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Adhesive selection for hybrid spot-welded/bonded single-lap joints: Experimentation and numerical analysis

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ABSTRACT

The applications of adhesive joints are increasing in various industrial applications because they offer several advantages over traditional methods. The combination of adhesive bonding with spot-welding enables some advantages over adhesive joints such as increased stiffness, and higher static and fatigue strength. This work relates to the adhesive selection for single-lap adhesive joints by the bonding and hybrid (bonded and welded) techniques with different overlap lengths (L_O). The adhesives are the brittle Araldite AV138®, and the ductile Araldite® 2015 and Sikaforce® 7752. The experimental results were compared against a Finite Element (FE) study coupled with Cohesive Zone Modelling (CZM). The results validated the numerical technique and also showed varying strength improvements of the hybrid joints over bonded joints depending of the adhesive.

1. Introduction

The need of improved joining methods in structural applications has increased the use of adhesive joints at the expense of traditional methods such as welded, brazed, bolted and riveted joints. The applications of adhesive joints are increasing because they offer advantages such as reduced weight, smaller stress concentrations, ease of manufacture and the possibility to join dissimilar materials. However, they also have disadvantages such as the joint preparation and normal stresses in the adhesive layer's thickness direction (peel stresses). Strength prediction of bonded joints is usually performed by continuum mechanics or fracture mechanics. Continuum mechanics requires the knowledge of the bondline stress distributions, either by analytical or numerical methods [1]. The FE method is the most generalized numerical technique, and it can handle complex structures and non-linear material properties, where classical methods generally fail to work [2]. However, the accuracy of this technique highly relies on the proper selection of a correct failure criterion. Under the scope of fracture mechanics-based approaches, the Generalized Stress Intensity Factor (G-SIF) approach has been used for the strength prediction of bonded joints [3]. Russo and Zuccarello [4] used the G-SIF methodology as a design method for the strength prediction of metal-to-composite co-cured joints. A theoretical stress analysis was performed by the Lekhnitskii theory enabling computing the singularity orders of the singular stress field in the joints. The G-SIF permitted describing the singular stress fields at the adherends' interfaces, giving a relationship between the joint configuration and the singular stress field. The joints' strength was predicted as a function of the adherends stiffness, value of L_O, taper angle and imbalance. CZM are also based on fracture mechanics concepts and are increasingly being used in FE [5]. CZM simulate damage initiation by strength criteria but also introduce discontinuities ruled by energetic criteria, thus using both strength and fracture mechanics concepts. CZM modelling of bonded joints can be divided into local or continuum approaches [6]. In the local approach, damage is confined to zero thickness lines and surfaces (in two and three dimensions, respectively), promoting damage growth, while plastic dissipations take place at the continuum elements. In the continuum approach, a single row of cohesive elements is considered to fully represent the adhesive layer. This last technique has already shown to be accurate [7]. Kafkalidis and Thouless [8] used a FE approach coupled with CZM to study symmetric and asymmetric single-lap joints. The CZM parameters were tuned for the set of materials used in the work and afterwards applied to different bonded configurations. The

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correlation to the experimental data was accurate regarding the failure loads and respective displacements. Campilho et al. [9] predicted the tensile strength of adhesively bonded single-strap repairs with composite adherends. A numerical FE/CZM technique with a trapezoidal law simulated the ductile adhesive layer, giving an accurate representation of the experimental results.

Hybrid joining consists of merging adhesive bonding with another technique to produce weld-bonded, rivet-bonded or bolt-bonded joints. The main purpose is to gather the benefits of different joining techniques while overcoming their individual limitations. These hybrid joints can be used to improve the static or fatigue damage tolerance in structures, and have the advantage of not requiring fixtures during the adhesive curing [10]. Weld-bonded joints result from the combination of adhesive bonding with resistance spot-welding. Currently, this hybrid technique is used in several critical components in aeronautical applications, missile shells, spaceship sounders and car industry [11]. This technique is studied in the literature for static [12] and fatigue loads [13]. Resistance spot-welding is carried out by melting the adherends together through the concentrated flow of electric current. The result is a fused nugget of welded metal. Hybrid joints are particularly difficult to simulate using analytical models on account of the complex geometries. Thus, experimentation and the FE method are the main tools found in the literature to investigate the behaviour of such hybrid techniques. Different experimental studies were published, e.g. the works of Xu et al. [14] and Charbonnet et al. [15]. In the work of Melander et al. [16], the fatigue strength of weld-bonded steel sheets of 0.8 mm thickness was assessed, considering a structural epoxy suitable for high temperature curing. Tests were conducted at −20 and +50 °C, besides room temperature. A strength prediction technique was developed based on fracture mechanics and FE. The results testified the higher efficiency of weld-bonding compared to spot-welding on a peel test geometry. The experimental study of Moroni et al. [17] compared weld-bonded, rivet-bonded and clinch-bonded joints to purely adhesive, spot-welded, riveted or clinched joints. The Design of Experiments was used to assess the effect of the adherend materials, geometry (adherend thickness and weld/rivet/clinch pitch) and environment on the joints' strength, stiffness and energy absorption up to failure. The main conclusion of the work was the large improvement of the joints' energy absorption. Sadowski et al. [18] studied by experimentation and FE/CZM modelling the tensile behaviour of aluminium single-strap weld-bonded joints. The experimental work was carried out with the aid of 2 Digital Image Correlation (DIC) systems to monitor the specimens' strains up to complete failure and correlation with the numerical analysis. The numerical modelling consisted of three-dimensional (3D) simulations with triangular CZM elements for the adhesive layer, mesh-independent fasteners to model the weld-nugget and solid elements with a ductile damage model for the adherends. This approach agreed well with the simulations and DIC technique regarding the strain concentration sites. Campilho et al. [19] studied by experimentation and FE/CZM the behaviour of hybrid bonded/welded single-lap joints with the adhesive Araldite® 2015. The numerical analysis included a comprehensive stress analysis, whose main findings were that weld-bonded joints had the advantage of highly increasing the load transfer at the inner overlap regions, which then reflected on higher failure loads. The relative improvements over the bonded joints were highest for the smallest value of L_O (15 mm), and gradually reduced for higher values, because of the adherends' plasticization and smaller area influence of the spot-weld over the overlap. The FE/CZM technique was accurate in describing the joints' behaviour.

Depending of the type of adhesive used in hybrid joints, different results are expected regarding its influence on the overall joint performance. This work relates to the adhesive selection for single-lap adhesive joints by the bonding and hybrid (bonded and welded) techniques. The adhesives considered in this work are the brittle Araldite AV138®, and the ductile adhesives Araldite® 2015 and Sikaforce® 7752. C45E steel substrates (EN 10083-2: 2006) have been considered in the joints with different values of L_O. The experimental results are compared against a FE-based study in Abaqus® considering CZM for strength prediction, and also including an analysis of stress distributions and of the damage variable, to understand the differences between joint configurations.

2. Experimental work

2.1. Materials

In this work, joints were tested between C45E plain carbon steel (EN 10083-2: 2006) adherends, which was characterized in tension following the ASTM-E8M-04 standard in a previous work [19]. The resulting engineering stress–strain (σ–ε) curves for five tensile-tested specimens and respective FE approximation are presented in Fig. 1(a), giving: Young's modulus (E) of 204.32 ± 2.40 GPa, yield stress (σ_y) of 279.11 ± 0.82 MPa, failure strength (σ_f) of 347.51 ± 0.93 MPa and failure strain (ε_f) of 36.36 ± 2.45%. Three structural adhesives were considered: the brittle epoxy Araldite® AV138, and the ductile epoxy Araldite® 2015 and polyurethane Sikaforce® 7752. When selecting the adhesive, it was necessary to pay attention to the fabrication method of the hybrid joints: *flow-in* or *weld-through*. The *flow-in* method consists of spot-welding the joints followed by adhesive filling by capillarity and curing under heat. The *weld-through* technique, used in this work, consists of adhesively-bonding the adherends followed by spot-welding during the working time (WT) of the adhesive [20]. Thus, the adhesives were selected such that their WT enables spot-welding to be performed before adhesive curing. The adhesives were previously characterized regarding the mechanical and toughness properties [21–23]. Bulk specimens were tested to obtain E, σ_y, σ_f and ε_f. The Double-Cantilever Beam (DCB) test was selected to obtain the tensile fracture toughness (G_n^c) and the End-Notched Flexure (ENF) test was used for the shear fracture toughness (G_s^c, or in 3D G_{s1}^c for shear and G_{s2}^c for tearing). Fig. 1(b) shows typical σ–ε curves of the adhesives tested in bulk.

2.2. Fabrication and testing procedure

The generic dimensions of the joints are presented in Fig. 2. The geometrical parameters are (in mm): $L_O = 15$, 30, 45 and 60, width $b = 25$, total length between grips $L_T = 150$, adherend thickness $t_P = 2$ and adhesive thickness $t_A = 0$ for the welded joints and $t_A = 0.2$ for the bonded and weld-bonded joints. For the welded joint, only $L_O = 15$ mm was considered. It should be emphasized that the selected L_O values aim at analyzing the joint strength for different configurations (and, thus, different degrees of stress gradients), and also different relative influence of the weld-nugget averaged to the bond length. However, in industry applications, short L_O values as 15 mm are not the most common. All joint types were assembled using a jig to guarantee the adherends' alignment. The welding operation was carried out in a CEA® NKLT-28 welding machine with Ø6 mm electrode tips. The relevant welding parameters are: (1) the *squeeze time* – elapsed time (defined in 50 Hz cycles of applied current, as in the following parameters) from the initiation of joint squeezing and the application of electric current, (2) the *upslope* – number of cycles required to attain the user-defined welding current, (3) the *welding time* – duration in cycles of the welding process, and (4) the *welding current* – electric