PRACTICAL APPLICATION OF STATE-OF-THE-ART NDE TECHNIQUES:
EVALUATION OF GRAPHITE–EPOXY COMPOSITE WING COVERS

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INTRODUCTION

The X-29 experimental aircraft, based at the NASA Dryden Flight Research Facility, Edwards Air Force Base, California, represents a demonstrator for several state-of-the-art aerospace technologies. The most obvious of these is the forward–swept wing configuration, made possible in this high–performance aircraft by the use of graphite fiber–reinforced epoxy composite laminate wing surfaces. During a routine inspection of the aircraft, a delamination was found in the wing on the right underside of the airplane. A NASA review board investigated the damage and recommended to repair the delamination and to closely monitor its integrity during the post-repair period. The local strain on the surface of the repaired part was measured with strain gages monitored in real time during subsequent flights and the area was periodically inspected nondestructively in a reproducible manner to test for failure of the repair or growth of the delamination. The Materials Characterization Instrumentation Section of the NASA Langley Research Center was called upon to acquire quantitative ultrasonic NDE data from the repaired delamination and to analyze it using the advanced techniques available at that facility. These measurements were in addition to more subjective conventional ultrasonic pulse–echo inspections.

THE DELAMINATION

The delamination occurred on the inboard leading edge of the lower right wing cover, on a tab containing nut plates fastened by rivets for mounting the adjacent boot panel. Fig. 1 shows a sketch of the affected composite part. The composite is 48 plies thick at the edge, with the delamination occurring approximately 4 plies from the upper (interior to the wing) surface. The composite part is separated from a structural titanium spar by a layer of silicon–loaded epoxy, referred to as liquid shim, to reduce vibrations.

The delamination was repaired according to the following procedure. First, the cured liquid shim material was removed from between the composite and titanium spar behind the delamination. The crack was pried open slightly to aid in the injection of a liquid epoxy, Epon 934, into the crack. This epoxy is similar, but not identical, to the matrix material of the composite. A wedge was inserted between the composite and titanium spar to close the crack during cure of the epoxy. After cure, the wedge was removed and the gap between composite and titanium was filled with liquid shim.

Conventional pulse–echo ultrasonic inspection was performed, and the
Fig 1. Cutaway view of composite part showing the outline of the delamination as determined by conventional pulse-echo inspection.

boundary of the delamination was outlined on the lower surface of the composite by grease pencil mark. This outline is sketched in Fig. 1. The circled area to the right of the bolt hole indicates a region where it appeared that the epoxy had not penetrated the crack, leaving an air gap. The conventional inspection was archived by tracing the outline of the composite part and the apparent extent of delamination onto a 1/8" thick transparent plexiglas sheet using a grease pencil.

MEASUREMENT PROCEDURE

Our first set of measurements was performed on June 30, 1986, just following the repair on June 28. Following these measurements, strain gages were mounted to monitor the repair during flight. A second set of measurements was performed on July 21, after the airplane had been flown for a total of 5 flight hours, during which the plane underwent accelerations as high as 4 G's. A third measurement set was taken on September 25, after a total of approximately 27 flight hours following the repair, and during which the plane underwent accelerations as high as 8 G's. During these flights no anomalous signals were observed from the strain gages or other instrumentation in the area of the repaired delamination.

For our measurements we employed a 1/4" diameter 10 MHz broadband transducer with a plastic delay line 1-1/4" in length. A Metrotek pulser/receiver pair was used to drive the transducer and receive the echoes. The RF output of the receiver was sampled using a Data Precision 6000 waveform digitizer and the data were stored by a microcomputer on floppy disk for transfer to Langley, where the signals were analyzed on a VAX 11/750 computer. The equipment was set up with reproducible settings to allow quantitative comparison between data sets.

A mechanical template was fabricated to enable reproducible placement of the transducer for our measurements. The shape and size of the template is sketched in Fig. 2. The template was made from a 1/8" thick plexiglas plate. It was attached to the aircraft using screws placed through two slots cut in the template and tightened just snug. These slots allowed the template to be translated in the inboard/outboard direction. Tick marks at 1/8" intervals at the side of the inboard slot allowed reproducible positioning of the template. A third slot in the perpendicular forward/aft direction allowed the transducer to be positioned on the part, with 1/8" tick marks provided for site location.
Fig 2. Diagram of the template used for positioning the transducer. Template is mounted to the wing by screws through parallel slots, allowing the template to slide in the inboard-outboard direction. A perpendicular slot allows the transducer to be positioned on the composite.

The template was used for each set of measurements to position the transducer at points lying on a grid with 1/8" spacing between sites. The measured region spanned the area from approximately 3/4" outboard from the bolt hole, inboard to the slanted edge of the part. The grid of measurement sites consisted of 19 (forward–aft) columns with 8 rows each, except for those columns intersecting the slanted inboard edge, where the number of measurable rows varied as determined by the geometry of the part.

Fig. 3 shows a schematic diagram of the measurement sites for the measurements. Each square represents a measurement site, with open squares representing sites with no potential complications. These sites contained the majority of the repaired delamination. Crosshatching marks sites where the transducer delay line overlapped the bolt hole, the two rivets, strain gages or their wire leads. Sites thus identified were carefully examined for effects due to interaction with these features. Only those sites which significantly overlapped the bolt hole were unusable. Some sites were impossible to measure because of wires and solder pads mounted on the surface of the composite, and these are indicated in Fig. 3 by gray shading with broken outlines.

SIGNAL PROCESSING

The digitized RF data were processed by digital pulse shaping. The technique was described and results of laboratory studies with this technique were previously reported by Kishoni [1]. In this pulse shaping method an improvement in resolution was sought by mapping the system impulse response to a target waveform derived by windowing the system impulse response by a narrow Gaussian–windowed waveform. A target waveform was obtained by multiplying an echo from the front surface of the composite by a narrow Gaussian window. Filter coefficients were derived by minimizing the least-squares error between the target waveform and the result of running the original echo through the filter. The obtained filter was applied to all the digitized echo traces in each data set. This approach improved the resolution without a high price in noise enhancement.

After digital pulse-shaping to improve the axial resolution, the magnitude of the analytic signal of the resulting waveforms were computed. The analytic signal of a waveform has the waveform as its real part and its Hilbert transform as the imaginary part. The magnitude of the analytic signal represents a more accurate
measure of the signal envelope than the conventional rectification and smoothing [2].

An example of the improvement in resolution is presented in Fig. 4. In both panels, the signal magnitude is plotted versus range into the composite. In panel A, the result of simple rectification and envelope detection is plotted for a site over the repaired delamination. Note the tall echo from the front surface at the left, and the double-peaked echoes from the repaired delamination and the back surface. In panel B, the magnitude of the analytic signal of the filtered data is presented. Note the sharpened echo peaks, and the improved resolution of the repaired delamination from the back surface echo.

Fig 4. Example of the resolution improvement resulting from our signal processing technique. Panel A depicts a waveform from a site over the repaired delamination which has undergone simple rectification and envelope detection. Panel B shows the results on the same data following the application of our filter and computation of the analytic signal magnitude. Note the improved resolution of the reflections from the repaired crack and the back surface.
Fig. 5 shows analytic magnitude versus range and versus row number for data taken from column 1 remote from the delamination (upper panel) and in column 10 over the repaired delamination (lower panel). Row one measurements are nearest with row eight measurement farthest, and linear interpolation has been employed in the row dimension to increase the number of points plotted to 29. We note the "mountain range" of front surface echoes which are clearly defined in both panels. We note a clear "mountain range" of back surface echoes in the undamaged region, and a "double mountain range" in the repaired region, with the earlier echoes arising from the repaired delamination and the later ones from the back surface. From these data, we found that the delamination occurred four plies from the back of the composite.

![Diagram](image1)

Fig 5. Surface plots of analytic signal magnitude for measurements in a column away from the delamination (upper panel) and in a column over the repaired delamination (lower panel). For the purpose of these plots, data were interpolated between the eight measured rows of data.

Fig. 6 shows an expanded view of the echoes from near the back surface of the composite in column 11 from each of the three data sets. This figure clearly depicts the double "mountain range" of echoes, with the earlier (leftmost) echoes arising from the repaired delamination and the later (rightmost) echoes arising from the back surface. The double peaks represent a signature of the repair, in that the filled delamination allows ultrasound to pass through to the back surface of the composite. An unrepaired region of the delamination might contain air which effectively blocks the passage of ultrasound. This phenomenon is apparently at work at column 11 row 3, where the
Fig 6. Surface plots of the echoes arising from the repaired delamination and the back surface of the composite in column 11 of each of the three data sets. Note the disappearance of the back surface echo behind an air pocket remaining after the repair. Note also the shift in position of the peak of the echo from this air pocket between 0 and 5 hours, which remains stable between 5 and 27 hours. This peak shift is the only notable change in the signals in this study.
back surface echo goes away, just behind the large peak in each panel of Fig. 6. This region corresponds to the suspected air pocket identified by conventional inspection.

Fig. 6 shows the only noticeable change in the data over the course of this study. As noted above, at row 3 the back wall echo goes away in each panel, suggesting that the repair was not effective at that point. The change to note is where the prominent peak at row 3 shifts from an earlier position in the first measurement to a later position in the second measurement. This suggests a possible release of strains remaining at the edge of the cracked region after repair by crack growth toward the back surface of the composite. We note that the second and third measurements agree, indicating that the strains were relieved during the first few hours of flight after the repair.

Conventional pulse-echo measurements were performed in addition to our data acquisition. The edge of the delamination was mapped out by hand using visual interpretation of analog displays of the reflected signals, and the outline was marked by hand with grease pencil. These results were archived by tracing the outline by hand with grease pencil on an 1/8" thick plexiglas sheet held over the area. These inspections indicated that between the second and third inspections the repaired delamination had actually gotten smaller in lateral dimension. In contrast, our results indicate identical results from the second and third data sets, within normal experimental error, as seen in Fig. 6.

CONCLUSION

In conclusion, we found that the repaired delamination in the wing of the X-29 aircraft did not change significantly after a total of 27 flight hours. Subtle changes were observed between the first and second measurements near a pocket of air remaining after the repair. These small changes were possibly due to strain relief during the first few hours of flight following the repair, and remained stable after the second measurement. Our methods were found to be more repeatable than conventional inspection methods, which rely heavily upon the subjective interpretation of a technician. We found no change in the dimension of the delamination, while conventional inspection determined that the delamination perimeter decreased in dimension between the second and third inspection. Based on our findings, along with those of the conventional inspections, it was decided by project management that the repair was effective, and that no further ultrasonic monitoring was necessary, although real-time monitoring of strain gage data would continue for a period of time. We are confident, however, that if there is any need to inspect the area again, we can reproducibly scan the area and quantitatively compare the results with our previous measurements.

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REFERENCES
