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Experimental and numerical analysis of hybrid adhesively-bonded scarf joints

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ABSTRACT

Adhesive joints have been largely used in many areas such as automotive and aeronautic industries, navy, electronic components and construction, among others. The increased application of this joining technique is due to an easy manufacturing, lower costs, easiness to joint different materials, more uniform distribution of stresses and higher fatigue strength. The scarf joint is one of the possible joint configurations and it excels in not requiring to change the initial shape of the component. Improved stress distributions over single and double-lap joints are obtained, although it has some complexity in the manufacturing process. In many practical applications, joining between different adherend materials is required due to design constraints, which poses additional difficulties because of the different stiffness of the materials. This work presents an experimental and numerical study on hybrid scarf joints, between composite and aluminium adherends, and considering different scarf angles (α) and adhesives (the brittle Araldite® AV138 and the moderately ductile Araldite® 2015). Comparison with joints having material balanced adherends is also performed numerically. The numerical analysis by Finite Elements (FE) enabled obtaining peel (σ_y) and shear (τ_{xy}) stresses using the software Abaqus®, which are then used to discuss the strength between different joint configurations. Cohesive Zone Models (CZM) were used to predict the joint strength and the results were compared with experiments for validation. A significant variation of the joints' behaviour was found depending on α and the applied adhesive, which was directly linked to the stresses developed in the adhesive layer during loading. CZM were found to be an accurate design tool for the hybrid scarf joints.

1. Introduction

Due to the recent advances in adhesives' technology, adhesive joints have become more appealing and are now of common use on several application fields, namely the automotive and aerospace industries. Nowadays, and with these advances, adhesively-bonded joints have become more efficient, which has resulted in higher peel and shear strengths, and also in allowable ductility up to failure. As a result of the reported improvement in the mechanical characteristics of adhesives, adhesive bonding has progressively replaced traditional joining methods such as bolting or riveting [1]. There are various advantages to this joining technique, such as weight reduction, more uniform stress distributions, absence of damage in the bonded parts, and ability to bond different materials. However, bonded joints are yet not reliable in critical connections because of issues like fatigue and long-term behaviour uncertainties, and large scatter in the failure loads [2].

In recent years, the advances made on the manufacturing of composite materials, regarding production costs and continuous manufacturing, allowed them to be employed in the commercial automotive industry. With the employment of composites it is possible to obtain a reduction of vehicle weight, which is an important element for automotive manufacturers since it increases the vehicles' performance and it also reduces the fuel consumption [3]. With these advances, new joining methods have been developed like hybrid adhesively-bonded joints, which consist of bonding different materials, or of the combination of traditional joining methods, such as bolting or riveting together with structural adhesive bonding. Actually, in many high performance structures, it is necessary to combine composite materials with other light metals such as aluminium or titanium, for the purpose of structural optimization, e.g. as detailed by Graham et al. [4].

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In the industry, many joint configurations are possible, and the single-lap joint is undoubtedly the most used due to the fabrication ease and lack of any particular manufacturing skills. Although its geometry is rather simple, the σ_y and τ_{xy} stress distributions are highly complex. Other typical joint configurations are double-lap, stepped and scarf joints. Scarf joints are particularly interesting because, unlike single-lap joints, they do not cause bending of the adherends, which negatively influences the joint strength [5]. This is why scarf-bonded structures are increasingly being used in industrial applications. Nevertheless, it has been shown that the mechanical strength of these adhesively bonded joints is still affected by overstresses near the ends of substrates, although to a much smaller extent than with single and double-lap joints, and damage evolves according to the mechanical properties and the geometrical characteristics of the bonded structure. Moreover, since all the adhesive layer is subjected to significant stresses, these joints are particularly affected by creep and fatigue issues, especially with a ductile adhesive and at elevated/wet condition [6].

The design of the optimum scarf repair for a given application (especially for composite structures) is complex on account of the large amount of material and geometric variables that influence the scarf repair performance. Because of this, there are many different studies to find accurate design tools for the static strength of scarf joints or repairs. These can be experimental, analytical, or numerical. An example of experimental study on scarf repairs is the early work of Jones and Graves [7], which studied by experimentation the maximum load (P_m) and fracture paths of structures repaired by the scarf technique. The authors concluded that a flush repair with a scarf angle (α) of 3° was found to yield the best results, returning nearly 80 percent of the undamaged laminate strength. Found and Friend [8] experimentally evaluated the buckling behavior of scarf repaired structures by measuring strains at the repaired region with strain gages. The experiments revealed that the large strains induced by buckling led to debonding of the patch, followed by failure of the structure.

Joint analysis and strength prediction are often conducted by analytical or numerical methods, as in the FE work of Campilho et al. [9]. Apart from the single-lap joint configuration, many other geometries have been studied in the literature, e.g. in the work of Di Bella et al. [10]: double-lap, butt, corner, tubular, scarf, T-joints and others, each of these with particular applications. The analytical studies are limited to stress analyses that can or not include the component of strength prediction by suitable criteria, usually based on maximum stresses or strains [11]. The majority of the static predictive studies is numerical by FE, enabling to estimate the complex stress fields in the adhesive layer [12], or including strength prediction by the continuum mechanics approach, conventional fracture mechanics, CZM or damage mechanics. Gunnion and Herszberg [12] developed a FE model to allow a broad study into the effect of various parameters on the performance of a scarf joint. The stress distributions along the bondline were investigated, and the sensitivity of peak stresses was assessed with respect to changes in α, adhesive thickness (t_A), ply thickness, laminate thickness, over-laminate thickness and lay-up sequence. The most important findings of this work were the relatively low sensitivity of adhesive stress to mismatched adherend lay-ups and the dramatic reduction in peak stresses with the addition of an over-laminate. Moreira and Campilho [13] studied by CZM the strength improvement of adhesively-bonded scarf repairs in aluminium structures with external reinforcements. Several parameters were also analyzed, such as α and different configurations of external reinforcement (applied on one or two sides of the repair, and also different reinforcement lengths). The authors concluded that the use of external reinforcements enables increasing α for equal strength recovery, which makes the repair procedure easier.

Several researchers studied the adhesive bonding technique to join dissimilar adherends. Afendi et al. [14] predicted the strength of adhesively-bonded scarf joints between dissimilar adherends and bonded with an epoxy adhesive. The failure tests between dissimilar adherends (steel and aluminium alloy) were conducted under a remote tension load considering different values of α and t_A. The authors concluded by the FE analysis that a stress singularity exists at the steel/adhesive interface corner of the joint, which was also confirmed by failure surface observations wherein the failure has always initiated at this point. In the study of Yelpale et al. [15] the tensile strength of adhesively-bonded scarf joints was carried out experimentally and numerically for various α values. A commercially available araldite epoxy was used as adhesive and glass-epoxy composites and Bakelite were used as adherends to produce hybrid joints. The authors concluded that P_m for the hybrid joints occurred for $\alpha = 30^o$, that the increase of α causes a strength reduction and that the strength of scarf adhesive joints with glass epoxy adherends is higher than that with Bakelite adherends. Hafizan et al. [16] investigated the fatigue performance of equal-adherend adhesive joints and hybrid adhesive joints, considering the single-lap joint configuration. Three millimeter thick plates of aluminium A7075 and stainless steel 304 were used as the adherend material for the experimental tests, bonded with a high performance epoxy adhesive. The authors concluded that $t_A = 0.2$ mm and overlap length of 59 mm were the optimal parameters regarding the fatigue life. The fatigue performance of each type of joint using dissimilar materials was also assessed with these parameters for several stress levels. Results showed an increment of fatigue life with shear stress reduction.

This work presents an experimental and numerical study on hybrid scarf joints, between composite and aluminium adherends, and considering different values of α and adhesives (the brittle Araldite® AV138 and the moderately ductile Araldite® 2015). Comparison with joints having material balanced adherends is also performed numerically. The numerical analysis by FE enabled obtaining σ_y and τ_{xy} stresses using the software Abaqus®, which are then used to discuss the strength between different joint configurations. CZM were used to predict the joint strength and the results were compared to the experiments for validation.

2. Experimental work

The experimental work consisted of manufacturing scarf bonded joints between different adherend materials. The choice of materials was done based on the use in structural applications in the automotive and aeronautical industries. Therefore, one of the materials is the AW6082-T651 aluminium alloy, which has high strength. The mechanical results are presented in Table 1, following previously performed tensile bulk characterization [13] as depicted in the standard ASTM-E8M-04. The other adherend material is a unidirectional Carbon Fibre Reinforced Plastic (CFRP) composite with unit ply thickness of 0.15 mm. The unidirectional lay-up was considered to represent a joint in a load-oriented structure, although in many practical situations other lay-ups are considered. The adherends were manufactured manually by hand lay-up with 20 unidirectional layers and cured in a hot plates press during 1 h at 130 °C and 2 bar of pressure. In these curing and manufacturing conditions it is almost possible to null all the porosities. For the applied manufacturing conditions, and according to the manufacturer, the fibre volume fraction is near to 64%. Table 2 shows the elastic orthotropic properties used in the numerical simulations carried out in this work.

Table 1
Properties for the aluminium alloy AW6082 T651 [13].

Properties	Aluminium alloy AW6082-T651
Young's modulus, E [GPa]	70.07 ± 0.83
Poisson ratio, υ	0.3
Tensile yield strength, σ_y [MPa]	261.67 ± 7.65
Tensile failure strength, σ_f [MPa]	324.00 ± 0.16
Tensile failure strain, ε_f [%]	21.70 ± 4.24
Vickers hardness, [HV]	100