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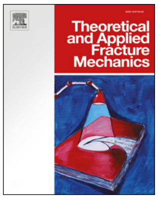

Taper's angle influence on the structural integrity of single-lap bonded joints

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ABSTRACT

The effect of conventional inside and outside tapers was addressed considering angles of 30°, 45° and 60°. The strain state of the joints was analyzed with an optical technique and an electrical gauge. Parametric studies were performed using the numerical method to investigate the role of taper geometries and taper angles on the stress distributions of adhesive joints. The statistical analysis of the numerical stresses reported within this paper allowed to get conclusions about which of the taper geometries conducted to higher adhesive compression levels. Experimental results showed that the reduction of the angles of taper increases the joint strength for all types of tapers and this was in agreement with the numerical results obtained from finite element analysis. The joints with outside tapers have higher tensile/shear strength than the joints with reverse or normal adhesive tapers. Local and global strains of the joints with the normal adhesive tapers showed different values, especially for the taper angle of 60°. The mid-line of the adhesive layer of the inside and adhesive tapers showed similar average shear-peel load levels, but because the inside taper geometry induces more compression of the adhesive and the position of the peaks of shear and peel stresses is not coincident, the inside tapering showed to be preferable.

1. Introduction

The development of feasible and durable adhesives has been the main reason for the increasing use of adhesive joints as an alternative to the traditional mechanical joints (bolted, riveted) or welded joints. The adhesive bonded joints present a large number of advantages such as smaller stress concentration, absence of fretting between materials to be joined, improved fatigue behavior and easier conformance to complex shapes, amongst many other factors [1].

Single lap joints (SLJ) have the simplest joint shape and their strength can be improved by the minimization of the peel and shear stresses [2,3]. According to Sancaktar and Nirantar [4] the failure of a SLJ is determined by the maximum stresses at the overlap edges, but joint modifications can produce more uniform stress distributions and, therefore, its effect should be taken into consideration in the design of adhesive joints. These authors concluded also that reducing the thickness of the adherends near the overlap edges the local stress values can be reduced and the failure load increases. In fact, such stresses are very important in the failure process and there are different parameters that affect the stress distribution, for instance adherends and adhesive strength and elastic modulus, adherends and adhesive thickness, overlap length and fillets at the overlap edges [3,5,6]. However, more recently, literature reports that modifying the shape of adherents can reduce the peak stresses in the mid-line of the adhesive layer and, consequently, increase the strength of the joint [7–12].

The effect of fillets at the overlap edges, for example, was studied by Solmaz and Turgut [13] using lap-shear tests on SLJ with different taper angles and overlap lengths. They concluded that increasing the taper angle the joint strength increases and, especially, the highest strength values were obtained with specimens having taper angles of 15°. Several authors studied how the joint geometry, as for example taper angle and taper position, affect the joint strength. Hildebrand [14] studied the effect of the joint-end geometry and concluded that the type of the taper end is crucial for the strength of single lap joints due combined effect of the high tensile, peeling and shearing loads. So, the efficiency of these types of joints can be significantly improved by a careful design of the joint ends. The author also concluded that tapering the adhesive fillet and using inside tapers reduces the strength in the adhesive. Bezine et al. [15] studied the influence of the overlap length and of the adherends shape on the joint stress distribution and concluded that the taper at the joints ends induces a decrease in the peeling and shear stresses. Later, Oterkus et al. [16] have presented a semi-analytical solution method in order to analyze the geometrically nonlinear response of bonded composite lap joints and concluded that the taper edges led to a considerable reduction in the peeling and shear stresses.

The material beahavior of the adhesive, brittle or ductile, also plays an important role in the behavior of the joint. Campilho et al. [17] studied the strength improvement of single-lap aluminium joints

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bonded with brittle and ductile adhesives. These authors concluded that brittle adhesives are very sensitive to peak stresses and they do not allow plasticization, but ductile adhesives fail under global yielding conditions and, consequently, the improvement in strength is not so significant. Zhao et al. [18] had also studied the type of adhesive and its influence in the joints strength showing that, in the case of joints bonded with brittle adhesives, the crack propagation occurs for a short period before it grows into catastrophic failure, but in the case of ductile adhesives there is large adhesive yielding and small crack propagation before final failure. They had also concluded that for joints bonded with ductile adhesives it is possible to appear more than one crack in the adhesive layer before failure. According to Banea et al. [19] the use of a ductile adhesive at the ends of the overlap joint combined with a brittle adhesive in the central part of the joint promotes an improvement in the maximum strength of the joints in quasi-static tests. According to these authors the load carried by the brittle adhesive is higher than the load supported by the ductile ones. On the other hand, nowadays, literature also proposes several methods to enhance the mechanical, electrical, and thermal properties of the adhesives, such as adding powders, micro and nanoparticles as well as random and woven fibers [20–25].

In this context, the first objective of the present work was to assess experimentally and numerically how the overlap length, the angle of the taper and the taper geometry influence the strength of the adhesive joints. The influence of the taper angle was studied using a procedure in which the overlap length remains constant. It is known that failure in bonded joints can occur in the adhesive, in adherends or at the interface adhesive-adherend. So it is very important to predict how the geometrical parameters of the taper can influence the failure type as well as the joint strength. DIC analyses were also done, in order to study the eventual differences on the local and global strain measurements and, additionally, the numerical stresses estimated for the three taper geometries were statistically analyzed.

2. Materials and experimental procedure

Several series of adhesive single lap joints (SLJ) were produced using adherends from a 4 mm thick AA5083 aluminum alloy plate and an epoxy adhesive Araldite® 420 A/B. The material properties of both adherends and adhesive materials are given in Table 1. The geometry and dimensions of the specimens are shown in Fig. 1, where adherends with 25 mm of width were used. Before bonding, superficial oxides were removed from surfaces to bond with water sandpaper 220 mesh and cleaned with acetone to eliminate contaminations. After bonding the adhesive was cured at a constant temperature of 50 °C for 4 h in a hoven Digiheat from the JP Selecta. Alignment tabs were used to reduce the singularity of the load which can originate out of plane bending moments that promote joint rotation and, consequently, high peel stress and shear stress in the adhesive.

Series of different overlap length, different type and taper angles were performed, as illustrated in Fig. 2 (adhesive is shown in green[1] color). For the specimens where the taper angle and taper type effect were analyzed, the overlap length was about 20 mm, while the effect of overlap length varied between 20 mm and 30 mm. Taper angles of 30°, 45° and 60° were studied which, according to Fig. 2, were introduced into the samples using the adhesive (Fig. 3a) or by machining the adherends (Fig. 2b and c).

Tensile/shear tests were carried out using an Instron universal tensile testing machine, Model 4206, in accordance with the standard ASTM D 1002-01. All tests were performed at room temperature using a strain rate of 1.3 mm/min. Global strain data of the specimens was evaluated using a 50 mm gauge length clip-on Instron extensometer, Model Ex2630-112. Local strain data acquisition was performed using an Aramis 3D 5M optical system (GOM GmbH) with Digital Image Correlation (DIC). Therefore, full-field displacements of the overlap region could be measured. It should be noted that before testing, the specimens were prepared by applying a random black speckle pattern, over the previously mat white painted surface of the samples, in order to enable data acquisition by DIC [26].

Table 1
Mechanical properties of the adherends and adhesive [18,19].

Property	AA5083 aluminum	Araldite® 420 A/B
Young's modulus, E [GPa]	71	1.85
Poisson's ratio, ν	0.33	0.33
Tensile yield stress [MPa]	148	17
Tensile failure strength [MPa]	326	30
Tensile failure strain [%]	16	22
Shear failure strength [MPa]	190	35
G_{IC} [N/mm]	–	3
G_{IIC} [N/mm]	–	12.5

In order to characterize the fractured surfaces, all specimens were analyzed in detail with a microscope Stemi 2000-C from Zeiss. These surfaces were observed also by scanning electron microscope (SEM) ZEISS MERLIN Compact/VPCompact in order to complement the analysis of fracture mechanisms. For this purpose, all the joints were sputtered coated with a 30 nm thick gold layer prior to SEM evaluation in order to minimize the charging effects. The mapping of fractured zones was done on the photographs using the AxioVision software from Carl Zeiss, to quantify the cohesive and the adhesive failures.

Finally, the lap-shear strength (τ_R) was calculated according to Eq. (1) [27]:

$$\tau_R = \frac{P}{b\ L} \tag{1}$$

where P is the load, b is the joint width and L is the length of the overlap joint.

3. Finite element model

A two-dimensional analysis of single lap joints with different geometry and taper angles was performed using ADINA® software. Finite Element (FE) simulations of these two-dimensional models, which are presented in Fig. 2, were performed to obtain the distribution of shear and peel stresses along the adhesive mid-thickness. FE analysis allows to emphasize the role of different geometries and taper angles on the distribution of stresses and, therefore, on the overall strength of joints. Moreover, these FE models were coupled with Cohesive Zone Models (CZM) to perform strength prediction of the bonded joints, where different methods to determine the CZM parameters can be found in the literature [28–31]. The basic concepts used in the definition of the constitutive law of cohesive element are those presented by Alfano and Crisfield [32], where the cohesive element uses a bilinear constitutive law that relates stresses and relative displacements of the homologous nodes of cohesive element. The damage initiation under mix-mode can be specified by the power law criterion or the Benzeggagh-Kenane criterion. After the onset of damage, the stiffness of the cohesive element is gradually reduced to zero [33].

The epoxy adhesive Araldite™ 420A/B supplied by Hunstman® (Salt Lake City, UT, USA) was previously characterized by Braga et al. [34] using the procedure described in the standard ASTM D638. Fig. 3 presents representative stress-strain curves for the experimental and numerical results. The numerical results were obtained using nine-node two-dimensional finite elements under plane stress conditions, geometrically non-linear conditions and large deformation analysis. The FE model recreated well the experimental stress-strain curve of the adhesive, but for higher deformation levels the distortion of mesh lead to

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[1] For interpretation of color in 'Fig. 2', the reader is referred to the web version of this article.