



Damage analysis of composite–aluminium adhesively-bonded single-lap joints



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ABSTRACT

Adhesive bonding is used to fabricate structures of complex shape that could not be manufactured in one piece. In many high performance structures, joints between composite materials with other light metals such as aluminium are required for structural optimization. This work numerically and experimentally addresses adhesive joints between aluminium and carbon–epoxy composites, considering different adhesives and value of overlap length (L_0). Numerically, the Finite Element Method (FEM) coupled with cohesive zone models (CZM) is used to perform a detailed stress analysis that enables the comparison between different planes in the joint and L_0 values. A damage analysis during damage and crack growth is also considered to fully describe the failure process. The use of the proposed numerical technique enables predicting the joint strength and creating a simple and rapid methodology that can be used in the design of hybrid structures, e.g. in the selection of the joint geometry and adhesive. The joints' strength and failure modes were highly dependent on the adhesive, and this behaviour was successfully modelled numerically. Using a brittle adhesive resulted in a negligible maximum load (P_m) improvement with L_0 . The joints bonded with the ductile adhesive showed a nearly linear improvement of P_m with L_0 .

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1. Introduction

The joints are always potential loci of damage initiation and, thus, it becomes highly relevant to reduce the number of joints in a structure as well as an efficient design [1]. Fastening is a simple joining technique, but the fastener holes damage the composite components by breaking the fibre continuity and introduce local damage, which affects the structures' strength. Adhesive bonding is a permanent process that uses an adhesive to bond the components of a structure. This bonding process is used to fabricate structures of complex shape that could not be manufactured in one piece, to provide a structural bond that ideally should be at least as resistant as the base materials. Adhesive bonding is a particularly attractive bonding method, which enables joining different materials without damage to the parent structures. Other advantages are smaller weight, more uniform stress distributions, water-proofing and prevention of galvanic corrosion [2,3]. In some cases, this joining technique is the only available solution, such as in thin-walled parts or plates with large thickness variation [4].

Additionally, the joined area extends longer than with rivets or bolts and stresses are more uniform (especially width-wise), which reflects on higher stiffness and strength. On account of this emerging field of application, different studies have been published that analyse the viability of bonded joints between composites and aluminium [5,6], composites and steel [7], amongst other combinations. A common feature of all these studies is the performance dependence on a careful design, such that the limitations of bonded joints do not compromise the structural efficiency, such as the sensitivity to peel stresses and stress concentrations in general, or even requirement of surface preparation during the assembly [8]. Driven by this fact, several researchers focused on analytical or numerical techniques to predict the joint strength. The early theoretical methods to estimate stress distributions in bonded joints are not the most suitable method of analysis because of neglecting effects such as adherends and adhesives plasticity, large displacements, among others. When facing complex geometries or to compensate for the limitations of theoretical methods, strength prediction methods for adhesively-bonded joints are nowadays based on the FEM [9,10] and advanced Fracture Mechanics-based techniques [11]. CZM coupled to FEM analyses simulate damage growth within materials or at interfaces between

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different materials [12,13]. The resulting predictions are generally accurate since failure is ruled by energetic criteria, and because the behaviour of materials can be modelled by cohesive laws with different shapes, depending on the experimentally observed behaviour. This technique is based on the establishment of traction–separation laws at the failure paths, and require the values of energy release rate in tension and shear (G_n and G_s , respectively) and respective critical values or toughness (G_n^c and G_s^c). The cohesive strengths in tension and shear (t_n^0 and t_s^0 , respectively) are other required parameters and pertain to damage initiation in the CZM laws. Numerical methods permit the structural analysis of complex shapes (for which no analytical solutions are available) and with complex geometrical and material models. With this, extensive experimentation for design validation can be greatly reduced, with advantages in the design cost and time to accomplishment. These techniques, supported by auxiliary works regarding design rules [14], comparative analyses between different adhesive types [15,16] and geometrical modifications to reduce stress concentrations [17], should be able to turn adhesive bonding into a highly viable tool in the fabrication of multi-material structures. During the design process, the suitability of this technique should be accompanied by technical and economic considerations [2,18].

Owens and Lee-Sullivan [19,20] addressed the stiffness behaviour of hybrid composite/aluminium joints, and developed an analytical model to predict the joint stiffness and respective loss with the crack growth. Flexible adhesives were found to increase the resistance to crack growth, thus increasing the joints' strength. Arenas et al. [2] addressed design variables such as the adhesive selection and surface treatment for the adherends in hybrid composite/aluminium joints by experimental testing and an optimization procedure based on multi-criteria decision tools (the analytical hierarchy process – AHP). As a result, it was possible to achieve a parameter combination that combines high joint strength and feasibility in the production process (e.g. time to adhesive preparation, safety or costs). The set of conditions comprised two adhesives (epoxy and polyurethane) and six surface preparation techniques for bonding. Based on the decision tool, the polyurethane adhesive in conjunction with peel-ply and sandpapering treatments for the composite and aluminium adherends, respectively, proved to be the optimal solution. Seong et al. [1] studied the effects of bonding pressure, value of L_0 , adherend thickness (t_p) and adherend type on the strength of composite-to-aluminium single-lap joints. One of the main findings was related to the existence of a limiting value of L_0 above which the joint strength was left practically constant due to the limited ductility of the adhesive. In the work of Di Franco et al. [21], a systematic experimental study was conducted regarding bonded and hybrid bonded/self-piercing riveted joints between composites and an aluminium alloy. Guidelines were proposed for bonded joint design. It was found that adding a self-piercing rivet to the bonded joint increased the load bearing capabilities of the joint, namely tensile strength, stiffness and energy absorption. Kweon et al. [5] tested double-lap composite-to-aluminium joints considering adhesive bonding, mechanical fastening and hybrid joints. Hybrid joining improved the strength only when mechanical fastening was stronger than adhesive bonding. Other experimental topics include the cryogenic performance of composite-to-aluminium joints [22], digital image correlation applied to strain measurement [23] or thermal stresses [24]. Rudawska [4] conducted a series of tests and CZM simulations of hybrid joints between different adherend materials (titanium, aluminium alloys and aramid–epoxy composites). The technique was accurate, with the maximum deviation (17%) for the titanium–titanium joints. The hybrid joints showed varying results depending on the chosen adherend combinations, with the best results being found for the

aluminium–aluminium joints. Anyfantis [25] studied by CZM modelling and experimentation double-lap joints between Carbon-fibre reinforced plastic (CFRP) composites and steel bonded with a ductile adhesive layer. The elasto-plastic loading and fracture response were modelled by a recently developed mixed-mode CZM law. A comparison was also performed to a numerical analysis based on the Damage Zone Theory (DZT). After validation of the CZM approach, which showed more accurate results than the DZT, a parametric study on the value of L_0 was conducted. The increase of L_0 showed to concentrate stresses in a smaller portion of the overlap, resulting in a non-linear strength improvement with this parameter. Other authors [26] used the CZM technique to model environmental degradation in composite-to-aluminium joints. Composite-to-aluminium bonded joints under a pure tensile loading were investigated by Khoshrovan and Mehrabadi [27] by experiments and FEM modelling, using the Virtual Crack Closure Technique.

The present work studies, by CZM modelling and experimentation, hybrid adhesively-bonded single-lap joints between aluminium and carbon–epoxy components. Two adhesives of different strength and ductility are considered, to promote failure under varying conditions (namely adherend and adhesive layer's failures) and to assess the numerical models' capability to correctly predict the experimental behaviour. A parametric study is performed regarding L_0 , which is usually the main geometric parameter that affects the joints' strength. The numerical work begins with a detailed stress analysis at different horizontal planes in the joints for a selected geometry, followed by a stress distributions' comparison for the different L_0 values. A damage analysis regarding the composite and adhesive layer's failure follows, for a detailed understanding of the joints' damage evolution during crack propagation up to complete joint failure. These studies are on the basis of a detailed discussion of the experimentally observed and predicted joint strength as a function of the adhesive type and L_0 , to provide design principles that can be applied to hybrid joints. The quantitative comparison between the experiments and numerical results is finally undertaken, with the aim of validating the selected numerical technique as a reliable and straightforward design tool.

2. Experimental work

2.1. Materials characterization

Unidirectional carbon–epoxy pre-preg (SEAL® Texipreg HS 160 RM; Legnano, Italy) with 0.15 mm ply thickness was considered for the composite adherends of the single-lap joints, with the [0]₂₀ lay-up. The adherends were fabricated by hand lay-up followed by curing in a hot-plates press with the supplier-recommended heat and pressure cycle. Table 1 presents the elastic properties of a unidirectional lamina, modelled as elastic orthotropic in the FEM analysis [28]. Table 2 shows the interlaminar and intralaminar cohesive properties of the pre-preg SEAL® Texipreg HS 160 RM, to be used in the CZM simulations. The properties described in Tables 1 and 2 were obtained considering the same composite fabrication process and pressure/temperature/time cycle than those used in the fabrication of the adherends for the

Table 1

Elastic orthotropic properties of a unidirectional carbon–epoxy ply aligned in the fibres direction (x-direction; y and z are the transverse and through-thickness directions, respectively) [28].

$E_x = 1.09E + 05$ MPa	$\nu_{xy} = 0.342$	$G_{xy} = 4315$ MPa
$E_y = 8819$ MPa	$\nu_{xz} = 0.342$	$G_{xz} = 4315$ MPa
$E_z = 8819$ MPa	$\nu_{yz} = 0.380$	$G_{yz} = 3200$ MPa

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