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# Effect of hole drilling at the overlap on the strength of single-lap joints

A.M.G. Pinto [a,*], R.D.S.G. Campilho [a,b,c], I.R. Mendes [a], S.M. Aires [a], A.P.M. Baptista [c]

[a] *Instituto Superior de Engenharia do Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal*
[b] *Faculdade de Economia e Gestão, Universidade Lusófona do Porto, Rua Augusto Rosa, 24, 4000-098 Porto, Portugal*
[c] *Departamento de Engenharia Mecânica, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal*

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ABSTRACT

Bonded unions are gaining importance in many fields of manufacturing owing to a significant number of advantages to the traditional fastening, riveting, bolting and welding techniques. Between the available bonding configurations, the single-lap joint is the most commonly used and studied by the scientific community due to its simplicity, although it endures significant bending due to the non-collinear load path, which negatively affects its load bearing capabilities. The use of material or geometric changes in single-lap joints is widely documented in the literature to reduce this handicap, acting by reduction of peel and shear peak stresses at the damage initiation sites in structures or alterations of the failure mechanism emerging from local modifications. In this work, the effect of hole drilling at the overlap on the strength of single-lap joints was analyzed experimentally with two main purposes: (1) to check whether or not the anchorage effect of the adhesive within the holes is more preponderant than the stress concentrations near the holes, arising from the sharp edges, and modification of the joints straining behaviour (strength improvement or reduction, respectively) and (2) picturing a real scenario on which the components to be bonded are modified by some external factor (e.g. retrofitting of decaying/old-fashioned fastened unions). Tests were made with two adhesives (a brittle and a ductile one) varying the adherend thickness and the number, layout and diameter of the holes. Experimental testing showed that the joints strength never increases from the un-modified condition, showing a varying degree of weakening, depending on the selected adhesive and hole drilling configuration.

## 1. Introduction

Bonded unions are gaining importance in many fields of industry and manufacturing owing to a significant number of advantages to the traditional fastening, riveting, bolting and welding techniques. These include the uniform stress distributions along the width, possibility to joint different materials, improved fatigue and damping characteristics and reduced cost. Apart from this, adhesive bonded joints are becoming more and more efficient owing to increasing research and development in their microstructure, offering higher peel and shear strengths combined with larger ductility up to failure, which often results in stronger unions than the parent materials [1]. Amongst the disadvantages are the requirement of surface preparation, vulnerability to extreme environmental conditions and varying properties depending on the manufacturing/curing conditions. Between the available bonding configurations, the single-lap joint is the most commonly used and studied by the scientific community due to its simplicity, although it endures significant bending due to the non-collinear load path. This eccentricity is responsible for peel peak stresses at the overlap edges which, added to the differential deformation effects along the overlap responsible for shear peak stresses, negatively impact on the joints effectiveness [2]. Other available configurations include the double-lap, stepped and scarf joints that provide improved stress distributions but are more complicated to manufacture. Owing to the aforementioned stress concentration issues in single-lap joints, much attention has been paid to the development of innovative techniques to surpass this limitation. These strength improvement techniques can be divided in to two major groups: geometric and material modifications, which positively affect the joints behaviour mostly by two mechanisms: reduction of peel and shear peak stresses at the critical regions (usually near sharp geometry changes) [3,4] or modification of the failure mechanism emerging from local changes [5].

Material modifications mainly attempt to optimize the material stiffness along the overlap to suppress stress concentrations at the overlap edges. One of these techniques consists on the use of bi-adhesives along the bondline. By using a stiffer adhesive at the inner overlap region than at the edges, a larger amount of load is transmitted by the inner region of the bond and the joints strength is increased, especially for brittle adhesives [6–8].

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[*] Corresponding author. Tel.: +351919863264; fax: +351228321159.
*E-mail address:* agp@isep.ipp.pt (A.M.G. Pinto).

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Young's modulus ($E$) grading of the adherends is another alternative. Ganesh and Choo [9] used this technique by continuously varying the braiding angle of the adherends' composite fibres to produce a varying value of $E$ along the bond length that increased the joints strength. Finite Element simulations showed that shear peak stresses in the adhesive bond can be reduced by 20%. Pinto et al. [10] showed by a Finite Element (FE) stress and failure analysis that increasing the stiffness of the adherends materials in single-lap joints leads to a reduction of the joint bending, which diminished stresses at the overlap edges and, consequently, increased the strength of the joints.

Geometric alterations are widely used to increase the strength of single-lap joints. Adhesive fillets at the overlap edges are one of the most widespread solutions, redistributing stresses at the overlap edges and, as a result, increasing the strength of the joints [11–13]. For maximum effect of this modification, i.e. minimizing peel and shear peak stresses at the overlap edges, fillets comprise all the patch thickness [14]. Tsai and Morton [15] addressed the influence of filleting on composite single-lap joints by plotting shear strains near the fillet using the Moiré Interferometry Method. The analysis showed a reduction of shear strains, and also of peel and shear stresses at the fillet region, subsequently increasing the joint strength. An improvement of this procedure was proposed by You et al. [16], which tested experimentally the use of fillets incorporating steel wires and wedges with varying shapes in single-lap joints with steel adherends. Three different shape/size combinations for the steel elements were considered, including circular and triangular shaped elements. An approximately 45% improvement was found for the joints tensile strength using a circular steel wire, with smaller improvements resulting from the other shapes. Adherend tapering at the overlap region is also documented in the literature. Sancaktar and Nirantar [17] concluded that adherend tapering significantly reduces peel and shear peak stresses in single-lap joints, which yields a strength improvement. These results are fully consistent with the work of Boss et al. [18]. Another solution consists on bending the adherends at the bonding edge for the optimization of the stress distributions by elimination of the joints eccentricity. This technique was analysed by photoelasticity by McLaren and MacInnes [19], showing its effectiveness for the uniformization of the adhesive stresses along the bondline. Fessel et al. [20] performed an experimental and FE study regarding tensile loaded steel single-lap joints, with emphasis on wavy and bent geometries. These modifications diminished peel and shear peak stresses at the overlap edges (from 8% to 40% compared to the flat geometry, depending on the adherends material and geometric parameters such as the overlap length). Campilho et al. [21] studied single-lap joints bonded with a brittle and a ductile adhesive to assess the strength improvement by the adherend bending technique, considering different degrees of eccentricity, including absence of eccentricity, for the optimization of the joints. Bending of the adherends showed to be quite positive in reducing peel peak stresses at the overlap edges, which gradually diminished by increasing the adherends bending. Shear peak stresses also turned less significant at the overlap edges with the increase of the adherends bending. Experimental and FE results showed a great advantage in using this technique for the brittle adhesive, conversely to the joints with the ductile adhesive. Actually, these were not so much affected by the proposed technique since ductile adhesives redistribute stress in the bond and limit the effect of peak stresses. Ávila and Bueno [22] tested a wavy geometry for single-lap joints with composite adherends (sinusoidal adherends shape at the overlap induced by the fabrication process). The authors concluded that this solution increased on nearly 40% the strength of the flat joints because of the elimination of the peel and shear peak stresses at the edges of the adhesive layer. Identical results found by Zeng and Sun [23] reported a large strength improvement of the joints emerging from the suppression of peel stresses and development of compressive through-thickness stresses at the overlap edges. Sancaktar and Simmons [24] tested an adherend notching technique at the overlap edges on aluminium single-lap joints under tension. The FE study carried out showed benefits in terms of stress distributions, namely a 66% reduction on peel peak stresses. Despite this fact, experimental testing revealed a strength improvement of only 8% compared to the standard single-lap joints. The numerical work of Yan et al. [25] focused on a similar notching technique by studying the influence of the length and depth of a parallel slot at the mid-region of the bond length. By using this technique, shear and peel peak stresses at the bond edges markedly decreased with a corresponding increase of load transfer at the usually lightly loaded inner region of the bond. Peel stresses were suppressed at the joint edges, which can lead to a strength improvement.

In this work, the effect of hole drilling in the adherends on the strength of single-lap joints was analyzed experimentally with two main purposes: (1) to check whether or not the anchorage effect of the adhesive within the holes is more preponderant than the stress concentration effect near the holes arising from the sharp edges and modification of the joints straining behaviour (strength improvement or reduction, respectively) and (2) picturing a real scenario on which the components to be bonded are modified by some external factor (e.g. retrofitting of decaying/old-fashioned fastened unions). Tests were made with two adhesives (a brittle and a ductile one) varying the adherend thickness and the number, layout and diameter of the holes.

## 2. Experimental work

### 2.1. Materials

The aluminium alloy for the adherends and the two adhesives selected for this study were properly characterized for a perception of their behaviour and interpretation of the experimental results, presented further in this work. The adherends were fabricated from the high strength aluminium alloy AW6082 T651, showing a manufacturer specified strength of 340 MPa achieved by artificial ageing at approximately 180 °C. This aluminium alloy was previously characterized [26] using dogbone specimens. The stress–strain ($\sigma$–$\varepsilon$) plots, obtained through tensile testing following the principles specified in the standard ASTM-E8M-04 [27], showed a nearly elastic–perfectly plastic law with the following mechanical properties: $E$ of $70.07 \pm 0.83$ GPa, tensile yield stress ($\sigma_y$) of $261.67 \pm 7.65$ MPa, tensile failure strength ($\sigma_f$) of $324 \pm 0.16$ MPa and tensile failure strain ($\varepsilon_f$) of $21.70 \pm 4.24$%. The two adhesives selected for this work, Araldite® AV138 and Araldite® 2015, were also characterized in tension and shear for the determination of all relevant parameters such as $E$, shear modulus ($G$), $\sigma_y$, $\sigma_f$ and $\varepsilon_f$ [28]. The tensile characterization for both adhesives was carried out by bulk specimens with the typical dogbone shape, fabricated according to the French standard NF T 76-142 [29] and da Silva and Adams work [30], which provides guidelines to produce high quality specimens, without voids. The fabrication of the specimens was achieved in a sealed mould by application of pressure and temperature according to the manufacturer indications. The adhesive was poured in a silicone mould with 2 mm thickness to produce a bulk plate that is machined to produce two dogbone specimens each. On the other hand, shear characterization of the two adhesives was achieved by Thick Adherend Shear Tests (TAST) with the procedure described in the standard ISO 11003-2:1999 [31]. For the