

# Effect of Mode Loading on FCRG Plate with Double Through Crack at Hole

M. Benachour, N. Benachour, M. Benguediab, A. Hadjoui

**Abstract**—The knowledge of the nature of loading is very important in order to hold account on the total behavior such as vibration, shock, fatigue, etc. Fatigue present 90% of failure when loadings fatigues are very complex. In this paper a study of double through crack at hole for plate subjected to fatigue loading is presented. Various modes loading are studied where the applied load is the same one. The fatigue life is given where the effect of stress ratio is highlighted. This work is conducted on aluminum alloy 2024 T351 used for much aerospace and aeronautics applications. The fatigue crack growth behavior with constant amplitude is studied using the AFGROW code when Forman model is applied. The fatigue crack growth rate and fatigue life for different loading modes are compared with variation of others geometrical parameter such as thickness and dimensions of notch hole.

**Keywords**—Fatigue crack, mode loading, aluminum alloy

## I. INTRODUCTION

TRADITIONALLY, the application of fracture mechanics has been used to describe and rationalize mechanical failure of different materials and has concentrated on crack growing under opening mode [1]. However, many service failures of structures occur from flaws either oriented at arbitrary angles to the far-field loading direction or subjected to multi-axial stresses or combined with different mode loading (tensile-bending, bending-torsion...). Experiments on fatigue strength under combined bending and torsion have already been carried out on metallic structures [2, 3]. In the work presented by Moussa et al. [4], the effects of relative position of two non-coplanar surface cracks are investigated in an infinite plate subjected under tension and pure bending. At the deepest point, the normalized stress intensity factor under pure bending is less than the corresponding obtained under tension. This effect is due to the decrease in the stress level under bending loads. In the investigation of Qu and Wang [5], three-dimensional finite element analyses are conducted to calculate the T-stresses for a quarter-elliptical corner crack in a finite thickness plate with a wide range of

crack aspect ratios and relative depths. It is observed that generally under remote tension both the T-stresses are always negative along the crack front for all crack geometries. Under remote bending, the T-stresses are negative for the extreme point along the greatest distance from the crack. Under different loading modes, TiAl alloy in fatigue tests is investigated by Cao et al [6]. The tensile fatigue tests show a decrease in fatigue life with increasing of the load amplitude. But for the bending test, the crack length increases with increasing fatigue cycle except for the data from the last specimen with a high fatigue cycle.

Experiments have shown that the stress ratio “R” influences the crack growth rate. It was argued that the reason for this influence is the crack closure effect [7]. The research conducted by Ferry et al [8] shown that two parameters are an important role in the damage processes: the stress ratio between bending and torsion, and the ratio R between minimum and maximum stresses. The results shown that, for bars loaded under bending and torsion, the initiation of the first defect depends on between bending and torsion and also on stress ratio R. Inc recent work, axial loading fatigue in the HCF regime is studied by Shiozawa et al [9] when mean-stress effects are investigated under three applied stress ratio. Results shown that the fatigue lifetime for transition in the fracture mode, depended on the applied stress ratio. Comparatively, in axial loading fatigue test, S–N curve showed a smooth and continuous shape under the three testing conditions. This was different from the clear duplex S–N curve obtained from a rotary bending fatigue test. For Zr-based BMGs material, Wang et al [10] have shown that the fatigue loading mode could influence the fatigue behavior. The fatigue results show that the fatigue lifetimes above the fatigue limit under compression–compression loading are longer than that under tension–tension loading. In addition, the fatigue-endurance limits under tension–tension and compression–compression loading were found to be greater than those under three and four-point bend loading.

The objective of the present work was to investigate the effect of different modes loading such as tensile, bending of double through crack at hole for plate subjected fatigue loading in opening mode. A constant amplitude loading was applied for different stress ratio for aeronautical aluminum alloy 2024 T351.

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## II. SIMULATION OF FATIGUE CRACK GROWTH

### A. Fatigue crack growth model

Many models are proposed by many authors. Elber [7] proposed a modification to the Paris growth law by using the effective stress intensity range to calculate the crack propagation under constant amplitude loads, taking into account the crack closure concept. Different models are elaborated to account of the effect of stress ratio and the total curve of fatigue crack growth. Forman et al [11] have proposed a new model to account of fatigue curve named Forman equation. This equation was an improvement of the Walker equation that included a means to account for the upper portion of the  $da/dN$  vs.  $\Delta K$  curve where the data become asymptotic to the value of  $\Delta K$  at fracture. This model implemented in AFGROW code [12] is used in this work (1).

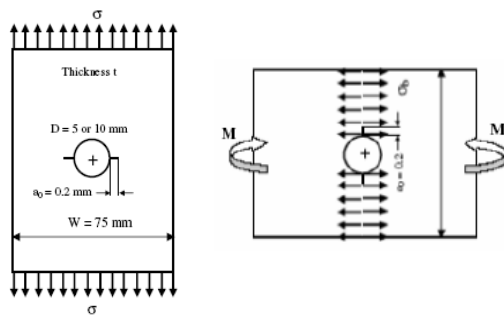
$$\frac{da}{dN} = C(K_{max} - K_{op})^m = C(K_{eff})^m \quad (1)$$

### B. Material and specimens

The material used in this study is the aluminum alloy 2024-T351 as rolled plates. Plates are subjected to numerical fatigue tests in L-T orientation. The basic mechanical properties for Aluminum alloys 2024-T351 are given in Table 1. Numerical fatigue crack growth used plate with double through crack at hole under tensile tests and bending tests (Fig.1).

TABLE I  
MECHANICAL PROPERTIES OF ALUMINUM ALLOY 2024 T351  
DATABASE OF AFGROW CODE

$\sigma_{0.2}$ MPa.	$K_{IC}$ MPa.(m) <sup>1/2</sup>	$K_{IC}$ MPa.(m) <sup>1/2</sup>	E MPa
386.1153	38.86	109.88	72.40



a- Plate in tensile test      b- Plate in bending test

Fig. 1 Plate with double through crack at hole

The stress intensity factor for the studied specimen with through crack at hole implemented in AFGROW code, depending on several parameters, is written below (2):

$$\Delta K = \sigma \sqrt{\pi \cdot a} \cdot \beta \quad (2)$$

In tensile loading case, the function  $\beta$  is written below (3):

$$\beta = \beta' \cdot F_w \cdot F_w' \quad (3)$$

where  $\beta'$  is shape function of infinite plate,  $F_w$  The finite width correction for this geometry expressed by (4) and (5).

$$\beta' = \sqrt{1 + R/a} \quad (4)$$

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi(R+a)}{W}\right)} \quad (5)$$

An additional correction factor was introduced in AFGROW to account of double crack at hole designed  $F_w'$  (6).

$$F_w' = (1) - \left[ \left( 1.32 \frac{w}{D} - 0.14 \right)^{-0.98 + \left( 0.1 \frac{w}{D} \right)^{0.1}} - 0.02 \right] \left( \frac{2a}{W-D} \right)^{\frac{2a}{W-D} + 2.5} \quad (6)$$

In the bending case [12], the function  $\beta$  is written below when the double cracked hole solutions are corrected from the single-crack solutions using the Shah Correction (4) where the factor correction  $F_w'$  is the same to the tensile loading.

$$\beta = \sqrt{\frac{1}{2\pi} \left( \frac{a/R+2}{a/R+1} \right)^{1.5} \sqrt{\frac{8R+2\pi a}{8R+\pi a}} F_c F_w F_w'} \quad (7)$$

$F_c$  and  $F_w$  are corrections factors in bending case, expressed below respectively by (8) and (9).

$$F_c = 0.9 + 0.083(1 - 10^{-0.04(a/R)}) + 0.017(1 - 10^{-3.0(a/R)}) \quad (8)$$

$$F_c = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi(R+a)}{W}\right)} \quad (9)$$

## III. RESULTS AND DISCUSSION

### A. Effect of stress ratio in tensile & bending load

Finite plate with double through crack at hole is subjected to a constant loading with various load ratios. The  $K_{max}$  fracture criteria are adopted for the limit of crack growth. Fig. 2 shows the effect of stress ratio on fatigue life N. As the stress ratio increases, the fatigue life increases. These results are in agreement with the results of some authors [13]. For different stress ratio ( $R = 0.1, 0.2$  and  $0.6$ ) the maximum crack length is between 23.45 and 24.32 mm. For  $R = 0.1$  and  $0.2$  after crack length ( $a = 12$  mm), the specimens are growth under the same crack growth rate. Contrary, for  $R = 0.3$ , the specimen grow under the same crack growth rate after 16 mm. The effect of stress ratio on fatigue crack growth rate is shown in Fig. 3. We notice at low stress ratio ( $R = 0.1, 0.2$ ), the

difference in fatigue crack growth rate is negligible. For high stress ratio ( $R=0.6$ ), we notice a shift towards lower values of amplitude of stress intensity factor.

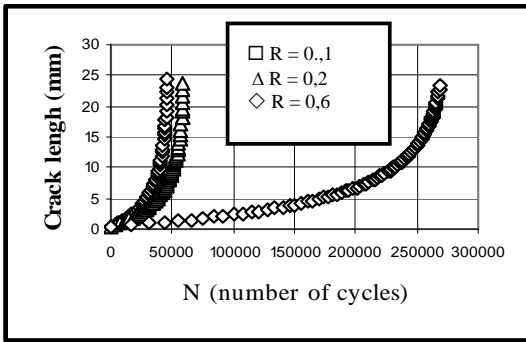


Fig. 2 Fatigue life of double through crack at hole in tensile loading

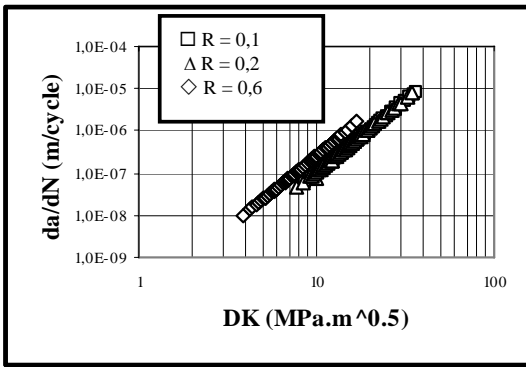


Fig. 3 Effect of stress ratio in tensile load

*B. Comparison between tensile and bending load*

Fig. 4 shows the difference of fatigue life respectively between tensile and bending fatigue load. In this difference, the fatigue life is very highly in fatigue bending comparatively to the tensile fatigue test. The difference in the final crack length is limited to 4 mm. After 20 mm crack length in bending, the crack growth under the same crack growth rate. Finally, we notice that the fatigue life is affected by mode loading under same applied load. In Fig. 5 and for the same stress ratio ( $R=0.2$ ), the fatigue crack growth rate is shown for tensile and bending load fatigue. The curves present the same slope and no shift was noticed. But the effect of bending was signalled at low stress intensity factor. We notice an increase of fatigue crack growth comparatively to the applied tensile load. For the considered thickness ( $t=2\text{mm}$ ), we notice that the stress state determined in tensile and bending is plane stress state.

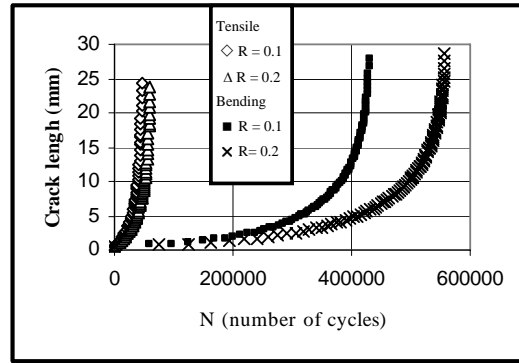


Fig. 4 Comparison of fatigue life curves

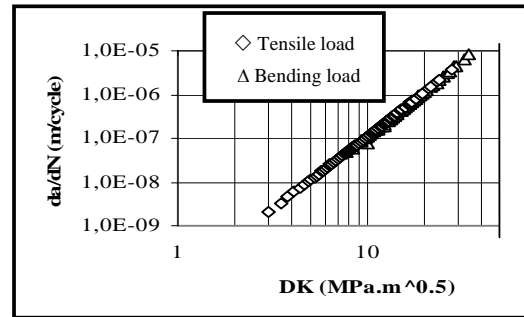


Fig. 5 Fatigue crack growth rate at  $R = 0.2$

*C. Effect of geometrical parameters*

In this section, the effects of plate thickness and diameter of hole was presented. In tensile and bending case load no effects of thickness are noticed on fatigue life and fatigue crack growth rate at the same stress ratio, but the stress state was changed to the strain state. The increasing of diameter hole affect the fatigue life and fatigue crack growth rate. The diameter hole effect are summarized in Table 2. On increasing of diameter hole in tensile and bending, we notice a decreasing in fatigue life, diminution of final crack length and the amplitude of stress intensity factor. The decreasing in fatigue crack growth rate is important for bending load comparatively to the tensile load. The ratio of decreasing is equal 1.96.

TABLE II  
EFFECT OF DIAMETER HOLE ON FATIGUE CRACK GROWTH

Load case	Hole (mm)	$N_f$ (Cycle)	$a_f$ (mm)	$da/dN$ (m/cycle)	$\Delta K_f$ ( $\text{MPa} \cdot \text{m}^{0.5}$ )
Tensile	5,0	59412	23.78	$8,265 \cdot 10^{-6}$	34.38
	10,0	30317	21.69	$7,258 \cdot 10^{-6}$	33.23
Bending	5,0	557500	28.53	$3,613 \cdot 10^{-6}$	27.56
	10,0	309500	25.26	$1,846 \cdot 10^{-6}$	22.87

$a_f$ : final crack length

## IV. CONCLUSION

In this paper simulation of fatigue crack growth of plate specimen with double through crack for aluminum alloy 2024 T351 are presented. The effect of mode loading such as tensile load and bending load are investigated. We notice that with the same loading and stress ratio, the fatigue crack growth rate (FCGR) decrease and the fatigue life increase in bending load case. The stress ratio R affects the total fatigue life. The increasing of this ratio, increase the fatigue life. In high stress ratio, a shift in the FCGR curve to lower stress intensity factor. The variation in increasing of hole diameter, decrease several parameter of fatigue crack (fatigue life, FCGR, final crack length and maximum stress intensity factor).

## REFERENCES

- [1] A.L. Kermanidis, S.P. Pantelakis. *Fat. Fract. Engng. Mater. Struct.*, Vol. 24, pp 699-710, 2001.
- [2] D.L. McDiarmid. *Aeronautical Journal*, p 325-29, 1974.
- [3] N. Hong, Q. Xin, F. Weixiun. *Fat. Fract. Engng. Mater. Struct* Vol. 15(2), pp 225-27, 1992.
- [4] W.A. Moussa, R. Bell, C.L. Tan. *Int. J. of Pres. Vessels and Piping*, Vol. 76, pp 135-145, 1999.
- [5] Qu Jie and Wang Xin. *Int. J. of Pressure Vessels and Piping*, Vol. 83, pp 593-606, 2006.
- [6] R. Cao, Y.Z. Lin, D. Hu, J.H. Chen. *Engn Fract. Mech.*, Vol. 75, pp 4343-4362, 2008.
- [7] W. Elber. *Engn. Fract. Mech.*, Vol. 2(1), pp 37-44, 1970.
- [8] L. Ferry, D. Perreux, D. Varchona, N. Sicot. *Comp. Scie. and Techn.* Vol. 59, pp 575-582, 1999.
- [9] K. Shiozawa, T. Hasegawa, Y. Kashiwagi, L. Lu. *Int. J. of Fatigue*, Vol. 31, pp 880-888, 2009.
- [10] Wang G Y, Qiao DC, Yokoyama Y, Freels M, Inoue A, Liaw PK. *Journal of Alloys and Compounds*, Vol. 483, pp 143-145, 2009.
- [11] R.G. Forman V.E. Heamey, R.M. Engle. *J. of Basic Engng, Trans of ASME*, Vol. 89, 1967.
- [12] J.A. Harter. "AFGROW Users guide and technical manual: AFGROW for Windows 2K/XP, Version 4.0011.14". Air Force Research Laboratory, 2006.
- [13] M. Benachour, M. Benguediab, A. Hadjoui, F. Hadjoui, N. Benachour. *Computational Materials Science*, Vol. 44, pp 489-495, 2008.