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Strength improvement of adhesively-bonded scarf repairs in aluminium structures with external reinforcements

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ABSTRACT

Adhesively bonded techniques are an attractive option to repair aluminium structures, compared to more traditional methods. Actually, as a result of the improvement in the mechanical characteristics of adhesives, adhesive bonding has progressively replaced the traditional joining methods. There are several bonded repair configurations, as single-strap, double-strap and scarf. Compared with strap repairs, scarf repairs have the advantages of a higher efficiency and the absence of aerodynamic disturbance. The higher efficiency is caused by the elimination of the significant joint eccentricities of strap repairs. Moreover, stress distributions along the bond length are more uniform, due to tapering of the scarf edges. The main disadvantages of this technique are the difficult machining of the surfaces, associated costs and requirement of specialised labour. This work reports on an experimental and numerical study of the tensile behaviour of two-dimensional (2D) scarf repairs of aluminium structures bonded with the ductile epoxy adhesive Araldite® 2015. The numerical analysis, by Finite Elements (FE), was performed in Abaqus® and used cohesive zone models (CZM) for the simulation of damage onset and growth in the adhesive layer, thus enabling the strength prediction of the repairs. A parametric study was performed on the scarf angle (α) and different configurations of external reinforcement (applied on one or two sides of the repair, and also different reinforcement lengths). The obtained results allowed the establishment of design guidelines for repairing, showing that the use of external reinforcements enables increasing α for equal strength recovery, which makes the repair procedure easier. The numerical technique was accurate in predicting the repairs' strength, enabling its use for design and optimisation purposes.

1. Introduction

Adhesive bonded joints have become more efficient in the last few decades due to the developments in adhesive technology, 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]. Adhesive bonding is a valid option due to its numerous advantages over the conventional bolting or riveting methods [2], e.g. more uniform stress distributions, reduced weight penalty, minimal aerodynamic disturbance and fluid sealing characteristics. It is common knowledge that stress concentrations still subsist in bonded joints along the bond length owing to the gradual transfer of load between the two adherends in the overlap region (also known as differential straining along the overlap), especially in single-lap joints [1,3]. As a result, shear stresses (τ) concentrate at the overlap edges, with only a very small amount of load being carried in the central region. Peel stresses (σ) also develop in the same regions owing to the joint rotation and curvature of the adherends [4]. Both of these can be harmful to the structure, especially when using relatively brittle adhesives, which do not permit plasticization at the loci of higher concentrations, i.e., the overlap edges, leading to premature failures [4]. Bonding of patches with adhesives at the damaged region, which provides durable and resistant unions [5], is being increasingly used in structural repairs. Typically, the initial strength and stiffness of the damaged components cannot be restored using this technique without a significant weight penalty. Thus, a substantial amount of research has been carried out in the last decades on the development of efficient adhesively bonded repairs and on adhesives technology [6,7]. The larger bond areas and the reduction of stress concentrations at the bond edges due to the adherend tapering effect justify the higher efficiency of the scarf repairs, compared to the easy-execution strap repairs [8]. The outcome of the

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optimisation of stresses is a higher strength for the same bond area than strap repairs [9], which renders scarf repairs more suited to critical applications. The substantial or full strength recovery achieved by this method, provided that the repair is correctly designed, usually makes scarf repairs as permanent [10,11]. Thus, in high responsibility structures requiring a full or significant strength recovery, or when a flush surface is imposed by aerodynamic or stealth reasons, an adhesively-bonded scarf repair is often used. However, it should be noted that small scarf angles, necessary to obtain higher efficiencies, may not be applicable since they require a larger repair area [8]. The scarf repair technique has become particularly important in the last decades, due to the increasing use of sandwich panels in aircraft structures [10]. Stepped repairs can rival the performance of scarf repairs in composite structures [12].

The majority of the works on the strength of scarf joints or repairs focus on their tensile behaviour, e.g. [13]. However, compression/buckling behaviour [14] and bending [8] are also addressed. The most common design approaches for scarf repairs are analytical methods [15,16], experimental strain-measurement based methods [17,18] and Finite Element (FE) analyses [19–21]. The analytical methods developed in this area typically focus on displacement and stress analyses, which do not capture the stress gradients along the adhesive thickness. Few works address composite repairs, but these do not account for different oriented plies of the adherends. The work of Ahn and Springer [22] is an exception, adapting the failure models of Hart-Smith [23] to take into account each individual ply of the composite. The strain-measurement methods are often used to monitor the condition of in-service-bonded structures and also for strength prediction [14]. The FE was also extensively used to obtain the stress fields and predict failure of these repairs, using appropriate failure criteria. In tension, experimental and FE studies showed an exponentially increasing strength with the reduction of the scarf angle, due to the corresponding increase in the bond area [13,24]. Odi and Friend [25] performed a 2D FE stress and failure analysis of tensile loaded scarf repairs, using scarf angles ranging from 1.1° to 9.2°. A quasi isotropic $[0_2/\pm45/90/\pm45/0_2]_S$ composite plate and patch lay-up was considered. The numerical model captured the τ stress variations along the bond length arising from different ply orientations. The numerical failure loads were obtained using different failure criteria for the laminates and the Average Shear Stress Criterion for the adhesive. The most accurate laminate failure predictions were obtained with the Maximum Stress Criterion, agreeing with the experimental results. Even though these numerical methodologies have a significant usefulness in predicting the failure loads and identify damage onset locations, they cannot account for the progressive damage evolution and identify failure paths, as cohesive zone models (CZM) are able to [26,27]. In addition, in these repairs, a significant difference exists between damage initiation and ultimate loads, due to σ and τ peak stresses developing at bond edges [28]. Thus, CZM implemented within FE models are a more accurate tool to predict the failure path and strength of adhesively-bonded repairs. Campilho et al. [28] numerically studied the tensile strength and failure modes of carbon-fibre reinforced plastics (CFRP) scarf repairs using a triangular CZM, for values of α from 2° to 45°. The authors concluded that the model successfully predicted the strength and failure modes in these repairs, and also that the adhesive fracture properties present a smaller influence on the repairs strength than the mechanical ones. In another work [13], a developed trapezoidal CZM was applied to tensile loaded 2D scarf repairs on CFRP laminates, for values of α between 2° and 45°. Validation was carried out by comparison with experiments. To account for the experimental fractures, the cohesive failure of the adhesive layer and composite interlaminar and intralaminar (in the transverse and fibre directions) failures were considered at different regions. The corresponding tensile and shear CZM laws were estimated with an inverse modelling technique. The accurate predictions of the fracture loads and failure mechanisms validated the proposed technique.

Another feasible technique to increase the strength of scarf repairs, opposed to that of using very small values of α, consists of the application of external doublers adhesively bonded at the scarf repaired region to protect the patch tips and to provide a larger cross-sectional area at the repaired region [29]. These doublers are generally very thin and should follow the repaired structure contour as closely as possible [30]. The most efficient solution is to bond these reinforcements on both the structure faces [31–33]. However, a more practical solution consists on their application only on the outer face of the repair [20,34]. This repair scenario can also be imposed by accessibility difficulties to the inner face of the structure, or be rendered unfeasible for sandwich structures [35]. Gunnion and Herszberg [36] investigated the effect of a composite reinforcement on both faces of scarf joints with 16 and 32 ply CFRP laminates applied to the full length and width of the joints. This technique resulted in a significant drop of σ and τ peak stresses within the bond, which otherwise develop near the scarf edges. Different lay-ups and increasing the number of reinforcement plies from the initial analysis (2 plies) provided no significant differences in reducing σ and τ peak stresses. The most comprehensive study regarding this issue consisted on a CZM-based numerical analysis on composite repairs with values of α = 5°, 10°, 15°, 25° and 45° [4]. This technique showed a significant reduction of σ and τ peak stresses at the scarfed region. The analysis evaluated the use of a single reinforcement to the scarf repair (overlaminating at the outer side of the repair) and double reinforcement (overlaminating at the outer and inner sides of the repair). Overlaminating lengths of 2.5 and 5 mm were considered. For all conditions the strength improved exponentially with the reduction of α. The study showed that increasing the overlaminating length highly increases the repair strength. On the other hand, double reinforcement is also recommended over single reinforcement, because of the improved stress reduction effect at the scarfed region on account of the larger reinforcement areas and suppression of the structure transverse deflection.

This work reports on an experimental and numerical study of the tensile behaviour of 2D scarf repairs of aluminium structures used in the aeronautical and aerospace industries bonded with the ductile epoxy adhesive Araldite® 2015 (from Huntsmann, Basel, Switzerland). The numerical analysis (by FE) was performed in Abaqus® and used CZM for the simulation of damage onset and growth in the adhesive layer, thus enabling the strength prediction of the repairs. A parametric study was performed on the value of α and different configurations of external reinforcement (applied on one or two sides of the repair, and also different reinforcement lengths).

2. Experimental work

The material used for the adherends is the high strength aluminium alloy AW6082 T651. This alloy was chosen due to its wide utilisation in structural applications under various extruded forms [37]. For the repaired structure, a sheet with 3 mm thickness was used and, for the reinforcements, a sheet with 1 mm thickness was considered. The stress–strain (σ–ε) curves for the aluminium alloy were obtained according to the ASTM-E8M-04 standard. The resulting mechanical properties are showed in Table 1 [38]. The adhesive Araldite® 2015, used in this work, is a two-part structural adhesive allowing large plastic flow prior to failure, which is an important feature for bonded structures as it prevents premature failures by undergoing plasticization when the adhesive limiting stresses are attained at stress concentration regions. These