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Assessing composite patch repair efficiency in thick and high elastic modulus structures

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Abstract. The effectiveness of structural repair using composite patches depends on both geometric and mechanical parameters, including the properties of the patch, the adhesive joint, and the repaired structure. In this study, the finite element method (FEM) was employed to investigate the influence of repaired structure parameters effect, specifically thickness and Young's modulus, on the repair efficiency. Unlike previous studies, which focus on aerospace applications, this work explores the potential to extend composite patch repair techniques to other domains such as hydrocarbon, marine, and civil engineering, where structures are characterized by higher Young's modulus and thicknesses. The analysis examines the stress intensity factor (SIF) at crack tips on both the repaired and unrepaired faces, as well as shear stresses within the adhesive layer. The results reveal that while single-patch repairs are effective for thinner structures (e.g., aircraft fuselages under 4 mm), double-patch repairs are necessary for thicker structures, such as those in hydrocarbon or marine engineering, to stabilize cracks on both faces. Furthermore, using a thinner double patch repair provides similar SIF reductions as a thicker patch, offering significant mass savings—a critical factor in engineering design. These findings highlight the adaptability of composite repair techniques across various industries, demonstrating the potential for broader application beyond aerospace, with implications for enhanced structural integrity and reduced weight.

Keywords: adhesive; crack; patch composite; shear stress; SIF; stiffness; thickness

1. Introduction

The repairing cracked structure technique, by a composite patch, is frequently used in the industry and especially in the aerospace industry, as a solution for retarding the initiation and propagation of fatigue cracks. This technique involves to bond a composite patch on the cracked area by an adhesive. This adhesive must facilitate the transfer, of the normal stresses concentrated in the crack heads, to the patch, and ensure a good adhesion plate-patch. Compared to conventional mechanically fixed techniques such as riveting and welding repair, the use of the bonded composite patch as a repair technique, has many advantages, such as, for example, good resistance to fatigue and corrosion, high stiffness and low density. These conventional methods are a sources of stress concentration by notch effect, which increases the risk of initiation and propagation of new fatigue cracks.

This technique has been, the subject of several research works, including numerical, analytical

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and experimental used to improve the performance in terms of service life of aging aircraft. Thus, Baker (1984), Baker (1988), Rose (1982) were virtually the first researchers are used this technique as a means of repairing cracked aircraft structures, they find that this technique proves to be a relevant, effective, efficient, quick and less costly solution. Other authors, Alderliesten (2009), Qing *et al.* (2006), Mhamdia *et al.* (2011), Gkilas *et al.* (2012), Bachir Bouiadjra *et al.* (2016), Benyahia *et al.* (2014), Oudad *et al.* (2012), Lena *et al.* (1998), they using the finite element method to analyse the repaired cracks behaviour in terms of the stress intensity factor reduction (SIF). Ramji *et al.* (2013) they analysed the patch shapes effect on the repair performance, have shown that a repair using the octagonal patch, results in a reduced in SIF. In the same context, Boualem *et al.* (2024) show that the presence of a bonding defect significantly affects stresses in the adhesive joint, which become important if the joint is subjected to a higher applied load. On the other hand, the geometric modification made to the plate considerably reduces the various stresses in the adhesive joint even in the presence of a bonding defect. Ait Kaci *et al.* (2017) show clearly that the stacking sequence for the composite patch must be selected to absorb optimally the stresses from the damaged area and to position the various layers of the composite under the first layer whose fibers orientation will remain in all cases equal to 0°. The use of a hybrid composite reduces significantly the J Integral and the stresses in both damaged plate and the adhesive layer. Aminallah *et al.* (2023) have shown that the optimum of stacking sequences allows reducing stresses significantly, and thus permits designers to improve the quality of repairs. Bouchiba *et al*. (2016), by developing a static approach to optimize the composite patch shape, they show that the butterfly shape leads to a stress intensity factor (SIF) reduction in repairing crack heads in opening mode, and the stress relaxation in the adhesive layer. Nour *et al.* (2016), analysed the rectangular patch effect on the repair performance of the two cracks interaction. This analysis is done in terms of stress intensity factor reducing in mode I. Hu *et al.* (2024) have shown that the geometric factors affect the loading performance and alter failure modes by adjusting stress distribution in the repair system, whereas the cure pressure and surface treatment act on the bondline and change interfacial properties. Psarras *et al.* (2024) have shown that elliptical stepped patches can offer a near-optimum solution much more efficient than that of the conservative option of the circular patch, in terms of both strength and volume of healthy removed material. Rasane *et al.* (2023) show that the separation of the patch from the substrate largely depends on the geometrical factors of the patch, i.e., length, width and thickness. Show also that the optimum geometrical factors need to be incorporated for the effective and economical repair of the cracks. In this work show that the optimum combination of the geometrical factors, i.e., length, width and thickness of the polymer composite patch, is obtained using the Taguchi technique with the help of the results generated in the numerical analyses. Althahban (2024) have shown that width of the patches affected the efficiency of the rehabilitated cracked aluminum plate, also have shown that if compared with the specimen without the patch. The efficiency of the patch in reducing the SIF increased as the number of layers increased. This study assessed repairing metallic structures using the chopped strand mat GFRP. Furthermore, it demonstrated the superiority of rectangular patches over semicircular ones, along with the benefit of using double patches for out-of-plane bending prevention and it emphasizes the detrimental effect of defects in the bonding area between the patch and the cracked component. This underlines the importance of proper surface preparation and bonding techniques for successful repair.

Some studies have been done on the free edge shape of the patch to limit the shear stress peak in the adhesive, these works aim to evaluate the influence of the free edge shape of the composite patch on these peak reductions, Among these studies, the study of Xiong and Raizenne (1998), this study shown that, the patches with a decreasing thickness, decrease the stress in the adhesive layer because the geometry of the singularity, and they optimized the angle and the of the decrease the composite patch thickness length. Baghdadi *et al.* (2019), analyzed the repair performance in terme of reducing both, the stress intensity factor (SIF) and the maximum shear stresses in the adhesive layer simultaneous, for different cases of the composites patch shapes, in the first case (constant surfaces ant thicknesses of the patch shapes), the patch shape have no effect on the SIF, the sharp edges (obtuse, right and acute) of oblique shapes generate high shear stresses, in the second case, the reduced surfaces lead to significant mass gain with the same SIF values, and to an increase in the maximum shear stresses, in the latter case (constant volume) the patches shapes lead to a reduction of the SIF and the shear stresses and the maximum shear stresses in the adhesive layer. Aabid *et al.* (2024) have explored the repair of damaged plates through experimental, numerical, and analytical methods and they have found that bonded composite repairs are effective in controlling crack damage propagation in thin plates they also show that the use of double-sided composite repairs improve repair performance within certain limits and they focuses on these limits and optimizes double-sided composite repairs by varying adhesive bond and composite patch parameters.

Expand the repairing cracked structure technique, by a composite patch in another domain, such as a hydrocarbon, marine engineering, civil engineering, even some type of aeronautical structures is the objective of this works. These structures are defined by their height elastic modulus or their high thicknesses. So, this work aims to analyses, the structure parameters effect (thickness, and young modulus) on the repair performance in terms of the stress intensity factor (SIF) reduction and the shear stresses in the adhesive layer for different cases (Simple patch and double patch). A simulation based on the finite element method was used.

2. Geometric model

The geometric model developed consists of a 2024-T3 aluminum alloy plate, this plate is characterized by its height H=250 mm, its width W=125 mm and its thickness ep=variable (0,5. 1. 1,5. 2………10 mm). This plate is subjected to uniaxial tension stresses of varying amplitude, allowing the crack propagation in opening mode, the most dangerous mode. The composite patch

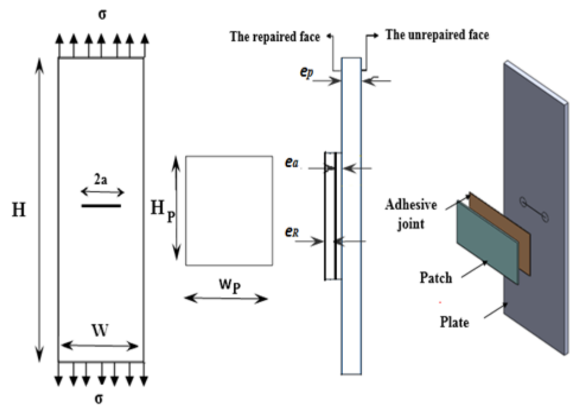


Fig. 1 Geometric model of the structure

Table 1 Mechanical properties of the materials

Properties	Plate AL (2024-t3)	Carbon /Epoxy Engineering Constants	FM-73 Adhesive Type
E_1 (MPa)	72 10^3	153 10^3	2.55 10^3
E_2 (MPa)	----	9,1 10^3	----
E_3 (MPa)	----	9,1 10^3	----
v_{12}	0.33	0.258	0.3
v_{13}	----	0.258	----
v_{23}	----	0.384	----
G_{12} (MPa)	----	4,57 10^3	420
G_{13} (MPa)	----	4,57 10^3	----
G_{23} (MPa	----	3,15 10^3	----

used as a repair patch, it's Carbon-epoxy, defined by its height Hp=40 mm, its width Wp=80 mm, and its thickness is eR=2 mm. The composite patch is supposed to be perfectly bonded to the plate by an FM-73 adhesive type, of thickness are ea=0.2 mm (Fig. 1). The mechanical properties of the plate, the patch and the adhesive are shown in Table 1.

3. Presentation of the calculation software used in this study

The performance of Abaqus 6.14 is used for the analysis of cracked aircraft plates and after repaired with composite patches. Abaqus software has many finite element analysis capabilities, ranging from a simple linear static study to another complex nonlinear static. The documentation of this software gives the procedures to be followed to make analyses of different fields of engineering.

4. Presentation of the model

The three-dimensional numerical model developed for this study consists of a cracked Al2024 T3 plate repaired with a composite patch (Carbon-epoxy) (Fig. 1). Finite element modelling requires the mesh of the structure to be analysed, the structure has been meshed globally using elements of the type C3D8 (An 8-node linear brick) (Fig. 2).

To obtain a correct representation of the displacement field near the crack, the elements called singular are used, as suggested by the Abaqus software documentation. The type of singularity $1/\sqrt{r}$, for the stress fields are obtained by moving all the intermediate nodes of the elements around the crack tip to a quarter of a distance from the nodes belonging to the considered crack tip. The mesh of the crack tip was exclusively refined using this special type element (Fig. 2). The total number of elements for the repaired structure depends on the thickness of the plate. For the rectangular patch, adhesive and the plate of thickness=2 mm, the total number of elements is shown in Table 2.

The side sizes of an element, far from the crack and in the near the crack, was represented in Table This sizes and types of mesh, remains the same for all the simulations in this work, to avoid

Table 2 Numbers and sizes of the mesh elements

The different components of the analysed structure	Numbers of elements	Sizes of elements
Aluminium 2024-T3 (EP=2 mm)	11796	2 mm
Crack Front	2500	0.078 mm
FM-73 Adhesive Type	3200	0.5 mm
Composite Patch	12800	0.5 mm

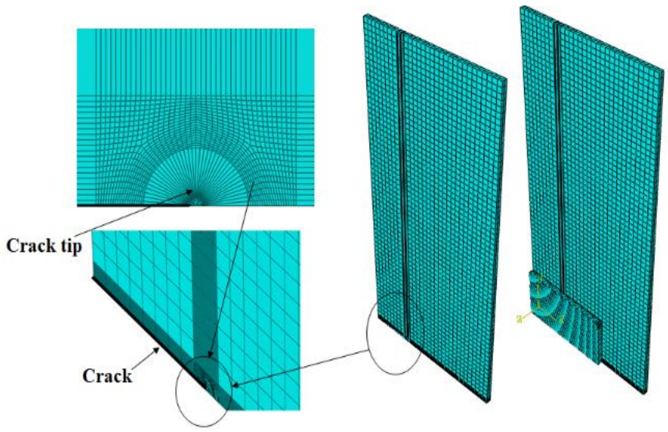


Fig. 2 Mesh of the structure

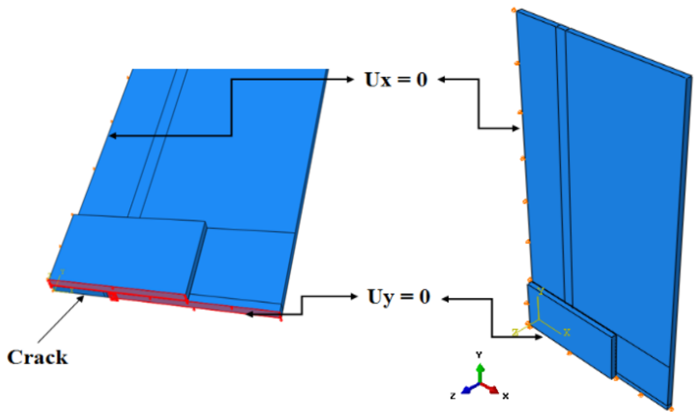


Fig. 3 Boundary conditions imposed on the structure

any influence of the mesh on the results.

Adhesive has been considered as a third material to introduce its actual mechanical properties. The interaction between adhesive and the cracked plate area, firstly, and between the composite patch and adhesive, secondly is considered perfectly welded (the two bodies can be considered welded during the simulations).

The symmetry allows the modelling of the structure quarter, which leads to a reduction in calculation times, the boundary conditions imposed on the plate analyzed are represented as follows (Fig. 3):

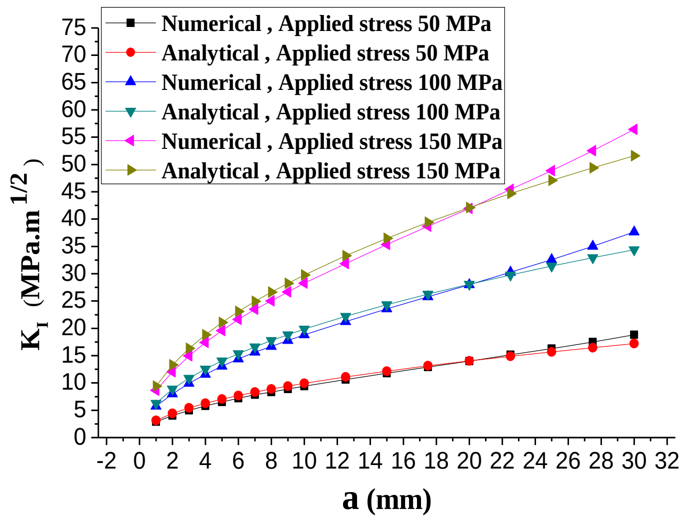


Fig. 4 Variation of the SIF at the crack tip as a function of the crack length, for different applied stress intensities

5. Validation of the model

To validate the model developed in this work, Fig. 4. shows a comparative analysis of the SIF variation obtained from the numerical model, developed in this work, and that resulting from an analytical model. The SIF is the only significant parameter, which allows to know the state of stress and deformation in any crack heads. For a central crack solicited in opening mode, the relation between the far applied stress on the plate (σ) and the stress intensity factor K_I is as follows

$$K_I = Y\,\sigma\,\sqrt{\pi a} \tag{1}$$

Where Y is a geometric factor, depends on the plate geometry and the crack shape. Y=1.12 (for a finished plate containing a central crack of size "2a"). The analysis of this result shows that the numerical and the analytic model lead practically the same results and whatever the applied stress intensities to the plate. This behaviour clearly illustrates that the model developed in this study and the boundary conditions imposed are reliable and allows a better mechanical behaviour analysis of the cracked structure and repaired with composite patch.

6. Results and discussion

The mechanical properties (elasticity modulus) and geometric (thickness) of the cracked plate, plays a determining role in the repair performance. In this work, the effect of these two parameters is studied in terms of stress intensity factor (SIF) in crack heads of the repaired face, of unrepaired face and the tangential stresses in the adhesive layer, the reduction of these two physical parameters is required for the stability and durability of the repair. To do this, the analysed models differ only, in the nature of this structure and its thickness.

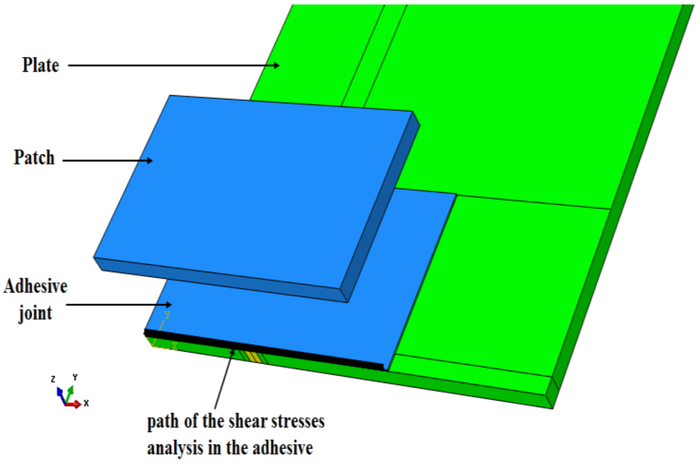
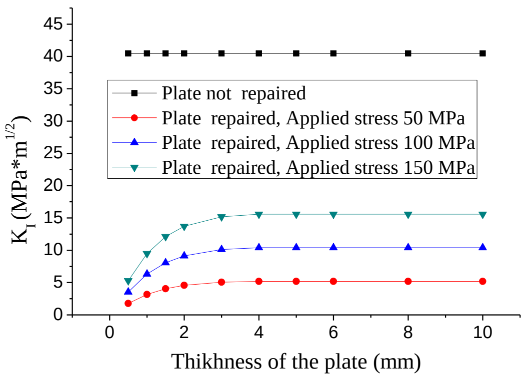
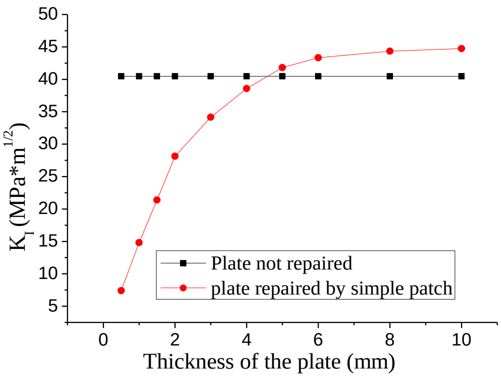


Fig. 5 Path of shear stresses Analysis in the adhesive layer



(a) The repaired face



(b) the unrepaired face

Fig. 6 Effect of the plate thickness on the SIF level, Applied stress 150 MPa. (a) repaired face, (b) unrepaired face

6.1 Effect of plate thickness

The influence of this last parameter (thickness) on the stress intensity factor (SIF) of the repaired face is shown in Fig. 6(a). However, this rupture criterion (SIF) is all the more important that the repair structure is thick. This behavior is more marked when the applied tensile stress is more intense. The repair of thin plates is much more reliable in terms of SIF reducing and whatever the applied stress intensities. This explicitly shows that the thickness of the structure is the key parameter of the repair performed (Fig. 6(a)).

Any repair by composite patch, aims not only to relax as much possible the fracture energy in crack heads, but also to reduce the intensity of these stresses in order to prevent the adhesion failure. So, it is important to maintain the shear stresses in the adhesive layer at the lowest possible level.

The structure thickness effect on the shear stresses level induced in the XOY, XOZ and YOZ planes of the adhesive layer, are analysed along of the crack propagation path (Fig. 5). the results

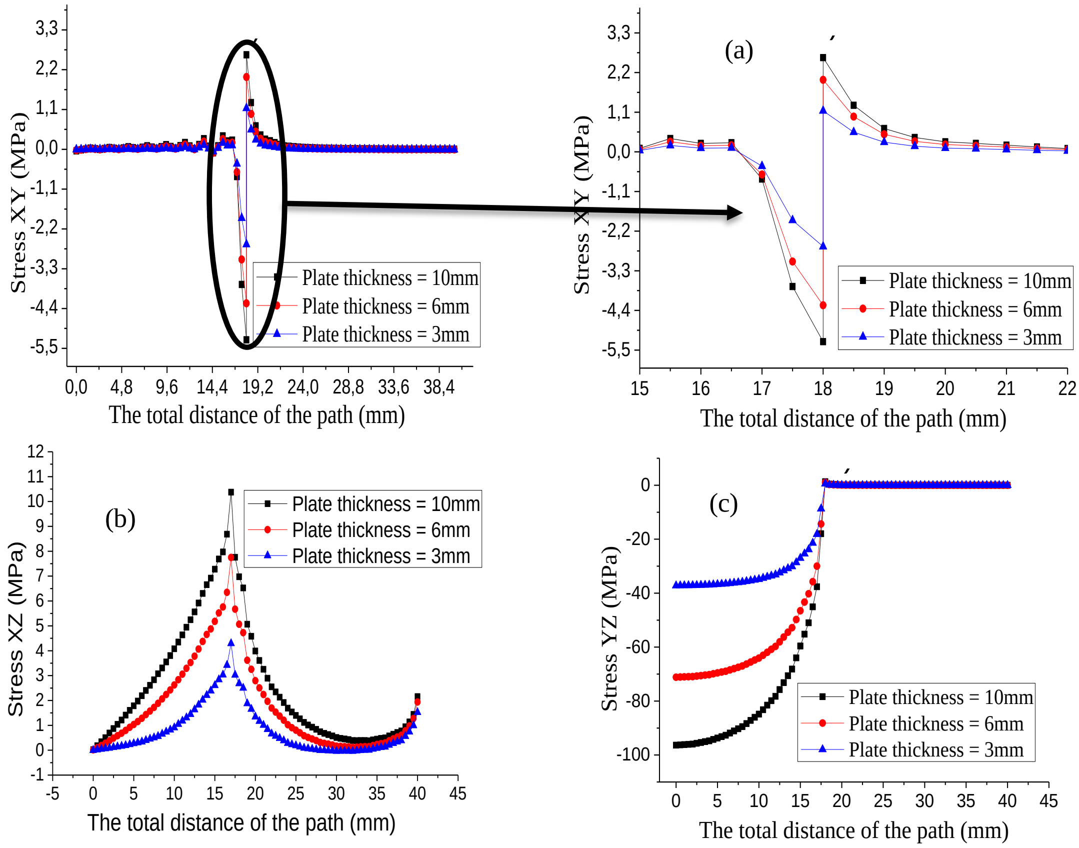
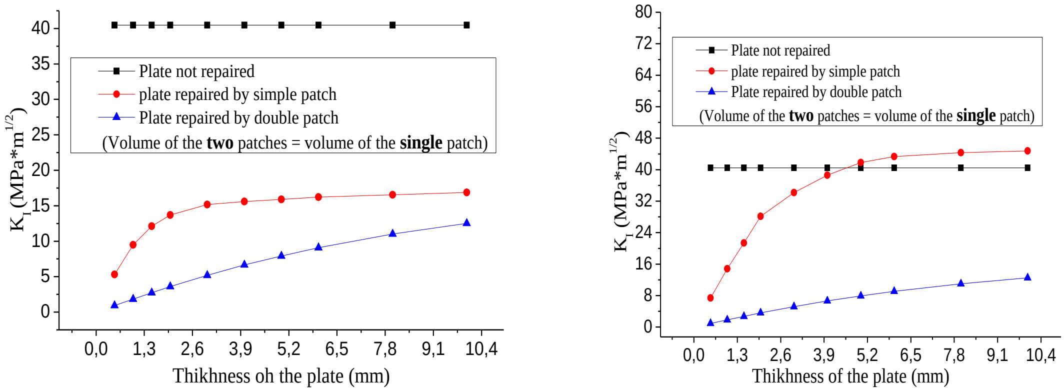


Fig. 7 The plate thickness effect on the shear stresses level in the adhesive layer along the crack propagation path, repaired crack a=18 mm, Applied stress=150 MPa

obtained are represented in the Fig. 7.

The analyse of this figure shows that the repair of thick structures generates the most significant tangential stresses. It is the normal tensile stress in localised in the repairing crack heads not transferred to the composite patch that is the main cause of this behaviour. The most important stresses are specific to the YOZ plane (Fig. 7(c)) and are located near the crack lips. This area of the structure, corresponding to that, where the displacements are the most important (the displacement of the crack lips), is a source of repair damage by the disbanding phenomenon between the adhesive and the plate. In fact, the local shear stresses, generated in this adhesive area, far exceed the threshold shear failure of this adhesive and lead to disbanding zones, resulting from the ruin of this area. This ruin is done by the initiation and propagation of new cracks in the adhesive layer.

For the better illustration of the structure thickness effect, in Fig. 6(b) indicates the SIF variation of the unrepaired face (Fig. 1). The analysis of this figure shows that, compared to the cracked structure not repaired, the composite patch effect reaches, in our simulation conditions, thicknesses of less than 4 mm. This effect is defined by the low values of this rupture parameter compared to those resulting from the cracked structure not repaired (Fig. 6(b)). In other words, the mechanical energy transfer, stored in repairing crack heads, from the plate to the composite patch



(a) The repaired face (b) the unrepaired face

Fig. 8 Effect of the plate thickness on the SIF level (simple patch and double patch), Applied stress 150 MPa (a) repaired face, (b) unrepaired face

through the adhesive layer is performed at distances of less than 4mm of the structure thickness. At this distance, the SIF value of the unrepaired face of the repaired structure by simple patch (the opposite face that containing the composite patch) corresponds to that, of the unrepaired structure (cracked structure not repaired).

At this structure point (4 mm of the structure thickness), the composite patch effect disappears, and the unrepaired face crack heads become more and more unstable.

The results illustrated in Figs. 6(b) and 7, show that the repair by simple composite patches of thick structures like hydrocarbon, marine engineering, civil engineering, is strongly not recommended because it generates a strong increase in shear stresses in the adhesive layer (Fig. 7) and promotes the crack propagation of the unrepaired face (Fig. 6(b)) opposite to that containing the composite patch. This behaviour seems to be explained by the fact, that under the effect of the applied stress, the displacement of the unrepaired face is too great compared to that the face repaired by composite patch generates a local bending of structures.

In other words, compared to the repaired face when the composite patch presence stops, by its high rigidity, the crack lips displacement, this composite patch promotes the development of the crack of the unrepaired face, this later being free (absence of the patch effect) and the de crack lips propagates without resistance.

In fact, the patch presence on the repaired face accelerates this growth, this clearly shows that the simple patch repair of transverse cracks initiated in thick structures can accelerate their instability on the unrepaired face.

6.1.1 Effect of the double patch repair in the case of thick structure

To minimize the risk of crack propagation of the unrepaired face (Fig. 1) of the thick structure (Such as hydrocarbon, marine engineering, civil engineering) and to reduce the shear stresses in the adhesive layer, the double composite patch repair (the repair of the two faces) is a reliable and adequate solution. Two cases were taken into account in this part of this work, with conservation of the simple patch volume (Volume of the two patches of the double repair=volume of two patches of simple repair), with reduction of the batch volume (Volume of the two patches of the double repair=volume of a single patch of simple repair). The Figs. 8 and 10. show the beneficial

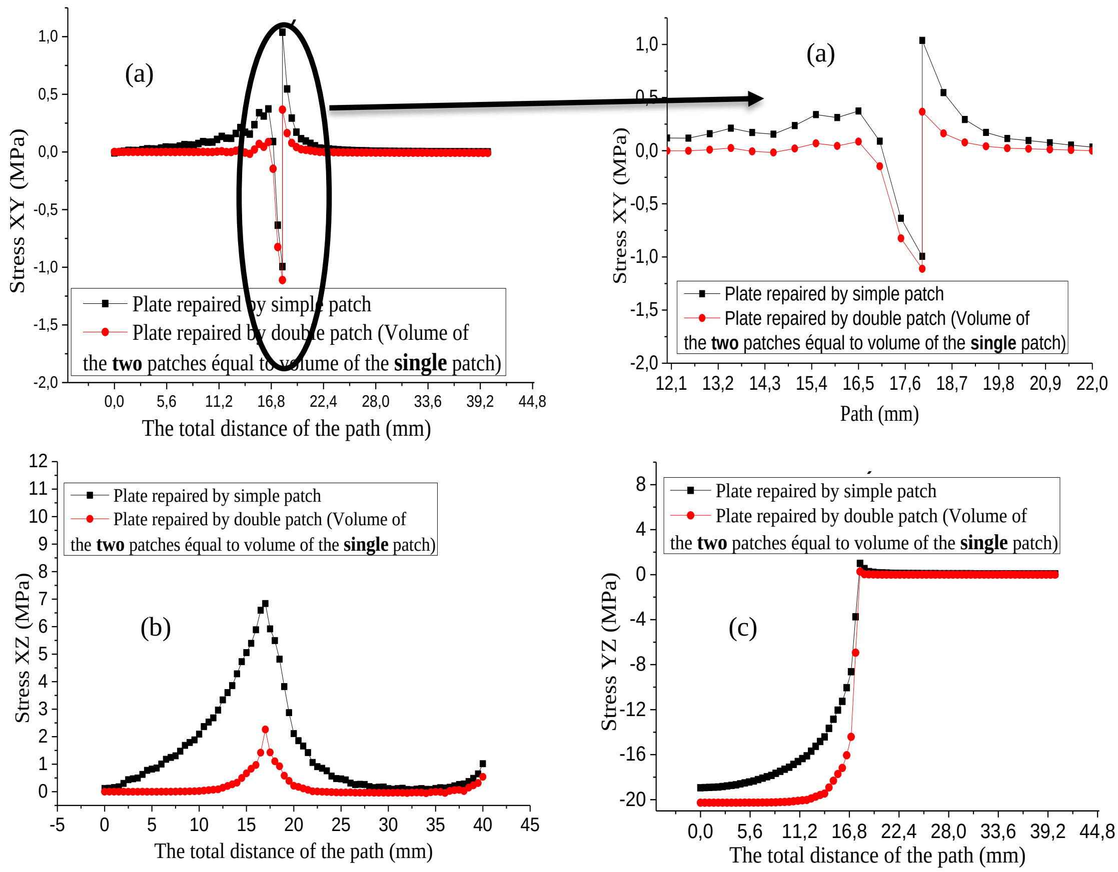


Fig. 9 Comparison between single patch repair and double patch repair on shear stress distribution in the adhesive layer along the crack propagation path, repaired crack *a*=18 mm, Applied stress=150 MPa

effect of the double repair of structures and particularly the repair of the thick structures. In this case, the stress intensity factor drops considerably. This clearly illustrates that in comparison to external repair (simple patch repair), the double repair is much more efficient, in terms of SIF reducing crack heads of both faces. This energy relaxation, due to the doubling of the stress transfer from the damaged zone to the patches. This result is observed whatever the repaired crack size. It is clearly shown that the external and internal repair (double repair) eliminates the harmful effects of external bending stresses due to simple repair. This phenomenon can lead, in this case, to instability, by increasing the fracture energy of the unrepaired face, totally relaxed by the symmetrical repair of the internal and external face of the structure (double repair). In fact, the double repair disadvantages the structure bending.

The double repair effect (with reduction of the simple patch volume) on the service life improvement of the cracked structures, in terms of shear stresses relaxation in three directions, in the crack propagation path, Fig. 5, is represented in Fig. 9. This result shows explicitly that the double repair is much more efficient and more effective than the simple repair. In fact, these shear stresses are strongly relaxed in the case of the double repair. The results obtained in the case of the double repair with a patch volume doubly greater than the simple repair (with conservation of the

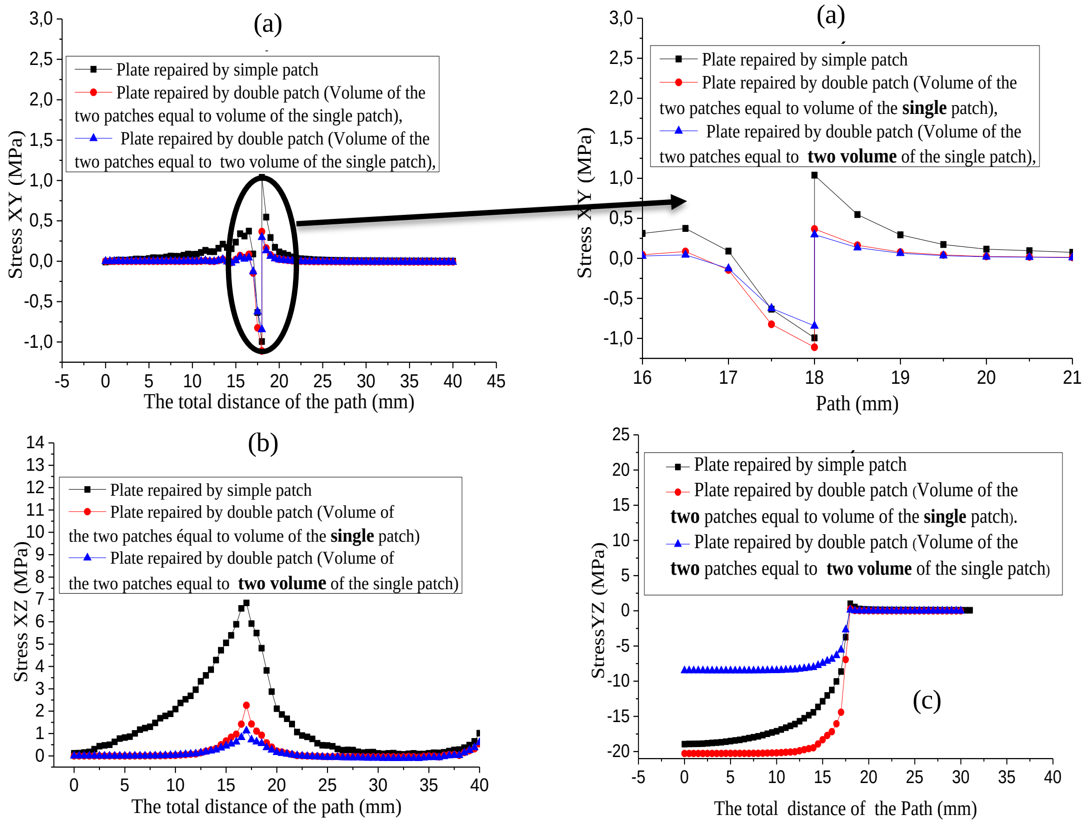


Fig. 11 Comparison between single patch repair and double patch repair, on shear stress distribution in adhesive layer along the crack propagation path, repaired crack a=18 mm, Applied stress=150 MPa

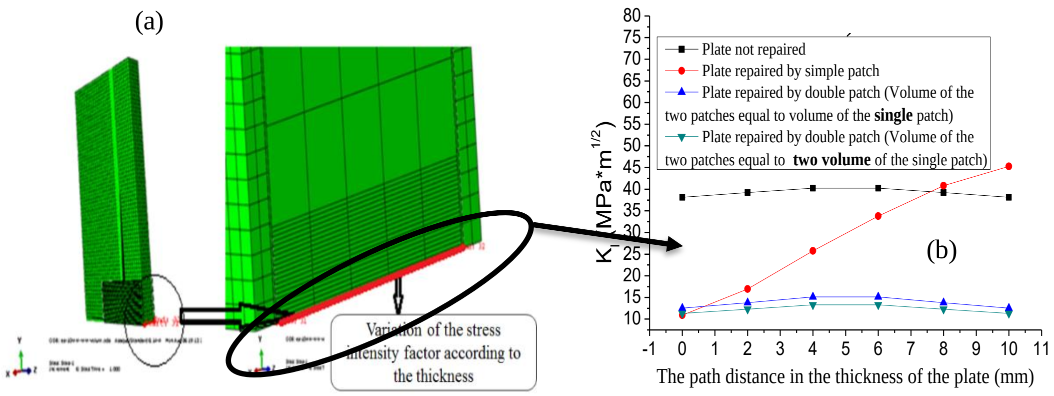


Fig. 12 Effect of double patch (double reparation) on the SIF level along the thickness of the cracked structure

simple patch volume in two repaired faces), show that double symmetrical patch repair clearly improves the service life of cracked structures, in terms of fracture energy (SIF) and the shear

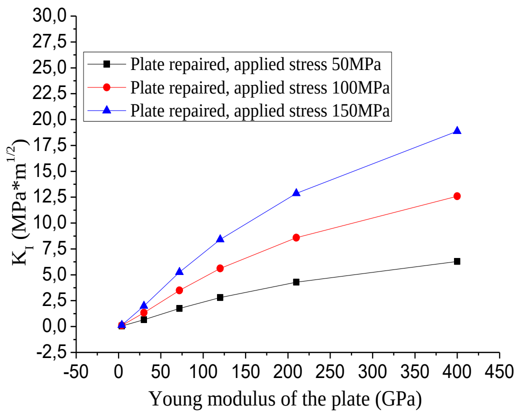


Fig. 13 Effect of the plate stiffness on the SIF level

stresses in the adhesive layer.

The reduction rate of the double repair reaching 70% of the unrepaired face, for the repair of thin structures (thickness<4 mm) compared to single patch, and up to 50% for the repaired face. concerning the thick structures repair (thickness=10 mm). and in the second case, the reduction rate of the double repair, reaching 80% compared to a single patch of the unrepaired face and up to 35% for the repaired face.

Whatever the cracked structure thickness, the double repair crack is very insensitive to the thickness patch variation (Fig. 10), in term of SIF. In fact, a double repair, (with reduction of the patch volume), is somewhat less efficient, from a point of view, a relaxation of the shear stresses in the adhesive layer, than that using repair materials doubly thicker (with conservation of the simple patch volume) (Fig. 11 (a), (b), (c)). This clearly shows that the performance of the double repair, in terms of reduced fracture energy in repairing crack heads and shear stresses in the adhesive layer, using a patch twice as thick (with conservation of the simple patch volume) is comparable to that resulting a patch twice as thin (with reduction of the simple patch volume) as shown in Figs. 11 and 12.

Fig. 11(b) clearly shows that during the double repair, the stress transfer due to the singularity of the crack is done at greater distances from the damaged areas with the composite patches. This behavior is defined by the very small variation of the stress intensity factor along the plate thickness (Fig. 11 (a)).

6.2 Young's modulus effect of the plaque

To complete this study, in Fig. 13 shown the Young's modulus effect of cracked plate and repaired by composite patch on the SIF. However, the charge transfer from this plate to the composite patch through the adhesive layer is even worse when the cracked structure is stiffer. In this case, the high rigidity of the plate supports the highly concentrated stress in crack heads. A large proportion of this energy, stored in the plate, favors the advance of the crack by leading to higher fracture energy values, this behaviour is accentuated by an intensification of the tensile stresses. Conversely, the charge transfer is better, in the case of the repair of weakly stiffness plates.

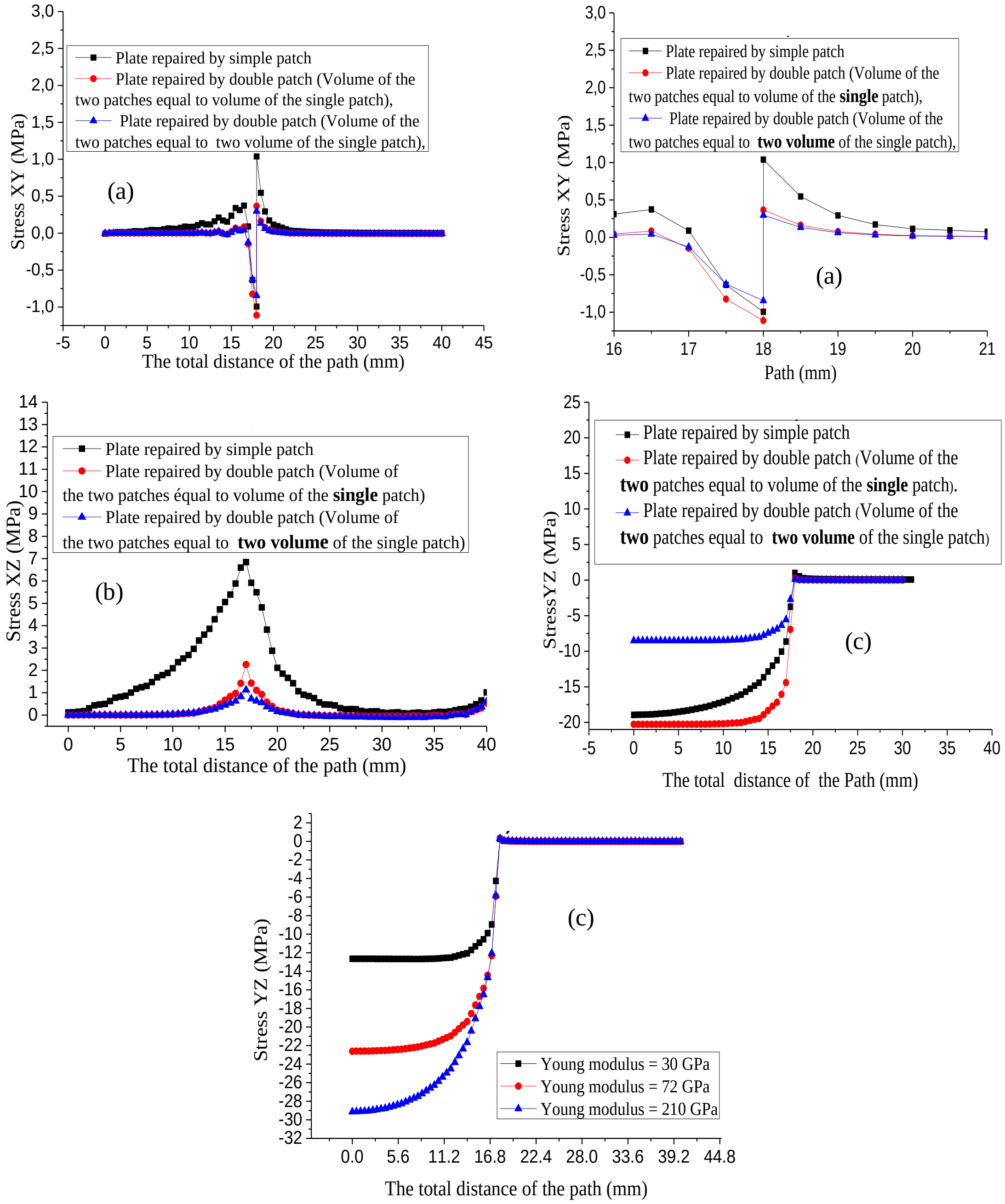


Fig. 14 Effect of the plate stiffness on the shear stresses level in the adhesive layer along the crack propagation path, repaired crack *a*=18 mm, Applied stress=150 MPa

This behavior is also observed in the case of the shear stresses, generated in the XOY, XOZ and YOZ planes of the adhesive film during the repair (Fig. 14) in the crack vicinity. in fact, a plate of high stiffness induces in this layer the high-level shear stresses. This is mainly due to the poor transfer of stress, from the crack to the composite patch. In contrary to the first two planes XOY and XOZ (Fig. 14 (a) and (b)), the tangential maximum stresses specific to the third plane (YOZ) are incomparably more important (Fig. 14(c)). These forces, localized on the crack lips and of comparable level to the rupture threshold of the adhesive, can lead to repair degradation by adhesive layer disbanding. To minimize this risk, it is therefore necessary to repair such structures with composite patches of very high stiffness Such as Boron/epoxy.

7. Conclusions

In addition to the repair of thin aircraft structures like fuselage, the composite patch repair technique can be used to improve the service life of structures used in hydrocarbons, marine engineering, civil engineering, our also some thick aircraft structures like wing spar etc. These structures are defined by their high elastic modulus and their thicknesses. The results obtained in this work show that:

• the mechanical parameters of the repaired structure determine the durability and the repair performance, these parameters analyzed in this work, are respectively the thickness and the elasticity modulus of the repaired plate.

• Our results explicitly illustrate that the external repair is only effective for transverse cracks initiated in practically thin structures less than 4mm thick, such as the aeronautical structure, the crack front of the unrepaired face becomes more and more unstable with the increase in the structure thickness, the intensification of the fracture energy of the unrepaired face cracks heads is characteristic of this behavior. Beyond this size (4mm), the double repair proves to be of great utility for the stabilization of such a crack. It follows a greatly reduced of fracture energy (stress intensity factor) compared to that obtained from a simple repair. In the case of accessibility to the internal face, the double repair is more effective, more efficient and more durable in terms of SIF reduction and the shear stresses in the adhesive layer.

• The results obtained show also that the repair of structures with high stiffness by carbon-epoxy patch presents a great risk of damage in terms of increase in fracture energy in repairing crack heads and intensification of shear stresses in the adhesive layer. So, the repair in such structures must be done with more stiffness patches, such as the Boron-epoxy.

• Finally, the results obtained show that the double repair performance using twice thicker patches as a single patch (Volume of the two patches of the double repair=volume of two single patch of simple repair), in term fracture energy reduction in repairing cracks heads and shear stresses in the adhesive layer, is comparable to that resulting from a twice as thin patch (Volume of the two patches of the double repair=volume of single patch of simple repair). in other word, a double repair using a doubly thinner patch leads practically to compare values of the SIF than those resulting from the same repair using patches twice as thick. The latter generates slightly higher shear stresses in the adhesive layer.

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