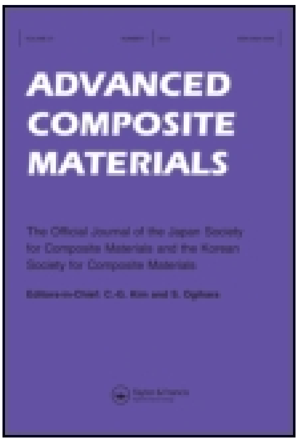

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Experimental study of repair efficiency for single-sided composite patches bonded to aircraft structural panels

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Abstract—Fatigue response of cracked aluminum panels repaired with a single-sided composite patch is examined. Fatigue tests were carried out under various temperature and humidity conditions. From the experimental results of fatigue tests, the repair efficiency for single-sided composite patches bonded to cracked aluminum panels is evaluated using the range of stress intensity at crack tip. The effect of temperature on the repair efficiency can be found by comparing the results of crack growth at 353 K, 300 K and 223 K. Likewise, the effect of humidity on their repair efficiency can be found by comparing the results of crack growth at 90%, 50% and 25% relative humidity. Other factors that reduce the repair efficiency are also discussed.

Keywords: Patch repair; composite patch; cracked aluminum panel; repair efficiency; stress intensity range; environmental condition.

1. INTRODUCTION

In the repair of aging aircraft structures, crack patching using high strength composite materials is a simple and effective repair method for damaged components such as cracked aluminum panels in fuselages and wings. The composite patches

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bonded to cracked aluminum panels increase the damage tolerance and extend their fatigue lives by slowing crack growth.

This simple and highly effective repair method has received wide attention and it becomes a major concern to evaluate the repair efficiency for the design of composite patches. Baker [1] showed experimentally and analytically that the repair efficiency is reduced by significant cyclic disbonding in the bondline of the single-sided bonded patch repair. Denny and Mall [2] experimentally examined the effect of disbond locations and size in bonded reinforcement. Sun *et al.* [3] developed a finite element method for analyzing the stress intensity factor of cracked panels repaired with a single-sided composite patch and investigated the interfacial disbond growth. The thermal effect on adhesively bonded composite repair was taken into consideration in the finite element analysis [4, 5].

It is important to clarify the effects of temperature and humidity on repair efficiency because the repaired aircraft structural panels are exposed to severe environmental conditions in the actual flight. This paper describes the results of fatigue tests for cracked aluminum panels repaired with a single-sided composite patch under various temperature and humidity conditions. From the experimental results, the repair efficiency is evaluated and the effects of temperature and humidity on repair efficiency are discussed.

The repair efficiency for single-sided composite patches bonded to cracked aluminum panels is evaluated using the range of stress intensity at the fatigue crack tip. In this study, the stress intensity range of repaired aluminum panels is calculated on the assumption that the relationship between stress intensity factor range ΔK and crack growth rate $\mathrm{d}a/\mathrm{d}N$ for repaired aluminum panels obeys the Paris relation of unrepaired aluminum panels. The Paris relation of unrepaired aluminum panels is shown as follows:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^n, \tag{1}$$

where C and n are the material constants of unrepaired aluminum panels. Using the Paris relation with the data of $\mathrm{d}a/\mathrm{d}N$, the ΔK is calculated as follows:

$$\Delta K = \left(\frac{1}{C}\frac{\mathrm{d}a}{\mathrm{d}N}\right)^{1/n}. \tag{2}$$

The repair efficiency RE on stress intensity range ΔK is defined as:

$$RE = 1 - \frac{\Delta K_\mathrm{p}}{\Delta K_\mathrm{u}}, \tag{3}$$

where ΔK_p and ΔK_u denote the stress intensity ranges for patched and unpatched specimens.

2. TEST SPECIMENS AND EXPERIMENTAL PROCEDURE

2.1. Materials and test specimens

The specimens used in this study were designed to simulate the repair of aging aircraft structural panels. The geometry of the specimen is schematically shown in Fig. 1. 2024-T3 and 7075-T6 aluminum panels are used in the fatigue tests under temperature and humidity conditions, respectively. Rectangular aluminum panels were pre-cracked before patching. The pre-crack perpendicular to the longitudinal direction is located in the center of the panel. The length, width and thickness of the panel are $L = 248$ mm, $W = 118$ mm and $t_{\mathrm{Al}} = 2$ mm, respectively, and the nominal length of pre-crack is $2a = 25$ mm. Circular composite patches made of glass/epoxy composite (Cytec Industries Inc.) are completely bonded to one side of the cracked aluminum panel over the pre-crack by using an adhesive film of AF-163-2K (3M Inc.) in the standard bonding process. The laminate configuration of the composite patches is $[0°/0°/0°/\pm45°/0°/0°]_{\mathrm{S}}$ where the fiber direction of 0° is parallel to the longitudinal direction of the panel. The circumference of the patch is tapered to reduce peel stresses at the edge. The diameter and thickness of the patch are $D = 50$ mm and $t_{\mathrm{p}} = 3.2$ mm. This thickness of the patch was designed according to the stiffness ratio, $E_{\mathrm{p}}t_{\mathrm{p}}/E_{\mathrm{Al}}t_{\mathrm{Al}}$, equal to 1.1, where E_{p} and E_{Al} denote the Young's moduli of the composite patch and the aluminum panel, respectively.

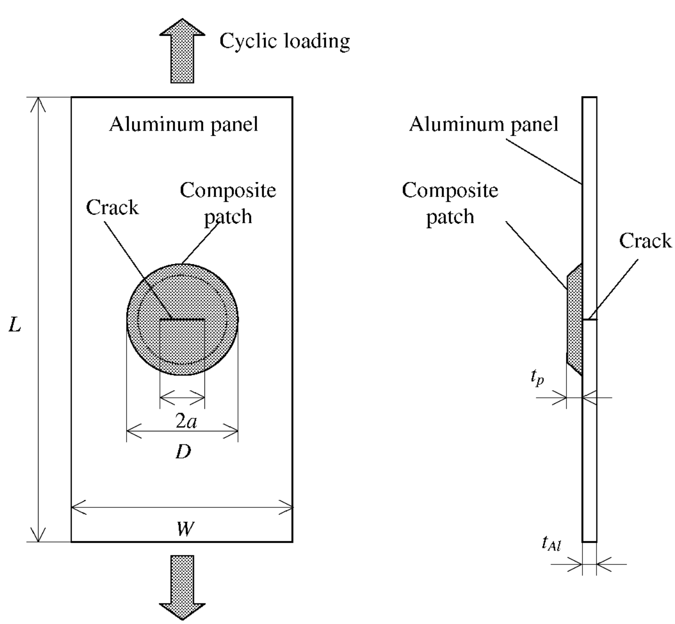

Figure 1. Cracked aluminum panel repaired with a single-sided composite patch.

2.2. Experimental procedure

Fatigue tests were carried out using a servohydraulic fatigue testing machine. A specimen was set up in a chamber with a temperature and humidity controller and temperature and humidity conditions were strictly controlled during the fatigue tests. The cracked 2024-T3 aluminum panels repaired with a single-sided composite patch were kept at 353 K (80°C), 300 K (27°C) and 223 K (−50°C) in their natural humidity. For comparison, the cracked 7075-T6 aluminum panels repaired with a single-sided composite patch were kept in 90%, 50% and 25% relative humidity at 298 K (25°C). Before the fatigue tests, specimens had been kept in those humidity conditions for 15 days in the chamber and the fatigue tests were conducted successively under the same environmental conditions.

The specimens are subjected to a constant amplitude cyclic loading in the longitudinal direction as shown in Fig. 1. A sinusoidal loading with a 79.4 MPa peak stress, a stress ratio of 0.25 and a cycle frequency of 0.5 Hz is applied. Crack length is measured from the reverse side of the patched specimen using a traveling microscope. When the crack length was over 60 mm, the experiment was terminated.

3. RESULTS AND DISCUSSION

3.1. Effect of temperature

The results of fatigue tests for cracked 2024-T3 aluminum panels repaired with a single-sided composite patch under different temperature conditions are shown in Fig. 2. The crack length for patched specimens was measured at intervals of between 1050 and 2140 cycles. Only data obtained at intervals of between 6170 and 6604 cycles are shown in the figure. After the fatigue test, the evidence of

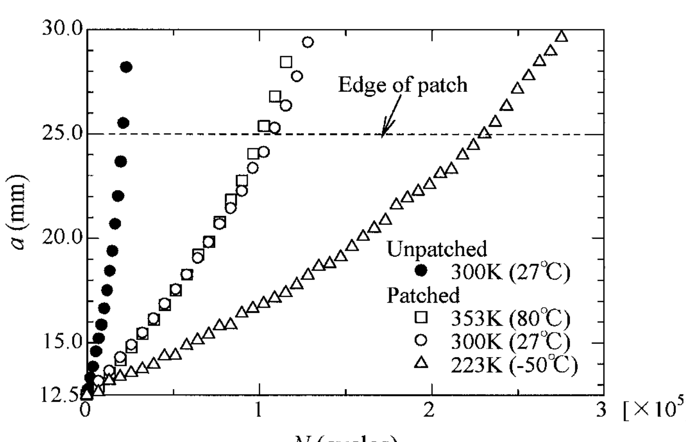

Figure 2. Crack length *versus* fatigue cycles in repaired 2024-T3 aluminum panels under temperature conditions.

disbond growth at the patch-panel interface along the fatigue crack was observed for each patched specimen. The repair effect of the patch is recognized in retarding crack growth compared with the unpatched specimen. Comparison of the results under temperature conditions indicates that there was a significant thermal effect on the crack growth behavior.

The relationship between crack growth rate $\mathrm{d}a/\mathrm{d}N$ and crack length a is shown in Fig. 3. The crack growth rates are obtained by means of the seven point ASTM method [6] using the experimental data in Fig. 2. To express the global relationship between $\mathrm{d}a/\mathrm{d}N$ and a, the crack growth rates are fitted with a quadratic curve, i.e. $\mathrm{d}a/\mathrm{d}N = A_1a^2 + A_2a + A_3$, by the method of least squares. The crack growth rates for patched specimens are drastically reduced compared with those for the unpatched specimen. Those results also indicate the dependence of temperature on crack growth rate. The crack growth rates at high temperature are larger than those at low temperature.

The repair efficiency *RE* under temperature conditions is shown in Fig. 4. The values of *RE* under temperature conditions were obtained using the data of $\mathrm{d}a/\mathrm{d}N$ on the quadratic curves shown in Fig. 3 through the Paris relation. The values of C and n in the Paris relation are $(C, n) = (3.64 \times 10^{-8}, 3.73)$, $(7.15 \times 10^{-9}, 4.28)$ and $(1.69 \times 10^{-10}, 5.54)$ at 353 K, 300 K and 223 K, respectively. These values were obtained from the experimental data of cracked 2024-T3 aluminum panels in Ref. [7]. By comparing the values of *RE*, the effect of temperature on repair efficiency is clarified. The repair efficiency at high temperature is greater than that

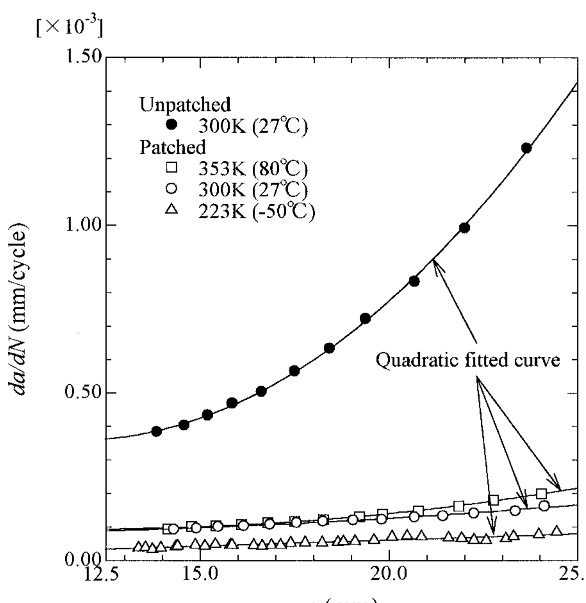

Figure 3. Crack growth rate *versus* crack length in repaired 2024-T3 aluminum panels under temperature conditions.

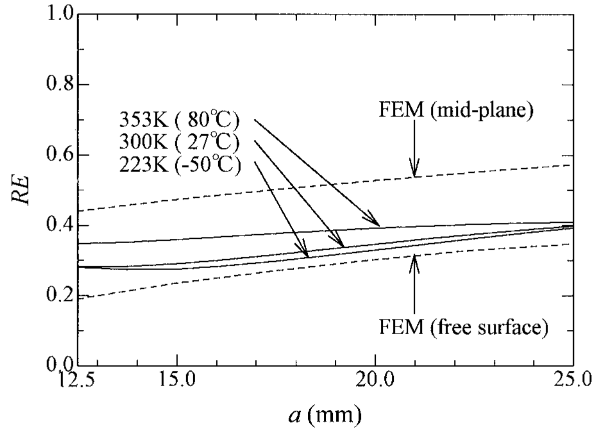

Figure 4. Repair efficiency in repaired 2024-T3 aluminum panels under temperature conditions.

at low temperature. In Fig. 4, the repair efficiency obtained by the finite element method with Mindlin plate elements [8] is also shown. Two broken lines show the values of *RE* at the mid-plane and free surface of the cracked panel repaired with a completely bonded patch. Compared with the numerical *RE* at the mid-plane, the experimental *RE* under each temperature condition has a lower value and shows the reduction in repair efficiency. The out-of-plane bending of the panel and the disbond growth with the extension of crack length may cause this reduction. The reduction due to the disbond growth is not clear because the reduction due to the out-of-plane bending is overestimated in this numerical analysis.

3.2. *Effect of humidity*

Figure 5 shows the results of fatigue tests for cracked 7075-T6 aluminum panels repaired with a single-sided composite patch under humidity conditions. The crack length for patched specimens was measured at intervals of between 730 and 1062 cycles and the data at intervals of between 2400 and 2885 cycles are shown in the figure. Although evidence of disbond growth along the fatigue crack was observed for each patched specimen, all patched specimens exhibited a significant repair effect in retarding crack growth comparing the unpatched specimen. By comparing the results under humidity conditions, it may be seen that the crack growth at high humidity is faster than that at low humidity.

Figure 6 shows a plot of crack growth rate $\mathrm{d}a/\mathrm{d}N$ *versus* crack length a. The crack growth rates are obtained by means of the seven point ASTM method [6] using the experimental data shown in Fig. 5. To express the global relationship between $\mathrm{d}a/\mathrm{d}N$ and a, the crack growth rates are fitted with a quadratic curve, i.e. $\mathrm{d}a/\mathrm{d}N = A_1a^2 + A_2a + A_3$, by the method of least squares. The repair effect is clearly shown by a comparison of the crack growth rates for the unpatched and the patched specimens. Moreover, it is evident that the crack growth rates under humidity conditions are significantly influenced by moisture absorption into

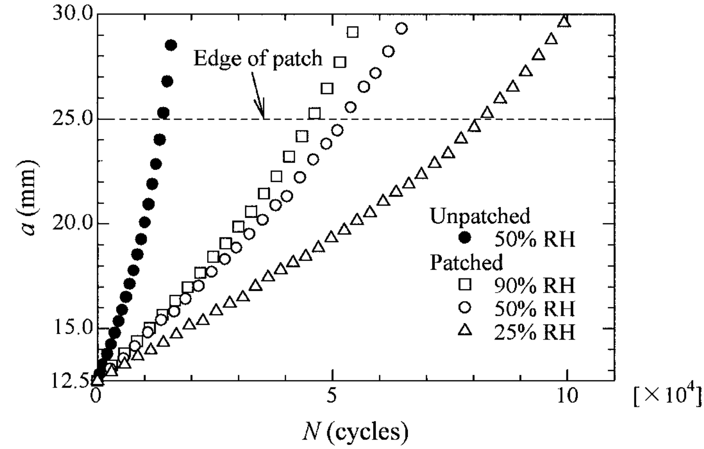

Figure 5. Crack length *versus* fatigue cycles in repaired 7075-T6 aluminum panels under humidity conditions.

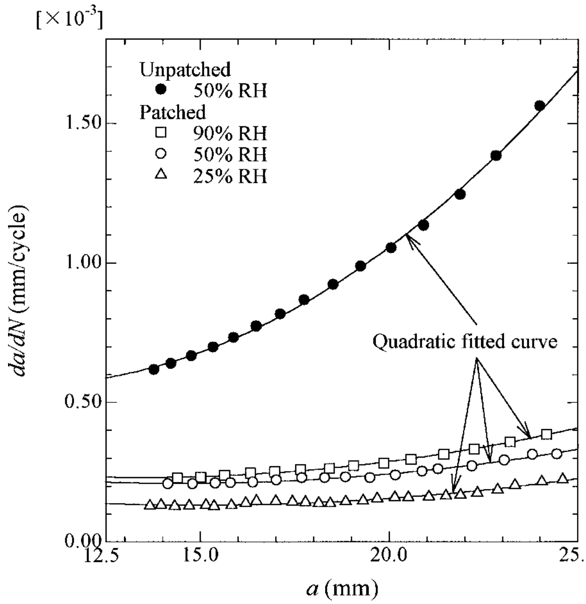

Figure 6. Crack growth rate *versus* crack length in repaired 7075-T6 aluminum panels under humidity conditions.

the patch. For example, the crack growth rates for the specimen in 90% relative humidity are greater than those in 25% relative humidity.

Figure 7 shows the repair efficiency RE under humidity conditions. The values of RE under humidity conditions were obtained using the data of $\mathrm{d}a/\mathrm{d}N$ on the quadratic curves shown in Fig. 6 through the Paris relation. As the values of C and n in the Paris relation, $(C, n) = (3.13 \times 10^{-7}, 2.94)$ are used, which are obtained from the experimental results of the unpatched specimen. Comparison of the values

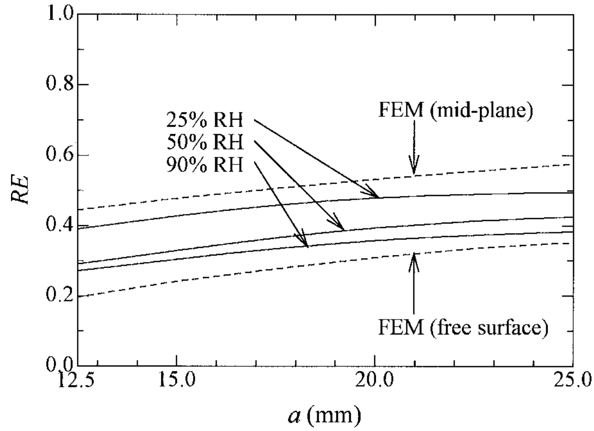

Figure 7. Repair efficiency in repaired 7075-T6 aluminum panels under humidity conditions.

of *RE* shows the effect of humidity on the repair efficiency. The repair efficiency at low humidity is larger than that at high humidity. In Fig. 7, the repair efficiency obtained by the finite element method with Mindlin plate elements [8] is also shown. Two broken lines indicate the values of *RE* at the mid-plane and free surface of the cracked panel repaired with a completely bonded composite patch. Compared with the numerical *RE* at the mid-plane, the experimental *RE* under each humidity condition has a lower value. This mismatch may be caused by the reduction of repair efficiency due to the out-of-plane bending of the panel and disbond growth.

4. CONCLUSIONS

By comparing the results of crack growth at 353 K, 300 K and 223 K, it is found that the greatest reduction of repair efficiency appears at the low temperature 223 K. Likewise, comparison of the results of crack growth at 90%, 50% and 25% relative humidity indicates that the greatest reduction of repair efficiency occurs at the high humidity 90% relative humidity. Moreover, a reduction of repair efficiency due to the out-of-plane bending of the aluminum panel and disbond growth during the fatigue tests is also observed.

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