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REDUCTION OF RESIDUAL STRESSES IN COMPOSITE PATCH

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SUMMARY: Composite patching technique is widely used in aircraft to extend the fatigue life effectively with low repair cost. Composite patch repair has advantages to the conventional rivet repair method. It is cost-effective, reliable, and has high strength and longer fatigue life. One of the hot issues in composite patching is to reduce the thermal residual stresses between composite patch and aluminum surface which occurs after bonding of composite patch. In this paper, one of the way which can reduce the thermal residual stress is shown. The static strength and fatigue life are measured by experiments. For this study, the edge crack patching and center crack patching cases are adopted for different curing cycles. The ultrasonic C-scan method is used to detect the crack propagation and debonding area of the specimen. For the analysis, three layer Mindlin plate elements are used, and Paris' law is adopted to predict the fatigue life of composite patch specimen. The experimental and analysis results for fatigue life show good agreement. The thermal residual stresses are calculated by FEM, and higher curing temperature shows higher thermal residual stresses.

KEYWORDS: composite patch, thermal residual stress, thermal mismatch, fatigue life, debonding area, three layer technique, patch strength.

INTRODUCTION

Composite patching technique is widely used in aircraft to extend the fatigue life with low repair cost[1,2]. Composite patch repair has advantages to the conventional rivet repair method. It is cost-effective and reliable, and has high strength and longer fatigue life. In rivet repair, a number of rivet holes are drilled which increases repair cost. Around these holes, the secondary cracks may initiate and propagate leading to corrosion, and the situation goes worse and worse. In composite repair, it is easy to repair the cracks and is cost-effective. It can also remove the secondary crack propagation and corrosion problem by sealing the cracked surface, and more reliable repair can be obtained. One of the hot issues in composite patching is to reduce the thermal residual stresses between composite patch and aluminum surface which occurs after bonding of composite patch. In this paper, one of the way which can reduce the thermal residual stress is shown. The static strength and fatigue life are measured by experiments and those are compared with the results by finite element analysis.
The edge crack and center crack patching cases are studied for different curing cycles. The ultrasonic C-scan method is used to detect the crack propagation and debonding area of the specimen. For the analysis, three layer Mindlin plate elements are used, and Paris' law is adopted to predict fatigue life of composite patch specimen. The most important and difficult point lies on the surface treatment of the bonding surfaces. Without proper procedure of surface treatment, a good bonding performance can not be expected. The effect of ill-conditioned surface treatment is also discussed. With these experimental and analytical results, more reliable composite repair technique is proposed, and application areas are discussed.

**EXPERIMENTAL PROCEDURES**

For the preparation of specimen, aluminum 2024-T3 plate was cut by water jet in appropriate size as in Fig. 1, and 13mm edge and center crack was also cut by water jet. The sharp crack was made by fatigue loading by Instron machine. For composite patch, four plies of unidirectional AS4/3501-6 was cured by autoclave and cut accordingly. The cracked aluminum plate and composite patch was bonded and cured using FM73 adhesive. The performance of patch strongly depends on the condition of surface treatment and caution should be made on this point[3]. To investigate the effects of curing cycles on the fatigue life, three different curing conditions, case A: 121°C(250°F)/1 hour, case B: 82 °C(180 °F)/4 hours and 104 °C(220 °F)/0.5 hour and, case C: 82 °C(180 °F)/8 hours, were selected. Fatigue tests are performed under 6Hz and zero stress ratio condition. The applied load is 25KN for edge crack case and 34KN for center crack case.

**EXPERIMENTAL RESULTS**

To measure the crack length, optical microscope is used. The static strength of patch specimen was increased about thirty percents compared with non-patch specimen, and the fatigue life of patch specimen was also increased four or five times compared with non-patch case as shown in Fig. 2. These show the effectiveness and possibility of composite patching technique in cracked panel. Among three different curing cycles, the case C, which has the lowest curing temperature, shows the longest fatigue life. This implies that the curing cycle, which can minimize the thermal residual stress, is best for the extension of fatigue life of patching structure. The lower the curing temperature, the longer the fatigue life is. If a stop hole is drilled at the crack tip and patched, the fatigue life is much more increased. The ultrasonic C-scan method is used to investigate the crack propagation and debonding area. If the bonding surface is not properly cleaned, the debonding area is increased and the fatigue life is also dramatically decreased.

**FINITE ELEMENT ANALYSIS**

**Fatigue Life**

For the prediction of fatigue life by finite element method, the Mindlin plate elements in ABAQUS are used in composite, adhesive, and aluminum layer, respectively. The half model
and three layer model are shown in Fig. 3 and Fig. 4, respectively. The used material property data are represented in Table 1. To combine these three layers, appropriate constraint equations are used between mid-surfaces and bonded-surface nodes. The effective temperature concept is used to apply the temperature loading conditions. To calculate the stress intensity factor, the modified crack closure method is adopted combining the strain energy release rate concept. As is well known, the single side patching produces out-of-plane bending effects, and the stress intensity factor should be modified to include the translation and rotation effects, which was used in Ref.[4,5]. When the patch is bonded on aluminum surface, the neutral plane of patch specimen no longer exists on the neutral plane of aluminum. And, therefore, the value of the stress intensity factor can be affected whether the stress is selected at mid surface or free surface of aluminum. To account for this effect, the root mean square value of stress intensity factor is also considered. For the prediction of fatigue life, Paris’ law is adopted and the three different stress intensity factors are used in this calculation. These results are compared with experimental result. The analysis results for edge crack are compared in Fig. 5, and the solid square(Nexp2) and the blank square(Nexp1) are experimental results of fatigue life for case B(higher temperature curing) and the case C(lower temperature curing), respectively. When the free surface stress is used in the calculation of stress intensity factor, the fatigue life is over-predicted(circles). If the mid-surface stress is used, the fatigue life is too much under-estimated(stars). The root mean square concept(triangles) is best compared with experimental results. For center crack case, the analysis procedure is the same as in edge crack case, and the results in Fig. 6 shows similar pattern as in edge crack case.

**Thermal Residual Stress**

To calculate the thermal residual stresses in patched panel, the plane strain condition is assumed. The thermal stress distributions for single and double side patch are presented in Fig. 7 and Fig. 8, respectively. As depicted in these figures, the single patch shows a rapid stress gradient through thickness producing bending, but the double patch has no bending by symmetry and the stress distribution is gradual. The peel stress in single patch is higher than that in double patch, and the shear deformation in adhesive layer of double patch is greater than that of single patch. The through-thickness thermal residual stress in the middle of single side patch is shown in Fig. 9, and the stress sign is changed through thickness. The composite patch is under compression and the aluminum is under tension near the adhesive layer and compression at the free surface. The neutral line is located under the mid-line of aluminum plate. In double patch, the composite shows compression and the aluminum is tension.

**CONCLUSIONS**

In this paper, the effect of thermal residual stress on fatigue life in composite patch specimen was studied for different curing cycles experimentally, and those results were compared with analysis results. Three different concepts in the calculation of stress intensity factors were also compared to show the effective way in the calculation of fatigue life. The key factor determining the performance of patch structure is the appropriate surface treatment. Emphasis should be made in this procedure. There was no debonding at the edges until failure. The
composite patch repair can effectively extend the fatigue life of cracked panel, and the fatigue life was extended three or four times compared with no patch case. Also, the static strength was improved thirty to forty percents. The low temperature curing cycle which can minimize the thermal residual stress, is much better than high temperature curing cycle. In finite element analysis, the effective temperature concept is useful to have a reasonable result. The root mean square concept in the calculation of stress intensity factor shows better agreement with experimental result. The thermal residual stress distributions are quite different in single and double patch and the bending effect is significant in single patch.

REFERENCES

2. Belason, E., “Fatigue and Static Ultimate Tests of Boron/Epoxy Doublers Bonded to 7075-6 Aluminum with Simulated Crack”, 18th Symposium of the International Conference on Aeronautical Fatigue, Melbourne, Australia, 1995

Fig. 1 Dimension of composite patch specimen with edge crack
Fig. 2 Comparison of fatigue life and crack growth of edge crack patching for different curing cycles (6Hz, R=0, 24KN)

Fig. 3 Finite element modeling by Mentat
Table 1  Mechanical properties of materials used in the analysis

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<th>$E_2$ (GPa)</th>
<th>$G_{12}$ (GPa)</th>
<th>$G_{13}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
<th>$\nu_{12}$</th>
<th>$\sigma_{11}(%)^{10^{6}}$</th>
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<td>$12.8\times10^{6}$</td>
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Fig. 5  Comparison of fatigue life between test and analysis results for edge crack
Fig. 6 Comparison of fatigue life between test and analysis results for center crack

Fig. 7 X-directional stress contour of single side composite patch with curing cycle 1
Fig. 8 X-directional stress contour of double side composite patch with curing cycle 1

Fig. 9 Through-thickness X-stress distribution at the middle of patched panel