TENSILE BEHAVIOUR OF SINGLE AND DOUBLE-STRAP REPAIRS ON ALUMINIUM STRUCTURES

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ABSTRACT

In this work, an experimental study was performed on the influence of plug filling, loading rate and temperature on the tensile strength of single-strap (SS) and double-strap (DS) repairs on aluminium structures. The experimental programme includes repairs with different values of overlap length (L_O=10, 20 and 30 mm), and with and without plug filling. The influence of the testing speed on the repairs strength is also addressed (considering 0.5, 5 and 25 mm/min). Accounting for the temperature effects, tests were carried out at room temperature, 50ºC and 80ºC. This will permit a comparative evaluation of the adhesive tested below and above the Glass Transition Temperature (T_g), established by the manufacturer at 67ºC. The global tendencies of the test results concerning the plug filling and overlap length analyses are interpreted from the fracture modes and typical stress distributions for bonded repairs. According to the results obtained from this work, design guidelines for repairing aluminium structures were recommended.

KEY WORDS: Epoxy adhesive, Experimental testing, Plug filling, Strap repairs.

1. INTRODUCTION

Adhesive bonding as a joining or repair method has a wide application in many industries. Repairs with bonded patches are often carried out to re-establish the stiffness at critical regions or spots of corrosion and/or fatigue cracks [1]. However, the limited understanding of the behaviour of bonded assemblies over the life of structures (including under exposure to extreme temperatures and humidity) and the lack of universal failure criteria still limits their prompt usage on industry applications, at least without a significant amount of testing [2]. SS and DS repairs are a viable option for repairing. By this technique, a hole is drilled at the weakened region to remove the damaged and cracked material, which contains sources for the premature growth of damage [3]. For the SS repairs, a circular patch is then adhesively-bonded on one of the structure faces. SS repairs are easy to execute, but the load eccentricity leads to peel peak stresses at the overlap edges [4]. These, added to the shear peak stresses developing at the same regions due to the differential straining, justify the small efficiency of SS repairs [5]. DS repairs are identical but they involve two patches, one on each face of the structure. These are more efficient than SS repairs, due to the doubling of the bonding area and suppression of the transverse deflection of the adherends [4]. Shear stresses also become more uniform as a result of smaller differential straining. A two-dimensional (2D) approximation of this geometry is often used for design [5], consisting on replacing of the hole by a gap between two separated rectangular plates. This geometry, reasonably predicting the stresses of the three-dimensional (3D) repair, is acceptable only for the optimization of geometric parameters influencing the repairs strength [6].

A few studies can be found about the effect of plug filling with adhesive the gap between the plates (2D approximation) or hole (3D repair) left by the removal of the damaged material. Campilho et al. [7] addressed this technique by the Finite Element Method (FEM) on tensile loaded 2D SS and DS repairs with carbon-epoxy adherends. The SS repairs strength slightly decreased by the use of plug filling due to plug fracture prior to failure of the adhesive layer along the overlap, due to the lateral flexure of SS repairs [4]. Conversely, plug filling highly increased the DS repairs strength (≈10% strength improvement), due to the absence of flexure of the parent structure. Soutis et al. [5] evaluated by the FEM the influence of plug filling on the compressive strength of 3D DS repairs on composite structures. The compressive strength of the repairs reached almost the undamaged strength of the laminates by filling with adhesive the open-hole of the repairs. Campilho et al. [8] addressed by the FEM and using 3D models SS and DS repairs of composite laminates under tension, compression and bending. A 1.2% strength reduction was obtained for the SS repairs with plug-filling under tension compared to the unplugged condition, due to a plug failure prior to failure along the bond length.

Published studies on the subject of adhesives technology revealed that loading rate and temperature effects largely impact on the mechanical properties of adhesives [9]. A few number of studies can be pointed out considering strain rates higher than quasi-static conditions. Some examples are the works of Zgoul and Crocombe [10] and Srivastava [11]. One of the first attempts to model the time dependent behaviour of adhesives is the work of Delale and Erdogan [12], which modelled the visco-elasticity of adhesively bonded joints using Laplace transforms. Because of the complexity of the problem, they obtained the inverse transformations numerically. Malvade et al. [13] studied adhesively bonded double-lap joints in tension for variable extension rates and temperatures. The numerical simulations took advantage of the Raghava [14] and Von Mises yield criteria coupled with nonlinear isotropic hardening to simulate damage of the adhesive.

High temperature usually leads to a strength reduction of bonded assemblies [15], due to a degradation of the adhesive properties [16] and adherend thermal mismatch, when the joined materials have different coefficients of thermal expansion [17]. However, the main factor affecting the strength of adhesive bonds under extreme temperatures is the variation of the adhesive properties [18]. Adams et al. [19] experimentally studied the performance of single-lap joints at low and room temperatures, emphasizing on the significance of adherend mismatch, shrinkage and adhesive properties on the stress state of lap joints. The work by Grant et al. [18] provides a comprehensive evaluation of the temperature effects on the strength of adhesive bonded single-lap joints under tension and bending, and also T-joints. A reduction of stiffness and strength was found increasing the test temperature.

In this work, the influence of plug filling, loading rate and temperature on the tensile strength of SS and DS repairs on aluminium structures was studied experimentally. The testing programme includes repairs with different values of L_O (10, 20 and 30 mm) and with and without plug filling. An investigation is also carried out on the influence of the testing speed on the repairs strength (0.5, 5 and 25 mm/min). Accounting for the temperature effects, tests were carried out at room temperature, 50ºC and 80ºC, allowing a comparative evaluation of the adhesive tested below and above the T_g of the adhesive, defined at 67ºC.

2. EXPERIMENTAL

2.1. Selected materials and surface preparation

The adherends and patches were cut from aluminium plates (AW6063-T6). The two-part epoxy structural adhesive Araldite® 2015 was selected for this study, characterized by a large ductility in tension and shear. The bonding surfaces of the aluminium adherends and patches were manually abraded with an 80 grit paper and then cleaned with acetone.

2.2. Geometry and dimensions of the repairs

Fig. 1 presents the repairs tested: SS repair without plug-filling (a) and with plug-filling (b), and DS repair without plug-filling (c) and with plug-filling (d). Plug-filling of the 3D repair consists on filling with adhesive the spacing left by the removal of the damaged material, whilst for the 2D repair it consists of filling the gap between the adherends. The main purpose of this modification is to increase the load transfer between the adherends [8] originally only achieved by the patches, despite the possibility of a premature plug failure for some of the SS repairs due to transverse deflection [7]. Three values of L_O were studied (10, 20 and 30 mm) comprising all the repair geometries of Fig. 1. The fixed dimensions of the repairs are outlined in Fig. 2. The influence of the testing speed and temperature on the repairs behaviour was also evaluated, considering a DS repair without plug filling and L_O=10 mm.

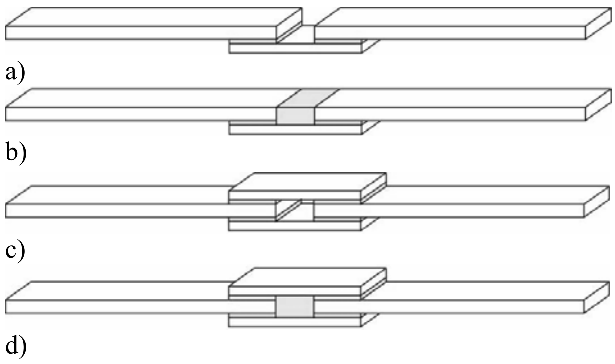

Figure 1. SS repair without (a) and with plug filling (b); DS repair without (c) and with plug filling (d).

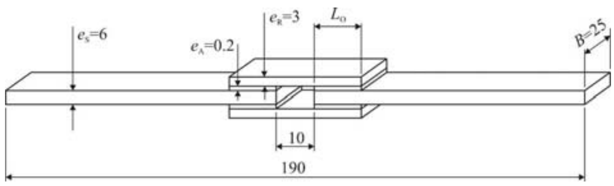

Figure 2. Nomenclature and fixed dimensions of the repairs (e_S-adherend thickness, e_A-adhesive thickness, e_R-patch thickness, L_O-overlap length, B-width).

Testing speeds of 0.5, 5 and 25 mm/min were evaluated, while test temperatures of 23ºC, 50ºC and 80ºC were considered. This range of temperatures will allow the assessment of the adhesive behaviour below and above T_g, defined at 67ºC.

2.3. Test conditions

The SS and DS repairs were tested in tension in a hydraulic testing machine (Instron® 8801) equipped with a 100kN load cell. All the repairs, except the ones tested at 50ºC and 80ºC, were tested at room temperature. Apart from the study on the rate effects, the repairs were tested at 0.5 mm/min. Four specimens were tested for each condition.

3. RESULTS AND DISCUSSION

3.1. Strength dependence with L_O

Fig. 3 and 4 plot the *P*-δ curves for the SS repairs with L_O=10 mm without and with plug-filling, respectively. The progressive failure of a specimen representative of the above mentioned geometry is represented in Fig. 5 (without plug-filling) and Fig. 6 (with plug-filling), with (a) relating to the unloaded specimen, (b) to the specimen under load and (c) to fracture.

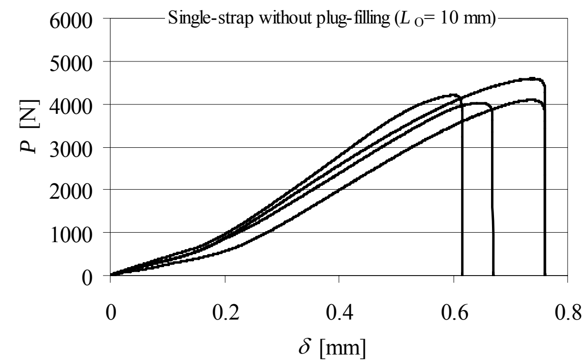

Figure 3. P-δ curves comparison for the SS repairs with L_O=10 mm (without plug-filling).

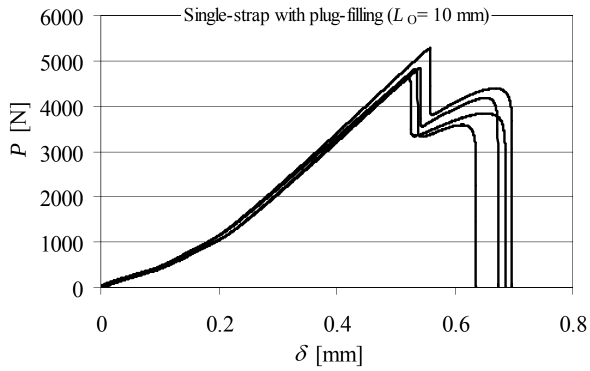

Figure 4. P-δ curves comparison for the SS repairs with L_O=10 mm (with plug-filling).

It should be emphasized at this stage that all specimens tested, except when mentioned otherwise, failed cohesively in the adhesive layer. The comparative analysis of Fig. 3 and Fig. 4 shows a major improvement on the maximum load (P_m) by using the plug. Fig. 5 and Fig. 6 show the substantial transverse deflection of the repairs, due to the asymmetry of loading that the adherends are subjected to [4]. This happening is also responsible for peel stresses peaking at the overlap edges and consequent weakening of the joints [7]. It is also visible in Fig. 6 that the plug-filled repair fails in two steps: in the first one, a cohesive fracture near one of the adherends butts occurs while the overlap is still under load. Subsequently, the repair fails at one of the overlaps. In view of this scenario, it can be concluded that the first step of failure for the plug-filled repair occurs at a higher load than P_m for the non-plugged repair, yielding a strength improvement. The subsequent drop of *P* is due to final failure at the overlap.

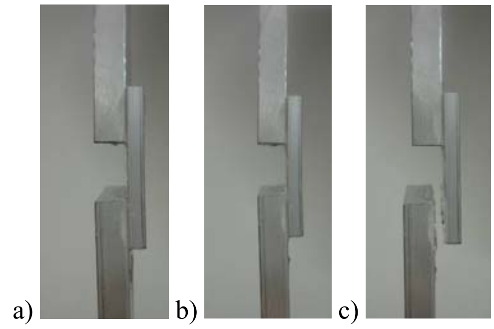

Figure 5. Failure of a SS repair with L_O=10 mm (without plug-filling).

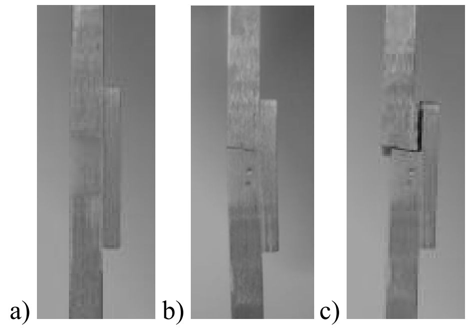

Figure 6. Failure of a SS repair with L_O=10 mm (with plug-filling).

The values of P_m and deviations for the different values of L_O are presented in Fig. 7 (SS repairs). These results show an approximate 15.6% strength improvement for the L_O=10 mm repairs by using a plug-filling. By increasing L_O, the opposite scenario took place, i.e., vertical failure near the plug prematurely to the value of P_m for the unplugged repair, yielding this modification ineffective [7]. Actually, the slight differences in Fig. 7 for L_O=20 and 30 mm are merely statistical. As a consequence of this behaviour, the positive effect of plug filling is only noticeable for sufficiently small values of L_O, since for bigger overlaps the vertical failure occurs prior to the overlap failure. It is also interesting to note a decreasing improvement of P_m with L_O, caused by increasing differential straining of the adherends with the increase of L_O, due to the larger loads sustained. In fact, whilst shear stress gradients are not important for small values of L_O, they gradually increase with this quantity, owing the increasing gradient of longitudinal strains in the adherends [4]. This is regarded in the literature as the main justification for a strength improvement of single-lap joints or single-strap repairs with L_O at a decreasing rate, eventually leading to a strength plateau [4, 20].

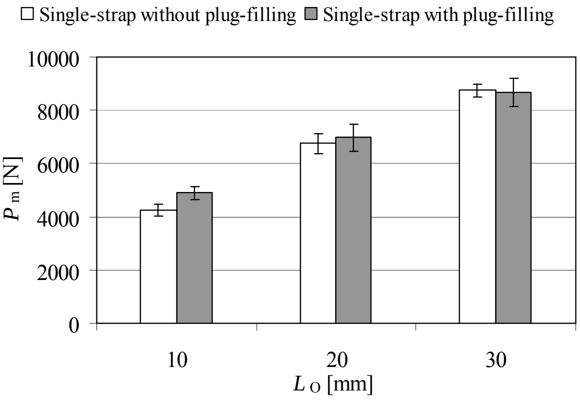

Figure 7. P_m versus L_O plot for the SS repairs (without and with plug-filling).

An equivalent analysis was performed for the DS repairs. Fig. 8 exemplifies the fracture process for both scenarios. The P-δ curves show the approximately linear behaviour up to failure for the repairs without and with plug filling. For the plug filled repair, this results from a simultaneous failure along the overlap and in the plug. DS repairs are under symmetric loads (Fig. 8), which eliminates the transverse flexure characteristic of SS repairs [4]. However, the patches are still under flexure, leading to peel peak stresses in the adherends [21]. Fig. 9 shows the evolution of P_m for the DS repairs with L_O. Compared to the corresponding SS values (Fig. 7), DS results show that P_m surpasses the double of the SS repairs strength, despite having twice the bonding area. This is justified by the smaller magnitude of peel and shear stresses [4]. The increase of P_m with L_O is not proportional, but is closer to being proportional than for the SS repairs, which can be explained by the reduction of differential straining effects [16]. Plug filling yields an identical absolute improvement of P_m for the three values of L_O since fracture was simultaneous in the plug and overlap. The resulting strength improvement varied between 17.1% for the L_O=10 mm repair and 4.6% for the L_O=30 mm repair.

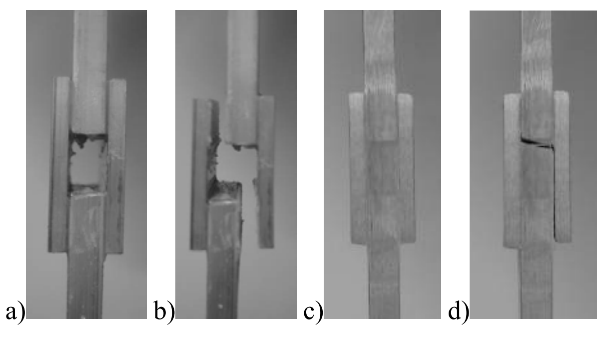

Figure 8. Failure of a DS repair with L_O=10 mm without (a and b) and with plug filling (c and d).

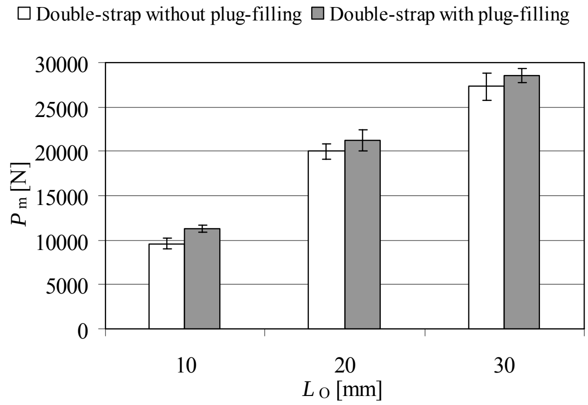

Figure 9. P_m versus L_O plot for the DS repairs (without and with plug-filling).

3.2. Strength dependence with the testing speed

Fig. 10 and Fig. 11 plot the P-δ curves for testing speeds of 0.5 and 25 mm/min, respectively.

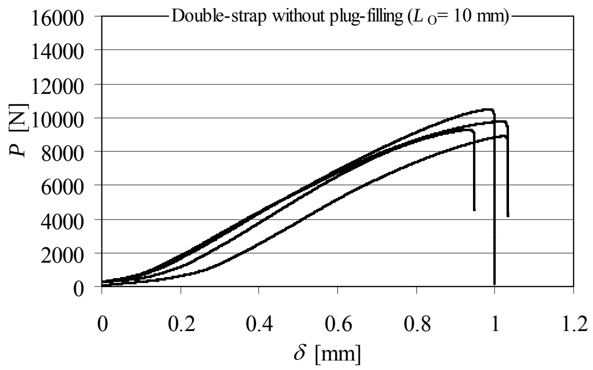

Figure 10. P-δ curves comparison for the DS repairs without plug-filling and L_O=10 mm (0.5 mm/min).

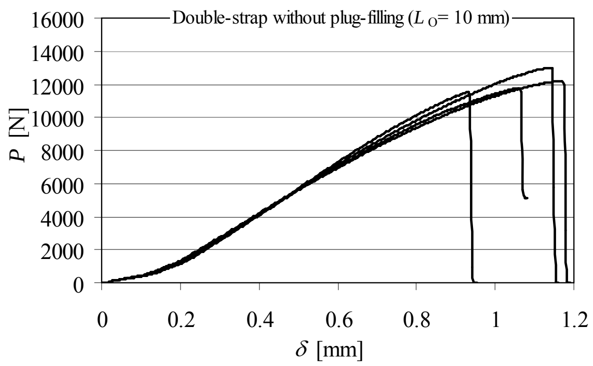

Figure 11. P-δ curves comparison for the DS repairs without plug-filling and L_O=10 mm (25 mm/min).

These figures show the difference in P_m between these two testing conditions, as P_m increases by a significant amount with testing at 25 mm/min. This is caused by the increased adhesive resistance to deformation and to molecular displacements with the increase of the testing speed, correspondingly increasing the required load to failure [22]. Despite this fact, the stiffness, i.e., the slope of the P-δ curves is left practically unchanged.

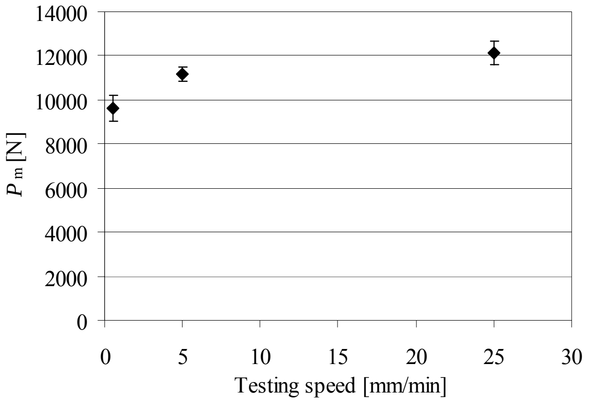

Figure 12. P_m for the DS repairs without plug-filling and L_O=10 mm as a function of the testing speed.

The average values of P_m are summarized in Fig. 12. The value of P_m increases with the testing speed, showing a bigger gradient for the smaller speeds, tending to reach a constant value for bigger testing speeds. An identical tendency was found by Zgoul and Crocombe [10], when testing a rate dependent adhesive using the single-lap joint configuration. In fact, as it is generally known, increasing the extension rate is always associated to an increase of the failure load of adhesives, accompanied by a reduction of ductility. This effect is particularly significant at high temperatures, when the adhesive becomes softened and, as a result, exhibits a higher degree of strain rate sensitivity [13].

3.3. Strength dependence with the testing temperature

The SS and DS repairs were also tested under varying operating temperatures (23ºC, 50ºC and 80ºC). Fig. 13 allows the comparison between the P-δ curves at 50ºC and 80ºC. Globally, the results showed a major strength and stiffness reduction with the increase of temperature, which was expected due to the known degradation of the adhesive properties with the temperature [16]. Actually, upon heating the adhesive, the solid polymer transforms from a rigid to a rubbery state. As a result, the molecules that are virtually frozen in position at room temperature begin to undertake rotational and translational motion. Owing to this, abrupt changes in the physical properties of the adhesive occur. It is also worth mentioning that the fracture was adhesive for all specimens tested at 50ºC and 80ºC, showing the marked degradation of the interfacial properties of the adhesive, comparing to its cohesive fracture properties. The average values of P_m for the different testing temperatures and respective variation (Fig. 14) show the expected progressive reduction of strength with the testing temperature [23].

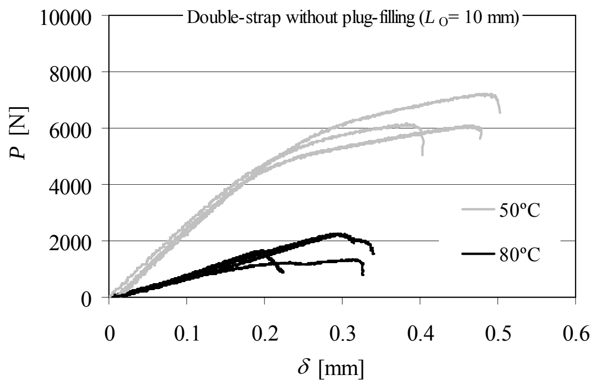

Figure 13. P-δ curves comparison for the DS repairs without plug-filling and L_O=10 mm (50ºC and 80ºC).

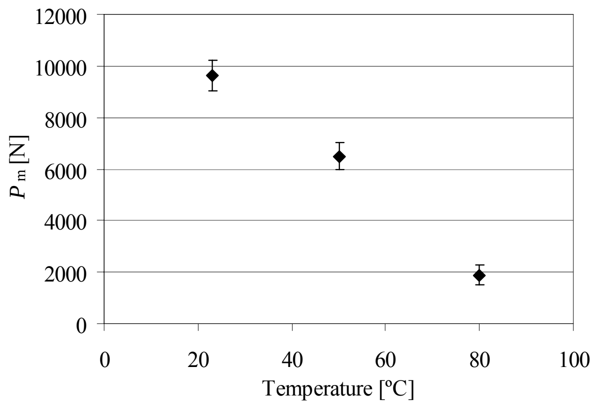

Figure 14. P_m versus L_O plot for the DS repairs without plug-filling and L_O=10 mm as a function of the temperature of testing.

4. CONCLUDING REMARKS

The influence of plug filling, loading rate and temperature on the tensile strength of single and double-strap repairs on aluminium structures was studied experimentally. Repairs were tested with and without plug filling and different values of overlap length (10, 20 and 30 mm). An investigation is also carried out on the influence of the testing speed on the repairs strength (considering 0.5, 5 and 25 mm/min). Accounting for the temperature effects, tests were carried out at room temperature, 50ºC and 80ºC, to permit a comparative evaluation of the adhesive tested below and above the Glass Transition Temperature of the adhesive (67ºC). It was globally shown that increasing the overlap length always causes a strength improvement of the repairs, but that this strength improvement is not proportional, mainly due to differential shearing effects between the adherends and patches. Plug filling of single-strap repairs is to be recommended for small overlap lengths, given that for bigger overlaps, due to the transverse deflection of single-strap repairs, the plug fails prematurely to the overlap. This caused the plug to the ineffective, since at the time of failure the plug was not contributing to the strength of the repairs. Oppositely, due to the absence of transverse deflection, for the double-strap repairs an improvement was found for all overlap lengths evaluated. Concerning the testing speed, an increase of the maximum load was found with this quantity, more significant for the smaller testing speeds and tending to a constant value of maximum load. High temperatures gradually decreased the repairs stiffness and strength due to the degradation of the adhesive. Principles for repairing aluminium structures were established in this work, which can be extrapolated for other materials and adhesives, although with some cautions since different adherends or patches can yield variations of the stress distributions and thus the strength of the repairs. Also the varying ductility of adhesives can source some variation to the presented results.

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