

EXPERIMENTAL AND NUMERICAL STUDY ON THE EFFICIENCY OF THE REPAIR OF COMPOSITE STRUCTURES CRACKED AND V-NOTCHED BY DIFFERENT TYPES AND SHAPES OF COMPOSITE MATERIAL PATCH

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Abstract: The subject of this article around two studies, including experimental and numerical, aiming to know the efficiency of the repair of a composite plate notched (V-shape) and cracked by composite patches of different (types and shapes) . The experimental study to find out which composite materials and shapes are resistant to fracture and notch, We used the finite element method (ABAQUS) for the numerical study to follow the variation of the damaged area ratio D_R , the stress intensity factor SIF and the stress distribution as a function of the crack size for located the most effective shape and type patch in repairing cracks and notch. From the results found we can deduce that the best type of patch used is Boron / epoxy and the full shape is the most efficient and resists structural failure, this is confirmed by the experimental test.

KEYWORDS: Finite element method (FEM), repair composite, Stress intensity factor (SIF), the damaged area ratio (D_R), Von Mises Stress, laminate.

1 Introduction

The Industrial Revolution involved abandoning the use of traditional materials for their inefficiency, where they developed their composition to what they are today under the heading of composite materials with important multifunctional advantages: lightness, mechanical and chemical resistance, reduced maintenance. They make it possible to increase the life of certain equipment through to their mechanical and chemical properties. They can be subjected to shocks and impacts at low speeds, the damage caused can then propagate until it failure. But in many applications, the high cost of complex laminate structures does not allow systematic exchange of damaged elements. We can then consider repair as a good economic and mechanical alternative. From this point of view, Mr. Berrahou [1-5] worked on studying the performance of the reform and deducing which engineering forms are the most efficient and quality in the repair.

Several papers [6-12] show that the determination of the stress intensity factor at the crack tip is one of the possible ways to analyze the performance of bonded composite repairs. We know that the finite element method gives with great precision the stress intensity factors at the crack tip.

Recently, several works on damage area theory have been published. Bouanani [13] estimated adhesive damage and failure in bonded composite repair using the modified damage zone theory. And there is some evidence that the adhesive damage is mostly located on the free edges of the patch and above the crack region. Ramji [14] tested several patch shapes and

concluded that the extended octagonal patch shape works best at reducing the stress intensity factor.

In the literature, the stress distribution around a circular and elliptical hole in composite plates has been studied by several researchers [15-18], who show that there is no exact analytical solution for this case, and all solutions are approximate or empirical solutions. The performance of a repair of notched and damaged laminate structures depends not only on the geometry, property or shape of the chosen patch but also on the stacking sequence. The orientation of the composite fibers has influences on the efficiency of the repair or it increases the patch stiffness and strengthens the structure, so can be considered as an optimization parameter. Cheng [19] and Wang [20] have researched this subject. Ait Said Ahcene et al studied of the mechanical fatigue behaviour under 3-point bending stress, of aramid/aluminium composite panel with honeycomb core [21].

Several studies have also discussed the effect of fiber orientations on the performance of the composite material in terms of repair efficiency [22-31], These and many other studies have also shown that fibers oriented in the same direction of tensile stress (longitudinal direction) are more efficient and more resistant to fibers oriented vertically (transverse direction) with tensile strength, the risk of damage is greater compared to the first direction. There are also some works focused on the natural materials used in composite materials [32-33]

Our work is based on two phases in which studied composite structure of boron / epoxy type laminated notched V shape and damaged by emanating crack and repaired by single composite (patch) of different types (Boron / epoxy and Graphite / epoxy), and different shapes (full, normal, V-shape). The first part includes a numerical study in order to analyze the efficiency of a repair of notched and cracked Boron / epoxy plates by patch of different geometric shapes and different types of composites, to conclude that the full shape is the most resistant to failure than the others, the Boron / epoxy is the best type used for a successful repair. The second part is an experimental study with a plate chosen from the similar step to confirm the results obtained from the simulation study.

2 Geometrical and materials models

We consider a cracked rectangular plate of composite materials (Boron / epoxy) with the following dimensions: (height $H_{PL} = 204\text{mm}$, width $W_{PL} = 152\text{mm}$ and thickness $e_{PL} = 3.2\text{mm}$) containing a V-shaped notch having the following dimensions: ($r = 15.2\text{mm}$, $b = 23.8\text{mm}$).

The plate was repaired with different shapes of simple patches made of composite materials (Boron / epoxy and Graphite / epoxy) of the constant thickness $e_{PAT} = 1.6\text{mm}$. In order to analyze the effect of the patch shape, three patch geometries were chosen in this study: full shape, normal shape and V- shape of the following dimensions: ($h = 75\text{mm}$, $W = 152\text{mm}$) for full shape and ($B = 95.2\text{mm}$, $R = 60.8\text{mm}$) for normal and V shape (Fig.1).

The patch is glued with 0.127 mm thick adhesive. The plies in our geometric model have unidirectional stacking where the fibers are oriented to follow (0°) longitudinal direction a 1/3 mm thick plate and patch. The structure made up of the plate is stressed by uniaxial tension $\sigma = 120\text{ MPa}$.

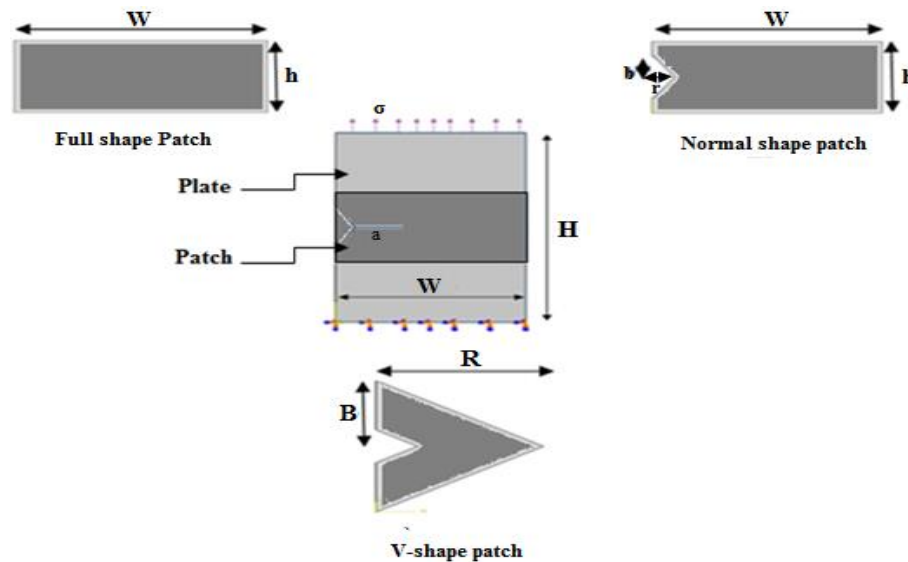


Fig. 1 the geometric model and patch dimensions: (a) full, (b) normal, (c) in V- shape.

The mechanical properties of the different types of materials are given in Table 1 below:

Table 1 Mechanical properties of the different materials.

Propriétés	Boron/ép oxy	Graphite/ép oxy	Adhésif(FM 73)
Longitudinal Young's modulus E_1 (GPa)	200	134	2.550
Transverse Young's modulus E_2 (GPa)	19.6	10.3	
Transverse Young's modulus E_3 (GPa)	19.6	10.3	
Longitudinal Poisson's ratio ν_{12}	0.3	0.33	0.32
Transverse Poisson's ratio ν_{13}	0.28	0.33	
Transverse Poisson's ratio ν_{13}	0.28	0.53	
Longitudinal shear modulus G_{12} (GPa)	7.2	5.5	
Transverse shear modulus G_{13} (GPa)	5.5	5.5	
Transverse shear modulus G_{23} (GPa)	5.5	3.2	

3 Finite element model

The analysis involves a three-dimensional finite element method using the finite element code ABAQUS [34]. The finite element model is composed of three subsections for a cracked composite plate with a V-shaped notch, the adhesive, and the composite patch. The plate has two layers of elements in the thickness direction, the patch and adhesive had a single layer of elements through the thickness. The mesh model contains 12148 quadratic hexahedral elements of type C3D20R, Total number of nodes 68829. This cracked specimen mesh repaired with different shapes of the patches used for digital three-dimensional analysis is shown in Figure 2.

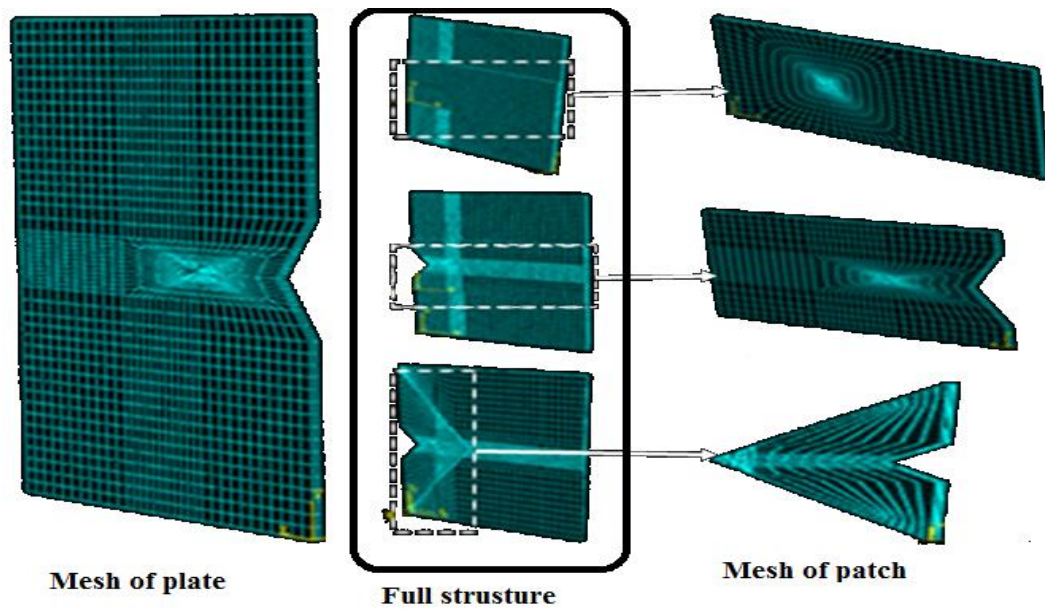


Fig.2 Used mesh of the cracked and repaired plate with V-notch and near crack.

4 Results and discussion

We have established two parts in this work: experimental and numerical. The experimental step constitutes a study on the effects of the different shapes of the boron/ epoxy composite patch in the repair of a V-notched and cracked plate of Boron/epoxy, with fiber orientation angles $\theta=0^\circ$ (longitudinal direction). The second step around a numerical analysis on the effect of the crack propagation on the variation of stress intensity factor SIF for a composite plate (Boron / epoxy), notched in V-shape, cracked and repaired by different patch shapes (full, normal, V-shaped) repaired by two patch types (Boron / epoxy, Graphite / epoxy), Variation of the adhesive damaged area for different types and shapes of patch and the stress distribution for a crack length equal to 15mm for plate repaired with different patch shapes and unrepaired.

I- Simulation part

In this section we used a simple four ply repair patch, each ply is oriented successively $[0,+45,-45,90]$, as indicated in figure 3 below. This stacking sequence gives better repair performance according to the Hautier study [35], which is why we have chosen this series.

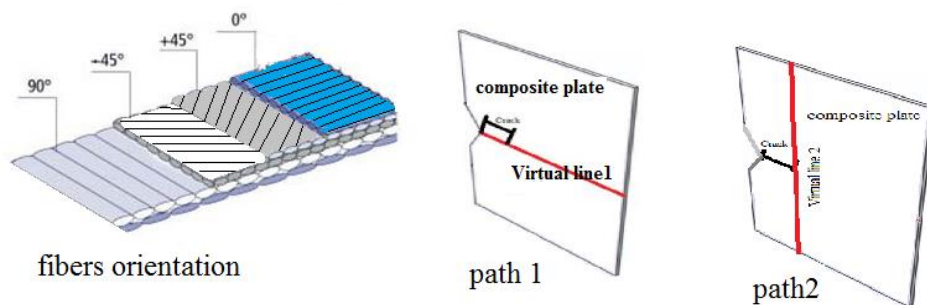


Fig. 3 Fibers orientation in the composite face (patch), and virtual lines

Effect of crack length on stress intensity K_{IC} factor variation

Concerning figures 4 and 5, its represents the variation of stress intensity factor SIF of a composite plate with V-shaped notch as a function of the crack size for a patch of deferent composite materials (Boron / epoxy and Graphite / epoxy) having different geometric shapes

(full, normal and V-shaped). From the results obtained it was observed that there is a direct relationship between the stress intensity factor and the crack length, so that the more the crack size is increased the values of the SIF are also increased regardless of the type of patch and their shape difference. Comparing the efficiency of the composite materials used, we see that Boron / epoxy is the optimum than Graphite / epoxy because its K_{IC} values are the lowest compared to the SIF values of the other composite material (Graphite / epoxy), it also turns out that the full shape is the best performing because it gives lower SIF values than the other two shapes (normal and V-shaped).

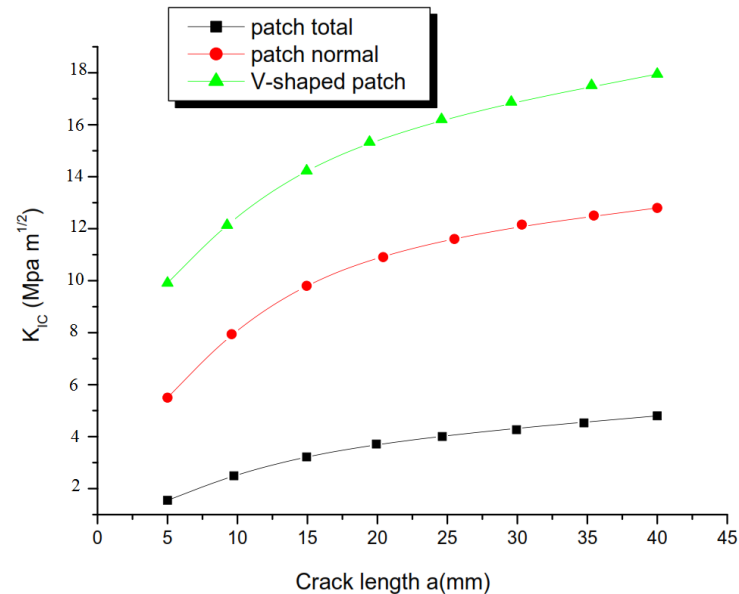


Fig. 4 stress intensity factor vs crack length for the different patch shapes (type of patch boron / epoxy).

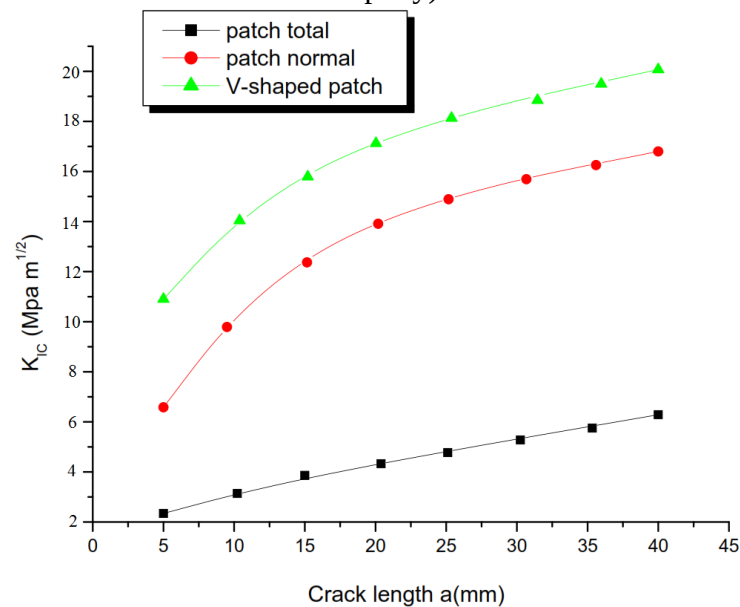


Fig. 5 stress intensity factor vs crack length for the different patch shapes (type of patch Graphite / epoxy).

Stress distribution according to patch types

Figure 6,7 represents the Von Mises stresses distribution for different patch shapes (full, normal, V-shaped) of a composite plate (Boron / epoxy) notched and damaged by a crack of length $a = 15\text{mm}$ repaired by two composite materials (Boron / epoxy see figure 6 and

Graphite / epoxy see figure 7). In general, after the analysis of the stress distribution curves, we notice whatever the shape of the patch or its type, the maximum stress values are concentrated at the crack tip, this is shown on the intervals $[10\text{mm} < X < 20\text{mm}]$ following the axis-xx (path 1) and $[30\text{mm} < Y < 45\text{mm}]$ following the axis-yy (path 2) see figure 3 which shows the virtual lines. We also note that the further we move away from the crack tip; the stress distribution becomes less concentrated or else becomes zero, regardless of the shape and type of patch used. We also notice that the composite material (Boron / epoxy) for the repair (patch) is given good behavior compared to the type (Graphite / epoxy) because it has low concentrations of Von Mises placed either longitudinally (σ_{xx}) or vertically (τ). The full patch shape is more efficient because it has the lowest values of σ and τ than the other patch shapes.

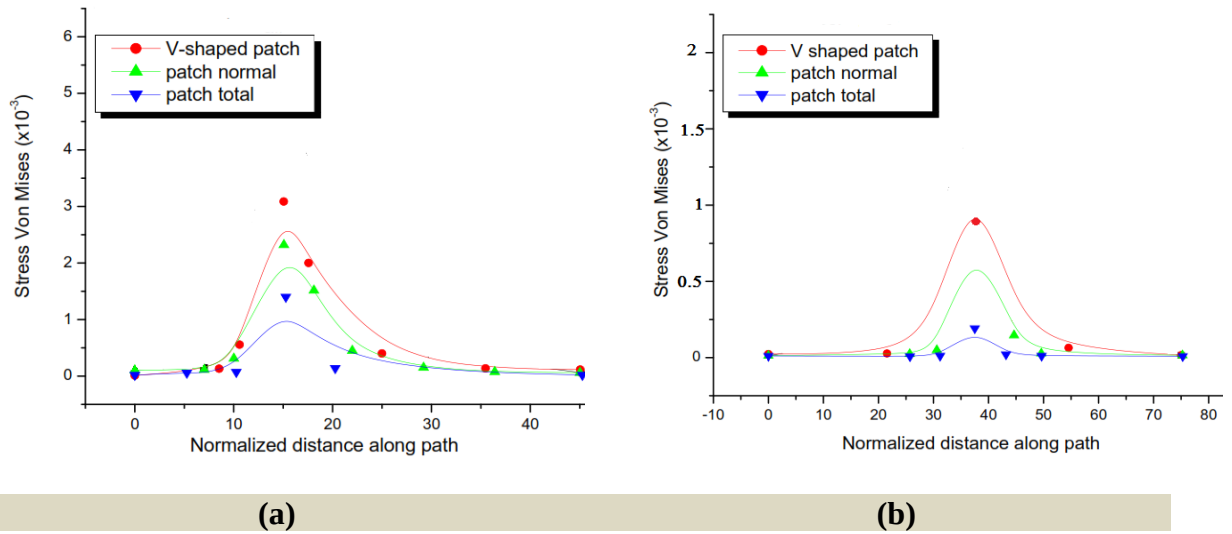


Fig. 6 Variation of Von Mises stress according to (a) σ_{xx} and (b) τ of boron/epoxy patch.

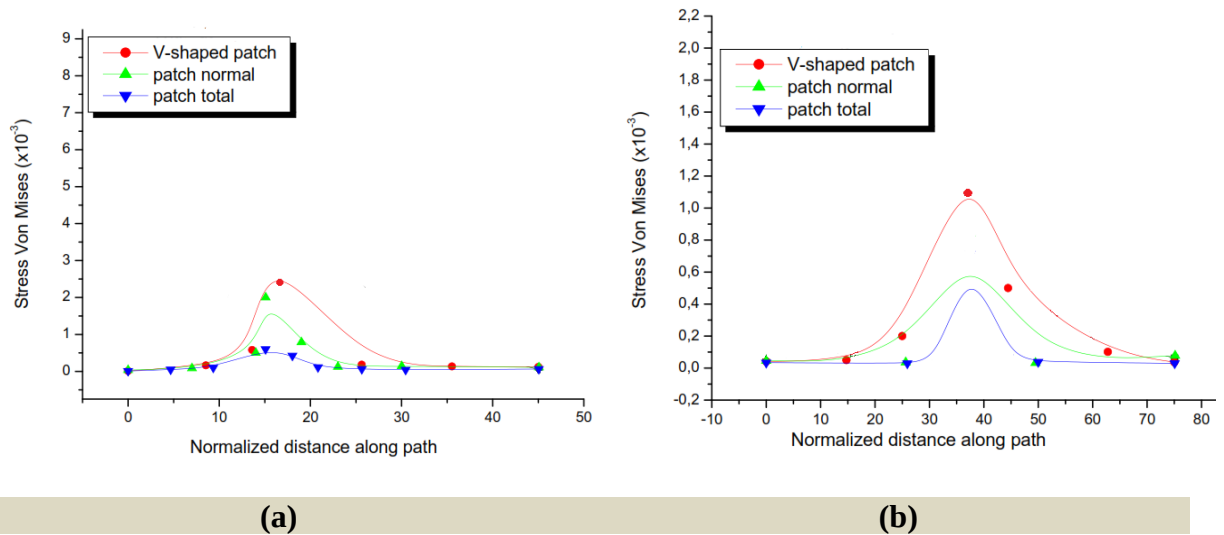


Fig. 7 Variation of Von Mises stress according to (a) σ_{xx} and (b) τ of graphite/epoxy patch.

Variation of the adhesive damaged zone for different types patch

The failure criterion is determined for each stress exerted when it reaches the maximum stress allowed in the material, the damage zone will be determined, as being the zone where the stress of the FM-73 adhesive exceeds 7.87 % of the damage area. Shang Bang after

carrying out studies on FM-73 that the latter no longer performs adequate function of binder when the value of the D_R ratio exceeds 0.24 which considers it to be critical [36]. The value of the damaged area ratio is calculated according to the following relationship:

$$DR = \text{sum of damaged areas} / \text{total adhesive area}$$

1- for total shape of patch

Figure 8 represents the results obtained which make it possible to follow the evolution of the adhesive damaged zone for a cracked plate of Boron / epoxy with crack length (5, 15, 40) mm repaired by different types of patch (Boron / epoxy , Graphite / epoxy) for total patch shape. You can see by following the damaged area that it increases with the crack size. For the boron / epoxy patch type we note that from $a = 5$ mm to $a = 15$ mm the damaged area appears very little which can say it is negligible, but for $a = 40$ mm it generates damage around the crack, but for the photos related to the type Graphite / epoxy, we notice that from $a = 5$ mm to $a = 40$ mm appears to increase the damaged area, especially around the crack and on the edges.

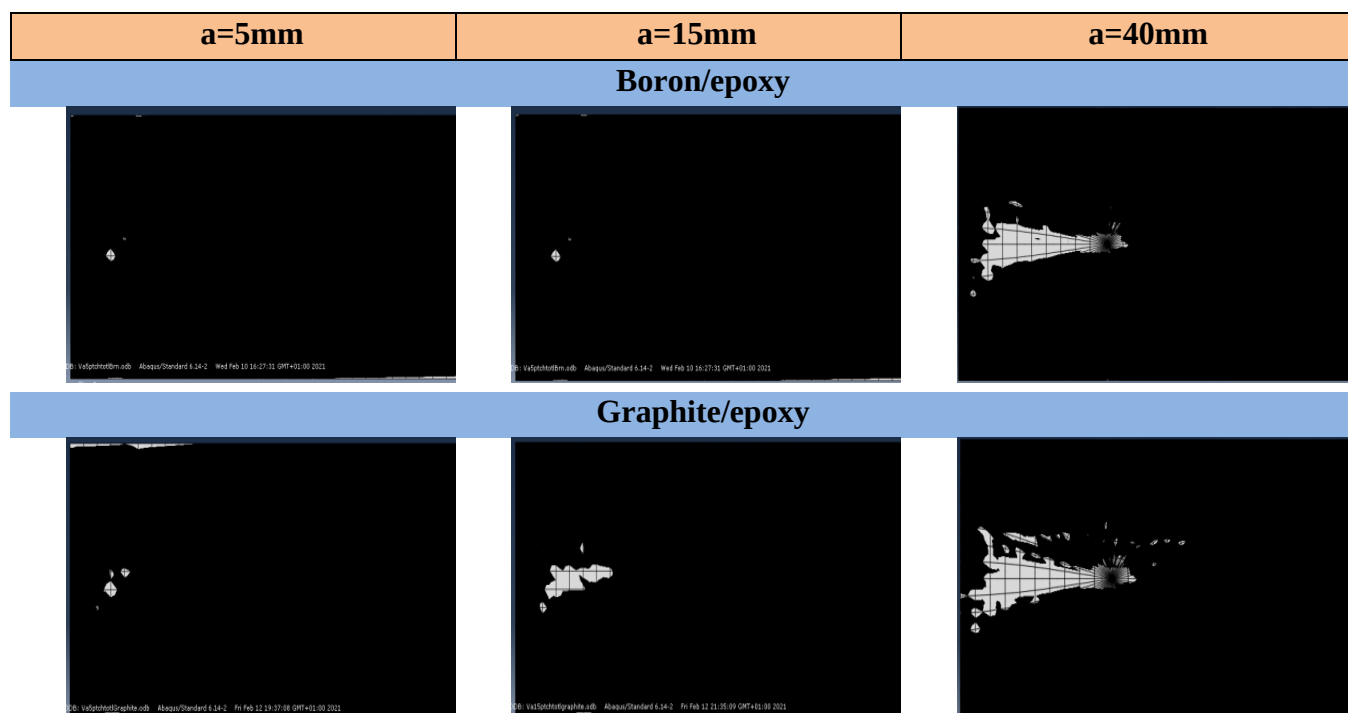


Fig. 8 Damaged area for total shape of patch (a) =5mm, (b) =15mm and (c) =40 mm.

2- for normal shape of patch

Fig 9 shows the variation of the adhesive damaged area for a V-shaped notched plate and cracked of length $a = (5, 15, 40)$ mm of Boron / epoxy and patched with normal shape of (Boron / epoxy and Graphite / epoxy). Note that the appearance of damaged area is increased depending on the crack size, either for the Boron / epoxy or Graphite / epoxy patch type, this increase appears especially near the crack.

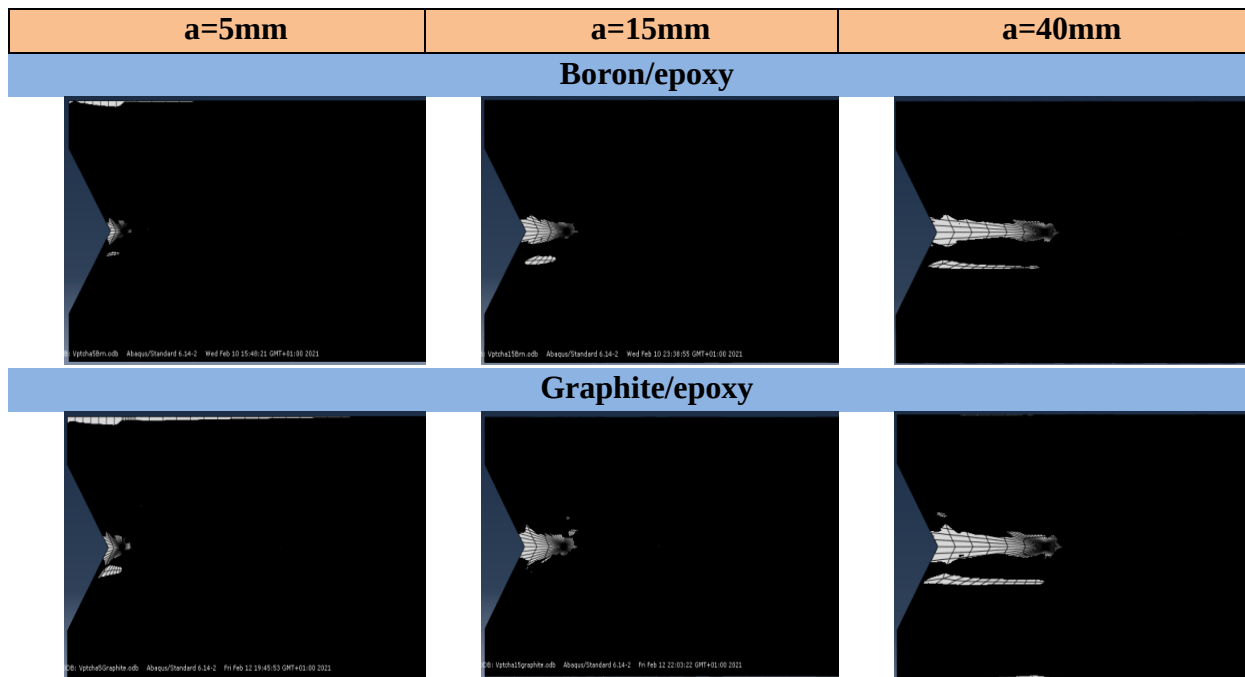


Fig. 9 Damaged area for normal shape of patch (a) =5mm, (b) =15mm and (c) =40 mm.

2- for V- Shape of patch

According to the following figure is shown the evolution of the damaged area of FM73 adhesive for a notched V-shaped plate, cracked of length $a = (5, 15, 40)$ mm of Boron / epoxy and repaired by two types of V shape patch (Boron / epoxy, Graphite / epoxy). It is noticed that the damaged zone increases with the increase in the crack size until it reaches its maximum for $a = 40$ mm at the levels of the crack and the edges of the patch, it is observed that the damage is very apparent for the type Graphite / epoxy patch.

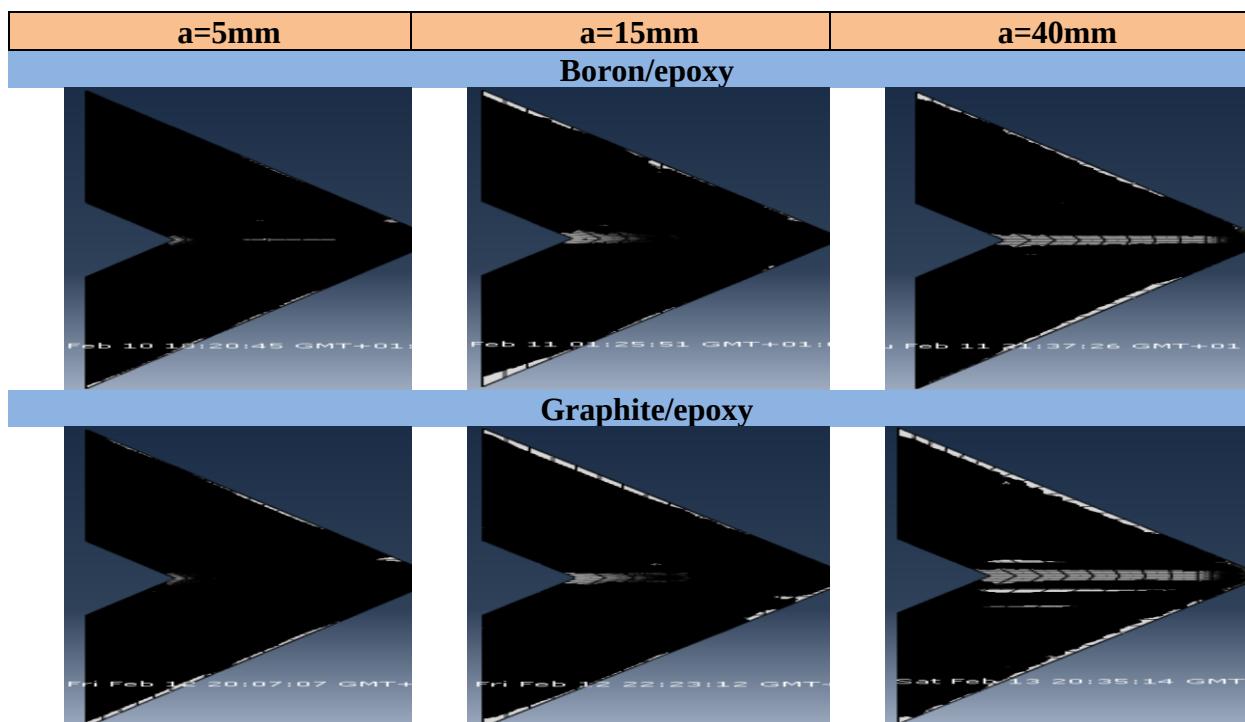


Fig. 10 Damaged area for V-shape of patch (a) =5mm, (b) =15mm and (c) =40 mm.

Effect of crack length on the damaged area ratio

Figure 7 shows the damaged area ratio as a function of the crack length for the different shapes patch (total, normal and V-shaped) for the following composite materials: Boron / epoxy and Graphite / epoxy, for the same adhesive FM73. The results show that the D_R values are all lower than that of the critical D_R value. The crack propagation leads to the increase in D_R ratio, so through comparing the materials used we saw that Boron / epoxy has lower D_R values than the other material (Graphite / epoxy), according to this comparison concluded that Boron / epoxy is the best composite material. We have seen the V-shaped patch the D_R value is greater compared to that of a total patch so it turns out that the total patch is the best because the D_R ratio values obtained by using this form are weaker than other shapes.

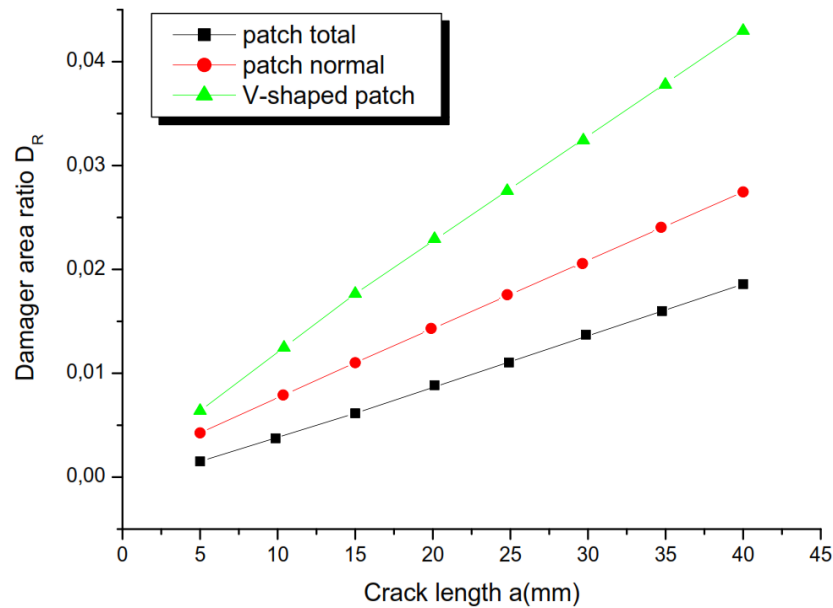


Fig. 10 Damaged area ratio vs crack length for different shapes of patch (boron/epoxy patch).

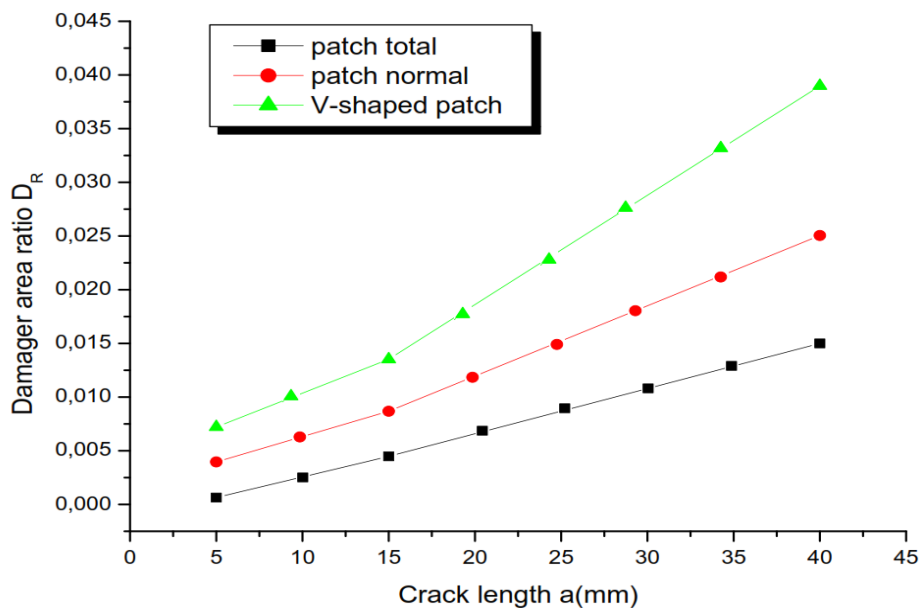


Fig. 11 Damaged area ratio vs crack length for different shapes of patch (graphite/epoxy patch).

II- Expérimental Part

Comparison of ultimate strength of different shapes of patch

This step includes an experimental test supporting the results obtained in the numerical step and specifying which shapes of the patches have a high performance and most resistant to damage for the same model that we used in the simulation part. We have carried three models of a Boron / epoxy plate is damaged by crack of length $a = 15\text{mm}$ repaired by different shapes of the patch (total, normal, V shape) of boron/epoxy type, the fibers are oriented on the direction following ($\theta = 0^\circ$) in the longitudinal direction that is to say parallel to the tensile force, we choose angle 0° because it is the most effective for the applied tensile strength, through this test we obtain results of the different forms of the patch which are indicated in Table 2 which expresses the experimental results of the different forms of the patch and Figure 12 is shown and compared the results obtained by a diagram represents the percentage increase of different forms of patch by compared to the ultimate strength, so we meant for comparison that the total shape having the great value of tensile strength stress and this is what makes it the most suitable and optimal shape for our repair.

Table 2 Experimental results of the different shapes of the patch

	Fiber orientaion (°)	Ultimate strength (MPa)
Full shape Patch	0	360
Normal shape patch	0	305
V-shape patch	0	250
Without patch	0	175

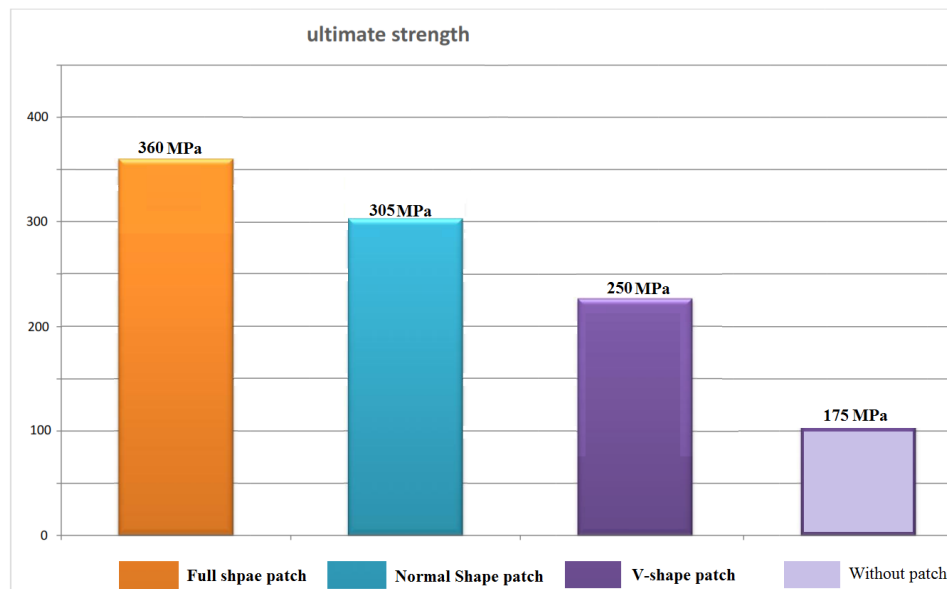


Fig. 12 Comparison of ultimate strength of different shapes of patch.

Repair with single and double boron / epoxy

The boron / epoxy laminate composite specimen $[45 / -45 / 0/90]$ has a V-shaped notch see figure1, repaired by simple is a symmetrical double patch in boron / epoxy of 4 plies $[0]_4$. The plies of the repair composite are oriented along the length of the specimen and in a direction parallel to the loading, the patch being glued to the plate by the adhesive FM73.

The results in Figure 13 clearly show that the double patch has a beneficial effect compared to the single patch. Indeed, the increase in rigidity and tensile strength by the use of the double patch can be estimated at 5% compared to the single patch. The comparison with the unrepaired structure shows the two repair techniques estimated to increase stiffness to 23% and tensile strength to 51%.

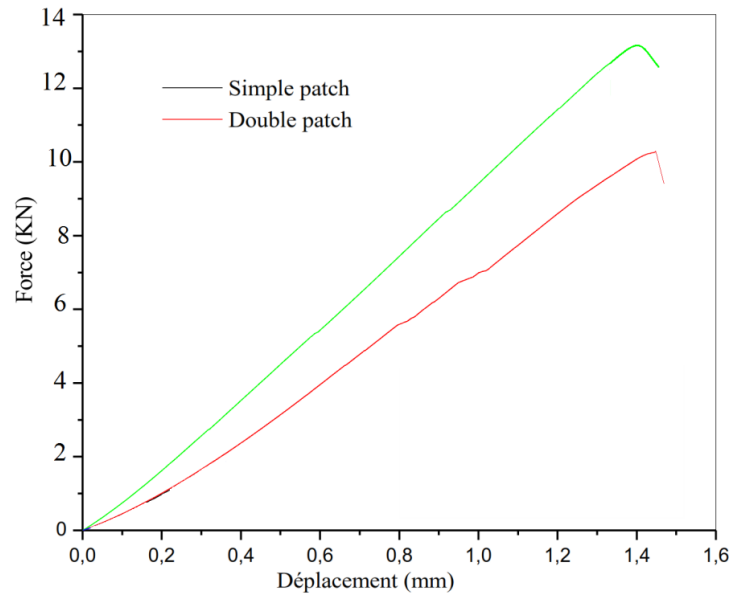


Fig. 13 Repair with single and double boron / epoxy patches.

CONCLUSION

In the current work, we investigated which shapes are most effective in repairing nicked and cracked composite structures, and this study included the experimental and the modeling sides, and it was concluded that:

- the total shape of a fiber orientation of 0° is the best for repairing cracks, as it gives the highest values of ultimate length compared to other types of patches
- the stress intensity factor (K_{IC}), and the damaged area ratio (D_R) increases as the crack length increases relatively.
- the boron / epoxy type patch gives good crack repair results either in relation to the reduction in stress intensity factor or else reduction in the adhesive damaged area ratio.

And as a general conclusion of the experimental and modeling study, was reached that the total patch shape is the optimal shape because it gives us all the lowest values for the stress intensity factor K_{IC} and stress distribution and also gives us in the experimental study the greatest value to support the tensile strength. Hence we consider that the total shape and type Boron / Epoxy is the best choice in the field of repair.

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