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Fatigue life Analysis of a Thin Cracked Aluminum Alloy Panel Repaired with a CFRP Patch

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Abstract: *The investigation aims to predict the fatigue life of thin cracked aluminum alloy skin repaired with an adhesively bonded composite patch.In the first part of study, the number of fatigue cycles required to initiatea crack on a existing pre-crackedbare specimen were experimentally obtained for different crack lengths. Further, its effect on the stress intensity factor was studied to find out the fatigue life of the bare specimen. In the second part, the effectiveness of the cracked specimen repaired by an asymmetrically bonded CFRP patch was investigated through experimentation.The skin of the centre- cracked specimen was made of 1 mm thick 6061-T6 aluminumalloy. The pre-crack of different crack length were cut using wire-EDM. The pre-existing center lengthswere chosen to be: (i) 10 mm (ii) 15 mm (iii) 20 mm (iv) 25 mm and(v) 30 mm. The skin with a centre crack of 25 mm was chosen for the further study on the specimen repaired by a unidirectional CFRP patch bonded through epoxy resin. Different configurations of CFRP plies with change in stiffness ratio and length of plies were experimentally tested on a tension-tension fatigue testing machine to determine the fatigue repair strength. The number of cyclesrequired to initiatethe crack and the failure cycleswere found to beincreased with the decrease in maximum applied fatigue stress. The fatigue life of specimen repaired with a CFRP patch was increased substantially over the un-patched bare specimen. Also, the fatigue life of the repaired specimen was found to be increased substantially with theincrease in stiffness ratio and the length of CFRP patch.*

Keywords: *Aluminum alloy 6061-T6, center crack, CFRP patch, fatigue life, initiation cycles*

I. Introduction

Most of the structural component may be susceptible to a crack growth which in many cases becomes the reason for failure of the component, rather than yielding. Composite patches, bonded on cracked or corroded metallic aircraft structures, have shown to be a highly cost effective method for extending the service life and maintaining high structural efficiency [1-4].The composite bonding methodprovides many benefitscompared to other repair techniques like bolting or riveting, including high fatigue life, high stiffness to weight and strength to weight ratio, less corrosion and can be given any complex shapes[5-10]. Carbon fiber reinforced polymer patchesare most widely used in aeronautical applicationsas they offer their high stiffness and strength to weightratios[11-12]. The performance of composite patches depends on the properties of both reinforcement and adhesive. A bonded composite patch should be designedsuch as to restore the original strength of cracked structure, subjected to quasi -static loading [11-12]. The stress intensity factor for the cracked structures is mostly reduced by reinforcing the appropriate composite or metallic patch. The structures repaired with composite patches are more effective than those of metallic patches

II. Specimen Preparation

2.1. Skin geometry

The skin was cut to a size of 400 mm × 60 mm along rolling direction from a 1 mm thick 6061-T6 aluminum full size sheet of 1.2m x 2.4m, employing a shearing machine. A centre pre-crack of different crack lengthwas cut through a wire-EDM. The crack length *2a* was chosen to be 10 mm, 15 mm, 20 mm, 25 mm and 30 mm to study its effect on the stress intensity factor and fatigue life. To study the effectiveness of repair strength, the similar size of the skin was used and the pre-crack length *2a* = 25 mm was kept constant for all the specimens. A centre crack in a structural plate is morefrequently encountered in the field work of repairing a skin of a structure. Therefore, centre cracked skin was chosen for specimen. Figure 1 shows the specimen geometry of skin repaired with asymmetrically bonded CFRP patch.

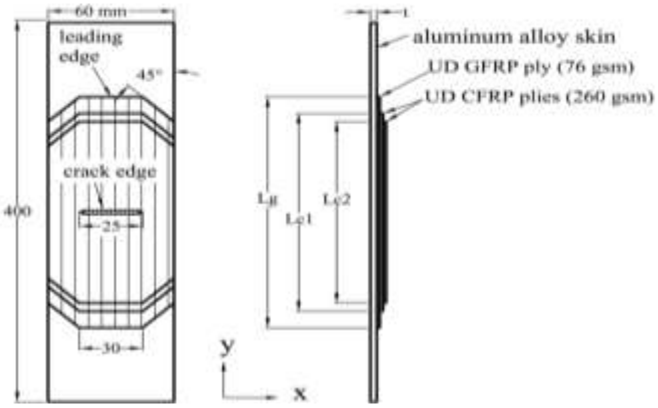

Fig. 1 Specimen geometry of skin repaired with asymmetrically bonded CFRP patch.

2.2 Reinforcement

Uni-directional (UD) carbon fiber sheet of 260 gsm with a net binder was chosen as the reinforcement material for FRP patch. A thin ply of 76 gsm UD glass fiber was used between the CFRP plies and the aluminum skin surface to avoid galvanization of aluminum skin.The patch was bonded using epoxy resin in addition with 0.5% of aminosilane and 10% of hardner. Table 1 shows the ply lengths and stiffness ratio of the patched specimens.

Table 1:Lengths of FRP patches and the stiffness ratio

Sr no.	Number of UD-CFRP plies	UD-GFRP length in mm	UD-CFRP Length/ply in mm	Stiffness ratio
1	3 (Short patch)	80	40, 52, 64	0.98
2	3 (Long patch)	100	60, 70, 80	0.98
3	4	90	40, 50, 60, 70	1.24
4	5	100	40, 50, 60, 70, 80	1.54

III. Experimental Testing

The experiments were carried out on the bare specimens as well as the specimens of skin repaired with carbon fibre-epoxy patches on a computerized axial tension-tension fatigue test machine (Figure 2) by applying fatigue load at the frequency of 10 Hz. The maximum fatigue stress $\sigma_{max}$was applied in the range of 25% to 65% of the yield stress (277 MPa) of the aluminum alloy skin. The minimum applied stress σ_{min} was set at 10% of the corresponding σ_{max}.The tests were conducted to explore the relation between stress and the number of cycles required to fail the specimen. (S-N plot) for the bare specimens as well as the specimens repaired with different patch configurations.

During the experimentation, two failure states were monitored; cycles to initiate a crack N_i and cycles to fail the specimen completely N_f. The fatigue loading was continued till the entire specimen fails. Numbers of cycles required to cause the complete failure of the specimen were recorded. After the initiation of crack growth the failure mode was monitored closely during the experimentation.

Fig. 2 Photograph of the experimental set-up for uni-axial fatigue testing.

IV. Result And Discussion

4.1. Fatigue test on an bare aluminumalloy skin with a pre-centre crack:

The specimen with center crack was loaded under tension-tension fatigue test machine. The various crack length tested were with the following crack length: (i) 30 mm (ii) 25 mm (iii) 20 mm (iv) 15 mm (v) 10 mm. With the variation in crack length, fatigue life, crack growth phenomenon and cycles required to crack initiation N_i were studied.

4.1.1. Crack initiation in pre-cracked bare specimen.

The fatigue tests were conducted on the bare pre-cracked aluminum specimen to explore the phenomena of crack initiation and the number of cycles required to initiate the crack N_i were recorded. From the experimentally obtained results, two kinds of relations were generated, (i) maximum applied fatigue stress vs. crack initiation cycles N_i and (ii) stress intensity factor K vs. crack initiation cycles N_i. During the experimentation, it was observed that, after certain load cycles; the initially sharpened pre-crack tip was slowly rounded almost to a semi-circular crack front of approximately 0.28 mm diameter. A depressed area i.e. dimple formation, was also seen in front of the crack tip as shown in Figure 3. On further loading, a crack tip was initiated on the rounded edge of the pre-crack after N_i cycles.

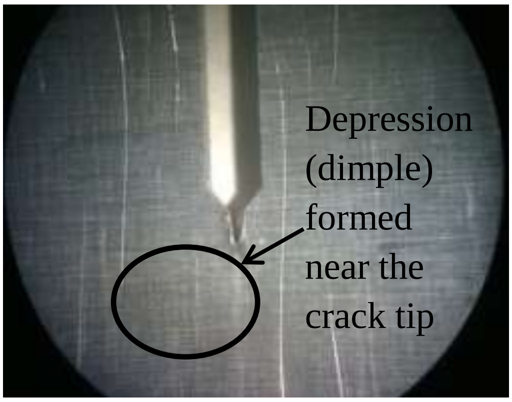

Fig. 3 Magnified view of crack tip with depresion formed near the crack tip

Figure 4 shows the relation between K_I and N_i for various different crack lengths.The curves were best fitted with 3rd degree polynomial. For three cases out of five, the relation between K_I and N_i was close to each other. It was found that the higher K_I was required to initiate a crack for the pre-crack length of 25 mm. For the pre-crack length of 10 mm, K_I required to initiate the crack was found to be lowest among all the cases.

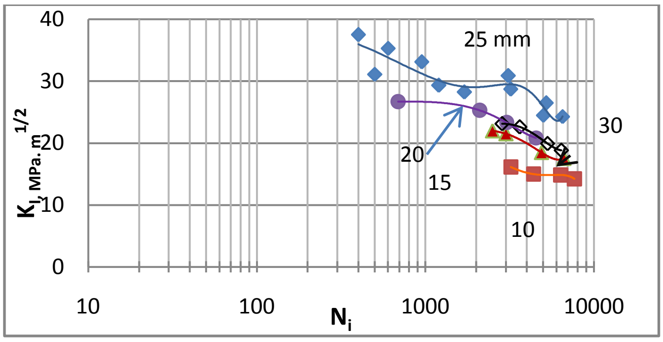

Fig.4 Comparison of K_I-N_i curves for the specimen with different crack length

4.2 Tension-Tension fatigue test on patched specimen

The performance of the pre-cracked skin repaired with a CFRP patch specimenson the improvement in the fatigue life was explored and the crack initiation behaviour was analyzed. The specimens were continuously monitored by illuminating the area near the crack on the un-patched side using bright light. The crack initiation pattern was found to be similar to that of the bare specimen. The separation of patch in front of the crack tip and around the crack edges could not be seen as the CFRP was black in colour. However, the specimen was coin tested (tapping with a coin) and it was felt that the separation took place all along the length of crack. The rate of crack growth increased slowly in the beginning and then with faster propagations per cycle. The crack in the aluminum skin grew all the way to separate the skin into two parts. Then the full load was taken by the patch. After additional 2000 cycles or so, the separation of the patch was initiated close to the leading edge of the outer CFRP ply. The glass fibres underneath the leading edge of C64 ply were broken. The portion of the patch where only GFRP ply was present, no separation between GFRP ply and skin was observed as shown inFigure 5. Thus complete failure occurred with the specimen broken into two parts through the separation of patch from skin. The separation which started at the crack edge even before the skin was broken into two parts grew all the way to cause separation of the specimen into two parts.

Figure 6 and Figure 7 shows the comparison between number of cycles required to initiate the crack N_i and number of cycles required for complete failure of specimen into two parts N_f for various patch configurations.

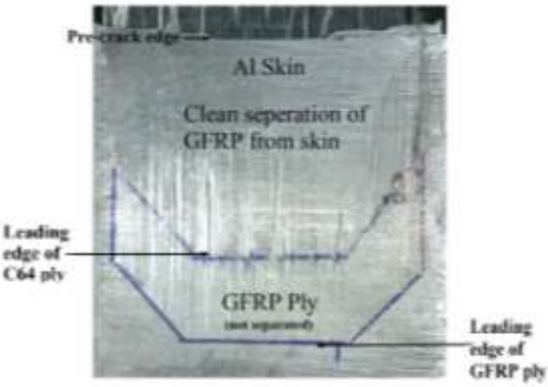

Fig. 5 Clean separation from skin and broken GFRP ply at leading edge of CFRP ply

4.3 Overall discussion:

The experimental investigation was carried out to study the performance of the thin cracked aluminum alloy repaired with the reinforcement of a polymer patch bonded by epoxy resin. Fatigue life of bare specimen was found to be increasing with decreasing pre-crack length.In further part of the investigation, the pre-cracked specimen was repaired with a single sided CFRP patch to study the effectiveness on the fatigue life of a repaired panel. Once, the crack was initiated it propagated throughout and separation took place all along the length of crack at crack plane. The rate of crack growth increased slowly in the beginning and then with faster propagations per cycle. The crack in the aluminum skin grew all the way to separate the skin into two parts. After breakage of specimen into two parts the total load was taken by the patch; the patch separation was initiated from leading edge of the CFRP patch and after certain cycles the patch was separated from skin due to breaking of GFRP ply. The clean separation was observed between the skin surface and GFRP ply.

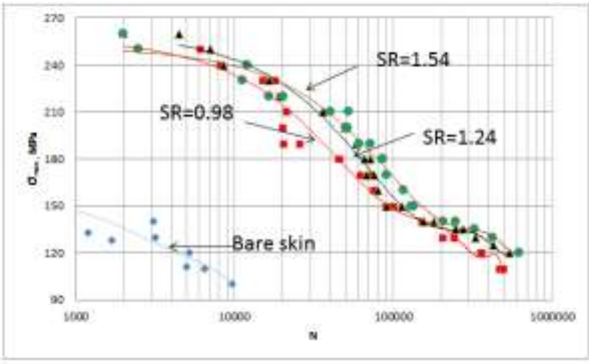

Fig. 6 σ_{max} vs. Initiation life, N_i

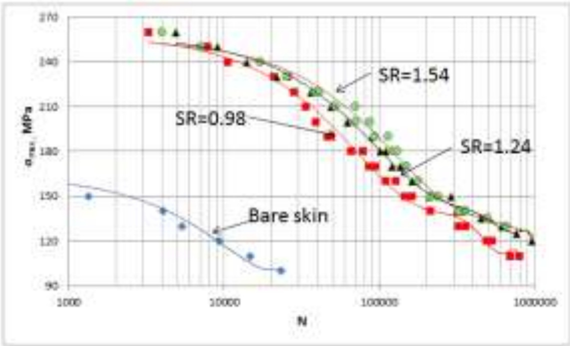

Fig. 7 σ_{max} vs. Failure life, N_f

V. Conclusion

From the experimentation, it was observed that the specimen repaired with CFRP patch has substantial increase in fatigue life over the specimen without repair. The fatigue life of specimen repaired with three plies-long length patch was higher than the specimen repaired with three plies-short length patch. The fatigue life of repaired specimen increased with the increase in the stiffness ratio.

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Conflict of interest: the authors declare that there is no conflict of interests regarding the publication of this paper.

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