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Prediction of fatigue crack growth of repaired Al-alloy structures with double sides

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Abstract

During navigation, aircrafts are subject to fatigue damage. In order to rehabilitate damaged structures some techniques are often used to resolve this problem. Efficient repair technique, called composite patch repair, was used to reinforce the damaged structures and stop cracks. In this paper, effect of composite patch repair (Boron/Epoxy) on fatigue crack growth (FCG) was investigated on 2219 T62 Al-alloy. Effects of double patch repair in single notch tensile specimen (SENT) on FCG were studied and compared to single patch repair. Results show beneficial effect of patch repair on fatigue life and FCGR in comparison with the un-patched specimen. In addition, effect of mean stress characterized by stress ratio was highlighted. Fatigue behavior of investigated Al-alloy was compared.

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Keywords: Fatigue crack, patch repair, Al-alloy, mean stress;

1. Introduction

(10 pt) Al-alloys series 2xxx are widely used in aircraft structural applications. Aircraft structures are subjected to cyclic loading which consequently leads to damage. 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 introduced by researchers in aeronautical and maritime research laboratories for Royal Australian Air Force in the early 1970's [1]. This efficient repair technique, called composite patch repair, was used to reinforce the damaged structures and extend the life service of aging aircraft and offers significant advantages over traditional repair methods (riveting, fastening, welding).

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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].

Nomenclature

a	crack length
a_0	initial crack length
ΔK	stress intensity factor range
da/dN	fatigue crack growth rate
σ_m	mean stress
R	stress ratio
β	geometric correction factor
t	thickness of specimen
W	width of specimen
W_p	width of patch
L_p	length of patch

Several Al-alloys were used in aircraft structures in different tempered situation and chemical composition. In series 2xxx of Al-alloy, Ong and Shen [5] conducted fatigue crack of one side repaired 2024 T3 Al-alloy plate. In this investigation effect of patch materials on fatigue crack growth (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. Under constant amplitude loading, fatigue behavior of patched aluminum alloys 2024 T3 was investigated by Duquesnay et al. [6]. In this investigation, it was shown that patched bar 2024 T3 aluminum alloy present a good resistance in comparison with the un-patched bar. In experimental study [7], lifetime extension of the reinforced specimens is significant assuming the same load level for patched and un-patched specimens. Effect of the number of patch layer (4, 8, and 16) on fatigue crack growth was studied by Hosseini-Toudeshky [8] on single-side repaired aluminum plate. Numerical study conducted by Belhouari et al. [9] has shown that the use of double patch repair reduces appreciably the stress intensity factor compared to the single patch. In recent investigation of Bachir Bouiadjra et al. [10] it is noticed that the use of the double symmetric patch increases considerably the repair performances. It is noted that the difference of the stress intensity factor between a single and double symmetric patch is stabilized when the patch thickness is greater than 2 mm.

In experimental and numerical study of the fatigue behavior of one-side composite patched large-scale steel plates conducted by Tsouvalis et al. [11] shows that the fatigue life of reinforced specimens by patch was increased up to 2 times compared with that of the un-patched reference ones. In an experimental investigation conducted by Liu et al. [12] on fatigue crack growth behavior of reinforced steel structures by double-sided composite patch repair, it was shown that in this scheme an increasing in fatigue life by 2.2 to 2.7 times compared with un-patched steel plate. But in single-side, fatigue life was increased by 1.2 to 1.4. The present paper aims to study the fatigue crack growth of a cracked aluminum plate (SENT specimen) with a double-sided composite patch repair (Graphite/Epoxy). Based on experimental fatigue crack growth of un-patched 2219 T62 Al-alloy plate, a comparison in fatigue life and fatigue crack growth rates was made between repaired by double, single sided plate and un-repaired plate.

2. Material and fatigue crack growth

The material used in this investigation is 2219 T62 in L-T orientation. Basic mechanical properties for this material are presented in Table 1 (Afgrow database). Mechanical properties of composite patch (Graphite/Epoxy) are shown in Table 2. Simulation of fatigue crack growth in mode I is completed by using a Single Edge Notch Tensile specimen (SENT) subjected to uniform tensile cyclic load (100 MPa). Geometrical parameters of tested specimens are indicated in Fig. 1. The adhesive used for patching is FM73 with shear modulus G_{xy}=413.69 MPa.

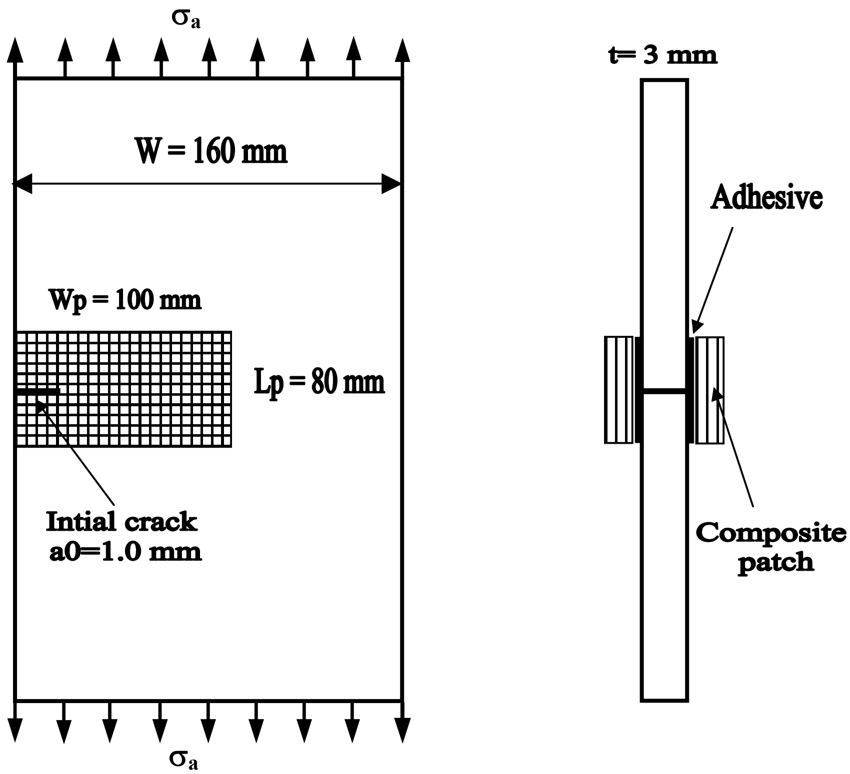

Fig. 1. Investigated patched SENT specimen

Table 1 Mechanical properties of 2219 T62 Al-Alloy

$\sigma_{0.2}$ (MPa)	E (GPa)	K_{IC} (MPa.m$^{1/2}$)	K_C (MPa.m$^{1/2}$)	ν
303.37	68.948	29.669	59.338	0.33

Table 2. Mechanical properties of Graphite/Epoxy

E_L (GPa)	E_T (GPa)	G_{XY} (GPa)	ν
206.84	19.305	5.171	0.2

The stress intensity factor for the studied specimen implemented in AFGROW code depends on several parameters and is written as follow:

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

Function β is the geometry correction factor, proposed by Newman [13]. For patched specimen function β is modified and depends on the presence of composite patch, width of the patch and numbers of plies. Variation of recalculated function β is given by Fig. 2 for un-patched, single patch (8 plies) and double patch (2 x 4 plies) for final crack length limited by Kmax failure criteria. For the same total of plies no variation was shown between the presence of single and double patch.

For fatigue crack growth prediction, NASGRO model implanted in AFGROW software is used in this study. Parameters of this model are based on experimental data of the studied material. Principal parameters of NASGRO model for the studied materials are presented in Table 3.

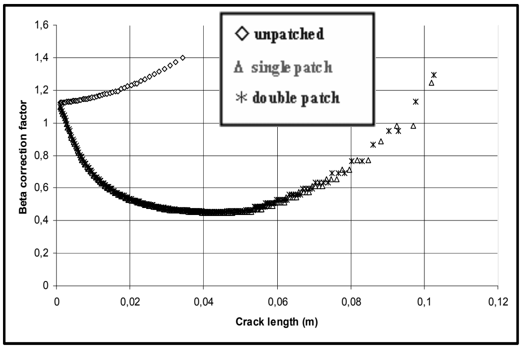

Fig. 2 Geometrical correction function β for SENT specimen

Table 3. Parameters of crack growth model for 2219 T62 Al-alloy

C	n	p	q	ΔK_{th} at R=0
7.4543×10^{-10}	2.657	0.5	1	3.956

3. Prediction of fatigue crack growth Copyright

Patched with single and double patch and un-patched SENT specimens are subjected to a constant cyclic loading under the variation of loading amplitude. The K_{max} criterion was adopted for the limit of crack growth. This section provides and discusses the results obtained from empirical analyses including the effect of single, double patch repair on fatigue life and fatigue crack growth rate of the repaired plate.

Fig. 3 show the effect of loading amplitude at R=0.2 on fatigue life for double patched specimen with four plies on one side. The maximum loading amplitude varies from 80 MPa to 150 MPa. It is noticed that an increase in loading amplitude leads to a decrease in fatigue life. This effect was shown in experimental investigation by Benachour et al. [14] in fatigue crack growth of un-patched four bending specimen. For example at crack length a=40 mm, fatigue life increase from 1×10^5 cycles to 6.1×10^5 cycles. At failure (final crack length), the ratio for fatigue life varies from 3.6 times to 6.5 times.

Effect of double patch on fatigue life compared to single patch and un-patched specimen is shown in Fig. 4. The presence of patch (double patched) with eight plies in total increase the fatigue life from 9.4×10^4 cycles to 3.7×10^5 cycles i.e the ratio in fatigue life is about 3.88. The final crack length for the un-patched specimen is limited to 51 mm but for single and double patch under same loading is limited to 102 mm. This increasing in final length is due to the presence of patch and consequently an increasing in strain and stress fracture toughness (K_{IC} and K_C). These results show the efficacy of the reparation method in the retardation of fatigue failure. Fatigue crack growth rates (FCGR) were affected by the presence of patch repair (Fig 5.). An increase was shown in comparison with the un-patched specimen. The decrease in FCGR at crack length "a" equal to 40 mm for double patched specimen (i.e single patch) is about 1.8 times compared to the un-patched specimen.

Effect of mean stress characterized by r-ratio is shown in Fig. 6. An increasing in fatigue life with increasing in mean stress (i.e R-ratio) is shown when maximum loading applied is kept constant. The fatigue life at σ_m (mean stress) equal to 75 MPa (R=0.5) is about 8.54×10^5 cycles but at σm= 60 MPa is equal to 3.54×10^5 cycles. The ratio of mean stress equal to 1.25 between R=0.1 and R=0.5 indicates an increasing in fatigue life ratio of about to 2.41 times.

4. Conclusion

In the present investigation, fatigue crack growth behavior of cracked SENT specimen in 2219 T62 Al-alloy repaired by double composite patch (Graphite/Epoxy) is studied. The fatigue predictions lead to the following conclusions:

- In specimen repaired by double patch, fatigue life decrease when loading amplitude increase.
- No effect on fatigue life and FCGR was shown between double and single patched specimen with the same numbers of plies.
- Fatigue behavior for patched specimen with double and single patch was strongly affected
- The fatigue life extension of the repaired specimens is significant assuming the same load level for patched (double/single) and un-patched specimens. Retardation ratio in fatigue life is about 1.8 times.
- An increasing in mean stress increase the fatigue life when the maximum stress applied is kept constant.

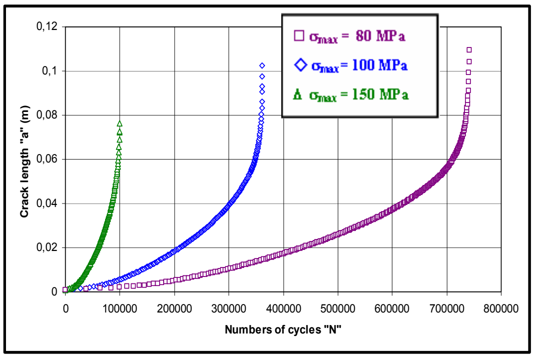

Fig 3. Effect of amplitude loading on fatigue life of double patch repair of SENT specimen at R=0.2

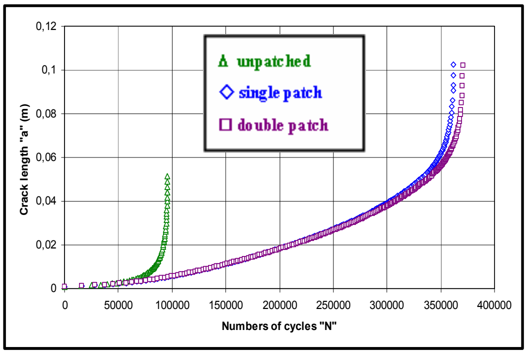

Fig 4. Comparison of fatigue life for double, single patch repair and un-patched specimen at R=0.2

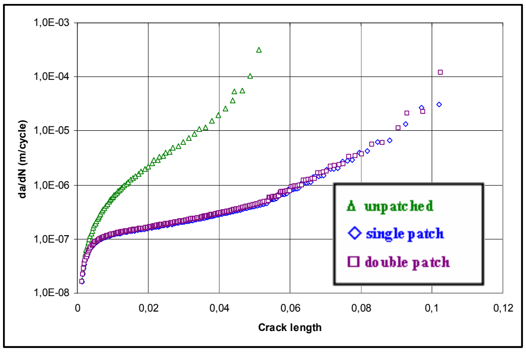

Fig. 5 Comparison of FCGRs for double, single patch repair and un-patched specimen at R=0.2

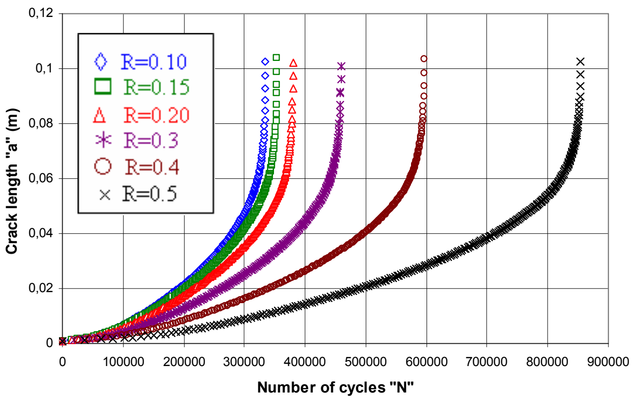

Fig. 6 Effect of mean stress on FCGRs of double sides patch repair of SENT specimen

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