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Numerical study of fatigue behavior of the aluminum 7075-T6 cantilever beam with angular cracks in different stress ratios

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ABSTRACT

The numerical simulation of fatigue behavior of the Aluminum 7075-T6 cantilever beam with an angular crack has been investigated. Cracks are located separately in three different positions of the investigated beam. To predict the fatigue behavior of the cantilever beam the crack propagation was manually simulated. Compression load is applied in different stress ratios between zero and one; then, the obtained numerical results of this research are compared with the experimental results. It is observed that increasing the stress ratio increases the percentage of the fatigue life of the sample significantly. Ascending growth of fatigue life is slow and more severe by increasing of the stress ratio for the first and the third position, respectively. By increasing the stress ratio, the rate of deviation of the crack decreases and it converges to 0° in parallel to the width of the beam. This result is also observed with an increase in the distance from the support of beam. Furthermore, it is also revealed that by the increase in the initial length of the crack, the fatigue life initially reduces with smaller ratios. However, along the larger cracks, the decreasing ratio of fatigue life increases significantly.

1. Introduction

Aluminum alloys are considered as one of the most widely used metals in various industries, including aerospace. On the other hand, the prices of constructing aerospace structures are high. Therefore, preventing fracture failure can significantly reduce prices. Crack is considered as the most common factor in the failure of aerospace structures (Anderson, 2004).Fatigue loading is one of the factors of causing cracks in the workpieces (Tu, 2016). One of the important parameters in the fracture mechanics is the stress intensity factor, which shows the resistance of the workpiece to the crack growth (Seethraman et al., 2015). Accordingly, when a workpiece with a crack, is exposed to the external load, stress concentration is produced around the tip of the crack. Whenever this concentrated stress reaches a critical value, the failure occurs. The value of the stress intensity coefficient, which is calculated for this critical stress, is called the stress intensity factor (KIc) (Sih, 1991). According to studies by different researchers, the two parameters of the KI and KII are important parameters that control the failure behavior in combined modes of loading (Liu, 2007). Furthermore, depending on how the external load is applied, the growth of the cracks occurs under three basic modes of failure (Sih et al., 1975). Mode I

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or opening mode is the most common form of rupture due to the crack growth. In this mode, the cracking surfaces are displaced vertically and in the opposite direction relative to other surfaces; moreover, the tensile stress is perpendicular to the crack plate. Mode II is in planner shear mode, in which two cracking areas slip in a direction perpendicular to the tip of the crack; also, the shear stress is parallel to the crack plate and perpendicular to the crack front. Another mode of cracking is modes 3 or rupture mode, in which the slip of the two crack plates occurs in a direction parallel to the crack profile line. The crack growth can occur due to the static, dynamic or fatigue loading. Important matter in the crack growth under cyclic loads is the number of cycles (N), which is required to increase the length of the crack from ai to af. Virtual crack extension (VCE) is one of the techniques of the crack growth under the fatigue loading. In this method, by knowing c and m, which are the property of material (Table 4), life can be calculated in accordance with equation 1 and with numerical integration. In this calculation, the variation of the stress intensity factor (Δk) relative to the crack length (a) must be available.

$$\int_{a}^{a_f} dN = \int_{a}^{a_f} \frac{da}{c(\Delta K)^m}. \tag{1}$$

The first research on the theory of the fatigue failure was developed by Halmanov & Cherepanov (1972). Their results showed that the growth of the crack can be approved with two hypotheses; first, the crack under a cyclic load is extended; and second, energy dissipation is a constant property of the material. In 1998, Edward (1988) conducted a study on the beam with a transverse crack. They showed that if the applied forces cause the crack to extend, the necessary conditions for the expansion and growth of crack is developed. This creates a region with a high stress concentration around the tip of the crack, which, due to the continuity of the applied force causes rupture and eventually failure in the work piece. The results of this study led to the achievement of the stress concentration factor in the tested material. By conducting another test on longitudinal cracks, it was revealed that by applying similar force in this different state, the crack closure happens; this does not eventuate to fatigue failure due to the lack of progressive cracking and plastic region.

Then in 2000, for the first time, Sinha et al. (2000) examined the effects of the stress ratio on the fatigue behavior of cracks. The results of this study showed that microstructure crack begins to grow in the stress ratios under the long-term threshold fatigue. Another study on the effects of cyclic loading on the growth of fatigue cracking was conducted by Benachour and Hadjoui, (2010). This study was carried out on aluminum 7075-T6 with the maximum stress ratio of 0.1, represent the effect of cyclic loading on the fatigue and growth rate of the cracks (Benachour and Hadjoui, 2010). Golestani (2011) experienced an increase over 200% in the fatigue life of the patched work pieces compared to the patch less work pieces during experiments on aluminum 1035 with a thickness of 2.5 mm, which indicates a great way to repair the structures of spacecraft with a little time and money. He also showed that the maximum and minimum fatigue life expectancy is related to cracks with a 0- and 30° angle, respectively. As the angle of the crack increases from 0° to 45°, the life of the components increases under the fatigue load. A major investigation on the cracks in the aluminum beam in 2016 was conducted by Breitbarth & Besel (2016). In this study, various types of crack tips under cyclic loads were studied by 3D finite element simulation. In these tests, the local strain rate in the analyzed region was measured by advanced digital analysis devices under different loading conditions. This test calculated the rate of strain in the tip region of the crack. The combination of the experimental results and finite element leads to calculating the amount of stored energy in the tip region, which is a very useful parameter for calculating the fatigue caused by cyclic loading and the amount of the damage due to the crack fatigue. Another experiment was conducted in this area based on different thicknesses of aluminum alloys. In this study, a nonlinear finite element model was developed to describe the details of shape and size of the plastic region for different thicknesses. Also, the plastic region was compared in terms of shape and size with the surface strain sample. It was observed that the plastic region of the crack tip is closer to the surface than the middle plate. In this experiment, an equaling of a 3D-dimensional plastic region to 2D region was proposed to reduce the complexity of the calculation (Camas, 2018). In another study in 2017 (Yu et al. 2017), the fatigue growth in Aluminum 7075 Alloy under failure modes I and II was investigated. It was found that in most cases in the test samples with the combined loading type, the growth path of crack using the accepted maximum tangential stress theory is unpredictable. Instead, in some cases, this path of deviation is precisely predictable with the maximum shear stress theory.

In a study conducted by Mada (2018), an equivalent integral method was used to compute the J-integral. This numerical method was investigated by comparing the J-cyclic integral and the J-integral, which was calculated by the function defined in ABAQUS under uniform tension loading. Based on this numerical method, the critical values of the J-integral were investigated by a developed code for the study of the crack growth behavior under mode I fracture. The special modes of the crack growth based on the J-integral were obtained using the written code, and were in good agreement with the results of the experimental tests. In the final results of this study, it is stated that with the change of the angle, a different value is obtained for the J-integral. Paris and Erdogan, (1961) presented a method for modeling of fatigue crack growth. Hudson and Scardina, (1963) investigated the effect of the stress ratio on the failure due to the fatigue. Siddiqui and Ahmed, (1991) studied the reliable fatigue and fracture of the platform stress in the bases under random loading. Pugno et al., (1997) provided Paris's general law for the growth of the fatigue cracks with diverse shapes. According to the previous activities, it seems that most studies focus on the transverse cracks in a specific crack position in the beam. A single study has not conducted to investigate the overall effect of the stress ratio, position and angle of crack in the exact prediction of the fatigue cycle. Also, the numerical study of the crack growth path and the effect of mechanical parameters on it are other parameters that were not evaluated in previous studies. For this purpose, an aluminum 7075-T6 alloy cantilever beam with cracks is used, which its experimental results are available. Accordingly, a crack with an initial length 5 mm and angle of 30° relative to the width of the beam, in three different positions from the beam, under 4 different stress ratios of 0, 0.25, 0.5, and 0.75, and with the compressive force at the free end of the beam is evaluated. Therefore, based on the modeling of the finite element, the manual growth of crack and the use of the Paris's law, the exact path of the crack growth and the cyclic fatigue based on the applied force are examined and the results are presented. Also, the results of this study are compared with the experimental results carried out in this field, which confirms the results of the current research.

2. Material selection and model geometry

In this study, the aluminum 7075-T6 alloy has been used. The reasons for this choice are the availability of the fracture mechanics properties of this material and the high applicability of this alloy in the aerospace industry. The mechanical properties of the aluminum 7075-T6 alloy have been shown in Table 1, which was derived from the ASME standard.

Table 1. Mechanical properties of the aluminum 7075-T6 alloy (American Society of Mechanical Engineers)

S_y (MPa)	S_{ut} (MPa)	E(GPa)
503	572	71

The selected geometry is a cantilever beam with rectangular cross section and length of 2 meters. In order to investigate the fatigue lifetime efficiency in the beam, the initial cracks were created with a length of 5 mm, a depth of 50 mm, and a crack angle of 30° relative to the width of the beam. To investigate the effect of cracks in the fatigue life of the beam, the fatigue behavior of these cracks in three different positions in the beam is investigated. In Fig. 1 a schematic illustration of this beam can be seen with a crack located in 20 cm from the support of the beam.

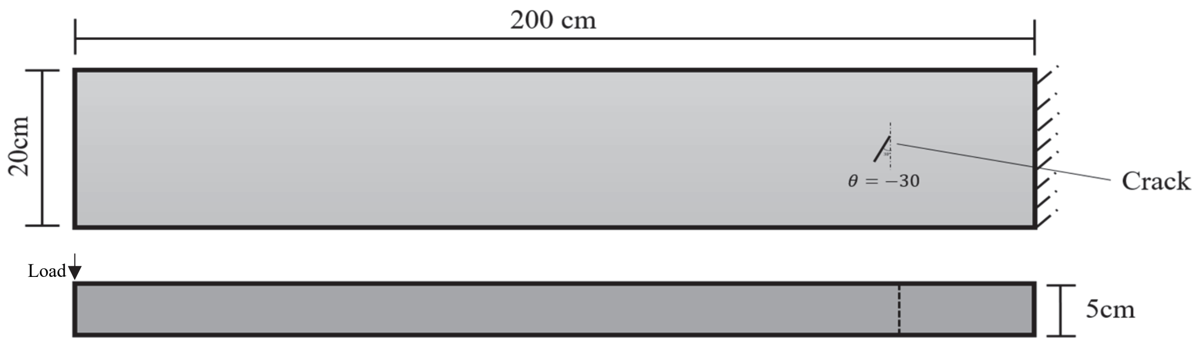


Fig. 1. Dimensions of the beam and position and angle of the cracks.

3. Fatigue Modeling

The cracks are located at a distance of 20, 100 and 164 cm from the support. The aluminum 7075-T6 plate is with the dimensions of 200 × 20 × 5(cm^3). The initial length and angle of the cracks are 5 mm and 30° relative to the width of beam, respectively. Also, it is located in depth of 5cm in the beam. The applied bending load in the fatigue test is 8kN and it is applied at the free end of the beam in the stress ratios of 0, 0.25, 0.5 and 0.75 with a frequency of 20 Hz (Tables. 2 and 3). To determine the applied force on the basis of the tensile strength of the material in accordance with Fig. 2, the fatigue strength of the low cycle and high cycle is considered equal to 85% and 50% of the material's tensile strength, respectively (Eq. 2).

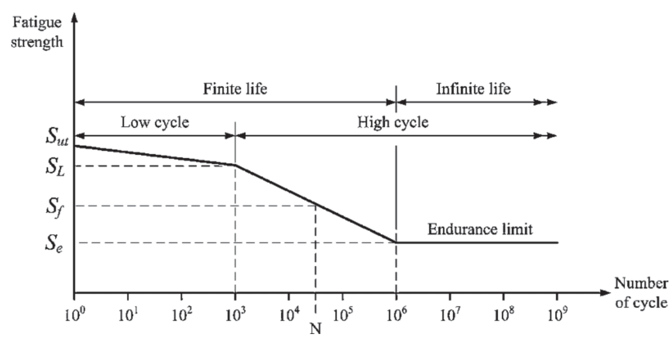


Fig. 2. S-N diagram based on applied force

$$\sigma = \frac{MC}{I} = \frac{F \times 200 \times 10^{-2} \times 2.5 \times 10^{-2}}{\frac{1}{12} \times 200 \times 10^{-2} \times (5 \times 10^{-2})^3} = 2.4 \times 10^{-4} F \quad (2)$$

$$F_{low\ cycle} = 0.85 S_{ut} \rightarrow 2.4F \times 10^{-4} = 0.85 \times 572 \times 10^6 \rightarrow F = 20.2KN \quad (3)$$

$$F_{high\ cycle} = 0.5 S_{ut} \rightarrow 2.4F \times 10^{-4} = 0.5 \times 572 \times 10^6 \rightarrow F = 11.9KN \quad (4)$$

The allowable low and high cycle fatigue force is calculated 11.9 and 20.2 kN, respectively. Furthermore, because the purpose of this study is to determine the fatigue cycle to the moment of failure and to calculate the real life of the work piece, therefore the forces are reduced to 8 and 19 kN, respectively.

Table 2. Maximum and minimum compressive forces in different stress ratios

Stress ratio	Min force (kN)	Max force (kN)	Average force (kN)	domain
0	0	-8	-4	4
0.25	-2	-8	-5	3
0.5	-4	-8	-6	2
0.75	-6	-8	-7	1

Table 3. Maximum and minimum compressive forces in different stress ratios

domain	Average force (kN)	Max force (kN)	Min force (kN)	Stress ratio
9.5	9.5	-19	0	0
7.125	11.875	-19	-4.75	0.25
4.75	14.25	-19	-9.5	0.5
2.375	16.625	-19	-14.25	0.75

Table 4. The values of c and m for different stress ratio.(Tang et al., 2016)

R	c	m
0	2.10E-11	4.29
0.25	2.42E-11	4.35
0.5	2.86E-11	4.52
0.75	2.91E-11	4.67

4. Finite Element Modeling

3D model of a cracked beam with a different position of the cracks is modeled in ABAQUS (Abaqus software Unified FEA, 2012). (Fig. 3). Considering that the results of modeling are compared with the results of an experimental test, all dimensions of the model and angle of crack in the model of ABAQUS are considered the same as the experimental specimen.

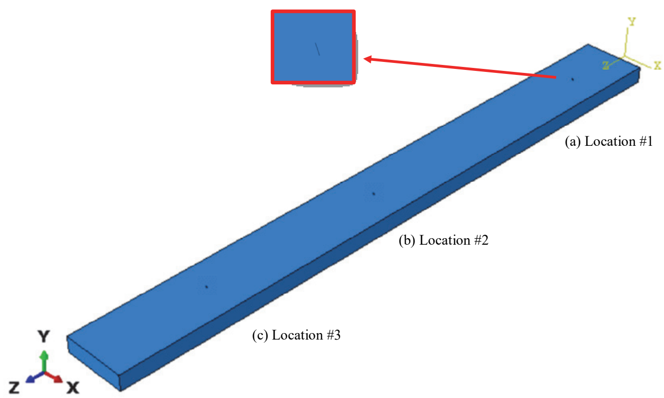


Fig. 3. The geometric model of the crack position at the distances: (a) 20 cm; (b)100 cm; and (c) 164 cm of the support of the beam

In order to model the crack in the ABAQUS, in the interaction module, a notch or seam with no applied boundary conditions on them should be created. Due to the changes in the length of the cracks in the specimens as well as the changes in the angle of the crack as the cracks grow, the number of elements created in the different models varies and in general there are about 15,300 elements in the samples. The number of elements is determined experimentally by examining the answers and controlling the convergence of the answers. The elements used in the model are C3D8R with 8 nodes and the meshing technique in this area is sweeping. Fig. 4 shows the mesh of the tip region and the surrounding area of the crack which is separated by the partition. In this figure, the meshes of the crack tip are magnified.

In order to ensure that the problem is not susceptible to the number of meshes, the stress intensity factor of mode I fracture for the number of different meshes is calculated. The stress intensity factor converges after 390 elements at the tip of the crack.

5. Results and discussion

The method of presenting the results in this research is as follows: First, the result of the present study which was carried out by numerical modeling in ABAQUS V6.14-2017 software is presented. Then, the results of the fatigue cycle in this study are compared with the available experimental data. In the following, the changes in the fatigue life due to the variation of the length of the cracks and the comparison of experimental and numerical results are presented in some graphs. Finally, the diagram of path (angle) of the crack growth to the moment of failure for the two positions of the cracks is shown.

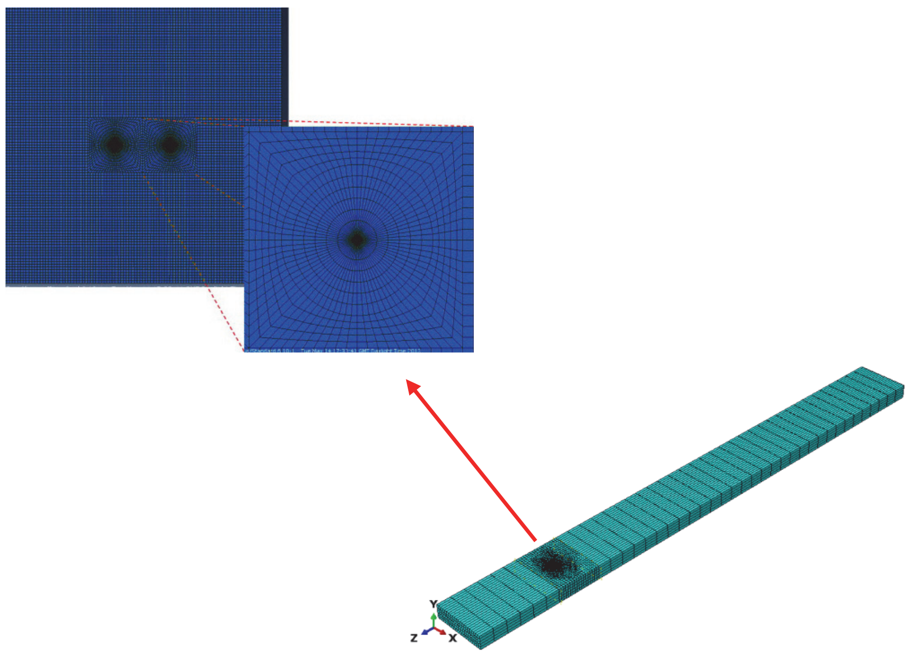


Fig. 4. Meshing and representation of crack tips model

Fig. 5 shows the crack growth path. As it is mentioned, the crack exists at an initial angle of 30° in the beam. Prediction of the crack growth due to the lack of precision growth path at any moment is complicated. The cracks propagate with the initial angle after initial loading and expansion. In this case, the combined modes (I and II) are involved in the propagation of the cracks. In the second step, the growth angle of the crack decreases to reach linear state. In this situation, mode I of loading plays a major role. The difference between the first stage of the crack propagation and the second stage is the addition of the loading mode II due to the presence of the crack angle. As a result, the growth of the cracks occurs with the interference of the mode II and in a combination mode. In this case, the difference between *K*I and *K*II is very small. So, the result of these two should be considered as *K*eq; and thus, life calculations continues with the *K*eq value derived from the reference (Radja, 2013). After calculating *K*eq, the value of *ΔK*eq can be calculated.

$$K_{eq} = \sqrt{{K_I}^2 + 1.03{K_{II}}^2} \tag{5}$$

Therefore, the propagation of the crack continues, so that the growth angle significantly reduces and the difference between KI and KII increases; in this case, the K2 value can be neglected in comparison with KI. (Fig. 5).

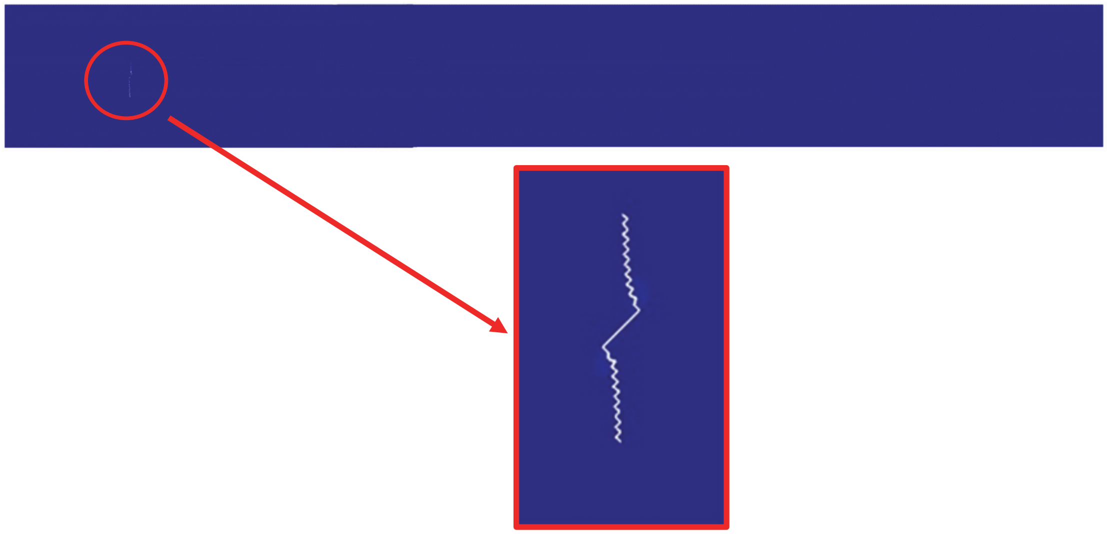


Fig. 5. Displays of the crack growth path at an initial angle of 30°

Fig. 6 shows the stress contour for four stress ratios of crack in a position of 20 cm of the support of beam. In the stress ratio of zero, the density of the stress around the tip of the crack has the highest value and at the stress ratio of 0.75 is the lowest. Hence, with the increase in the Von- mises stress around the crack tip, after each loading cycle, crack expansion occurs and cracking fatigue happens more rapidly.

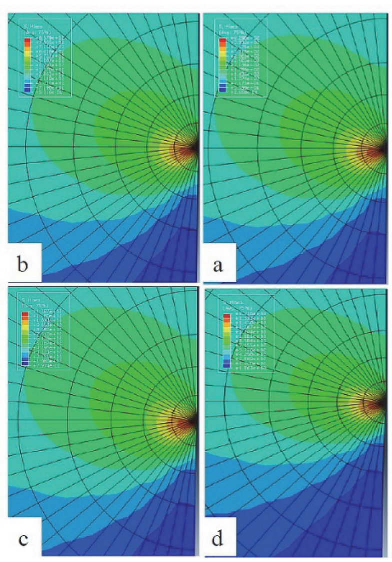
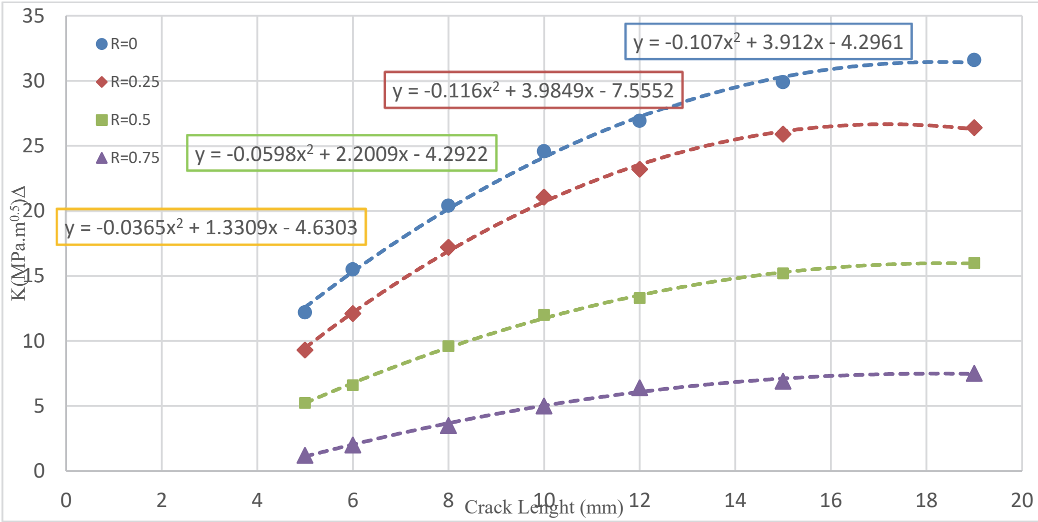


Fig. 6. Distribution of the von-mises stress in the tip region at 20 cm of the support in the stress ratio: (a) R = 0; (b) R = 0.25; (c) R = 0.5; and (d) R = 0.75.

Fig. 7 shows the variations in the stress intensity factor relative to the length of the crack for the two positions of the cracks. In order to obtain the changes of ΔK versus a, in a loading with a constant domain ΔP, it is sufficient to first calculate the KI_{max} for the loading of Pmax and KI_{min} for Pmin; and subsequently, $\Delta K=KI_{max}-KI_{min}$ is obtained. Now the crack is propagated virtually at the small interval Δa, which is calculated along the crack. Thus, the □a is obtained in the term of a in the form of a table (Figs. 7 and 8) which can be used in numerical integration relationships. Based on the figure, with the increase in the crack distance from the support of beam, the results of the variation in the stress intensity factor change with a greater slope and, as a result, the slope of the curve equation increases. Then, it is possible to achieve the fatigue life by writing an algorithm to calculate the integral of Paris. The constants *c* and *m* are presented in Table 4. Table 5 gives numerical results. By increasing the stress ratio for all three positions, it is observed that the fatigue cycle increases.



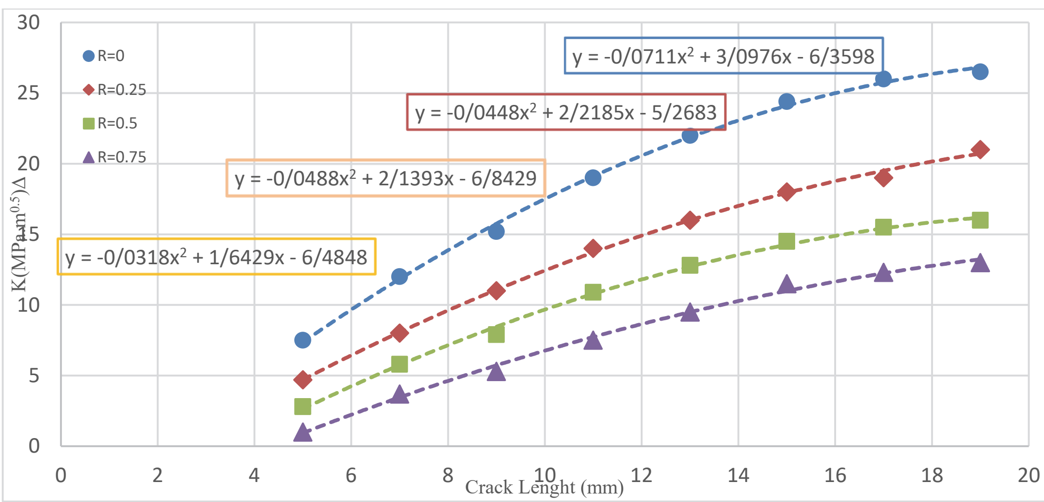


Fig.7. Changes of ΔK relative to the crack length for cracks located in (a) 20 cm; (b) 100 cm from the support

The lower the difference between the maximum and the minimum force is, the lower the difference of stress intensity factor is. Furthermore, according to Paris' law, the number of fatigue cycles increases with decreasing stress factor. The last position of the crack, which fatigue does not happen in any of the four stress ratios, is 170 cm .according to the Paris's law, the conditions for the failure do not occur.

Table 5. Results of fatigue life analysis (10^3 cycles) based on the finite element simulation and force application of 19kN

R=0.75	R=0.5	R=0.25	R=0	(distance from support) Crack location
986	57	5.3	1.8	20 cm
1723	214.6	76.8	10.58	100 cm
69717	9114	1053	29.30	164 cm

Table 6. Results of fatigue life analysis (10^6 cycles) based on the finite element simulation and force application of 8kN

R=0.75	R=0.5	R=0.25	R=0	(distance from support) Crack location
5490	247	22.09	6.8	20 cm
14900	970	282	39.58	100 cm
infinite	68000	9800	233	164 cm
-	-	-	infinite	170 cm

According to Table 6, by increasing the stress ratio, the growth of the low cycle compared to the high cycle fatigue increases with lower rate. At the second position of the crack, the high cycle fatigue life in the stress ratio of 0.5 is 3.43 times of fatigue cycle in the ratio of 0.25. However, in the low cycle fatigue the ratio is 2.85, which is 20% lower. Furthermore, in the high cycle fatigue, by the increase in the distance of crack from the support of beam, the fatigue life significantly increases.

6. Comparison of the numerical and experimental results

Table 7 shows the fatigue cycle results from the numerical modeling (present study) and the available experimental results (Mohammadi, 2014). A good agreement between experimental and numerical results is seen. However, there are some differences in the experimental and numerical results which are because of the ideal assumptions such as the lack of geometric imperfections and the residual stress caused by the thermal treatment of aluminum, which are not included in the software. It is necessary to note that only laboratory data related to the 8kN bending force was available; So, only the numerical results of 8kN is considered. Furthermore, due to the less difference between numerical and experimental results of low-cycle rather than the high-cycle fatigue, the experimental results can be considered with a good approximation close to the obtained numerical results. It should be noted that in the distance of 164 cm from the support and at a stress ratio of 0.75, according to Paris's law, fatigue fracture conditions do not arise and crack passes the infinite cycles. However, in other stress ratios, as it is shown, fracture occurs after a number of cycles. Also, according to the numerical and experimental investigation, the distance of 170 cm from the support of the beam can be described as the last point of the beam that crack with the considered length in any stress ratio is not fatigued. By the increase in distance from the support of beam, the fatigue cycle for failure increases. Also, based on the results of the table, the increase of fatigue cycle has a direct relationship by increasing stress ratios. By increasing the stress ratio at each position, the difference between the error rate in the experimental and the numerical results increases, which is due to a significant increase in the number of fatigue cycles; so that the least error in the experimental and numerical results is related to the crack in the first position and the stress ratio of 0.25 and the maximum error is related to the crack in the third position and the stress ratio of 0.75. By increasing the crack distance from the support and the stress ratio, exceeding rate in the number of fatigue cycles continues more rapidly.

Table 7. Comparison of fatigue life (106 cycles) obtained from experimental experiments (Mohammadi, 2014) and numerical values by the maximum bending force of 8kN

R=0.75		R=0.5		R=0.25		R=0		crack location (distance from support)
Experiment	FEM	Experiment	FEM	Experiment	FEM	Experiment	FEM	
4620	5490	210.5	247	18.21	22.09	5.9	6.8	20 cm
13670	14900	910	970	267	282.34	37.9	39.58	100 cm
--	--	58200	68000	8500	9800	215	233	164 cm

Fig. 8 has been presented in the logarithmic scale to better understanding the comparison of experimental results and this research. Estimates of the fatigue life based on the increase in the length of the crack are shown in Figs. 9 and 10. Based on the graphs, it is found that by an increase in the length of the crack, changes of fatigue life are initially negligible. However, further increase in crack length increases the slope of the diagram and the fatigue life decreases more quickly. This matter also confirms the results presented in Figs. 7 and 8. As ΔK increases, according to the Paris's law, a decrease in the fatigue life can be seen. Also, based on the diagram, the experimental and numerical results are closer to each other by the increase in the length of the cracks, so that along the cracks above 150 mm, the numerical and experimental results overlap. Also, there is a little difference between the experimental and numerical results by decreasing the stress ratio to its minimum value, which is visible in the graph. Numerical results in all models are larger than experimental results due to ideal assumptions such as the absence of geometric imperfections or residual stresses in the work piece. It can expect that for the crack at a distance of 1 meter and 2 meters (the second and third position, respectively), the numerical and experimental results are nearly the same showing the validity of numerical results. Furthermore, because experimental results obtained from the fatigue life expectancy for the different stress ratios at the second and third position of the cracks is not available, only the numerical results are considered.

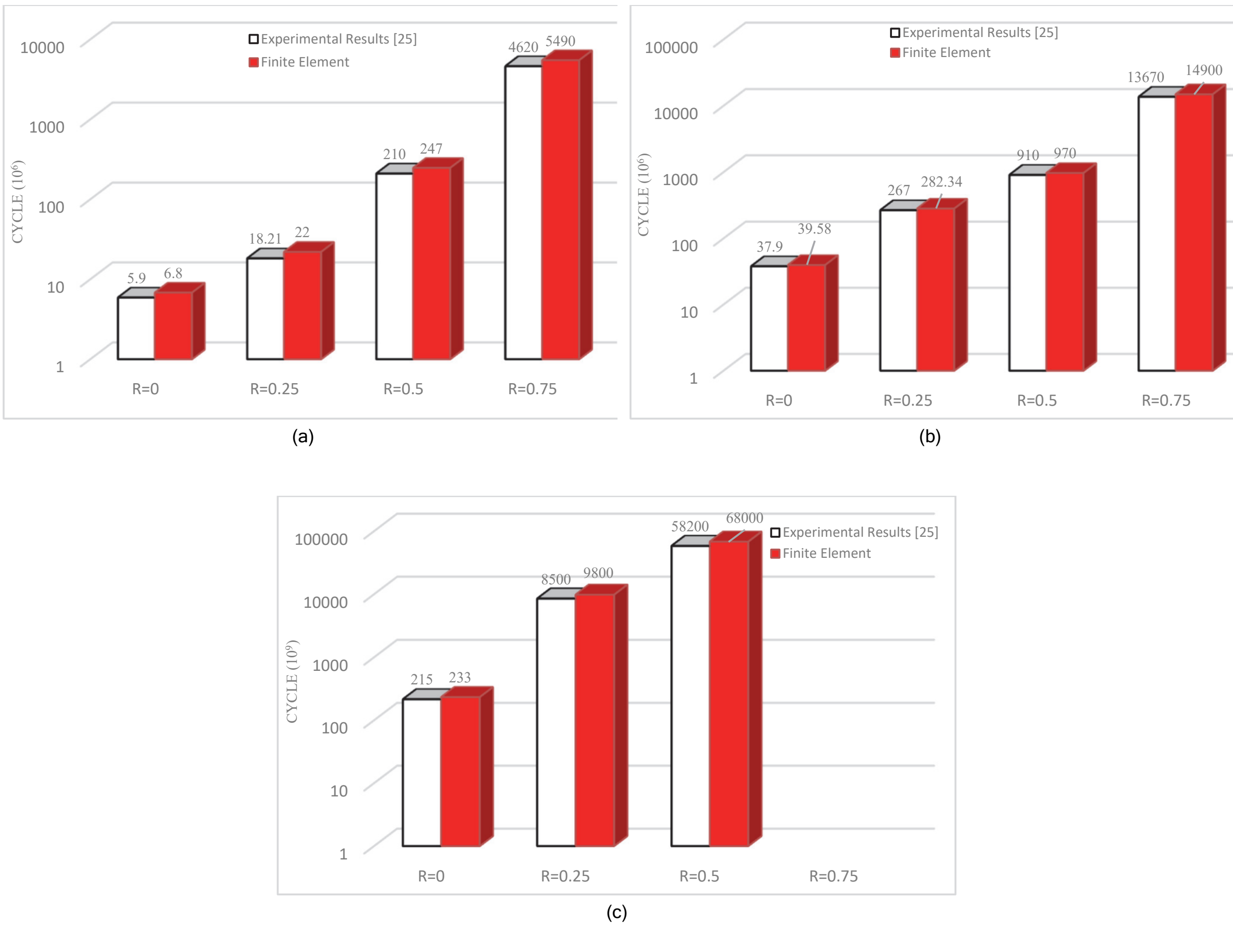
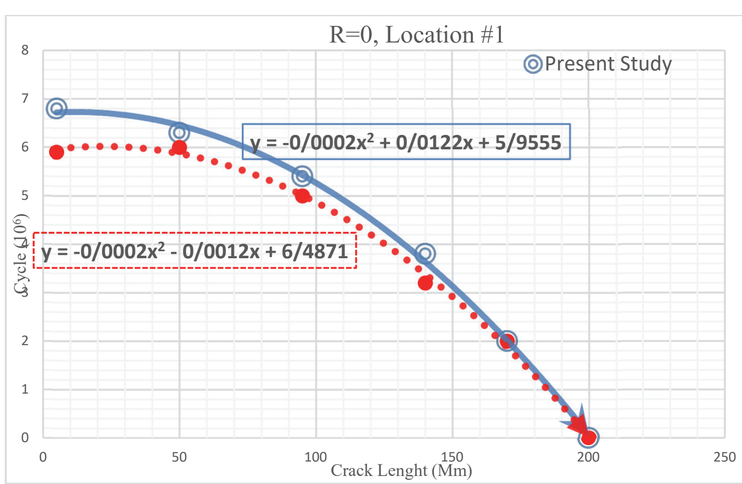


Fig. 8. Comparison of numerical and experimental results (Mohammadi 2014) for a crack at a distance of (a) 20 cm; (b) 100 cm; and (c) 164 cm from the support of beam for each four stress ratios



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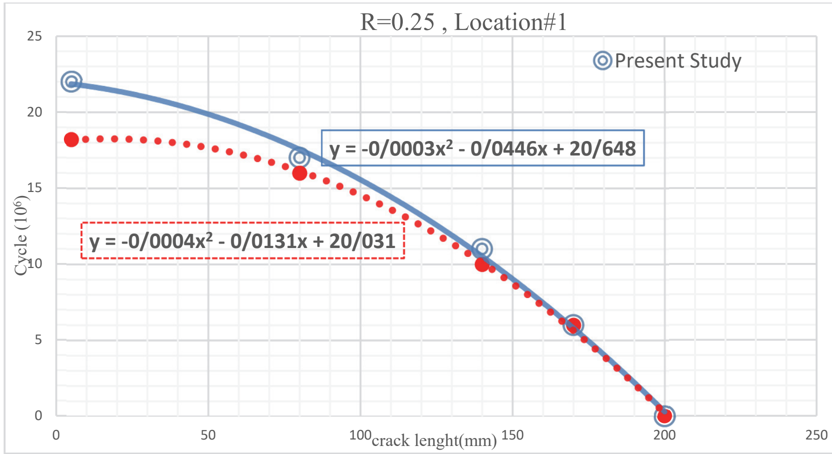

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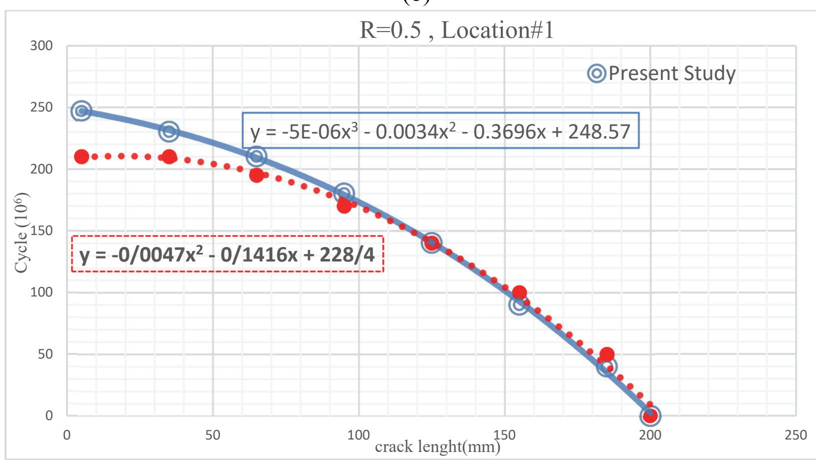

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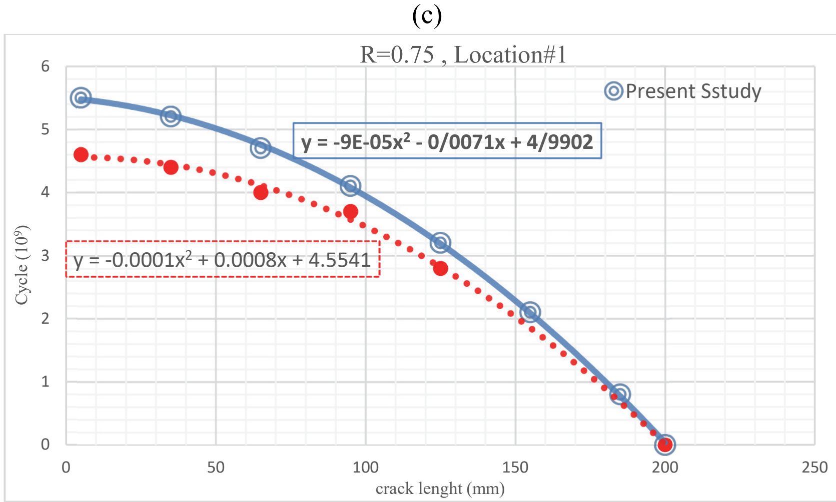
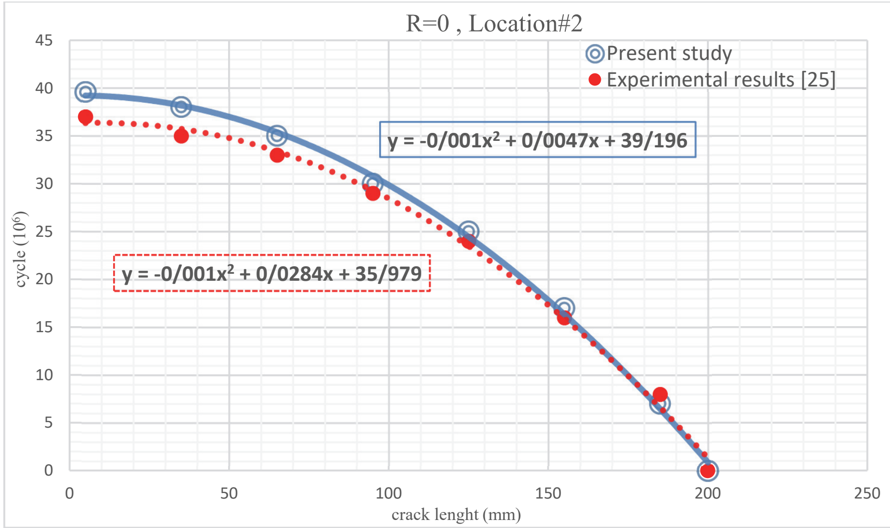


(d)

Fig. 9. Numerical and experimental results (Mohammadi 2014) of changes in fatigue life in terms of crack length at a distance of 20 cm from the support and stress ratios of: (a) 0, (b) 0.25, (c) 0.5, and (d) 0.75



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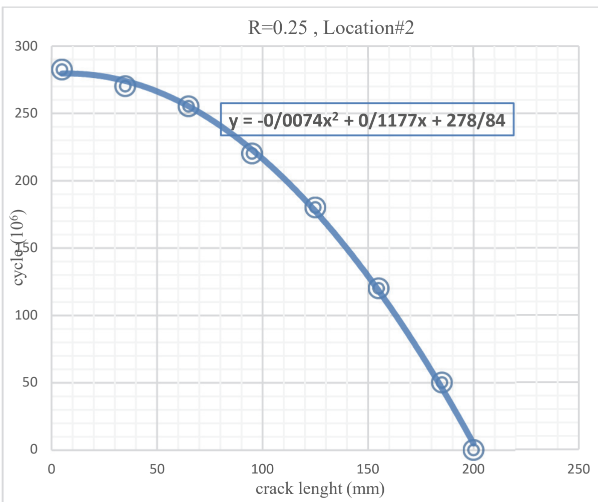

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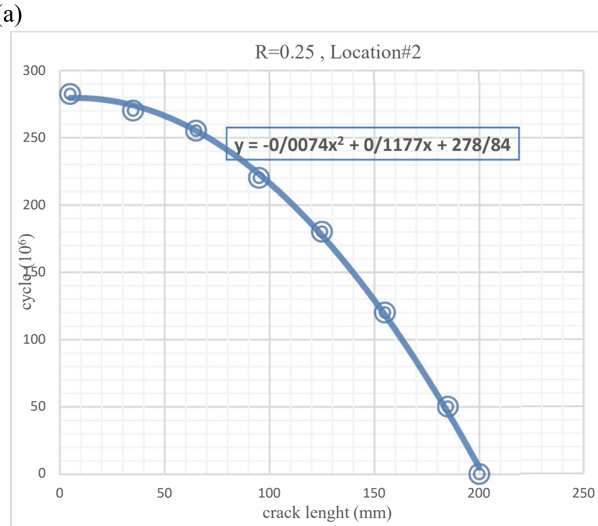

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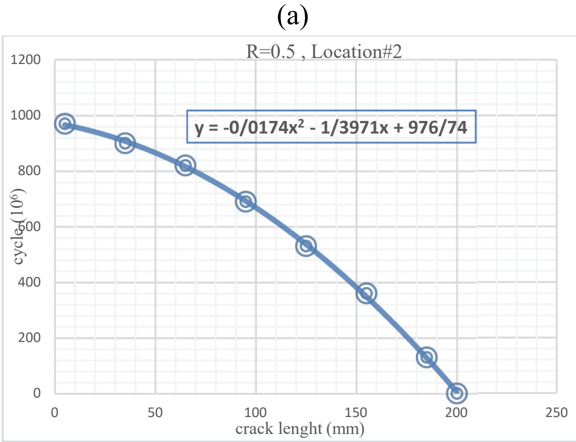

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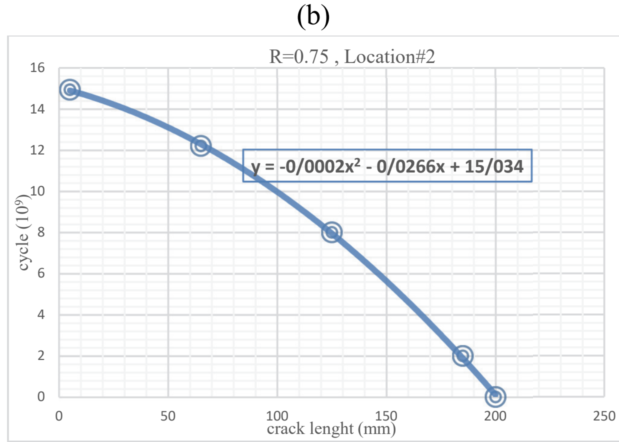
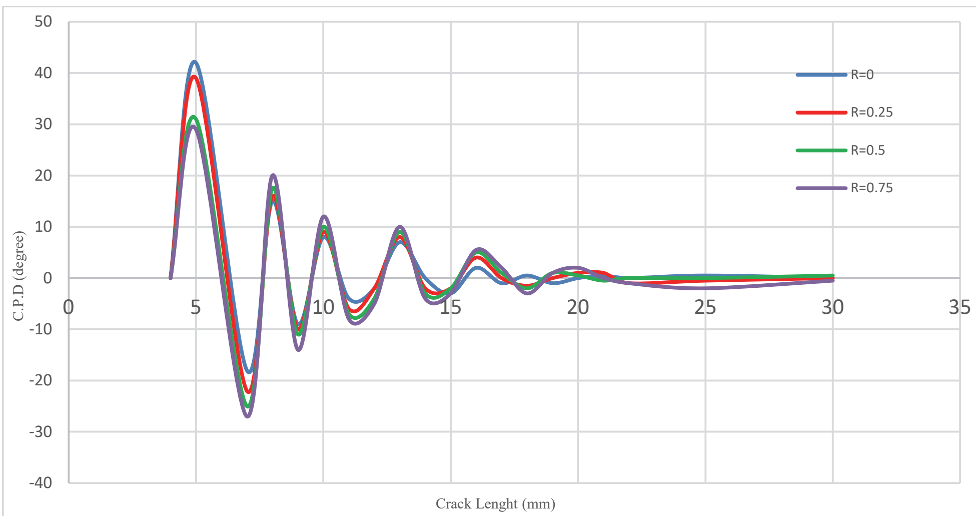


(d)

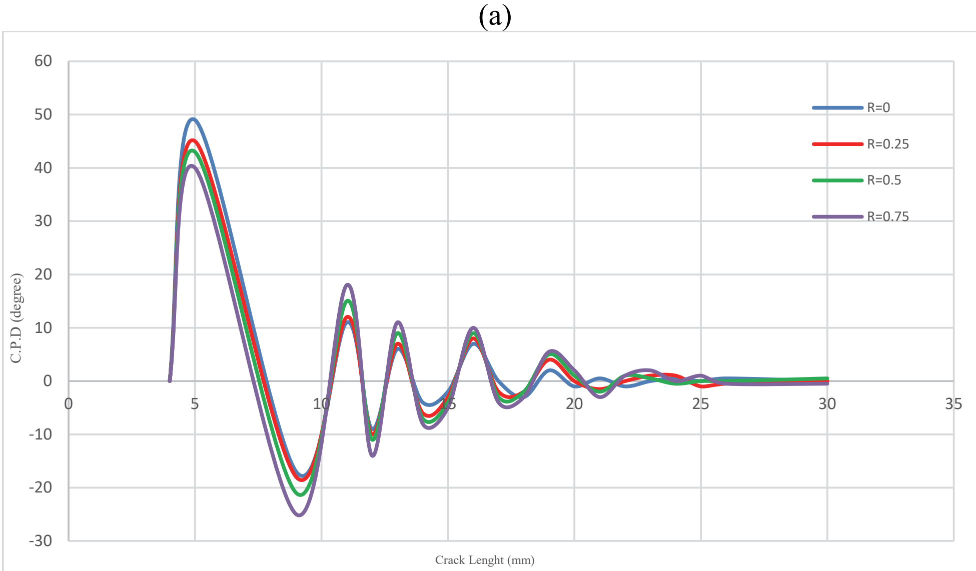
Fig. 10. Diagram of changes in fatigue life in terms of crack length at a distance of 100 cm from the support and stress ratios of: (a) 0, (b) 0.25, (c) 0.5, and (d) 0.75

7. Crack propagation direction (C.P.D)

Diagrams related to crack propagation direction are presented for each of the four stress ratios and for the 8 kN force in Fig. 11. As it is shown, initially crack propagates with angle of 48° at the first position and stress ratio of zero. By manually extending the crack to a very small extent, this angle gradually reduces. It converges to 0° as result of linearization. According to the diagrams, it can conclude that the rate of the reduction of the growth angle of the crack in the position closer to the support of the beam is rapid due to the high density of stress in this region during the applying force and the higher KI value. Also, for the cracks with different initial length, it can be shown that the linearization rate of the crack and the decrease in the growth angle happens at a faster rate. Therefore the convergence of the growth angle to zero along the larger cracks occurs more quickly. By moving away from the supports of the beam, the rate of convergence of the crack direction from angular to linear and from parallel to the width of the beam is decreased. This also occurs with an increase in the stress ratio in all the crack positions. By increasing the crack distance from the support of the beam, the linearization rate of the crack decreases; so that at the distance 20 cm from the support and the length of the crack 20 mm, angular variations are almost zero; but, at the distance of 100 cm, and along the same size of crack, angular variations emerges.



(a)



(b)

8. Conclusion

In this study, the overall procedure of work summarizes as follows. Initially, an Aluminum 7075-T6 cantilever beam with a desired dimension, with an initial crack length of 5 mm and angle of 30° relative to the width of the beam in 3 different positions from the support of the beam, and four different stress ratios was investigated. Numerical results of the fatigue cycle of beam are compared with available experimental results and the results are well adapted with each other. Also, in another part of this study, the changes in the fatigue cycle of beam with cracks were investigated with increasing cracks length and the results are compared with experimental results. At the end of the study, the growth path of the cracks was analyzed in the cross section of the beam and the graphs are presented. Accordingly, the following results are obtained from this study.

- The last position of crack in the beam, in which fatigue fracture doesn't occur for cracks under the compression bending force of 8 kN, is located at a distance of 170 cm of support. This position can experience the infinite life.
- By increasing the stress ratio for the crack in the third position (distance of 164 cm), a significant increase in the fatigue life occurs.
- In the stress ratio between 0 and 1, the highest and least fatigue life is related to the cracks located in the third and first position, respectively.
- The growth rate of fatigue life is slower by the increase in stress ratio for crack in the first position and much higher for third position.
- By increasing the length of the cracks, the fatigue life initially decreases with fewer rates. But, as long as the length of crack increases, it can be seen that the fatigue life reduces more rapidly; So that the reduction rate of fatigue life for last 10 cm of crack is equal to ten times of first 10 cm of crack.
- The crack in the first position and the stress ratio of 0 under the applied force of 8 kN, initially propagates at an angle of 48° relative to the initial direction of the crack (30°). With very small amounts of manual growing of crack, the growth path of crack slowly converges to linear mode and it becomes parallel to the width of the beam. Linearization speed and decreasing the angle of deviation of cracks depends on the crack position, the stress ratio and stress intensity factor of crack tip.
- By increasing the stress ratio in all the crack positions, the convergence rate of the crack growth angle reduces to 0° as a result of linearization.
- Comparing the finite element and the experimental results confirms the accuracy of the numerical results of this study.

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