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Nondestructive Evaluation (NDE) of Composite-to-Metal Bond Interface of a Wind
Turbine Blade Using An Acousto-Ultrasonic Technique.

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Abstract

An acousto-ultrasonic inspection technique was developed to evaluate the structural integrity of the epoxy bond interface between a metal insert and the fiber glass epoxy composite of a wind turbine blade. Data was generated manually as well as with a PC based data acquisition and display system. C-scan imaging using a portable ultrasonic scanning system provided an area mapping of the delamination or disbond due to fatigue testing and normal field operation conditions of the turbine blade. Comparison of the inspection data with a destructive visual examination of the bond interface to determine the extent of the disbond showed good agreement between the acousto-ultrasonic inspection data and the visual data.

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Introduction

Sandia National Laboratories has been investigating tubular composite-to-metal lap joints^{1,2}. As a tool to determine the quality of the joint bonds, pulse-echo ultrasonic C-scan NDI techniques have been used. The principles of ultrasonic C-scan imaging with manual and automated scanners can be found in a number of sources^{3,4}. The ultrasonic C-scan method was shown to be successful in detecting and mapping incomplete adhesive fills, interface debonds and composite delaminations in laboratory prepared and tested samples. As an extension to this work, the composite-to-metal joints in the root section of selective full-scale wind turbine blades were tested. This report describes an acousto-ultrasonic variation of the C-scan NDI technique that has been developed for looking at these joints. A schematic view of a full-scale wind turbine blade with a representative composite-to-metal joint is shown in Figure 1. Ultimately, the acousto-ultrasonic NDI technique is being developed to be used on full-scale wind turbine blades in the manufacturing, testing and field environments.

Ultrasonic Inspection Techniques

An investigation of characterizing the root bond area shown in Figure 1 for defects was undertaken using ultrasonic techniques. Normal pulse-echo, through transmission, and pitch-catch techniques were examined. A cross section of the root bond area showing the geometry and propagation path of ultrasonic pulses by these techniques is displayed in Figure 2. Since the fiberglass epoxy composite approached 1.25 inches thick for the

wind turbine blade under examination, considerations of ultrasonic reflections, scattering, and attenuation of the pulses from the multiple interfaces within the composite were important.

Pulse-echo and pitch-catch techniques were investigated with limited success. Clear back-surface echoes from the bond interface ① as shown in Figure 2 or from the back-surface of the steel insert at ② were not distinct from all the echoes generated from the multiple interfaces of the composite. In general, ambiguous results were obtained with the pulse-echo and pitch-catch techniques. However, a through transmission (TT) technique proved to show unambiguous results where areas of disbonds, delaminations, and voids could be mapped out and detected with certainty.

As an example, Figure 3 shows the ultrasonic C-scan results obtained with a TT technique for a 305 mm square test sample that had two strips of disbonds purposely manufactured into the test piece that consisted of the structural components of the fiberglass composite bonded to a steel plate. Adequate C-scan images of the same disbond areas could not be obtained with the pulse-echo or pitch-catch techniques. The results of Figure 3 were obtained with an automated ultrasonic data acquisition and display system using a water bath to couple the ultrasonic energy between the transducers and the test piece. However, water immersion techniques will not be appropriate for wind turbine blade examinations. In addition, the blade will be installed in a fixture or wind turbine where the inside surface of the turbine blade will not be accessible for application of an ultrasonic transducer for the TT technique. For these reasons, an acousto-ultrasonic (AU) inspection technique was developed. The AU technique would approximate the detection capability of the TT technique as near as possible.

The AU technique developed is illustrated in Figure 4 where contact transmitter and receiver ultrasonic transducers are used at the OD surface of the turbine blade. The receiver transducer is attached to the OD surface of the steel insert inboard of the fiberglass composite. As illustrated in Figure 4, the ultrasonic pulse generated by the transmitter enters the composite, travels through the composite thickness, and then enters the steel insert where it propagates down the insert and finally arrives at the receiver transducer. The first arrival of the pulse at the receiver is most sensitive to the energy entering the steel insert directly below the transmitter since the acoustic wave velocity in the steel is faster than that in the composite and very little energy is lost in the steel.

For a disbond in the epoxy adhesive interface, a crack in the composite, or distributed damage in the composite, little if any energy enters the steel insert directly below the transmitter. Therefore, the first arrival signal recorded by the receiver will be diminished or of zero amplitude depending on the severity of the damage in the structure below the transmitter. As the transmitter is moved away from the receiver, a gradient of the signal amplitude recorded by the receiver will be observed. However, the gradient should be uniform for a normal undamaged blade around the circumference of the blade for a given axial separation of the transmitter and receiver transducers. Abrupt decreases, non uniform gradients, or very low values of the recorded AU signal amplitude by the

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receiver as the transmitter is translated along the axial or circumferential directions of the insert would indicate possible disbonding, cracking, or material degradation of the composite at the location of the transmitter.

The AU technique was implemented using the test sample of Figure 3 by attaching the receiver transducer to the bottom side of the steel plate of the sample. The detection of the two strip disbonds was observed by an abrupt loss of signal recorded at the stationary receiver as the transmitter passed over the disbonds. This test demonstrated the capability of the AU technique to simulate the TT examination and it could be used in a similar way to assess and identify certain areas of damage and disbonds at the metal insert of a full-scale turbine blade.

AU Signal Amplitude Results Obtained on Actual Wind Turbine Blades

AU signal amplitude data using the technique as shown in Figure 4 was collected on 3 full-scale turbine blades at the steel insert root bond area. The root bond area as shown in Figure 1 consisted of the area included by 360 degrees around the cylindrical steel insert and 20 inches in the axial direction starting at the inboard edge of the fiberglass composite. For reference points, this area was divided into 4 inch square circumferential and axial segments as shown in Figure 5. The grid of the segments that was scribed on the surface of the blade was used as reference lines for mapping the amplitude of the AU signal over the root bond area. For the first blade early in the developmental stages of the project, the AU signal amplitude was recorded manually by observing the signal height on the oscilloscope screen as the transmitter transducer was placed point-by-point in the area defined by the grid lines.

Manual AU Data Acquisition and Display for a Wind Turbine Blade

The first AU examination was performed on a wind turbine blade while it was attached to the fixture of a fatigue tester. The blade had undergone a number of high load fatigue cycles at the time of the AU examination. The AU amplitude data was taken by moving the transmitter point by point by hand along a grid line in the axial direction at one-inch increments while the receiver was stationary at the bottom of the grid line as shown in Figure 4. In a similar manner, axial AU amplitude data was taken at grid lines separated by 2 inch intervals in the circumferential direction until the entire area of the insert was examined.

A pair of 400 kHz 1 inch diameter contact transducers⁵ were used for the transmitter and receiver transducers. A 0.25 inch thick RTV silicone rubber pad was bonded to the transmitter to provide coupling of the acoustic energy from the transducer into the composite. The surface of the composite was also coated with an ultrasound gel couplant to facilitate the transfer of the acoustic energy from the transmitter as the transducer was moved over the surface of the composite. A pulser/receiver module⁶ with 60 dB gain was used to generate and amplify the acoustic signals. The receiver transducer signal amplitude was recorded from 0 to 10 where 10 was full screen height on the oscilloscope

screen. Coverage of the entire steel insert area resulted in a table of AU amplitude data that contained 20 rows for the axial direction and 34 columns for the circumferential direction.

A color contour plot of the tabular data was made by entering the AU data into a Microsoft Excel spreadsheet. Figure 6 displays an equivalent gray scale mapping of the AU data over the steel insert area of the blade. The AU data in Figure 6 indicated that some damage was present at this stage in the fatigue cycle schedule near the high and low pressure sides of the blade as referenced in the sketch of Figure 5. Maximum loading occurs at the outboard end of the steel insert during the fatigue test and during the normal operation of the blade in these two areas. After the AU examination was performed, the blade was fatigue tested to failure. It is noted that the failure of the blade was expected and it did occur in these two areas of the blade.

At this stage of the project, the interpretation of the AU data was encouraging but not conclusive. It did show that the method had the potential of indicating early damage in the root bond area of a steel insert of a wind turbine blade during testing and could be applied manually using a minimum amount of equipment.

Automated Data Acquisition and Correlation of AU Results with Dissection of a Turbine Blade

To gather conclusive results, a second turbine blade that contained an in-service failure of the bond was examined. A visual examination of this turbine blade showed that a failure existed at the composite-to-steel bond interface but the area of the disbond was unknown. This blade was then used to obtain an AU signal amplitude mapping of the disbond and the results were compared with visual inspection by cutting the composite along the four inch square grid lines and removing them from the steel insert.

To improve on the manual data collection process which was tedious and slow, an automated data collection scheme was implemented. The improved system used a PC ultrasonic data acquisition and display system⁷ integrated with an encoded manual scanner for recording the position of the transmitter. AU data was collected fast and efficiently in 0.25 inch increments in both the axial and circumferential directions using the PC data acquisition and display system. The PC manual scanner system provided a direct mapping of the AU signal amplitude by C-scan color images of the scanned area. A single C-scan image was made by enclosing an area 20 inches in the axial direction and 12 inches in the circumferential direction in about 10 minutes.

For a single C-scan image of the AU amplitude data, the receiver transducer was attached to the steel insert at the center segment of a group of 3 circumferential 4 inch segments. The X-Y plot was generated by moving the transmitter in the axial direction (X axis) by 20 inches and in the circumferential direction (Y axis) by 12 inches. As a result, a 20x12 inch C-scan area plot of the AU amplitude data was developed for the group of 3 circumferential segments. To cover the entire circumferential area of the blade, a total of

6 C-scan images were made. For each X-Y plot, the AU signal was gated in time delay for the data acquisition system to cover the entire 20 inch length of the axial scan.

Figure 7(a) displays a montage of the 6 C-scan images collected around the entire circumference of the blade. The C-scan images of Figure 7(a) were rendered in a simple gray scale since the normal 16 color scale could not be reproduced in this publication. Some detail of the AU signal variations is therefore lost but an assessment of the disbonded area is clearly indicated in the gray scale images. The area of Figure 7(a) shown in black where a low AU signal amplitude was recorded indicated the area of disbond.

Figure 7(b) shows the corresponding visual examination of the bond interface of this blade by cutting the segments of the composite and removing them from the steel insert. The removed pieces of the composite were reassembled with the metal-to-composite bond interface facing outward. A photograph of the reassembled pieces is shown in Figure 7(b) where the bond failure is shown in black due to a dark metal oxide present on the adhesive surface of the failed area. A comparison of Figures 7(a) and 7(b) shows that the AU data correlated well with the disbond visually observed after removing the composite with the exception of two small areas. The area to the right of center in Figure 7(a) indicated an area of low AU signal but not completely disbanded. It is possible that the composite was held in compression against the metal surface so that a so-called kissing bond existed in this small area. Also, the area just above the left eyebolt hole in Figure 7(a) is shown in black because the metal path to the receiver was obstructed by the eyebolt hole. This area does not show a disbond in Figure 7(b).

The steel insert area of a third blade was also examined with the PC data acquisition and display system. A manufacturing defect was suspected in this blade but the location and extent of the defect was not known. Figure 8(a) shows the montage of the 6 C-scans of the AU signal amplitude. The AU signal amplitude data was processed so that a black color was assigned to signal amplitudes below a given threshold value. The result is shown in Figure 8(b). The area of the defect is then clearly indicated in Figure 8(b) by the area in black. After the AU examination was made, a partial removal of the composite skin at the area of C-scan number 3 showed that a large void existed in one of the layers in the composite and the void area correlated well with the C-scan image number 3.

Conclusions

From the examples shown in this paper, the demonstrated acousto-ultrasonic method can provide useful information of disbond, delaminations, voids, and composite damage in the root bond area of the steel insert of a wind turbine blade. The method can be used on the factory floor for quality control by detecting manufacturing defects such as voids in the bond interfaces of the composite as well as at the composite-to-metal interface. The method can be used as a diagnostic tool to assess the accumulative damage that occurs

during fatigue testing by mapping changes of the AU signal amplitude during progressive stages of the test. The scanning equipment is portable so that AU examinations can be made in the field to assess accumulative damage that may occur during the normal service life of the blade.

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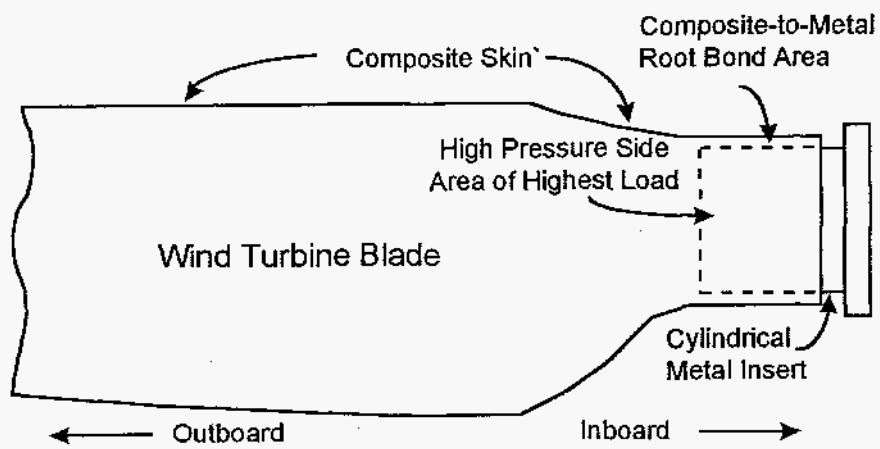


Figure 1. A schematic view of the root bond area at the cylindrical steel insert end of a wind turbine blade.

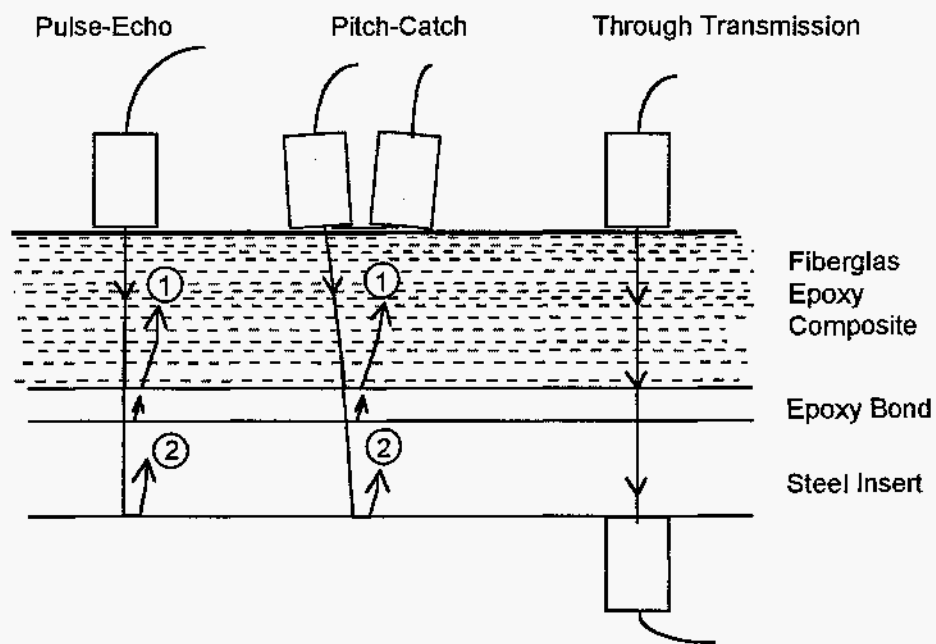


Figure 2. Ultrasonic transducer arraignment for pulse-echo, pitch-catch, and through transmission techniques.

Low Value (Disbond) High Value (Good Bond)
Through Transmission Amplitude 16 Color Scale

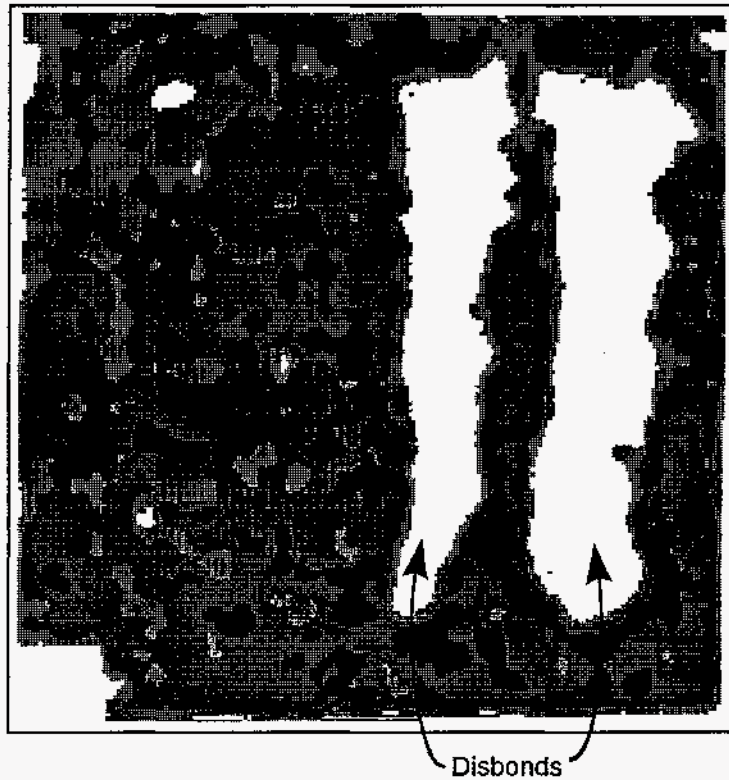


Figure 3. C-scan image of the through transmission amplitude for a 305 mm square test sample of the composite bond and steel insert where 2 disbonds were constructed into the adhesive interface.

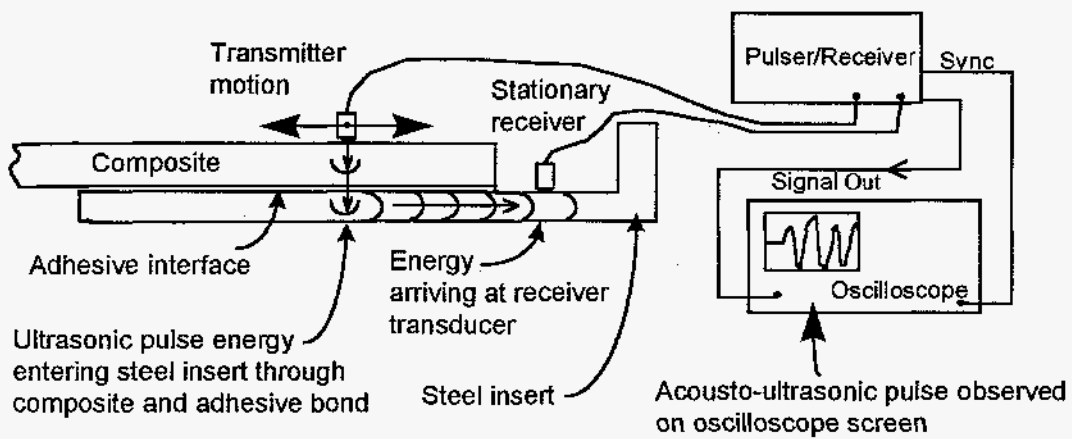


Figure 4. Schematic diagram of the acousto-ultrasonic technique as applied to the root bond area at the steel insert of a wind turbine blade.

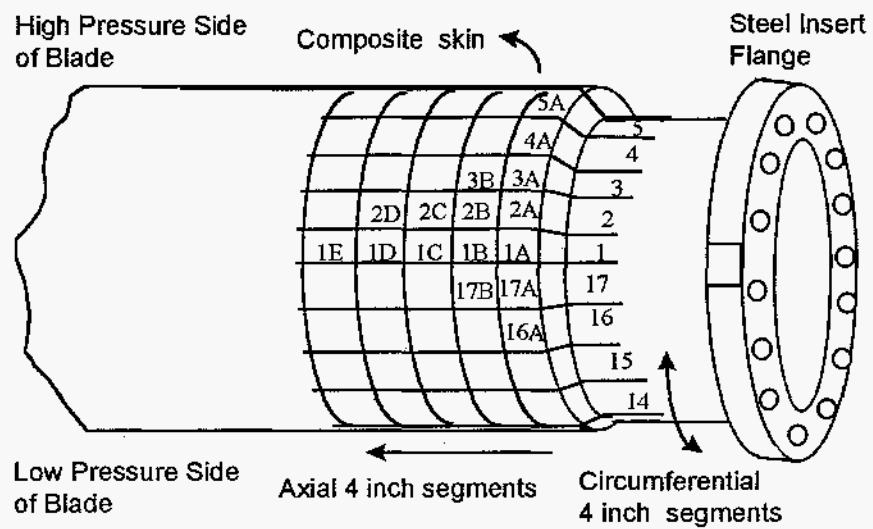


Figure 5. Diagram of the layout of the grid lines scribed on the wind turbine blade at the root bond area of the steel insert.

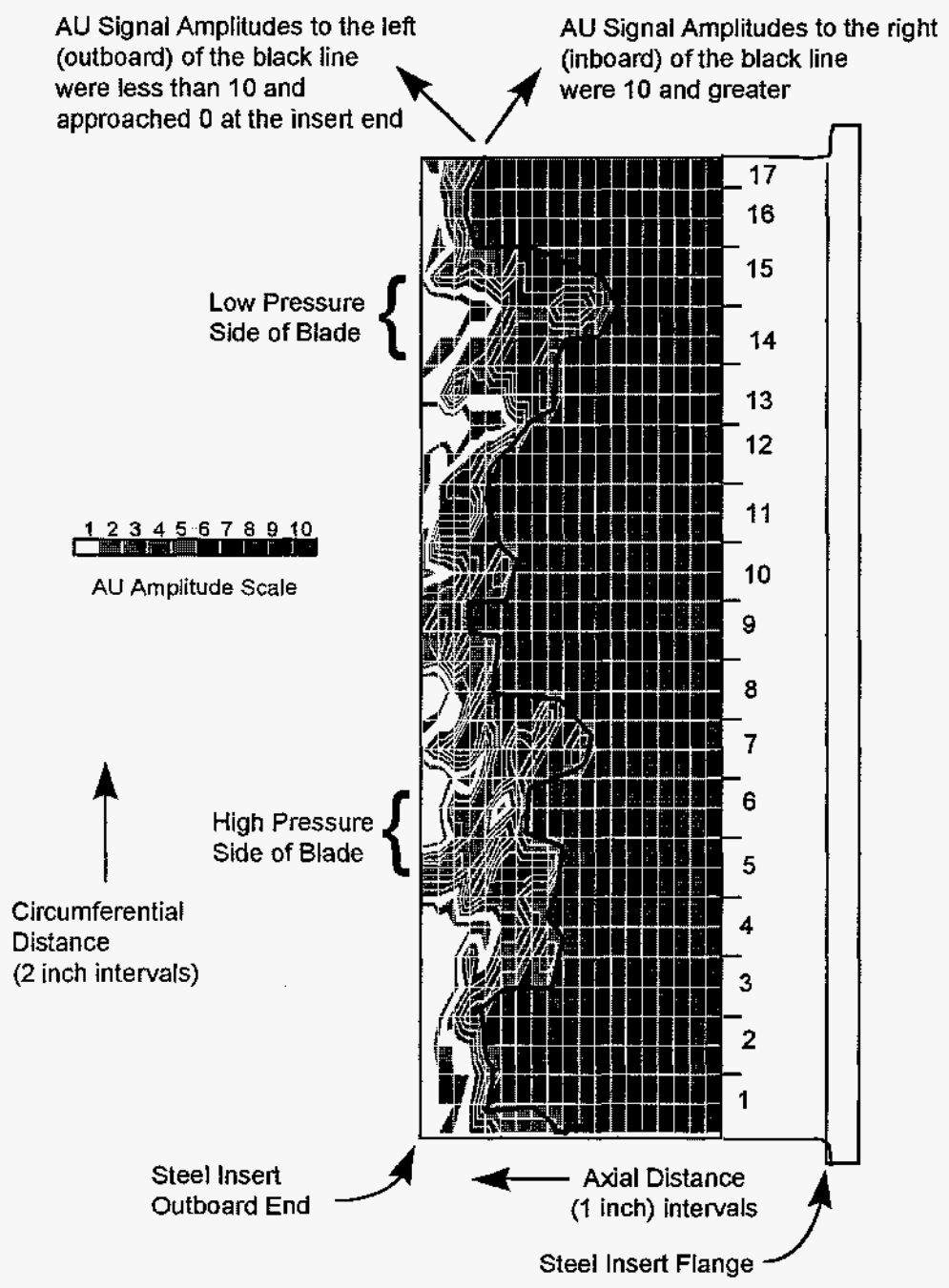
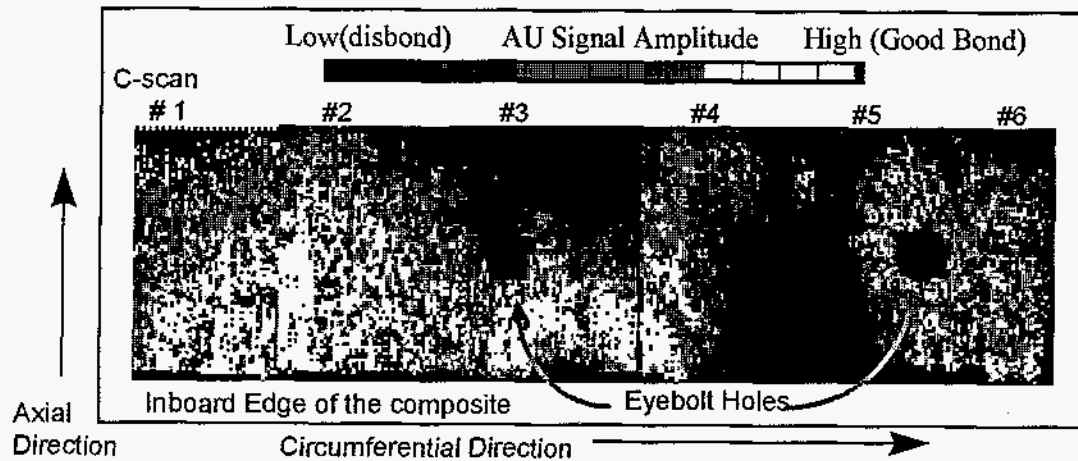
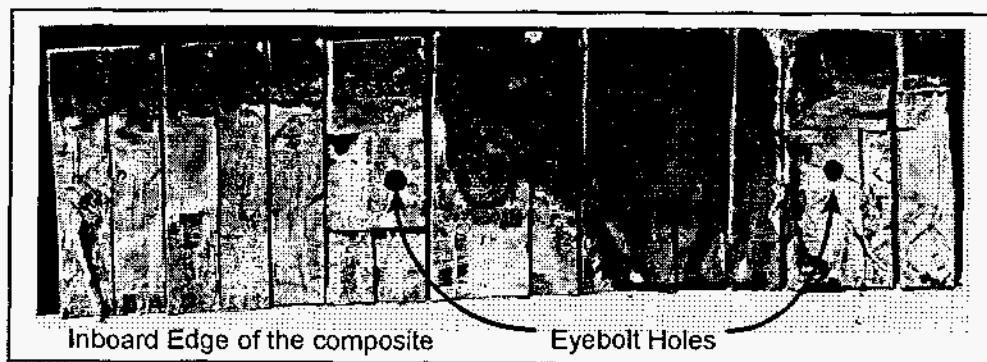


Figure 6. Contour plot of the amplitude levels of acousto-ultrasonic signals taken around the root bond area at a steel insert of a wind turbine blade.

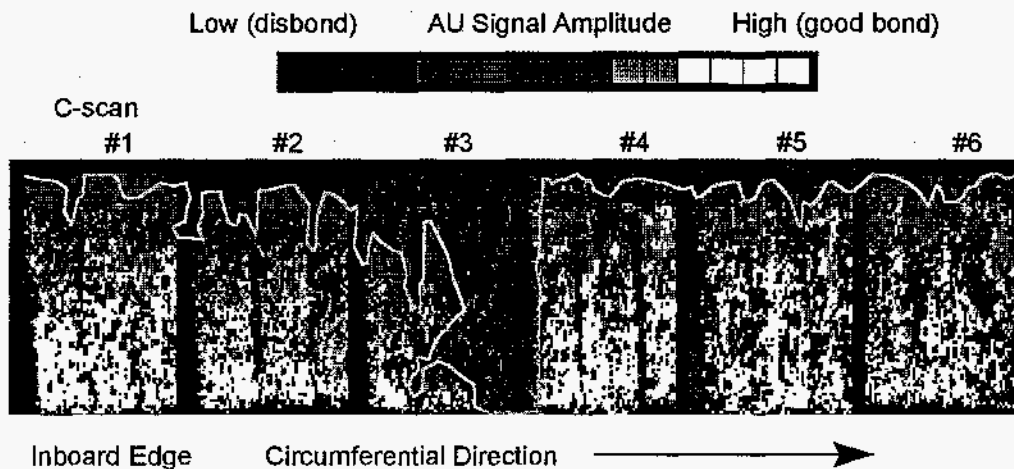


(a) Acousto-ultrasonic Amplitude C-scan Image of Entire Root Bond Area of the Steel Insert

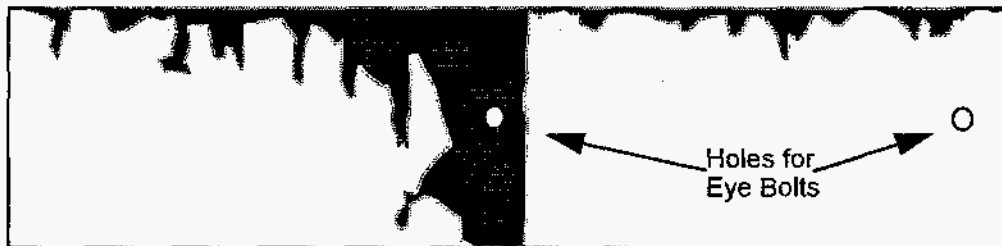


(b) Photograph of Pieces of the Composite Removed from the Steel Insert Root Bond Area in Sections Placed Together in the Same Orientation as the above C-scan Image

Figure 7. C-scan image (a) of the AU signal amplitude taken over the root bond area compared with a photograph (b) of the same area after the composite skin was removed from the steel insert of a wind turbine blade.



(a) Acousto-ultrasonic Amplitude C-scan Image for the Entire Root Bond Area of the Steel Insert for Turbine Blade #3



(b) Processed AU Signal Amplitude Showing All Signals Below a Threshold Value in Black

Figure 8 . C-scan image (a) and processed data (b) of the AU signal amplitude taken over the root bond area at the steel insert of a wind turbine blade.