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Investigation of the Effect of Composite Patch Dimensions on Patch Efficiency in Cracked Plate Repair by Considering Different Crack Angles

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Abstract

In this study, the effect of thickness, length and width of each of the composite patches of boron, glass, graphite and carbon epoxy on the stress intensity factor of the first and second modes in one-sided and two-sided repair of the cracked aluminum plate at different crack angles 0 to 90 degrees has been studied. For this purpose, the repaired cracked plate with each of the composite patches is modeled in 3D in Abaqus software. The results show that in both one-sided and two-sided repair modes, increasing the patch thickness except for the glass patch has reduced the stress intensity factor of the first and second modes. The results also show that increasing the length of the patches for all four patches in both one-sided and two-sided repair modes for all angles from 0 to 90 degrees slightly increases the stress intensity factor. Increasing the width of the glass patch in one-sided repair has a different behavior than the other three patches, so that it does not change almost at an angle of 0 to 30 degrees, but decreases slightly from an angle of 30 to 90 degrees, but the other three patches increase from 0 to 45 degrees and decrease from 45 to 90 degrees, and the stress intensity factor of the second mode for all four patches in all angles decreases with increasing patch width.

Keywords: cracked plate, composite patch, crack angle, stress intensity factor, two-sided repair.

1- Introduction

One of the best ways to inhibit crack growth is to use composite patches. Composite patches have many advantages over other methods of inhibiting crack growth, such as metal patches, crack stop holes, welding the crack, filling the crack with glue, Shot peening, etc. [1-3]. One of the most important advantages of repairing with composite patches is that there is no need for drilling in repairing cracks with composite patches, and this makes the strength of the structure not decrease during the repair, because drilling reduces the strength of structures. The thickness required for composite patch repair is about 33% to 50% of the thickness required for aluminum patch repair [4]. Another advantage of repair with composite patches is that composite patches have a higher resistance to weight ratio than metal patches and are more resistant to corrosion and damage [5]. In repairing cracks with composite patches, the weight of the structures does not increase and this is another very good advantage of repairing cracks with composite patches [6].

Composite patches are widely used for repairing cracks in aerospace, marine industrial, tank, pipe, etc. [7-9]. As an example, crack repair in underwater structures has been investigated in the research [10] and the research results have shown that composite patches can be used for underwater structures and repair with composite patches has good results. Also, composite patches can be used in combination with other repair methods, which has better performance than separate repair with each method. Composite patch and stop holes, composite patch and bolt clamping, etc. are examples of combined repair methods [12-11].

Repairing cracked parts with composite patches reduces the stress intensity factor near the crack tip and in this way, composite patches reduce the stress intensity factor and thus inhibit crack growth. Repairing cracked parts with composite patches reduces the Possibility of parts fracture and almost doubles the life of repaired parts [6]. Increasing the thickness of the adhesive in using the repair method with composite patches increases the stress intensity factor, but on the other hand, because with increasing the thickness of the adhesive the stress in the adhesive itself decreases, increasing the durability of the patch [13]. As the stiffness of the composite patch used for repair increases, the stress in the cracked plate decreases but the stress in the patch itself increases [14]. In one-sided repair with composite patches, on the non-repaired side, the stress intensity factor is much higher than on the repaired side with the patch and with increasing patch thickness, the difference in stress intensity factor on both repaired and unrepaired sides increases [15].

Repair with double-sided composite patches has better performance than one-sided repair and further reduces the stress intensity factor [16]. In both one-sided and two-sided repair methods, the stress intensity factor decreases with increasing patch thickness [17]. The thickness and material of the patch are very influential in the efficiency of the repair method with composite patches. The results of research [18] have shown that the thickness greater than the Young modulus affects the stress distribution. The effect of patch dimensions on one-sided repair has been investigated in research [13] and the results have shown that increasing the patch length causes the stress intensity factor to increase slightly, and increasing the patch width for some thicknesses and materials reduces the stress intensity factor, but for others it may not affect the repair performance. In composite patch repair, if the patch width is not much larger than the crack length, the crack will soon reach the end edges of the patch during growth and in research [19], it is recommended to use a patch width much larger than the crack length so that the crack does not pass through the edges of the patch soon and stays under the patch for a long time. In research [13] has shown that among the four composite patches studied, the highest and lowest efficiencies are related to boron and glass epoxy patches, respectively and the two carbon and graphite patches have almost the same efficiency. In one-sided repair with composite patches, the off-plane bending causes the repaired plate to experience bending stresses [20].

In this research, the effect of thickness, length and width of each of the composite patches of boron, graphite, glass and carbon epoxy on the stress intensity factor of the first and second modes in one-sided and two-sided repair of cracked aluminum plate and at different crack angles 0 to 90 degrees will be studied. For this purpose, by repairing cracked aluminum plate with composite patches in Abaqus and considering different lengths, widths and thicknesses for each patch, the results of the effect of each parameter on the stress intensity factor of the first mode and the second mode in the crack angle of 0 to 90 degrees are extracted.

2- Problem definition and finite element modeling

In this research, Abaqus software is used to evaluate the efficiency of composite patches in repairing aluminum plate contains angled crack. For this purpose, a 125 × 85 mm aluminum plate with a thickness of 4 mm has been used. Initially, a 12 mm long crack with an angle of

45 degrees in the middle of the aluminum plate is considered. 20 Mpa tensile load is applied to the top and bottom edges of the plate. Graphite, carbon, boron and glass epoxy composite patches have been used to repair the plate. The initial dimensions of single-sided and double-sided composite patches are 40 × 50 mm with a thickness of 1.5 mm. 0.1 mm thick FM-73 adhesive is used for repair with composite patches. The properties of composite patches and adhesive are presented in Table 1. The geometry of the problem under study in this research is shown in Figure 1. The contour integral method was used to calculate the stress intensity factor around the crack tip. 8-node linear three-dimensional elements (C3D8R) are used in the modeling. Finite element modeling of cracked aluminum plate repaired with composite patches in Abaqus software is shown in Figure 2.

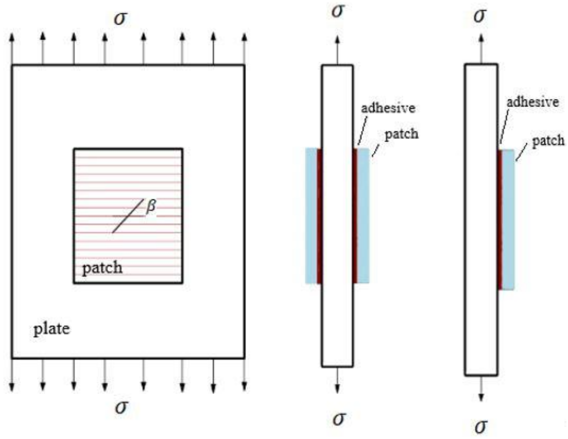
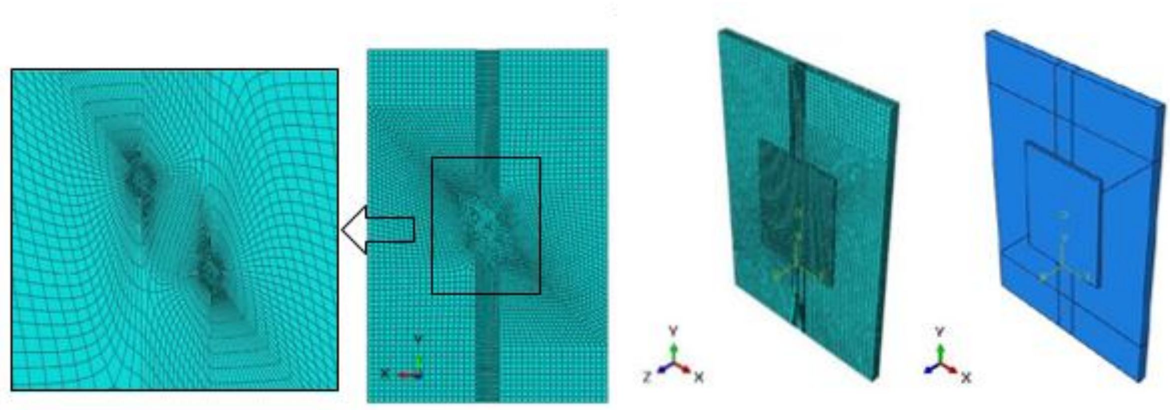


Figure 1- The geometry of cracked aluminum plate repaired with a one-sided and two-sided composite patch



(a) **(b)**

Figure 2- a) Finite element modeling of cracked plate repaired with a composite patch in Abaqus software b) Mesh around the crack tip

Table 1- The properties of composite material and adhesive (E and G in Gpa) [21]

Material	E_1	E_2	E_3	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
Carbon-Epoxy	134	10.3	10.3	5.5	5.5	2.3	0.33	0.33	0.53
Adhesive -FM 73	2.21	-	-	-	-	-	0.43	-	-

3- Finite element analysis validation

To validate finite element analysis, we compare the results obtained for the stress intensity factor of the first mode K_I and the second mode K_{II} for crack with an angle of 45 degrees from the theory relations 1 and 2 with the results obtained from finite element analysis.

$$K_I = \sigma\sqrt{\pi a}\cos^2\beta \tag{1}$$

$$K_{II} = \sigma\sqrt{\pi a}\sin\beta\cos\beta \tag{2}$$

In relations (1) and (2), σ = 20 Mpa is the applied stress to the plate, a = 6 mm is the half of crack length, $\beta = 45^{\circ}$ is the crack angle. Due to the fact that the crack angle is 45 degrees, the stress intensity factor of the first mode and the second mode obtained from the theoretical relations (1) and (2) are the same and equal to 43.42 $\text{Mpa.}\sqrt{\text{mm}}$. The stress intensity factor of the first mode obtained from finite element analysis is 41.20 $\text{Mpa.}\sqrt{\text{mm}}$, which is 5.11% different from the stress intensity factor obtained from the theory relation (1). Also, the stress intensity factor obtained for the second mode of finite element analysis is 45.60 $\text{Mpa.}\sqrt{\text{mm}}$, which is 5.02% different from the stress intensity factor obtained from theory relation (2). Therefore, considering that the maximum percentage difference between the first mode and the second mode is 5.11%, and this shows that the results obtained from finite element analysis have acceptable accuracy.

4- Analysis of the obtained results

In this section, the results obtained from finite element modeling of cracked aluminum plate repair with composite patches in Abaqus software are analyzed. First, the stress intensity factor changes of the first and second modes along the thickness of the aluminum plate in the repaired state with one-sided and two-sided composite patches made of graphite, glass, boron and carbon epoxy are investigated. In this case, the thickness of the main plate is 4 mm and the crack angle is 45 degrees and also the dimensions of one-sided and two-sided composite patches are the same. The stress intensity factor changes of the first mode and the second mode in the direction of plate thickness, for aluminum plate containing crack with an angle of 45 degrees in one-sided and two-sided repair mode with composite patches are shown in Figure 3.

According to Figure 3, in one-sided repair mode due to off-plate bending, the stress intensity factor of the first mode decreases on the repaired side and increases on the non-repaired side. For the second mode, in the repaired state, the stress intensity factor decreases, but in the unrepaired side, the stress intensity factor does not change almost. Therefore, in one-sided repair mode, we use the average value of stress intensity factor in the direction of thickness to compare with unrepaired mode and two-sided patch repair mode. Off-plane bending in one-sided repair of cracked plate with glass epoxy patch and Von Mises stress contour in adhesive and glass epoxy patch is shown in Figure 4. Off-plane bending in one-sided repair of cracked plate with glass epoxy patch and Von Mises stress contour in adhesive and glass epoxy patch is shown in Figure 4. In the case of double-sided repair, due to the symmetry of the composite patches on both sides of the plate, the stress intensity factor of the first mode and the second mode in the direction of plate thickness is reduced by one ratio.

According to the diagrams in Figure 3, in one-sided and two-sided repair mode with composite patches, the highest decrease in stress intensity factor is related to boron patch, which in one-sided repair mode, the stress intensity factor of the first mode and second modes decresed18.11% and 27.00%, respectively. Also, boron epoxy patch in two-sided repair mode reduces the stress intensity factor of the first mode and the second mode by 64.66% and 72.23%, respectively. The lowest reduction of stress intensity factor in one-sided and two-sided repair mode is related to glass epoxy patch, which in one-sided repair reduces the stress intensity factor of the first and second modes by only 9.22% and 13.90%, respectively. Also, glass epoxy patch in two-sided repair mode reduces the stress intensity factor of the first and second modes by 22.23% and 29.37%, respectively. Graphite and carbon patches also reduce the stress intensity factor of the first and second modes approximately to the extent of boron patch. The percentage reduction of the average stress intensity factor (corresponding to the middle of the thickness) for all four composite patches in one-sided and two-sided repair mode is presented in Table 2.

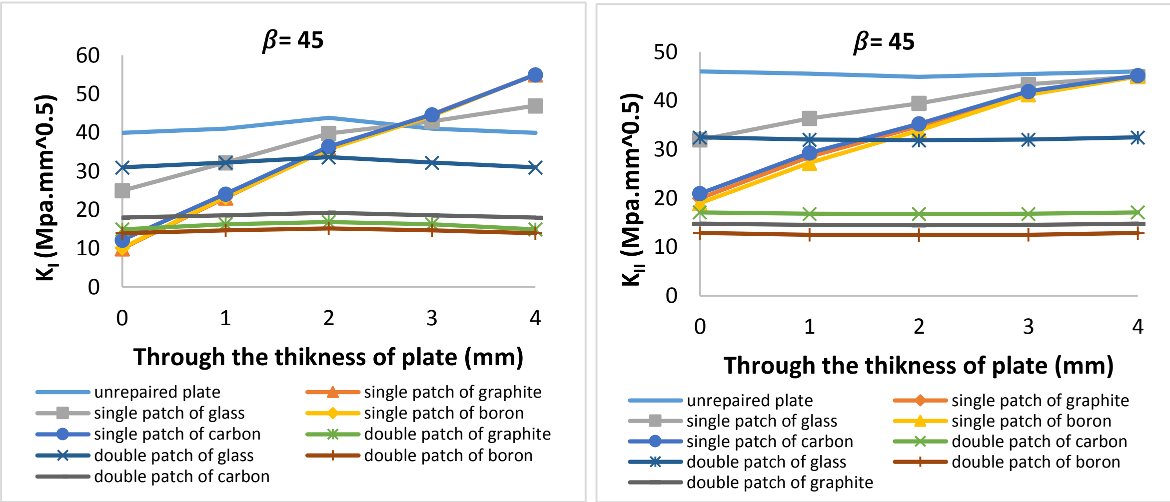
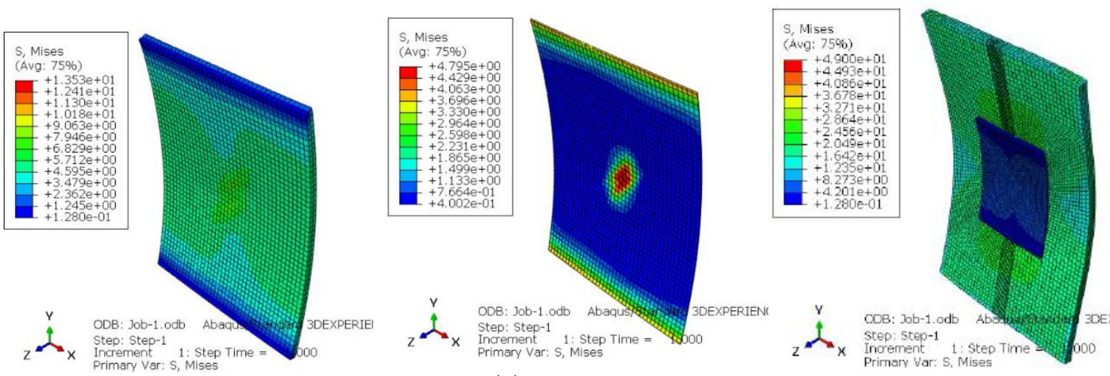


Figure 3 - Changes in the stress intensity factor of the first mode and the second mode in the direction of the thickness of the cracked plate repaired with composite patches

Table 2- The Percentage of reduction of average stress intensity factor of the first mode and the second mode of cracked plate repaired with composite patches (β = 45)

Composite patch	Single Boron	Double Boron	Single Graphite	Double Graphite	Single carbon	Double Carbon	Single Glass	Double Glass
Percentage reduction of K_I	18.55	65.23	18.07	61.47	17.02	56.05	9.27	23.28
Percentage reduction of K_{II}	۲۴.۴۲	۷۲.۱۵	۲۲.۴۸	۶۷.۶۹	۲۱.۴۱	۶۲.۵۶	۱۲.۰۳	۲۸.۹۲



(a)

(c) (b)

Figure 4- a) Out-of-plane bending in repairing cracked plate with glass epoxy patch b) Von Mises stress contour in adhesive c) Von Mises stress contour in glass epoxy patch

Figure 5 shows the stress intensity factor changes of the first and second modes according to different angles of crack of aluminum plate repaired with boron, graphite, carbon and glass epoxy composite patches. According to the graphs of changes in the first mode stress intensity factor in terms of crack angles in Figure 5, for all four repair patches in the one-sided repair mode, the first mode stress intensity factor gradually decreases from zero to 90 degrees, so that the maximum stress intensity factor of the first mode is at an angle of zero degrees and its minimum value, which is equal to zero, is at an angle of 90 degrees. But the stress intensity factor of the second mode increases from an angle of zero to 45 degrees and decreases from 45 degrees to 90 degrees, so that the maximum is at an angle of 45 degrees and at two angles 0 and 90 degrees its value is zero and the graph of the stress intensity factor of the second mode is almost symmetric in terms of crack angles with respect to the line perpendicular to the horizontal axis passing through the 45degree angle, Therefore, the amount of increase in the range of 0 to 45 degrees is not much different from the amount of decrease in the range of 45 to 90 degrees. For example, in one-sided repair with carbon epoxy patch, increasing the crack angle by 15 degrees from 30 to 45 degrees, increases by 6.03 $\mathrm{Mpa}.\sqrt{\mathrm{mm}}$ the second mode stress intensity factor and also, increasing the crack angle by 15 degrees from 45 to 60 degrees has reduced the second mode stress intensity factor by 5.36 $\mathrm{Mpa}.\sqrt{\mathrm{mm}}$. In one-sided repair with graphite epoxy patch, 15degree increase in crack angle from 15 to 30 degrees, the first mode decreased by 18.23% and the second mode increased by 75.86%. In two-sided repair, as in the case of one-sided repair, in the crack angle of 0 to 90 degrees, the stress intensity factor of the first mode decreases and the second mode increases from 0 to 45 degrees and decreases from 45 to 90 degrees. The amount of decrease in stress intensity factor of the first mode with increasing crack angle in two-sided repair mode is less than one-sided repair mode but the amount of increase in the stress intensity factor of the second mode in the range of 0 to 45 degrees and decrease in the range of 45 to 90 degrees in the case of two-sided repair is slightly more than one-sided repair. For example, in one-sided repair with graphite epoxy patch, increasing the crack angle by 15 degrees from 15 to 30 degrees has reduced the stress intensity factor of the first mode by 18.23%. but in the case of two-sided repair, the stress intensity factor of the first mode is reduced by 15.20% and also, for the second mode, increasing the crack angle by 15 degrees from 15 to 30 degrees in one-sided and two-sided repair has increased 75.86% and 78.96% of the stress intensity factor of the second mode, respectively, and as we can see, the stress intensity factor of the second mode in two-sided repair has increased slightly more than one-sided repair.

Also, according to Figure 5, we find that in one-sided repair mode, by increasing the crack angle from 0 to 90 degrees, the amount of reduction of the stress intensity factor of the first mode for all four patches come closer to each other, so that from an angle of 45 degrees to 90 degrees, the diagrams are very close to each other, and in this range of angles, the amount of reduction of the stress intensity factor of the first mode of all four patches is very little different from each other and in particular, from an angle of 60 to 90 degrees, the plate repair diagrams with all four composite patches are matched with the unrepaired state diagram, and this shows that in this range, the repair with composite patches does not have a significant effect on reducing the stress intensity factor of the first mode.

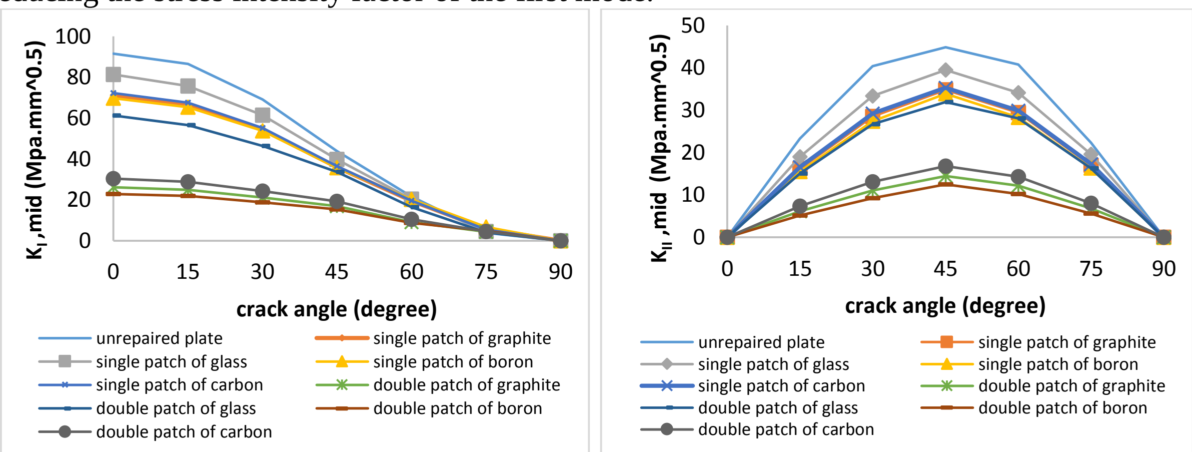


Figure 5 - Stress intensity factor changes of the first mode and the second mode according to different crack angles of aluminum plate repaired with composite patches

For the second mode, from the angle of 0 to 15 and from 75 to 90 degrees in the two-sided repair mode, the repair diagrams of all four patches are close to each other and are almost compatible and have the same function and here, unlike the first mode, the repair diagrams do not match the unrepaired plate diagrams in any range of angles and this shows that in all angles of the crack, repair with composite patches affects the second mode, but in some ranges of angles, the amount of the effect is high and in others it is less. also, according to Figure 5, for the first mode, in the range of 75 to 90 degrees, one-sided and two-sided repair diagrams of the plate are matched and this shows that in this range of angles, one-sided and two-sided repair has almost the same function on reducing the stress intensity factor of the first mode, of course in this range, the amount of reduction in the stress intensity factor of the first mode is very small.

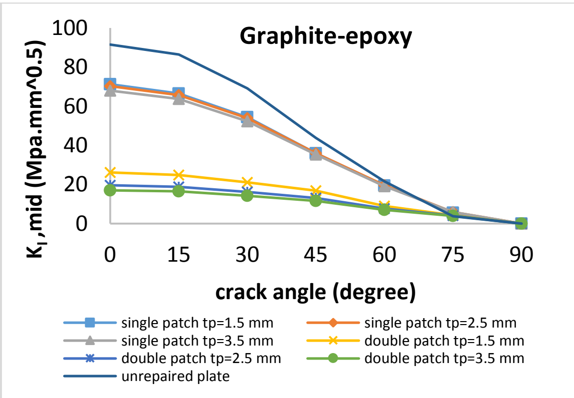
4-1- The effect of patch thickness on stress intensity factor

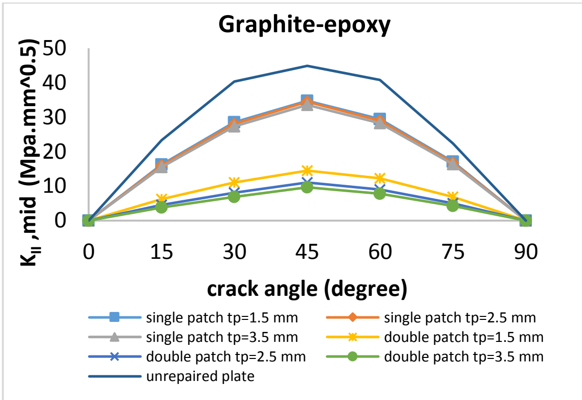
In this section, the effect of patch thickness on the repair efficiency of cracked plate with composite patches will be investigated. To do this, considering three different thicknesses of 1.5, 2.5 and 3.5 mm for boron, graphite, glass and carbon epoxy composite patches, we repair the cracked plate with different crack angles of zero to 90 degrees. The effect of patch thickness at each crack angle for each composite patch on the stress intensity factor of the first and second modes is shown in Figure 6. In this study, the length and width of one-sided and two-sided patches are the same, and also the thickness of the adhesive is the same, and the only variable in this study for all patches is the thickness of the composite patch.

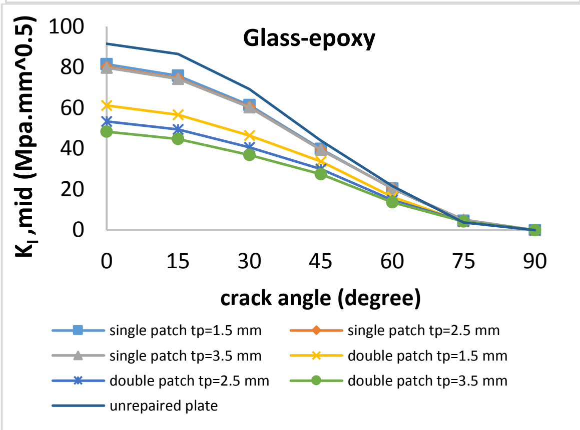
According to Figure 6 for graphite epoxy patch in two repair modes with one-sided and two-sided patch in all angles, with increasing the thickness of the patch, the stress intensity factor of the first mode and the second mode decreases. Increasing the thickness of the graphite epoxy patch by 2 mm in one-sided repair and at a crack angle of 30 degrees has reduced the stress intensity factor of the first mode and the second mode by 3.96% and 4.48%, respectively, and the stress intensity factor of the second mode has decreased more than the first mode. For glass patch in one-sided repair mode from zero to 60 degrees with increasing the thickness of the patch, the stress intensity factor of the first mode decreases, but from angle 60 onwards with increasing the thickness of the patch, the stress intensity factor of the first mode not only does not decrease but it increases slightly, but the second mode decreases at all angles as the patch thickness increases. For example, in one-sided repair and at a crack angle of 75 degrees, a 2 mm increase in the thickness of the glass epoxy patch increases the stress intensity factor of the first mode by 15.98% and is a considerable amount. It should be noted that for glass patch, the ratio of increasing the stress intensity factor of the first mode with increasing the thickness of the patch at angles of 60 onwards is less than the ratio of decreasing the stress intensity factor of the second mode at these angles. In the case of double-sided repair with glass epoxy patch, increasing the thickness of the patch from an angle of zero to 75 degrees reduces the stress intensity factor of the first mode, but from an angle of 75 onwards, the stress intensity factor of the first mode increases with increasing patch thickness but the stress intensity factor of the second mode decreases in all angles with increasing patch thickness. In double-sided repair, with increasing the patch thickness, the ratio of increasing the stress intensity factor of the first mode from angle 75 onwards is less than decreasing the stress intensity factor of the second mode in these angles. For boron and carbon epoxy patches, like graphite epoxy patches, in both repair modes with one-sided and two-sided patches in all angles with increasing the patch thickness, the stress intensity factor of the first mode and the second mode decreases. Increasing the thickness of the carbon epoxy patch by 2 mm in one-sided repair and at a crack angle of 15 degrees has reduced the stress intensity factor of the first mode and the second mode by 3.30% and 4.68%, respectively.

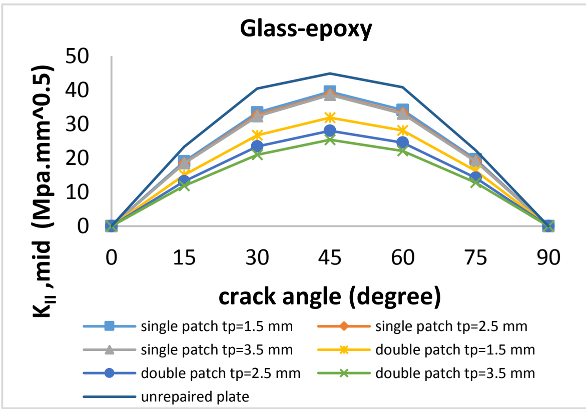
According to Figure 6 for all composite patches in double-sided repair, increasing the patch thickness has a greater effect on reducing the stress intensity factor of the first and second modes and causes a further reduction of the stress intensity factor compared to one-sided repair.

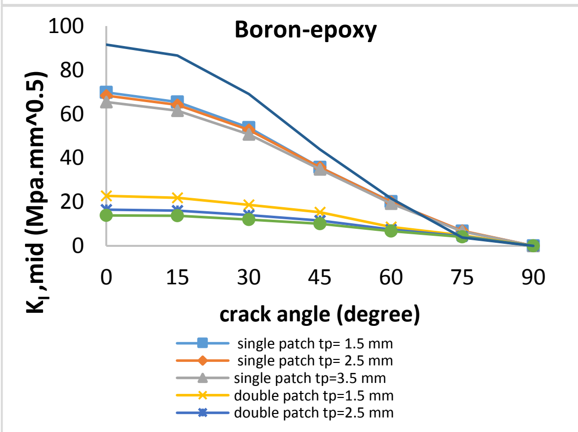
A 2 mm increase in the thickness of the boron epoxy patch in double-sided repair at a 45degree crack angle reduced the stress intensity factor of the first mode by 34.01%, while in single-sided repair at the same crack angle it only reduced the first mode by 2.54%. Also, for all composite patches at an angle of 0 to 45 degrees, the rate of decrease in the stress intensity factor of the first mode with increasing patch thickness is greater than the angle of 45 to 90 degrees, and the greatest decrease in stress intensity factor of the first mode with increasing patch thickness, at an angle of 0 degrees. but in relation to the stress intensity factor of the second mode, increasing the patch thickness at an angle of 30 to 60 degrees causes a further decrease in the stress intensity factor of the second mode compared to other angles and the greatest effect of patch thickness on the second mode is at a 45degree angle, at this angle, with increasing patch thickness, we will have the largest decrease in the stress intensity factor of the second mode.

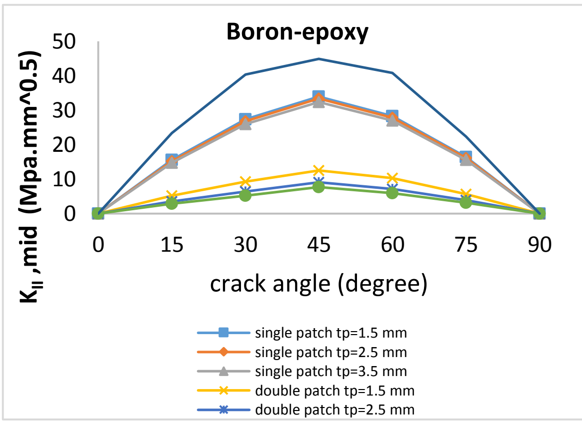












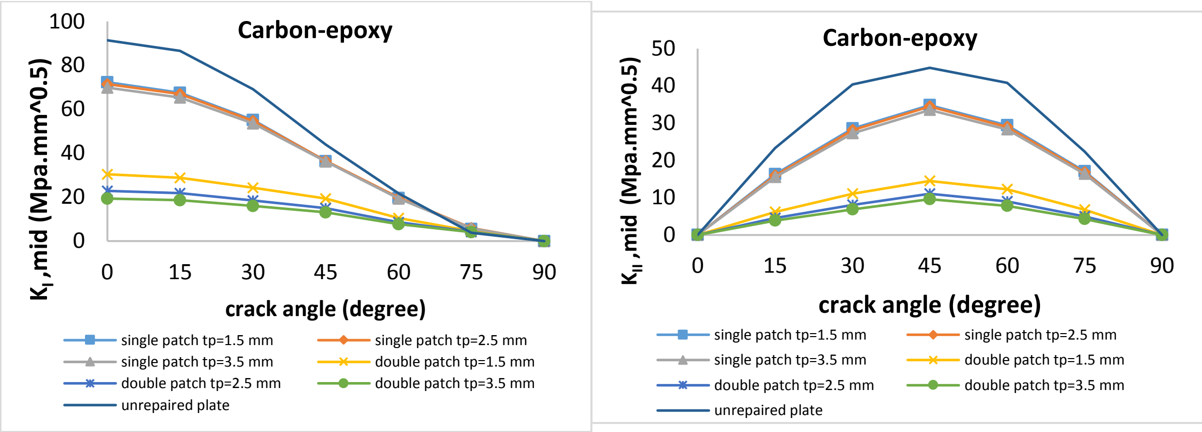


Figure 6 - Changes in the average stress intensity factor in terms of crack angle for composite patches with different thicknesses

The different thicknesses considered for glass epoxy patch in one-sided repair of cracked aluminum plate at 45degrees crack angle are shown in Figure 7. According to Figure 7, which shows the Von Mises stress contour, with increasing the thickness of the patch, the maximum stress of Von Mises in the patch has decreased, so that by increasing the thickness of the glass epoxy patch by 2 mm, the maximum stress of Von Mises in the patch by 17.89% Decreased.

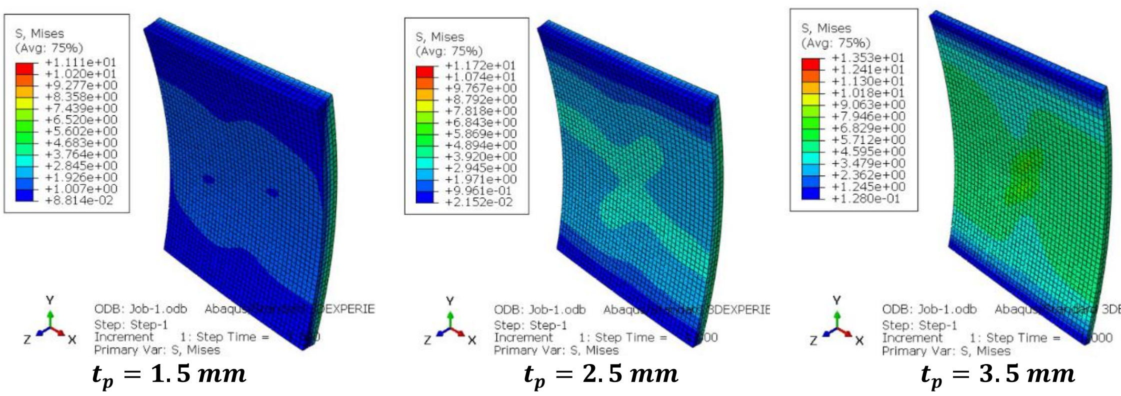


Figure 7- Different thicknesses considered for glass epoxy patch in one-sided repair of cracked aluminum plate at crack angle 45 degrees

4–2 –The effect of patch length on stress intensity factor

In this section, the effect of increasing patch length on patch efficiency in crack repair is investigated. To investigate the effect of increasing the patch length, we consider the lengths of 50, 60, 70 and 80 mm for graphite, glass, carbon and boron epoxy composite patches and examine the effect of increasing the patch length on each of the composite patches. The different lengths considered for composite patches are shown in Figure 8. In this study, the width and thickness of the patches are fixed and we consider 50 and 1.5 mm, respectively. The stress intensity factor variations of the first and second modes in terms of different crack angles (0 to 90 degrees) for different lengths of boron, carbon, graphite and glass epoxy composite patches are shown in Figure 7. According to Figure 7, for all four composite patches in two modes of one-sided and two-sided repair and in all crack angles, by increasing the length of the patches, the stress intensity factor of the first and second modes increases and the amount of increase in stress intensity factor of the first mode and the second mode in two-sided repair mode is more than one-sided repair and in one-sided repair, the stress intensity factor increases slightly. For example, in one-sided repair with graphite epoxy patch at a crack angle of 30 degrees with increasing the patch length by 30 mm, the stress intensity factor of the first and second modes has increased by 1.50% and 1.01%, respectively, and in this case, the first mode has increased slightly more than the second mode, and as mentioned at the beginning, the amount of increase in stress intensity factor with increasing patch length in one-sided repair is very small so that for graphite patch is less than 2% and the same for other patches. Also, in double-sided repair with graphite epoxy patch at a crack angle of 30 degrees, with a 30 mm increase in patch length, the stress intensity factor of the first and second modes has increased by 12.82% and 2.53%, respectively, and in this case the first mode has increased by 10.29% more than the second mode, and this shows that the increase in patch length has caused a further increase in the first mode compared to the second mode in two-sided repair and at a crack angle of 30 degrees.

In the one-sided repair of the cracked plate with carbon epoxy patch, a 30 mm increase in patch length at a 45degree crack angle increased 2.09% of the first mode stress intensity factor, and in two-sided repair at the same crack angle, it increased the first mode stress intensity factor by 12.65%. Also, in one-sided repair with glass epoxy patch, a 30 mm increase in patch length at a 45degree crack angle increased the stress intensity factor of the second mode by 0.86%, and in two-sided repair at the same angle of crack, it increased the stress intensity factor of the second mode by 2.88%. In repairing plate with boron epoxy patch at a crack angle of 15 degrees, by increasing the length of the patch by 20 mm (from 60 to 80 mm), the stress intensity factor of the first and second modes in the one-sided mode increases by 0.83% and 1.09%, respectively, and the second mode has increased slightly more than the first mode, and in general both values are not very high, and in this repair angle, the stress intensity factor of the first mode and the second mode in two-sided repair has increased by 17.12% and 13.25% more than one-sided repair, respectively.

Also, according to Figure 8, for all four patches, approximately from an angle of 60 degrees onwards, the stress intensity factor diagram of the first mode of the unrepaired state corresponds to the one-sided repair diagrams and this shows that from this angle on, composite patches do not have a significant efficiency to reduce the stress intensity factor and as a rule, increasing the patch length at these angles is of no use, but also causes the stress intensity factor to be higher than the unrepaired condition. Also, in double-sided repair from angle 75 onwards, the diagram of the non-repaired plate and the repair diagrams are matched, and in this case, the composite patches are not effective in reducing the stress intensity factor of the second mode and causes the stress intensity factor of the repaired plate to be higher than the stress intensity factor of the plate in the unrepaired state.

Therefore, according to the results of increasing the patch length, in some crack angles, whether single-sided or double-sided repair, it causes a further increase in the stress intensity factor of the first mode compared to the second mode and vice versa for some other angles, but the amount of stress intensity factor increases with The increase in patch length in two-sided repair mode is greater in both modes than in one-sided repair. It should be noted that in general, the amount of increase in stress intensity factor with increasing the length of patches is not much, but in any case, because it increases the stress intensity factor, thus with increasing the length of the patch, repair patches will be less effective.

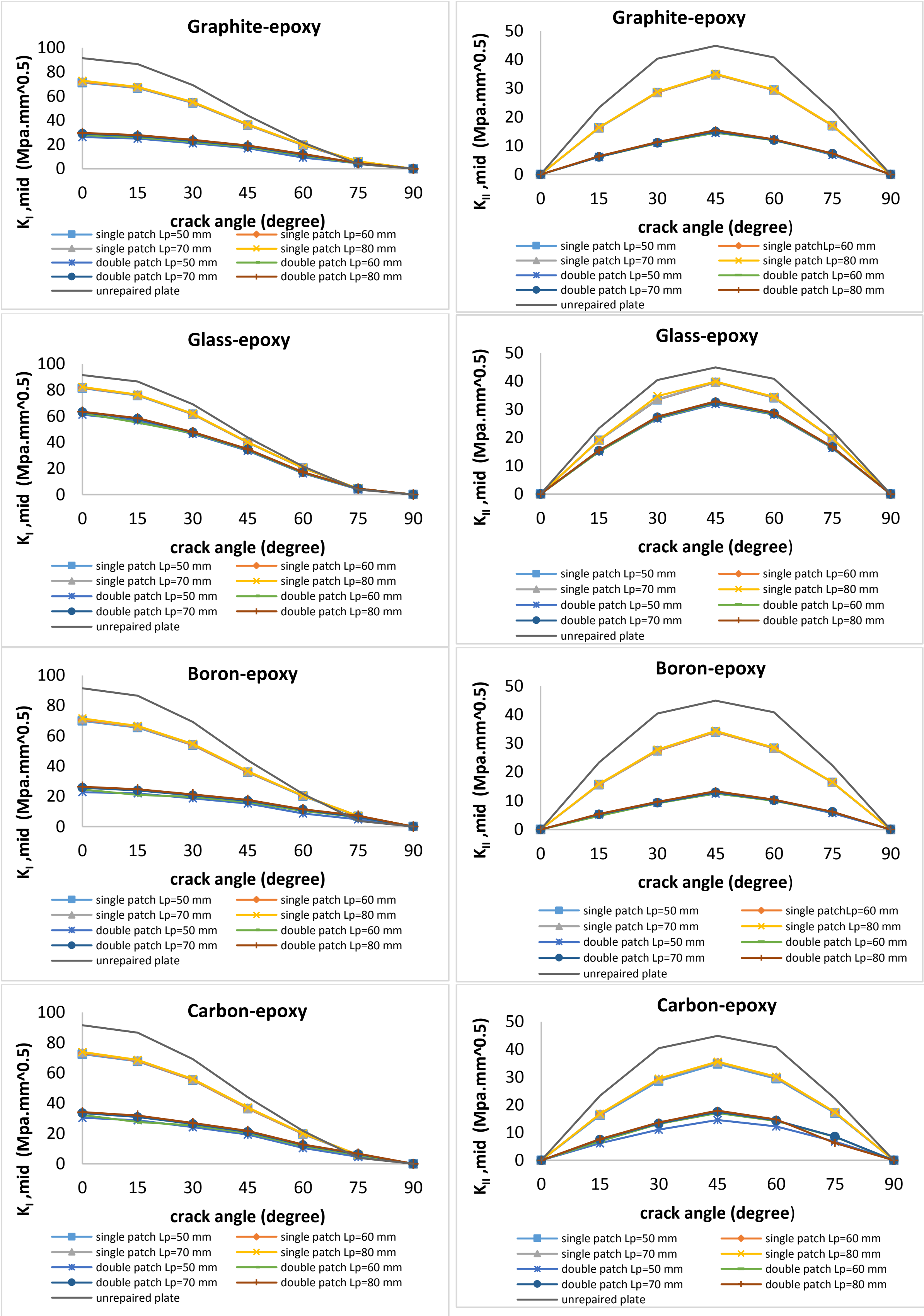


Figure 8 - Variation of average stress intensity factor in terms of crack angle for composite patches with different lengths

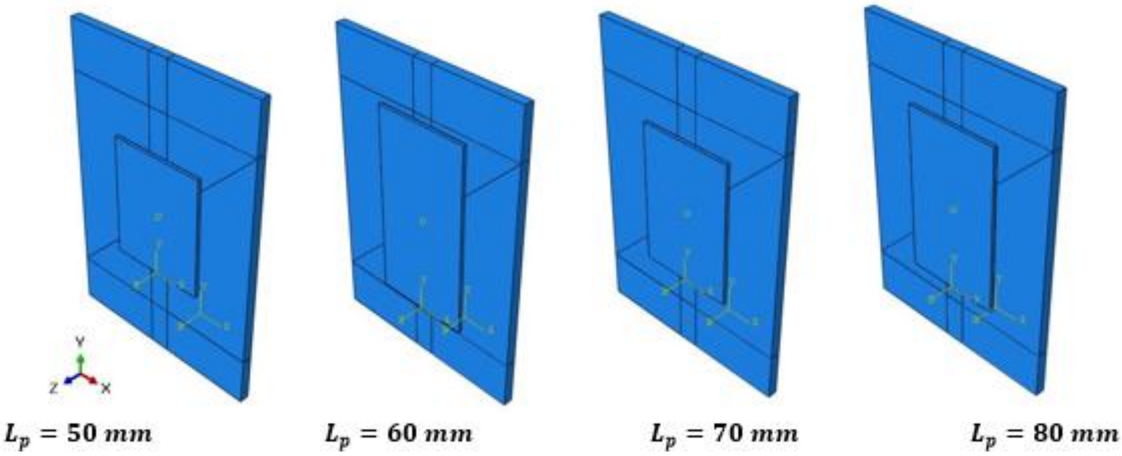
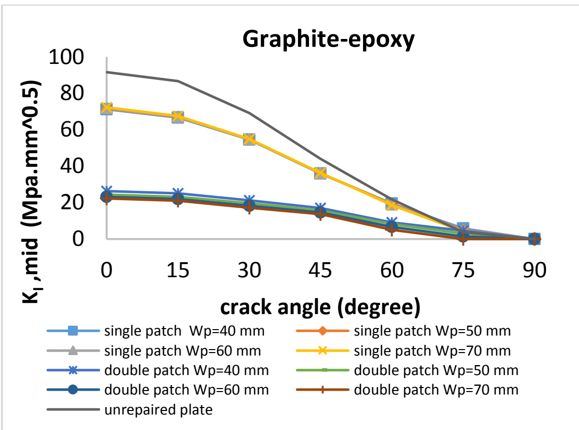


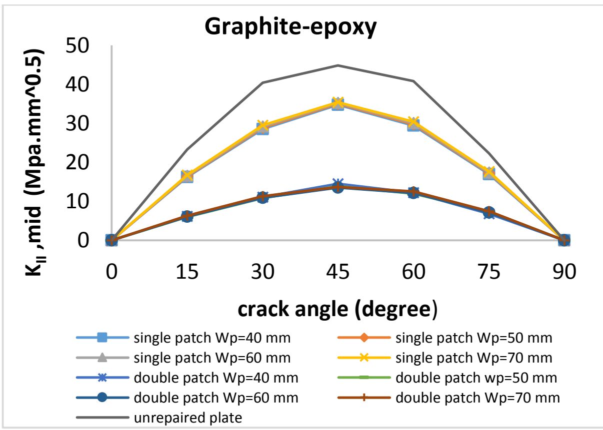
Figure 9 - Different lengths considered for composite patches in the repair of cracked plate

4-3- The effect of patch width on stress intensity factor

To investigate the effect of the width of composite patches on the stress intensity factor of the first and second modes, we use patches with a width of 40, 50, 60 and 70 mm and the results for all four patches are shown in Figure 10. According to Figure 9, increasing the width of graphite, boron and carbon epoxy composite patches in the one-sided repair of the cracked plate for crack angles from 0 to 45 degrees has increased the stress intensity factor of the first mode and If the crack angle increases (from zero to 45 degrees), the amount of increase in stress intensity factor decreases with increasing patch width, so that at an angle of 15 degrees with an increase of 30 mm width of the patch in one-sided repair with graphite patch has increased 1.20% stress intensity factor of the first mode and while at a 45 degree angle increase of 30 mm width of the patch has increased 0.61% stress intensity factor and is almost half at an angle of 15 degrees. For angles greater than 45 degrees and up to 90 degrees, increasing the patch width reduces the stress intensity factor of the first mode, so that at an angle of 75 degrees in one-sided repair with graphite epoxy patch, a 20 mm increase in patch width (from 40 to 60 mm) has reduced the stress intensity factor of the first mode by 18.86% and as the crack angle increases (from 45 to 90 degrees), the amount of decrease in the stress intensity factor of the first mode increases with increasing patch width.

but glass epoxy patch in one-sided repair has different behavior in changing the stress intensity factor of the first mode compared to changing the patch width in different crack angles compared to the other three patches. For the glass epoxy patch, with increasing the patch width from 50 mm onwards for the crack angle of 0 to 30 degrees, the stress intensity factor of the first mode is almost unchanged (It should be noted that with an increase of 10 mm in the first stage from 40 to 50 mm decreased slightly, but after that remained constant), but from an angle of 30 to 90 degrees, with increasing the width of the patch, the stress intensity factor of the first mode has decreased.





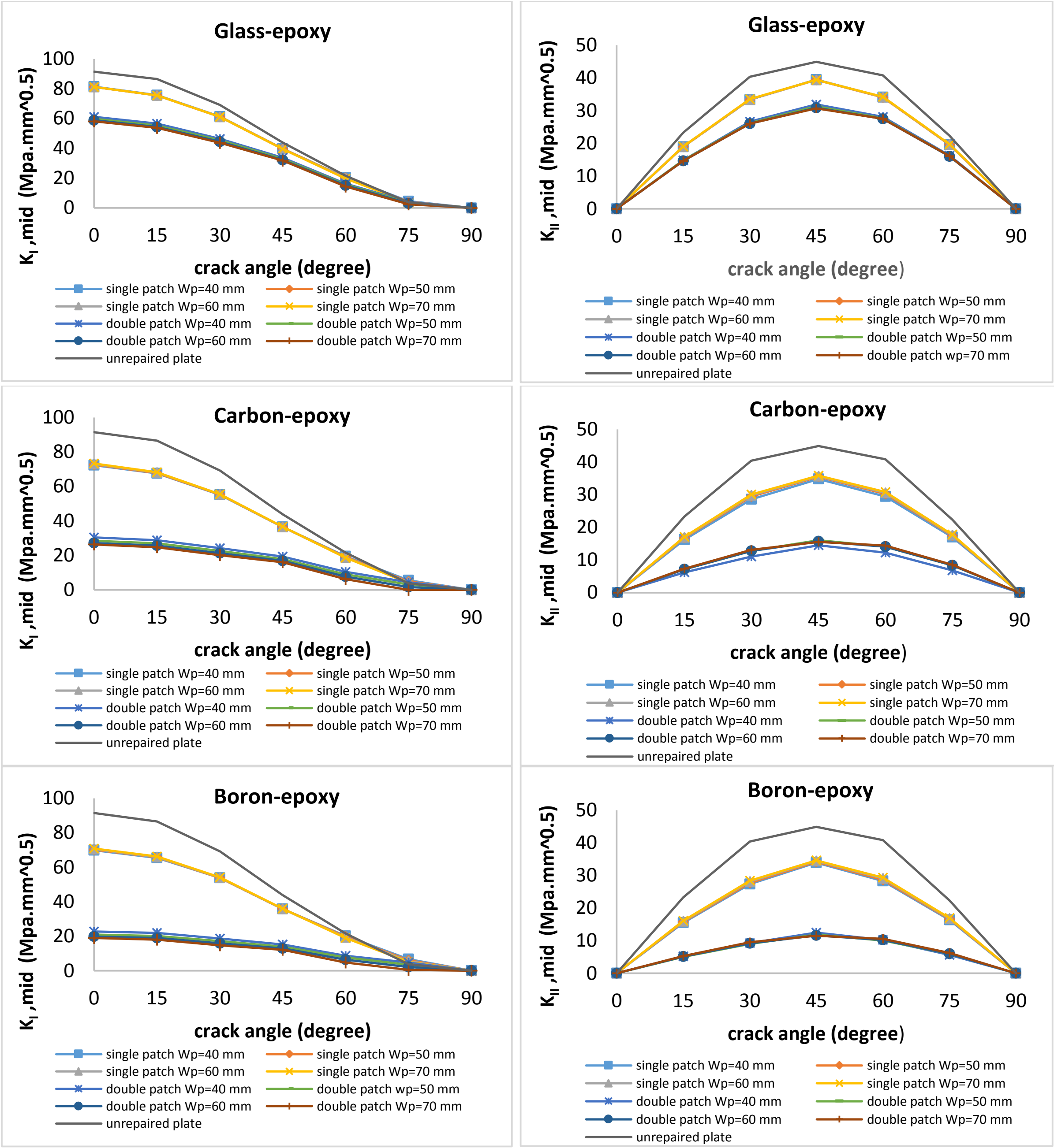


Figure 10 - Variation of average stress intensity factor in terms of crack angle for composite patches with different widths

But the second mode stress intensity factor for all four patches in one-sided repair increases from zero to 90 degrees with increasing patch width and the amount of increase from zero to 90 degrees decreases with increasing patch width. For example, at a crack angle of 15 degrees, a 30 mm increase in the width of the carbon epoxy patch in one-sided repair increased the stress intensity factor of the second mode by 5.17%., while at an angle of 60 degrees, increasing the width of the patch to the same value as before, has increased the stress intensity factor by 4.79%. In one-sided repair with boron epoxy patch at a 30degree angle, increasing the patch width by 30 mm has increased the stress intensity factor of the first mode and the second mode by 0.58% and 3.76%, respectively, also at an angle of 60 degrees, the stress intensity factor of the first mode decreased by 5.52% and the second mode increased by 3.89%, and also for glass epoxy patch in one-sided repair and at a 45degree angle with a 30 mm increase in patch width, the first and second modes have been reduced by 0.78% and 0.15%, respectively, which are very small values.

For two-sided repair from angle 0 to 90, with increasing the width of the patch, the stress intensity factor of the first mode decreases and the amount of reduction of the stress intensity factor from the angle of 0 to 90 degrees increases with increasing the width of the patch, so that in graphite patch repair, increasing the patch width by 30 mm at an angle of 15 degrees has reduced the stress intensity factor by 15.96%, but at a 60 degree angle has reduced the stress intensity factor of the first mode by 82.56%, and also for carbon epoxy patches at an angle of 60 degrees, a 30 mm increase in patch width has reduced the first mode stress intensity factor by 40.77%.

But the stress intensity factor of the second mode in two-sided repair for three patches of boron, carbon and graphite from an angle of 0 to 45 increases slightly with increasing the width of the patch and at an angle of 45 degrees, with increasing the width of the patch, the stress intensity factor of the second mode decreases. For example, at a 30degree angle in two-sided repair with boron epoxy patch, a 30 mm increase in patch width increased the second mode stress intensity factor by 3.02%, and at a 45-degree angle, the second mode stress intensity factor decreased by 8.08%. but for angles greater than 45 degrees and up to 90 degrees in two-sided repair, the stress intensity factor of the second mode increases again with increasing the width of the patch and the ratio of increasing the stress intensity factor of the second mode in the second phase (from an angle of 45 to 90 degrees) is higher than the first phase (from an angle of 0 to 45 degrees). For example, for a carbon epoxy patch at a 30degree angle, increasing the patch width by 30 mm in two-sided repair, increased the stress intensity factor of the second mode by 18.53%, while at a 75degree angle, a 30 mm increase in patch width caused a 25.58% increase in the stress intensity factor of the second mode. But for a glass epoxy patch from 0 to 45 degrees, increasing the patch width in double-sided repair reduces the stress intensity factor of the second mode. For example, a 30 mm increase in the width of the glass patch in double-sided repair and at a 45degree crack angle reduced the stress intensity factor of the second mode by 3.89%.

5- Summary and conclusion

In this research, the effect of the dimensions of boron, glass, carbon and graphite composite patches on one-sided and two-sided repair of cracked aluminum plate has been investigated by considering different crack angles from 0 to 90 degrees and the most important results of the research are as follows:

1- In one-sided and two-sided repair, the maximum and minimum reduction of stress intensity factor is related to boron epoxy and glass epoxy, respectively. In one-sided repair and at a 45degree crack angle, the boron epoxy patch reduced 8.89% and 13.10% more stress intensity factor of the first and second modes, respectively, than the glass epoxy patch.

2- For glass epoxy patch in one-sided repair from angle 60 onwards and in two-sided repair from angle 75 onwards, increasing the thickness of the patch increases the stress intensity factor of the first mode, but the stress intensity factor of the second mode in one-sided and two-sided repair in all angles 0 to 90 degrees, decreases with increasing patch thickness.

3- For all three boron, graphite and carbon epoxy patches in one-sided and two-sided repair for all considered angles, by increasing the patch thickness, the stress intensity factor of the first and second modes decreases.

4- By increasing the crack angle (from 0 to 90 degrees), the effect of patch thickness on reducing the stress intensity factor of the first mode decreases, and the greatest decrease in stress intensity factor is with increasing the patch thickness at zero angle and also, for the second mode, the greatest effect is in reducing the stress intensity factor at an angle of 45 degrees, and from 0 to 45 degrees, the effect of patch thickness on reducing the stress intensity factor of the second mode increases, and from 45 to 90 degrees, the effect of patch thickness on reducing the stress intensity factor of the second mode decreases.

5- As the thickness of the patch increases, the maximum Von Mises stress in the patch decreases, so that for the glass epoxy patch in one-sided repair and at a 45degree crack angle with a 2 mm increase in patch thickness, the Von Mises stress in the patch is reduced by 17.89%.

6- With increasing the length of the patch in one-sided and two-sided repair, the stress intensity factor of the first mode and the second mode increases slightly and the amount of increase in two-sided repair is more than one-sided repair, and also the amount of increase in stress intensity factor of the first mode with increasing the length of the patch in one-sided and two-sided repair is more for some angles than the second mode, and vice versa for some other angles.

7- For all four patches examined, in one-sided repair from an angle of 60 to 90 degrees, the stress intensity factor diagram of the first mode of the repaired plate and without repair, coincides, and this shows that in this range of angles, the composite patch has no significant effect on reducing the stress intensity factor of the first mode and in this range of angles, increasing the patch length causes the stress intensity factor to be higher than the unrepaired plate, and also in the case of two-sided repair, in the range of 75 to 90 degrees, increasing the length of the patch causes the stress intensity factor of the first mode to be higher than the unrepaired condition.

8- In one-sided repair, increasing the width of graphite, boron and carbon epoxy composite patches in the crack angle of 0 to 45 degrees has increased the stress intensity factor of the first mode, and from the angle of 45 to 90 degrees has reduced the stress intensity factor of the first mode of all three patches. but the stress intensity factor of the first mode of glass epoxy patch is different with increasing the patch width compared to the other three patches, so that it has not changed in the crack angle of 0 to 30 degrees, but has decreased from 30 to 90 degrees. and the stress intensity factor of the second mode for all four patches decreased with increasing the patch width from 0 to 90 degrees.

9- In two-sided repair for all angles and for four patches, increasing the patch width reduces the stress intensity factor of the first mode but the stress intensity factor of the second mode in two-sided repair increases slightly from zero to 45 degrees for all three patches of carbon, boron and graphite and in the angle of 45 degrees decreases a little, but from the angle of 45 degrees to 90 degrees it increases again, and the stress intensity factor of the second mode of glass epoxy patch decreased from 0 to 90 degrees with increasing patch width.

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7- Appendix

Notation

E Young’s modulus
G shear modulus
K_I mode I stress intensity factor
K_{II} mode II stress intensity factor
L_p patch length
W_p patch width
β crack angle
2a crack length
t_p patch thickness
v Poisson’s ratio