Evaluation of Mixed-Mode Center Crack SIF in a Curved Plate Repaired by Stop Holes, Composite Patch, and Hybrid Methods

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Abstract: In this research, using the 3D finite element method and considering different materials for a composite patch, the effect of separate and simultaneous use of stop holes and composite patch (one-sided and two-sided) on reduction of SIF in a curved plate including mixed-mode crack is investigated. Glass-epoxy, graphite-epoxy, carbon-epoxy, and boron-epoxy are used for repair patches. For the one-sided patch, the effects of different geometric parameters on the efficiency of the repair are investigated. For all four composite patches, as the thickness of the patches increases, KI and KII decrease, but with increasing the patch length, KI and KII increase. The research results also show that with increasing the width of the glass-epoxy patch, KI and KII almost do not change, but for other patches, as the patch width increases, the SIF increases. The effect of the radius of curvature of the plate on the efficiency of various repair methods is also investigated. In all repair methods studied, SIF decreases with increasing radius of curvature of the curved plate. Different repair methods are compared and the best method with the highest efficiency is introduced. The best repair mode is the hybrid repair method (stop-holes and two-sided boron-epoxy patch), which reduces K_I and K_{II} by 84.50 and 86.6%, respectively. Finally, the effect of adhesive thickness used for patch bonding on hybrid repair method efficiency and durability is investigated. for all four materials of patches understudy, KI and KII increase with increasing the thickness of the adhesive, but on the other hand, as the thickness of the adhesive increases, the maximum Von Mises stress in the adhesive decreases.

Keywords: Composite Patch, Crack Repair, Crack Stop Holes, Fracture Mechanics, Stress Intensity Factor

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Biographical notes: Sirvan Mohamadi received his PhD and MSc in Mechanical Engineering from K. N. Toosi University of Technology, Tehran, Iran, and his BSc from the University of Tabriz, Iran in 2006. He has completed his PhD research in estimating the life of a helicopter rotor from the perspective of fracture mechanics in 2015. He is currently Assistant Professor at the Department of Mechanical Engineering, Kurdistan University, Sanandaj, Iran. His current research interest includes stress analysis and strength of structures, fracture mechanics, and fatigue. **Sadegh Daryaei** received his BSc in Mechanical Engineering from the University of Kurdistan, Iran in 2020. His current research interest is fracture mechanics.

1 INTRODUCTION

In many structures used in various industries, machinery, helicopters, pressure vessels, pipes, etc. for various reasons such as impact, corrosion, improper production process, and ... Cracks and defects may occur. At the same time, due to the high cost of replacing parts and machines, in many cases, it may be preferable to carry out repairs instead of replacing them. If parts, structures, and machinery are repaired properly, they will be more useful and economical to use. One of the best methods of repairing metal and non-metal structures is the use of composite repair patches, which have many advantages over other types of repair methods. Composite patch increases fatigue life, reduces corrosion, and is easily formed. In structures containing cracks, the patch reduces the SIF and thus slows down and stops the growth of the crack. The main advantage of the patch repair method is that the weight of the structure does not increase much. The composite patch does not require high temperatures during installation and thus does not create residual stress. Also, the composite patch requires less skill to install than welding. The use of repair patches in helicopters is very limited. Basically, in helicopters, any kind of repair for its dynamic parts such as blades, shafts, etc. is prohibited, and after the end of its working life, these parts will be replaced [1]. However, in emergency cases, these patches can be used temporarily to repair helicopter components [2-3].

The effect of one-sided and two-sided composite patches on crack growth in an aluminum single-notch tensile specimen has been investigated in a research work [4]. In this research work, the life of the repaired plate with a two-sided patch was 3.88 times higher than the life of the state without the patch. In addition, with the number of equal layers, the life of the one-sided and two-sided states did not differ. Elastic-plastic analysis of the structure of a cracked aircraft repaired with a composite patch was investigated in another research work [5]. The obtained results show the difference between the plastic area of the patched and unpatched side by 50%. According to the existing relations, for one-sided patching, due to the inequality of the patched and unpatched SIF, the equivalent value was defined as K_eq = 1.35 K_patched for the SIF. For the two-sided patch state, r_p (radius of the plastic area around the crack) is 65% less than the one-sided repair. An analytical model for designing one-sided composite patches for repairing cracked plates was presented in research work [6]. Parametric analysis shows that the patch thickness has a greater effect on SIF than the patch Young's modulus. FEM analysis shows that the length of the patch (in the same direction as the crack), as well as its width, did not affect the G_I (energy release rate). Finite element analysis of a composite patch for repairing metal and composite plates was presented in another research work [7]. FRANC2D / L was used to investigate the problem. It was proved that the patch reduces the SIF and as a result, the crack slows down and stops. Fatigue behavior of 7075 - T6 aluminum plate repaired with one-sided carbon epoxy composite patch was investigated in another research work by performing tests considering different initial lengths for the crack [8]. The amount of the fatigue life increase due to patching is 2.2 and 4.3 times the unpatched state for the initial crack lengths of 9 and 3 mm, respectively. It is clear that for smaller initial cracks, the repair patch is more efficient. Therefore, it is better to apply the patch as soon as the crack is detected. The fatigue crack growth behavior of aluminum used in ships and aircraft repaired by composite patches in corrosive environments was investigated in research work [9]. The results show that applying salt water to the samples during testing increased the crack growth rate. In reference [10], the efficiency of the composite patch was compared with that of the metal patch. The increase in fatigue life was 95% and 230%, when using metal and composite patches, respectively. Fatigue crack growth analysis of aluminum plate repaired by carbon- epoxy composite patch was performed in another work [11]. With the application of repair patches, the life was increased between 2.27 to 4 times. For a thin plate, the life of the plate increases with increasing the patch thickness. Strength and fatigue testing of composite patches for repairing ship plating steel plates was performed in one of the research works [12]. FEM analysis shows a 200% of life, while the test shows a 100% increase in fatigue life (reason: adhesion separation and patch cracking). Boron-epoxy patch has extended the plate fatigue life more than graphite-epoxy. The effects of one- and two-sided patching on the repaired composite laminate exposed to multiple impacts were investigated in research work [13]. The double-sided geometry withstood more load, had less displacement and supported more elastic energy. For double-sided patching, longer impact fatigue life was also obtained due to greater stiffness. Impact analysis of composite patches with different shapes at low speed for composite aircraft structure was investigated in research work [14]. Based on the lowest stress concentration, the oval patch was selected as the best patch shape. Crack growth and patch separation analysis of aluminum pipe repaired by composite patch under tensile fatigue load were investigated in another work [15]. One of the results was that if the direction of the patched fiber is in the direction of the load, it will have the greatest contribution to the load-bearing. The laboratory and numerical fatigue crack growth in aluminum pipes including mixed-mode cracks repaired by a composite patch were investigated in research work [16]. Patching had a great effect on reducing SIF. For longer cracks, the patch effect is more important. In reference [17], the SIF for cracks repaired with a composite patch under mechanical load in aerospace structures was investigated. It was observed that the separation effect becomes very important when its development direction is perpendicular to the crack. As mentioned in reference [18], patch separation near the crack leads to a greater increase in crack growth rate than patch separation at the patch edge. The important conclusion obtained in reference [19] is that the effect of different parameters on the performance and durability of one-sided composite patches depends not only on the thickness of the main plate and the patch but also on the material of the patch. The effect of different parameters on the damage and residual strength of the composite patch under fatigue load was investigated in another study [20]. Different shapes of the patch were examined and it was observed that the square patch is the best case and, compared to the case without the patch, the remaining strength increased by 27.6%. Finite element analysis of cracked metal plate repaired with a composite patch in research work [21] was performed and the effect of patch thickness on SIF was investigated. The results show that the symmetrical patch significantly reduced the SIF compared to the one-sided patch. In addition, as the thickness of the patch increases, the SIF decreases. For the steel plate, the carbon-epoxy patch performed better than other materials. The use of hybrid methods to repair parts is limited to a little research and the results of the research show that the use of combined methods (patch-stop hole, welding-rivet, glue-rivet, etc.) is more efficient than separate repair with each of the methods, in addition, due to the use of curved plates in various industries such as aerospace and shipbuilding, etc., doing this research is important.

In this research, using the 3D finite element method and considering different materials for a composite patch, the effect of separate and simultaneous use of stop holes and composite patch (one-sided and two-sided) on reduction of SIF in a curved plate including mixed-mode crack is investigated. For the one-sided patch, the effects of different geometric parameters on the efficiency of the repair are investigated and the parameter with the greatest impact on the performance of the repair patch is determined. Glass-epoxy, graphite-epoxy, carbon-epoxy, and boron-epoxy are used for repair patches. The effect of the radius of curvature of the plate on the efficiency of different repair methods is also investigated. Different repair methods are compared and the best method with the highest efficiency for repairing cracked curved plates in mixed-mode is introduced. Finally, the effect of adhesive thickness used for patch bonding on repair efficiency and durability is investigated. Studies show that the effect of simultaneous application of repair patch and crack stop holes on reducing SIF in the curved plate including mixed-mode crack has not been performed in previous investigations.

2 PROBLEM DEFINITION AND FINITE ELEMENT MODELING

In this study, to investigate the effect of stop holes on both sides of the crack and composite patches on the reduction of SIF in the mixed-mode crack, a curved plate (a sectional cut at an angle of 30 degrees from a cylinder with a radius of 1 meter) containing a 30 mm long crack with an angle of 45 degrees is considered. The length of the circumferential side and the thickness of the model are 0.5 m and 4 mm, respectively. The plate is made of an aluminum alloy with an elastic modulus of 74 GPa and a Poisson's ratio of 0.33. The top and bottom edges of the plate are bounded in a radial direction and a tensile load of 1 MPa is applied to it. For repair with stop holes, holes with a diameter of 5 mm were drilled at a distance of 3 mm from the crack tip. Also, for patch repair, composite patches are cut segmentally with a 15-degree angle from a cylinder with a radius of 1 m. The length of the peripheral side of the patch is 250 mm and the width of the patch is 260 mm. In this study, composite patches of different materials of boron, carbon, graphite, and glass epoxy are used. To connect the composite patches, a thin layer of FM73 adhesive with a thickness of 0.1 mm is used, and because in this research the goal is not to investigate the separation and damage of the adhesive, so in modeling, the adhesive is considered as a solid layer. The properties of composite patches and adhesive are presented in “Table 1”. XFEM is used to calculate the stress intensity factor (SIF) at the crack tip and 20-node hexagonal elements (C3D20R) are used in the modeling. The model of cracked curved plate has meshed with 71620 elements. The model of the cracked curved plate repaired with stop holes and a composite patch in Abaqus software is shown in “Fig. 1”.

Table 1 Properties of composite patches and adhesive (E and G in Gpa)

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	-	-

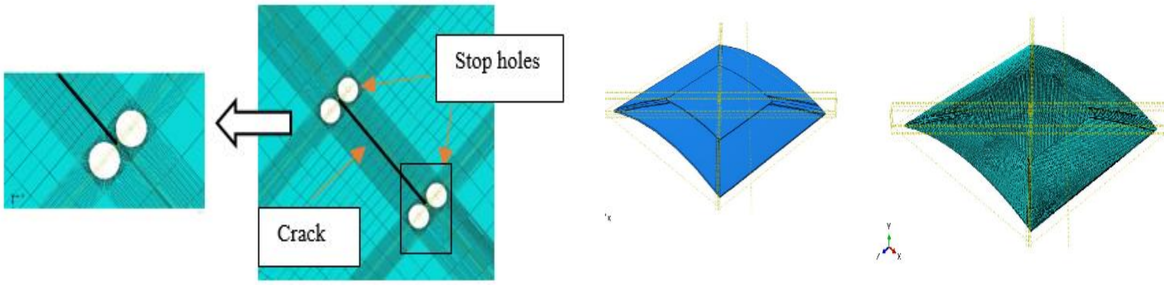


Fig. 1 Model and meshing around crack tip and crack stop holes in Abaqus software.

For the validation of the finite element analysis, K_I and K_{II} were obtained for an unrepaired flat plate containing a 30 mm long crack with a 45-degree angle from theoretical relations (1) and (2). Then the results were compared with the SIF obtained from the 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 = 1 Mpa is the stress applied to the edges of the plate, a = 15 mm is half the crack length, and β = 45° is the crack angle. K_I and K_{II} obtained from finite element analysis are 3.50 Mpa.√mm and Mpa.√mm 3.45, respectively. K_I and K_{II} obtained from the theoretical relations are the same and equal to 3.43 Mpa.√mm. Considering that the maximum difference of the first and the second mode SIF calculated from the theoretical relations and finite element analysis is 2%, this shows that the modeling performed has acceptable accuracy.

3 REPAIRS OF THE CURVED PLATE WITH COMPOSITE PATCHES

In this section, the repair of the curved plate with composite patches is investigated.

3.1. Repair of the Plate with A One-Sided Composite Patch

Figure 2 shows the changes in K_I and K_{II} along the plate thickness for curved plates with a radius of curvature of 1 and 3 meters repaired with one-sided composite patches of carbon, graphite, boron, and glass-epoxy. As can be seen, the K_I decreased on the repaired side but increased on the unrepaired side. In addition, the K_{II} of the repaired side differs from the unrepaired side, but this difference is less than the first mode.

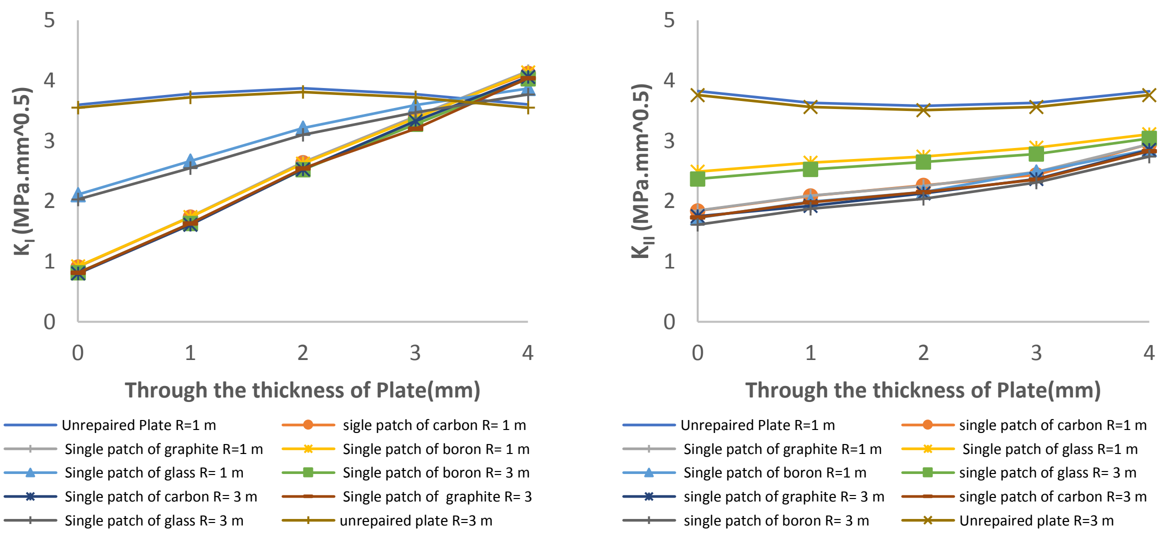


Fig. 2 Variations of K_I and K_{II} along with the plate thickness for the curved plate repaired with single patches.

According to "Fig. 2", boron, graphite, and carbon epoxy patches have reduced the SIF further than the glass epoxy patch. The greatest reduction in SIF is caused by the use of the boron-epoxy patch, which reduces SIF slightly more than carbon and graphite patches. For the second mode, the percentage of SIF reduction for all three patches of boron, carbon, and graphite is close to each other. The use of a one-sided boron-epoxy patch in modes I and II reduced the SIF by 31.40 and 39.27%, respectively (R = 1 m). In general, in the one-sided repair, composite patches reduce K_{II} more than K_I (“Fig. 2”).

3.2. The Effect of Patch Dimensions on The Efficiency of The Composite Patch Method

In this section, the effect of the dimensions of composite patches (length, width, and thickness) on the reduction of K_I and K_{II} is investigated.

3.2.1. Patch Thickness

To investigate the effect of the patch thickness on repair efficiency, patch thicknesses of 1, 1.5, 2, 2.5, and 3 mm are considered for all four composite patches of boron, carbon, graphite, and glass-epoxy. Figure 3 shows the changes in K_I and K_{II} in terms of patch thickness for both radii of curvature of the plate 1 and 3 meters.

According to “Fig. 3”, for all four composite patches of boron, graphite, glass, and carbon-epoxy, as the thickness of the patches increases, K_I and K_{II} decrease, and the patch efficiency increases. For both 1 and 3-meter radii of the curved plate, the amount of SIF reduction is greater in the second mode. For example, for the glass-epoxy patch, increasing the patch thickness from 1.5 to 2.5 mm reduced the K_{II} by 12.63%, while the K_I decreased by only 6.45% (R=1 m). The results of research [19] also show that in general, increasing the patch thickness reduces the SIF. Another point is that compared to a curved plate with a radius of 1 meter, K_I and K_{II} are less for a plate with a radius of 3 meters. As the radius of curvature increases, for the glass-epoxy patch, K_{II} decreases more than K_I, but for the three boron, carbon, and graphite-epoxy patches, K_I and K_{II} decrease almost equally. For the glass-epoxy patch, K_{II} and K_I decreased by 5.22% and 3.44%, respectively, by increasing the radius of curvature by 2 m at a thickness of 2.5 mm.

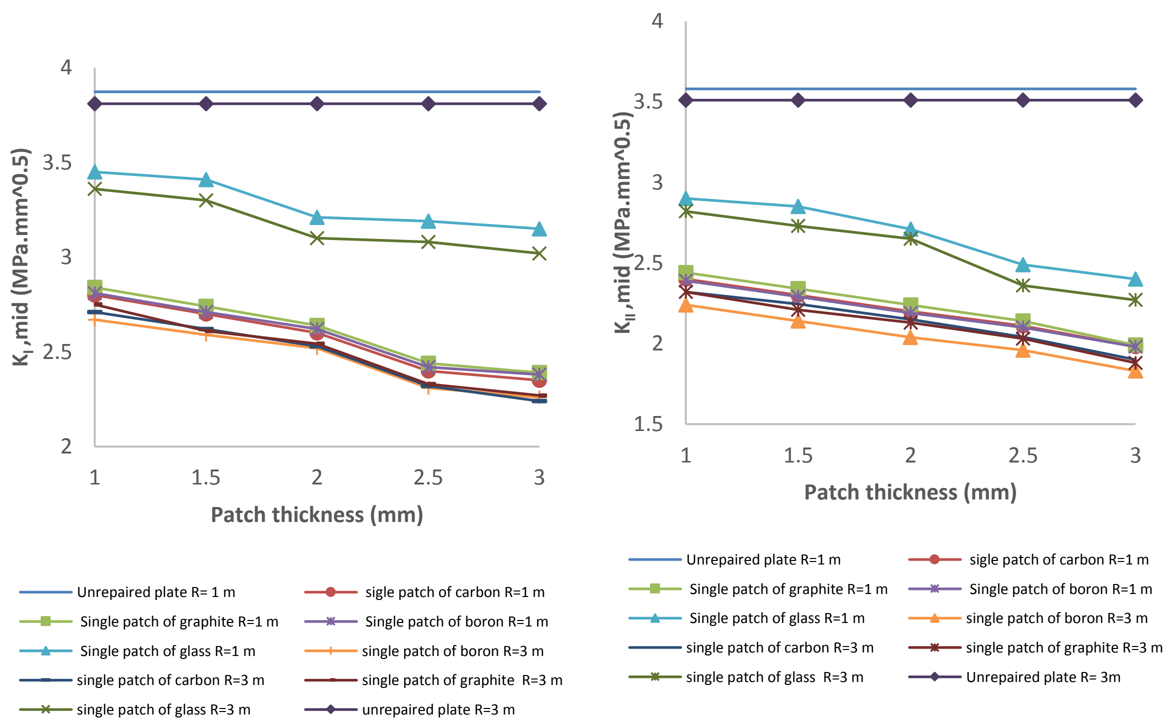


Fig. 3 Variations of K_I and K_{II} in terms of the patch thickness.

3.2.2. Patch Length

In this section, for the two radii of curvature of 1 and 3 meters of the curved plate, the effect of patch length on K_I and K_{II} is investigated (“Fig. 4”). According to “Fig. 4”, with increasing the patch length, K_I and K_{II} increase and the amount of K_{II} increase is greater than K_I. For example, increasing the length of the carbon-epoxy patch from 250 to 300 mm increases the K_I and K_{II} by 7.40% and 13.63%, respectively (R = 1m). Therefore, increasing the patch length is not a good way to increase repair efficiency. The results of the study [22] also confirm that increasing the patch length increases the SIF on the cracked flat plate. Increasing the graphite-epoxy patch length from 250 to 350 mm has increased K_I and K_{II} almost equally.

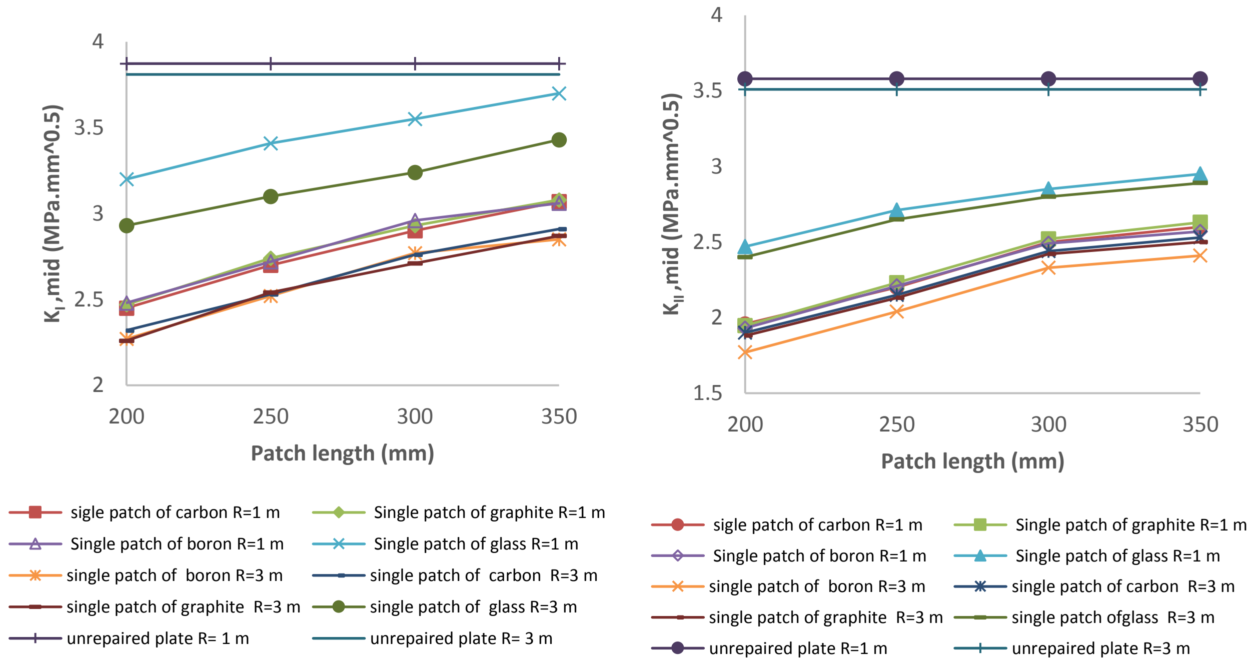


Fig. 4 Variations of K_I and K_{II} in terms of the patch length.

3.2.3. Patch Width

In this section, the effect of the patch width on K_I and K_{II} for a curved plate with a radius of curvature of 1 and 3 m is investigated ("Fig. 5"). According to "Fig. 5", with increasing the width of the glass-epoxy patch, K_I and K_{II} almost do not change, but for other patches, as the patch width increases, the SIF increases and the amount of K_I increase is slightly greater than K_{II}. Increasing the width of the graphite-epoxy patch from 210 to 260 mm increases the K_I and K_{II} by 10.93% and 9.35%, respectively (R = 1m). As the radius of curvature increased, the K_I of the glass-epoxy patch decreased more than the other patches, but the K_{II} of all patches decreased almost equally. In repair with 310 mm wide glass-epoxy patch, increasing the radius of curvature from 1 to 3 m reduced K_I and K_{II} by 8.83% and 1.84%, respectively.

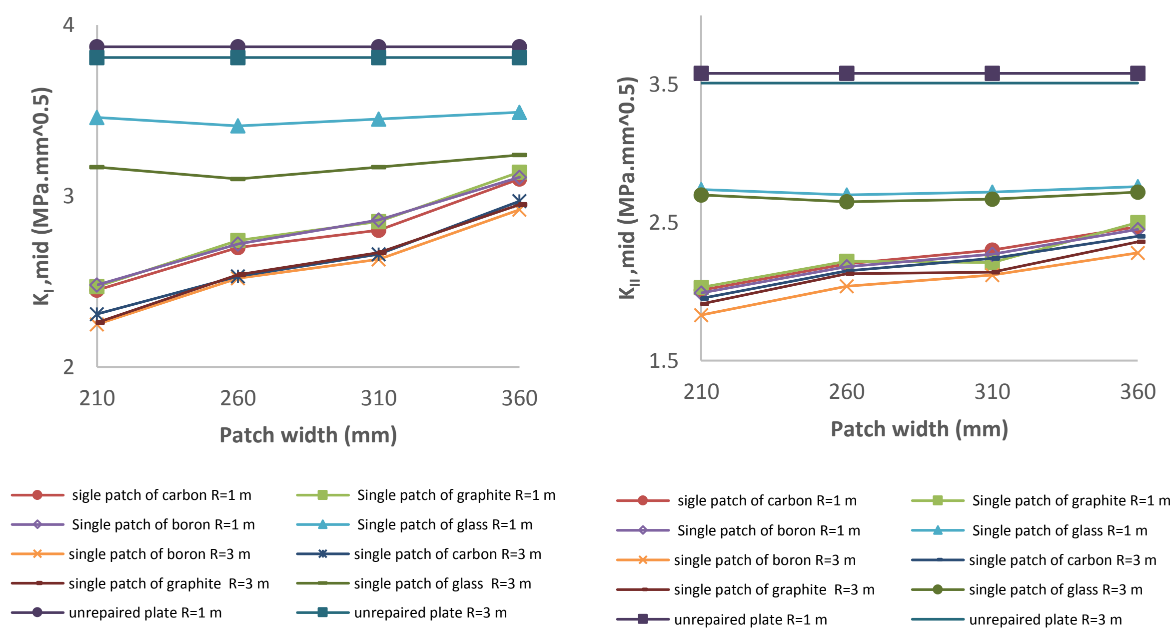


Fig. 5 Variations of K_I and K_{II} in terms of patch width.

3.2.4. Comparing the Effect of Different Parameters on Repair Efficiency

For a curved plate with a radius of curvature of 1 m, K_I and K_{II} decrease by 4.80 and 1.49%, respectively, with an increase of 0.6 mm in the thickness of the boron-epoxy patch (40% of the initial patch thickness). Also, by increasing the patch length by 100 mm (40% of the initial patch length), K_I and K_{II} increase by 12.50% and 16.28%, respectively. Meanwhile, with a 104 mm increase in patch width (40% of the initial patch width), K_I and K_{II} increase by approximately 12.54 and 12.38%, respectively. Therefore, compared to the thickness of the patch, changing its length and width has a greater impact on repair efficiency. Although increasing the thickness of the patch has a positive effect on the efficiency of the patch, increasing the length and width of the patch does not have a positive effect.

3.3. Repairing the Curved Plate with A Double-Sided Composite Patch

In this section, the repair of the cracked curved plate with a two-sided composite patch for two curvature radii of 1 and 3 meters of the curved plate is investigated and compared with the one-sided repair mode (“Fig. 6”). The length, width, and thickness of the patches used are the same in one-sided and two-sided modes.

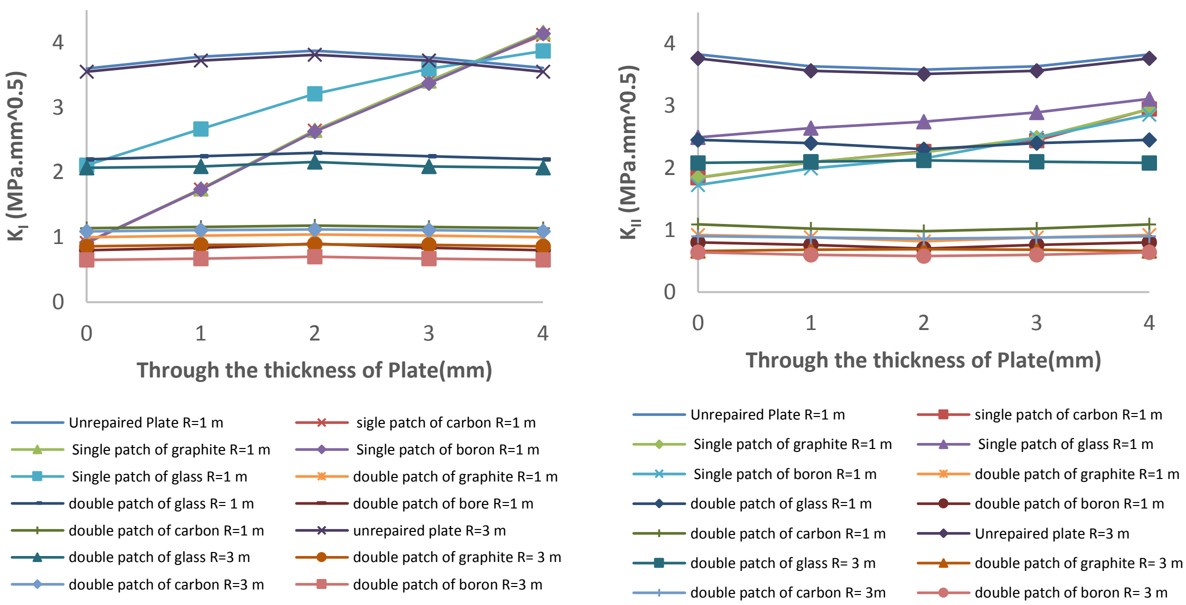


Fig. 6 K_I and K_{II} along with the plate thickness for the curved plate repaired with one and two-sided composite patches.

According to “Fig. 6”, the use of double-sided composite patches has further reduced the SIF compared to one-sided patches. For example, in one-sided repair mode, graphite patch reduces K_I and K_{II} by 30.84 and 37.17%, respectively, while in two-sided repair, the corresponding numbers are 73.06 and 77.14%, respectively (R = 1m). In the case of double-sided repair, in both curvature radii of 1 and 3 m of the curved plate, the highest SIF reduction belongs to the boron-epoxy patch, which reduces K_I and K_{II} by 76.76% and 80.44%, respectively (R = 1m). The use of the double-sided composite patch, unlike the one-sided patch, reduces K_I and K_{II} almost equally. The lowest SIF reduction is for the glass-epoxy patch.

The effect of increasing the patch thickness on stress intensity factors in one- and two-sided repair of the cracked curved plate can be seen in “Table 2” (R = 1m). According to “Table 2”, in both one- and two-sided repair modes, the SIF of the first and second modes decrease with increasing the patch thickness. For different thicknesses, the maximum reduction of K_I and K_{II} is achieved in repair with boron epoxy composite patch, so that in two-sided repair and for a thickness of 1 mm, the patch has reduced K_I and K_{II} by 76.76 and 80.44%, respectively. Therefore, according to “Table 2”, the best case for repair with composite patches is double-sided repair with boron epoxy patch, and on the other hand, the more we consider the thickness of the boron epoxy patch, the higher the repair efficiency.

According to “Fig. 6”, the use of double-sided composite patches has further reduced the SIF compared to one-sided patches. For example, in one-sided repair mode, graphite patch reduces K_I and K_{II} by 30.84 and 37.17%, respectively, while in two-sided repair, the corresponding numbers are 73.06 and 77.14%, respectively (R = 1m). In the case of double-sided repair, in both curvature radii of 1 and 3 m of the curved plate, the highest SIF reduction belongs to the boron-epoxy

patch, which reduces K_I and K_{II} by 76.76% and 80.44%, respectively (R = 1m). The use of the double-sided composite patch, unlike the one-sided patch, reduces K_I and K_{II} almost equally. The lowest SIF reduction is for the glass-epoxy patch.

Table 2 The effect of increasing the thickness of patches on stress intensity factors in different repair methods (R=1 m).

SIF \ Patch thickness		1 mm	1.5 mm	2 mm	2.5 mm	3 mm
SIF(K_I)	Single Glass	3.45	3.41	3.20	3.19	3.15
	Single Graphite	2.84	2.73	2.65	2.44	2.39
	Single Boron	2.81	2.70	2.62	2.42	2.38
	Single carbon	2.81	2.69	2.62	2.39	2.35
	Double Glass	2.30	2.09	1.93	1.87	1.85
	Double Graphite	1.04	0.86	0.78	0.72	0.70
	Double Boron	0.90	0.75	0.68	0.65	0.63
	Double carbon	1.18	1.060	0.97	0.93	0.90
SIF(K_{II})	Single Glass	2.90	2.85	2.79	2.41	2.4
	Single Graphite	2.44	2.32	2.23	2.14	1.99
	Single Boron	2.39	2.28	2.20	2.11	1.98
	Single carbon	2.4	2.29	2.21	2.11	1.98
	Double Glass	2.25	2.04	1.89	1.85	1.81
	Double Graphite	0.88	0.74	0.68	0.63	0.60
	Double Boron	0.76	0.65	0.59	0.56	0.45
	Double carbon	1.04	0.86	0.79	0.77	0.74

The effect of increasing the patch thickness on stress intensity factors in one- and two-sided repair of the cracked curved plate can be seen in “Table 2” (R = 1m). According to “Table 2”, in both one- and two-sided repair modes, the SIF of the first and second modes decreases with increasing the patch thickness. For different thicknesses, the maximum reduction of K_I and K_{II} is achieved in repair with boron epoxy composite patch, so that in two-sided repair and for a thickness of 1 mm, the patch has reduced K_I and K_{II} by 76.76 and 80.44%, respectively. Therefore, according to “Table 2”, the best case for repair with composite patches is double-sided repair with boron epoxy patch, and on the other hand, the more we consider the thickness of the boron epoxy patch, the higher the repair efficiency.

3.4. The Effect of Radius of Curvature of The Plate on The Efficiency of The Composite Patch Method

In this section, the effect of the radius of curvature of the plate on the efficiency of the composite patch method is investigated. The boron-epoxy patch is used for this analysis. According to “Table 3”, as the radius of curvature of the plate increases, the SIF decreases. For example, by increasing the radius of curvature from 1 to 3 m, K_I and K_{II} decreased by 3.96 and 5.12%, respectively.

Table 3 Variation of SIF (MPa.mm^0.5) in terms of the radius of curvature of the plate repaired with the composite patch method.

R(m)	0.4	0.7	1	3	7	Flat plate
SIF(K_I)	3.051	2.754	2.625	2.522	2.47	2.47
SIF(K_{II})	2.549	2.268	2.149	2.038	1.97	1.97

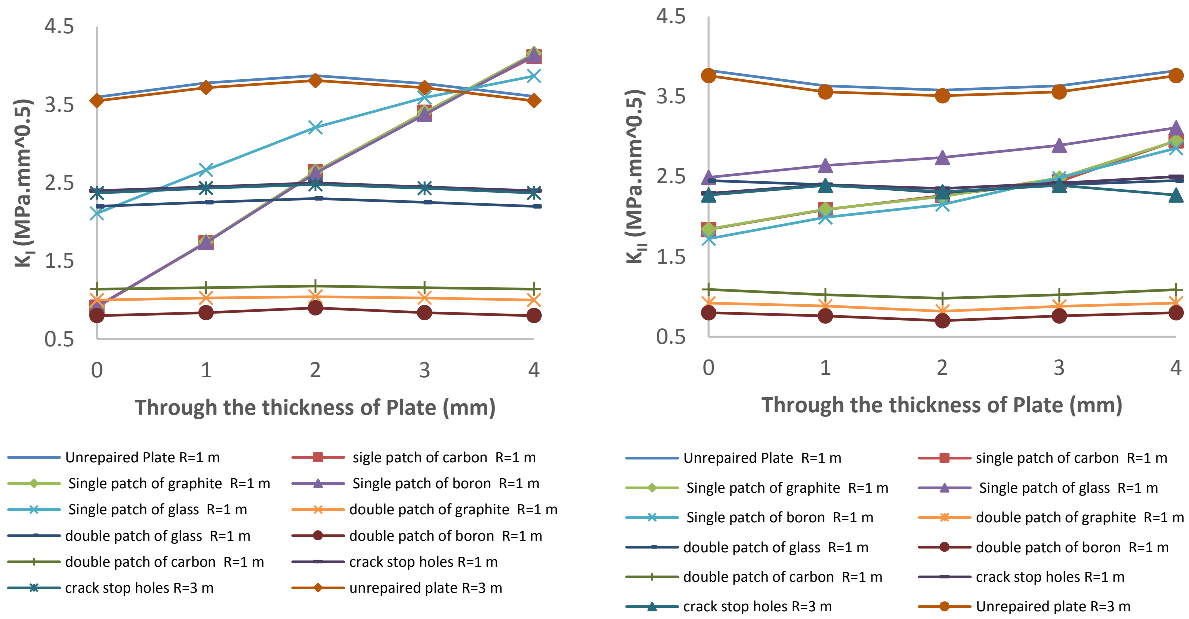


Fig. 7 Variations of SIF along with the plate thickness, for the curved plate repaired with composite patch and stop holes.

4 REPAIRING THE CURVED PLATE WITH STOP HOLES

In this section, the repair of the curved plate by stop holes method is investigated, and its efficiency is compared with the method of composite patches ("Fig. 7").

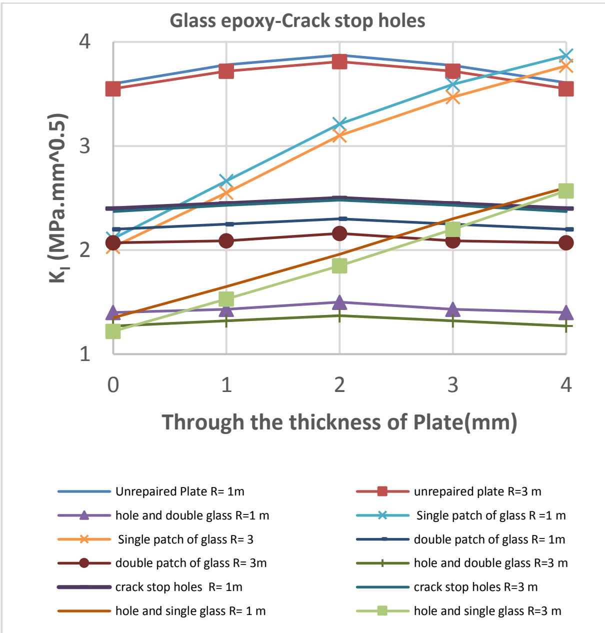
According to "Fig. 7", the use of stop holes on both sides of the crack further reduces the K_I compared to repair with all four one-sided composite patches, and for the second mode only reduces the K_{II} more than the glass-epoxy patch. Double-sided patches resulted in more reduction in K_I and K_{II} than the stop holes. The double-sided boron-epoxy patch (highest efficiency among patches) reduced K_I and K_{II} by 41.31 and 45.30%, respectively, more than the stop holes method. In the first and second modes, for plates with two different radii of curvature of 1 and 3 meters, the stop-hole method is applied, and the results obtained for both curvatures are very slightly different. Therefore, the radius of curvature does not have much effect on the efficiency of the stop holes method. As shown in "Table 4", in this method, by increasing the radius of curvature from 1 to 7 m, K_I and K_{II} decreased by only 1.6 and 2.5%, respectively.

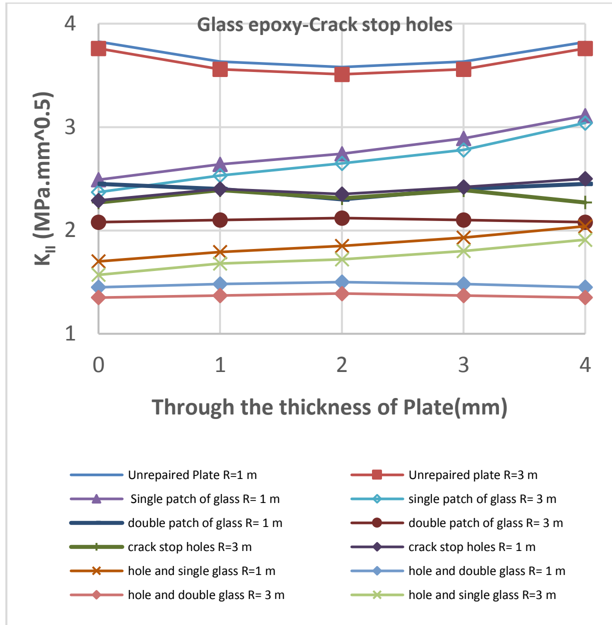
Table 4 Variation of SIF (MPa.mm^0.5) in terms of the plate radius of curvature (stop holes method).

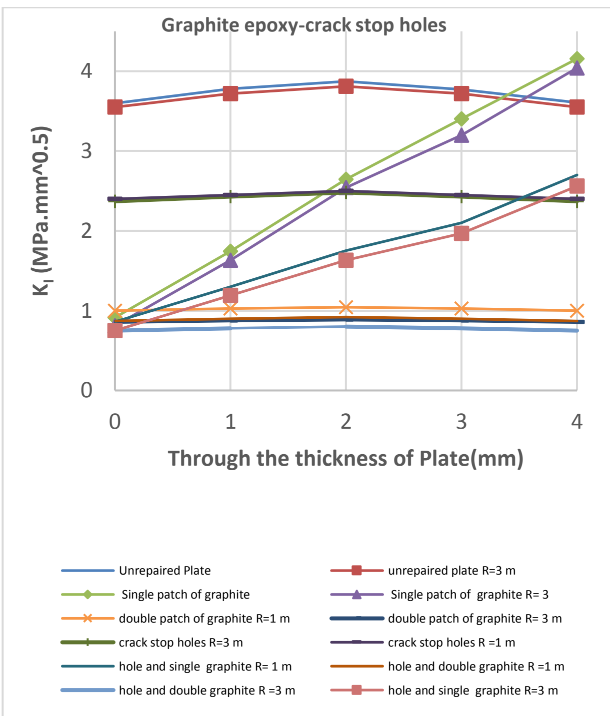
R(m)	0.4	0.7	1	3	7	Flat plate
SIF(K_I)	2.75	2.57	2.5	2.48	2.46	2.46
SIF(K_{II})	2.61	2.42	2.35	2.31	2.29	2.29

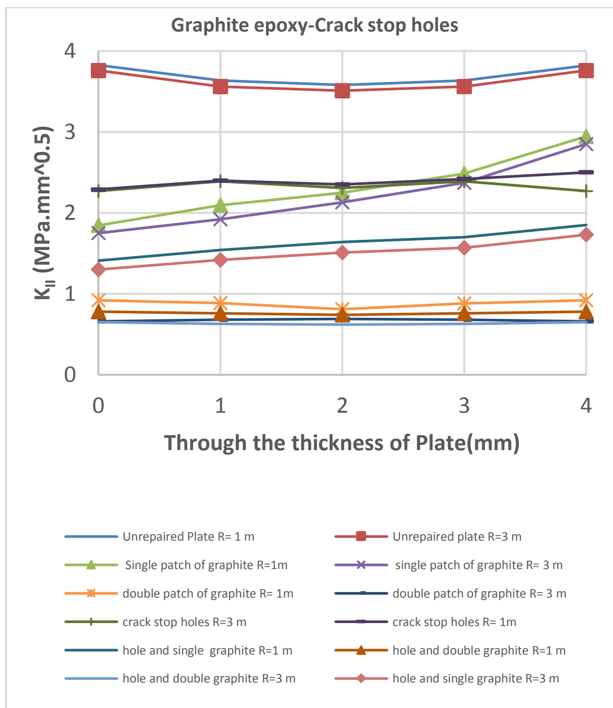
5 REPAIRS OF THE CURVED PLATE WITH THE COMBINED METHOD OF STOP HOLES AND COMPOSITE PATCH

In this section, the combined repair method of composite patches and stop holes are investigated and compared with other methods ("Fig. 8"). As can be seen, the use of a combination of stop hole-composite patch methods further reduces KI and KII compared to the separate use of these methods. For example, a combination of stop-holes and one-sided graphite patch reduces KI and KII by 54.81 and 54.18%, respectively, while stop-holes and one-sided graphite patch methods reduce KI by 35.45 and 30.84%, respectively. Applying the combined method reduces KI and KII almost equally. The best repair mode in this study is a combination repair with stop-holes and a two-sided boron-epoxy patch, which reduces KI and KII by 84.50 and 86.6%, respectively.


Glass epoxy-Crack stop holes
K_I (MPa.mm^0.5)
Through the thickness of Plate(mm)
Unrepaired Plate R= 1m
unrepaired plate R=3 m
hole and double glass R=1 m
Single patch of glass R =1 m
Single patch of glass R= 3
double patch of glass R= 1m
double patch of glass R= 3m
hole and double glass R=3 m
crack stop holes R= 1m
crack stop holes R=3 m
hole and single glass R= 1 m
hole and single glass R=3 m


Glass epoxy-Crack stop holes
K_{II} (MPa.mm^0.5)
Through the thickness of Plate(mm)
Unrepaired Plate R=1 m
Unrepaired plate R=3 m
Single patch of glass R= 1 m
single patch of glass R= 3 m
double patch of glass R= 1 m
double patch of glass R= 3 m
crack stop holes R=3 m
crack stop holes R= 1 m
hole and single glass R=1 m
hole and double glass R= 1 m
hole and double glass R= 3 m
hole and single glass R=3 m


Graphite epoxy-crack stop holes
K_I (MPa.mm^0.5)
Through the thickness of Plate(mm)
Unrepaired Plate
unrepaired plate R=3 m
Single patch of graphite
Single patch of graphite R= 3
double patch of graphite R=1 m
double patch of graphite R= 3 m
crack stop holes R=3 m
crack stop holes R =1 m
hole and single graphite R= 1 m
hole and double graphite R =1 m
hole and double graphite R =3 m
hole and single graphite R=3 m


Graphite epoxy-Crack stop holes
K_{II} (MPa.mm^0.5)
Through the thickness of Plate(mm)
Unrepaired Plate R= 1 m
Unrepaired plate R=3 m
Single patch of graphite R=1m
single patch of graphite R= 3 m
double patch of graphite R= 1m
double patch of graphite R= 3 m
crack stop holes R=3 m
crack stop holes R= 1m
hole and single graphite R=1 m
hole and double graphite R=1 m
hole and double graphite R=3 m
hole and single graphite R=3 m

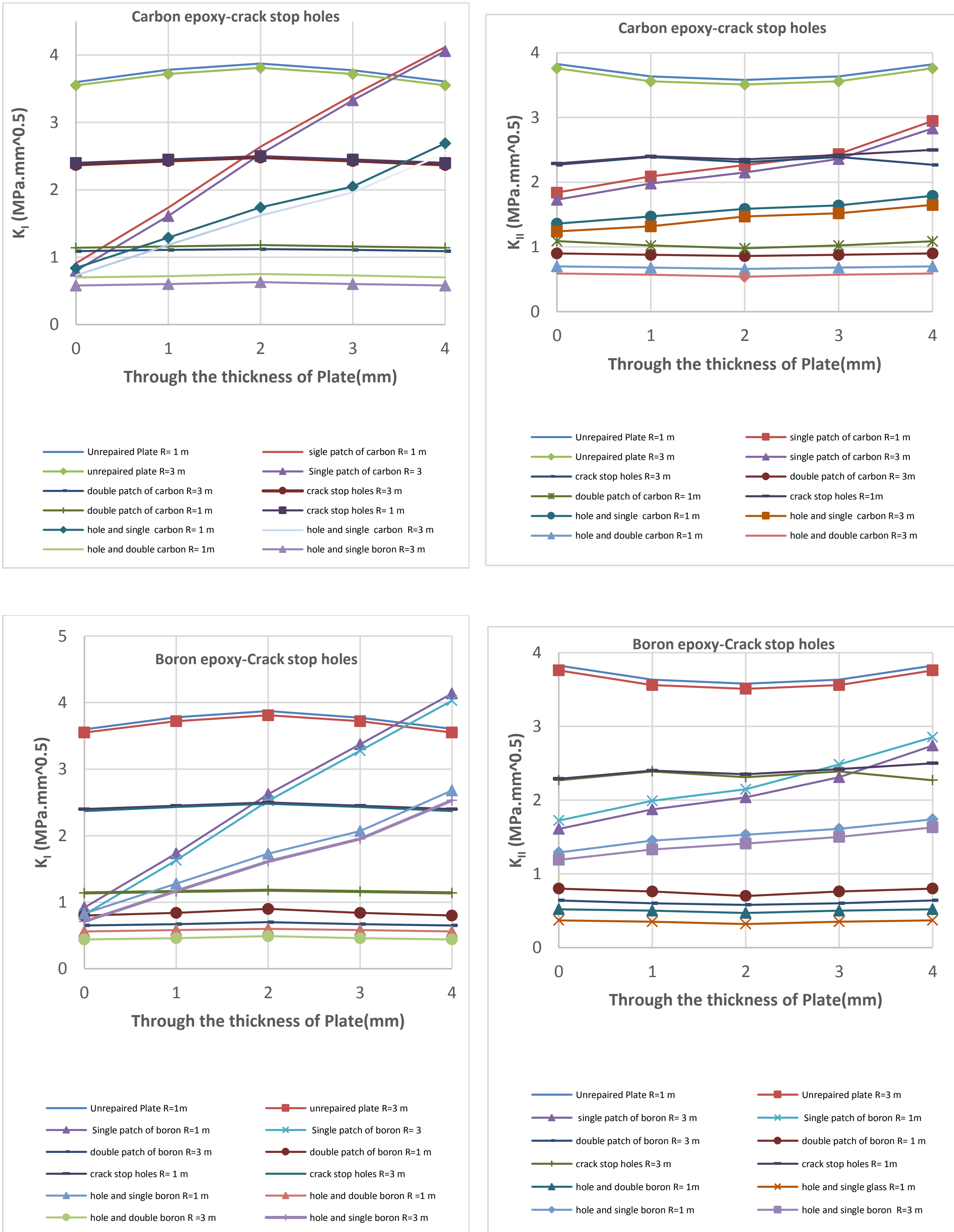


Fig. 8 SIF along with the thickness of the plate repaired with the patch, stop holes, and hybrid.

Table 5 Variation of SIF in terms of the radius of curvature of the curved plate repaired with the hybrid method

R(m)	0.4	0.7	1	3	7	Flat plate
SIF(K_I)	2.14	1.93	1.75	1.63	1.52	1.52
SIF(K_{II})	2.02	1.85	1.64	1.51	1.4	1.4

Table 5 shows the effect of plate radius of curvature on the performance of the combined repair method of stop-holes and graphite patch. As can be seen, increasing the radius of curvature from 1 to 3 m reduces the KI and KII by 6.85 and 8.60%, respectively.

6 INVESTIGATING THE PERCENTAGE REDUCTION OF SIF IN VARIOUS METHODS

Figure 9 shows the K_I and K_{II} percentage reduction for cracked curved plate repaired by various repair methods for different patch materials of boron, carbon, graphite, and epoxy glass (R = 1m).

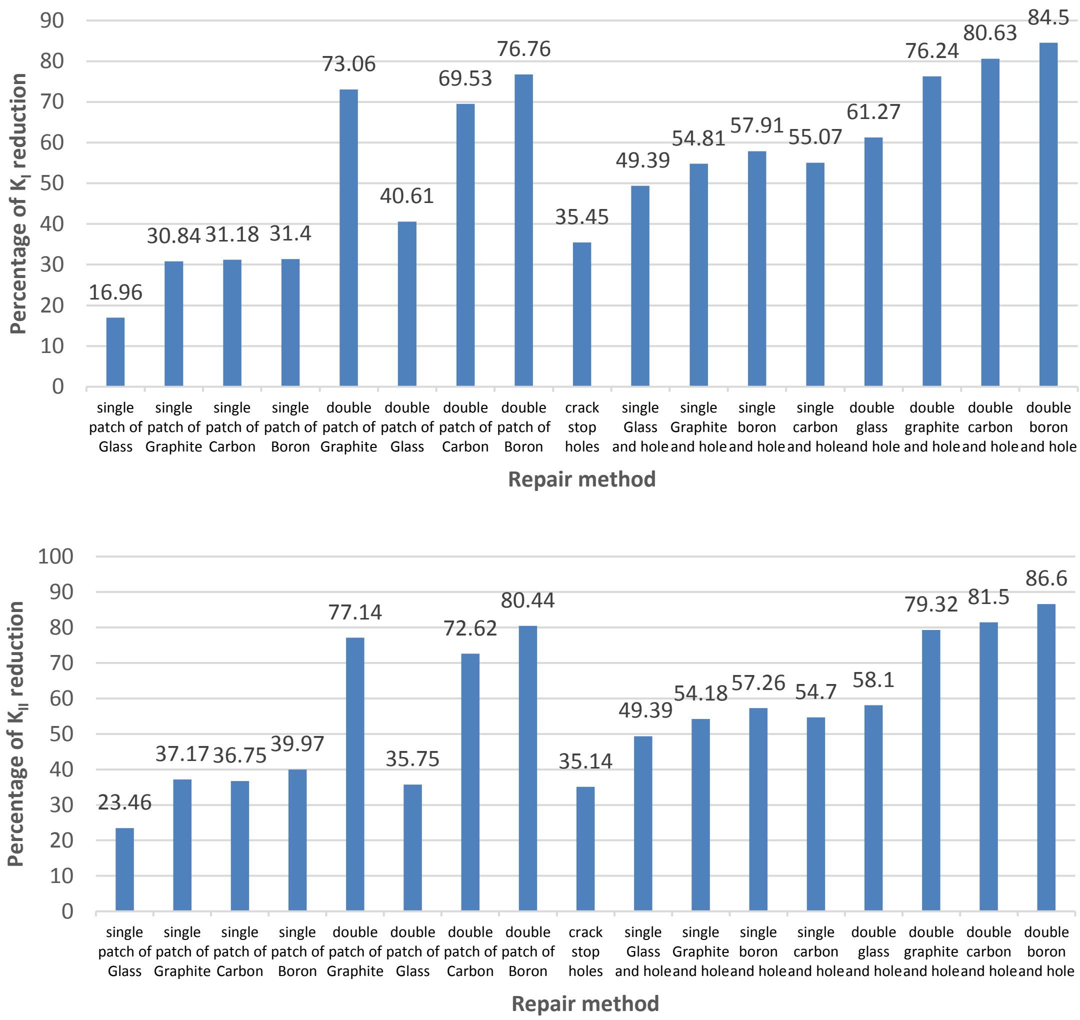
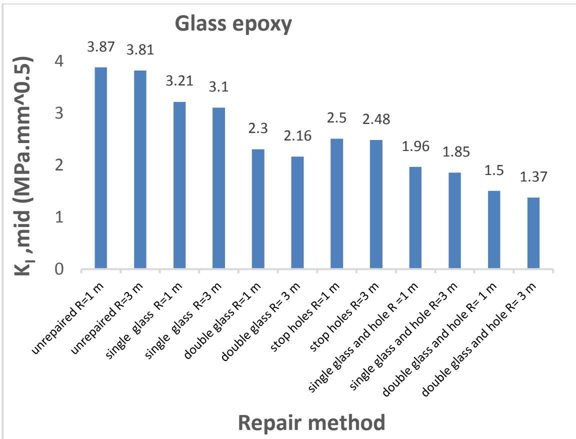
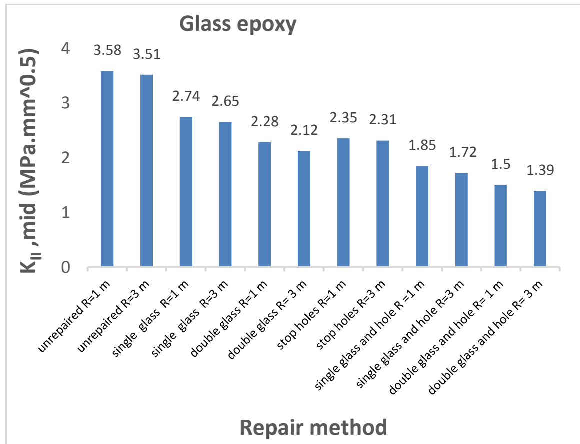


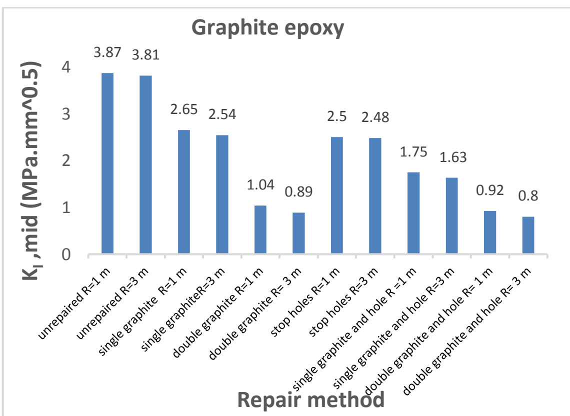
Fig. 9 Percentage reduction of K_I and K_{II} of cracked curved plate repaired by different methods.

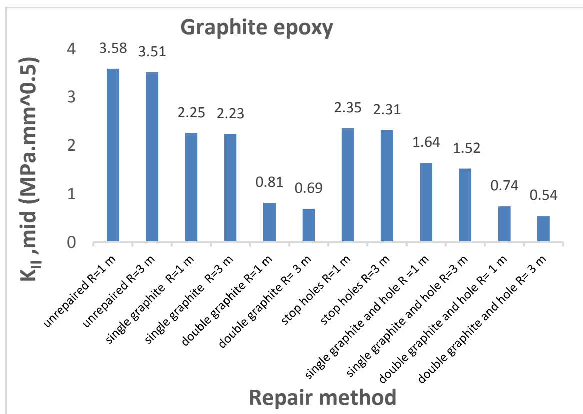
According to "Fig. 9", in the one- and two-sided composite patch repair methods, the highest reduction of KI and KII belongs to boron-epoxy and the lowest efficiency belongs to the glass-epoxy patch. In addition, the percentage of KII reduction in the composite patch repair method is higher than KI. Another point is that the use of double-sided composite patches reduces KI and KII more than one-sided mode. For example, the use of a double-sided graphite-epoxy patch reduces KI and KII by 42.22 and 39.97%, more than one-sided, respectively. The combined method, for all different patch materials, in the first and second modes reduces the SIF more than the separate methods of patch and stop-holes.

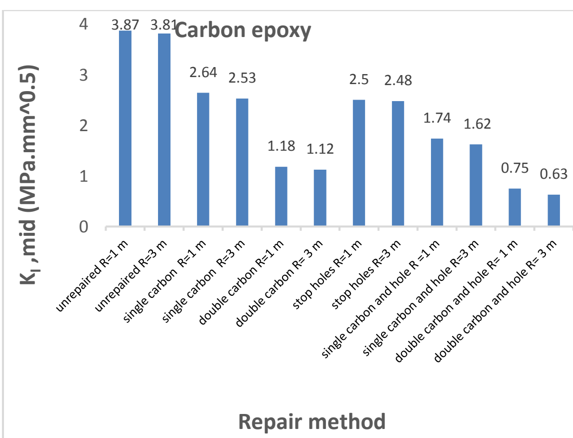
Figure 10 shows the average values of KI and KII in different repair methods and for different materials of composite patches. It is clear that in the repair method with one- and two-sided composite patches, for all materials used in this research, the average value of KII has decreased more than KI. In addition, in stop-holes and combined methods, in two different radii of curvatures of 1 and 3 meters, the average KI and KII are reduced almost equally.

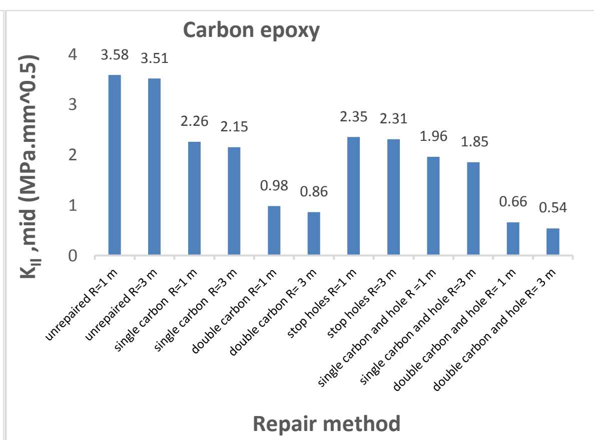












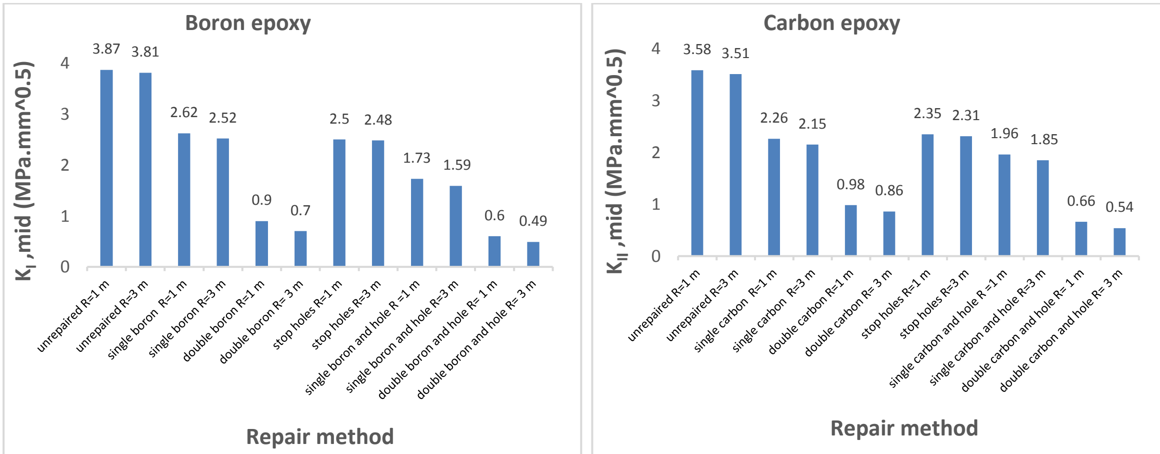


Fig. 10 The average value of SIF of different repair methods for the radius of curvature of 1 and 3 meters.

7 THE EFFECT OF INCREASING THE CRACK LENGTH ON REPAIR EFFICIENCY

In this section, the effect of increasing the crack length on K_I and K_{II} in different repair methods is investigated. In this analysis, the graphite-epoxy patch is used. According to “Fig. 11”, with increasing crack length, for both plate radii of curvature of 1 and 3 m, K_{II} increases more than K_I. For example, in the one-sided repair of the graphite-epoxy patch, with a 50% increase in crack length from 30 to 45 mm, K_I and K_{II} increase by 28.49 and 30.22%, respectively (R = 1m). In the stop-holes repair method, with increasing crack length from 30 to 60 mm in radii of curvatures of 1 and 3 m, K_I increased by 59.20 and 59.67% and K_{II} by 61.7 and 63.20%, respectively.

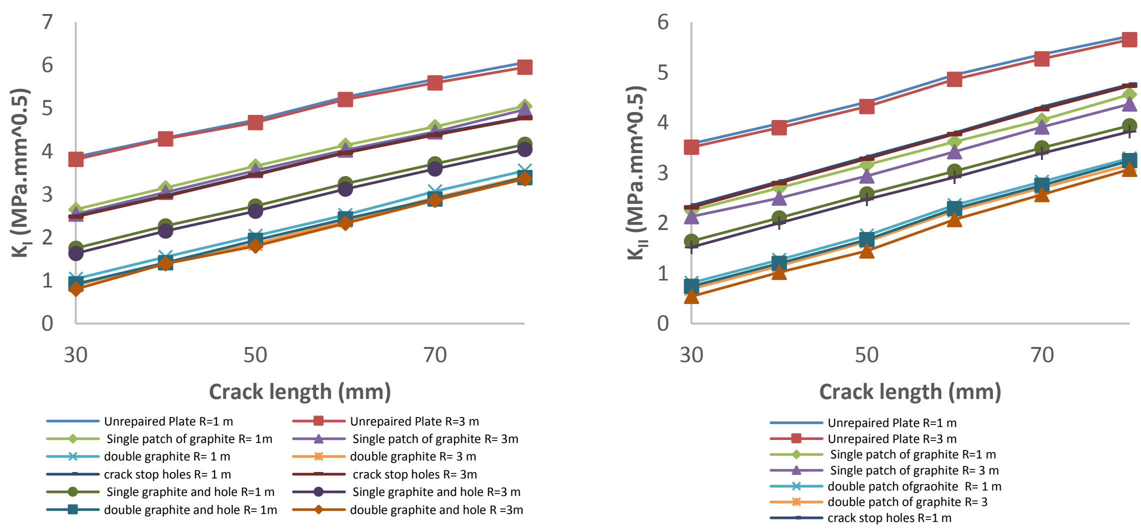


Fig. 11 Effect of the crack length on KI and KII of the curved plate repaired with different repair methods

8 THE EFFECT OF ADHESIVE THICKNESS ON THE EFFICIENCY OF THE COMBINED REPAIR METHOD

In this section, the effect of adhesive thickness on the efficiency of the combined repair method for the two radii of curvature of 1 and 3 meters of the curved plate is investigated (“Fig. 12”). For this purpose, adhesives with different thicknesses of 0.1, 0.2, 0.3, and 0.4 mm are used. According to “Fig. 12”, as the thickness of the adhesive increases, K_I and K_{II} increase, and the amount of K_{II} increase is slightly greater than K_I. For example, in the case of the glass-stop holes hybrid repair method, the K_I and K_{II} increase by 54 and 65%, respectively, with a 0.3 mm increase in adhesive thickness (R = 1m). In the case of combined repair of boron-stop holes, with a 0.3

mm increase in adhesive thickness, K_I and K_{II} increase by 52 and 61%, respectively (R = 3m). Another point is that, for all the patches used and in both radii of curvature of 1 and 3 meters, with increasing the thickness of the adhesive, the stress created in the adhesive decreases. For example, by increasing the thickness of the adhesive from 0.2 to 0.4 mm, in the graphite-stop holes hybrid repair method and for curvature radius of 1 m, the maximum Von Mises stress decreases from 0.16 to 0.1 MPa (“Fig. 13”).

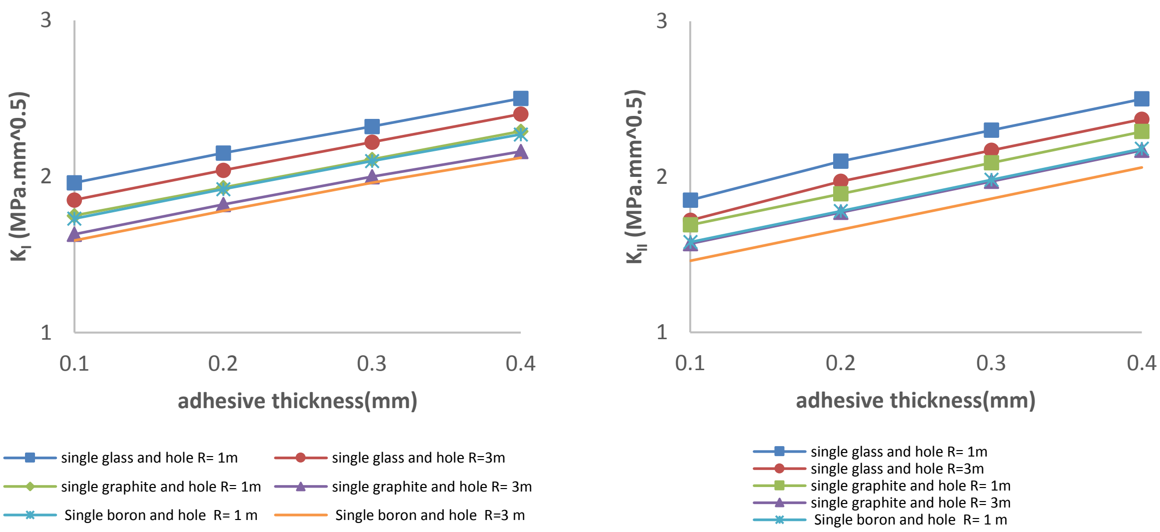
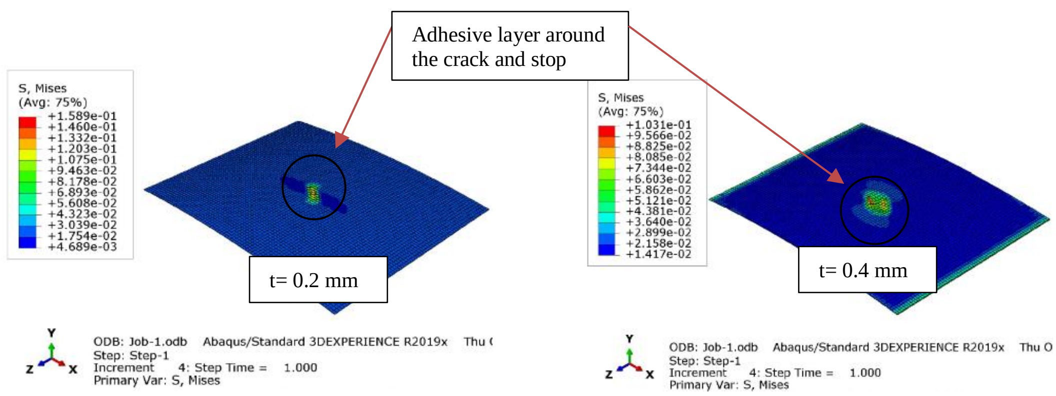


Fig. 12 The effect of adhesive thickness on SIF of the curved plate repaired with the hybrid method.



(a) **(b)**

Fig. 13 (a): Von Mises stress in the adhesive layer (t_a = 0.2mm), and (b): (t_a = 0.4mm).

9 SUMMARY AND CONCLUSION

In this research, the repair of a curved aluminum plate containing a central mixed-mode crack was investigated by the methods of stop-holes, one- and two-sided composite patch, and the hybrid method of stop holes-composite patch. The most important results are presented below.

1- In the case of repair of the cracked curved plate with the composite patch, the highest reduction of KI and KII belongs to the boron-epoxy patch and the lowest repair efficiency belongs to glass-epoxy. Also, the efficiency of graphite and carbon patches in reducing SIF is almost the same.

2- The best repair mode in this research is the hybrid repair method (stop-holes and two-sided boron-epoxy patch), which reduces KI and KII by 84.50 and 86.6%, respectively.

3- In the repair method with one- and two-sided composite patches, for different materials of patches, KII is reduced more than KI.

4- In both radii of curvature of 1 and 3 meters of the curved plate, with increasing the thickness of the patch, KI and KII decrease, and its effect on reducing KII is greater.
5- As the patch length increases, KI and KII increase, and the amount of KI increase is more than KII.
6- With increasing the width of the glass-epoxy patch, KI and KII almost do not change, but for the rest of the composite patches studied in this research, with increasing the patch width, KI and KII increase by a very small amount.
7- Using the stop-holes method reduces the SIF more than the one-sided composite patch repair method for all the patch materials studied in this research but compared to the two-sided repair method, it reduces the SIF less.
8- Combined stop holes- composite patch repair method has more efficiency than using crack stop holes and composite patch methods.
9. In all repair methods studied, SIF decreases with increasing the radius of curvature of the curved plate. In the stop-holes and hybrid methods, in two radii of curvature of 1 and 3 m, the average KI and KII are reduced almost equally. Changing the radius of curvature has little effect on the efficiency of the stop-holes method.
10- In the hybrid repair method, for all four materials of patches understudy and in both radii of curvature of 1 and 3 meters of the curved plate, KI and KII increase with increasing the thickness of adhesive and the amount of KII increase is slightly higher. On the other hand, as the thickness of the adhesive increases, the maximum Von Mises stress in the adhesive decreases.

REFERENCES

[1] Shahani, A. R., Mohammadi, S., Damage Tolerance and Classic Fatigue Life Prediction of a Helicopter Main Rotor Blade, Meccanica, Vol. 51, 2016, pp. 1869-1886.

[2] Russelle, A., Naganambi, N., Numerical Investigation of Bonded Repair for TDS of Helicopter and Characterization of Kevlar/Epoxy Composite Patch, Procedia Materials Science, Vol. 5, 2014, pp. 204-211.

[3] Li, H. C. H., Wang, J., and Baker, A., Rapid Composite Bonded Repair for Helicopter Tail Drive Shafts, Composites Part B: Engineering, Vol. 43, No. 3, 2012, pp. 1579-1585.

[4] Benachour, M., Benachour, N., Benguediab, M., and Seriari, F. Z., Prediction of Fatigue Crack Growth of Repaired Al-Alloy Structures with Double Sides, Eighth International Conference on Material Sciences (CSM8-ISM5), Physics Procedia, Vol. 55, 2014, pp. 83-89.

[5] Albedah, A., Bouiadjra, B. B., M Es-saheb, W., and Binyahia, F., Elastic Plastic Analysis of Bonded Composite Repair in Cracked Aircraft Structures, Journal of Reinforced Plastics and Composites, Vol. 30 , No. 1, 2011, pp. 66–72.

[6] Kwon, Y. W., Lee, W. Y., Analytical Model for Single-Side Patch Design of Composite Repair, Naval Surface Warfare Center, Carderock Division Structures and Composite Division, MD 20817, March, 2013.

[7] Ramakrishna, Ch., Krishna Balu, J., Rajashekar, S., and Sivateja, N., Finite Element Analysis of the Composite Patch Repairs of the Plates, Int. Journal of Engineering Research and Application, Vol. 7, No. 2, 2017, pp. 10-18.

[8] Es-Saheb, M., Khan, S., and Mohsin, M., Fatigue Behaviour of AA 7075-T6 Plates Repaired at Different Crack Lengths, Chemical Engineering Transactions, Vol. 56, 2017, pp. 1627-1632.

[9] Schubbe, J. J., Bolstad, S. H., and Reyes, S., Fatigue Crack Growth Behavior of Aerospace and Ship-Grade Aluminum Repaired with Composite Patches in A Corrosive Environment, Composite Structures, Vol. 144, 2016, pp. 44-56.

[10] Saeed, Kh., Adhesive Effect on The Performance of The Repair Efficiency of Bonded Aluminum Alloy, Proceedings of 93rd IIER International Conference, Los Angeles, USA, 20th-21st January, 2017.

[11] Khan, S., Es-Saheb, M., Fatigue Crack Growth Analysis of Cracked Aluminum Plates Repaired with Bonded Composite Patch, International Journal of Mechanical and Production Engineering, Vol. 3, No. 8, 2015, pp. 5-8.

[12] Karr, D. G., Baloglu, C., Cao, T. J., Douglas, A., Nielsen, K., Ong, K. T., and Rohrback, B. S. N., Strength and Fatigue Testing of Composite Patches for Ship Plating Fracture Repair, SSC-469, 2015.

[13] Coelho, S. R. M., Reis, P. N. B., Ferreira, J. A. M., and Pereira, A. M., Effects of External Patch Configuration on Repaired Composite Laminates Subjected to Multi-Impacts, Composite Structures, Vol. 168, 2017, pp. 259-265.

[14] Gangadharan, S., Baliga, S. V., Sonawane, N. H., Sathyanarayan, P., and Kamdar, Sh., Impact Analysis of Composite Repair Patches of Different Shapes at Low Velocities for Aircraft Composite Structures, J. Aeronaut Aerospace Eng., Vol. 5, No. 4, pp. 173, 2016.

[15] Zarrinzadeh, H., Kabir, M. Z. and Deylami, A., Crack Growth and Debonding Analysis of An Aluminum Pipe Repaired by Composite Patch Under Fatigue Loading, Thin-Walled Structures, Vol. 112, 2017, pp. 140–148.

[16] Zarrinzadeh, H., Kabir, M. Z., and Deylami, A., Experimental and Numerical Fatigue Crack Growth of An Aluminium Pipe Repaired by Composite Patch, Engineering Structures, Vol. 133, 2017, pp. 24–32.

[17] Oudad, W., Bachir Bouiadjra, B., Belhouari, M., Ziadi, A., Stress Intensity Factor for Repaired Crack with Bonded Composite Patch Under Mechanical Loading in Aircraft Structures, 12ème congrès de Mécanique 21-24, Casablanca (Maroc), Avril, 2015.

[18] Mohammadi, S., Yousefi, M., and Khazaei, M., A Review on Composite Patch Repairs and The Most Important Parameters Affecting Its Efficiency and

Durability, J. Reinf Plast Compos, 2020, https://doi.org/10.1177/0731684420941602.

[19] Mohammadi, S., Parametric Investigation of One-Sided Composite Patch Efficiency for Repairing Crack in Mixed Mode Considering Different Thicknesses of The Main Plate, Journal of Composite Materials, 2020.

[20] Li, K., Li, Ch., Tie, Y., and Yu, Y., Influence of Patch Parameters on Damage and Residual Strength of Adhesively Bonded Composite Repair Under Fatigue Loading, Materials Physics and Mechanics, Vol. 24, 2015, pp. 391-402.

[21] Walde, Sh., Lilhare, S., Finite Element Analysis of Composite Patch Repaired Cracked Metal Plates and Effect of Patch Thickness on SIF, International Journal of Engineering and Technical Research (IJETR), Vol. 4, No. 3, 2016, pp. 43-46.

[22] Albedah, A., Mohammed, S. M., Bouiadjra, B. B., and et al., Effect of the Patch Length on The Effectiveness of One-Sided Bonded Composite Repair for Aluminum Panels, Int J Adhes Adhes, Vol. 81, 2018, pp. 83–89.