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**A PRELIMINARY STUDY OF
ULTRASONIC DETECTION OF
CRACKS THROUGH THICK
COMPOSITE DOUBLERS (PREPRINT)**



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14. ABSTRACT Composite doublers have been introduced as a repair method to take a substantial portion of the structural load away from the region around a crack in aluminum aircraft structures. The subsequent use of nondestructive evaluation methods to test the quality of the composite doubler bond and to characterize the crack beneath the doubler is described. In particular, the use of scanning ultrasound methods is evaluated along with appropriate analysis methods to characterize the crack.					
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A PRELIMINARY STUDY OF ULTRASONIC DETECTION OF CRACKS THROUGH THICK COMPOSITE DOUBLERS

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Introduction

Composite doublers have been introduced as a repair method to take a substantial portion of the structural load away from the region around a crack at a rivet in an aluminum aircraft structure. A great deal of work has been done in developing nondestructive inspection (NDI) procedures for this repair method as summarized in detail by Roach et al. [1]. One critical NDT task is to monitor existing cracks and look for new cracks under the repair. For thinner doublers, this can be done successfully using basically the same eddy current approach that is currently used in the absence of the doubler. As the doublers get thicker, lift-off issues make the use of eddy current impractical. The focus of the preliminary study reported here is to investigate the application of ultrasonics to the detection of cracks through thick composite doublers. A classical C-scan approach is taken along with a correlation approach which bases crack detection on the similarity in A-scans measured at adjacent measurement positions.

The basic structure of interest involves two aluminum plates joined with sealant and mechanically fastened. Under normal conditions, the sealant will transmit ultrasound, making the lower aluminum piece accessible to ultrasonics. The composite doubler is bonded to the skin (outer layer) over the position of the detected crack. A cartoon representation of the assembly is shown in Fig. 1. Ultrasonic measurements can be made in pulse-echo or in pitch-catch as depicted in the figure; however, this study focuses on pitch-catch measurements. The lower figure schematically represents some of the complicating factors which are not addressed in this preliminary study but which will ultimately need to be addressed including: short cracks under rivet heads, cracks under the tapered portion of the doubler, and cracks below gaps in the sealant or below disbonds at the doubler/aluminum interface (the faying layer).

The remainder of this paper begins with an experimental procedures section which addresses test samples and ultrasonic measurement procedures. Data analysis is then covered with both the classical C-scan approach and the new correlation approach briefly outlined. The creation of threshold images based on C-scan and correlation data is also addressed. Example results are then shown for ultrasonic measurements made both with and without the composite doubler. The paper closes with a brief conclusion section.

Experimental Procedures

Test Sample

A two-piece sample was used for this study, that is, the composite doubler was not bonded to the aluminum structure. This arrangement allows ultrasonic measurements to be made with and without the doubler in place. A 43-ply boron/epoxy doubler approximately 10 mm thick was used. In addition, the test sample was composed of a 6.5 mm aluminum skin and two 6.3 mm aluminum sections mechanically fastened to the skin, representing the substructure. Faying surface sealant was present between the layers.

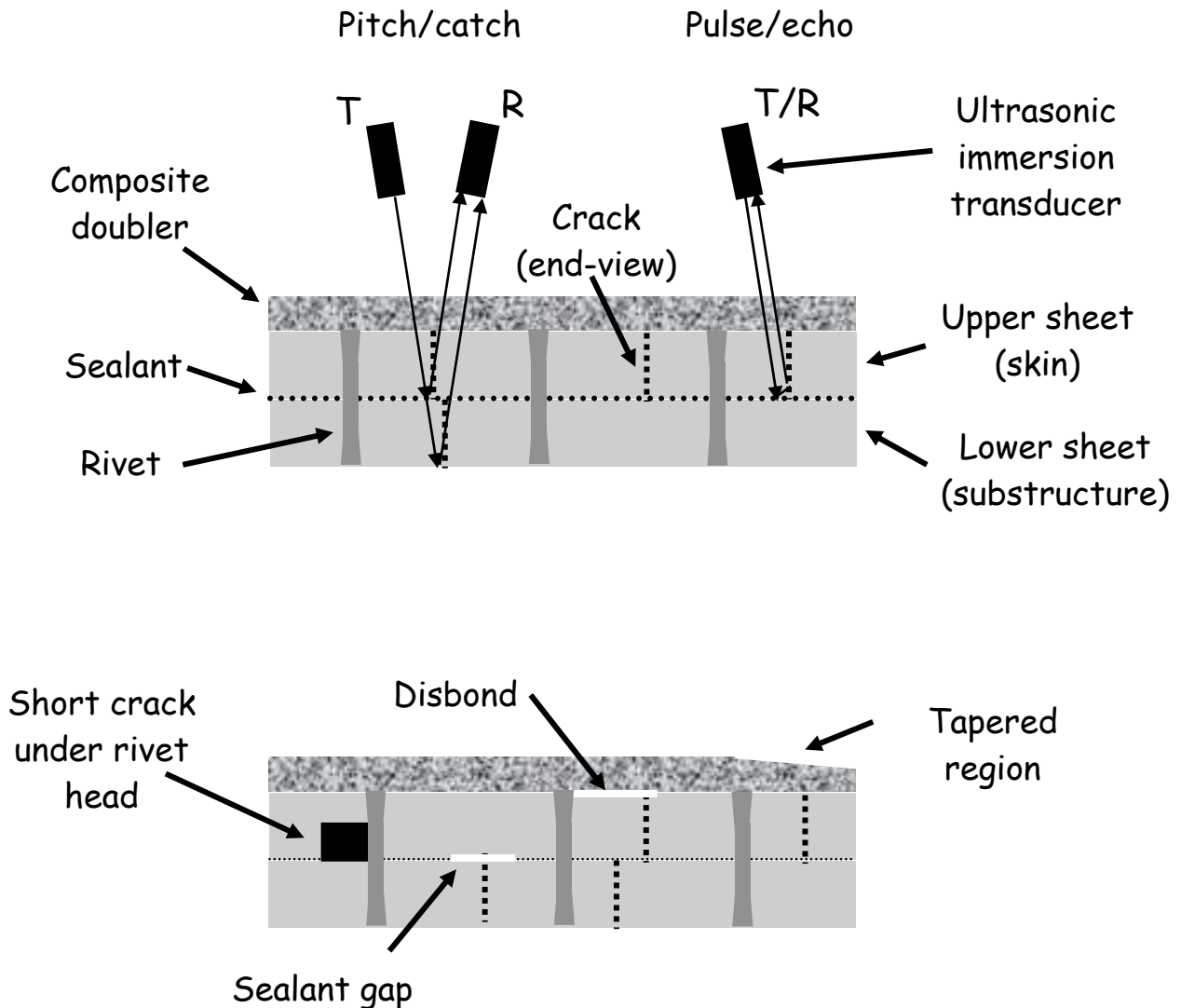


Figure 1. Composite doubler repair schematic with general ultrasonic measurement representation (upper) and complications (lower).

EDM notches were machined to extend radially from 4 rivet holes in the skin and from 4 rivet holes in the substructures as shown in later figures. The EDM notches were used to simulate open cracks running through the thickness of each plate with lengths of 15, 10, 5, and 1 mm. The two-piece sample was supplied by Boeing.

Ultrasonic Measurement

Pitch-catch ultrasonic measurements were made in immersion mode at oblique incidence using both planar and focused piston source transducers (see Fig. 2). Transducers with center frequencies ranging from 5 to 15 MHz were used; however, attenuation in the thick composite doubler will ultimately dictate use of the lower frequency probe. Transducers were driven broadband by a Panametrics 5052PR pulser/receiver. Signals were digitized at 100 MS/s with 64 averages taken at each measurement position to reduce electronic noise. Raster scans were performed over the sample regions of interest with 1 mm spacing between measurement positions. Ultimately, measurements would involve polar scans centered

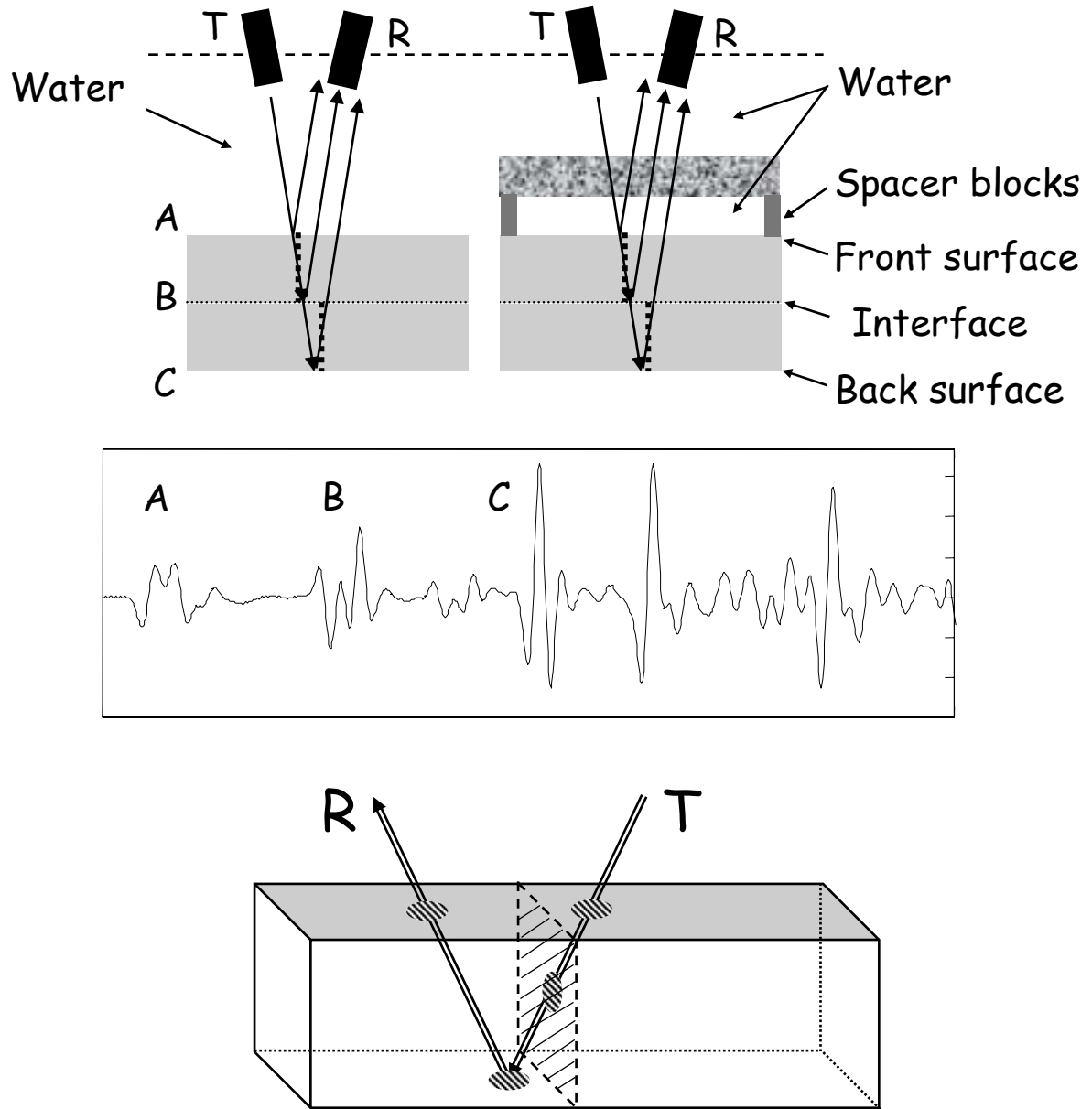


Figure 2. Experimental setup (upper) with example A-scan (lower).

on individual rivets in pseudo immersion. Transducers were aligned to allow the incident beam field to hit the cracks broad-side, thus simulating a polar scan in the region of the crack (see the lower schematic in Fig. 2). Measurements were made at shallow angles (approximately 5°) to keep the longitudinal transmission into the sample relatively high while still achieving an acceptable angle of attack on the simulated cracks. Acoustic characterization of the composite and subsequent beam field optimization are beyond the scope of this preliminary study but will be critical tasks as the project moves forward.

Figure 2 shows the basic experimental arrangement with and without the composite doubler. For simplicity, the composite doubler was supported above the aluminum structure using spacer blocks. This approach creates some added complexity but provides flexibility during this development stage over attaching the composite doubler to the aluminum structure using, for example, double-sticky tape. As

identified on the schematic and on the wave train (A-scan), given the shallow incident angles, signals are received from the front surface of the skin, the faying surface, and the back surface of the substructure. Notice that cracks in either aluminum layer can be detected using the back surface reflection. Given a thin sealant layer and with aluminum sheets of the same thickness, other than the front surface reflection and the (first) interface reflection, all subsequent signals will be comprised of the summation of reflected signals. For example the first reflection from the back surface of the lower sheet occurs in the same time window as the second reflection off of the interface. This summation can be constructive or destructive, creating the potential for a very interesting signal analysis problem. For the measurements reported here, reduction of the second interface reflection and/or the back surface reflection due to interaction with the crack caused a reduction in signal amplitude in the back surface reflection time window.

Data Analysis

Signals were processed to form classical C-scan images and to form correlation images. The correlation approach, which is signal amplitude independent, is being developed as a compliment to the amplitude dependent C-scan approach. The formation of threshold images (not shown) is also discussed. The correlation and threshold approaches are briefly outlined below with more details available upon request.

C-scan Images

Classical C-scan images were formed based on gated absolute-value peak detection of received signals. The basic process begins with an xy or polar scan. The measured A-scans are written into a three-dimensional matrix with the rows and columns of the matrix registered with the measurement locations and with the A-scans written into the third dimension. A C-scan image can be formed by establishing a time gate, finding the maximum absolute value (or maximum min-to-max deviation) within the time gate for each A-scan, writing these maximum values into a two-dimensional matrix which mimics the scan pattern, and forming an image based on this two-dimensional matrix. A typical received signal train is shown in Fig. 2. C-scan images can be formed with the gate positioned to select any of the reflected signals. Cracks in the skin can be detected based on signals from the interface layer or from the back surface of the substructure. Clearly, cracks in the substructure are only detectable based on signals that have reflected off of the back surface of the substructure. Typically, crack detection in pitch-catch would be based on a loss of signal amplitude due to blocking of the acoustic beam. Consistent with this argument, cracks in the skin can be detected due to a loss in amplitude of the signal reflected at the interface. For the experimental arrangement used here, intersection of the sound beam with the crack in either layer generally caused a reduction in the received off of the back surface. However, as previously alluded to, when the signals within a gate are formed by the summation of two or more reflected signals, with the potential for either constructive or destructive interference, losses in one reflected signal due to a crack could cause either an increase or decrease of the peak value within the time gate.

Correlation Images

The correlation approach being developed at the University of Missouri-Columbia (MU) was originally motivated by kissing bond detection for same material joining problems (e.g., inertial or friction stir welding). The goal was to detect weak interface signals at very low signal-to-noise ratio (SNR) associated with the kissing bond condition. In contrast to the classical C-scan approach which is amplitude based, this approach relies on the similarity in signals measured at adjacent measurement positions as a means of detection. Similarity between signals is quantified by the cross-correlation between signals at zero lag. [2] As emphasized in this study, the approach is being developed to detect cracks based on a decrease in similarity of reflected signals due to interaction with a crack. The approach is also being considered for application in pulse-echo where detection would be based on an increase in signal similarity due to the crack echo signal buried in noise.

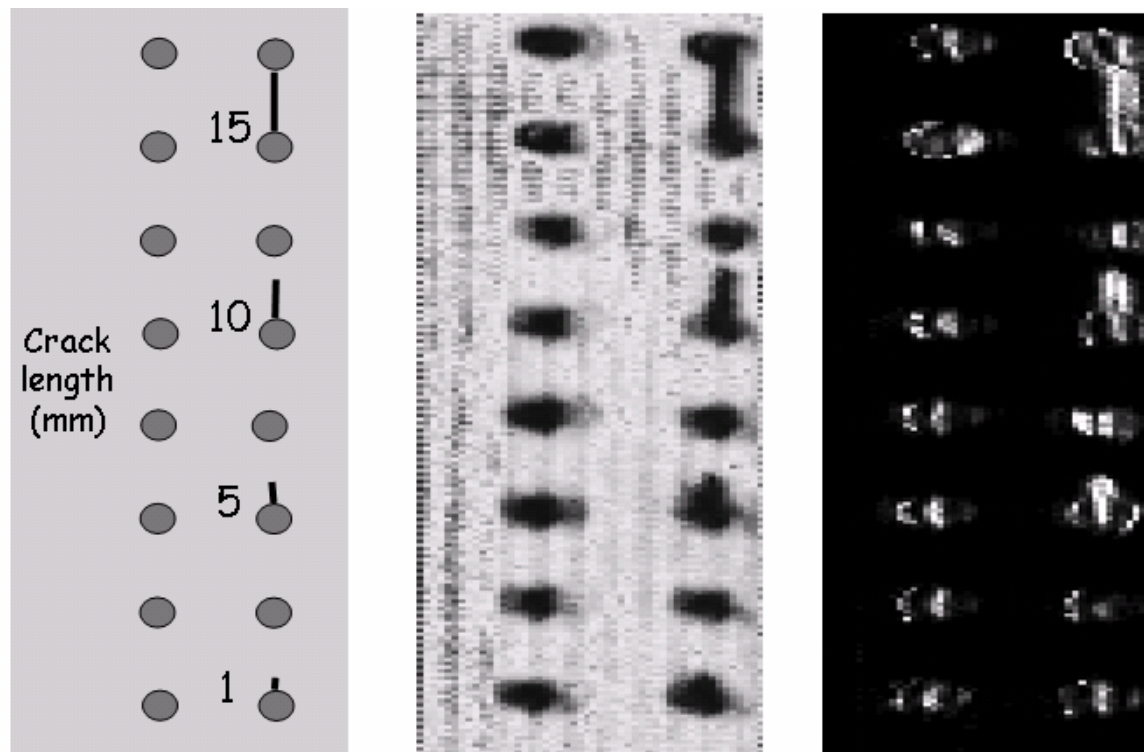


Figure 3. C-scan (left) and correlation (right) images for cracks in the skin without the composite doubler. Images are based on the signal reflected from the interface (signal B in Fig. 2). The schematic shows two rows of 8 rivets along with the position and length of each crack.

The basic approach for forming correlation images uses the same A-scan data used to form C-scan images. Formation of a correlation image is more complicated, but the basic approach is the same: establish a time gate, calculate the correlation coefficient between adjacent A-scan in the three-dimensional matrix, write these correlations into a two-dimensional matrix, and form a correlation image based on these correlations. Complications can arise from: initial alignment of A-scans, local alignment of signals, skipping signal measurement positions, and image formation using matrices with blank elements. A detailed discussion of correlation image formation is beyond the scope of this paper; however, the final result is an image of correlation coefficients which can be compared with peak values as displayed in a C-scan image.

Threshold Images

Development of an acceptable thresholding procedure for this complicated geometry is in its early stages. As such, threshold images are not shown at this point; nevertheless, a brief description of the basic approach will be given. As being developed for this project, threshold images are binary in nature with pixels whose initial C-scan or correlation value breaks a specified threshold set to 1.0 (claiming “detection”) and all other pixels set to zero. For C-scan and correlation data, detection is based on values that are below a specified threshold. That is, detection is based on a reduction in peak amplitudes or a reduction in signal correlations due to the presence of a crack. Threshold values are chosen to control the false-call rate (the probability of a false positive) based on peak amplitude or correlation distributions. These distributions are established based on data gathered in crack-free regions.

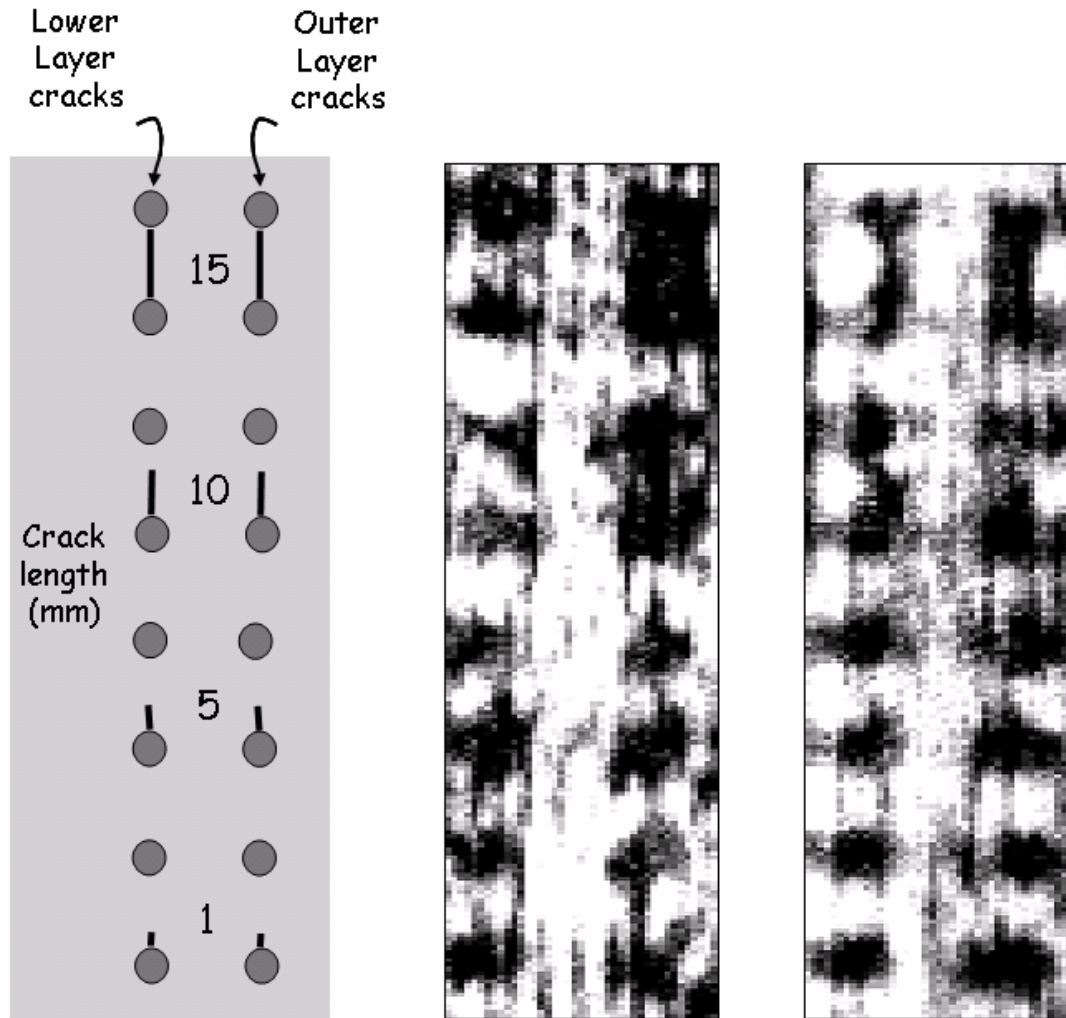


Figure 4. C-scan images of cracks in both layers with the composite doubler in place. The left image is based on interface reflections (signal B in Fig. 2) and can show only skin layer cracks. The right image is based on back surface reflections (signal C in Fig. 2) and can show cracks in either layer. The schematic shows two rows of 8 rivets along with the position and length of each crack in the skin (in line with the right column of rivets) and in the substructure (in line with the left column of rivets).

This basic thresholding approach is augmented to take into account the prior knowledge that cracks will initiate at rivet holes and propagate in a radial direction from the hole. Without such prior knowledge, we might consider each pixel or arbitrarily shaped groups of pixels and ask if the average value of these pixels is consistent or inconsistent (the basis for detection) with the same type of data for crack-free regions. Given the prior knowledge, we are able to ask the same basic question only focused on narrow rectangular regions of pixels that are anchored to each rivet hole and extending radially outward.

Results

C-scan and correlation images are presented with and without the composite patch and for cracks in both aluminum layers. Images are intended for presentation in color; as such, even with some optimization for

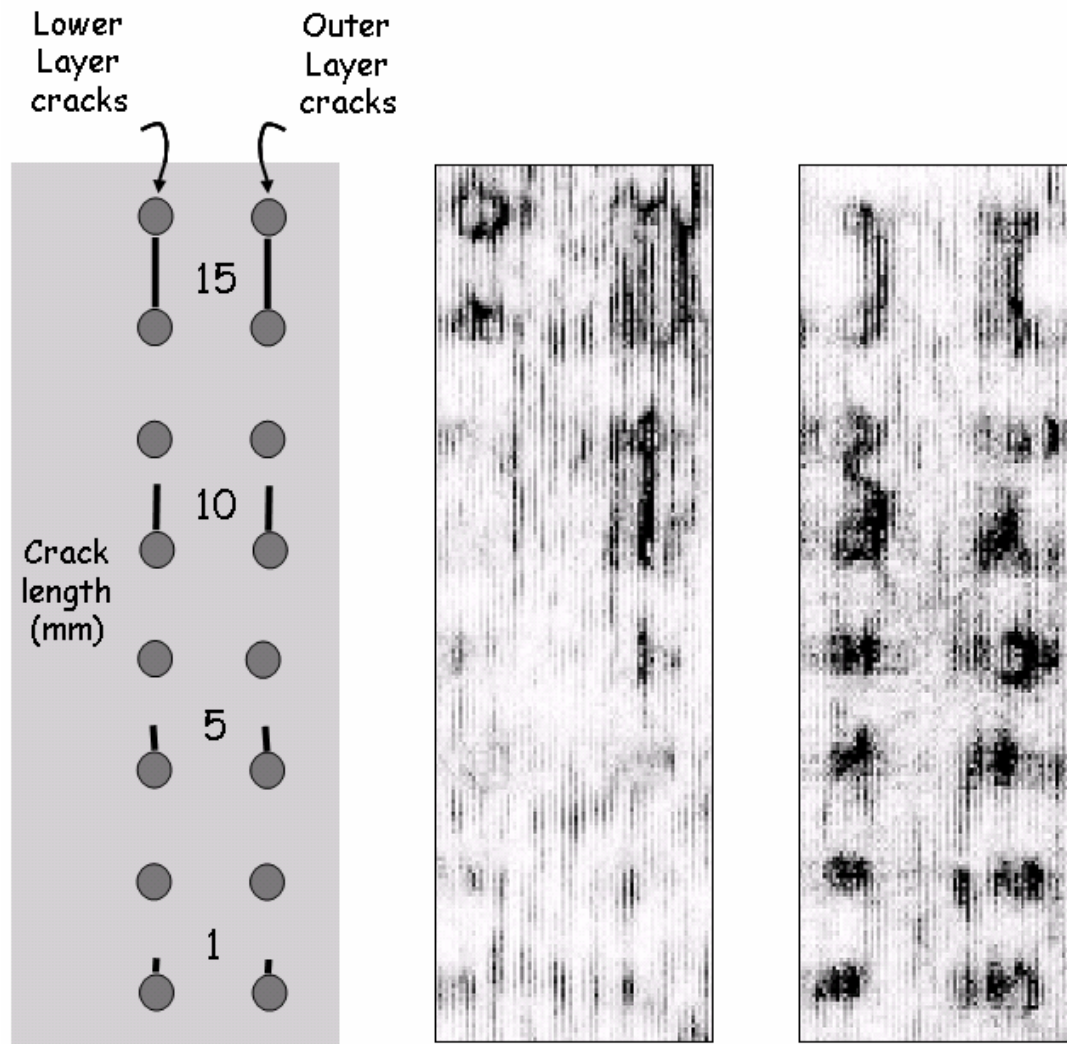


Figure 5. Correlation images of cracks in both layers with the composite doubler in place. The left image is based on interface reflections (signal B in Fig. 2) and can show only skin layer cracks. The right image is based on back surface reflections (signal C in Fig. 2) and can show cracks in either layer. The schematic shows two rows of 8 rivets along with the position and length of each crack in the skin (in line with the right column of rivets) and in the substructure (in line with the left column of rivets).

grayscale presentation, information is lost with the grayscale images. Additional comments are in order relative to the appearance of the figures. Recall that transducers were aligned to allow the incident beam field to hit the cracks broad-side, thus simulating a polar scan in the region of the crack (see Fig. 2). As such, the images are nearly equivalent to polar scan results for portions of the image along a vertical line between rivets, but the circular rivets appear stretched in the transverse direction (horizontal on the images). Also note that the beam intersects the crack after reflection and then prior to reflection as the scan progresses laterally across the region of a crack. Therefore, the apparent position of the crack will be a function of which layer contains the crack and which reflected signal is used for imaging. In any case, a crack indication in an image will show artificial width as the crack blocks the beam over a substantial number of scan lines. The vertical striping artifacts that appear on the images would seem to be

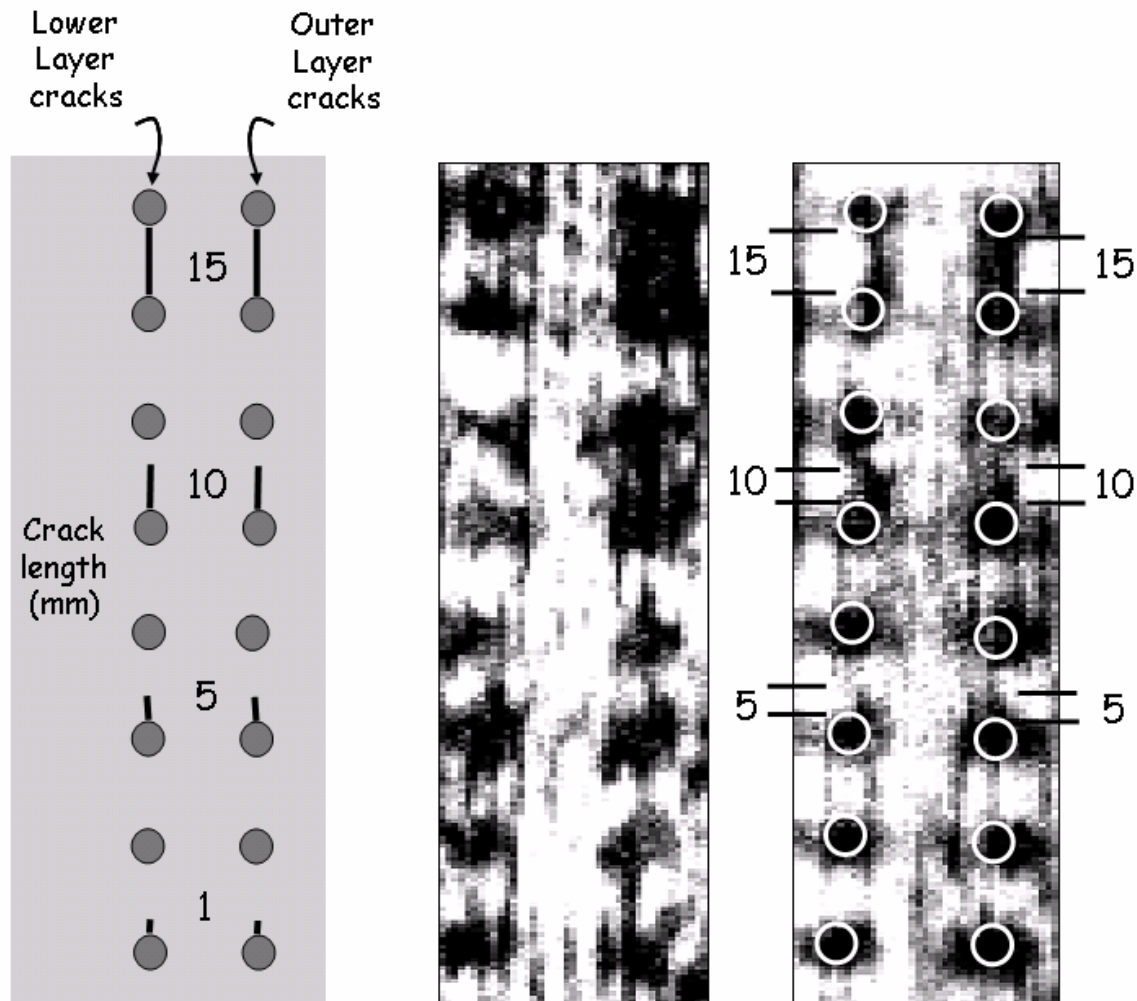


Figure 6. Images based on the C-scan data as shown in Fig. 4 with rivet and crack positions identified on the back surface reflection images.

associated with the aluminum structure since they are aligned with the rivets and appear in images both with and without the composite doubler. The origin of the stripes is under investigation.

Figure 3 shows C-scan and correlation images for cracks in the skin without the composite doubler. Images are based on the signal reflected from the interface (signal B in Fig. 2). The position and length of the cracks is depicted in the schematic in Fig. 3. The three longer cracks are easily detected by either approach with the apparent crack length in the image closely related to the actual crack length. Detection of the 1 mm crack is rather ambiguous, but this is to be expected given the lack of transducer field optimization at this point.

Figures 4 and 5 shows C-scan and correlation images, respectively, for cracks in both layers with the composite doubler in place. These images are repeated in Figures 6 and 7 with rivet and crack positions roughly identified on the back surface reflection images. The schematic in each figure shows the positions of the 4 cracks in the skin (in the right column of rivets) and the 4 cracks in the substructure (in

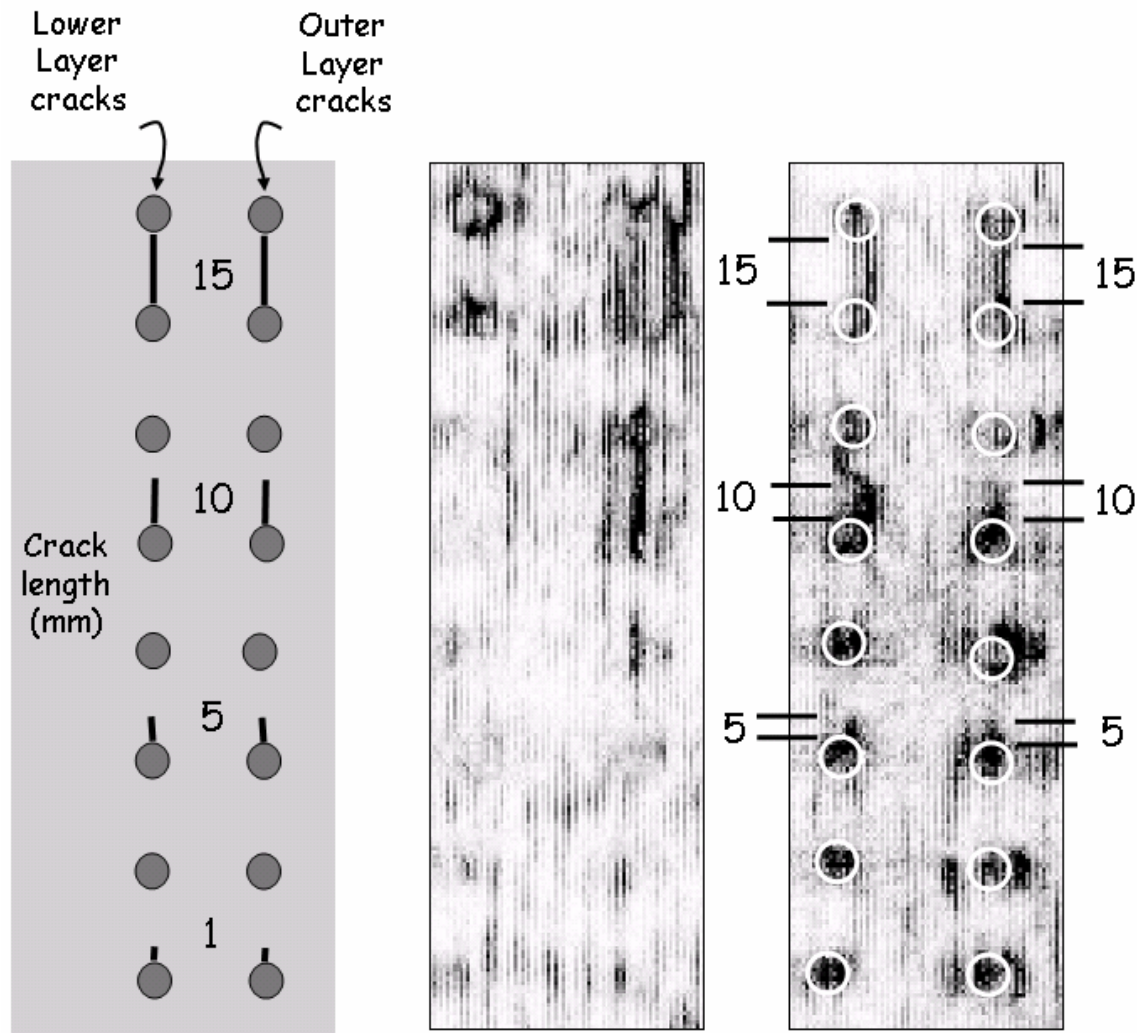


Figure 7. Images based on the correlation data as shown in Fig. 5 with rivet and crack positions identified on the back surface reflection images.

the left column of rivets). In each figure, the left image is based on interface reflections and can be used for only detection of cracks in the skin. The right image is based on back surface reflections and can show cracks in either layer. In all images, the longer two cracks are easily detected. In some of the images, detection of the 5 mm cracks would be ambiguous without prior knowledge of crack locations. Detection of the 1 mm cracks is again very difficult without optimized beam field and scan patterns.

Conclusion

A classical C-scan approach and a new correlation based approach have been used to show that ultrasonics can be used to detect cracks in both layers of a riveted aluminum structure with sonification through a 43-ply composite doubler. The correlation approach was extended from its origins in weld inspection to application here for crack detection. For weld inspection, the correlation approach was applied in pulse-echo to look for increased correlations in arbitrarily shaped and positioned image

regions. For this project, the correlation approach was extended for application in pitch-catch to look for decreased correlations in rectangular image regions extending radially from rivet holes. A qualitative assessment at this point would indicate that the correlation approach performs better than the classical C-scan approach; however, the amplitude independent correlation approach is being developed as a complement to the amplitude dependent C-scan approach, not as a replacement approach. As the project moves into transducer optimization, improved thresholding, and the use of more realistic material samples, a more formal performance evaluation will be pursued.

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