Fatigue crack growth behavior of patched and un-patched structures

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Abstract. Aluminum alloy is an important material used for aircraft structures especially for fuselage. During service, an aircraft is subjected to severe structural fatigue loads (constant, variable or random) which can cause damage of structure. The adhesively bonded composite repair is an efficient and cost-effective method to extend the fatigue life of cracked components in advanced aerospace structures. In this study, we investigated the fatigue crack growth (FCG) behavior of aluminum cracked plate with semi circular notch without repair. In this part, effects of stress ratio, notch geometry are studied. In second part FCG behavior of cracked aluminum plate repaired with bonded composite patch are analysed. Adhesively bonded composite patch repair technique has been successfully applied to military aircraft repair and expanded its application to commercial aircraft industry recently. We investigated the fatigue crack growth behavior of thin plate repaired with bonded composite patch using the stress intensity factor range (ΔK) and fatigue crack growth rate (da/dN). The stress intensity factor of patched crack was determined from empirical result by comparing the crack growth behavior of specimens with and without repair. Fatigue crack growth of 7050 T74 aluminum alloy is investigated by using NASGRO model. For un-repaired structures, obtained results illustrate a general increase in da/dN with R for a given ΔK. An important effect of stress ratio, R, has been observed clearly for this material at high DK. Fatigue life and FCGRs were considerably affected by notch geometry. In repaired structures with adhesively bonded composite (Graphite/Epoxy) using single sided repair, fatigue life was increased comparatively to the un-repaired structures. FCGRs are also affected, a decreasing was shown and crack growth was retarded, this is due to reduction of stress intensity factor and the normal stress at the crack tip. Effects of some parameters are investigated on fatigue behavior of repaired structures namely orientation, number and thickness of ply in bonded composite patch.

Introduction

Aluminum alloy series 2xxx, 6xxx, 7xxxx and 8xxx enjoy the widest use in aircraft structural applications. Among these materials, aluminum alloys 7050 and 7075 remains the most commonly used in different temper situation after 2024 aluminum alloy. During navigation aircraft structures (fuselages) are subjected to cyclic loading which consequently leads to damage and creating cracks. Hence, a repair of the damaged part of the structure to restore the structural efficiency and thus assure the continued airworthiness of the aircraft has become an important issue in recent years. The technique of repairing cracked metallic structures using high strength composite materials (high strength fibbers and adhesives) is known as crack patching. This technique was pioneered by researchers in aeronautical and maritime research laboratories for Royal Australian Air Force in early 1970's [1]. This efficient repair technique, called composite patch repair, was used to reinforce the damaged structures and extend the service life of aging aircraft and offers significant advantages over traditional repair methods (riveting, fastening, welding). Repair of cracked components by an adhesively bonded composite patch has gained acceptance in aerospace structures [1-3]. Investigation into the crack growth behavior of the bonded patch repaired structures has been the primary focus of the majority of previous studies [4].

Experimental and analytical study performed on 7075 T6 aluminum alloy panel repaired with one sided adhesively bonded composite patch were investigated by Sabelkin et al. [5]. In this investigation, the bonded patch repair of a cracked panel provides a considerable increase in the residual strength as well as fatigue life. In study conducted by Ong and Shen [6], various factors affecting the repair of 2.5 mm thick 2024-T3 aluminium plates have been investigated, especially patch materials. Effect of patch materials on FCG was studied namely boron/epoxy patch and graphite/epoxy patch. Results show that both boron/epoxy and graphite/epoxy composite patches attain sufficiently high fatigue lives to meet the damage tolerance requirement.

The main loading effect is due to the load ratio R when the FCGR was significantly affected [7, 8]. Fatigue behavior of patched aluminum alloys 7075 T6 was investigated by Duquesnay et al. [9]. Under constant amplitude loading, effect of stress ratio, R, on stress life behavior was highlight. At same cycles of failure (≈ 105 cycles), an increasing in maximum shear stress was shown in increasing of stress ratio. In recent experimental investigation of fatigue crack growth behaviour performed on 2027 T4 aluminium alloy [10], a stress ratio and material dependence effects on the fatigue crack growth were observed and plasticity-induced closure is dominant. Under different stress ratio, Kermanidis et al. [11] have show a shift of crack growh curves for aluminium alloy 7475 T7351 and 2024 T851. In a part of experimental investigation performed on CCT specimen, Kim et al [12] have shown effect of stress on fatigue crack growth rate of 7050 T7451 Al-alloy.

In fatigue crack growth study conducted by Chung et Yang [13], it was found that the fatigue life of patched plate in 6061 T6 aluminum alloy increases about 4-6 times compared to the un-patched plate. In recent work [14], lifetime extension of the reinforced specimens is significant assuming the same load level for patched and unpatched specimens. Effect of numbers of patch layer (4, 8, 16) on fatigue crack growth was studied by Hosseini-Toudeshky [15] on single-side repaired aluminum plate. In thin plate (2.29 mm), results have shown that an increasing in patch layer, increase the fatigue life. Fatigue life in repaired plate was increased about 2-4 times compared to the un-repaired plate. Crack growth orientation is an others parameter who affects the fatigue crack growth. Sinha et al. [16] attributed the differences observed between the fatigue crack growth rate for two load ratio (R=0.1 and R=0.8) in both directions T-L and L-T for the alloy Ti-6Al-4V unlike the level closure. 300002000The investigation of Hariprasad et al. [17] have shown that the crack growth resistance was affected and important for L-T, L-S and T-S orientation comparatively to the T-L, S-T et S-L orientation for aluminum alloy (Al-8.5 pct Fe-1.2 pct V-1.7 pct Si).

The aim of the present paper covers studying the fatigue crack growth of a single-sided composite patch repair (Graphite/Epoxy) as applied a cracked aluminium plate with semi circular notch at edge. Additionally, effect of stress ratio, crack orientation and dimension of notch are investigated in un-patched 7075 T7451 aluminum plate. A comparison in fatigue and fatigue crack growth rate is made between repaired and un-repaired aluminum plate is made.

Fatigue crack growth behavior of 7075 T7451 Al-alloy

Material and specimen. Specimen used in this study is 7050-T7451 aluminum plates with semi circular notch at edge of thicknesses 3.0 mm subjected to uniform cyclic tensile stress (see Fig. 1). Mechanical properties of this material in two orientations are presented in Table 1. Semi-circular notch depend on width of specimen $(\rho = W \times 0.0625)$. Mechanical properties of composite patch (Graphite/Epoxy) are presented in Table 2 and adhesive film used for patching is FM-73 where shear's modulus is Gxy= 413.68 MPa and thickness t = 0.15 mm.

Table 1. Mechanical properties of 7050 T7451 Al-alloy

Orientation specimen	$\sigma_{0.2}$ (MPa)	E (GPa)	K_{IC} $MPa\sqrt{m}$	K_C $MPa\sqrt{m}$	ν
L-T	455.06	71.70	34.06	68.13	0.33
T-L	448.16	71.70	27.47	54.94	

Table 2. Mechanical properties of 7050 T7451 Al-alloy

E_L (GPa)	E_T (GPa)	G_{XY} $(MPa\sqrt{m})$	ν
455.06	71.70	34.06	0.33

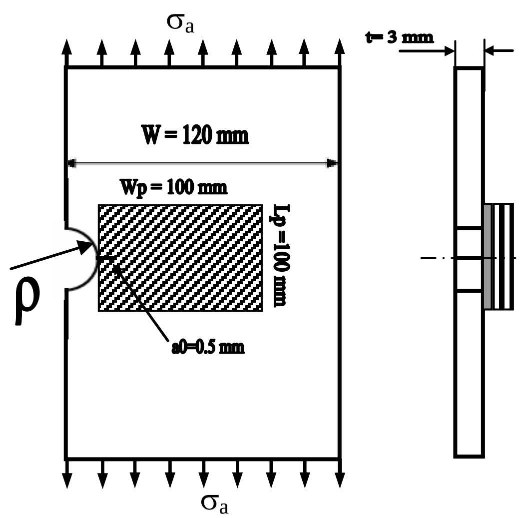

Fig.1. Geometrical model and the patch repair configuration under investigation

The stress intensity factor for the studied specimen "SENT specimen with semi circular edge notch" has been developed by Newman [18] and implemented in AFGROW code. The equation of this factor depends on several parameters and is written bellow (Eq. 1):

$$\Delta K = \sigma\sqrt{\pi a / Q}.\beta(a/w) \tag{1}$$

Where β and Q are respectively the boundary correction factor and the shape factor.

In patched specimen, function β depends on presence of composite patch and width of the patch and numbers of plies (8 and 10 plies). Variation of recalculated function β is given in Fig 2.

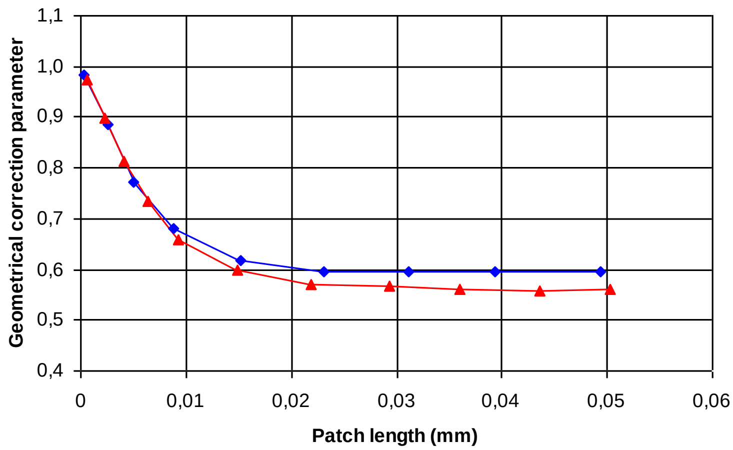

Fig. 2. Geometrical correction function β for patched SENT specimen with semi-circular notch

Fatigue crack growth parameters. NASGRO model (Eq. 2) implemented in AFGROW [19] code is used for prediction of fatigue life and fatigue crack growth rate (FCGR). The main parameters of fatigue crack growth for studied materials at R = 0 in two orientations are listed in Table 3.

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_{crit}}\right)^q} \qquad (2)$$

Table 3. Mechanical properties of 7050 T7451 Al-alloy

Orientation specimen	C	n	p	q	ΔK_{th} at $R=0$
L-T	7.58×10^{-10}	2.084	0.5	1.0	2.637
T-L	1.28×10^{-10}	2.865	0.5	1.0	

Results & discussion

Patched and unaptched SENT specimen with semi-circular notch in L-T and T-L orientation are subjected to a constant cyclic loading (σ_{a_max}=100 MPa). The Kmax criterion was adopted for the limit of crack growth. This section provides and discusses the results from empirical analyses including the effects of various parameters/factors on fatigue life and fatigue crack growth rate of the repaired and un-repaired plate.

Fatigue crack growth of unpatched specimen. Effect of stress ratio, R, on fatigue life in Al-alloy 7050 T3651 is shown on Fig. 3 and Fig. 4. In fatigue, it is noticed an increasing in fatigue life with increasing of stress ratio when applied maximum loading (σ_{a_max}) was maintained constant.

FCGRs for different stress ratio are shown on Fig. 4. The curves illustrate a general increase in da/dN with R for a given ΔK. An important effect of R has been observed clearly for this material at high ΔK. Results shown that threshold stress intensity factor was affected by R-ratio. Fatigue life is also affected by crack orientation.

In Fig. 5 it was shown that fatigue life for L-T orientation is important comparatively to the T-L orientation. This difference is affected by grain size in both directions [17]. In analysis of FCGR curves, an increasing in difference of FCGRs between L-T and T-L orientation after $20\,\mathrm{MPa}\sqrt{m}$ is shown. At same stress intensity factor 30 $MPa\sqrt{m}$, FCGRs ratio (T-T/L-T) is about 3.3 times. At fracture in T-L orientation of specimen (i.e 40 $MPa\sqrt{m}$), fatigue crack growth rate is increased 20 times comparatively to L-T orientation at the same stress intensity factor. Effect of notch dimension on fatigue life is presented in Fig. 7. An increasing in notch dimension (6.25 to 7.5 mm), fatigue life was decreased to about 3000 cycles.

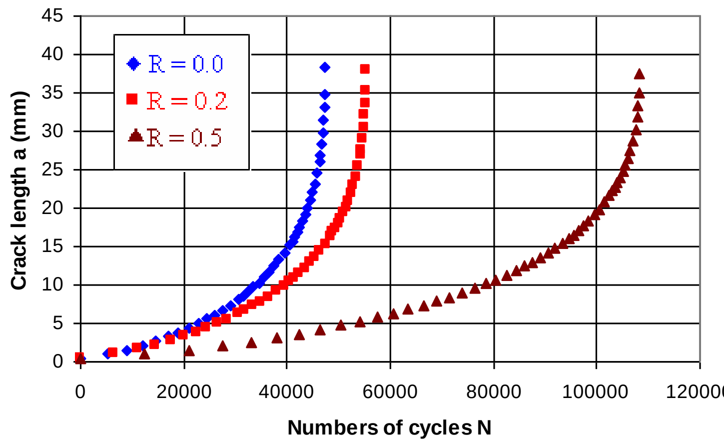

Fig. 3. Stress ratio effect on fatigue life for unrepaired plate in L-T orientation

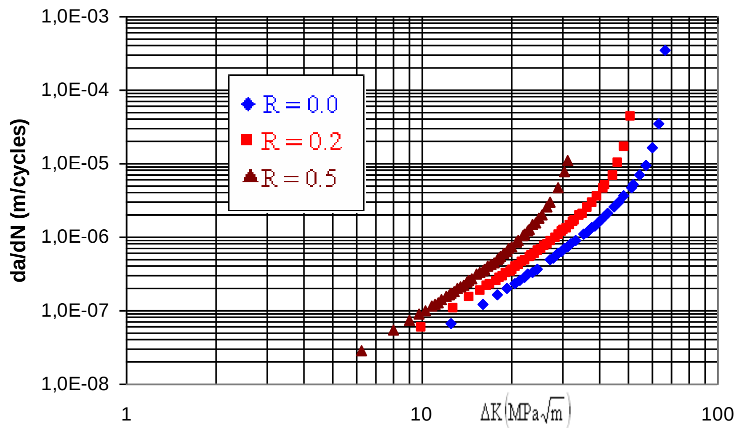

Fig. 4. Stress ratio effect on FCGR for unrepaired plate in L-T orientation

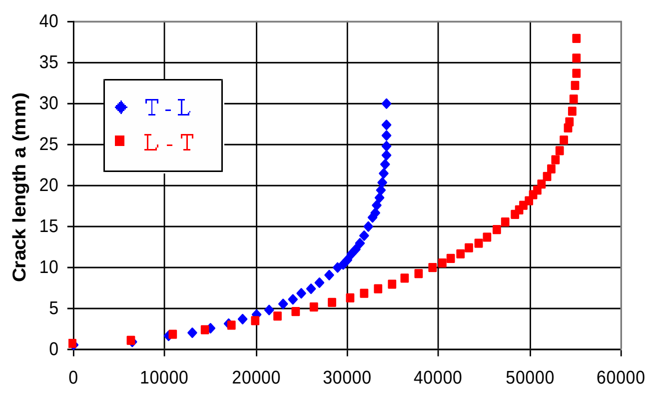

Fig. 5. Effect of crack orientation on fatigue life of un-repaired plate at R=0.2

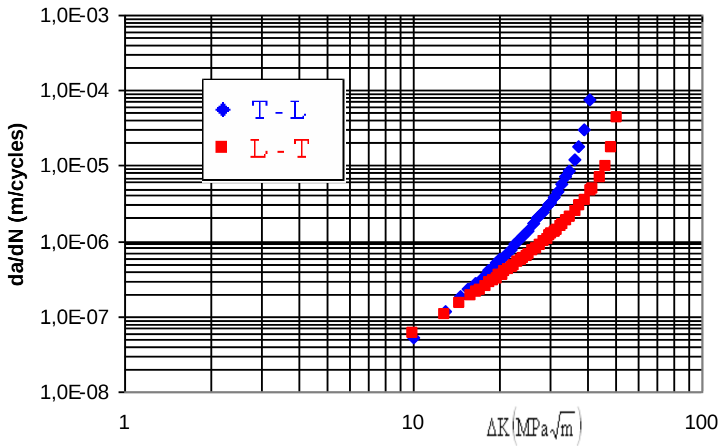

Fig. 6. Effect of crack orientation on FCGR of un-repaired plate at R=0.2

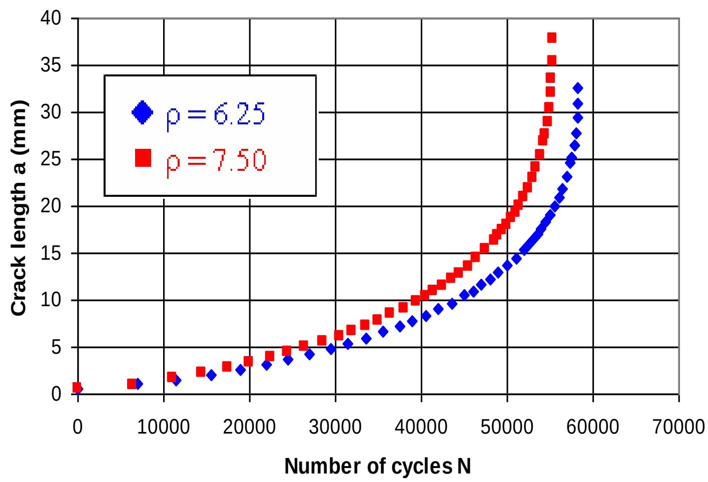

Fig. 7. Effect of notch dimension on fatigue life of un-repaired plate at R = 0.2

Fatigue crack growth of patched specimen. Graphite/Epoxy is used for repairing cracked specimen with eight (08) plies. Effect of composite patch repair on fatigue is shown on Fig. 8. for R=0.2. it is noticed an increasing in fatigue life using composite patch repair comparatively to un-repaired specimen. Under same loading condition, the fatigue life of patched specimen is about 2.5 times comparatively to the un-repaired specimen. The use of the composite patch repair presented a gain of 12 mm in crack length comparatively to the un-repaired case.

Fatigue crack growth is also affected by the presence of patch (Fig. 9). Between initial crack (0.5 mm) and 3 mm of crack no effect of patch repair on FCGR is noticed. From crack length 3 mm to 10 mm, FCGR is maintained constant and present retardation. A significant reduction in fatigue crack growth rate after 10 mm of crack length is shown. FCGR ratio between un-patched/patched specimens varies from 1.8 to 8.65 times. Fig. 10 exhibit the variation of crack length versus number of load cycles for repaired specimen with various numbers of graphite /epoxy patch layers. The crack growth lives of the repaired specimen with the thickness of 3 mm increase with increasing the number of patch layers. In case of ten (10) patch layers, fatigue life is increased of about to 9000 cycles compared to eight (8) patch layers.

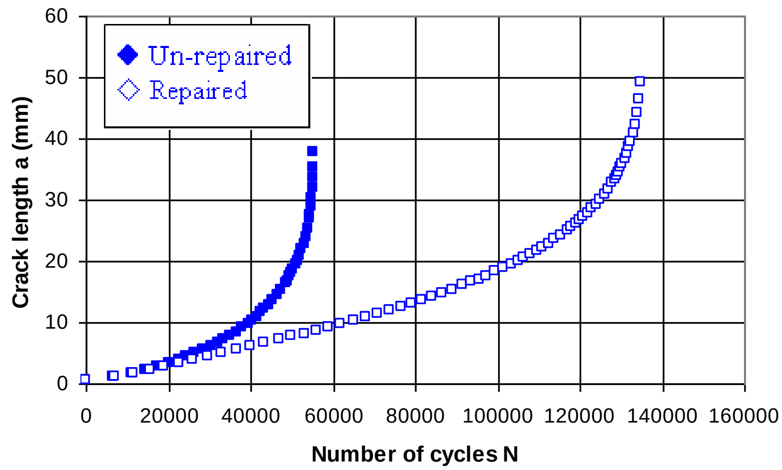

Fig. 8. Effect of composite patch repair on fatigue life at R=0.2

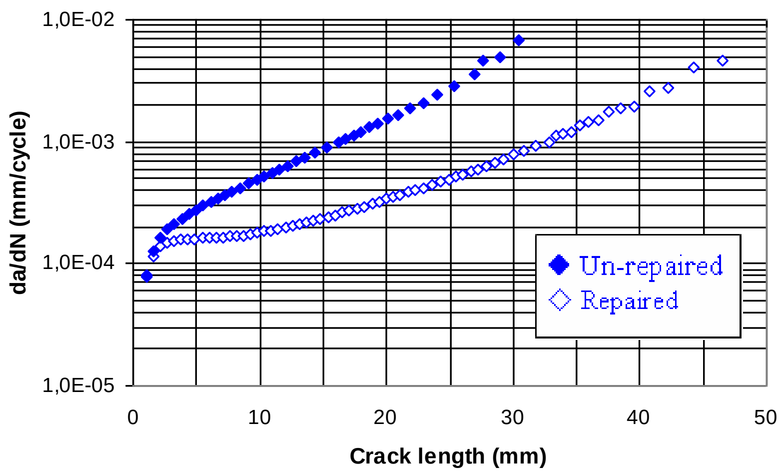

Fig. 9. Fatigue crack growth rate for repaired and un-repaired specimen at R =0.2

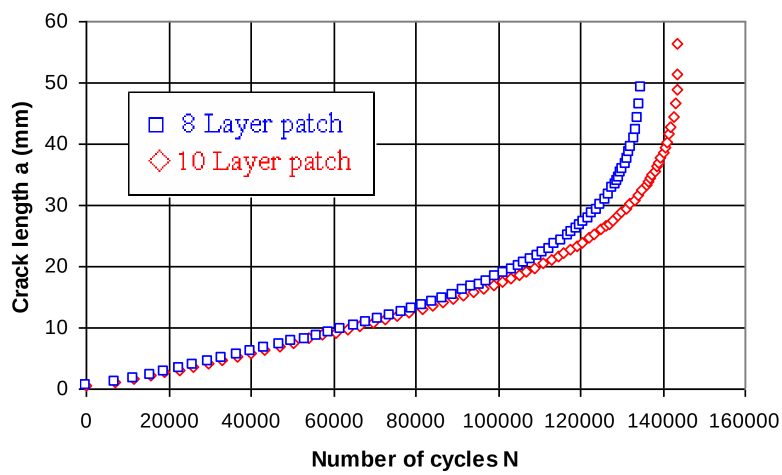

Fig. 10. Effect of layers patch on fatigue life of 7050 T7451 Al-alloy

Conclusion

In this paper, fatigue crack growth behaviour of Single edge notch with semi-circular notch aluminum plate un-repaired and repaired with single side composite patches (Graphite/Expoxy) was investigated. The following conclusions were obtained from investigating the effect of some parameters on un-repaired plate and effect of patch on the crack propagation.

1. Fatigue life and FCGRs were affected by increasing of stress ratio.
2. Fatigue behavior (fatigue life, FCGRs) is also affected by crack orientation when L-T orientation presents a best resistance comparatively to T-L orientation.
3. Notch dimension is other parameters that depends the fatigue life.
4. Comparative fatigue behavior of repaired and un-repaired shows beneficial effect of composite patch repair on extension in service life and reduction of FCGRs.
5. The fatigue life of patched plate increases about 2.5 times compared to the un-patched plate.
6. No high effect was shown in increasing in layers patch from eight to ten on fatigue life.

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