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Fatigue Behavior of Cracked Al 6061-T6 Alloy Structures Repaired with Composite Patch

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ABSTRACT

Due to the development of high-strength fibers and adhesives, it is now possible to repair cracked metallic plates by bonding reinforced patches to the plate over the crack. In this study, pre-cracked aluminum 6061-T6 alloy plates repaired with bonded carbon/epoxy composite patch are applied to investigate the effect of various patch shapes on the tensile strength and the fatigue behavior of the structure. A non-patch-bonded case and 2 types –50×50, 40×20 mm– composite patch-bonded cases were tested to obtain fracture loads and fatigue crack growth rate. The results showed that the patch-bonded repair improves the static strength by 17% and the fatigue life by 200% compared to non-repaired case. It means that patch-bonded repair is more effective in the fatigue life. It was also revealed that the patching method along crack growth direction is more efficient in cost and weight reduction. By observing the fractography, patch-bonded repair specimens demonstrated zigzag fracture patterns compared with the non-patched specimens, which shows a typical ductile fracture.

Key Words: Composite patch-bonded repair, Aluminum 6061-T6 alloy, Fatigue life, Crack growth rate, Fractograph

1. Introduction

Aluminum alloys are widely used as structures, because these mechanical structures are lightweight, strong and low priced. Additionally, aluminum alloys have equal toughness values at even very low temperatures. Hence, for aircrafts exposed to various cruise conditions, very low temperatures in supersonic flight, and high temperatures in ground parking, aluminum alloys are good structural materials and are suggested as suitable materials. Therefore, engineers tend to focus on the repair and reinforcement of these structures.

Recently, as a reinforcement technique for the aging aircraft, composite patch-bonded repair methods were suggested to industrial engineers. These bonded joints do not have any of the problems that appear in mechanical joints; obviously weakness and stress concentrations around machining holes. In general, because of no additional defect, many engineers recommend bonded-joints.

The application of an adhesively bonded composite patch to repair cracked metallic structures is a desirable procedure since it provides a high structural efficiency and extends the life of a flawed structural component at an economical cost. A bonded composite patch reduces the stress intensity factor by bridging the stresses between the cracked plate and the composite patch. Furthermore, a bonded composite patch reduces the stress field in the vicinity of the crack leading to retardation in the crack growth and improves the fatigue life. In addition, bonded composite patches have the inherent advantage of a high stiffness and strength to weight ratio. Therefore, composite patches have been gaining more and more acceptance since their development in the late 1960's.

In recent years, many researchers have studied different aspects of repair with bonded composite patches. For instance, Baker and Jones conducted experimental and analytical studies to investigate the fatigue life propagation of centrally cracked aluminum panels patched with boron/epoxy composites1).

Naboulsi and Mall analyzed the fatigue crack growth of adhesively repaired panel with perfectly and imperfectly bonded composite patch using three layer FEM model2). Denny and Mall investigated the characterization of disbond effects on fatigue crack growth behavior in aluminum plate with bonded composite patch3). However, until now there were no observations of the aluminum 6061-T6 alloy as a patch-bonded structure. Inspections for the fractography of the composite patch-bonded specimen after a fatigue test have not yet been completed.

The present paper describes an experimental evaluation of the tensile and fatigue response of various types of patch-repaired specimens with a central hole crack. It also presents a comparison of non-repaired specimens with patch-repaired specimens. Moreover, the effect of surface treatment and patch size in patch-repaired specimens is demonstrated by fatigue test results.

2. Preparation of specimens and experiments

2.1 Materials

2.1.1 Structural and Patch Materials

6061aluminum alloy plate demonstrating both anticorrosive qualities and strength were selected as a specimen. The chemical compositions of this Al 6061-T6 alloy are Mg (1.00%), Si (0.60%), Mn (0.28%), Cr (0.20%), Fe (0.05%) and Aluminum. Modulus of elasticity (E) and Poisson's ratio (v) are 60 GPa and 0.33, respectively.

Carbon/Epoxy composites are used as patch materials. All composite patches are manufactured with unidirectional (along the load direction) 6 ply prepregs, and the thickness of each patch is approximately 0.48mm. Patches were rectangular in shape and pre-cured using autoclave, before bonding to the specimen (Maximum temperature: 121°C). Two types of patch, 50x50 and 40x20 mm, were cut using a diamond cutting machine. Moduli of elasticity (E_1, E_2) were 130 and 12 GPa, respectively. Poisson's ratio (v) was 0.33.

2.1.2 Adhesive films

FM73 Adhesive Film (American Cyanmi Co.) was applied to stick to each of the materials. Its mechanical properties are offered by the technical order of manufacture; modulus of elasticity, 1.0713 GPa, and Poison's ratio, 0.32.

2.2 Specimen preparation

2.2.1 Specimen shapes

Tensile and fatigue specimens were cut using a wire-cutting machine as described in ASTM B 557-94 [4]. Specimens were produced with a 0.8mm thickness, 240mm length and 100mm width. The gauge length of the specimen was 50mm. A 10mm diameter hole and a starter notch were created in the center of the specimen using the same machine. The starter notch initially measured 2mm long to serve as a starter crack in the specimen. The dimensions of the specimen and notches are shown in Fig.1 (left-below).

2.2.2 Specimen treatments[5]

To remove gross contamination together with powdery or loosely adhering oxide and achieve successful joining, specimen treatments were performed in detail.

First of all, degrease the aluminum surfaces with Acetone (CH_3COCH_3) and sulfuric chromic acid etching with an etching solution: 1*ℓ* water, 125*mℓ* sulfuric acid (H_2SO_4), and 20g sodium dichromate ($Na_2Cr_2O_7.2H_2O$) by depositing aluminum specimens in the solution at 60°C~ 65°C for 30minutes. Clean the surface with water. After completing the previous process, anodize the specimen with 10wt% phosphoric acid (H_3PO_4) solution of 20°C under 10volts for 20minutes. Finally, clean the specimen with water again.

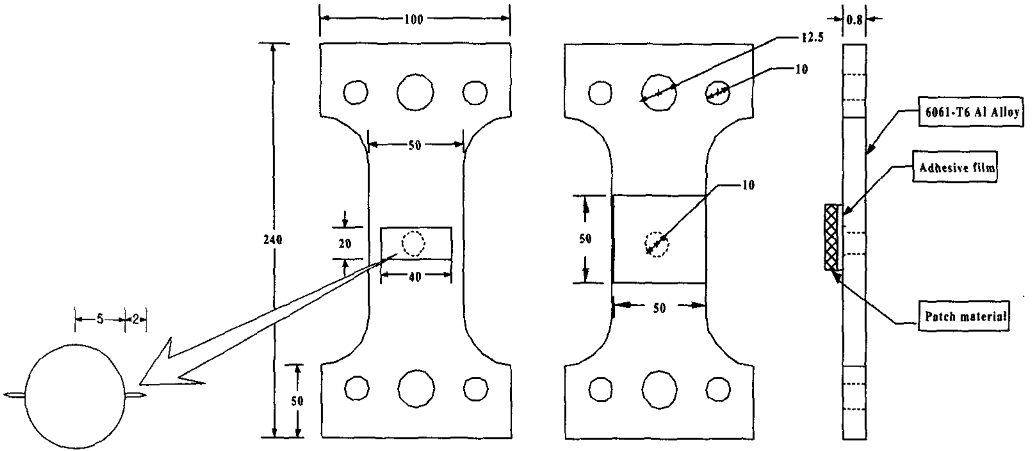
2.2.3 Specimen manufacturing

An adhesive film was put between the chemical etched aluminum plate and the patch material, and then formed at 120°C for 1hr at a pressure of 0.28±0.03Mpa using a hot press machine.

Fig.1 also shows the patch-bonded specimens. The patch sizes are 40x20mm, 50x50mm, respectively. The shapes of the bond-repaired specimen are the same as Fig.1. Yoon[6] shows the specimen in detail. In addition, 50x50mm specimens with no surface treatment are added to investigate the effect of surface treatment on the fatigue life.

2.3 Tensile Test

A new type of grip to prevent a slip and bearing failure is designed for the test of tensile strength.[7] A hydraulic actuator-driven 25KN capacity universal test



(a) Patch size (40x20) (b) Patch size (50x50) (c) Side view

Fig. 1 Specimen Configuration and notch details.

machine (INSTRON 8872) is used for tensile testing. Tests were conducted at displacement-control modes at room temperature with the crosshead speed fixed at 0.03mm/sec. This process was continued until specimen failure.

2.4 Fatigue Test [8)]

During the fatigue tests, a uniformly distributed stress in loading direction was applied with cyclic frequency, 8Hz, and stress ratio, R=0.1. Crack lengths (on the unpatched face of the repaired plate) of fatigue cycles were measured using a traveling telemicroscope, which is able to measure the crack length by 1/100mm.

The maximum stress was determined to be less than 30% of the maximum tensile strength of the non-patched specimen, which was acquired from the previous static tensile test. The method for measuring crack length is as follows. First, the pre-crack was created with 0.5mm from the crack notch tip under 25% of the maximum tensile load (amplitude: 958 N, set point: 1170 N). The next test began with a crack length of 7.5mm under 20% of the maximum tensile load (amplitude: 766 N, set point: 936 N). The measurement of crack length was conducted at the region where the fatigue crack was propagated vertically to the load axis.

3. Results and discussion

3.1 Effects of patch shapes on tensile strength

Fig.2 and Table 1 show the results of the tensile test. The effect of patch is computed on the basis of the ratio of patched specimens to an unpatched specimen.

In case of static tensile tests, full-patched specimen was the highest in the strength. For example, there is the maximum fracture load in 50x50mm patch repair, but there is a marginal effect in 40x20mm patch repair. This confirms that a larger area patch is more effective to control crack growth by distributing load uniformly. From the table 1, the effect of patch also was large in fully patched specimen.

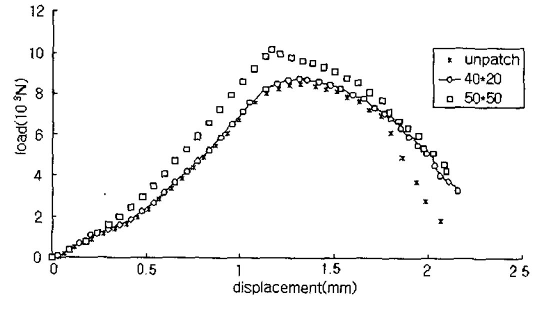


Fig. 2 Comparison of tensile strength.

Table 1 Result of maximum tensile load.

Patch type	Maximum tensile load (N)	Effect of patch (%)
unpatch	8465	-
40x20mm	8718	3
50x50mm	10160	17

3.2 Effects of patch shape on fatigue life

Fatigue crack growth rate (da/dN) is sensitive to temperature, frequency and stress ratio in test. In this study, the same frequency and stress ratio were adapted to find the effect of patch shapes on fatigue life. Fatigue life was determined by the number of cycles to fracture.

Experimental results of fatigue crack growth versus fatigue cycle for different cases are shown in Fig. 3. The indication [] of [50*50] means the specimens without surface treatment. Fig. 3 shows the effectiveness of the adhesively bonded patches either 40x20 or 50x50 in retarding the crack growth and extending the fatigue life several times when compared with unpatched case. Fig.3 also shows the effect of surface treatment on fatigue life. As shown in Fig.3, the fatigue life of unpatched specimens is 140,000 cycles while [50*50], 40x20 and 50x50 patch specimens are 260,000, 440,000 and 450,000 cycles respectively. In the case of 50x50 patch-bonded specimens, the fatigue life is increased 70% compared with non-surface treatment specimen. It means that the surface treatment for the aluminum structure affects hugely the patch-bonded structure in the fatigue strength.

In tensile strength, 50x50mm patch repair is more effective than 40x20mm patch repair. However, there is practically no difference of fatigue life between 50x50mm patch repair and 40x20mm patch repair. It can be concluded that the patch bond repair along the crack propagation has a strong effect on the extension of fatigue life. Table 2 summarizes the increase in fatigue life of each repaired specimen.

Fig.4 shows the fatigue crack growth rate in terms of crack length. An insertion of Fig.4 shows fatigue crack growth rate of the patch-bonded specimens in detail. Unpatched specimen (*, unpatch) and non-treatment patch-bonded specimen (△, [50x50]) were fast in crack growth from the beginning. Crack growth rate of patch repair with surface treatment is slower than unpatched specimens and non-surface treatment specimens. Table 3 shows linear fits for the crack growth rate of each patch configurations. Form the results, the gradient of the unpatched specimen was steepest and the gradient of surface treatment patched specimens was gentler. However, non-surface treatment patched specimen was sharper than the treatment specimens.

From the results of Fig.3 and Fig.4, it can be assumed that patch repair along the direction of the crack progression is more efficient in cost and weight reduction. For strength and remaining lives, it is also very important to maintain and develop proper surface treatment skills

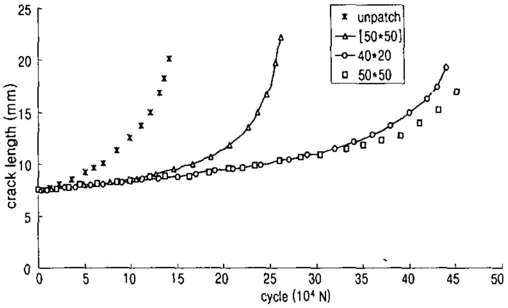


Fig. 3 Crack length vs. fatigue cycles.

Table 2 Summary of fatigue life.

Patch type		Fatigue life (cycle)	Effect of Patch(%)	Effect of Surface Treatment (%)
Unpatched		141,328	-	-
Patched	40*20	440,059	211	-
	50*50	451,435	219	72
	[50*50]	261,601	85	

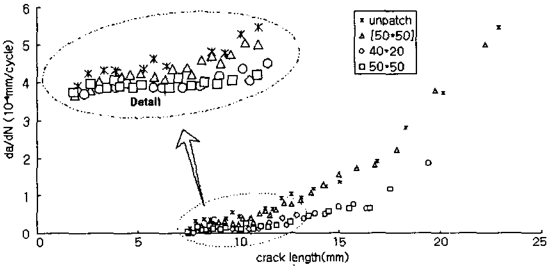


Fig. 4 Fatigue crack growth rate.

Table 3 Summary of crack growth rate (linear fit).

Patch type		Linear fit $da/dN=ma+n$	
		$m\ (10^{-6})$	$n\ (10^{-5})$
Unpatched		20	10
Patched	40*20	5	3
	50*50	4	2
	[50*50]	9	6

§ ***a*** :crack length of the specimen

3.3 Discussion for the experimental results

From the previous results, it is confirmed that the patch repair is effective in reinforcing the specimens with a crack. And it is essential for the surface treatment of the specimen before the patch repair. And it is also revealed that the patch repair is effectual in the fatigue life of the specimens. Additionally, 40×20 patch bonded specimens have similar fatigue lives compared with 50×50 patch bonded specimens

3.4 Fractography

The fracture behavior was observed by SEM in unpatched and patch-bonded repairs.[9] Fig.5 – Fig.7 show the fatigue crack surfaces for the unpatched and patch-bonded repairs, respectively.

Fig.5 shows the fatigue fracture surface of the unpatched specimen. Fig.5 (a) exhibits the flow of crack propagations at the magnification of 100 for the fatigue specimen. The white slender arrows indicate the direction of crack growth. Cracks progress in the center of the fracture surface. Fig.5 (b) and (c) reveal specific areas in a magnification of 200 on the fracture surface. Bold black arrows in Fig.5 (c) indicate dimples on the fracture surface. Prolific dimple shape means that the ductile fracture mode were discovered in these specimens.

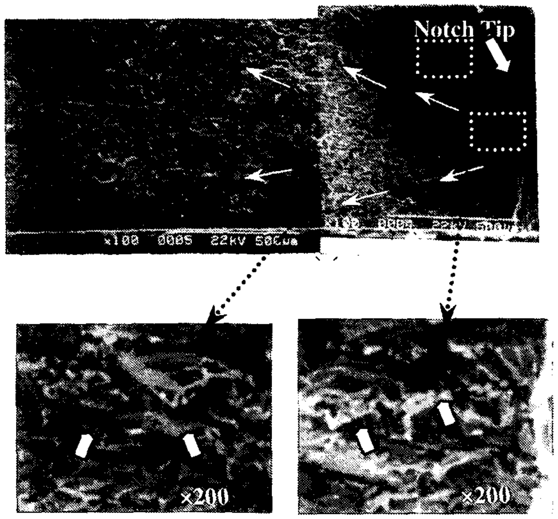


Fig. 6 Fatigue fracture surface of 40×20mm patch specimen. (a) Fatigue fracture of the specimen. (b)(c) Higher-magnification view of the secondary cracks and steps, shown in (a).

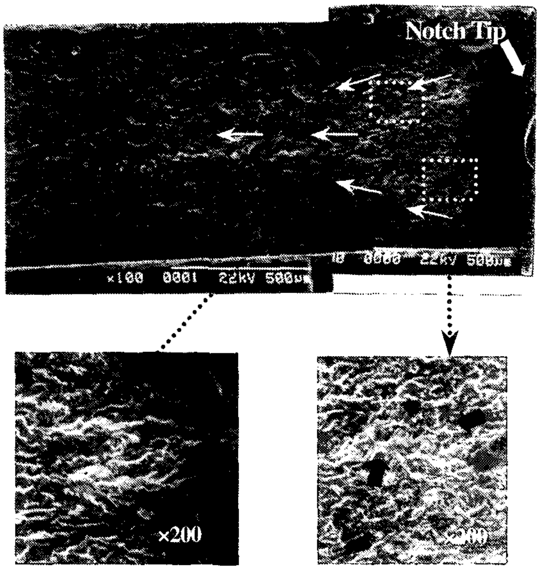


Fig. 5 Fatigue fracture surface of unpatched specimen. (a) Fatigue fracture of the specimen. (b)(c) Higher-magnification view of the elongated dimples shown in (a).

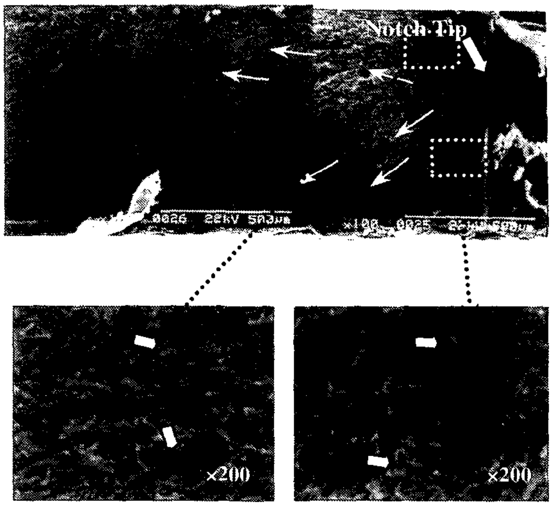


Fig. 7 Fatigue fracture surface of 50×50mm patch specimen. (a) Fatigue fracture of the specimen. (b)(c) Higher-magnification view of the secondary cracks and steps, shown in (a).

Figs. 6 and 7 show the fatigue fracture surfaces of the 40x20 and 50x50 patch bonded specimens, respectively. Slender white arrows indicate the direction of the crack propagations. The cracks progress dispersedly. In both figures, (b) and (c) are higher-magnification views of the fracture surface.

Even aluminum alloy is a ductile material typically having dimples on the fracture surface, the fracture surfaces of patch-reinforced specimens show zigzag and secondary crack patterns. And it was shown that branching and secondary cracks make the crack progress slow by divergence of the fatigue load.

4. Conclusions

The tensile strength and the fatigue crack growth behavior of the aluminum 6061-T6 alloy plate repaired with adhesively bonded carbon/epoxy composite patch were investigated. Two types of patch shape were studied. Unrepaired specimen and non-surface treatment specimen were also tested for the comparison. The following conclusions can be made based on the results of this study.

1) The patch repair of the cracked aluminum plates improved their static strength by 17%. However, the repair extended their fatigue lives by 200% compared to non-repaired case. It is clear that the patch-bonded repairs have a strong effect on the endurance of the structure.

2) Fatigue life of (40× 20mm) patch-bonded specimen are nearly the same as that of (50× 50mm) patch-bonded specimen. Consequently, the patching method along the crack growth direction is effective for the extension of fatigue life.

3) It was also confirmed that proper surface treatment skills should need to improve the fatigue life in the patch-bonded specimens.

4) The fracture patterns of the patch-bonded specimen showed secondary cracks and zigzag patterns, while the non-patched specimens show a typical dimple shape of ductile fracture pattern.

Acknowledgement

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