Available online at www.sciencedirect.com

ScienceDirect

Ciência & Tecnologia dos Materiais 29 (2017) e114–e118

http://ees.elsevier.com/ctmat

Special Issue “Materiais 2015”

Strength and failure modes of single-*L* adhesive joints between aluminium and composites

N.R.E. Domingues[a], J.C. Trojan[b], R.D.S.G. Campilho[a, *], R.J.C. Carbas[b], M.D. Banea[c],
L.F.M. da Silva[b]

[a]*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*
[b]*Departamento de Engenharia Mecânica, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal*
[c]*Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, CEFET/RJ, Brasil*

Abstract

Adhesive bonding is a process of permanent union between the components of a structure, which is used to manufacture complex shape structures, which could not be manufactured in one piece, aiming to provide a structural joint that theoretically should be at least as resistant as the base material. Composite materials reinforced with fibres are becoming increasingly popular in many applications, as a result of a number of competitive advantages over conventional materials. Regarding the manufacture of composite structures, although the currently used techniques reduce to the maximum the connections, these are still necessary due to the typical size of the components and design, technological and logistical limitations. Moreover, it is known that in many high performance structures, it is necessary to join components in composite materials with other light metals such as aluminium, for the purpose of structural optimization. This work aims to experimentally and numerically study single-*L* adhesive joints between aluminium components and carbon-fibre reinforced composite structures under peeling loads, considering different geometric conditions and adhesives. It was found that the adhesive ductility and aluminium plate thickness are highly relevant parameters to improve the joints strength.

Keywords: Adhesive joints; finite element method; cohesive zone models; single-*L* joints.

1. Introduction

Adhesive-bonding has grown fast in the last decades to increase the performance of structures due to its inherent advantages. During the design process of a structure that requires joining, adhesive-bonding should always be weighed against traditional techniques, due to new possibilities of lesser weight, increased stiffness and reduced costs [1]. Fibre-reinforced composite materials are becoming increasingly popular. Composite materials are typically used in structures that require high specific strength and stiffness, which reduces the weight of components. The increasing use of composites in the aerospace industry acquired knowledge and design tools enabled expanding these materials to industries like boat building, automotive and military [2]. Although the manufacturing methods reduce to the maximum the connections, it is still necessary to join parts due to the typical size of the components and design, technological and logistical limitations [3]. Moreover, in many high performance structures, it is necessary to combine composite materials with other light metals such as aluminium or titanium, for the

---

[*] Corresponding author.
E-mail address: raulcampilho@gmail.com (R.D.S.G. Campilho)

http://dx.doi.org/10.1016/j.ctmat.2016.04.009

purpose of structural optimization [4]. Joint analysis is often conducted by analytical or numerical (Finite Element, FE) methods [5]. Apart from the single-lap joint configuration, many other geometries have been studied in the literature: double-lap, butt, corner, tubular, scarf, *T*-joints and others [6].

Peel loadings have been studied for a long time [7,8]. Nase *et al.* [9] tested different adhesives in *T*-peel and fixed arm peel tests. Low-density polyethylene/ isotactic polybutene-1 (iPB-1) peel films were investigated. Different amounts of iPB-1 content were tested by the *T*-peel specimen, and an exponential decrease of the strain energy release rate (G^c) was found with increasing this content. The fixed arm peel tests showed interlaminar and translaminar propagation, characterized by fracture mechanics parameters. Lin *et al.* [10] studied 180º peel tests and concluded that the peel load was dependent on the adhesive thickness (t_A) and test velocity. Zhang and Wang [11] used a Cohesive Zone Model (CZM) to model a peel test. The joints were particularly influenced by the peel rate. Applications of *T*-joints can be found in many industries such as ship building, in which bulkheads are joined to the hull [2]. Shenoi and Violette [12] addressed the effect of *T*-joint geometry under peel loadings using experimentation and numerical techniques. Single-*L* joints consist of bonding a 90º corner adherend (*L*-part) to a flat adherend. Li *et al.* [1] studied single-*L* joints under tensile and bending loads. The overlap length (L_O), t_A and *L*-part thickness (t_{P2}) played an important role on stresses. Zhang *et al.* [13] proposed a two-dimensional (2D) theoretical model to analyse peel stresses of single-*L* adhesive joints between composites and aluminium. The peeling stress distributions were a damping harmonic function with period and maximum value depending on the constituents' materials and joint geometry. FE results were compared with the proposed model, giving a good correlation.

This work aims to study, by experimentation and CZM, single-*L* adhesive joints between aluminium components and carbon-epoxy composite plates under a peel loading, considering different values of t_{P2} and adhesives of distinct ductility. The numerical analysis will enable a full understanding of the joints' behaviour, in terms of stress distributions, damage evolution, strength and failure modes. As a result, it will be possible to optimize the geometry and material parameters of the joints.

2. Experimental Part

2.1. Materials

Unidirectional carbon-epoxy pre-preg (SEAL® Texipreg HS 160 RM; Legnano, Italy) with 0.15 mm thickness was considered for the composite adherends of the single-*L* joints. Table 1 presents the elastic properties of a unidirectional lamina [14].

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) [14].

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

The aluminium adherends are made of a laminated high-strength aluminium alloy sheet (AA6082 T651). The mechanical properties of this material are available in reference [15]. The bonded joint analysis included two structural adhesives: the brittle epoxy Araldite® AV138 and the ductile polyurethane Sikaforce® 7752. Characterization of the adhesives was undertaken in previous works: *E* and shear modulus (*G*), failure strengths in tension and shear (corresponding to the CZM cohesive strengths in tension (t_n^0) and shear (t_s^0) and values of fracture toughness in tension (G_n^c) and shear (G_s^c) [5,15]. The tensile elastic and strength/strain data was obtained by bulk tests, while the relevant material properties in shear were assessed by Thick Adherend Shear Tests (TAST). The G_n^c and G_s^c values were estimated in reference [15] by inverse fitting techniques.

2.2. Joint dimensions, fabrication and testing

Fig. 1 shows the dimensions of the single-*L* joints (in mm): L_O=25, width *b*=25, specimen length L_T=80, flat adherend thickness t_{P1}=3, t_{P2}=1, 2, 3 and 4, curved element free length L_A=60, curved element radius *R*=5 and t_A=0.2. The composite plates' fabrication was undertaken by hand-lay-up followed by curing in a hot-plates press. The curved elements were bent using a manual bending machine. The bonding procedure was as follows: (1) manual abrasion of the aluminium and composite adherends at the bonding surfaces, (2) bonding in a steel mould using calibrated spacers to guarantee the selected t_A value and (3) application of pressure with grips. The joints were tensile tested in an Instron® 3367 testing machine, at room temperature