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Experimental investigation into the tensile strength post-repair on damaged Aluminium 2024 -T3 plate 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 minimize their drawbacks as much as possible. The objective of this work is to present an experimental study into the repair of an aluminum 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 clearly showed that the repair by the combination of the two processes clearly 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 generally 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], by riveting [2] by bolting [3] or by other method as in the study of Zhen-Yu Chen [4] and more recently a new repair trend where Elyas Ghafoor [5] were able to strengthen cracked steel components under fatigue loading using innovative techniques through the introduction of wire arc additive (WAAM). the experimental results were able to show that this technique generates an increase in the number of cycles at rupture without the crack propagating and minimizes the strong constraint 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 widely used, particularly in aeronautics, due the advantages it provides. Indeed, maintenance inspectors can recommend the structural repair depending on the extent of damage, which should be the simplest and least expensive option while restoring the strength of the structure. Indeed, the repair must not only provide excellent 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, in order to stop or slow down the propagation of the crack.
Composite materials are used in many fields thanks to their low weight, fatigue strength, corrosion resistance and enhanced damage tolerance [6]. The composite material patch can play 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 with damage such as cracks, notches or impacts.
The use of composite patches has interested several researchers such as Baker et al. [8-9] for the repair of damaged structures. In an experimental study, Hosseini-Toudeshky et al. [10] investigated the growth of fatigue cracks on aluminum 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 aluminum specimens with edges cracks 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 aluminum plate under mixed mode loading. Basaid et al. [13] employed a fiberglass/epoxy patch for the maintenance of damaged plates in Air-Algérie maintenance workshops. Similarly for Gu et al. [14], used basic fiberglass/epoxy patches to repair aluminum plates with cracks and studied the development of cracks in the plate and the delamination behavior in the patches under static stresses. Benkheira et al. [15] conducted an experimental analysis under tensile loading to investigate the effect of repairing by single and double patches of boron/epoxy laminated composite plates with a central circular notch, presenting a comparison between these two repair modes. Nadia et al. [16] analyzed the mechanical and

failure behavior of a damaged structure repaired by a composite patch in the presence of defects in the adhesive layer. Madani et al. [17] carried out both experimental and numerical studies of the mechanical behavior of several plates with notches of various shapes by tensile tests. Aldeen, A et al. [18] studied the effect of isothermal and isochronous aging to investigate precipitate evolution and recrystallization of zirconium alloy N36 after β-quenching.

Rivallant et al. [19] introduced a discrete 3D finite element method (FEM) model that uses cohesive elements to simulate both inter-lamina delamination as well as intra-lamina matrix cracking. similarly R. Rashnooie et al. [20] were able to successfully simulate crack growth in composite plates using an element method modeling approach extended finishes (XFEM), they were able to take into consideration the propagation of damage in the adhesive layer, the different layers of the composite as well as the delamination of the metal-FRP interface. The proposed XFEM model successfully simulates the fatigue behavior 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 stresses in the damaged area and thus ensure the structure a long service life. Horn et al. [22] have shown that it is necessary to optimize the length and the 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.

Analyzing stresses in the adhesive joint is essential to avoid any deterioration of this layer, whose mechanical properties are weaker compared to the plate and the patch. Madani et al. [23] analyzed the stress distribution in an aluminum 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 analyze the effect of hydrothermal aging of the patch and the adhesive on the fatigue behavior of a damaged 2024-T3 aluminum 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 aluminum 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 very 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, fiber breakage and matrix degradation.

In light of the previously mentioned studies, the novelty of our research is in its purely experimental approach to analyze tensile tests on damaged and repaired 2024-T3 aluminum 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

For the present study, an analysis was conducted on a AL 2024-T3 plate with a central circular notch was analysed. The composite patch includes two types: carbon/epoxy and fiberglass/epoxy (Fig.1).

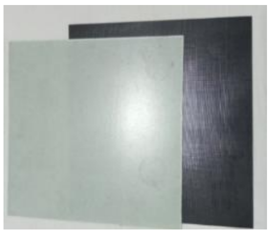


Fig.1. Fiber glass and carbon fiber composite patches made under vacuum.

The metal patch is of the same nature as the plate to be repaired. The composite materials used in this study come from the company 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 patch 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 8 plies (0°/90°/0°/90°/0°/90°/0°/90°) and had a nominal thickness of 1.86 mm. The fiber volume fraction is chosen, according to ISO 1268-2 standards, with the range of 30% and 45%.

a) b)

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 the bisphenol type A (Fig.2.a) and is combined with a low reactivity amine hardener (Fig.2.b). 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). 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 as depicted (Fig.3b). Sebsequently, the effect of an initial crack emanating from the notch on the degradation of the mechanical properties of the plate was assessed, to provide a repair to this geometric defect. The considered crack has an initial length of a=5 mm, and it was repaired with a bonded/riveted hybrid patch.

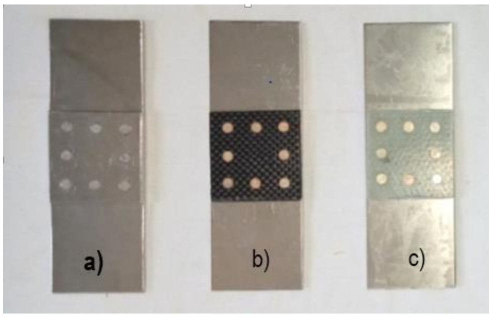


Fig.3. Representation of specimens prepared for tensile tests: a) With metal patch, b-c) with composite patch.

4. TEST SAMPLE CHARACTERIZATION

The relevant parameters to consider in the repair process are the thickness of the adhesive (ta), the length, the width, and the shape of the patch. However, due to the difficulty of highlighting these parameters during the study, ta and the rivet diameter will be kept constant. However, it will be 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 optimize the patch material compatible with the number of rivets required to maintain the load transfer efficiency.

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 was considered that the plate has a central circular hole with a diameter of d=10 mm (Fig.4a). A crack emanating from a notch will be considered in the fixed length study (Fig.4e). The width w of the sample is also considered, which will be 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. Lc is the length of the patch, ta the adhesive thickness, t the adherend thickness, D the hole diameter, d diameter of fastener head of the fastener inside the hole.

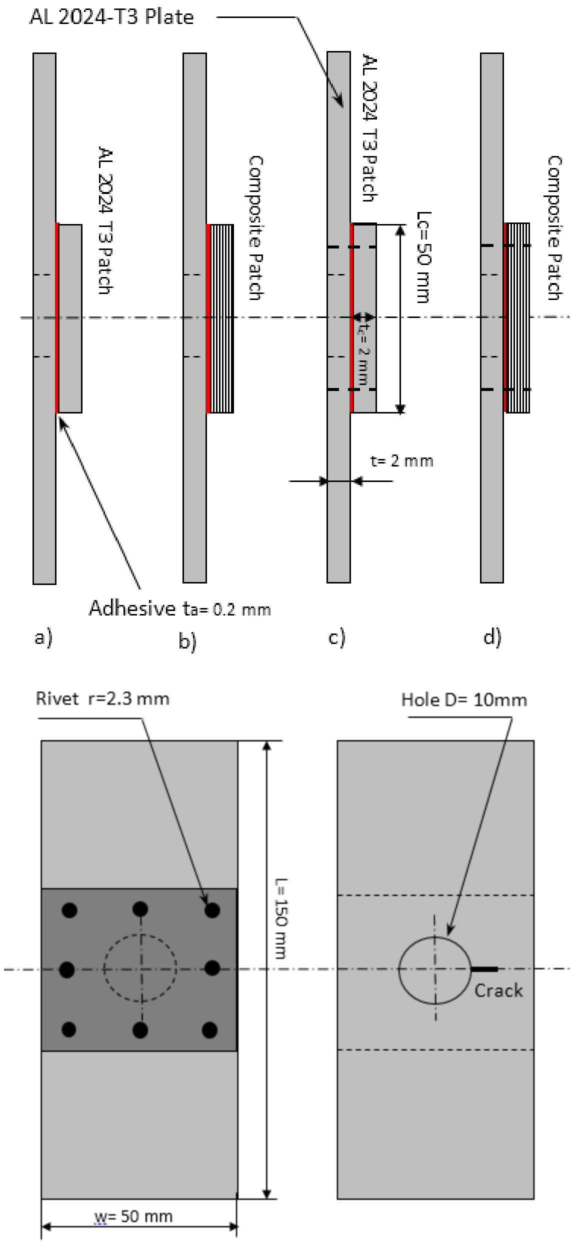


Fig.4. Schematic representation of a plate repaired with: a) Metal patch by adhesive, b) Composite patch by adhesive, c) Metal patch by rivet/adhesive, d) Composite patch by rivet/adhesive, e) Plate with crack emanating from notch.

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

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

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

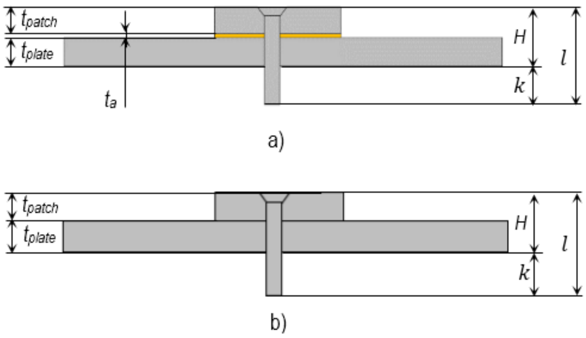


Fig.5. Countersunk rivet dimensions in patch repair with/without bonding.

Tab.1. Dimensional parameters of a riveted sample

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

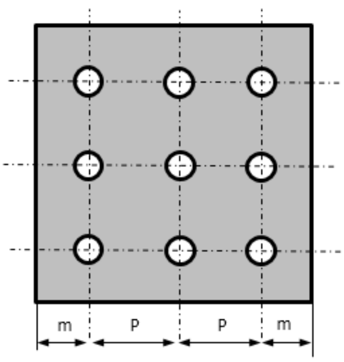


Fig.6. Arrangement of rivet holes in the patch.

- The pitch (P) of the rivet is defined as the distance between the center of a rivet and the center 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, for the case of bonded repair, the required dimensions of bonded specimens are shown in Fig.5 and Table.3. The thickness of the adhesive is kept within 0.234 ± 0.025mm.

Tab.2. Dimensional parameters of a riveted joint.

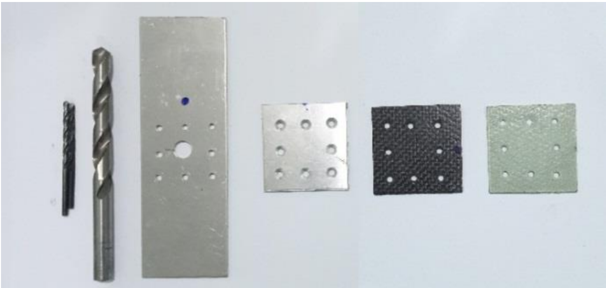
Adherend thickness *t* (mm)	4.15 ± 0.15
Lap length (mm)	50 ± 0.05
Sample width (mm)	50 ± 0.05
Rivet shank diameter d (mm)	3.2
Rivet head diameter D=2d (mm)	6.2
Rivet shank length *l* (mm)	5 ± 0.25

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 in order to avoid having hardened adhesive in the rivet holes. The cross-linking time was the same for both processes.



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

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. THE DIFFERENT REPAIR CONFIGURATIONS

The performance of different repairs was analyzed 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, fiberglass composite patch, and carbon fibre composite patch) (Fig.8). The three types of configuration are manufactured using the same materials, in order to obtain the most consistent results from one test to the next. The samples by repair type are shown in the following Table.4 (Fig. 8). The three modes of repair are also considered for the specimens with a crack emanating from the notch.

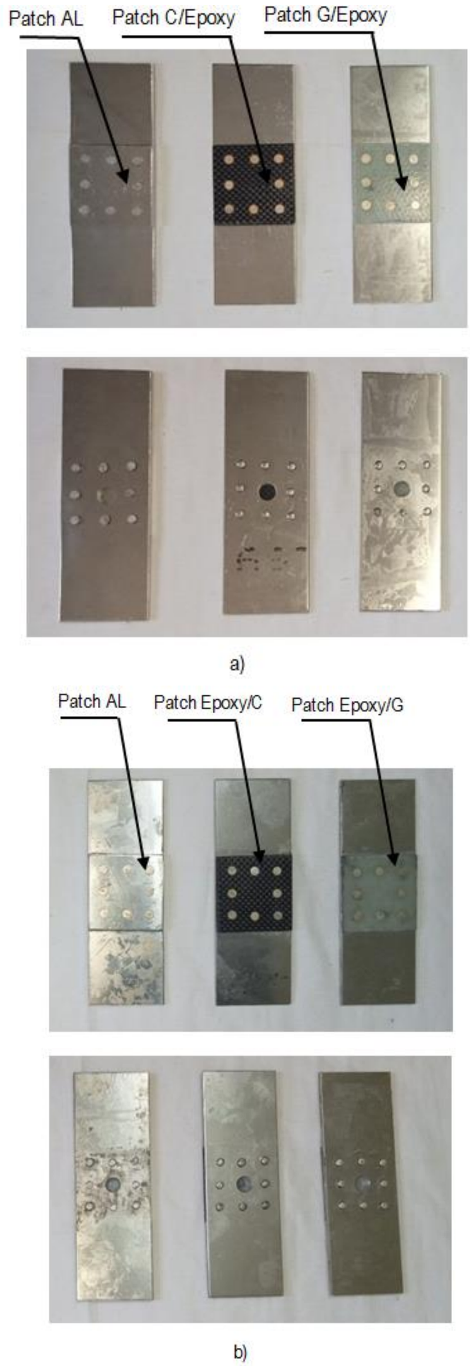


Fig.8. Presentation of different configurations of repair.a) Mode riveted b) Mode hybrid

Tab.4. Configuration of samples for tensile tests.

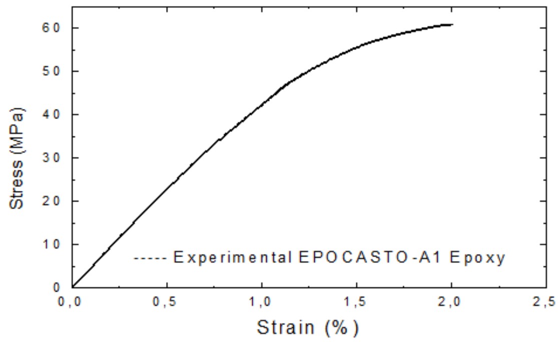
Configuration	Plate	Damage type	Patch material nature	Repair mode
1	AL	Notch	Aluminum	bonded
2	AL	Notch	Aluminum	Riveted
3	AL	Notch	Aluminum	Hybrid
4	AL	Notch	Composite Carbon / Epoxy	bonded
5	AL	Notch	Composite Carbon / Epoxy	Riveted
6	AL	Notch	Composite Carbon / Epoxy	Hybrid
7	AL	Notch	Composite Glass/ Epoxy	bonded
8	AL	Notch	Composite Glass/ Epoxy	Riveted
9	AL	Notch	Composite Glass/ Epoxy	Hybrid
10	AL	Crack manating from notch	Aluminum	Hybrid
11	AL	Crack manating from notch	Composite Carbon/ poxy	Hybrid
12	AL	Cracke manating from notch	Composite Carbon/ poxy	Hybrid

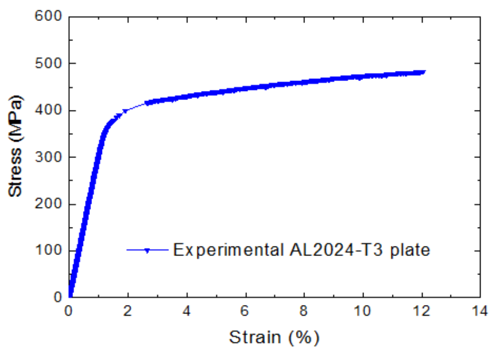
Tab.4. Configuration of samples for tensile tests.

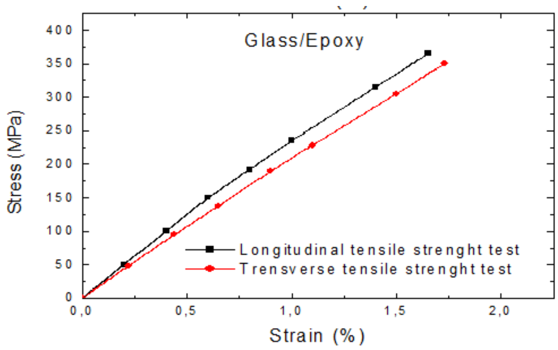
The tensile tests were carried out at CMEL (Coatings, Materials and Environment Laboratory) at the University of M'hamed Bougara in Boumerdes, Algeria using a ZWITCK Z010 tensile machine (Fig.9). The testing conditions were maintained at a temperature 23 ± 3°C and a relative humidity of 30 ± 10%, respectively, according to the ASTM D3039 and ASTM D3165 standards.(Fig.9). The tensile machine is equipped with a 50 kN load cell and a crosshead drive system powered by an electric motor. The machine is controlled by software, which allows 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 in order to better estimate the behavior of each structure.
The main mechanical characteristics of the materials used (Aluminum plates, composite patch and EPOCAST 50-A1/946 adhesive) for the numerical model are obtained from tensile tests (Fig.10) and are grouped in Table.5.







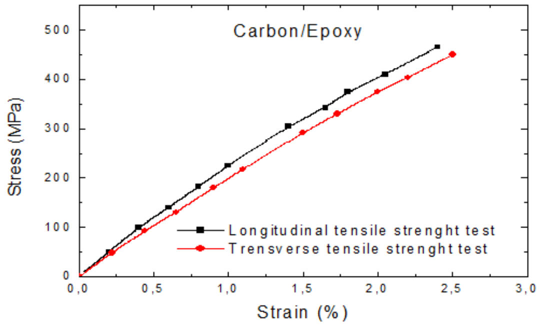


Fig.10. Traction curves carried out on a) EPOCASTO 50 -A1 adhesive, b) Aluminum plates, c) glass/epoxy composite and d) carbon/epoxy composite

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

Materials	AL 2024T3	Ply CRFP	Ply GRFP	Resin
Young Modulus (MPa)	74700	20400	17900	3460
Tensile strength (MPa)	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 %

4. RESULTS

4.1 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's important to note that various factors can influence the result, including the bond quality, the 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) as well as the interaction between the rivet and the edge of the notch. The presence of notches in plate components lead to a reduction in their strength compared to the unnotched plate. It was found that these notches can significantly influence on the expansion of damaged regions, especially when the rivet holes are located in near of the free edge of the plate. The tensile tests results of on notched and unnotched specimens are shown in Fig.11, which combines the load-displacement curves for notched and unnotched specimens

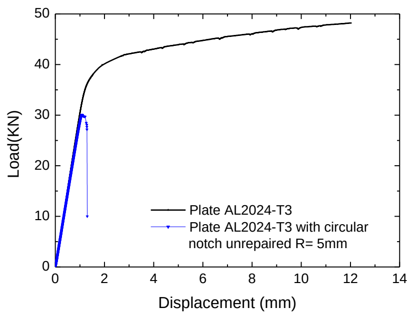


Fig.11. Load-displacement curves for notched and unnotched specimens.

The presence of a central notch with a radius of 5 mm weakens the material, leading to an approximate 30% reduction in its tensile strength. Indeed, it is worth noting that the tensile curve of the plate without a hole comprises two parts. The first part, corresponding to the elastic phase and exhibits a linear relationship. Subsequently, the second segment is nonlinear, displaying an alteration in 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.

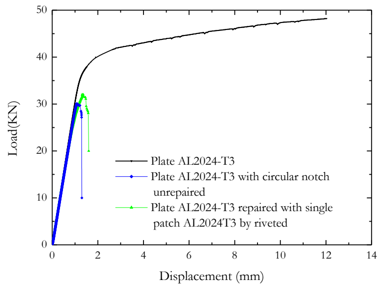


Fig.12. Load-displacement plot for a plate with single riveted aluminum patch and an unrepaired plate.

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 8 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 for 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 which are adjacent to the main notch

Currently, the aeronautical industries are very 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 aluminum 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 by bonding, riveting, and hybrid joining (riveting + bonding). The obtained curves are irrespectively of the repair technique used (whether bonded or riveted). The behavior 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 favorable 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%.

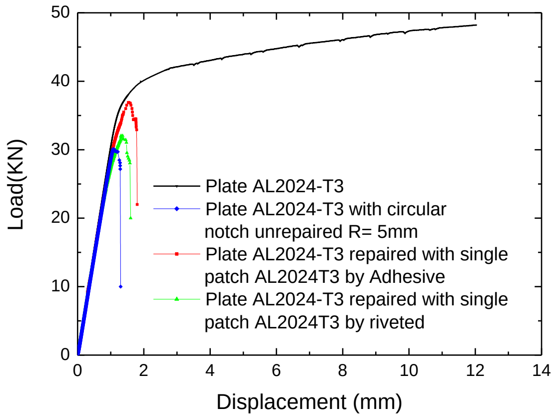


Fig.13. Load-displacement plot for repaired plate bonded aluminum patch and of unrepaired plate.

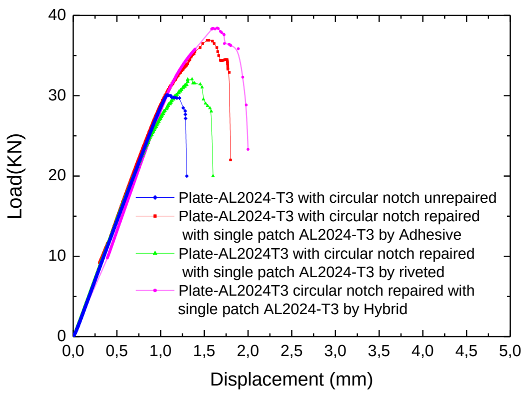


Fig.14. Comparison of load-displacement curves for the different repair techniques by aluminum patch (riveting, bonding, and hybrid joining).

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

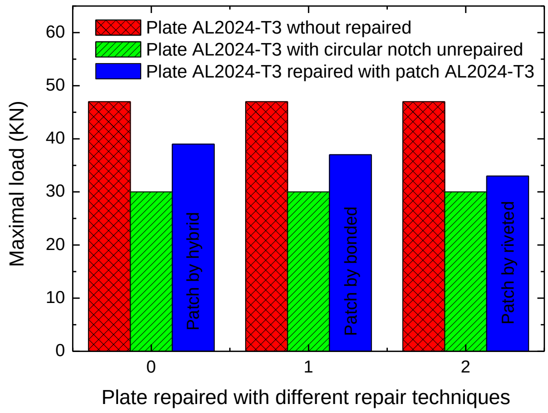


Fig.15 Maximal load for the different plates (0 repaired by hybrid process, 1 repaired by bonded aluminum patch, and 2 repaired by riveted patch).

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

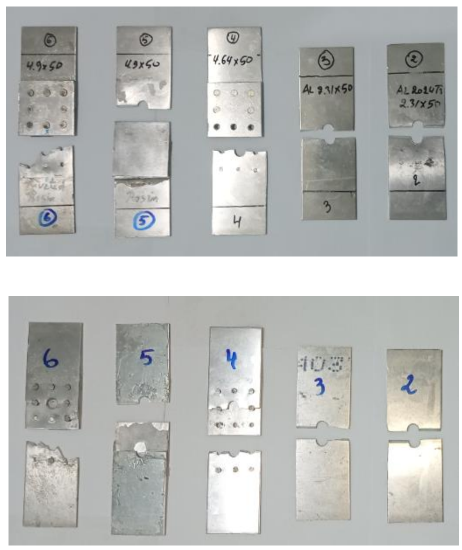


Fig.16. Unrepaired and repaired aluminum plates with different process after failure.

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 localized at the central notch compared to other repair techniques.

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 investigations 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 either 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. Indeed, a reliable improvement in the tensile strength is observed in fig. 17.
The behavior 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.

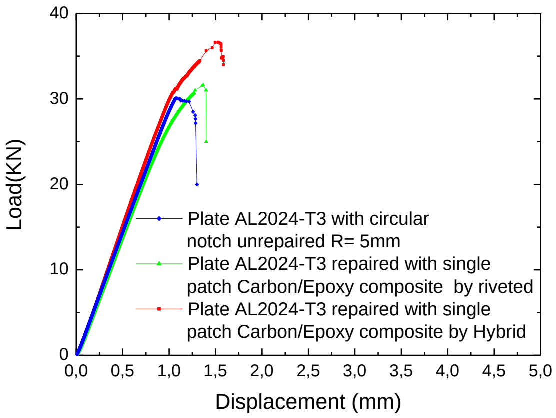


Fig.17 Load-displacement plot for the plate repaired by the single glass/epoxy composite patch.

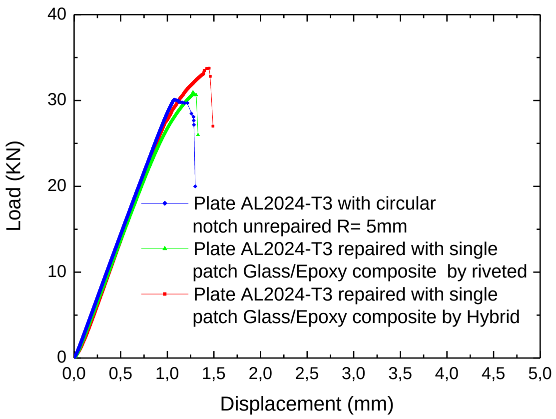


Fig.18. Load-displacement plot for the plate repaired by the single carbon/epoxy composite patch, considering different repair processes.

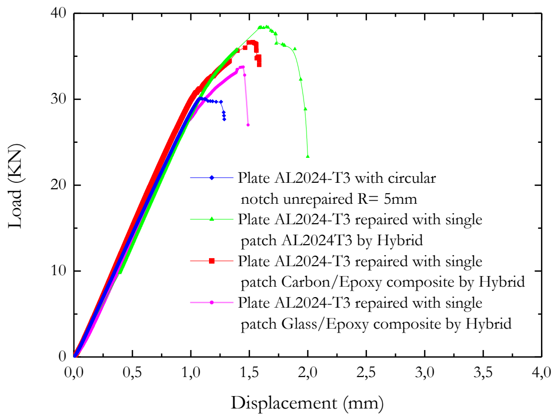


Fig.19. Comparison of the load-displacement curves of a notched plate with a drilled plate repaired with different types of patches using hybrid bonding/riveting.

Improving the strength of the structure repaired by the hybrid repair process (bonding and riveting) has shown its 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 manage to work together to 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).
In the hybrid repair, whatever 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, in order 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's important to ensure that the rivet and adhesive work together, and to look for another, more effective type of adhesive.

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

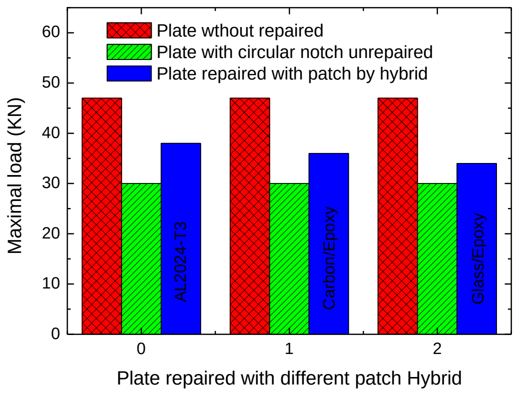


Fig.21 Maximal load for the different plates (0 repaired by hybrid process, 1 repaired by bonded aluminum patch and 2 repaired by riveted patch.

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).

4.2. Effect of presence of crack emanating from notch

The presence of a crack of length a=5mm 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.

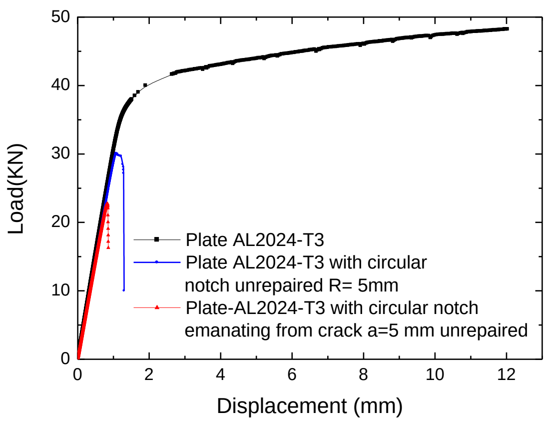


Fig.22 Effect of presence of crack on the variation of load-displacement diagram.

4.3.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 reinforce them preventively before the 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 cited below (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 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.

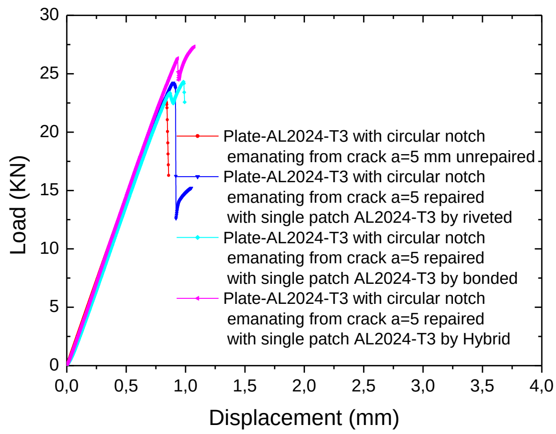


Fig.23. Load-displacement plot for the plate with a crack emanating from notch repaired by aluminum patch with different repair processes.

The presence of a crack emanating from a notch creates a strong concentration of stress, for this purpose 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 clearly 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.24. Damage to the notched plates repaired by an aluminum 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 aluminum 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.

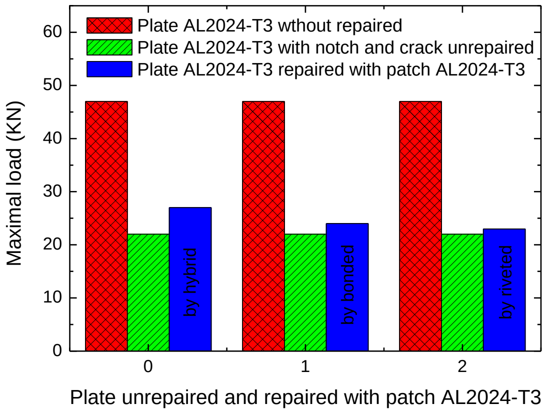


Fig.25. Maximal load for the different plates (0 repaired by hybrid process, 1 repaired by bonded aluminum patch and 2 repaired by riveted patch) in presence of a crack emanating from notch.

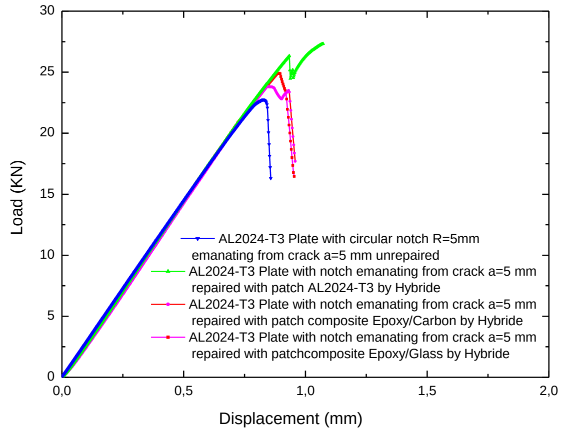


Fig.26. Comparison of the load-displacement curves of the plate in presence of crack emanating from notch and repaired with different types of patches using hybrid bonding/riveting.

Plate damage in the presence of a notch crack is shown in Fig.27, where it can be clearly 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, whatever is the nature of the patch.

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 repair patch (aluminum, glass/epoxide and carbon/epoxide) (Fig.28). The presence of a glass/epoxide repair patch in a plate in of the plate with a crack emanating from a notch only slightly improves the mechanical strength of the plate. However, the presence of an aluminum patch improves the strength even further.

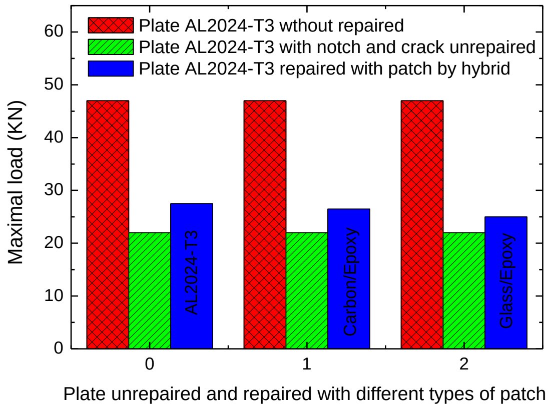


Fig.28. Maximal load for the different plates (0 repaired by aluminum patch, 1 repaired by bonded carbon/epoxide and 2 repaired by glass/epoxide) in presence of a crack emanating from notch repaired by hybrid repair.

6. CONCLUSION

This work addressed an experimental investigation on the influence of different types of repair (bonding, riveting and hybrid) using patches of different natures (aluminum, glass/epoxide and carbon/epoxide) on a damaged aluminum 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 processes, the arrangement and number of rivets must also be analyzed in detail. It has been 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 through the possible creation of delamination of the different layers.

- The aluminum 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 even 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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