesive Sikaforce® 7752 obtained in the above mentioned work, emphasizing the ductile behaviour of the adhesive.

2.2. Joint geometries

Fig. 2 presents the geometry of the DCB specimens. The dimensions of the specimens are total length $L = 140$ mm, initial crack length $a_0 \approx 55$ mm, adherend thickness $h = 3$ mm, width $B = 25$ mm and $t_A = 0.1$, 0.2, 0.5, 1 and 2 mm. The fabrication of the specimens involved grit blasting the bonding surfaces with corundum sand, cleaning with acetone and assembly in a steel mould. To achieve the different values of t_A uniformly throughout the adhesive layer, calibrated spacers of 1 mm were inserted between the adherends at the adhesive layer edges. A sharp pre-crack at the specimens' free edge was induced by a spacer composed of a 0.1 mm thick razor blade between 0.45 mm calibrated bars. These were stacked and glued together, making a total thickness of 1 mm. The cutting edge of the blade was offset from the sheets and positioned facing the adhesive layer before application of the adhesive such that, after curing of the adhesive, a sharp pre-crack was produced at the adhesive layer edge. Application of demoulding agent to the spacers enabled their extraction after curing of the adhesive. Curing was performed at room temperature. The spacers were removed and one of the

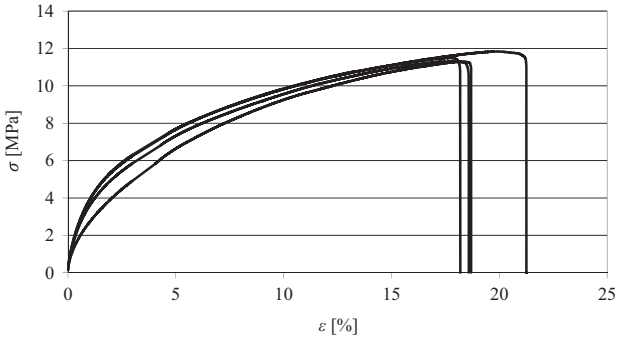

Fig. 1. Experimental σ–ε curves of the adhesive Sikaforce® 7752.