EXPERIMENTAL INVESTIGATION INTO THE TENSILE STRENGTH POST-REPAIR ON DAMAGED ALUMINIUM 2024 -T3 PLATES USING HYBRID BONDING/RIVETING

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Abstract: Since the implementation of repair processes by composite patch bonding, this process has consistently demonstrated high performance across various industrial sectors, especially in the fields of aeronautics, aerospace and civil engineering. Consequently, there are situations in which the riveting process becomes the sole solution, particularly when the structure is subjected to severe mechanical or thermo-mechanical stresses, since adhesives have low mechanical strength after aging. Each method has its own set of advantages and disadvantages. The current trend is to combine these two processes to minimise their drawbacks as much as possible. The objective of this work is to present an experimental study on the repair of an aluminium plate AL2024-T3 with a central circular notch using a patch of different nature (metal or composite), under tensile loading conditions. The repair composite considered is a carbon/epoxide. The results of the tensile tests showed that the repair by the combination of the two processes improves the mechanical strength of the damaged structure. A comparison of the results of the experimental curves obtained on riveted, bonded and hybrid assemblies has been taken into consideration.

Key words: composite patch, aluminium AL2024-T3, bonding, riveting, hybrid process

1. INTRODUCTION

Throughout their service life, aeronautical structures are subjected to various mechanical stresses. When a geometric discontinuity, such as a crack or notch, is present, these mechanical loads can lead to a high concentration of stress, which may precipitate the premature failure of the structure. Currently, new techniques are being developed with the aim of delaying the onset of cracks and, in most cases, reducing the rate of crack propagation, thus increasing the lifespan of structures.

In the repair process, we can cite repair by welding [1], riveting [2], bolting [3] or other methods as in the study by Zhen-Yu Chen [4], and more recently, Elyas Ghafoor [5] used wire arc additive manufacturing (WAAM) to strengthen cracked steel components under fatigue loading using innovative techniques. The experimental results showed that this technique increases in the number of rupture cycles without crack propagation and minimises the effect of stress in the vicinity of the damage. The technology for repairing damaged structures by bonding a composite patch has progressed considerably and is currently being widely used, particularly in aeronautics, due to the advantages it provides. Maintenance inspectors can recommend structural repair depending on the extent of damage, which should be the simplest and least expensive option for restoring the strength of the structure. The repair must not only provide resistance to ultimate loads but also ensure a long service life. Repairs (temporary or permanent) are carried out using bolted or riveted metal reinforcements or with bonded metal or composite reinforcements. This last solution is used in particular for laminated composite plates. Therefore, repairs are one of the issues that are the subject of studies on composite–metallic or composite–composite assemblies. The repair of a cracked structure can also be carried out by bonding an external patch to the structure to stop or slow down the propagation of the crack.

Composite materials are used in many fields because of their low weight, fatigue strength, corrosion resistance and enhanced damage tolerance [6]. The composite material patch plays an important role in the repair process due to its useful properties [7], and it is conventionally used in aeronautics for the repair of metal structures for damage such as cracks, notches or impacts.

The use of composite patches for the repair of damaged structures has interested several researchers, such as Baker et al. [8–9]. In an experimental study, Hosseini-Toudeshky et al. [10] investigated the growth of fatigue cracks on aluminium plates with a central mode I crack repaired using composite patches on one side only. On the other hand, Khalili et al. [11] conducted an experimental study on the effect of a composite patch applied to one side for repairing edge cracks in aluminium specimens using the Charpy impact test. Additionally, Maleki et al. [12] have studied the effect of applying a bonded composite patch to a cracked 2024-T3 aluminium plate under mixed mode loading. Basaid et al. [13] employed a fibreglass/epoxy patch for the maintenance of damaged plates in Air Algérie Maintenance workshops. Similarly, Gu et al. [14] used basic fibreglass/epoxy patches to repair aluminium plates with cracks and studied the development of cracks in the plate and the delamination behaviour in the patches under static stresses. Benkheira et al. [15] conducted an experimental analysis under tensile loading to investigate the effect of repair by using single and double patches of boron/epoxy-laminated composite plates with a central circular notch and also presented a comparison between these two repair modes. Nadia et al. [16] analysed the mechanical and failure behaviours of a damaged structure repaired by using a composite patch for defects in the adhesive layer. Madani et al. [17] carried out both experimental and numerical studies on the mechanical behaviour of several plates with notches of various shapes by using tensile tests. Aldeen, A et al. [18] studied the effect of isothermal and isochronous aging to investigate precipitate evolution and recrystallisation of zirconium alloy N36 after β-quenching.

Rivallant et al. [19] introduced a discrete 3D finite element method (FEM) that uses cohesive elements to simulate both interlamina delamination and intra-lamina matrix cracking. Similarly, R. Rashnooie et al. [20] successfully simulated crack growth in composite plates using an element method modelling approach extended finishes (XFEM); they took into consideration the propagation of damage in the adhesive layer, the different layers of the composite and the delamination of the metal–FRP interface. The proposed XFEM model simulates the fatigue behaviour of FRP-reinforced metal plates.

Ait Kaci et al. [21] have shown that a hybrid patch combining carbon fibre/epoxy and aramid/epoxy plies can reduce the stress in the damaged area and thus ensure the structure a long service life. Horn et al. [22] have shown that it is necessary to optimise the length and thickness of the repair patch and that these dimensions are important to increase the tensile strength of the repaired structure. The calculation of the stress distributions in the structure is therefore an important aspect in proposing an appropriate reinforcement solution.

Analysing stresses in the adhesive joint is essential to avoid deterioration of this layer as its mechanical properties are weaker than the plate and the patch. Madani et al. [23] analysed the stress distribution in an aluminium alloy 2024-T3 plate in the presence of a notch, repaired using a composite patch, through the FEM. The authors showed that the composite patch repair method greatly reduces the high stress concentration. Rezgani et al. [24] conducted experimental tests to analyse the effect of hydrothermal aging of the patch and the adhesive on the fatigue behaviour of a damaged 2024-T3 aluminium plate repaired by a carbon composite/epoxy patch. Wahrhaftig et al. [25] have proposed an equivalent stiffness system for calculating the minimum bending moment for concrete slender columns. Al-Abboodi et al. [26] have produced a device featuring a three-point curve test to evaluate the mechanical properties of a metallic glass alloy sample (Fe49.7 Cr17.1 Mn1.9 Mo7.4 W1.6 B15.2 C3.8 Si2.4) prepared by high-speed spark plasma sintering (SPS).

The weak point in reinforcing composite materials lies in the adhesive responsible for ensuring the adhesion of the reinforcement. According to reference [27], 53% of the observed failures in aeronautical structures repaired are due to the adhesive layer. These failures are essentially due to the transfer of loads from the adherend to the composite patch. This load transfer zone, in fact, results in a shear stress peak near the free edge of the composite patch. On the other hand, the nature of the adhesive joint has shown its effectiveness in absorbing and transferring the load from the damaged area. The adhesive used to bond the repair patch and the cracked plate together should also be prepared beforehand [28]. Maleki et al. [29] studied the failure of cracked aluminium plates repaired by one-sided glass/epoxy composite patches under fatigue loading. The acoustic emission technique was employed to monitor the effect of damage progression in the repair patch. Rivet patch repair involves placing a plate (metal or composite) over a damaged area and riveting the patch to the plate [30]. Riveting requires creating holes not only in the repair plate but also in the damaged structures. However, as composite materials are highly brittle, this operation introduces damage. Zitoune and Collombet [31] have shown that this damage can occur at the entrance, exit and periphery of the hole, creating delamination, fibre breakage and matrix degradation.

In the light of the previously mentioned studies, the novelty of our research is in its purely experimental approach to analyse tensile tests on damaged and repaired 2024-T3 aluminium plates. Employing various repair methods (riveting, bonding and hybrid repair) with three distinct types of patches, the study aims to compare their performance. It highlights that the presence of a patch does not always guarantee a significant improvement in the resistance of the damaged plate. Furthermore, it underscores specific findings, such as the potential undesirability of hybrid repair under certain conditions, and recommends the preferential use of a metallic patch in such scenarios. .

2. MATERIALS AND METHODS

In the present study, an analysis was conducted on an AL2024-T3 plate with a central circular notch. The composite patch includes two types: carbon/epoxy and fibreglass/epoxy (Fig. 1).

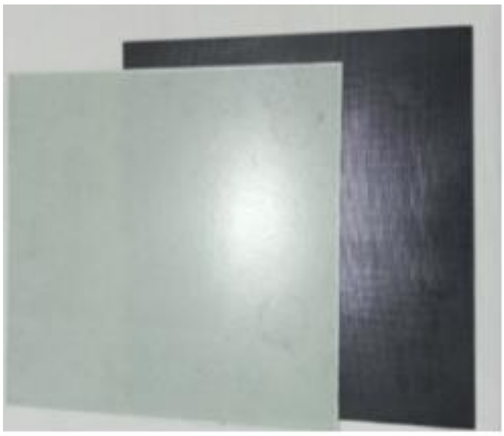

Fig. 1. Fibreglass and carbon fibre composite patches made under vacuum

The metal patch is of the same nature as the plate to be repaired. The composite materials used in this study were obtained from Air Algeria. They are mainly intended for aircraft repair, and the choice of the type of matrix and reinforcement is made according to the requirements of international aeronautical regulations. The composite plates and patches were fabricated from an eight-ply 300 gsm fabric. Polymer matrix composite materials are increasingly used in aeronautics due to their low mass. All the laminates were made up of eight plies (0°/90°/0°/90°/0°/90°/0°/90°) and had a nominal thickness of 1.86 mm. The fibre volume fraction was chosen according to ISO 1268-2 standards, with the range between 30% and 45%.

Fig. 2. (a) Resin EPOCAST 50-A1. (b) HARDENER 946

The adhesive consists of a homogeneous mixture of resin (EPOCAST 50-A1) and hardener (HARDENER 946 US), which is presented as a crosslinking agent (Fig. 2).

Epocast 50-A1 is a thermosetting resin. This matrix can be used for the manufacture or repair of composite structures in aeronautics. The product complies with the BMS 8-201 standard (Boeing Material Specification). This epoxy resin is of bisphenol type A (Fig. 2a) and is combined with a low-reactivity amine hardener (Fig. 2b). These resins pass successively from the liquid state to the gel state and then to the solid state. This characteristic process of thermosetting resins is called crosslinking.

3. EXPERIMENTAL STUDY

In the first part, experimental studies on metal patch repairs are presented (Fig. 3).

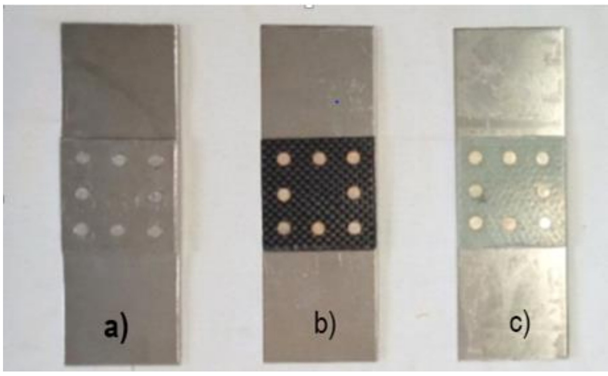

Fig. 3. Representation of specimens prepared for tensile tests: (a) With metal patch, (b,c) with composite patch

To assess the repair performance, static tensile tests were carried out on intact specimens (without the presence of geometric defects), then on specimens with a central circular notch (without repair) and finally on specimens repaired with riveted or bonded metal patches (Fig. 3a). In the second part, the damaged plate was repaired with a composite patch of the carbon/epoxy type or of the glass/epoxy type (Fig. 3b). Subsequently, the effect of an initial crack emanating from the notch on the degradation of the mechanical properties of the plate was assessed to repair this geometric defect. The considered crack has an initial length of a = 5 mm, and it was repaired using a bonded/riveted hybrid patch.

4. TEST SAMPLE CHARACTERISATION

The relevant parameters to consider in the repair process are the thickness of the adhesive (ta), length, width and shape of the patch. However, due to the difficulty of highlighting these parameters during the study, ta and the rivet diameter are kept constant. However, it is possible to remove one of these elements (adhesive or rivet) to assess the separate influence of the adhesive or the rivet.

The dimensions of the patch are fixed during this analysis. However, its nature is variable (aluminium patch, carbon/epoxy composite patch and glass/epoxy patch) to optimise the compatibility of the patch material with the number of rivets required to maintain the load transfer efficiency.

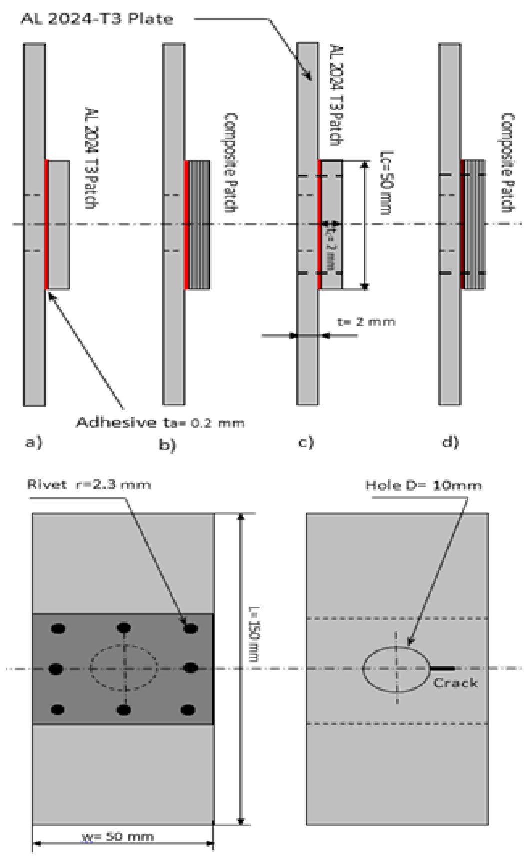

Fig. 4. Schematic representation of a plate repaired with (a) Metal patch by adhesive, (b) Composite patch by adhesive, (c) Metal patch by rivet/adhesive, (d) Composite patch by rivet/adhesive and (e) Plate with crack emanating from notch

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Fig. 4 shows the geometry of the repaired structure with the different natures of the repair patch depending on the bonding or hybrid mode (bonding + riveting). It is considered that the plate has a central circular hole with a diameter of d = 10 mm (Fig. 4a). A crack emanating from a notch is considered in the fixed length study (Fig. 4e). The width w of the sample is also considered, which is important to assess the influence of the number of rivets on the stiffness and strength of a hybrid repair. The length of the adherend (the metal plate) is defined as L is shown in Tab. 2. Lc is the length of the patch, ta is the adhesive thickness, t is the adherend thickness, D is the hole diameter and d is the diameter of the fastener head of the fastener inside the hole.

In practice, to determine the diameter of the rivet ($\mathrm{d_{rivet}}$) depending on the thickness of the sheets (Fig. 5), the following formula is used:

$$\mathrm{d_{rivet}} = \frac{45H}{15+H}\ (\mathrm{mm})$$

where *H* represents the thickness of the repaired set [mm]. The length of the rivet (l) is defined as shown in Fig. 5.

The parameters of the samples with the NAS1399 C4-4 type rivet in the case of a plate repair with a laminated patch are shown in Fig. 5 and in Tab. 1. This type of rivet is used for all the experimental tests, due to the compatibility of its parameters with the repair conditions (Fig. 6).

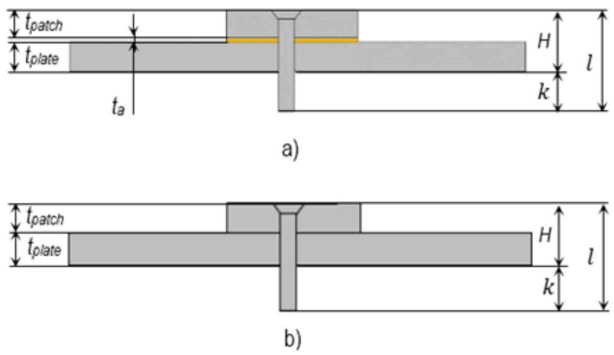

Fig. 5. Countersunk rivet dimensions in patch repair with/without bonding

Tab. 1. Dimensional parameters of a riveted sample

Rivet type	Rivet dimensions [mm]
Countersunk rivet	l = 1.1.*H*+0.6.d
Stem free length	k = (0.7–1.3).d
Rod length	$l = \sum t + k$

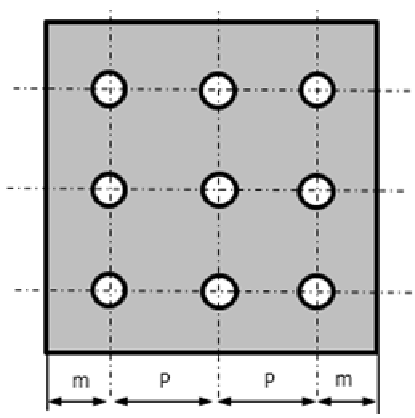

Fig. 6. Arrangement of rivet holes in the patch

In this work, we used the chain arrangement, in which the rivets are ordered and aligned with a respected spacing of the P value of 16.66 mm (Fig. 6).

– The pitch (P) of the rivet is defined as the distance between the centre of a rivet and the centre of the adjacent rivet in the same row (P = 5d).
– The margin (m) is the distance between the edge of the plate and the axis of the rivets of the nearest row (m = P/2).

However, in the case of bonded repair, the required dimensions of bonded specimens are shown in Fig. 5 and Tab. 3. The thickness of the adhesive is kept within 0.234 ± 0.025 mm.

Tab. 2. Dimensional parameters of a riveted joint

Adherend thickness *t* (mm)	4.15 ± 0.15
Lap length (mm)	50 ± 0.05
Sample width (mm)	50 ± 0.05
Rivet shank diameter d (mm)	3.2
Rivet head diameter D = 2d (mm)	6.2
Rivet shank length l (mm)	5 ± 0.25

Tab. 3. Dimensional parameters of a bonded joint

Adherend thickness *t* (mm)	4.28 ± 0.15
Overlap length (mm)	50 ± 0.25
Overlap width (mm)	50 ± 0.25
Adhesive thickness t_a (mm)	0.234 ± 0.025

5. PREPARING FOR PATCH REPAIR

The repair of the circular notch is carried out using an external patch (Fig. 7). Three repair modes were addressed, namely bonded patch, riveted patch and hybrid patch (Fig. 7). For the bonded patch, cleaning of the surface with acetone and the duration of crosslinking of the adhesive were taken carefully. For the hybrid repair, once the adhesive was put on the bonded area, the rivets were quickly put in their positions to avoid having hardened adhesive in the rivet holes. The crosslinking time was the same for both processes.

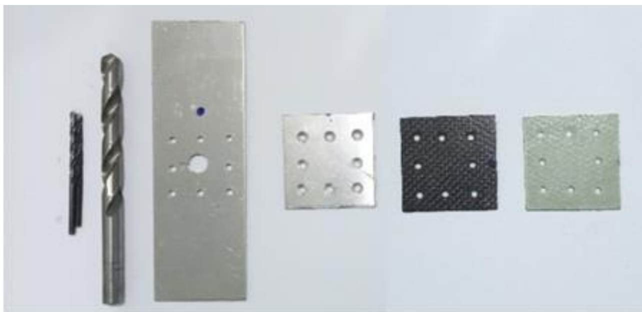

Fig. 7. Preparing for patch repair

The main step in preparing a repair using the riveting process consists of piercing the materials without damaging it for the aluminium and without inducing delamination for the composite.

6. DIFFERENT REPAIR CONFIGURATIONS

The performance of different repairs was analysed in this work. For this purpose, the samples used in the different repair modes have the same dimensions. For each repair mode (bonded, riveted and hybrid), three types of patches were considered (aluminium patch, fibreglass composite patch and carbon fibre composite patch) (Fig. 8). The three types of configuration are manufactured using the same materials, to obtain the most consistent results from one test to the next. The samples by repair type are shown in following Tab. 4 (Fig. 8). The three modes of repair are also considered for the specimens with a crack emanating from the notch.

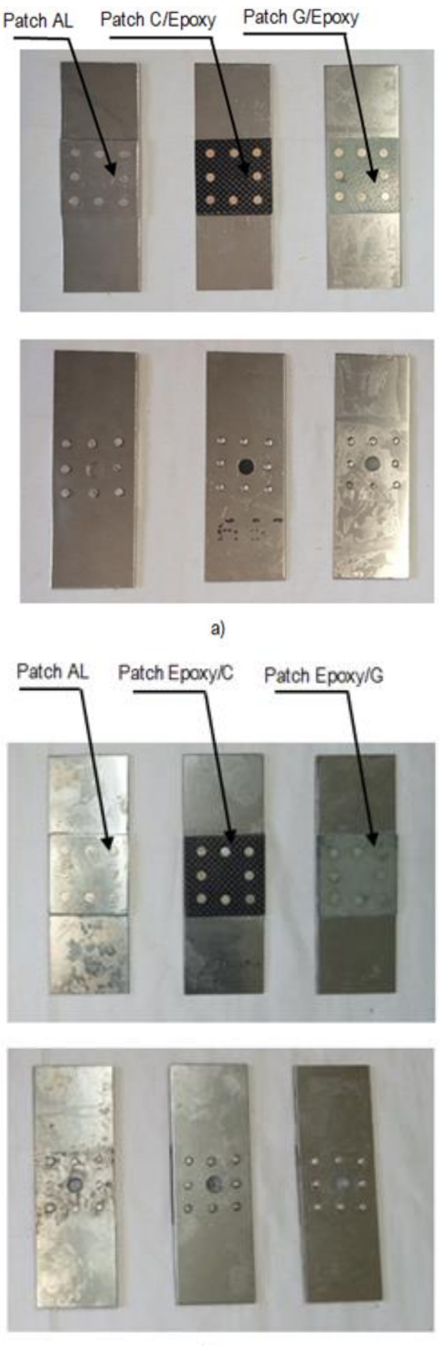

Fig. 8. Presentation of different configurations of repair. (a) riveted mode(b) hybrid mode

Tab. 4. Configuration of samples for tensile tests

Configur ation	Plate	Damage type	Patch material nature	Repair mode
1	AL	Notch	Aluminium	Bonded
2	AL	Notch	Aluminium	Riveted
3	AL	Notch	Aluminium	Hybrid
4	AL	Notch	Composite carbon/epoxy	Bonded
5	AL	Notch	Composite carbon/epoxy	Riveted
6	AL	Notch	Composite carbon/epoxy	Hybrid
7	AL	Notch	Composite glass/epoxy	Bonded
8	AL	Notch	Composite glass/epoxy	Riveted
9	AL	Notch	Composite glass/epoxy	Hybrid
10	AL	Crack manating from notch	Aluminium	Hybrid
11	AL	Crack manating from notch	Composite carbon/epoxy	Hybrid
12	AL	Cracke manating from notch	Composite carbon/epoxy	Hybrid

The tensile tests were carried out at Coatings, Materials and Environment Laboratory (CMEL) at the University of M'hamed Bougara in Boumerdes, Algeria using a ZWITCK Z010 tensile machine (Fig. 9). The testing conditions were maintained at a temperature 23 ± 3°C and a relative humidity of 30 ± 10%, respectively, according to the ASTM D3039 and ASTM D3165 standards. (Fig. 9). The tensile machine was equipped with a 50 kN load cell and a crosshead drive system powered by an electric motor. The machine was controlled by software, which allowed the results of the loads and displacements to be recorded. The tests were conducted at a crosshead travel speed of 1 mm/min. A 25-mm-gauge length extensometer was used to obtain the displacement on the samples. Fig. 9 shows an example of extensometer positioning.

Fig. 9. Illustration of the test bench for tensile tests

It was necessary to carry out three tensile tests for each configuration. The various load–displacement curves obtained were processed to have reproducibility to better estimate the behaviour of each structure.

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The main mechanical characteristics of the materials used (aluminium plates, composite patch and EPOCAST 50-A1/946 adhesive) for the numerical model are obtained from tensile tests (Fig. 10) and are grouped in Tab. 5.

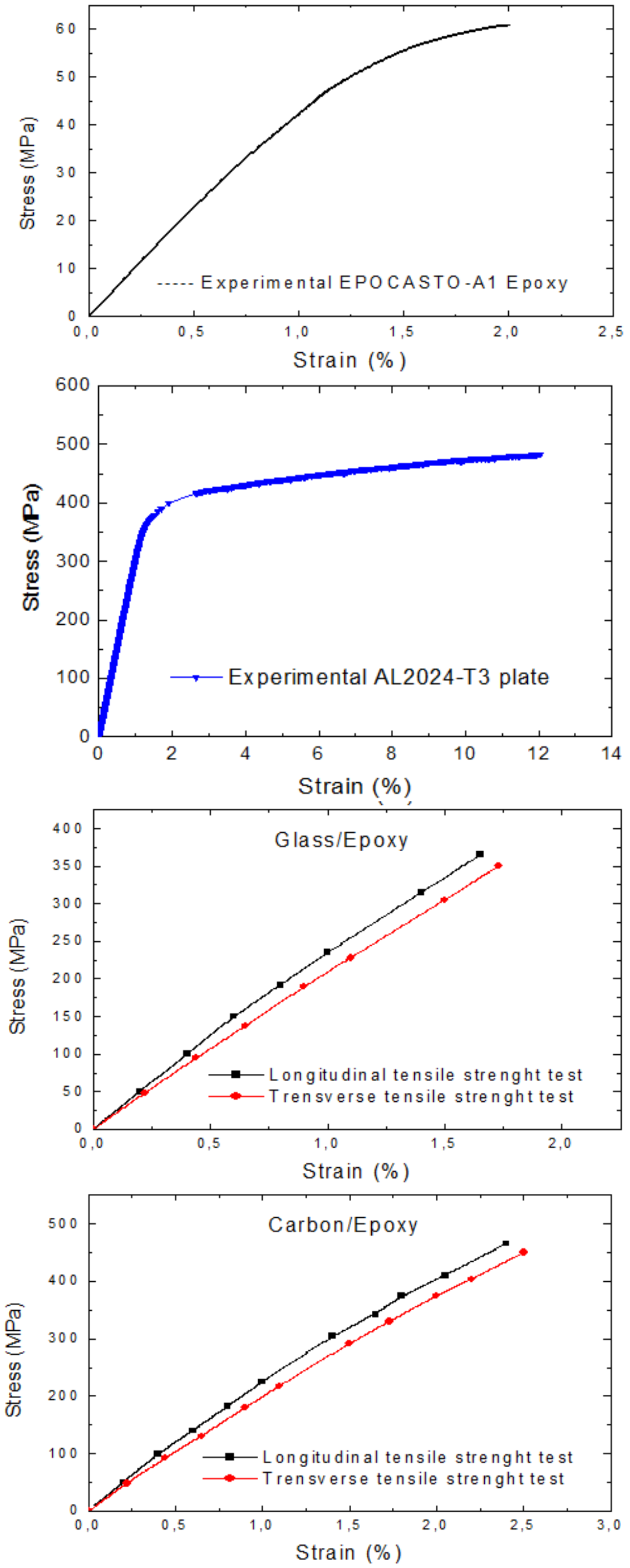

Fig. 10. Traction curves carried out on (a) EPOCASTO 50 -A1 adhesive, (b) aluminium plates, (c) glass/epoxy composite and (d) carbon/epoxy composite

Tab. 5. Mechanical properties of AL2024-T3, composite and resin EPOCASTO 50 -A1

Materials	AL 2024T	Ply CRFP	Ply GRFP	Resin
Young Modulus	74,70	20,40	17,90	34,60
Tensile strength	462	450	335	63.6
Yield stress (MPa)	311	-	-	-
Poison/ratio	0.33	0.3	0.3	0.3
Elongation (A%)	12 %	2.35	1.86	1.97 %

7. RESULTS

7.1. Effect on the nature of patches for different repair processes

The plates were subjected to a tensile load, and the load transferred by the rivets as well as by the adhesive was estimated. It is important to note that various factors can influence the result, including the bond quality, friction between the components (between the rivet head and the composite, and the deformed part of the rivet and the rivet shank and the interior of the hole) and the interaction between the rivet and the edge of the notch. The presence of notches in plate components leads to a reduction in their strength compared to the unnotched plate. It was found that these notches can significantly influence the expansion of damaged regions, especially when the rivet holes are located near the free edge of the plate. The tensile test results of notched and unnotched specimens are shown in Fig. 11, which combines the load–displacement curves for notched and unnotched specimens.

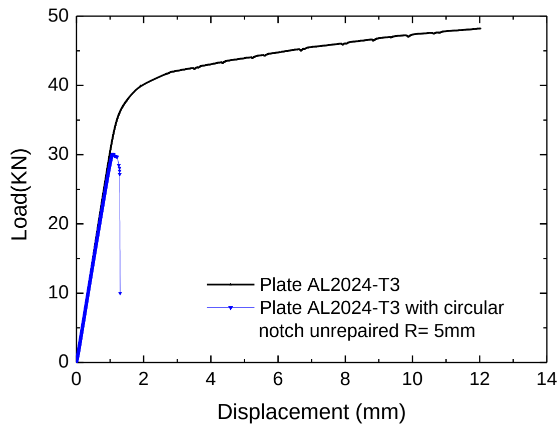

Fig. 11. Load–displacement curves for notched and unnotched specimens

The presence of a central notch with a radius of 5 mm weakens the material, leading to an approximately 30% reduction in its tensile strength. It is worth noting that the tensile curve of the plate without a hole comprises two parts. The first part corresponds to the elastic phase and exhibits a linear relationship. Subsequently, the second segment is nonlinear, displaying an alteration in the slope. This section is distinguished by a maximum stress featuring a plasticity threshold, succeeded by a phase of plastic flow with a very high tensile strength. The extensive plastic domain is a result of the material's ductility. However, the presence of a central circular notch reduces the nonlinear portion of the tensile curve.

The aluminium test specimen includes a 10-mm-diameter circular notch at the middle, followed by repairing using a single aluminium patch. The patch is riveted to the plate by eight aluminium rivets. Fig. 12 depicts the experimentally measured load variation with the applied displacement for a plate repaired with a single riveted patch, alongside an unrepaired plate. The advantageous impact of the patch is evident, with the loads at failure for the repaired specimens are notably higher than those at the unrepaired counterparts. A direct comparison with the unrepaired structure reveals that single patch repair techniques can enhance tensile strength by approximately 6%. On the other hand, for the plate with a central notch, the effect of the repair by riveting is almost negligible due to the presence of additional rivet holes adjacent to the main notch.

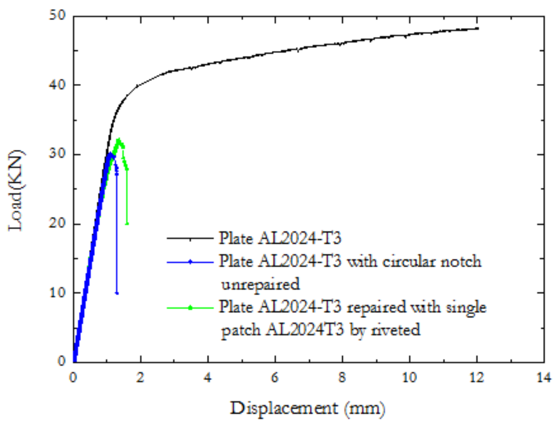

Fig. 12. Load–displacement plot for a plate with single riveted aluminium patch and an unrepaired plate

Currently, the aeronautical industry is interested in repairing structures by bonding external patches. The advantages of this method are related to the nature of the adherend, where the edge effects resulting from the drilling of the plates in the bolted or riveted repair prove to be very harmful to its mechanical strength. The predominant technique involves the repair of notched or cracked plates by affixing a bonded patch onto the affected region. In this context, numerous research efforts have been undertaken since the 1980s to explore the application of patches for the restoration of damaged structures. The external bonding patch repair technique entails adhesively bonding a damaged plate to composite or aluminium patches.

Fig. 13 depicts the experimentally measured load variation in relation to displacement for a plate repaired with a single bonded patch, as well as an unrepaired plate. The bonded patch applied to the notched plate diminishes stresses at the notch's edge, thereby enhancing the strength of the plate. This disparity arises from the transfer of load from the damaged zone to the repair patch through the adhesive layer. The maximum difference in tensile strength between specimens repaired with a bonded patch and unrepaired plates does not exceed 15%. Fig. 14 presents a comparison between the different repair techniques such as bonding, riveting and hybrid joining (riveting + bonding). The obtained curves are irrespectively of the repair technique used (whether bonded or riveted). The behaviour is mostly linear up to failure, although a minor slope reduction is visible for the repaired specimens. The findings unequivocally demonstrate that the bonded patch yields a more favourable effect compared to the riveted patch given the size of the repaired surface. On the other hand, repair by the combination of the two processes (bonded + riveted) in the repair generates a higher strength of the notched plate by approximately 20%.

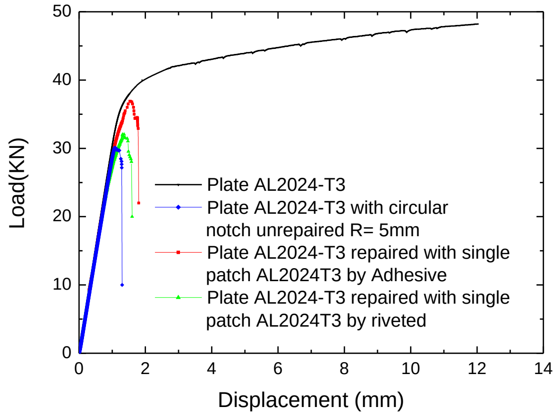

Fig. 13. Load–displacement plot for of the repaired plate using a bonded aluminium patch and unrepaired plate

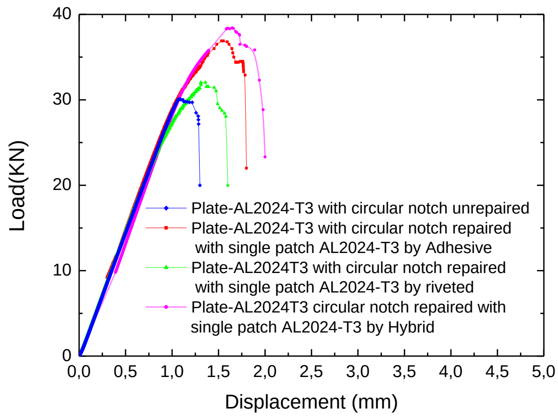

Fig. 14. Comparison of load–displacement curves for the different repair techniques by aluminium patch (riveting, bonding and hybrid joining)

The comparison between load–displacement curves shows that the maximum load for the undamaged plate drops considerably if the plate contains a notch (Fig. 15).

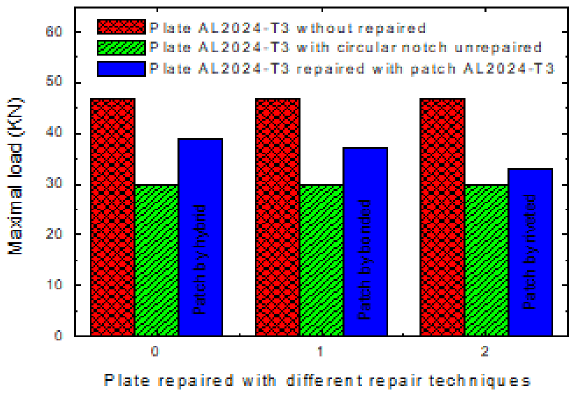

Fig. 15. Maximal load for the different plates (0 denotes repaired by hybrid process, 1 repaired by the bonded aluminium patch and 2 repaired by the riveted patch)

Patch repairing using the different techniques results in an increase in the strength of the damaged plate, which depends on the type of repair. Repair using the hybrid process produces a considerable increase in maximum tensile strength.

During the tensile test of the notched plates, cracks are initiated at the level of the central notch, which then propagate towards the free edge of the plate, as shown in Fig. 16. A deviation of the propagation path of the crack is observed in the case of a hybrid repair (specimen 6 in Fig. 16). The rivet holes create additional stress concentrations. The hybrid patch absorbs better some of the stress concentrations that are localised at the central notch compared to other repair techniques.

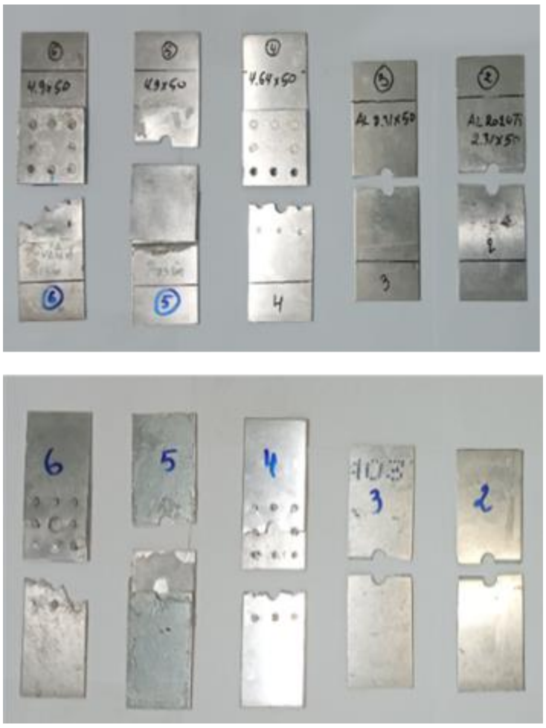

Fig. 16. Unrepaired and repaired aluminium plates with different processes after failure

The mechanical strength and life of a restored structure are markedly contingent on several factors, with particular emphasis on the mechanical and geometric attributes of the structure, the adhesive properties and the quality of the repair patch employed. It is crucial to underscore that the patch stands out as a primary component, directly influencing the performance of the repaired structure. Numerous studies have been conducted to enhance the effectiveness and longevity of composite patch repairs, ultimately striving to extend the service life of the restored structure. In this context, two types of composite patch are used, namely carbon/epoxy and glass/epoxy, aiming to assess the patch influence on the repair ability of a plate with notch and subsequent repair by composite patches. In this case, the patches are adhesively bonded to the plate, riveted or applied by a hybrid process (riveting + bonding). The results of the tensile tests are shown in Figs 17 and 18.

The obtained results show that the glass/epoxy composite patch does not have a major effect on the repair performance. A reliable improvement in the tensile strength is observed in Fig. 17.

The behaviour of the structure repaired by the glass/epoxy composite patch is practically the same as for the structure repaired by a metal patch. It is also noted that the improvement in the structural strength is low for the two repair methods. On the other hand, it is observed in Fig. 18 that the strength of the damaged plate repaired by the composite carbon/epoxy patch has slightly improved compared to the previous cases (repair by glass/epoxy patch) since the mechanical properties of the carbon/epoxy patch and the glass/epoxy patch are quite distinct.

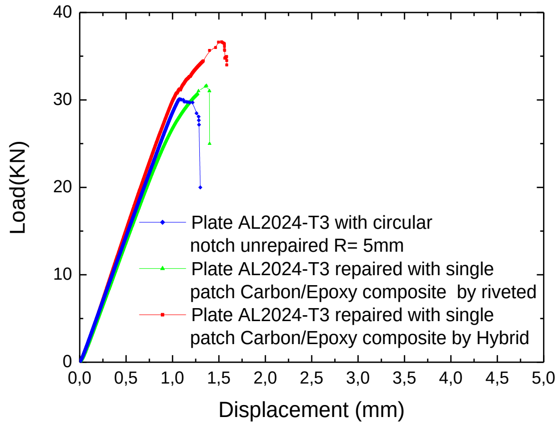

Fig. 17. Load–displacement plot for the plate repaired by the single glass/epoxy composite patch

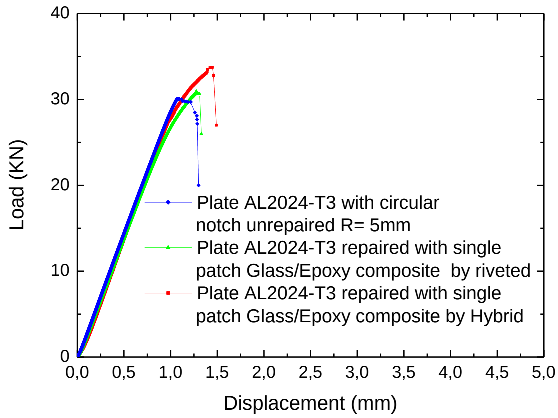

Fig. 18. Load–displacement plot for the plate repaired by the single carbon/epoxy composite patch, considering different repair processes

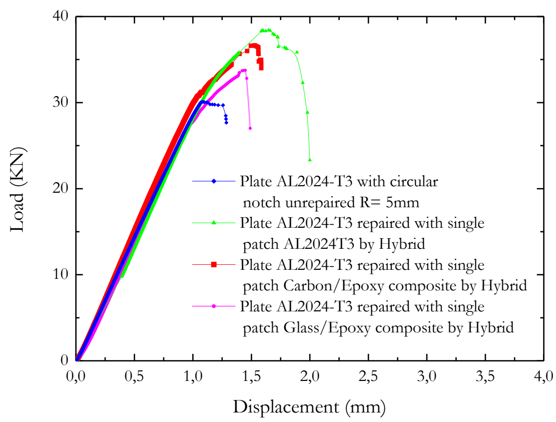

Fig. 19. Comparison of the load–displacement curves of a notched plate with a drilled plate repaired with different types of patches using hybrid bonding/riveting

Improving the strength of the structure repaired by the hybrid repair process (bonding and riveting) has shown effectiveness in improving the strength of the structure, even if the nature of the repair patch is varied. In plates repaired by the hybrid patch, and for all types of patch, the rivets and the adhesive layer together increase the structural strength.

Since the hybrid process (bonding + riveting) offers the best performance for increasing the strength of the damaged plate, a comparison of this process using different types of repair patch is shown in Fig. 19.

The hybrid repair process (bonding and riveting) was effective in improving the strength of the repaired structure, even when the nature of the repair patch was varied (Fig. 19).

Fig. 20. Damage to notched plates repaired by different types of patch using hybrid repair processes (bonding/riveting)

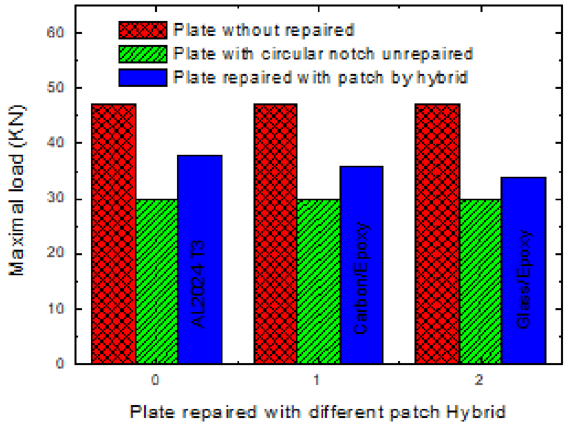

Fig. 21. Maximal load for different plates (0 denotes repaired by the hybrid process, 1 repaired by the bonded aluminium patch and 2 repaired by the riveted patch)

In the hybrid repair, regardless of the nature of the patch, it was found that the rivet and adhesive work together to transfer loads. This is a very important aspect to consider in the present study to achieve the objective of improving the strength of the damaged structure. It is preferable to reduce the number of rivets or eliminate those in the vicinity of the notch across the half-width of the plate. To achieve this, it is important to ensure that the rivet and adhesive work together and to look for another more effective type of adhesive.

Damage to plates repaired by the hybrid process (bonding and riveting) has the same appearance (Fig. 20): the crack initially starts at the notch and propagates along the half-width of the plate. Once in the vicinity of the rivet notch, the crack propagates slowly until the plate breaks completely.

The maximum force of the damaged plate in the presence of the hybrid process improves considerably and has a slightly higher value than that of the damaged plate without repair. Even in the presence of a repair patch, the maximum force always remains lower than that of the undamaged plate, whatever the nature of the patch (Fig. 21).

7.2. Effect of presence of a crack emanating from a notch

The presence of a crack of length a = 5 mm emanating from a notch (Fig. 22) considerably reduces the tensile strength of the plate by up to 50% compared to the continuous plate without notch. It was observed that the presence of the crack emanating from notch in the plate has a considerable effect on the tensile strength. On the other hand, its effect on the stiffness of the plate is almost negligible.

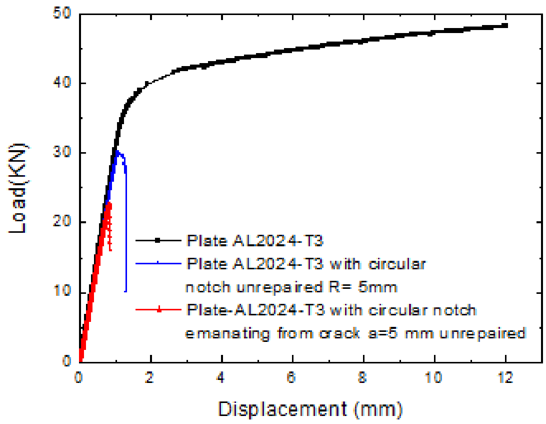

Fig. 22. Effect of the presence of a crack on the variation of the load–displacement diagram

7.3. Patch effect in plate repair in the presence of a notch crack

It is widely acknowledged that structures in service are often subjected to mechanical stresses, which could cause damage. In this case, one alternative to repairing these structures is to prevent them before a crack appears. Currently, new techniques are being developed to reduce the crack propagation and consequently increase the service time of structures. The most used technique consists of repairing the structure by placing a bonded or riveted patch part in the area damaged defined by the notch. For this purpose, the plate in the presence of a crack emanating from the notch was repaired by the three methods (Fig. 23).

The presence of a metal repair patch improves the mechanical strength of the damaged plate by increasing its maximum tensile force. The value of this force depends on the type of repair. The riveted patch only slightly improves the mechanical resistance

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of the damaged plate given the presence of additional holes. However, the patch bonded by the hybrid process further improves the resistance of the plate.

The presence of a crack emanating from a notch creates a strong concentration of stress; in this case, patch repair according to the three methods only slightly improves the resistance of the plate. The damage plate in the presence of a notch crack is shown in Fig. 24, where it can be seen that plate failure rapidly occurs in the presence of the crack and that its propagation is rapid towards the free edge of the plate, more precisely towards the rivet hole located at the mid-width of the plate.

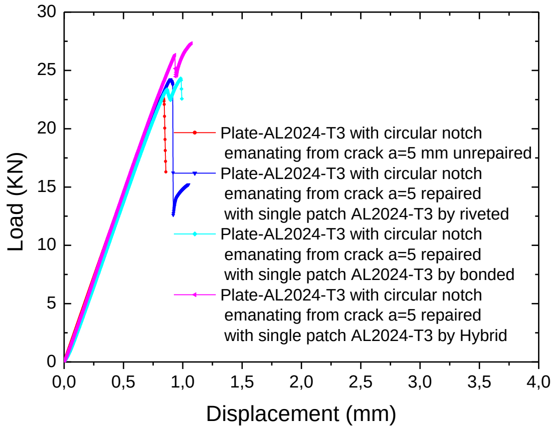

Fig. 23. Load–displacement plot for the plate with a crack emanating from notch repaired by aluminium patch with different repair processes

Fig. 24. Damage to the notched plates repaired by an aluminium patch using hybrid repair processes (bonding/riveting)

The maximum strength of the plate with repair varies according to the type of repair (riveting, bonding and hybrid) (Fig. 25). The presence of a riveted patch in a plate in the presence of a crack emanating from a notch does not improve the mechanical strength of the plate since the rivet hole is in the vicinity of the crack and the width of the plate will be reduced. However, the presence of a bonded patch slightly improves the value of the plate's strength, while the presence of a hybrid repair further improves the strength of the damaged plate and presents the highest load.

An attempt was made to determine the effect of the patch type in increasing the strength of the damaged plate in the presence of a notch crack using the hybrid repair process (bonding + riveting) since this is the most effective process compared with the other two tested ones (bonding and riveting) (Fig. 26).

It is clear that the aluminium patch performs better than the other two patch types (glass/epoxy and carbon/epoxy). This is because the presence of rivet holes creates defects in the composite patches (possible delamination) and stress absorption is not effective.

Plate damage in the presence of a notch crack is shown in Fig. 27, where it can be seen that plate failure occurs rapidly in the presence of the crack and that its propagation is rapid towards the free edge of the plate, more precisely towards the rivet hole located at the mid-width of the plate, regardless of the nature of the patch.

Fig. 25. Maximal load for the different plates (0 denotes repaired by the hybrid process, 1 repaired by the bonded aluminium patch and 2 repaired by the riveted patch) in the presence of a crack emanating from a notch

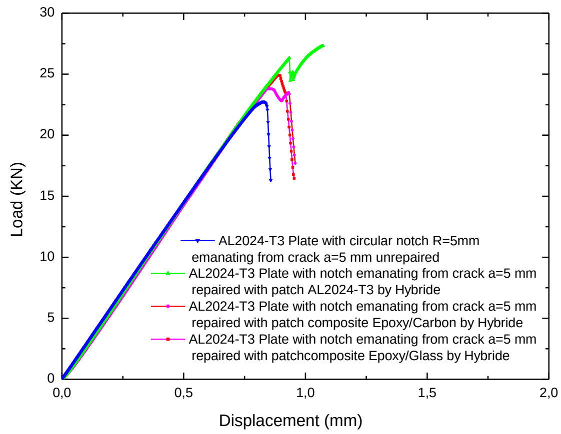

Fig. 26. Comparison of the load–displacement curves of the plate in the presence of crack emanating from a notch and repaired with different types of patches using hybrid bonding/riveting

Fig. 27. Damage to the notched and cracked plates repaired by different types of patches using hybrid repair processes (bonding/riveting)

The strength of the plate repaired by the hybrid process (riveting + bonding) varies according to the type of the repair patch (aluminium, glass/epoxide and carbon/epoxide) (Fig. 28). The presence of a glass/epoxide repair patch in a plate with a crack emanating from a notch only slightly improves the mechanical strength of the plate. However, the presence of an aluminium patch improves the strength further.

Fig. 28. Maximal load for different plates (0 denotes repaired by an aluminium patch, 1 repaired by bonded carbon/epoxide and 2 repaired by glass/epoxide) in the presence of a crack emanating from a notch repaired by hybrid repair

8. CONCLUSION

This work focused on the influence of different types of repair (bonding, riveting and hybrid) using patches of different natures (aluminium, glass/epoxide and carbon/epoxide) on a damaged aluminium plate subjected to tensile loading. In conclusion, improving the strength of the plate must take into account both the nature of the patch and the adhesive. In the riveting or hybrid repair process, the arrangement and number of rivets must also be analysed in detail.

It was found that the composite patch only slightly absorbs the stress concentration of the damaged area once it is pierced and that the presence of rivet holes in the composite leads to further damage because of the possible creation of delamination of the different layers.

- The aluminium patch works best in the presence of a hybrid repair.
- The presence of a crack at the notch considerably reduces the strength of the plate, and in the presence of a repair, the strength of the plate improves only slightly as the crack propagates rapidly towards the rivet hole.

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