ACOUSTO-ULTRASONIC TECHNIQUES FOR EVALUATION OF BOND INTEGRITY OF COMPOSITE REPAIR PATCHES

I. M. Daniel, J.-J. Luo and H.-M. Hsiao

Robert R. McCormick School of Engineering and Applied Science
Northwestern University
Evanston, IL 60208

INTRODUCTION

Composite materials offer many advantages over conventional materials in structural reinforcement and repair of aging aircraft. Composite repair patches are usually boron/epoxy or carbon/epoxy laminates adhesively bonded to the aluminum substrate where damage, such as fatigue or stress corrosion cracking, exists or is anticipated. Such patches are thin and lightweight, conform to curved surfaces and have high directional strength and stiffness. They can be installed relatively easily without causing damage to the existing structure and they do not cause any problems with fretting, corrosion, undesirable structural changes or balance.

Earlier studies on composite repairs were done by Baker et al. [1-3] and Ong and Shen [4]. A comprehensive study including analytical and experimental work is given by Atluri et al. [5]. More recent studies, both analytical and experimental, have been reported by Aglan [6-8], Sun [9] and Minnetyan and Chamis [10]. Whereas the effectiveness and airworthiness of composite repairs have been demonstrated, further demonstration of their reliability and predictability is demanded. The main unresolved problem is a reliable prediction of bond strength and fatigue life based on nondestructive measurements during service. Evaluation and development of nondestructive techniques is needed for assessment of quality and reliability of composite repair patches.

Various techniques have been considered for detection and characterization of bond integrity. They include ultrasonic, guided wave, thermal wave and acousto-ultrasonic techniques. The latter technique is used in this study for evaluation of bond integrity of composite repair patches.

EXPERIMENTAL PROCEDURE

The specimen type used was a double-lap butt joint consisting of two 51 mm (2 in.) wide, 115 mm (4.5 in.) long and 3.17 mm (0.125 in.) thick 2024-T3 aluminum plates joined together with two composite patches (Fig. 1). These patches were 76 x 51 mm (3 x 2 in.) 6-ply unidirectional boron/epoxy laminates (5521 F/4, Textron Specialty Materials). FM-73M adhesive film (CYTEC) was used for bonding the composite patches to the aluminum plates. Two 5.1 mm (0.2 in.) wide and 0.025 mm (0.001 in.) thick teflon strips were inserted at the juncture of the two aluminum plates at the interface between the adhesive film and the aluminum.

The patch bonding procedure used was essentially the one described in two recent publications [5,11]. The aluminum surface was lightly abraded with a Scotchbrite pad and wiped with a Kimwipe tissue dipped in MEK (methyl-ethyl-ketone). Then, it was brushed for ten minutes with silane solution (1 part silane in 100 parts of water). Subsequently,

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 17
Edited by D.O. Thompson and D.E. Chimenti,, Plenum Press, New York, 1998

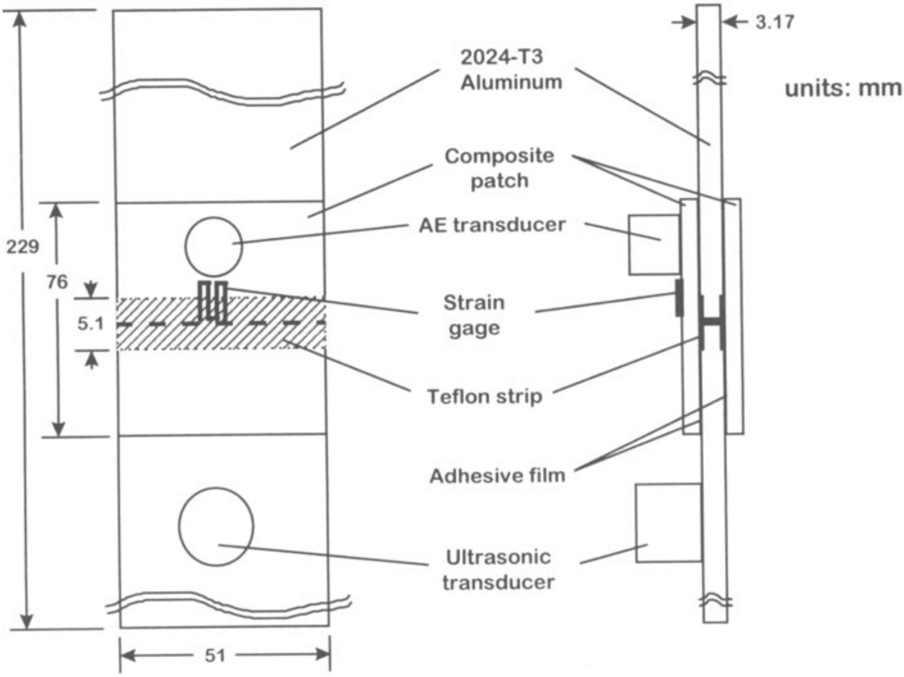


Fig. 1 Specimen geometry with transducers and strain gage.

FM-73M film adhesive and 6 plies of boron/epoxy prepreg were laid on the treated aluminum surface and a sealed vacuum bag applied on top. Co-curing of the patch and adhesive consisted of ramping the temperature at 2.2° C/min. (4° F/min.) up to 120° C (250° F), dwelling at 120° C (250° F) for one and one-half hours and cooling down at 2.2° C/min. (4° F/min). A 12.7 mm (0.5 in.) long strain gage was mounted on the patch over the location of the teflon strip.

For application of the acousto-ultrasonic (AU) technique two transducers were mounted on the specimen as shown in Fig. 1. A 1 MHz ultrasonic transducer was mounted on the aluminum surface near the patch. The receiver was an acoustic emission resonant transducer with a central frequency of 150 kHz (R15, Physical Acoustics). It was mounted on top of the composite patch as shown. Since the location and mounting of this transducer are critical, to insure reproducibility of results a special mounting fixture was built and used for the purpose. The ultrasonic transducer was excited with a toneburst pulse of five cycles of 150 kHz frequency at a repetition rate of 180 Hz. The acousto-ultrasonic test setup is illustrated in Fig. 2.

The specimen was subjected to tension-tension fatigue loading at a cyclic frequency of 4 Hz. Waveforms received by the acoustic emission transducers were analyzed by various means and characterized in terms of AU parameters.

RESULTS

A typical waveform obtained by the setup of Fig. 2 is shown in Fig. 3. The results were characterized in terms of the following AU parameters:

1. Ringdown stress wave factor (SWF)

$$(SWF) = PRC$$

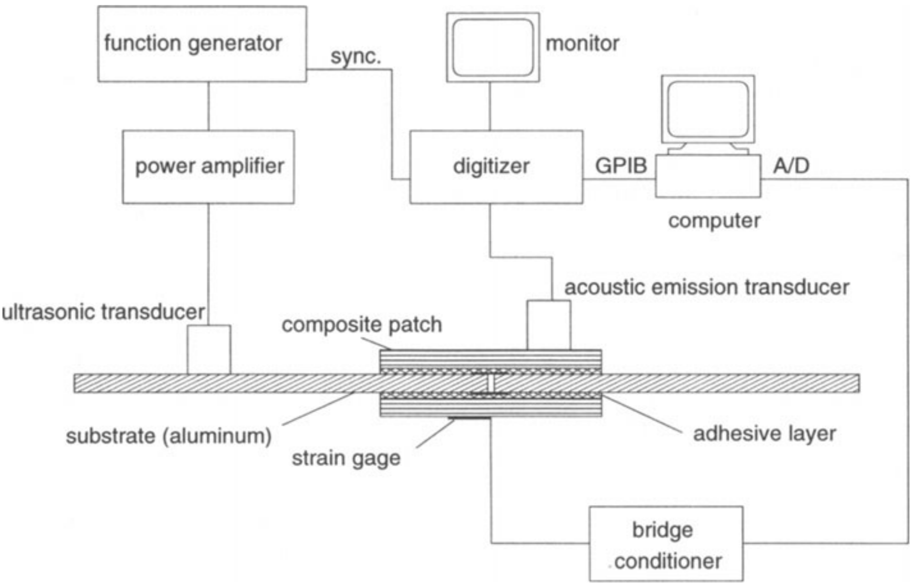


Fig. 2. Composite patch specimen and acousto-ultrasonic test setup.

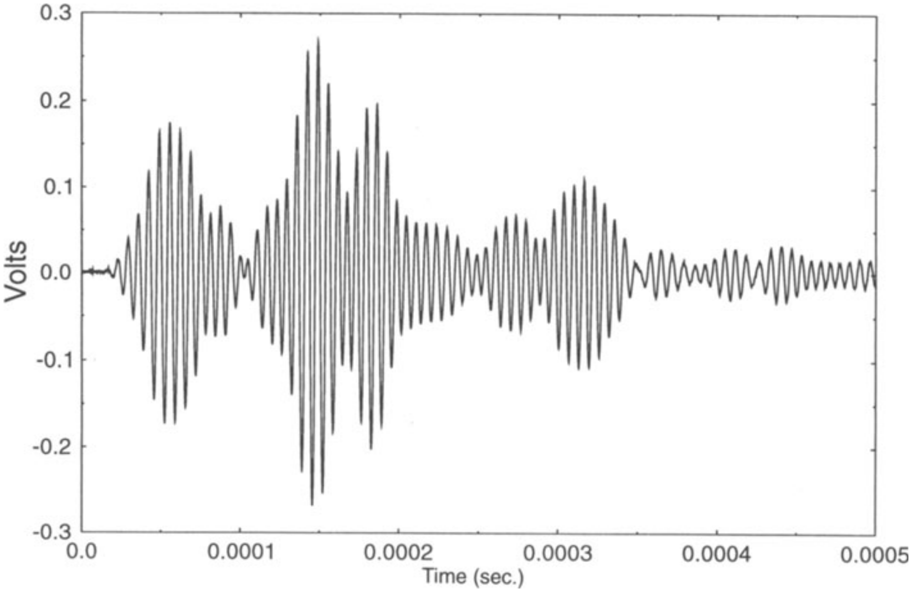


Fig. 3. Typical acousto-ultrasonic waveform.

where P = repetition rate
R = reset time
C = number of counts

The number of counts is defined as the number of positive crossings of a preset threshold level by the waveform. The SWF is related to the amplitude and frequency of the waveform.

2. Peak voltage, V_{max}.

3. Energy

The energy can be expressed in two different forms:

$$\text{Energy 1} = \int [f(t)]^2 \, dt$$

$$\text{Energy 2} = \int |f(t)| \, dt$$

where $f(t)$ is the waveform function. The second form above represents the area under the rectified waveform signal.

4. Acousto-ultrasonic parameter.

This parameter is defined as

$$(\mathrm{AUP}) = \sum_{i=0}^{p} V_i \left(C_i - C_{i+1}\right) = \int_{C_0}^{C_p} V dC$$

where V_i = voltage level
V_o, V_p = threshold and peak voltage levels
C_i = number of counts corresponding to voltage level V_i

Referring to Fig. 4, we can see that the (AUP) is approximately proportional to the area under the positive portion of the waveform, therefore, it is related to energy.

5. Waveform correlation factor.

This is defined as

$$(\mathrm{COR}) = \frac{\left(f_0, f\right)}{\| f_0 \| \cdot \| f \|}$$

where f_0 = initial (reference) waveform
f = current waveform

Results of the first test, conducted at increasing stress amplitudes, show the sensitivity of the various recorded signals, i.e., rate of acoustic emission counts, strain and waveform (Fig. 5). It is seen that the count rate and strain show small changes when debonding of the patch starts, but the waveform variation seems much more pronounced. Results from another test conducted at a stress amplitude of 138 MPa (20 ksi) are illustrated in Fig. 6. Here, the various AU parameters were normalized with respect to the initial

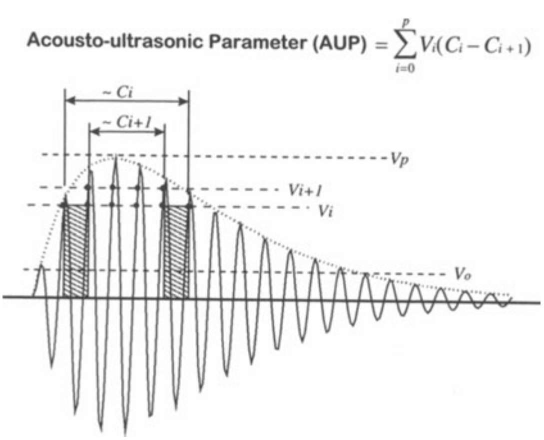


Fig. 4. Illustration of definition of acousto-ultrasonic parameter.

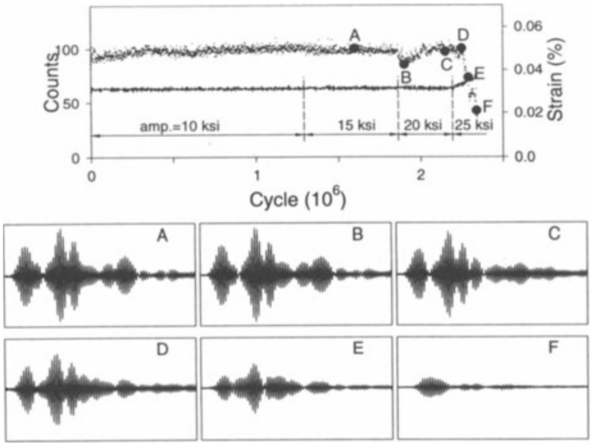


Fig. 5. Variation of counts, strain and waveform with fatigue cycles.

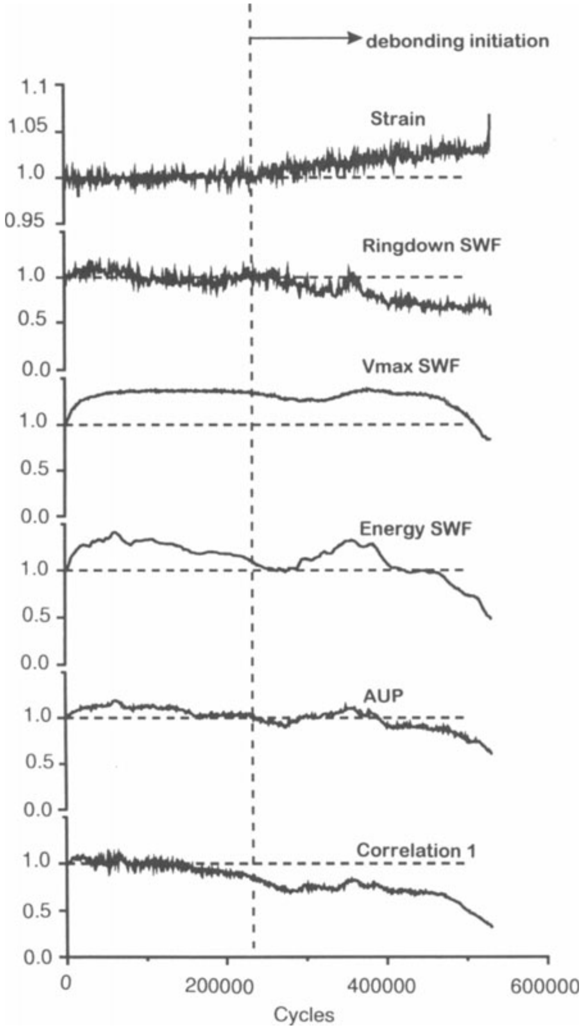
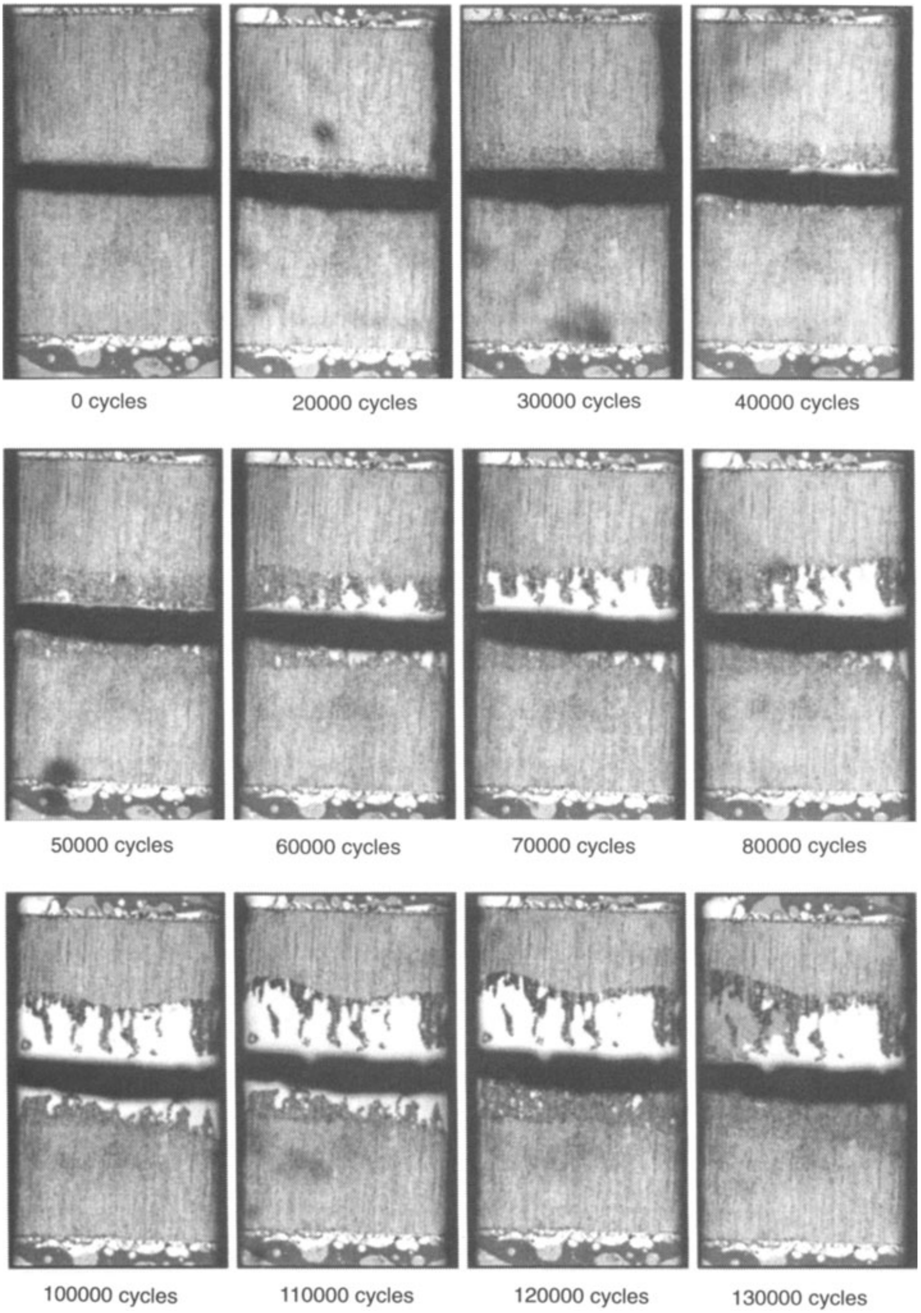


Fig. 6. Normalized acousto-ultrasonic parameters as a function of fatigue cycles.

(reference) state and plotted versus fatigue cycles. The strain gage signal serves as an indicator of debond initiation at around 200,000 cycles. Of the other measures, it appears that the waveform correlation factor is not only a viable and sensitive indicator of actual crack initiation but it appears to indicate microdamage preceding crack initiation.

In order to assess the sensitivity and effectiveness of the various AU parameters in detecting debond initiation and propagation, it is necessary to compare them with a more direct measurement of the debond crack. Patch debonding can be detected without much difficulty by ultrasonic C-scanning from the aluminum side for the case of a single patch. Attempts to do this from the composite side (in the case of a double patch) proved unsuccessful. This may be due to the small thickness of the boron/epoxy patch (0.76 mm), its high impedance and its inhomogeneity (140 μm diameter fibers).



0 cycles
20000 cycles
30000 cycles
40000 cycles
50000 cycles
60000 cycles
70000 cycles
80000 cycles
100000 cycles
110000 cycles
120000 cycles
130000 cycles

Fig. 7. C-scans showing patch debonding at various stages of fatigue life. (asymmetric single patch specimen)

Additional specimens with a single patch on one side were tested. This type of specimen results in earlier debond initiation. Debonding in this case can be detected easily by ultrasonic scanning from the aluminum side. C-scans obtained at 10,000 cycle intervals are shown in Fig. 7 for a test conducted at 52 MPa (7.5 ksi) stress amplitude. Some precursor bond damage can be detected at 20,000 cycles.

SUMMARY AND CONCLUSIONS

Composite repair patches are effective in arresting or showing down damage growth in metallic substrates. The most common form of damage in the composite repair patch is debonding starting around substrate cracks or the edges of the patch.

The acousto-ultrasonic method appears to be a viable one for assessing of composite repair integrity. Composite patch debonding can be detected and correlated with various readings and parameters, such as, strain, ringdown stress wave factor (SWF), peak voltage (V_{max}), energy, acousto-ultrasonic parameter (AUP), and waveform correlation factor. Of the various parameters used, the waveform correlation factor appears to be the most sensitive and reliable one.

ACKNOWLEDGEMENTS

This work was sponsored by the FAA Center for Aviation Systems Reliability administered by Iowa State University. We are grateful to Mrs. Yolande Mallian for typing the manuscript and to Drs. C. G. Sifniotopoulos and S. Rao for their assistance.

REFERENCES

1. A. A. Baker, "Repair of Defective Metallic Aircraft Components with Advanced Fibre Composites - An Overview of Australian Work," *Composite Structures,* Vol. 2, 1984, pp. 153-181.
2. A. A. Baker, R. J. Callinan, M. J. Davis, R. Jones and J. G. Williams, "Application of BFRP Crack Patching to Mirage III Aircraft," Proceedings 3rd Int. Conf. Composite Materials, ICCM 3, Paris, Pergamon Press, Oxford, 1980, pp. 1424-1438.
3. A. A. Baker, "Fibre Composite Repair of Cracked Metal Aircraft Components - Practical and Basic Aspects," *Composites,* Vol. 18, No. 4, 1987, pp. 293-308.
4. C. L. Ong and S. B. Shen, "Study on Composite-Patching Repairs for Metallic Aircraft Structures," Proceedings of 36th Int. SAMPE Symposium, Vol. 36, eds. J. Stinson, R. Adsit and F. Gordaninejad, April 15-18, 1991, pp. 2291-2305.
5. S. N. Atluri, J. H. Park, E. F. Punch, P. E. O'Donoghue, and Rhys Jones, "Composite Repairs of Cracked Metallic Aircraft Structures," DOT/FAA/CT 92/32 Report, May 1993.
6. H. Aglan, "Fatigue Lifetime Assessment of Adhesive Joints by Ultrasonic and Thermal Wave Imaging," *J. Adhesion Scie. and Technology,* Vol. 8, No. 2, 1994, pp. 101-115.
7. H. Aglan and Z. Abdo, "An Innovative Approach to Fatigue Disbond Propagation of Adhesive Joints," *J. Adhesion Scie. and Tech.,* Vol. 10, No. 3, 1996, pp. 183-198.
8. H. Aglan, T. Rowell, Z. Zhang, T. Ahmed and R. Thomas, "Evaluation of Bonded Boron/Epoxy Repairs on Aircraft Skin with Simulated Damage," presented at Review of Progress in QNDE, San Diego, 1997.
9. C. T. Sun, J. Klug and C. Arendt, "Analysis of Cracked Aluminum Plates Repaired with Bonded Composite Patches," *AIAA Journal,* Vol. 34, No. 2, 1996, pp. 369-374.
10. L. Minnetyan and C. C. Chamis, "Structural Durability of Damaged Metallic Panel Repaired with Composite Patches," *J. Reinforced Plastics and Composites,* Vol. 16, No. 3, 1997, pp. 200-216.
11. A. N. Rider, D. R. Arnott, A. R. Wilson and O. Vargas, "Influence of Simple Surface Treatments on the Durability of Bonded Aluminum Alloy Plates," *Mat. Scie. Forum,* Vols. 189-190, 1995, pp. 235-240.