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Fatigue Life Enhancement of Cracked Aerospace Grade Aluminium Repaired with Bonded Composite Patch: Experimental Study

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Bonded composite patch repair of cracked components and weakened aircraft structures has gained high acceptance and demand. In the present study, fatigue crack behavior of 2 mm thick V-notched aluminum 2024-T3 plates, repaired with composite patch was experimentally investigated. This includes assessment of repair efficiency and fatigue life of cracked samples repaired at different levels of crack length. The experimental results showed that the reinforcement of patch increases the fatigue life about 4.5 times. However, the repair efficiency decreases with initial crack length. Consequently, cracks must be repaired as soon as detected. The SEM images clearly demonstrate that the fracture mode of 2024-T3 is predominantly trans-granular with small sized dimples.

1. Introduction

Due to high demand for repair of aging aircrafts, bonded composite repair has been receiving substantial attention for decades (Baker, 2015). This method is very promising because it offers significant advantages over traditional repair like riveting, fastening or stop hole drilling. Bonded composite repair is the bonding of boron or carbon fiber reinforced epoxy patch onto a cracked or weakened structure. The composites have strength higher than the parent material (adherend) and are adhesively bonded. Composite patches are stronger and stiffer, less weight, have good fatigue performance, prevent corrosion. The patch reduces stresses in the underlying structure and may retard or arrest the crack growth (Jones and Callinan, 1979). Composite patches are preferred to metallic patch repairs because composites provide better structural integrity, easier to install, and conform more easily to complex geometries (Bouiadjra et al., 2015).

The Aeronautical and Maritime Research Laboratory for the royal Australian air force explored the bonded patch method in early 1970's. Then, Baker pioneered the research in this field (Baker et al., 2003). Later on, many researchers performed experimental and numerical investigations on different parent materials with different patch configurations like Bernasconi et al. (2013) worked on thick plated repaired with bonded composite patch. Khan et al. (2014) studied the repair of crack plates under block loading. Most of them reported that significant extension in fatigue life is obtained after repair (Albedah et al., 2015). Some authors like Bachir Bouiadjra et al. (2011), studied the variation of stress intensity factor (SIF) and concluded that SIF decreases dramatically after repair. Fekirini et al. (2008) showed that the SIF exhibits an asymptotic behavior with respect to crack length. This behavior is attributed to the fact that there is stress transfer from the cracked plate to the composite patch throughout the adhesive layer. Thus, the adhesive properties play a vital role in the repair efficiency of the patch (Schubbe and Mall, 1999). Concerning the mechanical properties of the patch, it is known that the boron/epoxy and the graphite/epoxy are used because of their excellent load transfer characteristics (Baker, 1984). The improvement of the patch performances by the assessment of the properties of the composite and the adhesive proved to be more difficult and expensive (Bachir Bouiadjra et al., 2010). Khan et al. (2014) studied the effect

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of bonded composite patch under stepped loading. They later studied the effect of increasing and decreasing blocks of loading and concluded that load amplitude variation is important parameter in calculating the repair efficiency (Albedah et al., 2016). One important parameter which requires more attention and systematic investigation is the patch thickness.

Most of the early investigations were carried out on thick aluminum plates by Schubbe and Mall (1998). Soutis and Hu (1997) reported that reducing patch thickness near the edges of overlap decreases the stress concentration. The results reported show that there is significant effect of thickness on repair efficiency of composite patch. However, there is not adequate work present in the literature on effect of patch thickness in thin aluminum plates. To study the effect of stiffness ratio, researchers investigated the thickness of plate by maintaining constant patch thickness due to the time involved in manufacturing the patches with different thickness. Bachir Bouiadjra et al. (2002) showed numerically that for a single patch repair, the increase of the patch thickness about 50 % reduces the SIFs at the same order and they affirmed that for a better distribution of the stresses, it is preferable to use a multiple layers of bonded composite patch. In this work, this issue is addressed with a systematic investigation of the effect of patch thickness on the repair efficiency for thin aluminum plates (Al 2024-T3), subjected to different stress ratios. Single side repair has been studied in this investigation, which is advantageous when it is not possible to access both sides of a weakened structure. Moreover, in single side repair, disassembling of structure is not needed. We investigated the repair performance at 3 initial crack lengths and three stiffness ratios in this study.

2. Experimental Techniques

2.1 Sample Preparation

The experimental program conducted in this study includes constant amplitude fatigue tests on unrepaired and repaired single edged notched tension (SENT) specimen. The specimens of dimensions 150 mm × 50 mm × 2 mm, were cut from Al 2024-T3 plates in L-T direction. An initial notch of 6 mm depth and 60° angle was cut in the center of each specimen as shown in the

Figure 1 as per ASTM E647 standards (International, 2011). The specimens were repaired with bonded composite patch of different thicknesses (t_r), comprises of 4 plies, 6 plies and 8 plies and initial crack lengths (a_0 = 3 mm, 6 mm and 9 mm). Patches are made of unidirectional carbon/epoxy pre-pregs of different layers oriented at zero degree cured at 120 °C for 90 min. Square shaped, full width patches of 50 mm × 50 mm were used throughout this investigation.

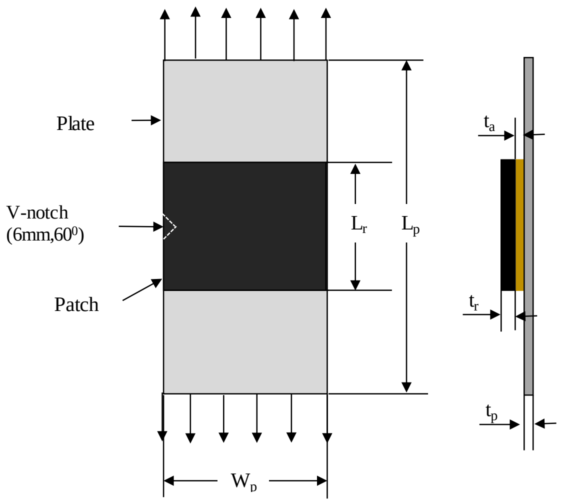


Figure 1: Specimen details

The surface of SENT specimens was prepared using Bell Process Specification method (Specification, 1972). The pre-cracked specimens were repaired with the composite patches bonded to the specimens using the adhesive araldite such that the lay-up principal direction is along the loading direction, as shown in Figure 1. The adhesive gets cured at room temperature and thus prevents the formation of thermal residual stresses. Material and geometric properties for the plate composite patch and adhesive are shown in Table 1 and 2.

The use of double symmetric patch eliminates the bending moment but the main disadvantage of the double symmetric patch is the difficulty in monitoring the crack growth. In our investigation, in order to minimise the bending effect for single sided patch, we have carefully chosen the stiffness ratio between the cracked plate and the composite patch. The stiffness ratio is defined as

$$S = \frac{E_r t_r}{E_p t_p} \tag{1}$$

Where, E is Young's Modulus, t is thickness, and “r and p” are subscripts designating the patch and plate, respectively. The stiffness ratio of the specimen with 8 plies is patch is 1.9. The preferred stiffness ratio for optimum performance is 1.2 to 2.0 (Schweinberg et al., 1995).

Table 1: Material Properties

Properties	Materials		
	Al 2024-T3	Carbon/Epoxy	Adhesive (Araldite)
Longitudinal Young’s Modulus (GPa)	72.4	134	2.52
Transversal Young’s Modulus (GPa)	72.4	10.3	2.52
Longitudinal Poisson Ratio	0.33	0.33	0.32
Transversal Poisson Ratio	0.33	0.53	0.32

Table 2: Dimensions of the material used

Material	Al 2024	Adhesive	Composite Patch
Length (mm)	$L_p = 150$	$L_a = 50$	$L_r = 50$
Width (mm)	$W_p = 50$	$W_a = 50$	$W_r = 50$
Thickness (mm)	$t_p = 2$	$t_a = 0.1$	$t_r = 0.18$ mm per layer

2.2 Test Procedure

Fatigue experiments were carried out on a 100 kN capacity Instron 8801 servo hydraulic machine. All tests were performed at room temperature using a sinusoidal waveform at a loading frequency of 20 Hz. The SENT specimens, both unrepaired and repaired, were loaded cyclically at stress ratio of R = 0.1 with a maximum stress amplitude of 70 MPa.

The specimens were pre-cracked to different initial crack lengths before repairing with composite patch. The pre-cracking was accomplished by cycling the specimens. This pre-cracking process was accomplished to ensure that the effect of the machined starter notch is removed. All samples were bonded under same pressure and temperature conditions to ensure the adhesive quality, constancy and thickness. Three samples at least were tested for each condition to ensure the result constancy and accuracy. For each test, the number of cycles with respect to crack length was recorded using high-speed camera for later processing.

3. Results and Discussion

3.1 Comparison of repaired and unrepaired specimens

To assess the durability of bonded repair, fatigue life of repaired specimen were compared with the baseline specimen. When the plate is loaded under cyclic loading, the crack length has direct influence on the fatigue life. Figure 2 shows the variation of the fatigue life (N) as a function of crack length for repaired and unrepaired cracks loaded at a stress ratio of 0.1. Two stress ratios have been studied to understand the behavior of patch repair at different mean load levels. The fatigue life is increased considerably after the reinforcement of patch. This is because the patch carries the loads as the crack grows.

The number of cycles to failure is about 81,800 cycles at R = 0.1 for unrepaired specimen. This has been improved to about 4.5 times after the reinforcement of patch on single side as shown in Figure 2. This means that the composite repair can highly improve the global lifespan of aircraft structures. In the literature, several ratios for the increase in the number of cycles to failure were given: four times, ten times, twenty times and even one hundred times. These differences are probably due to the load level, geometrical properties of patch or the presence of adhesive disbond during the crack propagation. The adhesive disband over the crack region can significantly reduce the stress transfer between the repaired plate and the composite patch causing a reduction of the repair efficiency. A well-designed repair can only be effective if the patch is strongly bonded to the parent adherend and therefore the issues of adhesive bond strength and bond durability are absolutely crucial for a fully successful repair (Albedah et al., 2015).

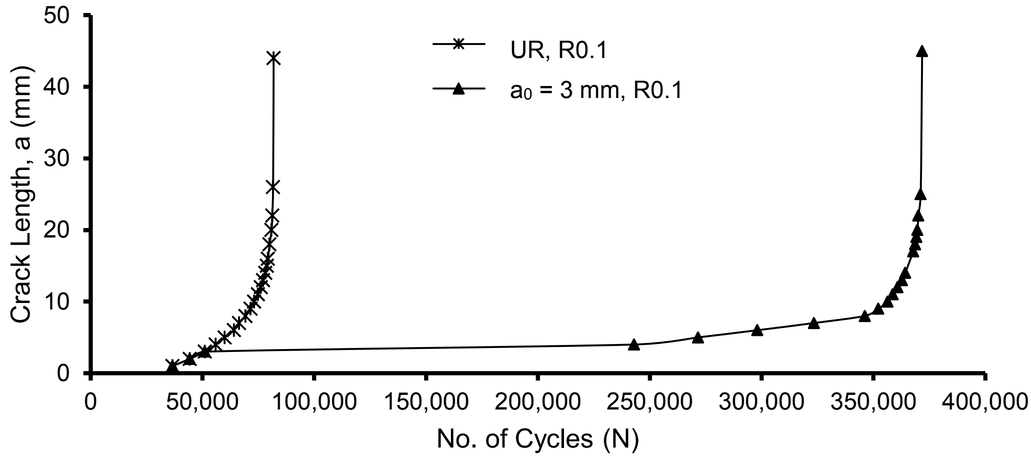


Figure 2: Comparison of repaired and unrepaired specimen

3.2 Effect of initial crack length

When a significant structural damage is detected, a decision must be made on the need for a repair. The choice of the initial crack length of patching is thus very important in achieving the repair objectives. In order to analyse the effect of the initial crack length (a_o) of patching on the repair efficiency, fatigue tests were conducted on 2024-T3 panels with different initial crack lengths of 3, 6 and 9 mm. Knowing that the plate width is 50 mm, the ratios between these crack lengths and the plate width (a_o/W) are: 0.06, 0.12, and 0.18. Figure 3 presents the fatigue life of repaired structures for different initial crack lengths of patching for 2024-T3. It can be seen that the repair efficiency depends strongly on the length of the initial crack. The fatigue life of the plate increases for small crack lengths.

It is observed that for an initial crack length of 3 mm, the fatigue life is 371,780 cycles at R = 0.1, which is 4.5 times more than the unrepaired specimen. For a_o = 6 mm (a_o/W = 0.12), the fatigue life was increased about 4.3 times. However, for an initial crack length of 9 mm (a_o/W = 0.18), the fatigue life has increased to less than three folds of unrepaired configuration. Also, it is noted that as the crack length increases, the fatigue life is decreasing asymptotically. This behavior will help designers to predict the approximate fatigue life of repaired structures with different initial crack lengths. Therefore, it is recommended, from the investigations that the crack must be repaired as soon as it is detected. An initial crack length of 3 mm has been adapted in the further investigations to study the effect of patch thickness.

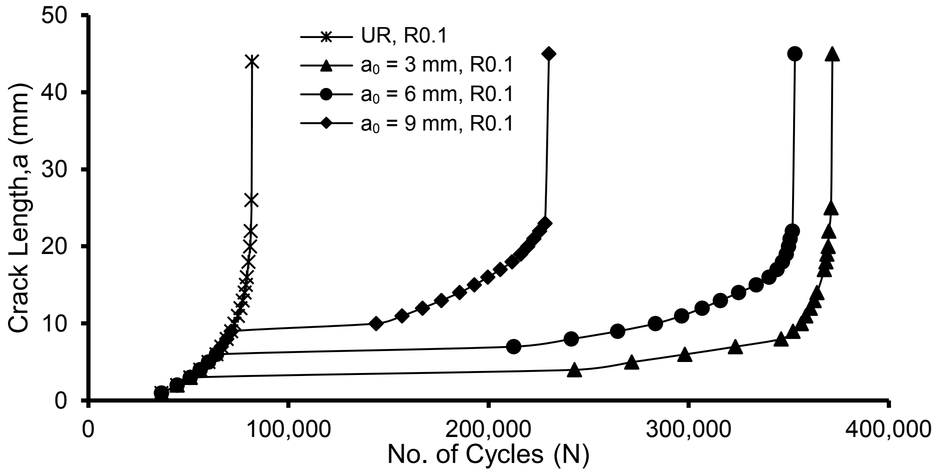
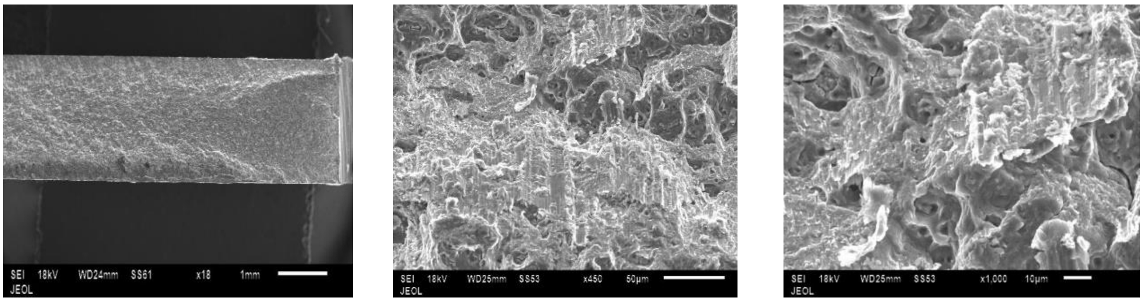


Figure 3: Initial crack length effect on fatigue life of repaired and unrepaired specimen for stress ratios R0 and R0.1

3.3 Microscopic Observation

Microscopic investigation is carried out on failed specimens of both repaired and unrepaired, to understand the fatigue crack growth and the fracture mechanisms involved and fractured surfaces obtained in both cases. The crack front growth is large in case of thick plates however, in thin plates also, the crack front is considerable. The experimental crack front shape is found to be elliptical, whereas in case of unrepaired specimen, is straight and perpendicular to thickness direction. This is found to be similar and in good agreement with the results found and reported in literature (Seo and Lee, 2002).

The fatigue crack growth behavior of repaired and unrepaired aluminum specimen can be explained by scrutinising the microstructure and the dominant ductile and brittle behavior involved. It becomes quite important to study the microstructure of both repaired and unrepaired specimen. The surface examination reveals the presence of both ductile and brittle fracture, Figure 4. The detailed examination at higher magnification, using SEM technique, shows the presence of voids, micro and macro dimples as well as ductile fracture in Figure 4(b) and 4(c) for unrepaired specimen. However, the initial crack region is shown in Figure 4(a).



(a) (b) (c)

Figure 4: SEM pictures of fractured specimen (a) Initial crack region; (b) Facets; (c) Voids

4. Conclusions

The main purpose of this study has been the determination of the repair efficiency of bonded composite patches in cracked thin aluminum 2024-T3 plates. The repair is realised by patching only one side of the panel in order to reduce the associated material, costs and time required. In most of the cases, the other side of the panels is not easily accessible. Moreover, this type of repair might be applied locally without the need of disassembling a complex structure. Experiments were carried out to study the fatigue behavior of 2 mm thin SENT specimens repaired with unidirectional carbon/epoxy patch using adhesive. The comparison of fatigue life of repaired and unrepaired specimen have shown significant improvement in fatigue life after repair. The failure was observed in adhesive and aluminum samples. No delamination of fibers was observed during the tests. The main conclusions drawn from this study are:

- Reinforcement of patch on cracked Al 2024-T3 thin plates increases the fatigue life by about 4.5 times, which is also dependent on initial crack length.
- The improvement in fatigue life is significant for small cracks. Hence, the crack should be repaired as soon as it is detected.
- Patch thickness has significant effect on fatigue life of repaired specimen. The improvement in fatigue life of specimen repaired with 4, 6 and 8 plies was about 20.2 %, 41.7 % and 193.4 %. This behavior will help designers to predict the approximate fatigue life of repaired structures.
- Fatigue crack growth rates (FCGR) were higher for unrepaired specimen.
- The ductile and brittle fracture behaviors are affected by the bonded composite repair. The repaired specimen tends to display more brittle behavior.

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