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Research Paper

Numerical analysis of the repair performance of Notched Cracked Composite Structure repaired by composite patch

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ABSTRACT

In this article we analytically examined by three-dimensional finite element method the repair performance of a plate made of different composite materials (Boron/epoxy, Graphite/epoxy and Glass/epoxy), notched on V-shape by a composite patch of different shapes (Total, Normal and V-shaped). The damaged area ratio of the adhesive layer, the stress distribution and the stress intensity factor at the crack tip were calculated in order to evaluate the performance of the composite materials in repairing this damage and to determine which shapes and types are most efficient in repair. At the end of the study, the results obtained showed that boron/epoxy is more resistant to fracture than other materials and that the total shape of the composite patch is the good shape for our repair because it gives good performance and is more efficient compared to other shapes (normal, V-shaped).

1 Introduction

In our modern time, the use of composite materials has become more used in the aeronautical, naval, aerospace and other industrial sectors. Because composite materials have great advantages, if they are well designed, they have properties that exceed those of the constituent elements. Among the properties that have been improved by forming composite materials, one can mention: resistance, hardness, resistance to corrosion, lightness and aging resistance. All these properties cannot be improved at the same time, because all these properties can no longer be achieved [1, 2]. Environmental conditions such as humidity and multi-axial mechanical forces are the main causes of aircraft structural damage. These problems limit the life of such structures. To improve the durability of aeronautical structures damaged by cracks, in terms of slowing down or even

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stopping crack propagation and for economic reasons, composite patch repair has proven to be convenient, effective, rapid, and less expensive [3-6].

The composite patch and the adhesive layer have many effective mechanical and geometric parameters which are taken into account in the quality of the repair. As well as, the shapes of the composite patches are a determinant of the effectiveness of the repair. This has become the goal of many researchers among them: Berrahou et al [7-9], Bouchiba et al [10], Benkheira [11], and Salem et al [12] developed a static approach to optimize the shape of the composite patch. They concluded that the shape reduces fracture energy at the crack tip and minimizes shear stresses in the adhesive layer. M'hamdia et al [13], by designing a new shape of patch, called double arrow patch, show that compared to the conventional rectangular shape, this shape gives rise to a more efficient and more effective repair in terms of reducing normal tensile stresses very concentrated at the crack tip.

Many articles have been published on the theory of damaged areas to analyze the performance of the repair of damaged structures. Bouanani [14] estimated adhesive damage and failure in bonded composite repair using modified damage zone theory. Berrahou [15-17] evaluated the damaged area of the adhesive then compared the results for the different shapes of the patch (rectangular, trapezoidal, circular and ellipsoidal), it was concluded that the patch is rectangular in shape and offers high security to reduce the risk of adhesive failure. In the literature, the stress distribution around a circular and elliptical hole in the composite plates has been studied by several researchers [18-20], who show that there is no exact analytical solution for this case, and all solutions are approximate or empirical solutions.

During the library study, we found many current studies that dealt with the subject of studying the behavior of notched plates, whether experimental studies or numerical modeling studies. Among these studies, T. M. Andrus and G. B. Sinclair [21] did research on V-notch stresses as notch-tip radii decrease using finite element analysis where the results showed that only for very small notch-tip radii do peak stresses with cohesive stresses active differ significantly from peak stresses with classical boundary conditions. Sawale et al. [22] did an experimental analysis of the stress concentration on the v-notched plate, in this study, the experimental and FEM is applied out to find stress concentration factor considering an aluminium plate with v-notch and the final point where been similar with data. In addition to Vimal Kannan and Babulal [23], their work was in a Comparative Study of Stress Analysis on Notched Plates between Analytical and Finite Element Solutions, Yong Liu et al. [24] have been their work on predicting the fatigue limit of notched plates using an effective zero-point notch stress method.

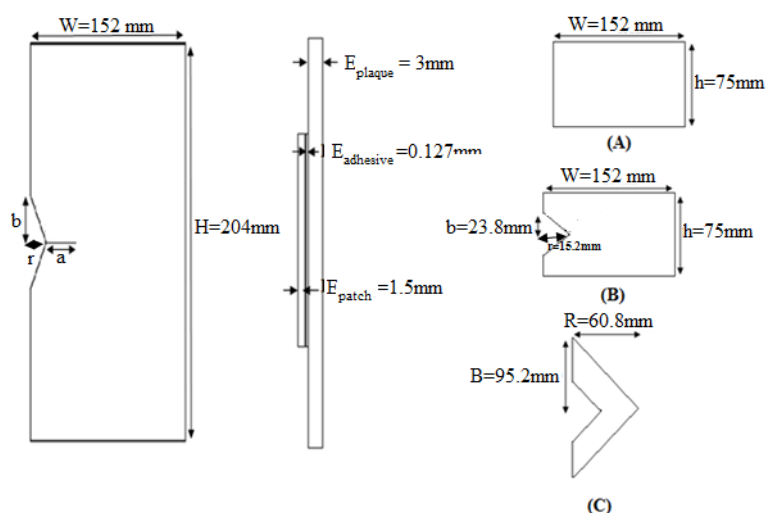


Fig. 1 – Geometric model of structure and (total, normal and V) patch shape.

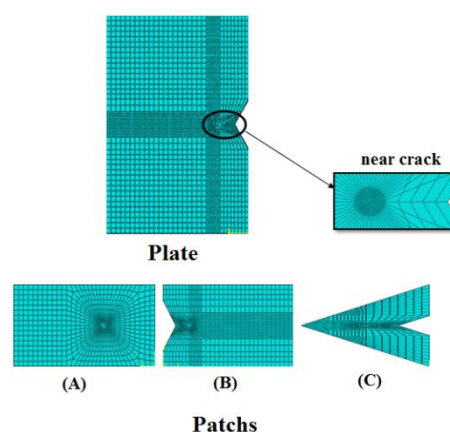


Fig. 2 – Patch and plate mesh.

This work aims to study the repair of composite plates using the technology of composite materials. In this work, we performed a numerical analysis using the limited three-dimensional finite element method (FEM) to repair notched plates with a horizontal crack at the tip of the V-shaped notch of composite materials (boron/epoxy, graphite/epoxy and glass/epoxy)

by means of boron/epoxy composite patch. After comparing the obtained results, we concluded which types and shapes are optimal for the composite materials used in manufacturing.

2 Geometrical and materials models

We consider a notched and cracked rectangular plate made of various types of composite materials (Boron/epoxy, graphite/epoxy, glass/epoxy) with the following dimensions: (height $H_{pl}=204\text{mm}$, width $W_{pl}=152\text{mm}$ and thickness $e_{pl}=3\text{mm}$) containing a V-shaped cut having the following dimensions: ($r=15.2\text{mm}$, $b=23.8\text{mm}$). The plate was repaired with a simple composite patch (Boron/epoxy) of constant thickness $e_{pat}=1.5\text{mm}$. In order to analyze the effect of patch shape, three patch geometries were chosen in this study: (A) total, (B) normal and (C) V-shaped, this patches and model of the structure shown in Figure 1. The patch is glued with 0.127 mm thick adhesive. The structure composed of the plate is stressed by uniaxial traction $\sigma=120\text{ MPa}$.

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

Table 1- Mechanical properties of different materials [22]

Description	Boron/epoxy	Graphite/epoxy	Glass/epoxy	Adhesive(FM73)
Young's modulus in X direction (GPa)	200	127.5	50	2.550
Young's modulus in Y direction (GPa)	19.6	9.00	25	
Young's modulus in Z direction (GPa)	19.6	4.80	25	
Poisson's Ratio in X-Y plan	0.3	0.342	0.21	0.32
Poisson's Ratio in X-Z plan	0.28	0.342	0.21	
Poisson's Ratio in Y-Z plan	0.28	0.38	0.21	
Shear modulus in X-Y plan (GPa)	7.2	4.8	7.2	
Shear modulus in X-Z plan (GPa)	5.5	4.8	5.5	
Shear modulus in Y-Z plan (GPa)	5.5	2.55	5.5	

3 Finite element model

The analysis involves a three-dimensional finite element method using the finite element code ABAQUS [25]. The finite element model is composed of three subsections for a cracked composite plate with a V-shaped notch, the adhesive, and the composite part (patch). The plate has two layers of elements in the thickness direction, the patch and the 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 is 68829. The size of the side of an element equal to 0.016 mm for the whole structure and 0.004 mm in the vicinity of the notch, the notched plate and the patch as well as the adhesive have a linear elastic behavior. This mesh of the notched and cracked specimen repaired with different shapes of the patches used for the three-dimensional numerical analysis is shown on the figure 2.

4 Results and discussion

In this article, the application of the global approach consisting of two parameters is presented: the adhesive-affected area ratio, the stress-intensity factor and von Mises stress allowing prediction of the service life of the repaired composite lamina by FRPC technique.

For this, a numerical calculation is made by looking at a plate made of notched composite materials in the shape of V, which has a crack at the notch tip subjected to a tensile force. Numerical modeling of the cracked structure allows, on the one hand, characterizing the singularity of the stress field at the front of the crack. On the other hand, this parameter controls the cracking which also makes it possible to predict the crack development up to the failure of the structure and the development of the damaged adhesive region.

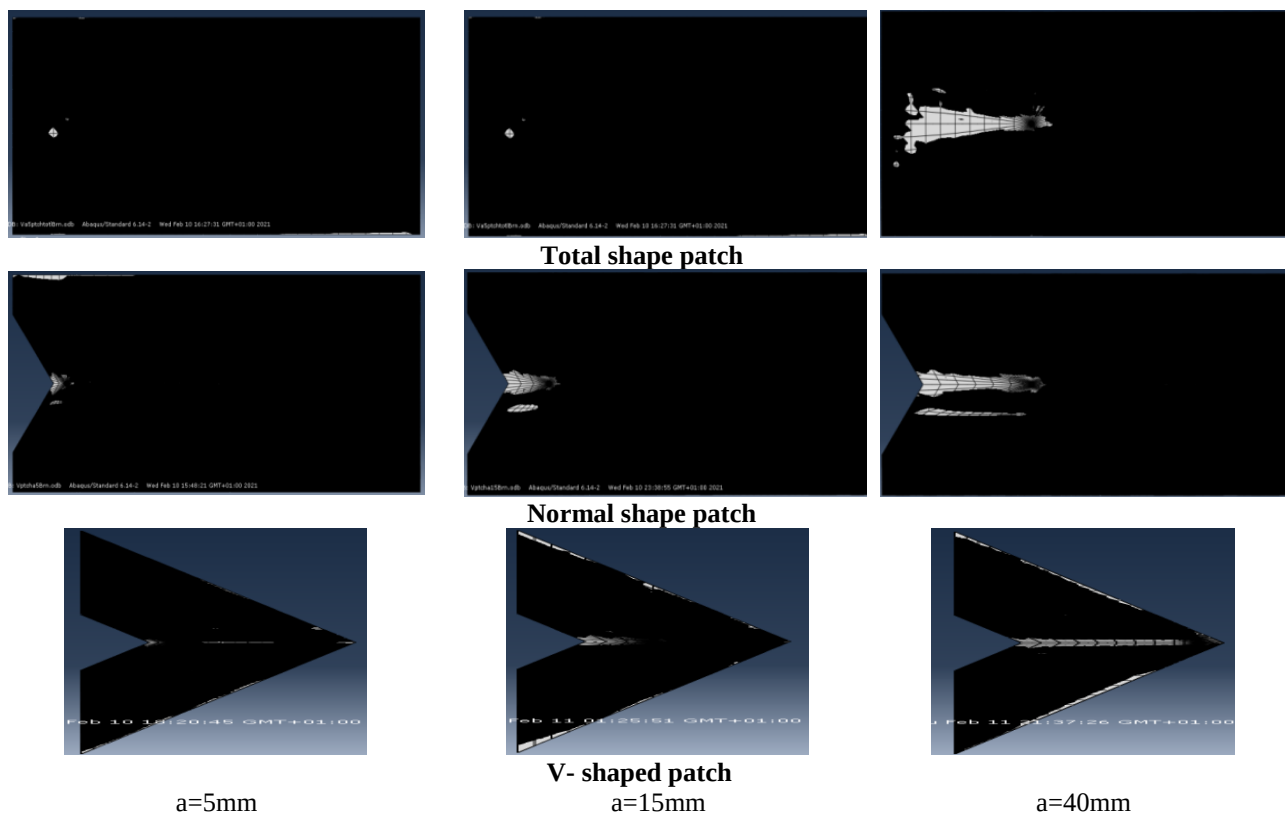


Fig. 3 – Damaged area of FM73 adhesive for different shapes composite patches (Total, Normal, and V-shaped) for Boron/epoxy plate.

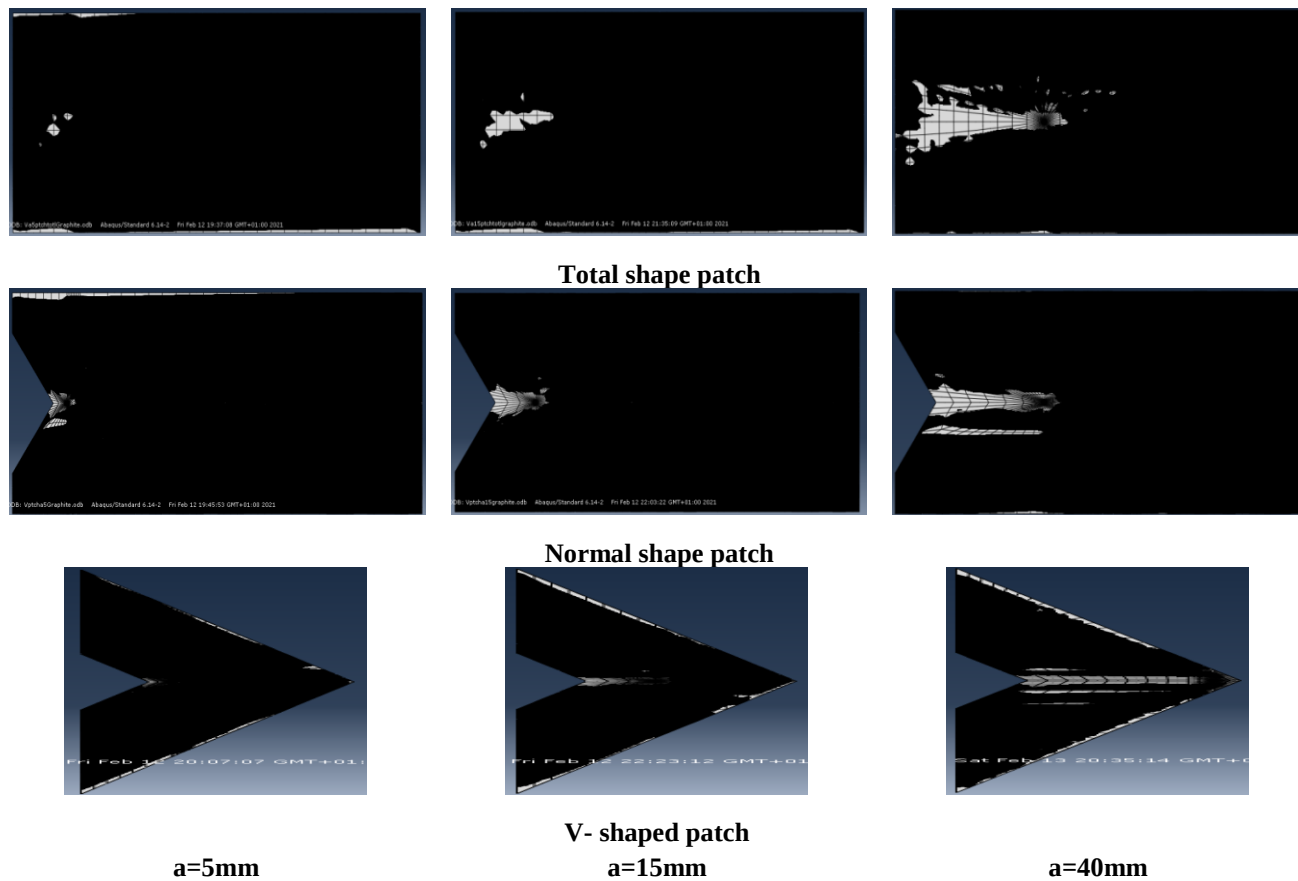


Fig. 4 – Damaged area of FM73 adhesive for different shapes composite patches (Total, Normal, V-shaped) for Graphite/epoxy plate.

4.1 Variation of the damaged zone of adhesive for different type's plates

We have established this part at the end of recovery of the evolution of the damaged zone in the adhesive layer in FM73 within a V-shaped notched plate in different types of composite materials (Boron / epoxy, Glass / epoxy and Graphite / epoxy) with a longitudinal crack a (mm) repaired with a composite patch (Boron/epoxy) of geometric shape (total, normal, V-shaped). The damaged area theory was used. The failure criterion is determined for each stress exerted when it reaches the maximum stress allowed in the material, the area of damage will be determined as the area where the stress of the FM-73 adhesive exceeds 7.87% of the area of damage. Shang Bang after having carried out studies on the FM-73 that the latter no longer provides an adequate function of binder when the value of the D_R ratio exceeds 0.24 which considers it as a critical value [25]. The value of the damaged area ratio is calculated according to the following relationship:

$$D_R = \text{sum of damaged areas} / \text{total adhesive area} \quad (1)$$

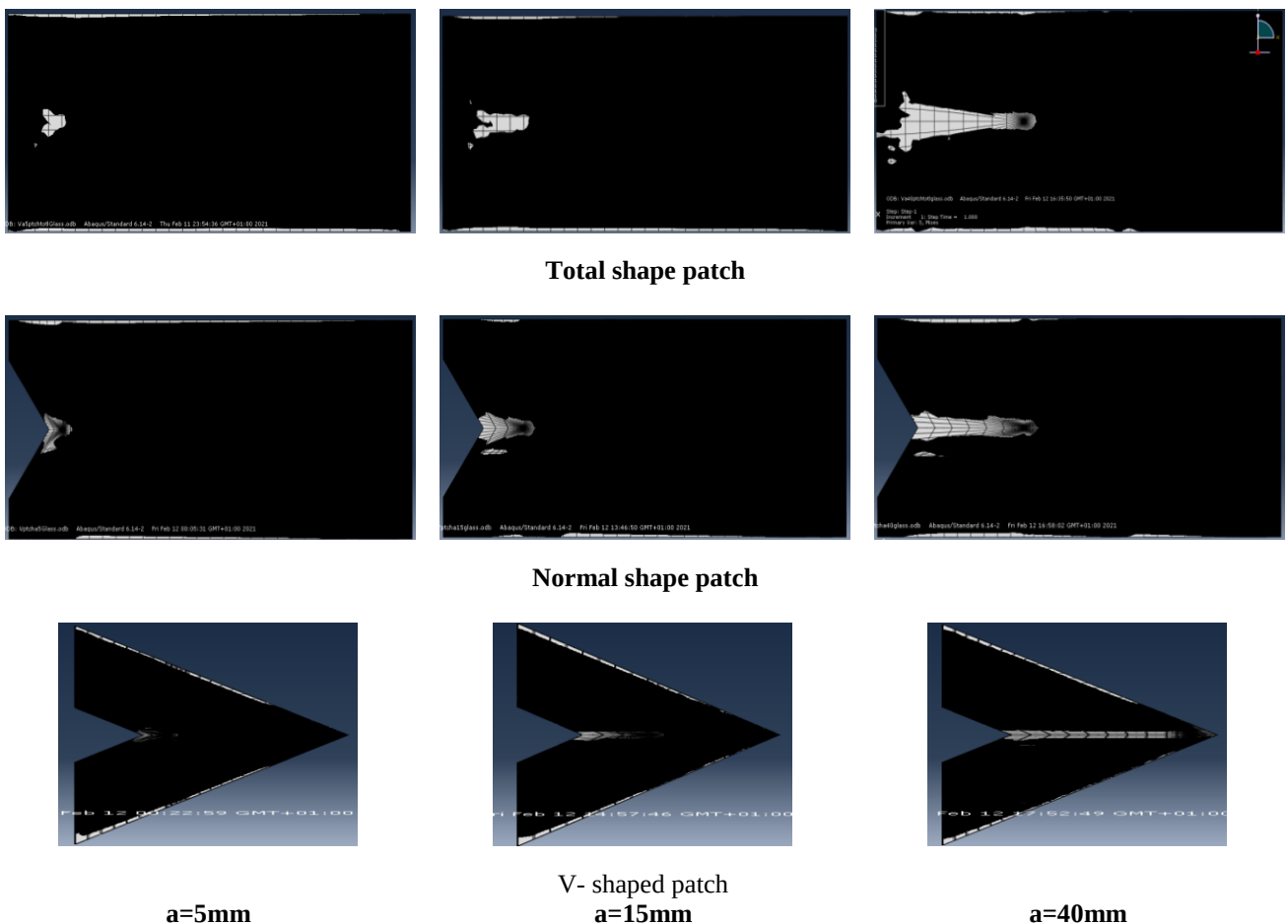


Fig. 5 – Damaged area of FM73 adhesive for different shapes composite patches (Total, Normal, V-shaped) for Glass/epoxy plate.

4.1.1 Boron/epoxy plate

Figure 3 represents the results obtained which make it possible to follow the development of the damaged area of the adhesive for a notched and cracked boron/epoxy laminate that was repaired by the same boron/epoxy composite and in different shapes (Total, Normal and V-shape). After observing the development of the damaged area of the adhesive, it can be said that the damaged area increases with the increase in the crack size, so that it appears very small around the crack tip at the crack length $a=5$ mm and then increases to reach its maximum at the crack length $a=40$ mm. It can also be noted that the patch V-shape is the most affected compared to other shapes.

4.1.2 Graphite/epoxy plate

Figure 4 shows the development of the damaged area of the adhesive for a graphite/epoxy cracked plate notched in V-shaped and of different crack lengths (5, 15, 40), that were repaired with a composite patch of different type (boron/epoxy) and of different shapes. We note through these figures that the appearance of the damaged area increases according to the size of the crack, and this increase appears in the crack vicinity and at the edges of the patch.

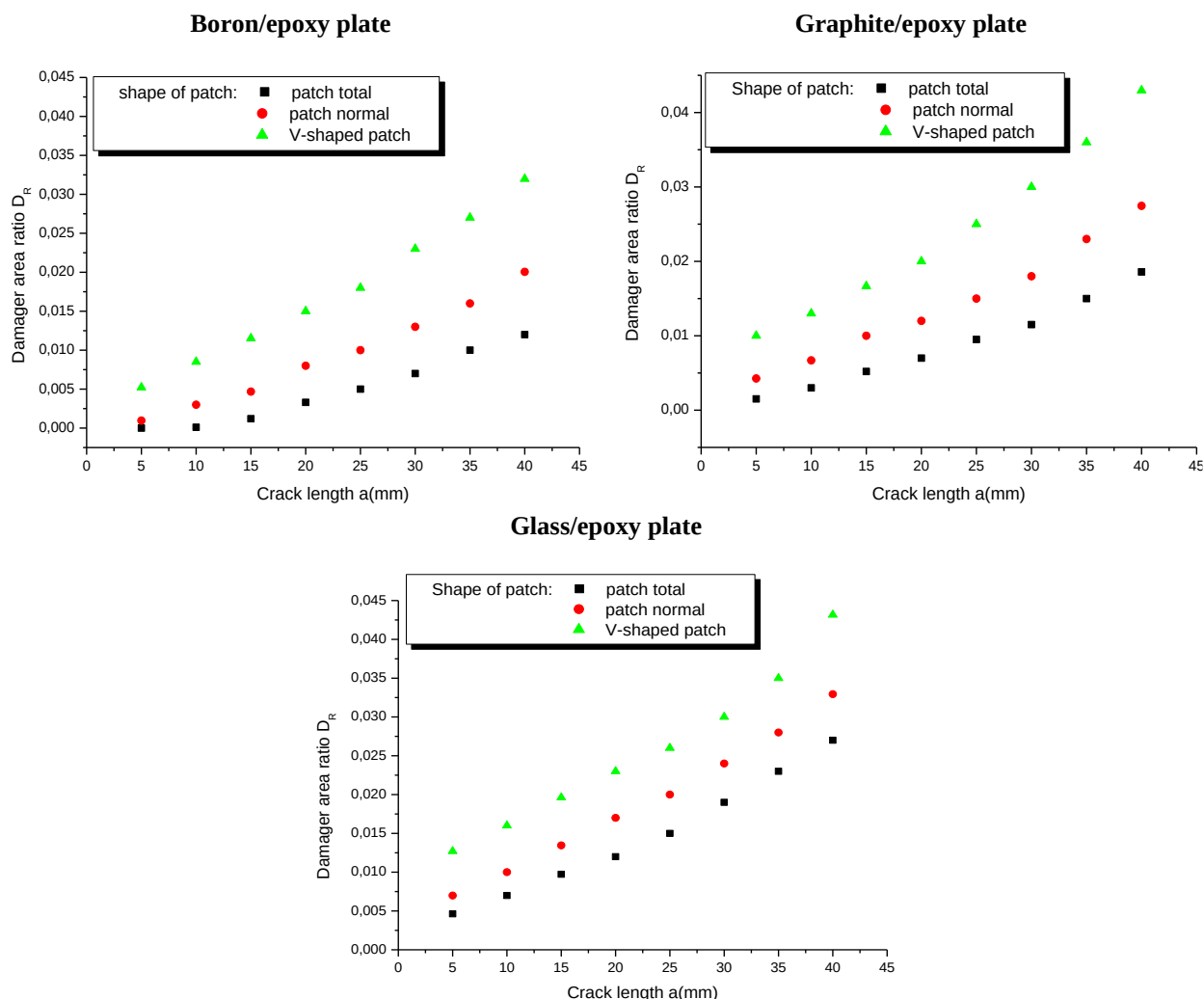


Fig. 6 – Damaged area ratio D_R for a plate of (Boron/epoxy, Graphite/epoxy and Glass/epoxy) repaired by different shapes composite patch.

4.1.3 Glass/epoxy plate

Figure 5 shows the results obtained for the differences in the damaged area of the adhesive for a cracked and notched glass/epoxy type plate with a slit length of $A = (5, 15, 40)$ mm that was repaired by patch of boron/epoxy shaped (total, plain and V shaped). It is noted that the damaged area increases with the increase in the crack size until it reaches its maximum at $a=40$ mm, and that this damaged area is at the level of the crack and at the edges of the patch for all forms of the patch.

4.2 Effect of crack length on damaged area ratio

Figure 6 represents the variance in the damaged area ratio (D_R) of the FM73 adhesive according to the crack size of notched and cracked plate made of several composite materials (boron/epoxy, graphite/epoxy and glass/epoxy), repaired by composite patch technique of Boron/epoxy with different geometric shapes (Total, normal and V-shape). The results show that all D_R values are less than the critical D_{RC} value (0.2474), which means that the patch has played its role in protecting the plate and absorbing the stress from the adhesive layer and protecting it from damage. According to the curves below, it

is noticed that the cracks propagation and their increasing size leads to an increase in the D_R ratio, as noted after comparing the results of the composite materials used, we saw that boron / epoxy is the most efficient compound because it gives lower D_R values compared to other materials. We also found that the D_R values of the V-shape are larger compared to the total patch or the normal patch, so it can be concluded that the total correction is better because the D_R values obtained using this shape are weaker than the other shapes.

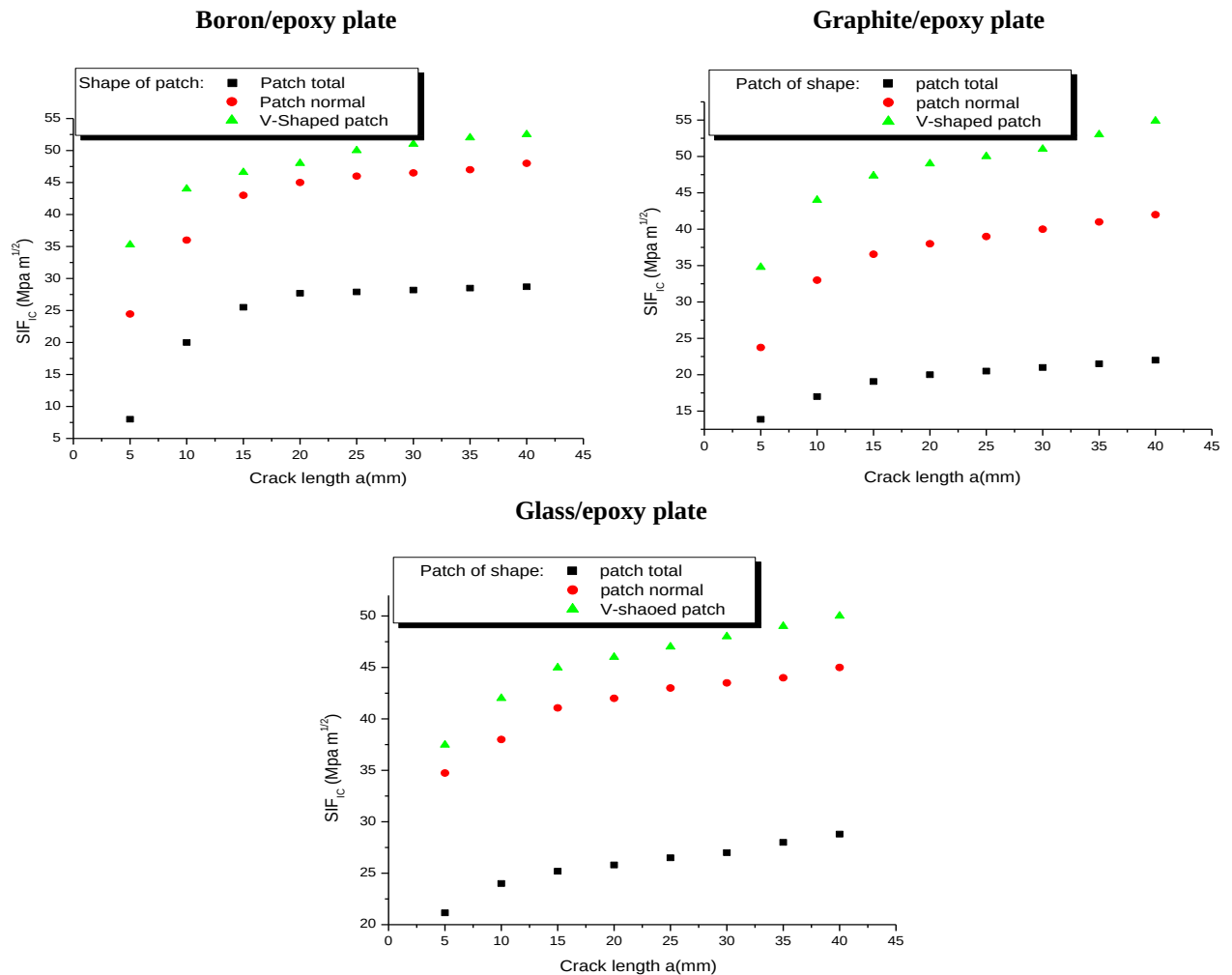


Fig. 7 – Stress intensity factor (SIF) for a plate of (Boron/epoxy, Graphite/epoxy and Glass/epoxy) repaired by different shapes composite patch.

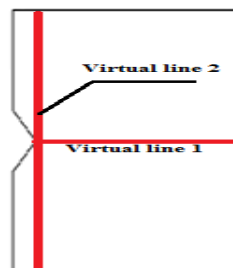


Fig. 8 – Virtual line (path1 and path2).

4.3 Effect of crack length on stress intensity factor variation

With respect to Figure 7, it represents the variance of stress intensity factor SIF according to the crack size of different composite materials (boron/epoxy, graphite/epoxy and glass/epoxy) of cracked and notched plate, and repaired with boron/epoxy composite material with different geometric shapes (Total, regular and V-shaped) of the same FM73 adhesive.

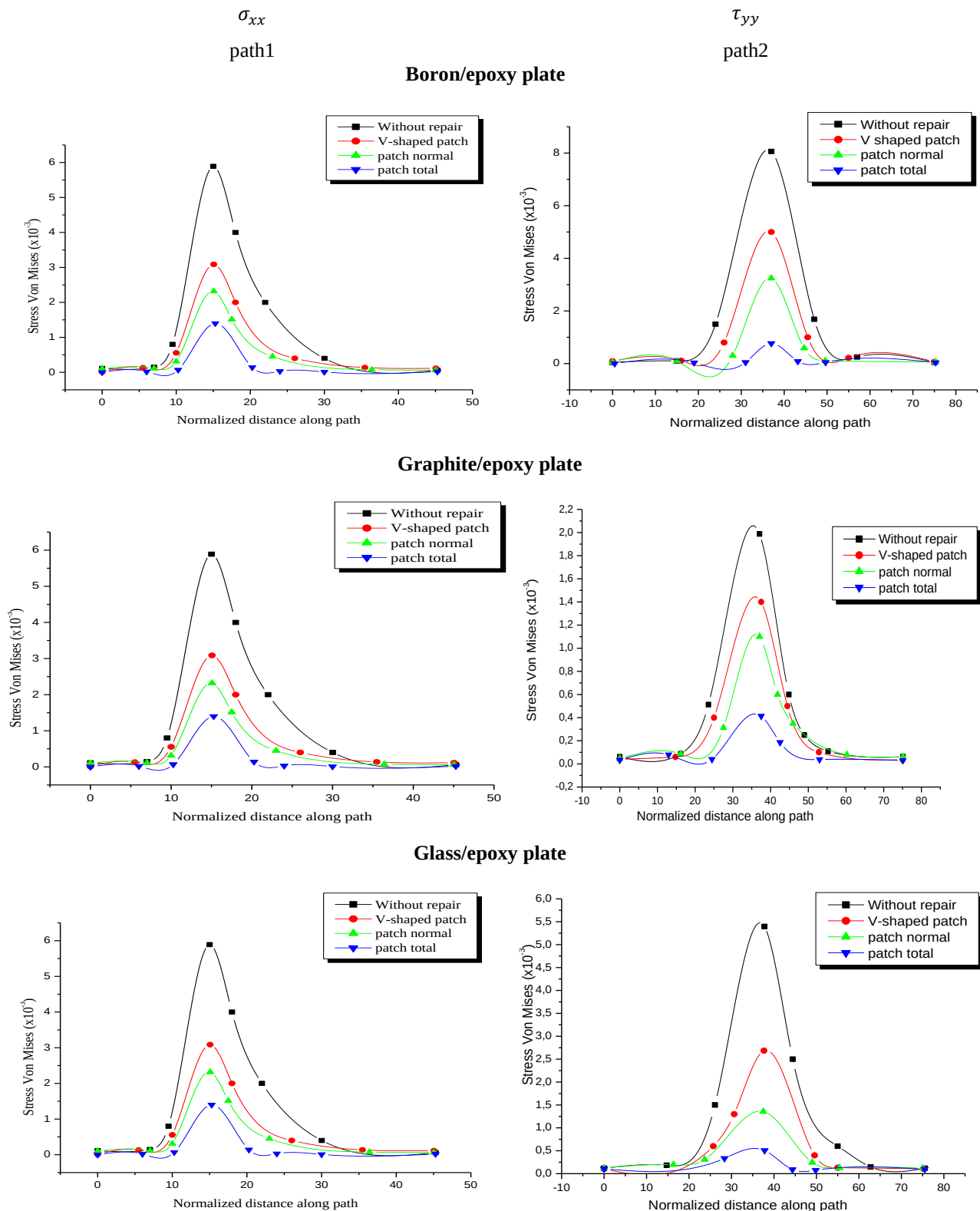


Fig. 9 – Distribution of Von Mises stress according to plate type.

From the obtained results, it was observed that there is a direct relationship between the stress intensity factor and the crack length, so that the greater the cracks size the higher the SIF values as well, whatever the type of plate. By comparing the composite materials used to repair damage, we see that boron / epoxy is the optimal and most efficient compared to graphite / epoxy and glass / epoxy, because its SIF values are the lowest compared to the SIF values of other composite

materials. It turns out that the total shape is the most effective because it gives lower SIF values than the other two shapes (normal and V- shape).

4.4 Von Mises stress distribution according to plate types

Figure 9 represents the distribution of Von Mises stress (σ_{xx} , τ_{yy}) according to virtual line 1 and 2 shown in Figure 7, for a plate made of various composite materials (boron/epoxy, graphite/epoxy and glass/epoxy) cracked and notched for V-shaped, fixed with Different shapes patch by FM73 adhesive (Total, normal and V-shaped) of boron/epoxy type patch and without repair. In general, the stress distribution of the cracked plate, which is repaired and unrepaired, is concentrated at the crack tip and found to be too high for the unrepaired plate, this is shown by the results obtained in figure 8, and we also note that the further away from the crack tip, the less the stress distribution becomes Focused. Regardless of the type of composite material used the shape of the repair patch or without repair. We note that the total shape of the composite material is more efficient because it has the lowest values of σ_{xx} and τ_{yy} than other forms of correction.

5 Conclusion

This work includes a numerical analytical study of the repair efficiency of cracked and V-grooved composite materials plates using composite technology. The objective of this article is to calculate the damaged area ratio D_R , determine the stress-intensity factor SIF and the distribution of Von mises stresses and then compare the results for different types of composite materials (boron/epoxy, graphite/epoxy and glass/epoxy), repaired by a (boron/epoxy) composite patch of Boron/epoxy, have various geometric shapes (total, normal and V-shaped). The results were obtained using the finite element method, this work allowed us to draw the following conclusions:

An increase in the crack size leads to an increase in the percentage of the damaged area ratio D_R .

The stress intensity factor is increased by crack propagation.

The stress distribution is high at the crack tip.

The performance of all shapes patch (Total, normal and V-shaped) was perfect because they did not allow access to the critical damaged area ratio D_{RC} (0.2474), but the Total shape can be said to be the best because it gives lower D_R values compared to the other shapes.

Through the results obtained in our analytical study, the most efficient composite material is boron / epoxy because it gives low values of either D_R or SIF or Von Mises stresses.

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