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Research Paper

Evaluation of Stress Intensity Factor in a Center Cracked Curved Plate Repaired with Stop Holes, Composite Patch, and Hybrid Methods

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ABSTRACT

Stop holes and composite patches are the most important methods used to repair cracked plates. In this research, using a 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 the reduction of SIF in a cracked curve plate is investigated. The best position and arrangement of crack stop holes and the best dimensions and material used for the composite patch are determined. Then, the effect of the radius of curvature of the plate on the efficiency of various repair methods is investigated. The results show that with increasing the radius of curvature of the plate, the SIF value decreases in all repair methods and the efficiency of the patch improves in the cases of using the patch or the hybrid method. Besides, from the radius of curvature of approximately 5 meters onwards, a further increase in the radius of curvature does not affect the efficiency of various repair methods. Simultaneous use of the graphite-epoxy double-sided patch and stop holes reduces SIF by 79.9% compared to unrepaired condition.

Keywords : Stress intensity factor; Crack repair; Composite patch; Fracture mechanics; Stop holes.

1 INTRODUCTION

THERE are cracks in many structures and the growth of cracks is inevitable. The presence of cracks in structures and parts causes problems such as reduced load-bearing capacity and reduced fatigue life. Reducing the amount of load applied to the parts to deal with cracks is not possible in any situation and place. On the other hand, replacing cracked components and parts to strengthen structures is not possible in some conditions, and it is a costly method. Therefore, the best and most economical way to increase the resistance of structures to crack growth, so that it does not affect their performance, is the method of inhibiting crack growth. There are several methods to inhibit crack growth in cracked plates and sheets, such as crack filling [1], crack spot welding, shot peening, composite

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patches, and stop holes [2, 3]. Composite patch and stop holes methods are common methods to inhibit crack growth [4-6]. One of the most common methods of reducing crack growth is the stop-hole method. This method is a simple and low-cost solution compared to other methods to reduce the stress intensity factor (SIF) and inhibit crack growth [7]. In the first method of creating a stop hole, by drilling at the tip of the crack, the growth of the crack can be inhibited and its expansion can be prevented. In this case, crack initiation from the edge of the hole is required for crack regrowth [8, 9]. The second method is to use stop holes on both sides of the crack. The function of this method is that the holes created on both sides of the crack affect the stress field of the crack tip and reduce the SIF and thus reduce the crack growth [10, 11]. In the study conducted by Shin [3], the method of holes around the crack and the method of filling the crack with epoxy resin, alumina powder, and a combination of both methods were compared. The results show that the method of holes around the crack is the best method to inhibit crack growth compared to other methods. Numerical results obtained from the study [10] show that the presence of holes on both sides of the crack reduces the stress concentration around the crack tip and the SIF. Another best way to control crack growth is to use composite patches. The use of composite patches has many advantages over other methods for inhibiting crack growth. One of the most important advantages of using the composite patch repair method compared to other methods is that no holes are created during the installation of the patch and as a result, the structure does not get weaker. Also, the required thickness for a composite patch is about 33 to 50% of an aluminum patch [12]. The composite patch reduces or eliminates crack growth by reducing the SIF. Using the composite patch method reduces the possibility of failure of repaired parts and in addition, it increases the life of the structures significantly. The main advantage of using the composite patch repair method is that the weight of the structure does not increase much [13]. Composites have a very high resistance to weight ratio compared to metals and are more resistant to corrosion and damage [14]. The results of the study conducted by [15] show that the effect of different geometric parameters on the efficiency of the repair patch depends on the thickness of the patch and the main plate as well as the material of the patch. The higher the patch stiffness, the less stress there is on the repaired plate [16]. As the length of the patch increases, the SIF increases slightly, and changing the width of the patch may not affect the repair performance for some thicknesses and patch materials, but may reduce the SIF for others [15]. Composite patches are also used in the marine industry to prevent crack growth [17]. The use of hybrid methods to repair parts has been investigated in limited research. The combined use of composite patch/hole [18], welding/rivet [19], and adhesive/rivet [20] are examples of hybrid methods for repairing structures. In reference [18], the combined method of stop tip hole and the composite patch is compared with the methods of stop holes and composite patch to reduce crack growth. The results show that the use of the combined method of the stop-hole/patch is more effective in reducing crack growth than the two separate methods of stop-hole and composite patch. In another study conducted by [21], the combined method of composite patches and bolts was used to repair aircraft structures made of aluminum alloy. The results show that the use of the combined method, composite patch, and bolts increases 49, 45, and 24% of tensile strength under net tension, respectively. Also, in the net shear mode, the load-bearing capacity in the combined, patch, and bolt methods increased by 28, 18, and 9%, respectively. Combined methods are widely used in the aerospace industry. Combined methods for repairing aircraft structures can also be studied in [22].

In this research, using a 3D finite element method and considering different materials for the composite patch, the effect of separate and simultaneous use of stop holes and composite patch (one-sided and two-sided) on reducing SIF on the cracked curve plate is studied. The vertical and horizontal position of the hole in relation to the crack tip, holes diameter, and radius of curvature of the repaired plate are selected as the parameters to be studied. Glass-epoxy, graphite-epoxy, and boron-epoxy are used for repair patches. The best position and arrangement of crack stop holes and the best dimensions and material used for composite patches are studied and the effect of radius of curvature of the plate on the efficiency of repair methods is also investigated. To the best knowledge of the authors, no research work has investigated the effect of the simultaneous application of repair patches and holes on the reduction of SIF in the cracked curved plate, considering different materials for the composite patch.

2 PROBLEM DEFINITION AND FINITE ELEMENT MODELING

A curved rectangular plate (a sectional cut at an angle of 30 degrees from a cylinder with a radius of 1 meter) made of 2024 aluminum alloy with an elastic modulus of 74 *Gpa* and a Poisson's ratio of 0.33 is considered. The length of the circumferential side and the thickness of the model are 0.5 *m* and 4 *mm*, respectively. The top and bottom edges of the curved plate are bounded in a radial direction, and a tensile load of 1 *MPa* is applied, perpendicular to the peripheral sides. A 30 *mm* long crack was considered in the middle of the plate. On both sides of the crack, stop holes of different diameters are used, which are located at different horizontal and vertical distances from the tip of the crack. Also, to use the patch and the hybrid methods, composite patches with a thin layer of FM73 adhesive with a thickness of 0.1 *mm* are used. The properties of composite patches and the adhesive are presented in Table 1. The composite patch is cut segmentally at an angle of 15 degrees from a cylinder with a radius of curvature of 1 *m*. The length of the peripheral side of the patch is 250 *mm*. The width of the patch is 260 *mm*. XFEM method is used to calculate the SIF at the crack tip and 20 node hexagonal elements (C3D20R) are used in the modeling. Fig. 1 shows the geometry of the problem under study. The model of the cracked curved plate repaired with stop holes and the composite patch in Abacus software, and the finite element model meshing is shown in Fig. 2.

Table 1
Mechanical properties of the components used in the FE analysis (*G* and *E* in *GPa*) [23], [24].

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
Adhesive -FM 73	2.21	-	-	-	-	-	0.43	-	-

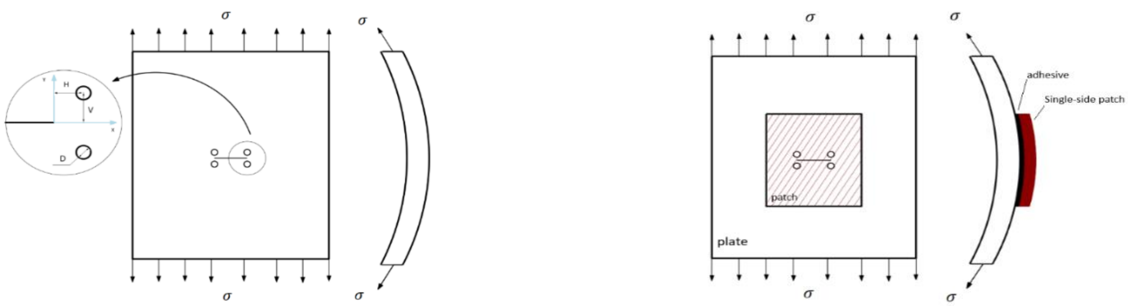


Fig.1
Schematic of the problem.

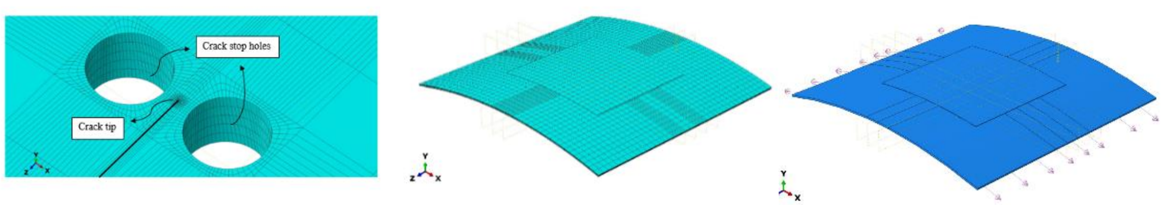


Fig.2
The model and meshing around the crack tip and crack stop holes in Abaqus software.

To validate the results of the finite element analysis, the SIF obtained from the three-dimensional analysis of a flat plate with finite width and central crack (Fig. 3) under stress $\sigma = 1$ *MPa* is compared with the SIF value obtained from Eq. (1) obtained by Rack and Cartit [25] ($2a = 30$ *mm*, $2b = 500$ *mm*).

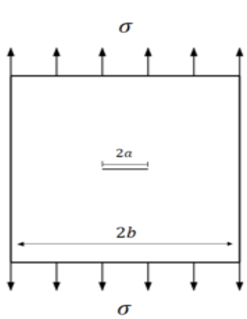


Fig.3
The limited width model with a central crack.

$$K_1 = \sigma\sqrt{\pi a}\left(\frac{1-\frac{a}{2b}+0.326\left(\frac{a}{b}\right)^2}{\sqrt{1-\frac{a}{b}}}\right) \tag{1}$$

In the above relation, 2a is the crack length, 2b is the plate width, and σ is the applied stress to the plate. As can be seen, the SIF obtained from both the finite element method and Eq. (1) is approximately equal (Table 2).

Table 2
The SIF obtained from numerical and analytical methods ($MPa\sqrt{mm}$).

Percentage of difference	Theoretical solution (Formula (1))	Numerical solution (Finite element)
0.07	6.876	6.881

3 INVESTIGATING THE EFFECT OF STOP HOLES ON REDUCING SIF

To investigate the effect of the stop holes method on the SIF reduction, four parameters of plate curvature radius (R), horizontal distance (H), and vertical distance (V) of holes from the crack tip and hole diameter (D) are considered as the main variables (Fig. 1). First, to investigate the effect of the holes distance from the crack tip on the reduction of SIF, three sets of stop holes with a diameter of 2 *mm* were considered at a fixed vertical distance from the crack tip (Fig. 4). The first holes are considered behind the tip of the crack in the coordinates H = -2, V = 3 (Fig. 4(a)). The second and third holes are located in the coordinates H = 0, V = 3 (Fig. 4(b)) and H = 2, V = 3 (Fig. 4(c)), respectively. According to the diagrams related to the hole with a diameter of 2 *mm* in Fig. 6, it is clear that the holes in the coordinates H = 0, V = 3 have the highest SIF reduction (11.47%). The results obtained in reference [10] also show that the best position to make holes on both sides of the crack to achieve the maximum reduction in crack growth is that the connection line of the center of the holes passes through the tip of the crack. The third category holes created in the coordinates H = 2, V = 3 not only do not reduce the SIF but also increase it by 18%. Making a hole near the crack changes the stress field around the crack tip and, depending on the location of the hole, it can increase or decrease the SIF and the probability of the crack growth. Next, the effect of the vertical distance of the hole from the crack tip on the reduction of SIF is investigated (Fig. 5). To do this, holes with coordinates H = 0, V = 2 and H = 0, V = 4 are considered. According to Fig. 6, it is clear that the hole with coordinates H = 0, V = 2, the hole closer to the crack tip, has the highest SIF reduction (21%). The results for the rest of the holes with different horizontal and vertical distances can be seen in Fig. 6. Therefore, it can be concluded that for the stop holes to have the highest SIF reduction, first, these holes should be in the horizontal distance of zero (H = 0), and secondly, they should be as close as possible to the crack tip (V has the lowest possible value).

In the following, the effect of the holes diameter on SIF reduction is investigated. For this purpose, a hole with a diameter of 5 *mm* at different horizontal and vertical distances is considered. The results show that, in comparison to a hole with a diameter of 2 *mm*, the use of a hole with a larger diameter further reduces the SIF at negative and zero horizontal distances and also increases the SIF further at positive horizontal distances (Fig. 6). Holes with a diameter of 5 *mm* created at zero horizontal distance and 3.5 *mm* vertical distance have the highest SIF reduction (37.13%). Fig. 7 shows the SIF changes for different vertical and horizontal distances of the hole from the crack tip and two hole diameters of 2 and 5 *mm*.

4 INVESTIGATING THE EFFECT OF ONE-SIDED COMPOSITE PATCHES ON SIF REDUCTION

Fig. 8 shows the SIF changes of the plate with stop holes on both sides of the crack (D = 5 *mm*, H = 0 *mm*, V = 3.5 *mm*) and the plate repaired with composite patches made of graphite, boron, and glass-epoxy (R = 1 *m*). According to Fig. 8, among the patched repair modes, the curved plate repaired with the boron-epoxy patch has the highest average SIF reduction (24.4%). This number is 23% and 13.6% for graphite and glass patches, respectively. Besides, the SIF reduction percentage of the two boron and graphite patches is not much different from each other. Patch Young's modulus is the most effective factor in repair performance. The Young's modulus of a glass-epoxy patch is lower than that of other patches, resulting in its lower efficiency. Reference [15] also showed that graphite and carbon patches have almost the same function in reducing SIF. According to Fig. 8, the holes on both sides of the crack reduce the average SIF more than the repair mode with the one-sided patch (37.13 vs. 24.4%).

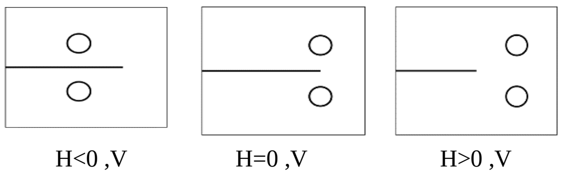


Fig.4
Different horizontal positions of the holes.

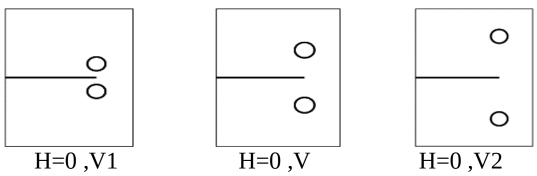


Fig.5
Three different vertical positions of the holes.

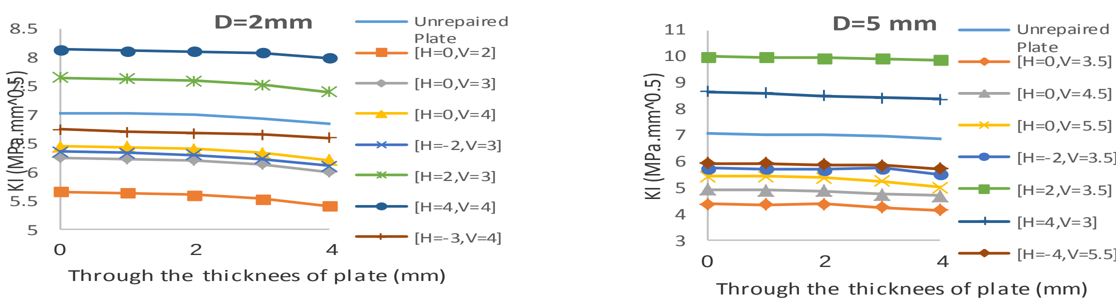


Fig.6
SIF along the thickness of the plate for the curved plate repaired with crack stop holes.

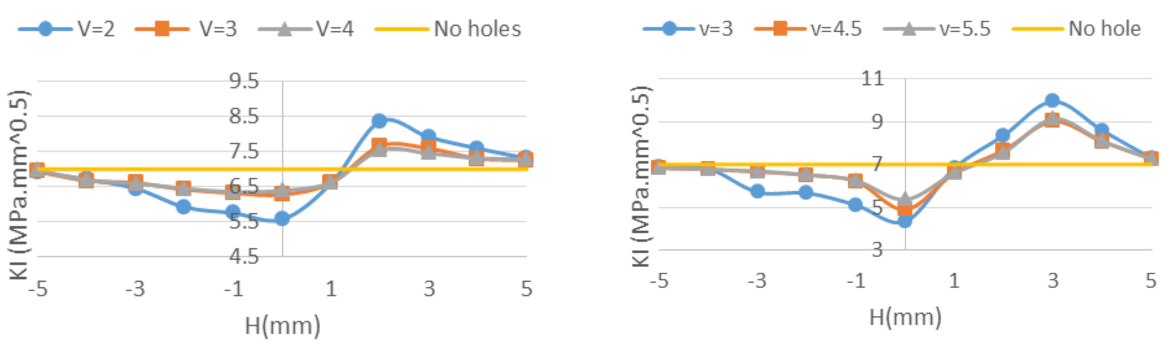


Fig.7
SIF change due to changes in the vertical and horizontal position of the crack stop holes.

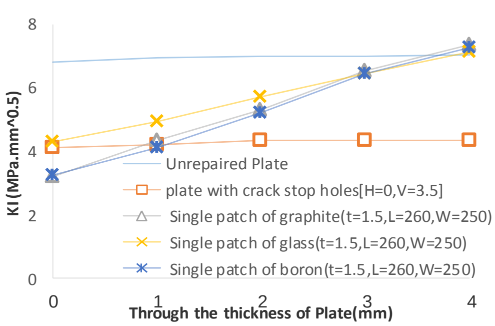


Fig.8
SIF along the thickness of the plate for the plate repaired with a Single patch and crack stop holes.

4.1 The effect of the patch thickness on SIF reduction in one-sided repair

In this section, the effect of the patch thickness on the reduction of average SIF is investigated (Fig. 9). In this study, the length and width of the patch are 250 and 260 *mm*, respectively. As shown in Fig. 9, for the glass-epoxy patch, in both radius of curvature of the plate 1 and 3 meters, with increasing the patch thickness, the SIF does not change significantly. For boron and graphite patches, the SIF decreases with increasing the patch thickness. In all three patches for the 3 *m* radius of curvature, the SIF is less than the 1 *m* radius of curvature mode. Also, on the flat plate, the SIF decreases as the patch thickness increases [26].

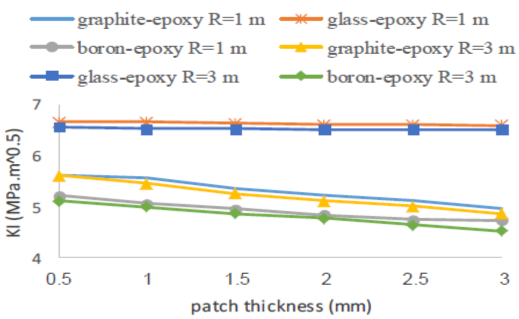


Fig.9
The average SIF in terms of the patch thickness for glass, boron, and graphite-epoxy patches.

4.2 The effect of the patch width on SIF reduction in one-sided repair

Fig. 10 shows the average value of SIF along the plate thickness in terms of the patch width. In this study, the thickness and length of the patch are equal to 1.5 and 250 *mm*, respectively. It is clear that for glass-epoxy patch, increasing the patch width has little effect on reducing SIF, but for boron and graphite patches, contrary to expectations, SIF increases slightly. Therefore, increasing the width of these patches is not useful for reducing SIF. Of course, the effect of the patch width on the repair efficiency depends on both the thickness of the patch and its material [15]. In a one-sided patch, the asymmetry and resulting bending moment increase with increasing the patch width. As a result, the SIF increases, and the patch efficiency decreases.

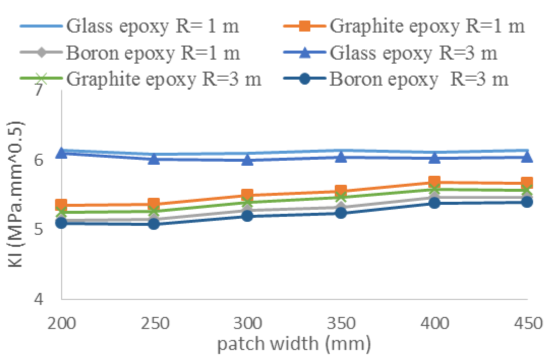


Fig.10
The average SIF in terms of the patch width for glass, boron, and graphite-epoxy patches.

4.3 The effect of the patch length on SIF reduction in one-sided repair

Fig. 11 shows how the average value of SIF changes in terms of the patch length. The thickness and width of the patch are equal to 1.5 and 250 mm, respectively. As can be seen, for the glass-epoxy patch, the SIF increases slightly by increasing the patch length. For boron and graphite patches, the SIF increases slightly from the patch length of 350 mm onwards. The results are true for both radii of curvature R = 1 m and R = 3 m. Therefore, increasing the patch length is not useful in general. Numerical and laboratory results of reference [27] also show that increasing the patch length increases the SIF and reduces the fatigue life of the repaired flat plate.

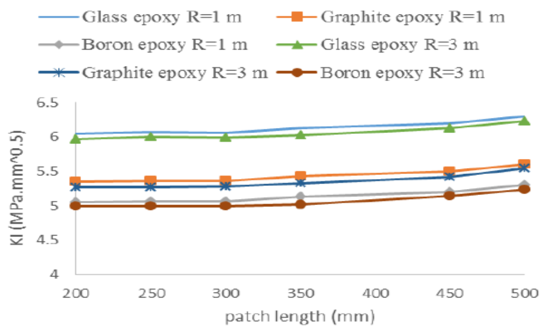


Fig.11
The average SIF in terms of the patch length for glass, boron, and graphite-epoxy patches.

5 THE EFFECT OF DOIBLE-SIDED COMPOSITE PATCHES ON SIF REDUCTION

Fig. 12 shows the different modes of the curved plate repaired with stop holes, one-sided and two-sided composite patches, considering various materials for the patch. In this analysis, the thickness, length, and width of one-sided and two-sided patches are the same and are equal to 1.5, 250, and 260 *mm*, respectively. According to Fig. 12, the holes on both sides of the crack reduce the SIF more than the one-sided patch repair mode, but there is more SIF reduction in the two-sided patch repair mode than in the one-sided patch and holes modes. One of the main reasons for the higher efficiency of the two-sided patch than the one-sided patch is that no additional bending moment is created when using the two-sided patch. The use of double-sided graphite and glass patches reduces SIF by 71.48% and 52.3%, respectively (R = 1 *m*). In reference [28], after applying a composite patch to the single-edge sample, the SIF value decreased by 65%. A two-sided patch always has more efficiency than a one-sided patch [29].

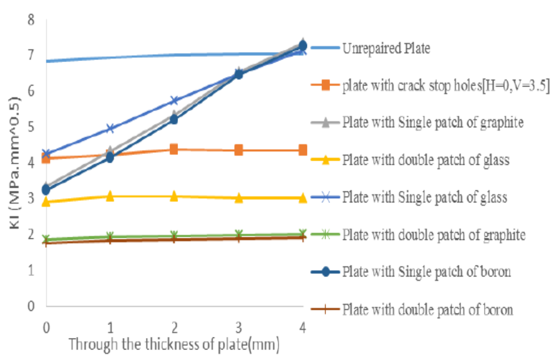


Fig.12
SIF along the thickness of the Plate, for different repair methods.

6 THE EFFECT OF SIMULTANEOUS APPLICATION OF STOP HOLES AND THE COMPOSITE PATCH ON REDUCING SIF (HYBRID METHOD)

In this section, the effect of the simultaneous application of stop holes and composite patches (hybrid method) on SIF reduction is investigated. Fig. 13 shows the SIF changes for a cracked curved plate with holes on both sides of the crack and a cracked plate repaired with a graphite-epoxy patch. Different modes are considered for the thickness, width, and length of the patch as well as the characteristics of the stop holes. According to Fig. 13, it can be seen that for the case of simultaneous use of holes and patches, when the mode of creating holes with specifications (D = 5 *mm*, H = 0 *mm*, V = 3.5 *mm*) and applying the graphite patch with a thickness of 2.5 *mm*, length of 260 *mm* and width of 250 *mm* is used, there is the greatest reduction in SIF. Clearly, the modes that individually have the most impact on reducing SIF, also have the best performance in the hybrid mode.

According to Fig. 14, for all four repair methods studied, compared to the plate with a radius of curvature of 1 *m*, the SIF is lower for the plate with a radius of curvature of 5 *m*. Previously, for separate cases of stop holes and one-sided patches, it was shown that increasing the radius of curvature to a constant value reduces the SIF, and also, in this method, which is a combination of both previous methods, as the radius of curvature increases, the SIF decreases.

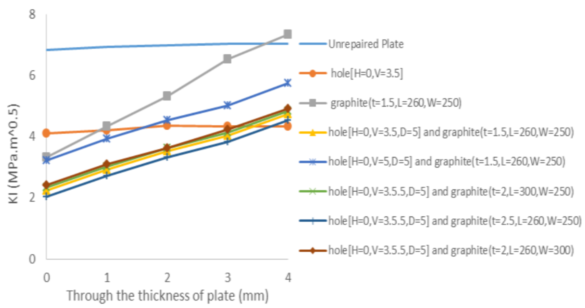


Fig.13
SIF along the thickness of the unrepaired and repaired Plate.

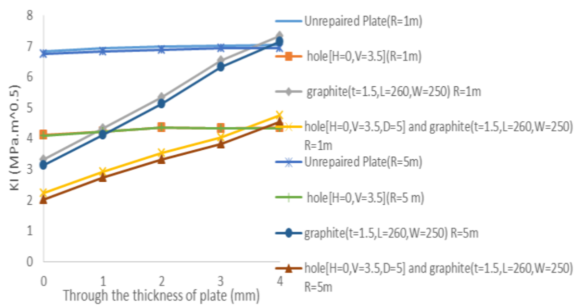


Fig.14
Effect of the radius of curvature of the plate on the repair efficiency in different repair methods.

According to Fig. 15, with simultaneous application of the one-sided graphite patch and the stop holes, the average SIF is reduced by 49.1% (approximately equal to the case of simultaneous application of boron-epoxy patch and stop holes). This number is 26.72% in the case of the simultaneous application of the glass-epoxy patch and holes. Thus, In the case of simultaneous application of holes and patches, compared to glass, the use of boron and graphite patches reduces SIF by 22.38% further. Fig. 16 shows the effect of the simultaneous application of double-sided patches and stop holes on SIF reduction. Simultaneous use of a two-sided graphite patch with the stop hole reduces SIF by 79.9% (approximately 30.32% more than simultaneous use of the one-sided graphite patch and holes). Simultaneous use of the double-sided glass patch and stop holes reduces SIF by 67.88%.

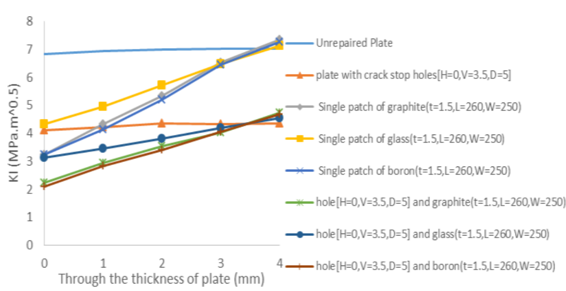


Fig.15
Comparison of the combined hole and single patch repair method with patch and hole repair methods.

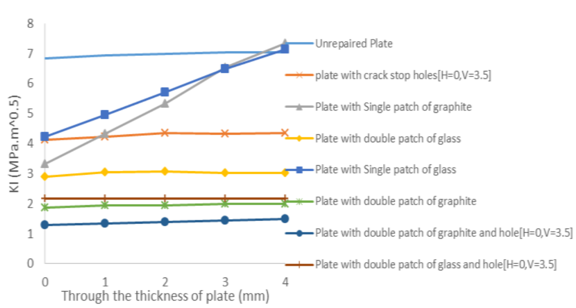


Fig.16
Comparison of the hybrid holes and two-sided patch repair method with patch and holes repair methods.

Table 3 shows the average SIF reduction relative to the unrepaired state for all three methods of repairing the plate with the hole, the composite patch, and simultaneously with the patch and the holes (radius of curvature 1 and 5 meters). Creating a hole around the crack tip changes the stress field in such a way that the SIF is reduced, and at the same time, the two-sided patch keeps the crack faces close together and causes the SIF to be reduced to a greater extent (without creating any extra bending moment). As a result, the simultaneous use of double-sided patches and holes can have the best efficiency in reducing SIF (Table 3).

Table 3
SIF reduction percentage for different repair methods (R=1, 5 *m*).

stop holes and double patch of graphite	stop holes and Single patch of graphite	double patch of graphite	Single patch of graphite	crack stop holes	Repair method
79.9	49	71.48	22.99	37.64	R=1 *m*
80.84	50.3	72.31	23.62	37.2	R=5 *m*

Table 4 shows the effect of the radius of curvature of the plate on the percentage reduction of the SIF relative to the unrepaired state for the 3 modes of the plate repaired with the stop holes, composite patch, and the hybrid method. As can be seen, compared to the non-repaired mode, for the plate repaired with the stop holes, the percentage of SIF reduction decreases slightly as the radius of curvature of the cracked plate increases. In other words, by increasing the radius of curvature of the plate, the efficiency of this method decreases. In the other two cases under consideration (patched and hybrid method), with increasing the radius of curvature of the plate, the percentage of SIF reduction increases, and, in other words, the patch efficiency increases. Therefore, as the radius of curvature of the plate increases, the SIF value decreases in each case and the patch efficiency improves in the cases of using the patch or the hybrid method (Fig. 17 and Table 4).

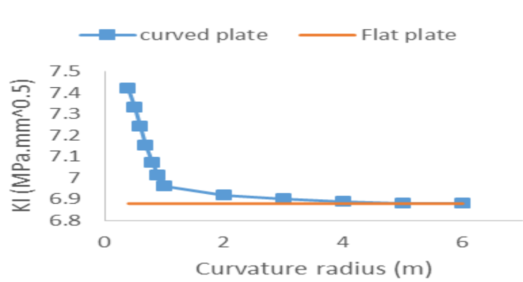
Table 4
SIF reduction percentage for different radius of curvatures of the plate in different repair methods.

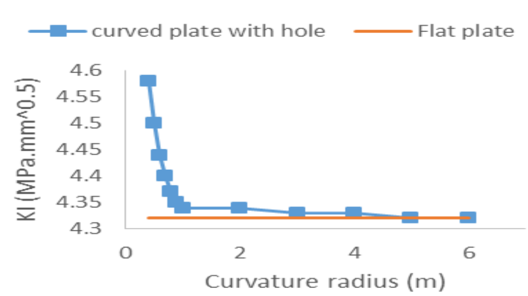
R (*m*)	0.4	0.7	1	5	6
Crack stop hole	38.27	38.46	37.64	37.2	37.1
One-sided patch	22.1	22.94	22.99	23.62	23.98
Crack stop hole and one-sided patch	46.2	48.25	49	50.3	50.58

7 THE EFFECT OF THE RADIUS OF CURVATURE ON REDUCING SIF

Fig. 17 shows the SIF changes by changing the radius of curvature of the plate (in different repair methods). Clearly, increasing the radius of curvature reduces the SIF. For the unrepaired cracked curve plate, from a radius of curvature of 5 *m* onwards, increasing the radius of curvature has almost no effect on SIF, and SIF for curved plates with a radius of curvature of 5 m or later is the same as SIF of flat plates. In other cases, the disappearance of the curvature effect occurs at a different radius of curvature (Fig. 17).

Fig. 18 shows the SIF changes by changing the radius of curvature of the plate for radii of curvature less and more than one meter. According to Fig. 18, mode R <1, in a radius of curvature of 1 *m*, for unrepaired curved plate and curved plate with stop holes, SIF is not much different from the SIF of a flat plate. At a curvature radius of 1 *m*, compared to a patched flat plate, the SIF of a patched curved plate is slightly larger. Also, the SIF value of the cracked curved plate repaired with a hole and patch in a radius of curvature of 1 meter is different compared to the flat plate repaired with a hole and patch, and this difference can be seen in the diagram. According to Fig. 18 for R> 1, compared to the other studied modes, in the case of a plate with stop holes, the SIF value matches the flat plate results sooner. In the case of the curved plate repaired simultaneously with the hole and patch, up to a radius of curvature of 6 meters, the results of the curved plate are still different from the flat plate.





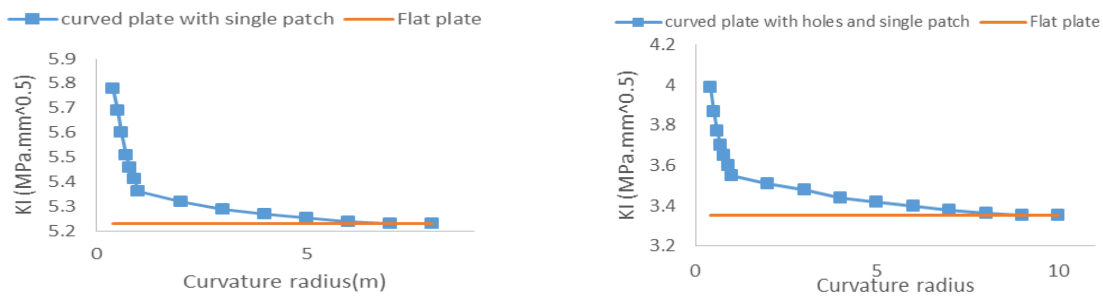


Fig.17
The SIF changes due to changing the radius of curvature of the plate for different repair methods.

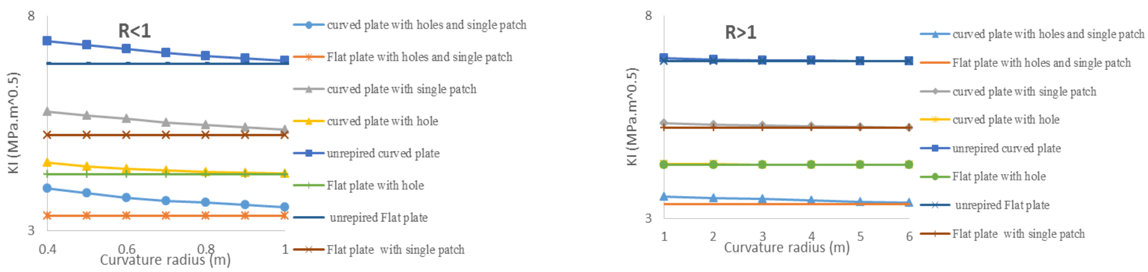


Fig.18
The effect of radius of curvature on the SIF for different repair methods.

8 CONCLUSIONS

In this paper, SIF changes in various methods of repairing a curved cracked plate, including stop holes on both sides of the crack, the use of one-sided and two-sided composite patches, as well as the simultaneous application of stop holes and composite patches are investigated and compared with the unrepaired state. The most important results are presented below:

1. Holes with a larger diameter and vertical distance closer to the crack tip have a greater effect on reducing SIF. Also, the best case for applying stop holes on both sides of the crack are the holes that have a horizontal distance of zero millimeters from the tip of the crack. Positive horizontal distances increase the SIF, and zero and negative horizontal distances decrease the SIF.
2. The use of one-sided composite patches made of different materials of boron, graphite, and glass for the cracked curved plate studied in this research reduces the average SIF by 24.4, 23, and 13.76 percent, respectively. Also, the use of double-sided graphite and glass patches reduces SIF by 71.48 and 52.3%, respectively (R = 1 *m*).
3. Increasing the thickness of the one-sided patch for all three materials of boron, graphite, and glass reduces the SIF by a small amount. Increasing the length of one-sided patches increases the SIF. Also, increasing the width of the patches does not have much effect on reducing or increasing the SIF.
4. For all cases under consideration, the SIF decreases with increasing the radius of curvature of the plate. For unrepaired cracked curved plates, from a radius of curvature of 5 *m* onwards, increasing the radius of curvature has almost no effect on the SIF. In other cases, the disappearance of the curvature effect occurs at different radii of curvature. By increasing the radius of curvature of the plate, in the case of using a patch or a hybrid method, the patch efficiency also improves.
5. In all the studied cases, by considering the constant diameter and horizontal and vertical distances of the holes from the crack tip, in the case of using boron and graphite patches, a greater SIF reduction is obtained than in the case of using the glass patch.
6. The holes on both sides of the crack reduce the SIF more than the repair mode with the one-sided patch, but in the repair mode with the two-sided patch, there is more SIF reduction than the one-sided patch and the holes.

7. For simultaneous use of holes and one-sided patches, when the mode of creating holes with specifications (D = 5 *mm*, H = 0 *mm*, V = 3.5 *mm*) and applying the graphite patch with a thickness of 2.5 *mm*, length of 260 *mm*, and width of 250 *mm* is used, there is the greatest reduction in SIF.
8. Simultaneous use of a two-sided graphite patch and stop holes reduces SIF by 79.9% (approximately 30.32% more than the simultaneous use of the one-sided graphite patch and holes). Simultaneous use of double-sided glass patch and hole also reduces SIF by 67.88% (R=1 *m*).

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