



Numerical Investigation of Fatigue Behavior of Non-patched and Patched Aluminum/Composite Plates

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Abstract

In this study, the fatigue behavior of composite patched and non-patched Al 5083 aluminum plates was numerically investigated. Al 5083 Aluminum plates with semi-circular notched (2, 3 and 4 mm long cracked) and “V” notched (30°, 45° and 60° angled) were used in the analyzes. Mechanical properties of Al 5083 Aluminum plate, DP460 type adhesive of produced by 3M and [0°]_g glass fiber reinforced composite patch material was used for the study. The Finite Element Method was applied for numerical study. Numerical analyzes were performed with the Ansys version 15.0 Workbench Package program. As a result of the numerical study, the highest fatigue life (1593.2 N) is seen on the 30° angled “V” notched and patched specimen. However, the fatigue life in non-patched specimen (30° angled “V” notched) was found to be 277.69 N. Thus, the study revealed that the composite patch’s contribution is very important.

Keywords: Aluminum, Composite, Patch, Notch, Crack, Fatigue analysis

1. INTRODUCTION

Aluminum and composite materials are used extensively in different industrial areas such as aviation, space, automotive and marine. Because of their intense use, experimental research is required to develop, as strength and repair, these materials. Experimental research to develop these materials requires significant financial resources and time. Therefore, there has been interest in numerical analysis. The main reason for interest in numerical analysis is that it is very close to experimental results. In addition, through numerical analysis programs, it is possible to find solutions to the damage that may occur in these materials in advance [1-11]. There are many numerical studies on different types of Aluminum and Composite materials [3, 6, 8, 9, 11]. However, these materials are used in many different areas. Therefore, every study on these materials is important.

Can C. [12] investigated experimentally and numerically the fiberglass epoxy composite patches applied on damaged Al 2024 T3 aluminum sheets. In study, the critical lines were determined and the stress distributions on the samples along these lines were examined. His study showed that the numerical results are very close to the experimental results. In a study performed by Ahmet S. [13], the Al 5754 aluminum material repaired with composite patch were experimentally and numerically investigated. As a result of his investigation, he stated that the stresses on double-sided composite

patched aluminum sheets are less. Uğur S. [14] experimentally performed the tensile and bending tests of the Al-2024 T3 aluminum adherend material repaired with a graphite/epoxy patch and compared the results with numerical analysis. He stated that the experimental and numerical analysis were in harmony as a result of the examination. Osman A. [15] investigated repairing damaged glass fiber reinforced epoxy composite plates by using composite patches. In the study, the effect of patch size and patch number changes on flexural stress behavior was investigated experimentally and numerically. As a result of the study, he stated that numerical analysis results and experimental results were very close. Mehmet R. [16] examined experimentally and numerically by repairing elliptical damaged glass fiber reinforced composite plates with the same material. In his investigation, he showed that the tensile stresses of the repaired glass fiber reinforced composite plates were compatible with the numerical ones. Abdülkerim P. [17] examined the repair performance by subjecting the repaired composite plates to a tensile test. The result of the research indicated that the experimental and numerical results were compatible.

The harmony of the results of the experimental and numerical studies mentioned above increases the importance of numerical studies. Therefore, in our study, the fatigue behavior of composite patched and non-patched Al 5083 aluminum plates (semi-circular and “V” notched) was numeri-

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cally investigated. Thus, the effects of both patch and notch shapes on fatigue life were found.

2. MATERIAL AND METHOD

In our study, numerical analyzes were performed using the Finite Element Method. Numerical analyzes were performed with the Ansys version 15.0 Workbench Package program [18, 19]. As materials, Al 5083 aluminum plate, [0°]₈ glass fiber reinforced composite patch and DP460 type adhesive of produced by 3M were preferred. The mechanical properties of these materials were used in numerical analysis. The mechanical properties of Al 5083 Aluminum plate, [0°]₈ glass fiber reinforced composite patch and DP-460 adhesive materials used in the analyzes are given in Table 1, Table 2 and Table 3, respectively [20-22].

Table 1. Mechanical properties of Al 5083 Aluminum plate [20].

Elasticity module	70000 MPa
Poisson ratio	0.3897
Tensile strength	345 MPa
Yield strength	270 MPa
Thermal conductivity	204 W/(m.K)
Thermal expansion coefficient	2.4e-005 1/K
Mass density	2660 kg/m ³
Specific heat	940 J/(kg.K)

Table 2. Mechanical properties of [0°]₈ glass fiber reinforced composite patch [21].

E_1	40510 MPa
$E_2=E_3$	13960 MPa
G_{12}	3100 MPa
$G_{13}=G_{23}$	1100 MPa
ν_{12}	0.22
$\nu_{13} = \nu_{23}$	0.15

Table 3. Mechanical properties of 3M brand DP460 type industrial adhesive [22].

Adhesive thickness	0.25 mm
Shear stress	23.99 MPa
Shear strength	33.35 MPa
Shear module	560 MPa
Elasticity Module	2077.1 MPa
Poisson's ratio	0.38
Tensile strength	44.616 MPa

In the study, Al 5083 Aluminum plates with semi-circular notched (with 2, 3 and 4 mm cracks) or "V" shaped notches (30°, 45° and 60° angled) were analyzed non-patched or patched. As patch material, [0°]₈ glass fiber reinforced composites were used. In numerical study, the effect of non-patched and patched aluminum plates on fatigue behaviors was investigated. Dimensions of Al 5083 Aluminum plates used in numerical studies are given in Fig. 1 and Fig. 2.

As seen in Fig. 1, Al 5083 Aluminum plates have semi-circular notch on one and both sides and 2, 3 and 4 mm long cracks advanced towards the interior.

As seen in Fig. 2, Al 5083 Aluminum plates have notches on one and both sides, these notches have 6 mm length and 30°, 45° and 60° angles. Dimensions of [0°]₈ glass fiber reinforced composite patch used in numerical analysis are given in Fig. 3.

As a result of the literature review, the thickness of the adhesive was selected as 0.25 mm [23-25].

3-Dimensional pictures of the materials used in numerical analysis are given in Fig. 4.

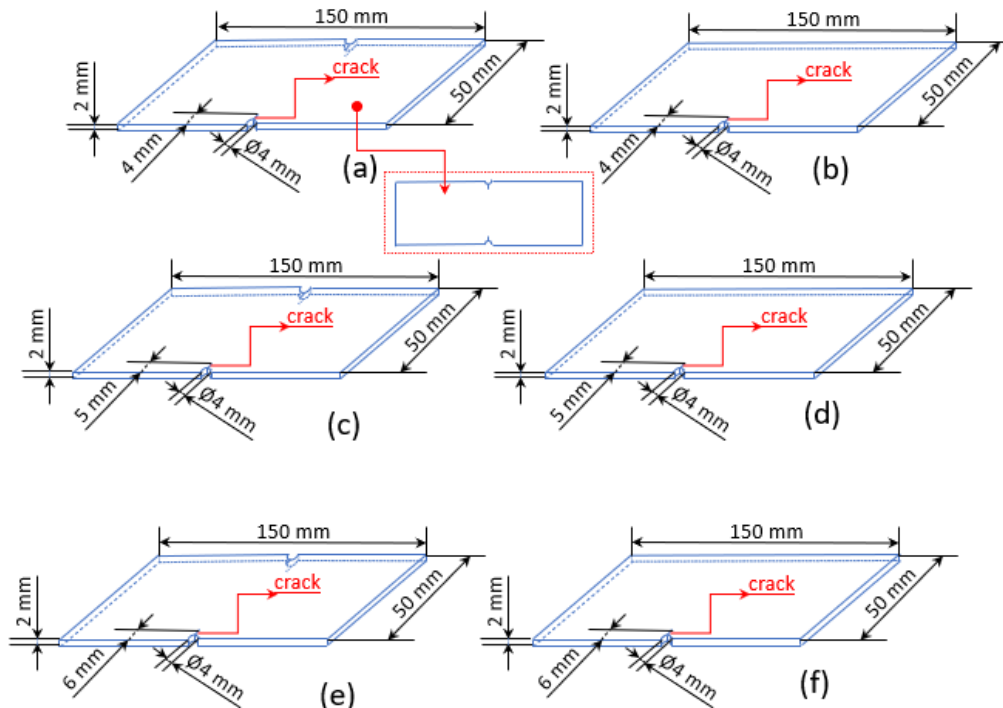


Figure 1. Dimensions of Al 5083 Aluminum plates with 2 mm (a, b), 3 mm (c, d) and 4 mm (e, f) cracks starting from the semi-circular notch (single and double sided).

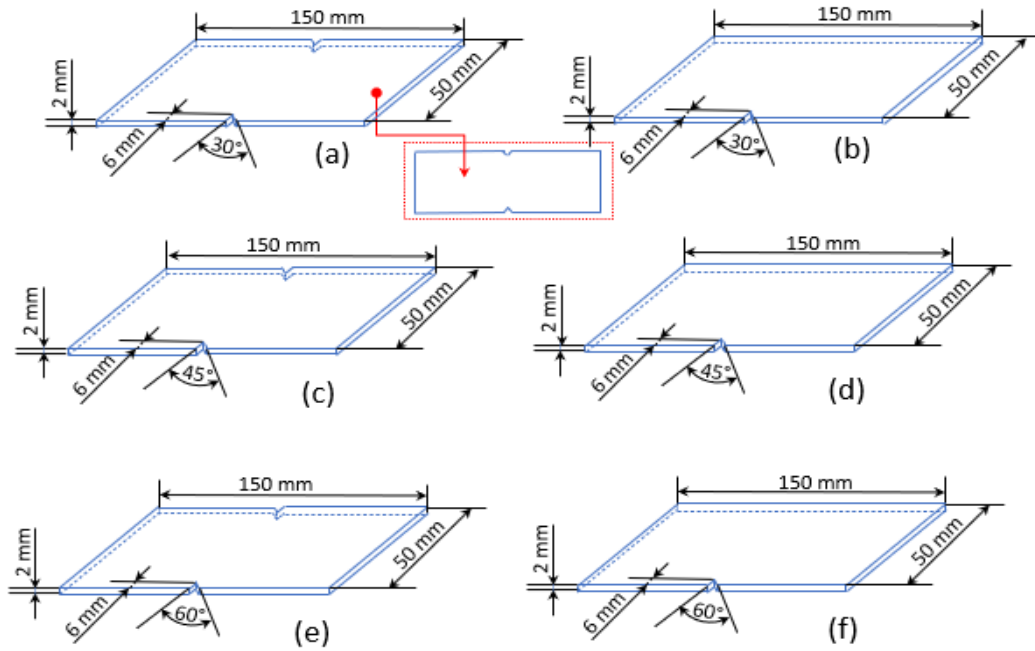


Figure 2. Dimensions of Al 5083 plates with notch length 6 mm, notch angles 30° (a, b), 45° (c, d), and 60° (e, f) (single and double sided).

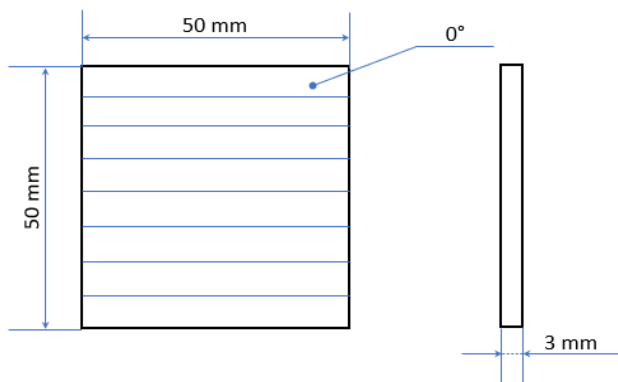
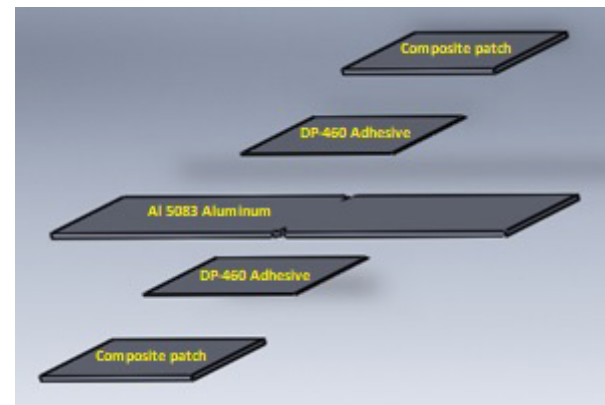
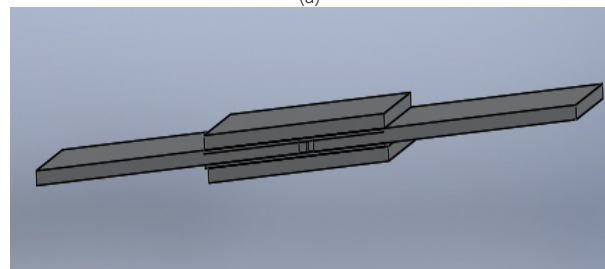


Figure 3. Dimensions of $[0^\circ]_g$ glass fiber reinforced composite patch.

The materials, whose technical drawings were prepared first, were drawn in 3D using the Solidworks program, and then transferred to the Ansys Workbench 15.0 Package program. In the study, the fatigue lives, Von-mises stresses and deformations of the materials were investigated by applying tensile-compression load ($R = -1$). One end of the sample is modeled in a fixed support state. At the other end, pressure was applied based on 45% of the yield stress value of the Al 5083 aluminum plate sample. While the yield value of the Al 5083 Aluminum material, which is the analysis sample, is 270 MPa, tensile-compression loads were applied with a value of 121.5 MPa, which is 45% of this value. Pressure was applied directly opposite the fixed end. In Ansys, adding material to the contact parts of the joint (a), the screen accessed with the model (b), determination of the support and pressure points (c) and the mesh applied (d) are given in Fig. 5.



(a)



(b)

Figure 4. 3D pictures of materials before (a) and after (b) joining.

The number of elements and nodes of single and double sided, semi-circular notched and cracked (with 2, 3 and 3 mm) samples after mesh structure are given in Table 4.

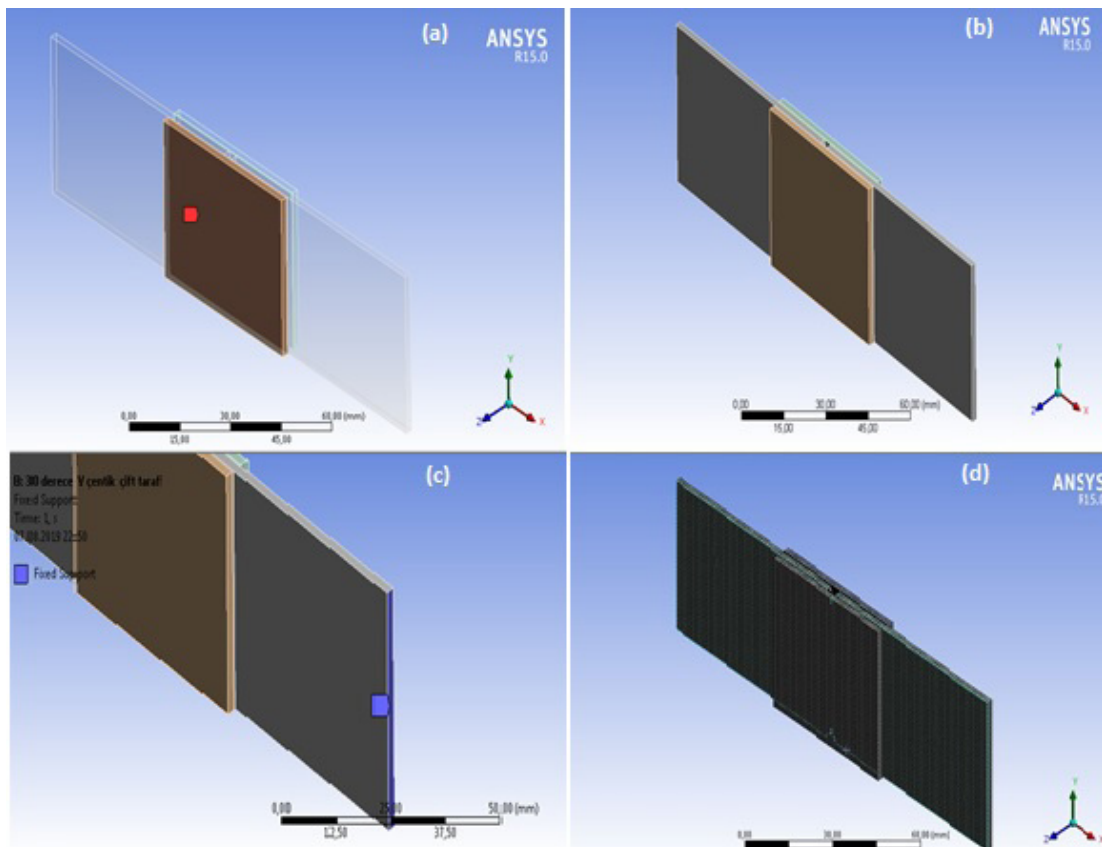


Figure 5. Pictures of adding material to the contact parts of the joint (a), the screen accessed with the model (b), determination of the support and pressure points (c) and the mesh applied (d).

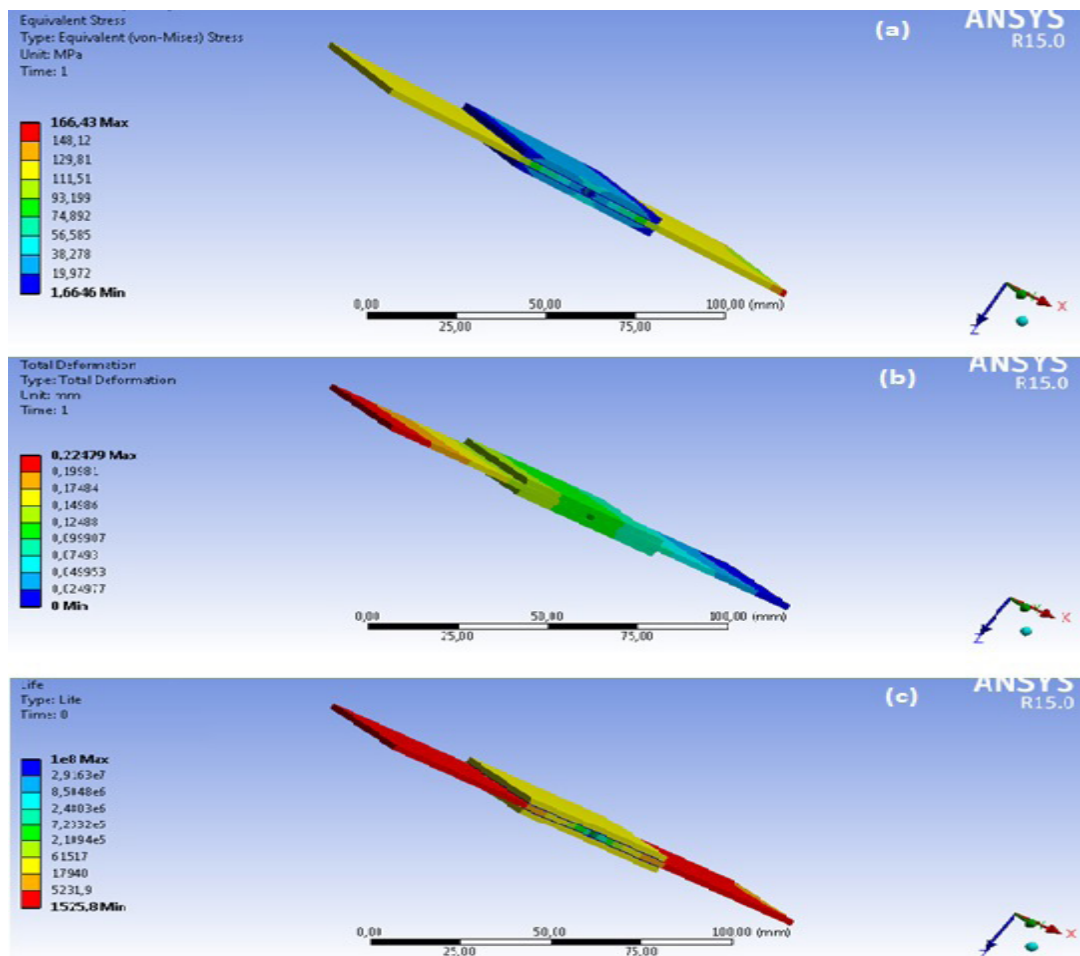


Figure 6. Pictures of Von-mises stress analysis (a), total deformation analysis (b) and fatigue life analysis (c) of the joints.

Table 4. The number of elements and nodes of single and double sided, semi-circular notched and cracked (with 2, 3 and 3 mm) samples.

Crack length	Semi-circular notches and cracks				
	One sided		Double-sided		
	Non-patched	Patched	Non-patched	Patched	
2 mm	Elements	7548	102548	15172	110172
	Nodes	53879	695099	85187	726407
3 mm	Elements	7560	102560	15276	110276
	Nodes	53953	695173	85727	726947
4 mm	Elements	7584	102584	15194	110194
	Nodes	54126	695346	85332	726552

The number of elements and nodes of the samples with single and double sided "V" notched (30, 45 and 60 angled) after the mesh structure are given in Table 5.

Von-mises stress analysis (a), total deformation analysis (b) and fatigue life analysis (c) of the joints in the study are given in Fig. 6.

3. RESULTS AND DISCUSSION

3.1. Fatigue life

The results of fatigue analysis applied to Al 5083 aluminum plates (non-patched and patched) with semi-circular notches (single and double sided) and cracks (2, 3 and 4mm) are given in Table 6. Here, N symbolizes the number of cycles.

Table 6. The results of fatigue analysis.

With semi-circular notch and crack	Number of cycles (N)			
	Single sided		Double sided	
	Non-patched	Patched	Non-patched	Patched
Crack length				
2 mm	347.67	1267	428.68	1266.70
3 mm	321.80	1266.90	373.86	1266.40
4 mm	265.04	1266.80	323.20	1266.30

As can be seen in Table 6, in numerical analysis, the fatigue life of the patched samples was found to be quite high (about 3.5 times on average). It has been observed that the increase in the length of the cracks (2, 3 and 4 mm) negatively affected the fatigue life. It has been observed that samples with

Table 5. The number of elements and nodes of the samples with single and double sided "V" notched (30, 45 and 60 angled).

"V" Notch angle	"V" notched				
	One sided		Double-sided		
	Non-patched	Patched	Non-patched	Patched	
30° Angled	Elements	71215	166215	15354	110354
	Nodes	128928	770148	86148	727368
45° Angled	Elements	70672	165672	15186	110186
	Nodes	128031	769251	85176	726396
60° Angled	Elements	15028	110028	15126	110126
	Nodes	84283	725503	84846	726066

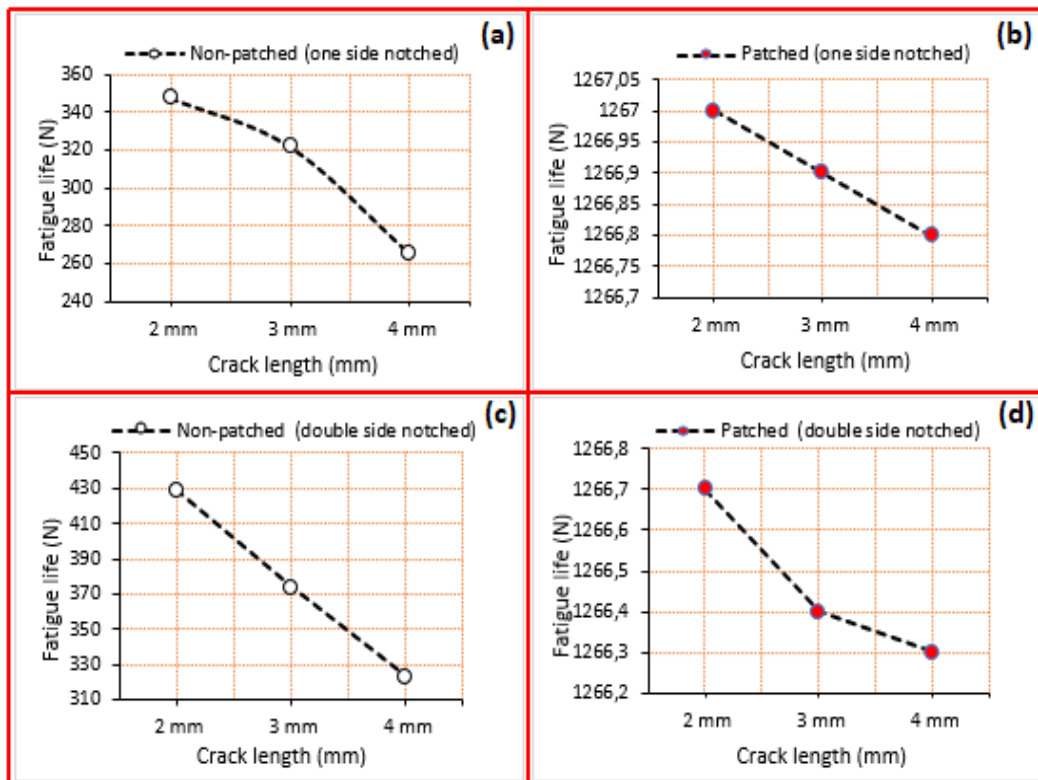


Figure 7. Fatigue lives of the samples.

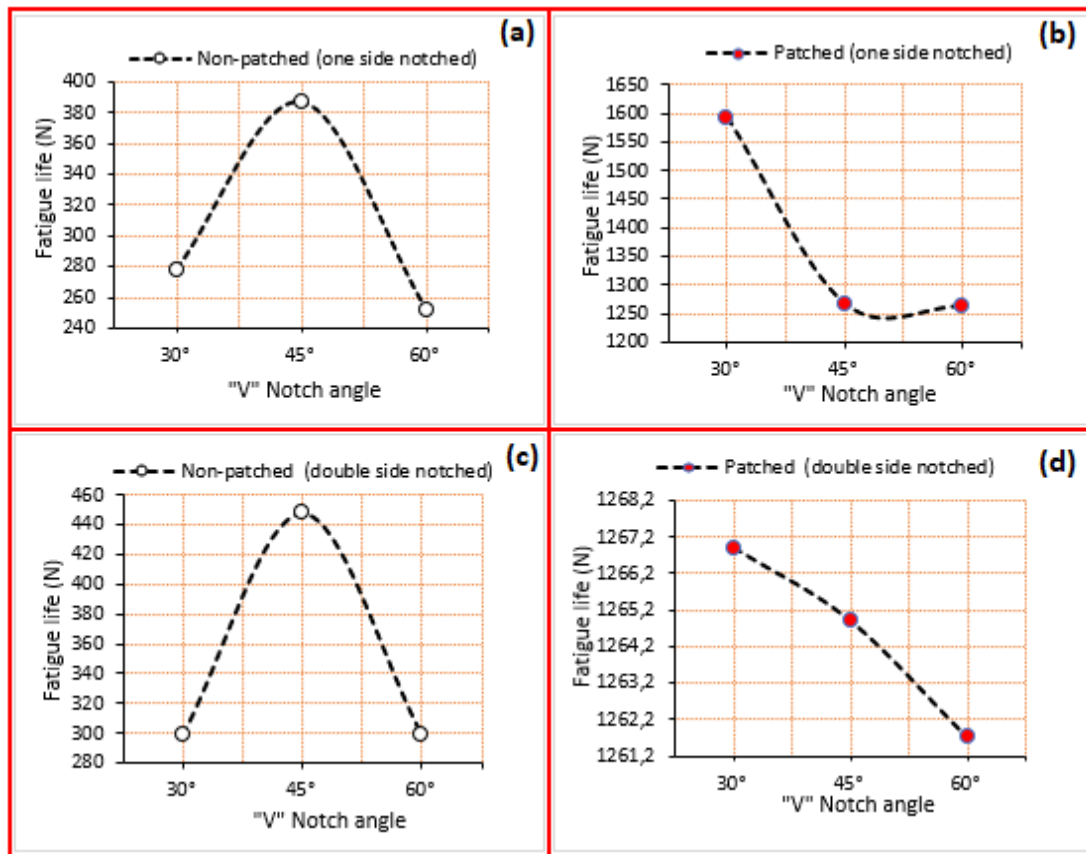


Figure 8. Fatigue lives of the samples.

Table 7. The results of fatigue life analysis.

With "V" notch Angle	Number of cycles (N)			
	Single sided		Double sided	
	Non-patched	Patched	Non-patched	Patched
30°	277.69	1593.2	298.45	1266.90
45°	387.11	1265.5	448.04	1264.90
60°	251.66	1262.3	298.70	1261.70

notches and cracks on one side have lower fatigue life than samples with notches and cracks on both sides.

As can be seen in Fig. 7 a, the increase in crack length caused a decrease in fatigue life. The fatigue lives of the notched (one-sided) and non-patched samples decreased due to increased crack length (Fig. 7 c). Fig. 7 b shows a decrease in fatigue life with increasing crack size. However, the fatigue lives of the samples are very close to each other in every crack size. When a comparison is made between Fig. 7 a and Fig. 7 b, it is seen that the fatigue life of the patched samples is quite high (Fig. 7 b and d). Therefore, it has shown that composite patches applied to semi-circular notched and cracked aluminum samples are very successful. In patched samples, as a result of the absorption of the applied load by the patches, the fatigue life has increased and the effect of crack lengths has been reduced to negligible. The linearity of the graph in samples with cracks on one side is due to the similarity of damage in one region of the load.

The results of the fatigue life analysis applied to single and double sided "V" notched (30°, 45° and 60° angled) Al 5083 aluminum plates (Non-patched and patched) are given in Table 7.

As seen in Table 7, in numerical analysis, non-patched samples have a lower fatigue life than patched samples. The fatigue life of the sample with 30° angled "V" notch (patched) on one side was found to be higher than all other samples. The fatigue life of the "V" notch with 30° angled is quite high because it is patched with composite material and has the least notch dimensions.

The fatigue life graphs of the samples with "V" shaped (30°, 45° and 60° angled) notches on their single and double sides are given in Fig. 8. The most striking point in the graph is that the fatigue life of the 45° angled "V" notch (non-patched) sample is much higher than the 30° and 60° angled samples (Fig. 8 a and c). On the other hand, the fatigue lives of 30° and 60° angled (non-patched) samples are close to each other, but the fatigue life of the 30° angled sample is longer (Fig. 8 a). The reason why the 45° angled "V" notched (non-patched) sample has the highest fatigue life is that the stress creates agglomeration at this point (Fig. 8 a and c). In Fig. 8 b and d, the highest fatigue lives are at 30° angled ("V" single notched) patched samples. On average, the fatigue lives of samples (patched) with "V" notches at 45° and 60° angles are close to each other (Fig. 8 b and d). It is also

understood from the graphs that the fatigue life of the composite patch samples is quite high (Fig. 8 b and d). As seen in Fig. 8, samples with "V" notches on single and double sides are 30° angled (patched) samples with the highest fatigue life. However, the highest fatigue life is the 30° angled, one side notched and patched sample.

3.2. Von-mises stresses

The results of the Von-mises stresses of the non-patched and patched semi-circular notched (and cracked) samples are given in Table 8. As can be understood from Table 8, the lowest Von-mises stress values are seen in composite patched samples. When the samples (patched) with "V" semi-circular notches and cracks (2, 3 and 4 mm long) on one side are compared with the samples (patched) with "V" semi-circular notches and cracks (2, 3 and 4 mm long) on both sides, it is seen that the stress values are very close to each other. This shows that the effect of the composite patch on the stress is quite high. Since the semi-circular notch and crack are symmetrical on the part, it slightly reduces the stress value.

Table 8. The results of Von-mises stresses.

With semi-circular notch and crack	Von-mises stresses (MPa)			
	Single sided		Double sided	
	Non-patched	Patched	Non-patched	Patched
Crack length				
2 mm	291.09	178.30	264.43	178.32
3 mm	300.94	178.31	281.85	178.34
4 mm	325.65	178.31	300.39	178.34

As can be seen from Fig. 9, while the stresses are less in patched samples, the stresses are higher in non-patched samples. Because, in composite-patched samples, some of the stresses are distributed over the composite and adhesive, so the stresses are less.

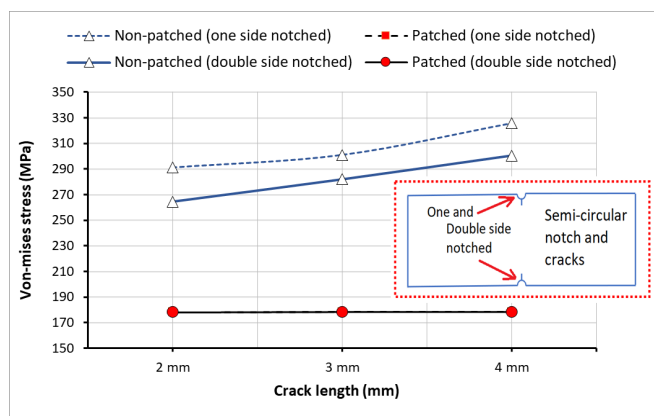


Figure 9. Von-mises stresses.

The results of the Von-mises stresses of the non-patched and patched "V" notched (30°, 45° and 60° angled) samples are given in Table 9.

Table 9. The results of Von-mises stresses.

With "V" notch	Von-mises stresses (MPa)			
	Single sided		Double sided	
	Non-patched	Patched	Non-patched	Patched
Angle				
30°	319.71	163.67	310.53	178.31
45°	277.41	178.38	258.8	178.41
60°	332.24	178.54	310.43	178.57

As seen in Table 9, the maximum stress values in patched samples are lower than non-patched samples. Because excessive stresses are distributed over the composite patch and adhesive. It is seen that the Von-mises stress values of non-patched 45° angled "V" notched joints are lower than those of 30° and 60° joints. It is seen that the 45° angle is a critical value in "V" notched connections and it is beneficial. The symmetrical notches in non-patched samples are beneficial in terms of stresses.

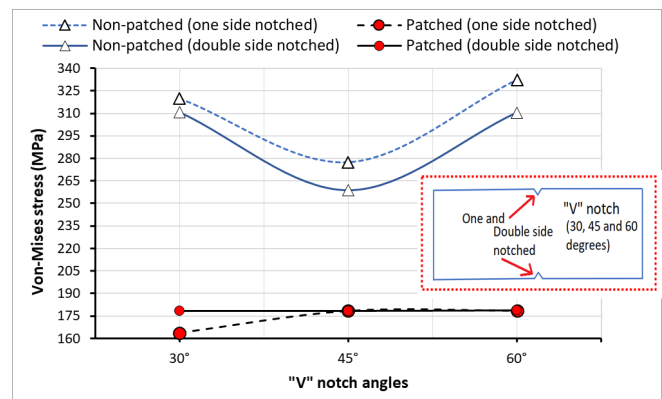


Figure 10. Von-mises stresses.

As can be seen from Fig. 10, while the stress is less in patched samples, it is higher in non-patched samples. Because, the composite patches have reduced the stresses.

3.3. Deformations

The results of the deformation of the non-patched and patched semi-circular notched (and cracked) samples are given in Table 10.

Table 10. The results of deformations.

With semi-circular notch and crack	Deformation (mm)			
	Single sided		Double sided	
	Non-patched	Patched	Non-patched	Patched
Crack length				
2 mm	0.26905	0.22522	0.26274	0.22451
3 mm	0.27571	0.22607	0.26513	0.22479
4 mm	0.28411	0.2262	0.26811	0.22475

As seen in Table 10, the deformation values in patched samples are lower than those non-patched. Because composite patches have helped prevent deformation in samples. In non-patched samples, deformation increased due to the increase in crack size.

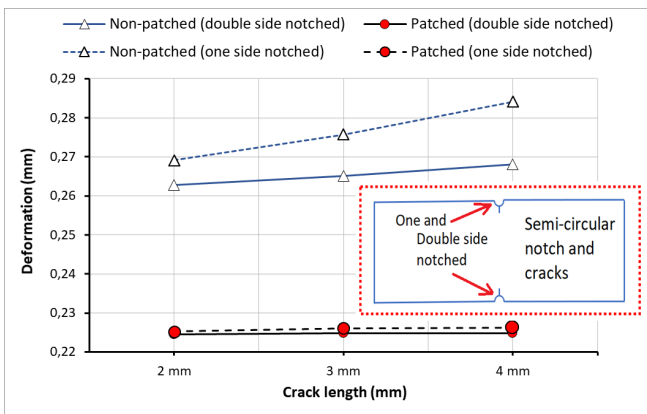


Figure 11. Deformation results.

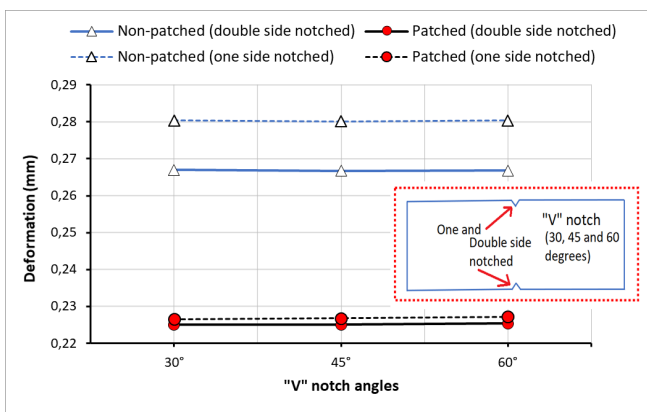


Figure 12. Deformation results.

As can be seen from Fig. 11, while the deformation is less in the patched samples, the deformation is higher in the non-patched samples. Because, in composite-patched samples, some of the stresses are distributed over the composite and adhesive, so the deformation is less.

The results of the deformation of the non-patched and patched "V" notched (30°, 45° and 60° angled) samples are given in Table 11.

Table 11. The results of deformations.

With "V" notch	Deformation (mm)				
	Angle	Single sided		Double sided	
		Non-patched	Patched	Non-patched	Patched
30°	0.28034	0.22650	0.26692	0.22505	
45°	0.28008	0.22672	0.26674	0.22499	
60°	0.28032	0.22720	0.26683	0.22532	

As seen in Fig. 13, while the deformation is less in the patched samples, the deformation is higher in the non-patched samples.

In addition, it is seen from Fig. 12 that the deformations of the single and double notched connections are very close to each other. This revealed that the contribution of the composite patch is very important.

4. CONCLUSIONS

In our numerical study, Al 5083 aluminum plate, glass fiber reinforced composite patch and DP460 adhesive were used. Analyzes were performed using the Finite Element Meth-

od. The Finite Element analyzes were made in Ansys Workbench. In the study, Al 5083 Aluminum plates with semi-circular notched (with 2, 3 and 4 mm cracks) or "V" shaped notches (30°, 45° and 60° angles) were used non-patched or patched. In numerical study, the fatigue lives, Von-mises stresses and deformations of the materials were investigated. Obtained results are presented below.

The fatigue lives of the patched samples with semi-circular notches and cracks (2, 3 and 4 mm long) on both sides was very close to each other. Fatigue lives decreases in proportion to the increase in the length of the crack, but this decrease seems to have a very low value. The fatigue lives of the samples with one-sided semi-circular notches and cracks were seriously affected by the increase in crack length. It has been stated in the literature that smaller cracks increase the patch efficiency [26-28]. In the analysis, the deformation was mostly seen in the area of the crack. The same situation is observed in double sided semi-circular and cracked samples.

One side "V" notched (30°, 45° and 60° angles) and patched specimens have been observed to increase fatigue life as the angle of the notch decreases. The highest fatigue life (1593.2 N) is seen on the 30° angled "V" notched and patched sample. However, the fatigue life in non-patched specimen (30° angled "V" notched) was found to be 277.69 N. As in the literature (in experimental studies with "V" notches), the positive effect of the composite patch on the fatigue life has been observed [29, 30]. The same situation is observed in double sided "V" notched samples. However, it is seen that the fatigue lives of the samples with double sided "V" notches does not change much with the angle.

In non-patched samples, the highest fatigue life was found with a 45° angled "V" notch on one side. Then, samples with 30° and 60° angles "V" notched are followed, respectively. The highest fatigue life of the non-patched specimens with "V" notches on double side is 45°, 60° and 30°, respectively.

The Von-mises stress and deformation values of single and double sided "V" notches (30°, 45° and 60° angles) and semi-circular notches (with 2, 3 and 4 mm cracks) were positively affected by the applied patches.

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