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# Evaluation of performance and effect of circular composite patch dimensions on one-sided and two-sided repair of cracked plate

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## Abstract

In this research, the performance of circular composite patch in repairing cracked plate and the effect of patch dimensions and adhesive thickness on repair efficiency have been evaluated and repaired cracked aluminum plate with one-sided and two-sided composite patches, modeled in 3D in Abaqus software. In this study, by considering different thicknesses and diameters for composite patches made of boron, graphite and glass-epoxy, as well as different thicknesses for the adhesive layer, the effect of patch dimensions and adhesive thickness on repair efficiency has been investigated. The results of this study show that for all three composite patches, increasing the thickness of the patch in one-sided and two-sided repair reduces the stress intensity factor and increasing the diameter of the glass patch in one-sided repair has almost no effect on efficiency, but increasing the diameter of boron and graphite patches Slightly increases the stress intensity factor and in two-sided repair, increasing the diameter of all three patches reduces the stress intensity factor. The results also show that increasing the thickness of the adhesive increases the stress intensity factor, but on the other hand, reduces the maximum Von Mises stress in the adhesive layer.

**Keywords:** stress intensity factor, circular composite patch, double-sided repair, cracked plate, patch dimensions

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## 1- Introduction

There are cracks in many structures and parts in different industries and the growth of cracks in these structures and parts is inevitable and the growth of cracks may lead to failure of parts and ultimately complete destruction of the structure. An example of the dangers and damages of crack growth can be seen in Flight no. 243 Boeing 737 of Aloha Airlines in Figure 1, where the growth of cracks from the connection holes in the fuselage caused a part of the fuselage to detach during flight. Therefore, in order to prevent the growth of cracks and the dangers caused by it in structures, if for some reason it is not possible to replace parts or it is not economically viable, cracks in damaged parts are

repaired in various ways such as filling the crack with glue [3], stop holes, welding the crack site, shot peening [4,5], and composite and metal patches [6].

**Figure 1- Destruction of part of the fuselage due to crack growth [1,2]**

Composite patch repair has many advantages over other crack repair methods. One of the most important advantages of repairing with composite patches is that there is no need for drilling in the repair and drilling during the repair reduces the strength of the structure. The thickness required for repair with composite patches is about 33 to 50% of the thickness of aluminum patches [7]. Another advantage of repairing with composite patches is that the weight of the structure does not increase. The life of parts repaired with composite patches is almost doubled and in repair with composite patches, the probability of failure of parts is reduced [8]. Repair with composite patches increases the remaining strength and also increases the fatigue life [9]. Composites have a high resistance to weight ratio compared to metals and are resistant to damage and corrosion [10]. Composites are widely used for crack repair in various industries such as aerospace structures, ships, tanks, pipes, etc., and the use of composite patches for crack repair in underwater structures and ships in research [11, 12] has been examined.

Repair with a high-stiffness composite patch increases the stress on the patch itself but decreases the stress on the repaired plate [13]. One of the important things to increase the repair efficiency is to increase the thickness of the composite patch [14]. Increasing the thickness of the composite patch reduces the stress intensity factor, but increasing the adhesive thickness increases the stress intensity factor [6]. In repair with composite patches, the stress intensity factor is significantly reduced, but the longer the crack length, the faster the stress intensity factor increases [15]. In the study [16], the effect of patch dimensions in different crack angles on the efficiency of one-sided and two-sided repair of the cracked plate has been investigated and the results have shown that at zero degrees crack angle with increasing the length of the composite patch in one-sided and two-sided repair the stress intensity factor has increased and with increasing the patch width in the one-sided repair mode, the stress intensity factor increases, but in the two-sided repair, increasing the patch width has reduced the stress intensity factor. In order for the crack to be under the patch during growth and not to come out of the under patch soon, it is better to use a patch with a width much larger than the crack length [17]. Increasing the thickness of the adhesive increases the stress intensity factor, but on the other hand, the stress in the adhesive decreases, and therefore the durability of the patch increases [18]. It must be ensured that in the design of composite patches the stress in the adhesive is in the design range [15]. In research [19], the aluminum plate has been repaired with a single-sided composite patch, and research has shown that fatigue life increases by at least fourfold, and in some cases may increase fatigue life by more than fourfold. Also, the results of research [19] have shown that the difference between the crack lengths on the repaired side and the non-repaired side is greater for high-thickness plates than for thinner plates.

Repair with two-sided composite patches further reduces the stress intensity factor than repair with one-sided patches [20]. One-sided repair of the plate with composite patches causes out of plane bending, which affects the efficiency of the patch in repair [6]. Out of plane bending in one-sided repair causes the plate to also experience flexural stresses [15]. In plate repair with composite patches on the unrepaired side, the stress intensity factor increases, and with increasing the patch thickness, the difference in stress intensity factor on both sides of the plate increases [21]. Four patches of boron, graphite, glass and carbon have been investigated in the study [16] and the research results have shown that boron patch has the highest efficiency and glass has the lowest efficiency and the two patches of carbon and graphite have almost the same behavior and efficiency. In research [22], the efficiency of a semi-circular composite patch has been compared with a semi-elliptical patch in one-sided edge crack repair, and the results have shown that a semi-circular patch further reduces the stress intensity factor and increases the repair efficiency.

In this research, the performance of circular composite patch in cracked plate repair is evaluated and the effect of patch dimensions and adhesive thickness on the one-sided and two-sided repair of the cracked plate is investigated. Composite patches of boron, graphite, and glass- epoxy have been used to evaluate the performance of the circular patch and to investigate the effect of the dimensions of the composite patches as well as the thickness of the adhesive on the stress intensity factor in repairing cracked aluminum plate. and by considering different thicknesses and diameters for each of the composite patches and different thicknesses for the adhesive, the effect of increasing each of the parameters on the stress intensity factor in one-sided and two-sided repair has been investigated.

## 2- Problem definition and finite element modeling

Rectangular cracked plate 105 × 65 mm with a thickness of 3 mm made of 2024 aluminum alloy with a modulus of elasticity 74 Gpa and Poisson's ratio of 0.33 in order to evaluate the performance of circular composite patch in repairing cracked plate and to investigate the effect of patch dimensions and adhesive thickness on repair efficiency, in Abaqus software is modeled in 3D. A tensile load of 15 Mpa is applied to the top and bottom edges of the plate. The plate contains a 9 mm long crack. In this study we repair cracked plate with circular composite patches with a diameter of 30 mm and a thickness of 1 mm made of boron, graphite, and glass epoxy. In repairing the plate with the composite patch, a thin layer of adhesive made of FM-73 with a thickness of 0.1 mm has been used. The geometry studied in this research can be seen in Figure 2. The properties of the composite patches and adhesives used in this study are presented in Table 1. The properties of patches are taken from references [23-24]. The contour integral method was used to calculate the stress intensity factor at the crack tip. 8-node linear three-dimensional elements (C3D8R) are used in the modeling. The model of cracked aluminum plate repaired with a composite patch in Abaqus finite element analysis software as well as the mesh around the crack tip is shown in Figure 3.

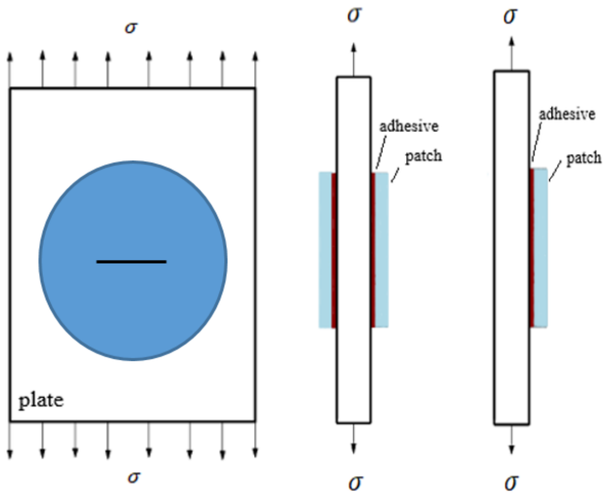
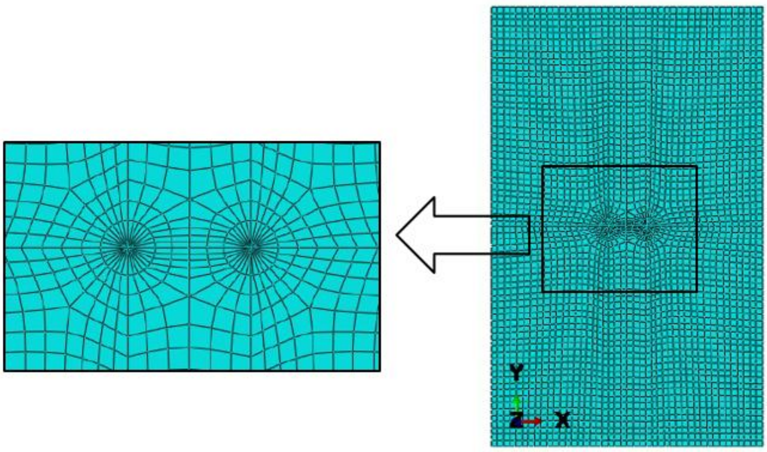
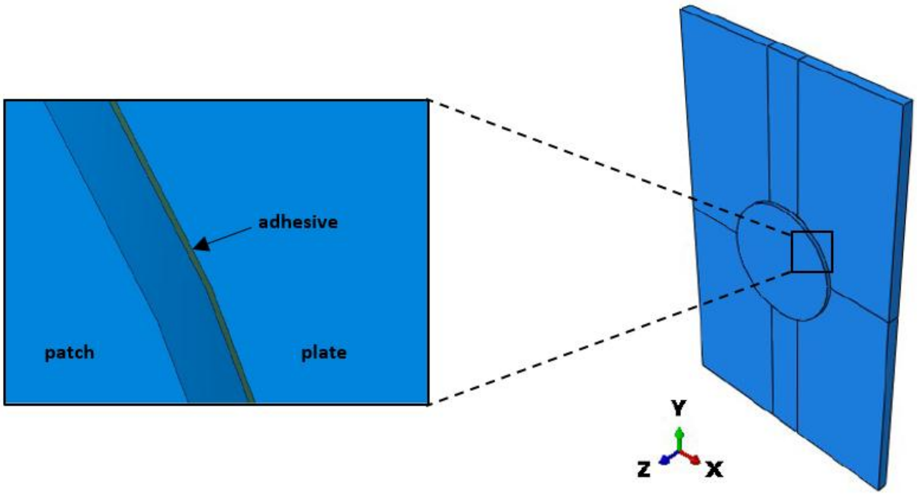



**Figure 2- The geometry of cracked plate repair with one-sided and two-sided composite patch**




**a) Cracked plate meshing and mesh around the crack tip**




**b) Finite element modeling of cracked plate repaired with composite patch in Abaqus software**

**Figure 3 - Finite element modeling of cracked plate repaired with composite patch in Abaqus software and mesh around the crack tip**

**Table 1- Properties of composite patches and adhesives (E and G in Gpa)**

| Material | $E_{11}$ | $E_{22}$ | $E_{33}$ | $G_{12}$ | $G_{13}$ | $G_{23}$ | $v_{12}$ | $v_{13}$ | $v_{23}$ |
|---|---|---|---|---|---|---|---|---|---|
| Graphite-epoxy | 172.4 | 10.34 | 10.34 | 4.82 | 4.82 | 3.10 | 0.3 | 0.3 | 0.18 |
| Glass-epoxy | 27.82 | 5.83 | 5.83 | 2.56 | 2.56 | 2.24 | 0.31 | 0.31 | 0.41 |
| Boron-epoxy | 208.1 | 25.44 | 25.44 | 7.24 | 7.24 | 4.94 | 0.1677 | 0.1677 | 0.035 |
| Adhesive-FM 73 | 2.21 | - | - | - | - | - | 0.43 | - | - |

## 3- Results of finite element analysis

### 3-1- Finite element analysis validation

To validate the results of finite element analysis, we compare the stress intensity factor obtained for unrepaired cracked plate from finite element analysis with the stress intensity factor obtained from theoretical relation (1).

$$K_I = Y\sigma\sqrt{\pi a}$$

In relation (1), σ = 15 Mpa is the stress applied to the plate, a = 4.5 mm is half the crack length and Y is the geometric coefficient obtained from the following relation (2).

$$Y = \sqrt{\sec(\pi a/w)}$$

In relation (2), a = 4.5 mm is half the crack length and w = 65 mm is the plate width. The stress intensity factor obtained from the theoretical relation $K_I = 57.07$ Mpa.√mm and also the stress intensity factor obtained from finite element analysis is $K_I = 59.17$ Mpa.√mm and the difference in stress intensity factor of both methods is 3.68% and this shows that the modeling performed is of acceptable accuracy.

**3-2- Evaluation of stress intensity factor**

In this section, we evaluate the stress intensity factor obtained from finite element analysis for cracked aluminum plate repaired with one-sided and two-sided composite patches made of boron, graphite, and glass-epoxy. Variation of stress intensity factor along the thickness of cracked aluminum plate repaired with one-sided and two-sided composite patches is shown in Figure 5. According to Figure 5, in the case of one-sided repair of the plate with composite patches, the stress intensity factor decreases on the repaired side of the plate, but increases on the unrepaired side, and this occurs due to out of plate bending in one-sided repair. However, in two-sided repair, due to the symmetry of the composite patches on both sides of the plate, unlike the repair mode with one-sided patches, the stress intensity factor is reduced by almost one ratio and the stress intensity factor does not change much in the plate thickness. Out of plate bending in one-sided plate repair with glass-epoxy composite patch in Abaqus finite element analysis software can be seen in Figure 4.

According to Figure 5, the maximum reduction of stress intensity factor in one-sided and two-sided repair modes has been obtained by using boron-epoxy patch, which reduces the stress intensity factor in one-sided and two-sided repair mode by 25.85% and 70.92%, respectively. And the lowest reduction in stress intensity factor in two repair modes is related to repair with glass-epoxy patch, which has the lowest efficiency among the patches under study. Glass patch in one-sided and two-sided repair mode has reduced the stress intensity factor by 14.01% and 32.00%, respectively. In the case of one-sided repair, the graphite patch reduces the stress intensity factor almost as much as the boron patch and has very little difference with the boron-epoxy patch. Two-sided repair of cracked plate with graphite-epoxy patch has reduced the stress intensity factor by 67.18%.

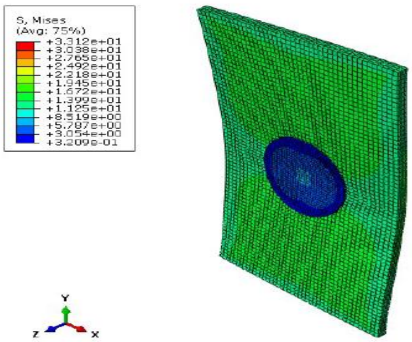



**Figure 4- One-sided repair of cracked plate with glass-epoxy composite patch in Abaqus software**

According to the evaluation of the stress intensity factor of cracked plate repaired with composite patches, for all three patches, two-sided repair further reduced the stress intensity factor than one-sided repair. for example, repair with boron-epoxy patch, which has the highest efficiency among the patches under study, in two-sided repair, the stress intensity factor is reduced by approximately 45% more than in one-sided repair. So according to the results, to repair cracks, if it is possible to repair two-sided, it is better to use two-sided repair, because, as shown, it further reduces the stress intensity factor compared to one-sided repair. However, in cases where it is not possible to repair the crack in both sided, such as repairing the crack in the hull of a ship or aircraft, we repair the crack with one-sided patches. Therefore, according to the investigations, whether there is a possibility of two-sided repair or not, to achieve higher efficiency, it is better to use boron-epoxy composite patch because it has the highest efficiency among patches in both one-sided and two-sided repair modes.

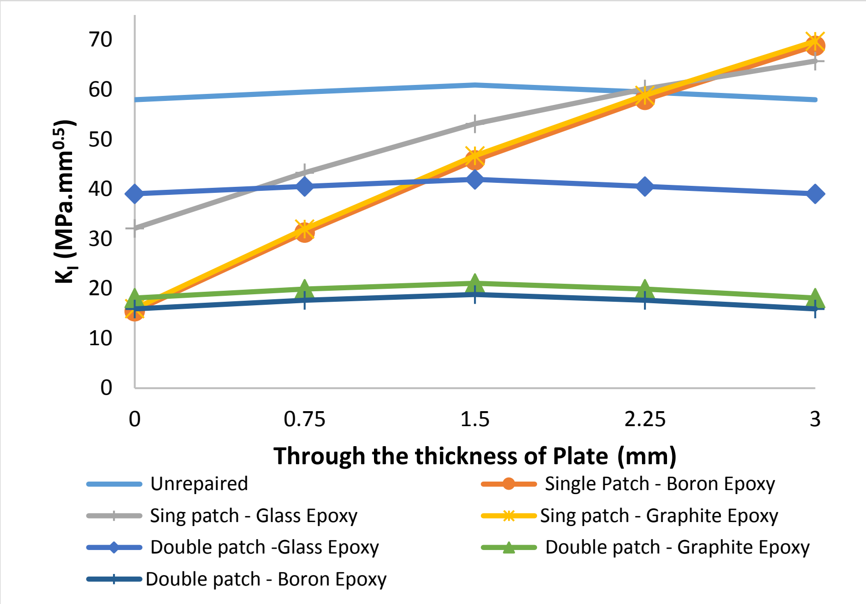



**Figure 5 - Variation of stress intensity factor along the thickness of the repaired plate with composite patches**

### 3-3- The effect of patch thickness on stress intensity factor

To investigate the effect of patch thickness on stress intensity factor, we use patches with thickness of 1, 1.5, 2, 2.5 and 3 mm. In this study, by keeping the diameter of the patches and the thickness of the adhesive constant and only by changing the thickness of the composite patches, we investigate the effect of increasing the patch thickness on the repair efficiency of the cracked plate with boron, graphite, and glass-epoxy composite patches in one-sided and two-sided repair mode and the results of the effect of patch thickness on the stress intensity factor are shown in Figure 6. In this study, the diameter of the patch and the thickness of the adhesive are 30 and 0.1 mm, respectively.

According to Figure 6, in one-sided repair, with increasing the thickness of the patches, the stress intensity factor has decreased and as we can see in the figure, increasing the thickness of the glass patch in one-sided repair has less effect on reducing the stress intensity factor than boron and graphite patches, by tripling the thickness of boron and graphite patch, the stress intensity factor has decreased by 7.79% and 5.78%, respectively, while by tripling the thickness of the glass patch, the stress intensity factor has decreased by only 3.76%. Also, in two-sided repair for all three composite patches, the stress intensity factor decreases with increasing patch thickness and the ratio of decreasing the stress intensity factor with increasing the patch thickness in two-sided repair is more than one-sided repair. For example, increasing the thickness of graphite patch from 1 to 3 mm in two-sided repair has reduced the stress intensity factor by 33.10%, while in one-sided repair, increasing the same amount of thickness has only reduced the stress intensity factor by 5.78%.

So, in general, in both one-sided and two-sided repair modes, increasing the patch thickness reduces the stress intensity factor, but keep in mind that in some industries, increasing the thickness may not be appropriate, for example, in aerospace industries and applications, if the patch thickness is considered too high, it may cause problems and disturb the aerodynamics of the structure and therefore, in such cases where there is a limit to the thickness of the patch, the thickness of the patch cannot be considered too much and a compromise must be made between how much to increase the thickness of the patch and how much to reduce the desired stress intensity factor, however, in cases where there is no limit to the thickness of the patch, it is better to use a patch with a high thickness, because in general, increasing the thickness of the patch reduces the stress intensity factor.

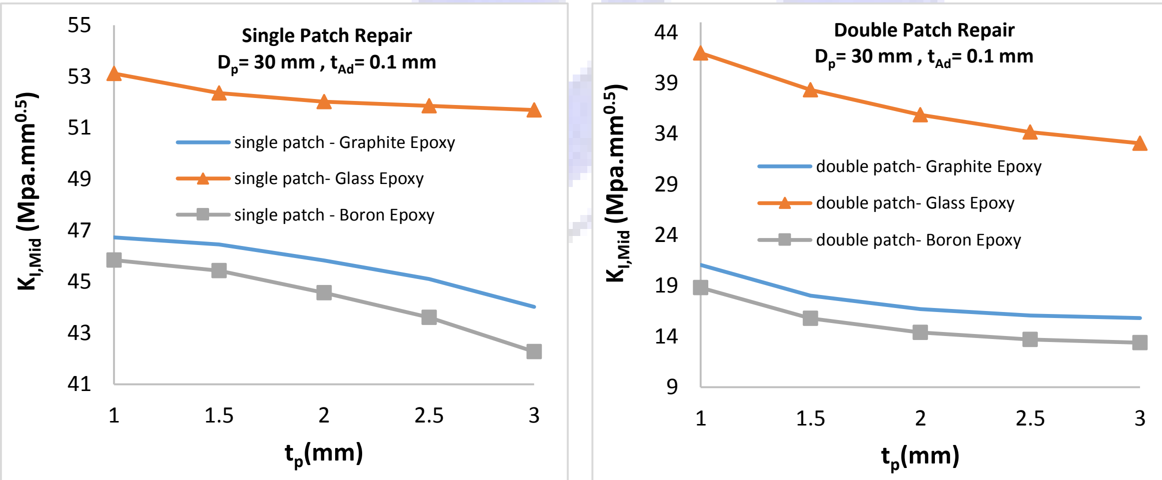
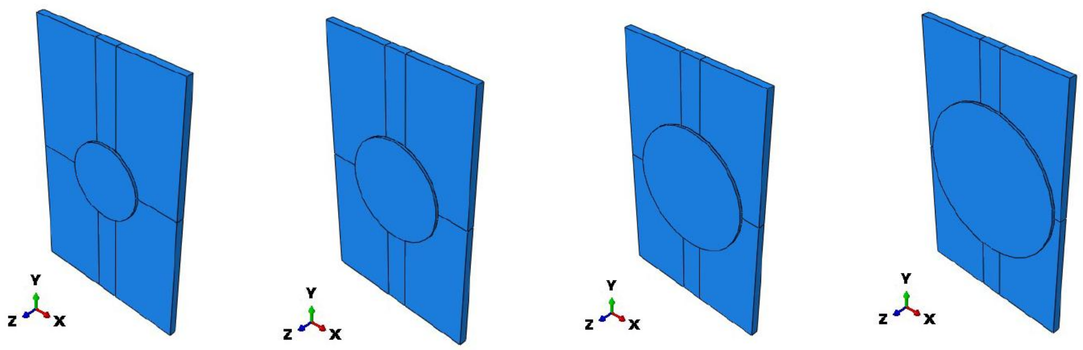



**Figure 6 - Variation of average stress intensity factor in terms of patch thickness for plate repaired with composite patches**

## 3-4-The effect of patch diameter on stress intensity factor

To investigate the effect of patch diameter on repair efficiency, we use composite patches with diameters of 30, 40, 50, and 60 mm and by keeping the thickness of the patch and the thickness of the adhesive constant, we repair the cracked plate with composite patches in both one-sided and two-sided modes. The different diameters intended for circular patches in one-sided and two-sided repair are shown in Figure 7. In this study, the thickness of the patch and the adhesive are equal to 1 and 0.1 mm, respectively. The results of the study of the effect of patch diameter on stress intensity factor are shown in Figure 8. According to Figure 8, in the case of one-sided repair, increasing the diameter of the glass-epoxy patch has almost no effect on the stress intensity factor, but increasing the diameter of boron and graphite patches slightly increases the stress intensity factor. For example, by doubling the diameter of the graphite patch in one-sided repair, the stress intensity factor has increased by 1.82%, and therefore in one-sided repair, increasing the patch diameter is not a suitable solution to reduce the stress intensity factor.




$D_p = 30\ mm$ $D_p = 40\ mm$ $D_p = 50\ mm$ $D_p = 60\ mm$

**Figure 7- The different diameters intended for composite patches in one-sided and two-sided repair**

But keep in mind that if the diameter of the composite patch is small, the crack will soon reach the edges of the composite patch as it grows and will come out from under the patch, therefore, using a patch with a larger diameter causes the crack not to reach the edges soon and to be under the patch for a long time. Therefore, the advantage of using a larger diameter patch in one-sided repair is that it leaves the crack under the patch for a long time, otherwise, except for the glass-epoxy patch, it increases the stress intensity factor. However, in the case of two-sided repair for all three composites patch of boron, graphite, and glass-epoxy, increasing the diameter of the patch reduces the stress intensity factor, but increasing the diameter of the glass patch has less effect on reducing the stress intensity factor than the other two patches.

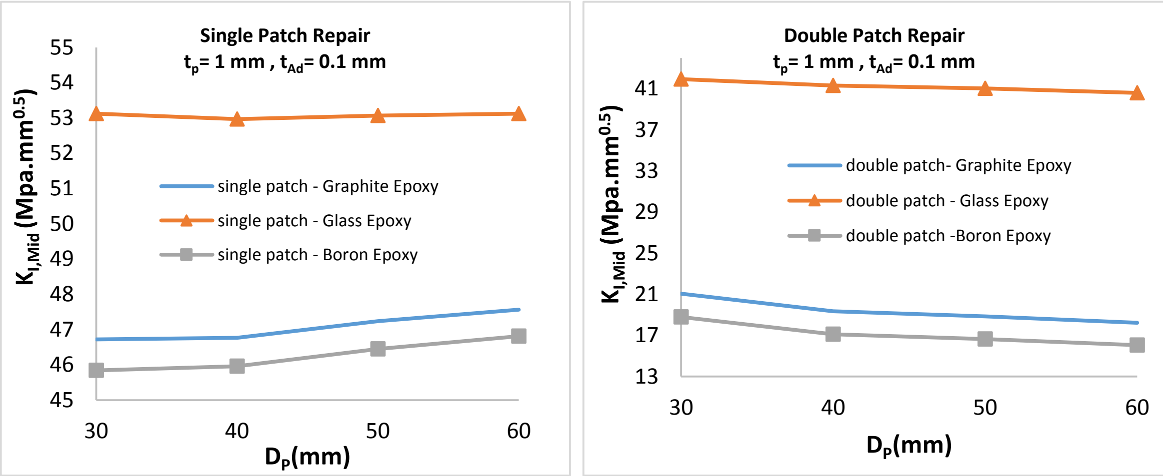



**Figure 8 - Variation of average stress intensity factor in terms of patch diameter for plate repaired with composite patches**

Therefore, in two-sided repair, increasing the diameter of the patch is a suitable solution to reduce the stress intensity factor and on the other hand, it causes cracks to be under the patch for a long time during growth. By doubling the diameter of boron and graphite patches in two-sided repair, the stress intensity factor has been reduced by 14.52% and 13.48%, respectively, and doubling the diameter of the glass patch only reduced the stress intensity factor by 3.22%.

### 3-5- Effect of adhesive thickness on stress intensity factor

In this section, the effect of increasing the adhesive thickness on the repair efficiency of cracked plate with composite patches is investigated. For this purpose, to investigate the effect of increasing the adhesive thickness on the stress intensity factor, the thickness of the adhesive layer is considered 0.1, 0.2, 0.3, 0.4, and 0.5 mm, respectively. The diameter of the patch and the thickness of the patch in this study are equal to 30 and 1 mm, respectively. The results of the effect of increasing the adhesive thickness on the stress intensity factor in one-sided and two-sided repair with boron, graphite, and glass-epoxy composite patches are shown in Figure 9.

According to Figure 9, in both one-sided and two-sided repair modes, increasing the adhesive thickness has increased the stress intensity factor and as a result, the repair efficiency has decreased. However, in both one-sided and two-sided repair modes, the amount of increase in stress intensity factor with increasing adhesive thickness in repair with glass-epoxy patch is less than the other two patches. For example, in one-sided repair with boron-epoxy patch, increasing the adhesive thickness from 0.1 to 0.3 mm has increased the stress factor by 5.91%, but in repair with glass patch, increasing the same amount of adhesive thickness has only increased the stress intensity factor by 1.98%. Also, according to Figure 9, the amount of increase in stress intensity factor with increasing adhesive thickness in two-sided repair is much more than one-sided repair, in two-sided repair with graphite-epoxy patch, by tripling the thickness of the adhesive (0.1 to 0.3), the stress intensity factor has increased by 26.43%, but in one-sided repair, increasing the same amount of thickness has only increased the stress intensity factor by 5.31%, and as we can see, in two-sided repair, the stress intensity factor is increased by almost 5 times the one-sided repair mode.

The results also show that by increasing the thickness of the adhesive in one-sided and two-sided repair, the maximum Von Mises stress in the adhesive layer decreases and thus increases the durability of the patch. So, although increasing the thickness of the adhesive has reduced the efficiency of the repair, but on the other hand, by reducing the maximum stress of Von Mises in the adhesive layer, it has increased the durability of the patch. The maximum Von Mises stress in adhesive layers with thickness of 0.1, 0.3 and 0.5 mm in one-sided repair of cracked plate with boron-epoxy patch can be seen in Figure 10. By tripling the thickness of the adhesive (0.1 to 0.3) in one-sided repair of the plate with boron-epoxy patch, the stress intensity factor has increased by 5.91%, but on the other hand, the maximum Von Mises stress in the adhesive layer has decreased by 37.37%.

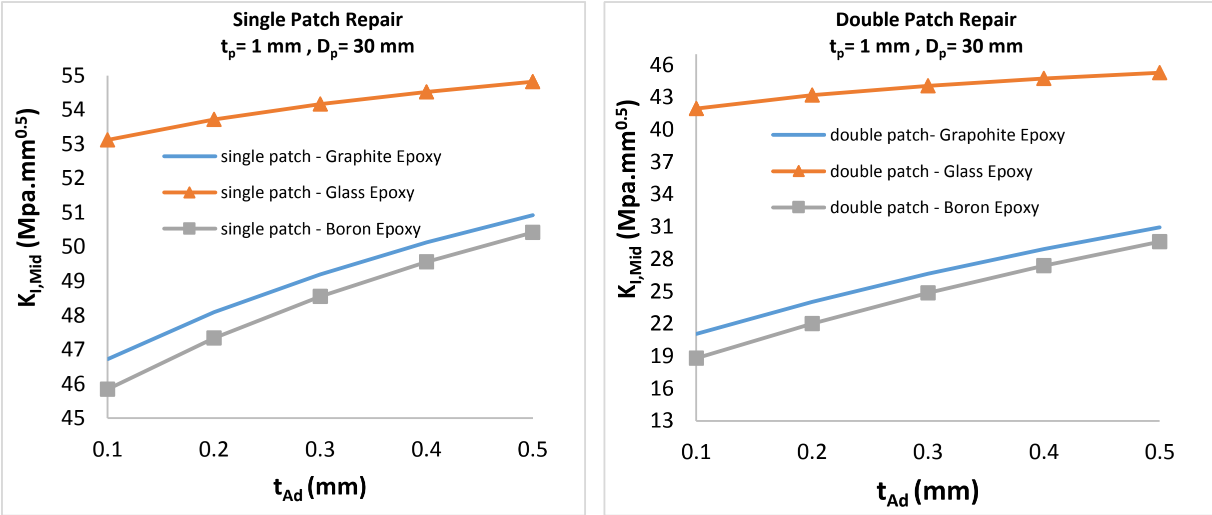
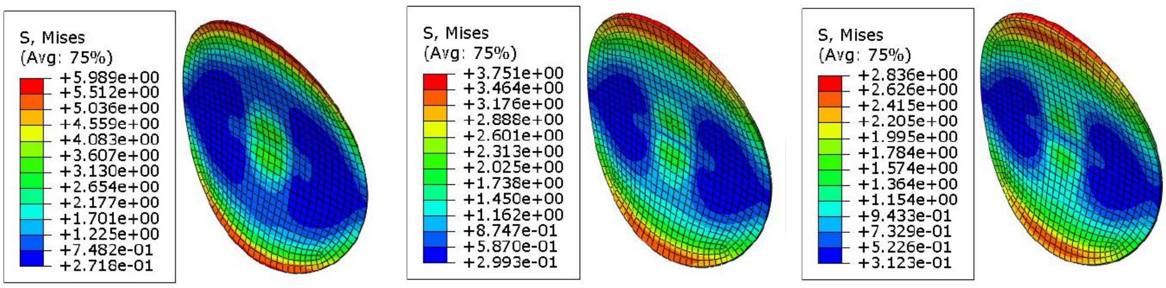



**Figure 9 - Variation of average stress intensity factor in terms of adhesive thickness for plate repaired with composite patches**




$t_{Ad} = 0.1$ mm $t_{Ad} =$
0.3 mm $t_{Ad} = 0.5$ mm

**Figure 10- Maximum Von Mises stress in the adhesive layer with different thicknesses in the one-sided repair of the plate with boron-epoxy patch**

## 4- Summary and conclusion

In this research, in order to investigate the performance of circular composite repair patches in repairing cracked plate and the effect of patch dimensions and adhesive thickness on repair efficiency, cracked aluminum plate with boron, graphite and glass-epoxy composite patches has been repaired in both one-sided and two-sided modes, and by considering different thicknesses and diameters for each of the patches and different thicknesses for the adhesive, the effect of each parameter on the repair efficiency of cracked plate has been investigated, and the most important research results are as follows:

1- In two modes of one-sided and two-sided repair, the highest reduction of stress intensity factor is related to repair with boron-epoxy patch and the lowest is related to repair with glass-epoxy patch.

2- Boron-epoxy patch in one-sided and two-sided repair modes reduces the stress intensity factor by 25.85% and 70.92%, respectively, and compared to glass-epoxy patch in one-sided and two-sided repair modes, respectively, causes a further 11.84% and 38.92% reduction in stress intensity factor.

3- One-sided repair with graphite-epoxy patch reduces the stress intensity factor almost to the same extent as one-sided repair with boron patch and there is very little difference. Double-sided repair with graphite-epoxy patch reduces the stress intensity factor by 67.18%.

4- Increasing the thickness of patches in one-sided and two-sided repair reduces the stress intensity factor, and the effect of increasing the thickness on reducing the stress intensity factor in two-sided repair is more than one-sided repair.

5- Increasing the thickness of glass-epoxy patch in one-sided repair has little effect in reducing the stress intensity factor compared to increasing the thickness of boron and graphite patches in one-sided repair.

6- Increasing the diameter of glass patch in one-sided repair has no effect on stress intensity factor, but increasing the diameter of boron and graphite patches in one-sided repair slightly increases the stress intensity factor. But keep in mind that using a larger diameter patch in one-sided repair will cause the crack to be under the patch for a long time during growth.

7- Increasing the diameter of patches in two-sided repair reduces the stress intensity factor, so in two-sided repair to further reduce the stress intensity factor, it is better to use a patch with a larger diameter, and on the other hand, a patch with a larger diameter causes crack to be under the patch for a long time during growth.

8- In both one-sided and two-sided repair cases, increasing the thickness of the adhesive has increased the stress intensity factor, but on the other hand, with increasing the thickness of the adhesive, the maximum Von Mises stress in the adhesive layer has decreased.

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## 6- Appendix

### Notation

| | |
|---|---|
| E | Young's modulus |
| G | Shear modulus |
| $K_I$ | Mode I Stress intensity factor |
| $K_{I,Mid}$ | Mode I average stress intensity factor |
| $D_P$ | Patch diameter |
| $Y$ | Geometric factor |
| 2a | Crack length |
| $t_P$ | Patch thickness |
| $t_{Ad}$ | Adhesive thickness |
| $v$ | Poisson's ratio |