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Research Paper

Effect of Patch Shape on the Repair Efficiency of a Cracked Aluminum Panel

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ABSTRACT

A 3-D finite element analysis was conducted on a thin aluminum plate with a 45 ° inclined central crack. A modeling of the bonding repair with composite patch of different shapes was carried out. In addition to the patch shapes studied in the literature, a new butterfly shape was proposed. The latter is defined by a length H, a width B and a neck C in the middle. The main objective is to analyze the effect of patch geometry on the rate of decrease of stress intensity factors. This rate is characterized by a coefficient R which combines between the mode I and the mode II of the rupture (KI and KII). Thus, an optimization of the patch shape is made with respect to the effectiveness in decreasing the stress intensity factor. The comparison between the results obtained with the different patch shapes has shown that the butterfly-shaped patch is more effective for relatively small surfaces. On the other hand, the extended octagon shape has been shown to be more effective for higher patch surfaces.

1 Introduction

Among the methods of repairing damaged structures, bonding a composite patch is currently the most used. In particular, composite patch repair has shown its effectiveness in the field of aeronautics and maritime structures [1]. According to research, most studies address the problem of shape optimization, i.e. the surface and the thickness of the patch [2-8]. Without omitting the effect of the parameters related to the adhesive such as the thickness and the type of the glue that have provoked several searches as for example in [9-11]. The technique of bonding a composite patch in a cracked structure was initially developed by Allan Baker in the late 1970s. This technique appeared to be an advantageous alternative to the more conventional techniques of repair, by riveting or welding structures metallic. Indeed, the bonding of a composite patch to the damaged structure significantly reduces the stress field on the damaged area. That leads to improve the structural strength and the extension of the lifetime of the structure under stress [12-13], without introducing a

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new hole or changing the microstructure of the material. In fact, there are two patch repair techniques, namely, simple patch repair [14] (asymmetric repair) and double side patch repair (symmetric repair) [12]. Generally, it is the double patch that is preferable, because of the deflection effects that the simple patch introduces into the charged structure [15].

Regardless of the type of repair (symmetrical or asymmetrical), parameters such as thickness, surface area, number of layers, fiber orientation and patch shape remain the most studied for their interdependent influence on repair efficiency. Indeed, Bachir et al concluded in [6] that a trapezoidal form is more powerful than a rectangular form. In the same context, Ramji et al carried out a comparative study in [12]. These authors studied several forms of patch and concluded that an extended octagonal patch has better performance for stress intensity factor reduction. For the number of layer and the thickness of the patch, Hosseini et al in [16] concluded that the performance of the patch is proportionally improved by increasing the number of layers and reducing the thickness of the plate. Furthermore, [17] established that increasing the life of the repaired plate is related to increasing the thickness of the patch. Also, for the type of composite used in the repair, Hosseini et al in [18] found that, for a 45 ° inclined crack in a thick aluminum panel repaired by an asymmetric glass / epoxy patch, the lifetime during the crack propagation is significantly improved.

The aim of this work is to analyze numerically the variations of the stress intensity factor of the model studied in [12] for different forms of patch, namely: circular, rectangular, elliptic square and extended octagonal. Next, it is proposed to model a form of butterfly patch and to study the effect of its geometric parameters on the decrease of the intensity of the stresses. On the basis of this second modeling, a comparison with the other forms will be made.

2 Geometries and mechanical properties of the model

The damaged structure is shown in Figure 1. This model is adapted from that proposed in [12]. The aluminum alloy plate 2014-T6 has dimensions 160 x 90 x 3.175 mm3 (Figure 1). It contains a central crack 2a = 10 mm. This latter is inclined by β = 45 ° with respect to the transverse axis of the plate.

The numerical model was developed on the basis of the model studied by M.Ramji in [12]. As presented in fig. 1, the aluminum plate contains an inclined central crack symmetrically repaired by a composite patch (carbon / epoxy) in the shape of 25×25 mm2 square. The objective is to analyze numerically the variations of the stress intensity factor of this model for different forms of patch: circular, rectangular, square, elliptic vertical and extended octagonal (see Figures 2a-2e).

Next, we propose to model a form of butterfly patch and to study the effect of its geometric parameters on the decrease of the intensity factor of the stresses (Figure 3). A comparison with the other forms will be made.

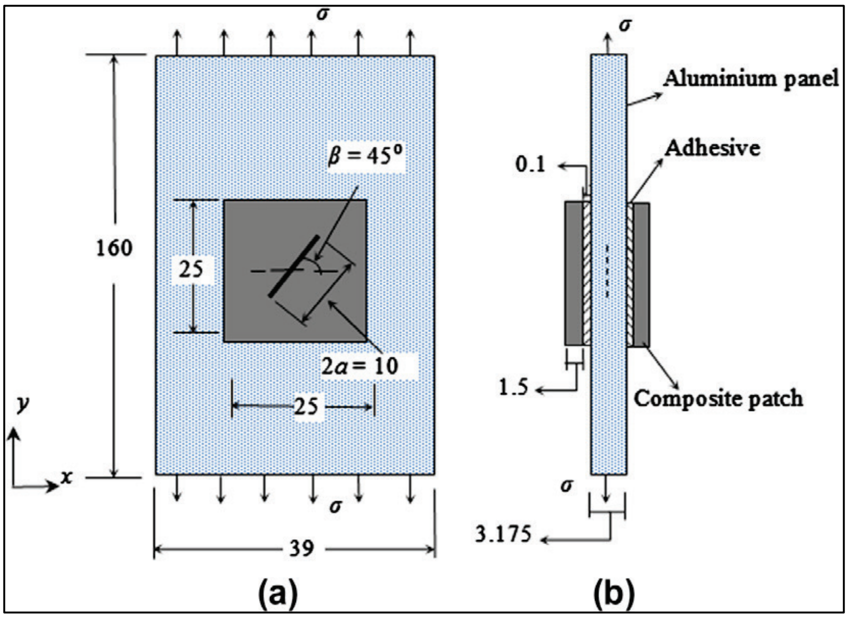

Fig. 1 – The geometry of the studied model adapted from [12], (Dimensions are in mm)

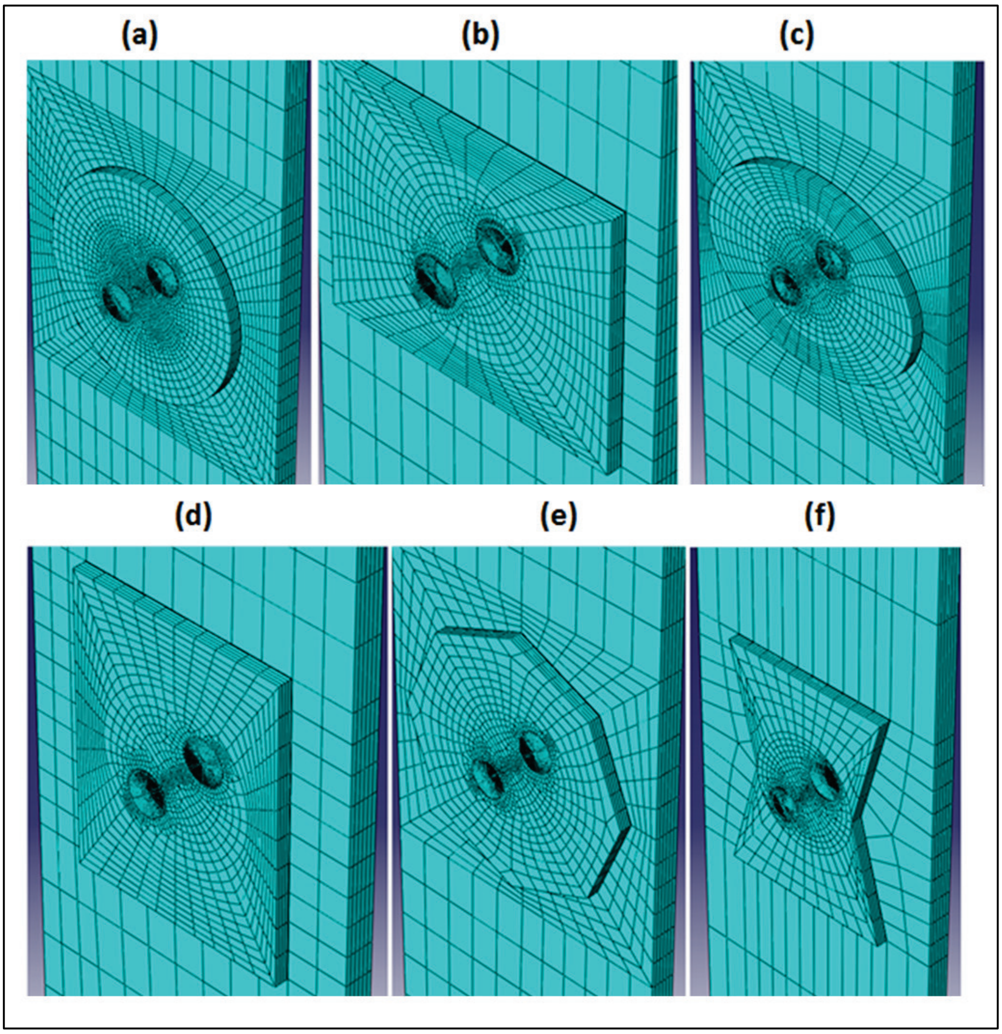

Fig. 2 – Different patch shapes: a) Circular, b) Rectangular, c) Elliptic, d) square, e) Octagonal and f) Butterfly shape

Mechanical properties of the plate, the composite patch and the adhesive are regrouped in table 1.

Table 1 - Mechanical properties of the plate, the patch and the adhesive

Materials	**E_x (GPa)**	**E_y, E_z (GPa)**	**υ_{xy} , υ_{xz}**	**υ_{yz}**	**G_{xy} , G_{xz} (GPa)**	**G_{yz} (GPa)**
Aluminum alloy (2014-T6)	73.1	-	0.3	-	-	-
Adhesive (AV138/HV998)	4.59	-	0.47	-	-	-
Carbon/epoxy	135	9	0.3	0.02	5	8

3 Geometry of the Proposed Butterfly-Shaped Patch

Figure 3 shows the geometry of the patch used for the repair. It should be noted that there are two possible configurations for this study. The first configuration is that of a vertical butterfly patch (B perpendicular to the applied load direction: Figure 4.a) and horizontal (B parallel to the applied load direction: Figure 4.b) with C and B equal to 16 and 25 mm respectively and H equals 26, 28, 30 and 32 mm which corresponds to the surfaces 533, 574, 615and 656 mm², respectively.

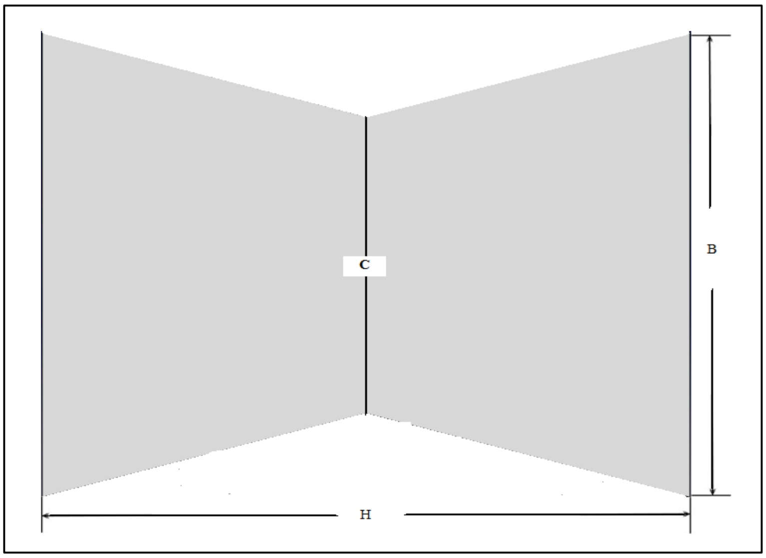

Fig. 3 – The geometry of the butterfly-shaped patch

4 Numerical modeling and boundary conditions

The model was solicited by applying a uni-axial load to the upper edge in the y-direction with a lower edge embedding. So, the plate is subjected to a tensile load of 15 KN (σ = 121.11 MPa).

The analysis was carried out using Abaqus 6.9 software. A three-dimensional finite element method with automatic meshing was carried out on the structure using 8-nodes brick elements. A refinement of the mesh was created in the vicinity of the crack tips as shown in figures 4. As the studied case presents an inclined crack, then the mode of opening and sliding in the plane of the crack are simultaneously present which leads to mode I and mode II of fracture. For reasons of non-symmetry, the whole structure must be modelled.

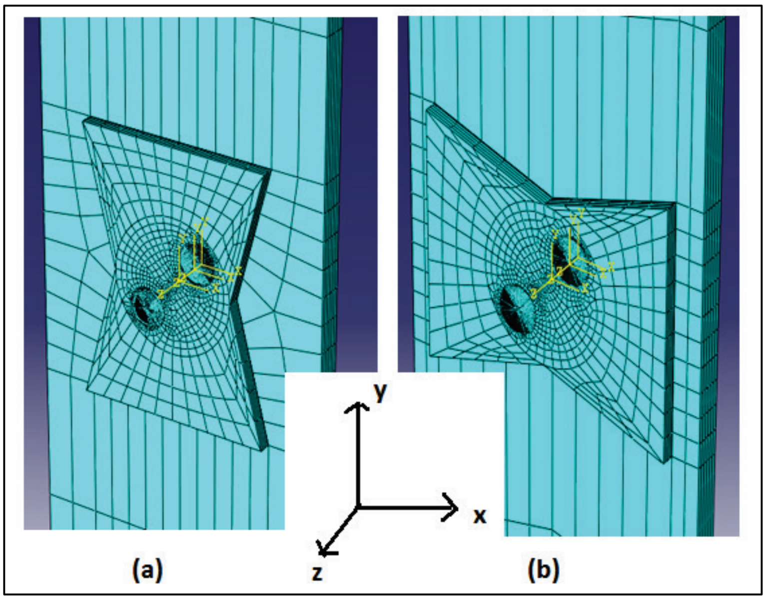

Fig. 4 – The two studied configuration of the proposed composite butterfly-shaped patch: a) the FE model of the vertical configuration and b) the FE model of the horizontal configuration

A validation of our model is presented in Figures 5.a and 5.b, where a comparison with the results of M. Ramji et all [12] is made. Figures 5.a and 5.b show a comparison of the distribution of KI and KII respectively. It can be seen from the figures that present results are in good agreement with the literature. Figure 4 gives the distribution of stress intensity factors (SIF) along the thickness of the cracked plate before repair.

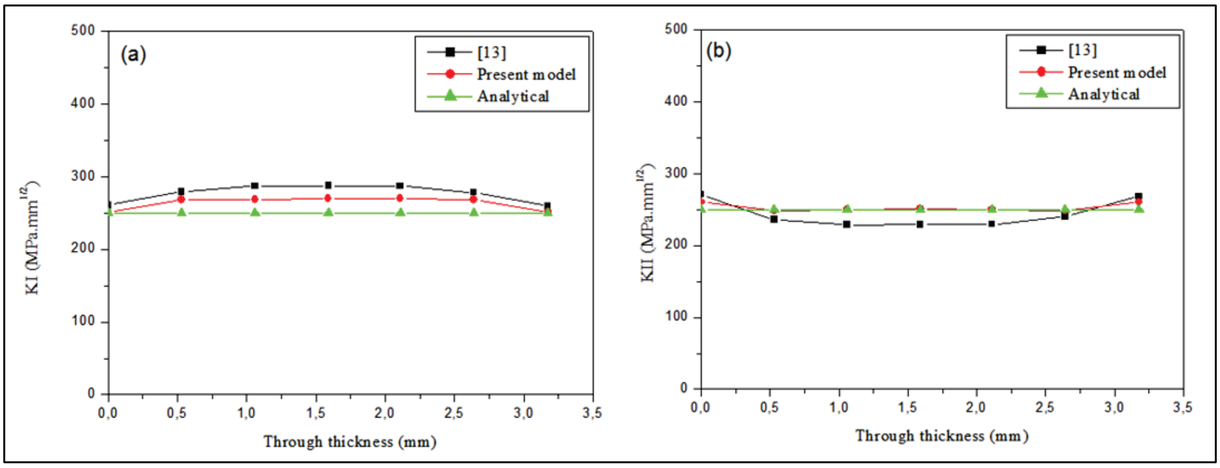

Fig. 5 – Comparison of the obtained Stress Intensity Factor (SIF) results with the literature and the theoretical results: a) variation of KI and b) variation of KII through the thickness of the plate

5 Results and discussion

5.1 Proposed Butterfly-shaped patch

To evaluate the effectiveness of a patch repair for a cracked plate in mixed mode, it is used the parameter R which is given by the following expression [19]:

$$R = \sqrt{\left[\left(\frac{K_I^U - K_I^R}{K_I^U}\right)^2 + \left(\frac{K_{II}^U - K_{II}^R}{K_{II}^U}\right)^2\right]} \quad (1)$$

Where K_I^U and K_{II}^U represent the Mode I and Mode II stress intensity factors for the unrepaired plate and K_I^R and K_{II}^R represent the Mode I and the Mode II stress intensity factors for the repaired plate.

Equation 1 combines between modes I and II and gives an estimate of the patch repair performance by a single parameter R which is taken as an indicator of the efficiency of the patch shape. Thus, the repair is as efficient as the parameter R is higher.

The different results obtained for the stress intensity factors KI and KII as a function of the length H of the patch are given in figures 6.a and 6.b. Also, the factor R which combines between the two modes of rupture is presented in Figure 6.c.

Figure 6.a shows that the horizontal patch reduces better the KI stress intensity factor. Indeed, for the latter, the mode I stress intensity factors are lower than those obtained by the vertical position of the patch. This is valid for all lengths of the patch. Inversely, the vertical patch is more efficient for the reduction of the stress intensity factors KII. Figure 6.b clearly shows that the KII values are lower and decrease with H in the case of a vertical patch. In any case, by combining the two modes of rupture by R indicator, it can be seen from figure 6.c that the repair by a vertical position of the patch is more efficient than the horizontal position. Effectively, R values obtained by vertical patch position are higher than those obtained by horizontal position of the patch. Furthermore, figure 6.c shows that patch performance increases with length H for both configurations.

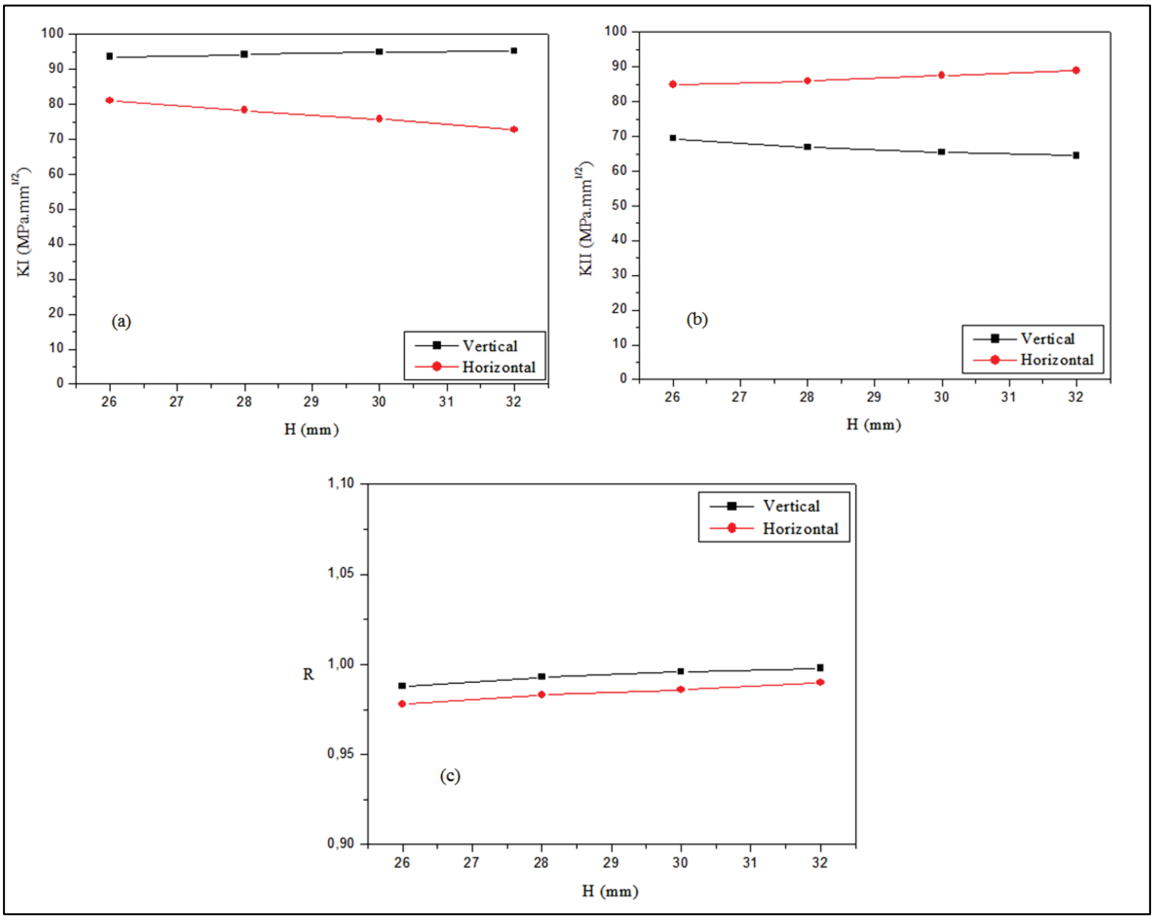

Fig. 6 – SIF and R factor variations versus the butterfly-shaped patch lengths H a) KI variation for horizontal and vertical configuration b) KII variation for horizontal and vertical configuration and c) R performance factor for horizontal and vertical configuration

5.2 Comparison between the different patch shapes

For this comparative analysis of the butterfly shape with the forms studied in the literature and for comparison convenience, the dimensions of the butterfly patch were chosen to coincide with surfaces 616, 706 and 804 mm^2 as available in [12]. Table 2 resumes the different dimensions for mentioned surfaces.

Table 2 – The butterfly-patch dimensions for comparison analysis

Patch surface (mm²)	B	C	H
616	24	17.06	30
706	25	19.125	32
804	26	19.943	35

As mentioned in section 2, the studied shapes are Circular, Rectangular, Square, Vertical Elliptic and Extended Octagonal (Fig. 2). The objective is to verify the performance of the proposed butterfly patch for reducing the stress intensity factors in mixed mode. The comparison is made for different patch surfaces, namely 616, 706 and 804 mm^2. The thickness of the patch is kept constant and is equal to 1.5 mm. For shapes where two configurations are possible, it has been chosen to analyze only the vertical position, because it is more efficient. For the octagonal shape, the extended octagonal was chosen because it further minimizes the stress intensity factor.

Table 3 summarizes the results obtained for the different forms. It should be noted that the forms compared with the butterfly patch were previously studied in [12].

Table 3 - R-value comparison for different shapes and surfaces

	R					
Patch surface (mm^2)	**Circular**	**Rectangular**	**Square**	**elliptic Vertical**	**extended Octagonal**	**butterfly Vertical**
616	0.9940	1.0084	1.0063	0.9964	1.0077	1.0038
706	1.0085	1.0217	1.0205	1.0111	1.0229	1.0241
804	1.0202	1.0337	1.0310	1.0205	1.0388	1.0281

Figure 7 shows the different results of the variations of R values as a function of the surface for the different patch shapes. It can be seen from the figure that the factor R increases with the increase of the surface patch.

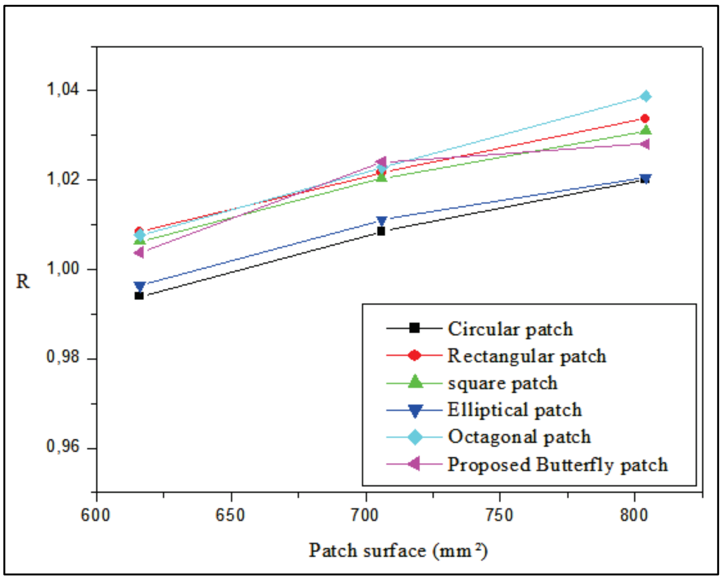

Fig. 7– Variation of performance indicator (R) according to surface area for different patch shape

In first observation, one can see that the extended octagonal patch is the most efficient to repair a cracked plate in mixed mode. This is for a larger patch surface. On the other hand, the efficiency of the butterfly patch is better for an intermediate surface, such as 706 mm^2 as indicated in figure 7. It should be noted that the vertical rectangular patch has a comparable efficiency to that of the extended octagonal patch. From what has been shown by the different results, one may deduce that there is no optimal form to the absolute. Indeed, to find a well-defined optimization, it must be found a compromise between the different geometrical parameters of the patch. These geometrical parameters contribute together in the optimization while keeping an optimal patch surface. So, in order to lighten the structure, it is primordial to optimize weight which remains by far the most influential factor on the overall behavior of the cracked structure. That said, a more in-depth study of the three shapes of patches, namely, octagonal, rectangular and butterfly should be considered to determine more optimized patch geometry. That said, a more pointed study of the three forms of patches, namely, octagonal, rectangular and butterfly must be considered to determine a more optimized patch form. Moreover, the thickness of the adhesive layer and its mechanical behavior must be carefully studied.

6 Conclusion

This study focused on the effect of patch shape on the repair efficiency of a cracked aluminum alloy plate. A finite element modeling has been carried out on a symmetrical repaired plate with 45° inclined crack in its center. In addition to the patch shapes proposed and studied in the literature such as octagonal patch, rectangular patch, square patch, circular patch and elliptical patch, a butterfly shape has been proposed. Then, the behavior in matter of stress intensity factors KI and KII has been analyzed for mode I and mode II of rupture, respectively. The analysis led to the following conclusions:

- The presence of a patch significantly reduces the intensity of the stress intensity factors, which results in delaying the re-initiation of the crack and therefore an increase in the lifetime of the cracked structure,
- For mixed mode failure mode, vertical butterfly shaped patch configurations are more suitable than horizontal patch configurations, this conclusion is confirmed for the butterfly-shaped patch,
- The effectiveness of the patch increases with the increase of its surface because it is the latter that transfers the stresses sustained by the structure in the vicinity of the crack,
- The shape of the patch significantly affects the failure behavior of the repaired structure, by the rate of the stress intensity factor reduction.
- For medium surfaces, the proposed butterfly-shaped patch is more effective in reducing the stress intensity factors.
- For large surfaces, the octagonal shape of the patch is more efficient in reducing the stress intensity factors.

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