DISBOND DETECTION IN BONDED ALUMINUM JOINTS USING LAMB WAVE AMPLITUDE AND TIME-OF-FLIGHT

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INTRODUCTION

In recent years, there was a need of developing efficient nondestructive integrity assessment techniques for large area laminate structures, such as detections of disbond, crack, and corrosion in fuselage of an aircraft. Together with the improving tomography and computer technologies, progress has been made in many fields in NDE towards a faster inspection.

Ultrasonically, Lamb wave is considered to be a candidate for large area inspections based on its capability of propagating a relatively long distance in thin plates and its media-thickness-dependent propagation properties [1-2]. Moreover, the occurrence of disbonds, corrosion, and even cracks often results in reduction of effective thickness of a laminate. The idea is to assess the condition of a structure by sensing the response of propagating Lamb waves to these flaws over long path length [3-4]. A series of tests in the sequence of disbond, corrosion, and crack have been done on various types of specimen to investigate the feasibility of this approach. This paper will present some of the test results for disbond detection on aluminum lap splice joints.

MEASUREMENTS AND TEST RESULTS

Laboratory specimens were made of aluminum sheets of 1 mm in thickness. Lap splice joint and doubler are the two geometries of structures primary interest [4]. The width of adhesive-bonded area in a lap splice joint or a doubler was typically 5 cm, and the thickness of adhesive layer(mostly, epoxy) was approximately 200 micrometers or less. Lap joints both with and without rivet holes were fabricated in order to see the effects of rivet rows on wave propagation. For testing, various sizes, shapes, and locations of disbonds in the interface of aluminum sheets were built in by leaving the designated areas free of epoxy when the sheets were adhered.

To propagate Lamb waves, a pair of piezoelectric transducers was placed on top of the aluminum specimen and was separated at a distance, which covers the whole bonded region of a lap joint or a doubler. Water was the couplant between transducer and aluminum plate. Pulsed, pitch-catch method was utilized for amplitude and time-of-flight measurements. Low-order Lamb modes, excited at a frequency in the range from 1 to 2 MHz, propagated across the bonded area with direction perpendicular to the length of the bond. During the testing, an automated scanner carried the transducer-pair moving in parallel to the length of the bond. At each location of the transducer-pair, amplitudes of the two predominant signals, the lowest-order symmetric Lamb wave (S0 mode), which was the first arrival, and antisymmetric mode (A0 mode), were monitored by peak detectors. Time-of-flight (T_0) of waves was obtained through a pulsed-phase-locked-loop circuitry in terms of frequency [5]. The percentage of change in frequency indicates the percentage of change in T_0. At the end of test, amplitude and time-of-flight as a function of transducers' position were plotted and used to locate disbonds. Scanning rate could be adjusted depending on the smoothness of the surface. The ultimate limit of time interval between acquisitions of two data points is approximately 60 microseconds, which is based on a 20 cm separation distance between transducers, and the velocity of the slower A0 mode is approximately 3.0 mm/µs in the working frequency range. Generally, a round trip of scanning was enough to average out fluctuations in magnitude of amplitude resulted from the movement of transducers. In all of our measurements on different specimens, data was repeatable with less than 10% uncertainties. A block diagram illustrating the setup for the measurement is displayed in Figure 1.

In order to assure bond quality of the fabricated specimens and to determine the actual size of any built-in disbonds, several of the laboratory samples were also inspected by a standard ultrasonic test c-scan performed in a water bath with a 5 MHz or a 10 MHz, 0.5 in diameter immersion transducer. Data was taken at approximately every 2.3 mm. Adhesive tapes were used to prevent water from penetrating into the interface and epoxy layer, which may create some artifacts due to the scattering of waves by the edges of tapes.

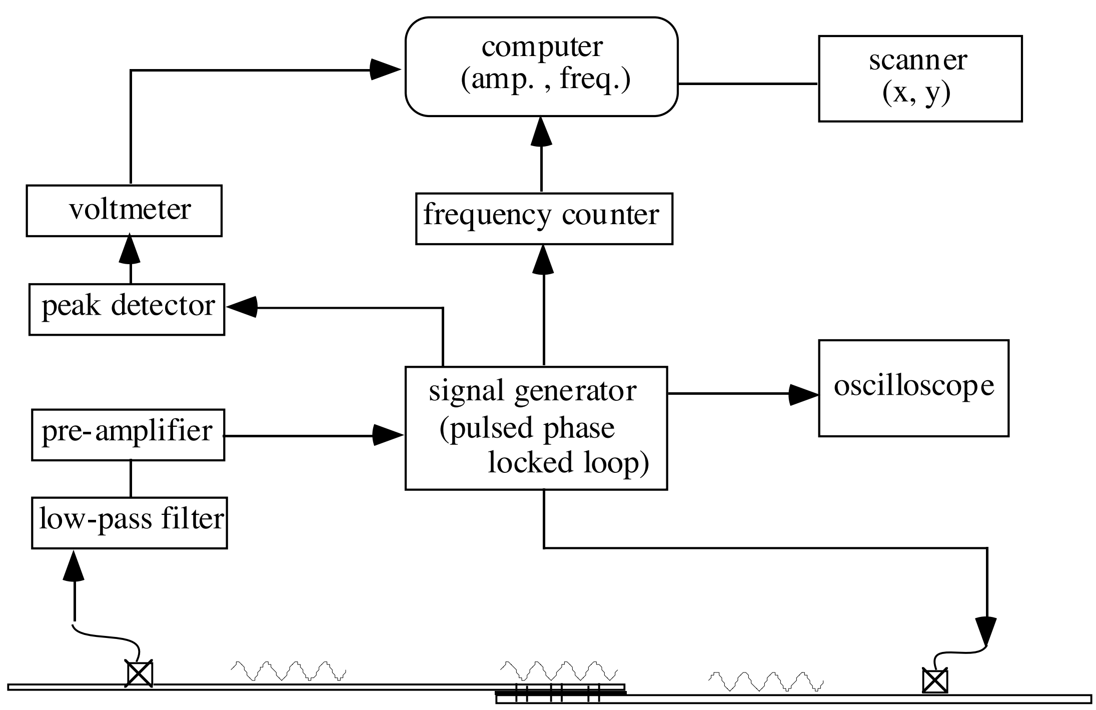

Figure 1. Block diagram of setup for Lamb wave measurement.

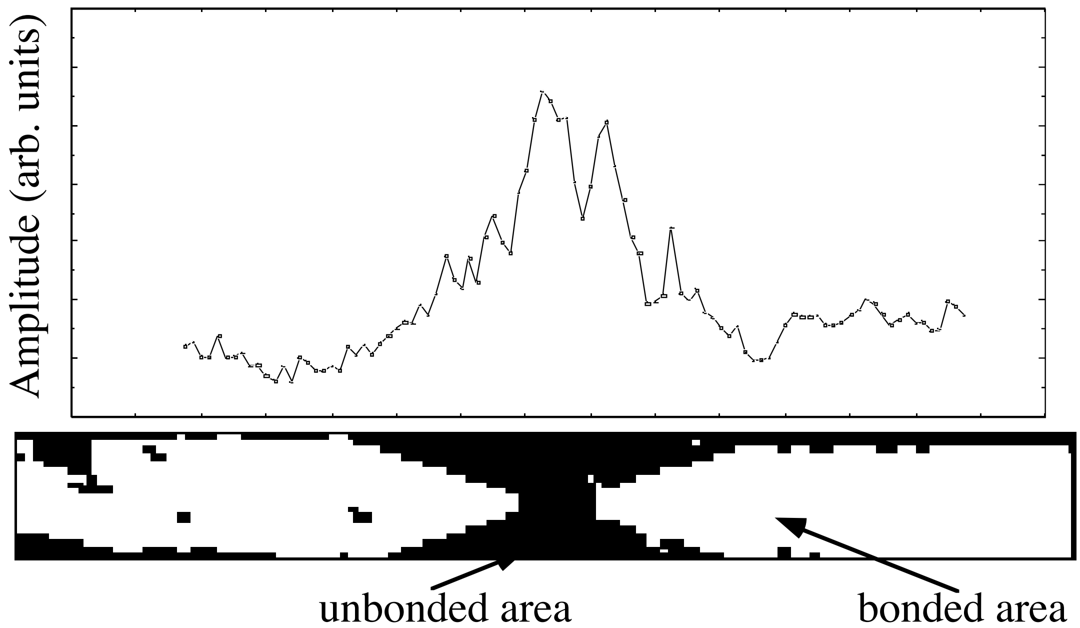

Figure 2. Curve shown is the amplitude variation of S0 mode as a function of transducer-pair's position. The image is obtained with UT c-scan for a doubler. The dark "I" shaped area is the designated unbonded area. Amplitude increases while wave propagates across the disbond area.

However, these artifacts can be recognized easily. The UT c-scan results were also used to compare with those obtained with Lamb waves technique quantitatively.

Curve shown in Figure 2 is the amplitude variation of Lamb waves vs. transducer-pair position taken on a doubler. This fabricated specimen has a "I"-shaped and all-way-through disbond as illustrated in the image of UT c-scan (bottom graph in Figure 2). As displayed, significant amplitude increase was observed when waves passed through areas with disbond, and its increased magnitude was proportional to the propagation path through disbond. Lamb waves are in-plane waves. Their amplitudes signify the integrated result of interactions of waves with material and structure over their path. Therefore, location of a disbond and percentage of areas with disbond(s) in the path of waves can be estimated with comparison method. However, the estimation may become misleading when there are multi-site disbonds. In this regard, measurement of time of flight would give additional information, since difference in wave velocity in bonded area and unbonded area has been observed.

Similar results were obtained for embedded disbonds. Figure 3 exhibits changes of amplitude when the transducer pair was moved in parallel to as well as in perpendicular to several doublers. In the former case, amplitude remained relatively constant until waves hit the disbonds. In the latter, signal level is relatively high when the path of wave is totally within single layer areas, and relatively low when the path is completely within bonded areas. As a matter of fact, the observed time-of-flight of waves is slightly different in the two areas. And, it is believed that waves propagated in a different mode in each area. Again, amplitude increased whenever there was a through or embedded disbond in the path of wave beam.

The amplitude increase of sound wave in disbond area can be attributed to less energy transferred to the bottom layer of a doubler. This interpretation became more evident

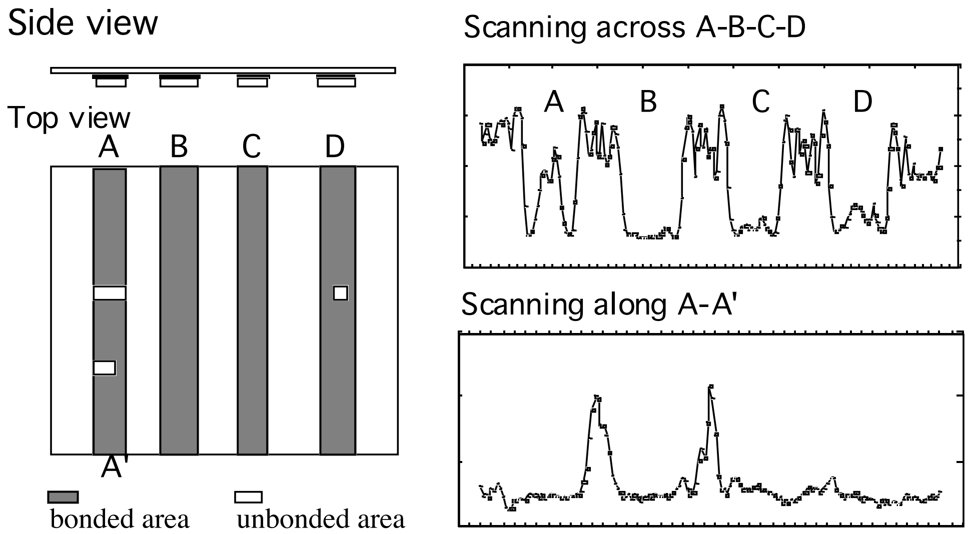

Figure 3. Geometry of a multi-doubler specimen is shown on the left. Amplitude variations are exhibited on the right with the scanning directions as indicated respectively.

when the same measurements were performed on a lap splice joint. For a lap joint, the bondline is the only mechanical connection between the two plates, and the amount of wave energy passing from one plate to the other is thus heavily dependent of bond quality. A disbond decreases the energy propagating in upper plate transferred to bottom plate, and results in a reduced amplitude picked up by a receiver transducer placed on it, which is what we observed. Figure 4 shows the results of measurement on an aluminum lap joint. Again, data was taken when the transducer-pair moved in parallel to the long dimension of the joint, with one transducer placed on each plate. Disbonds with dimensions 2 cm x 2 cm, 2 cm x 3 cm, 3 cm x 2 cm were built in for test. As can be seen, corresponding to four disbonds, there are four valley-like minima shown in the curve whose locations are coincident with the

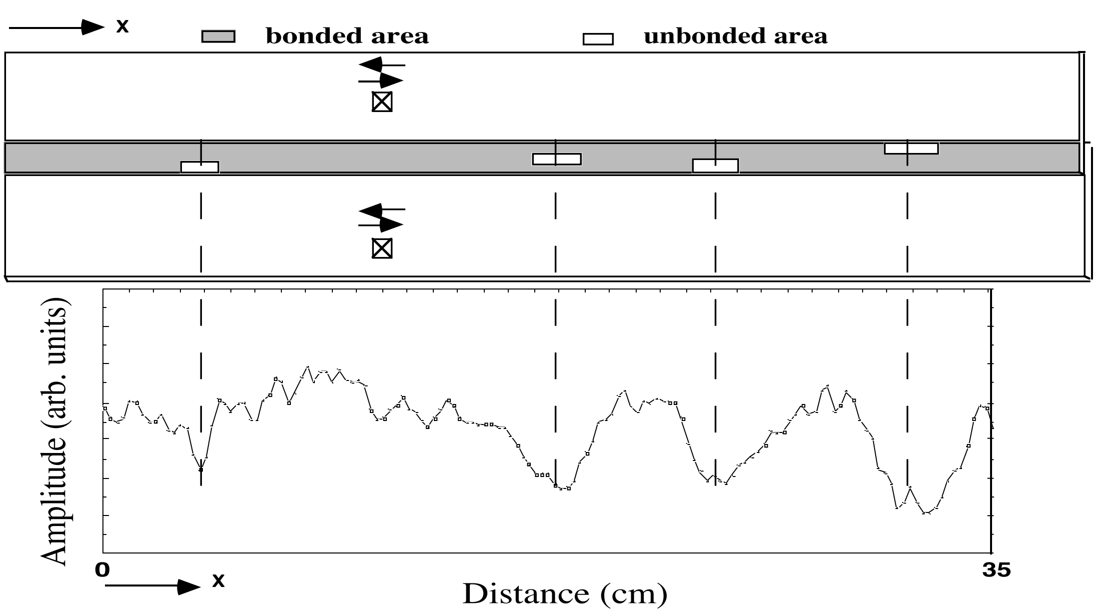

Figure 4. Amplitude variation of S0 mode as the transducer-pair scans in parallel to the long dimension of a lap splice joint. Locations of the minima in the curve are coincident with those of the built-in disbonds.

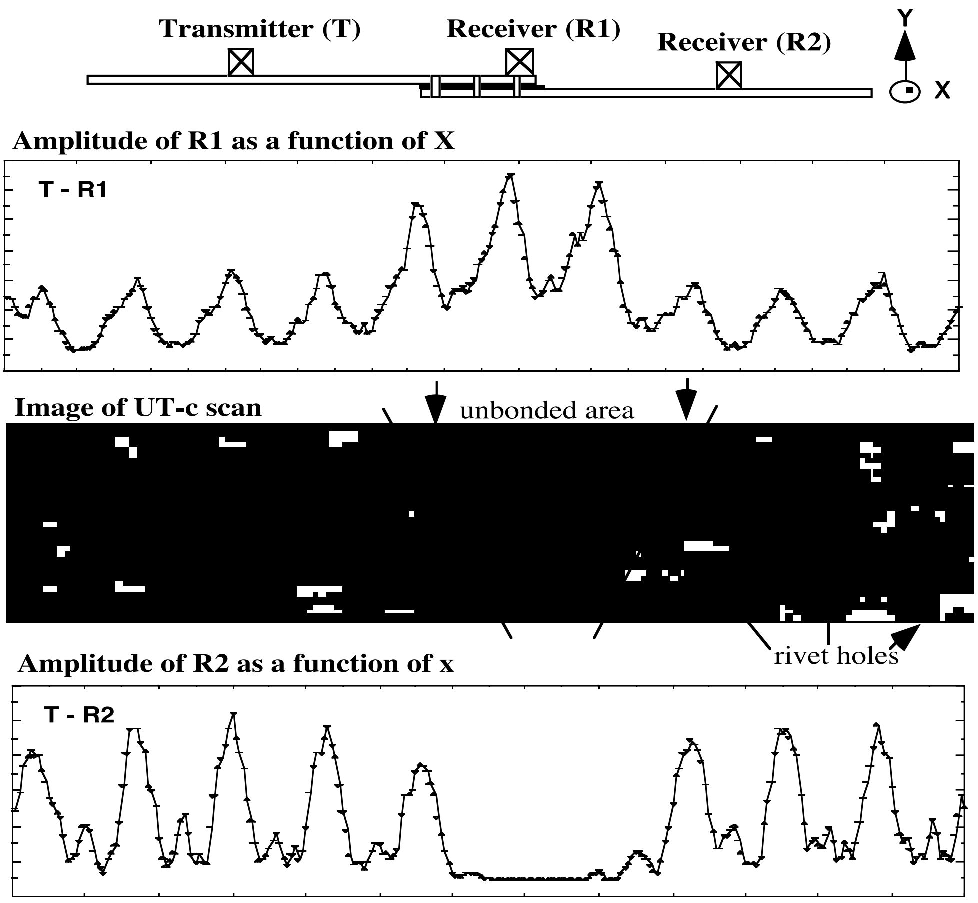

Figure 5. Curve shown at the top is amplitude as a function of transducer-pair's position when both transducers are placed on the top plate of a lap joint. Displayed in the middle of the figure is UT c-scan image of the specimen with disbond as indicated. Curve on the bottom is also the amplitude variation but when the transducers are on the different plates.

centers of fabricated disbonds. The amplitude decreases with a slope instead of a sharp drop to the minimum at each site because of the finite size of the defects and the sound beam.

Samples of lap splice joint with rivet were also tested and the amplitude variation pattern is more involved due to the scattering of waves by column of rivets. The typical diameter of a rivet is 0.7 cm, and that of a transducer used in our measurements is 1.27 cm. A portion of the transmitting wave would be scattered to other directions when the transducer-pair is aligned with the column of rivets, which results in a significant decrease in received amplitude. Therefore, a periodic up-and-down change in amplitude is observed when transducer-pair is scanned along a joint with evenly-spaced rivet columns. This periodic change adds some complexity in data interpretation for the disbond detection. Fortunately, the response of wave to a disbond of size larger than □cm in diameter is quite pronounced, and can be recognized. As a matter of fact, the disappearance of periodicity in amplitude variation can be used to determine the existence of defects. This approach was used in analyzing data collected from measurements engaged on lap joints in the skin of a Boeing 747 aircraft. Results were fairly consistent with those obtained by using other techniques and by visual inspection after this particular section of lap joint was removed from the aircraft and torn apart. Figure 5 exhibits the results of scanning on a laboratory-fabricated specimen. This epoxy-bonded sample has three rows of fasteners. The round black dots shown in the UT c-scan image indicate the positions of fasteners. Curve shown below the image is amplitude variation of the lowest order symmetric (S0) mode as a function of position of transducer-pair when each of them is on different plates. The peaks represent the maximum wave energy propagating between rivet columns. As discussed above, disbond would prevent transfer of wave energy between plates, which has resulted in a flat line in the curve meaning minimum energy is received. The small peaks located at the positions of rivet columns are the result of diffraction of waves by rivet column, and whose magnitude is quite dependent of the bond condition in the area surrounding the rivets and the distance between transducers. For comparison, curve displayed above the c-scan image is the amplitude changes when both transducer are placed on the upper plates. As can be seen, a larger amplitude reveals the existence of disbond, which is similar to what has been observed for doublers (figures 2 and 3). Amplitude variations of the lowest antisymmetric (A0) mode were also measured and displayed similar behavior to those of S0 mode. However, A0 mode seems more sensitive to unevenness in thickness of bondline. This could be due to the much smaller wavelength of this mode.

In general, velocity of Lamb wave is not only frequency dependent but also thickness dependent. To the propagation of Lamb waves, a disbond represents a relatively large decrease in effective thickness of the media, which could result in change of wave mode and/or change of velocity. A pulsed-phase-locked-loop was employed to monitor the change of velocity. This instrument compares the phase of its pulsed output signal (which is sent to transmitting transducer) with that of the returned signal (from the receiving transducer). Phase difference of the two signals varies with the change of sound velocity propagating in the medium when distance between transducers is fixed. Before the scanning a certain phase difference is chosen and locked. During the scanning, the loop responds to the sound velocity change by adjusting its output signal frequency (called reference frequency) in order to keep this phase different constant as it was locked. Therefore, a reading from a frequency counter would reveal the information of velocity changes. In fact, it can be proved that the percentage of increase in reference frequency is the percentage of decrease in time-of -flight. Figure 6 displays the change in reference frequency for the specimen with disbond shown in figure 5 in the case when two transducers were placed on different plates. As can be seen, reference frequency decreases in the area where there is a

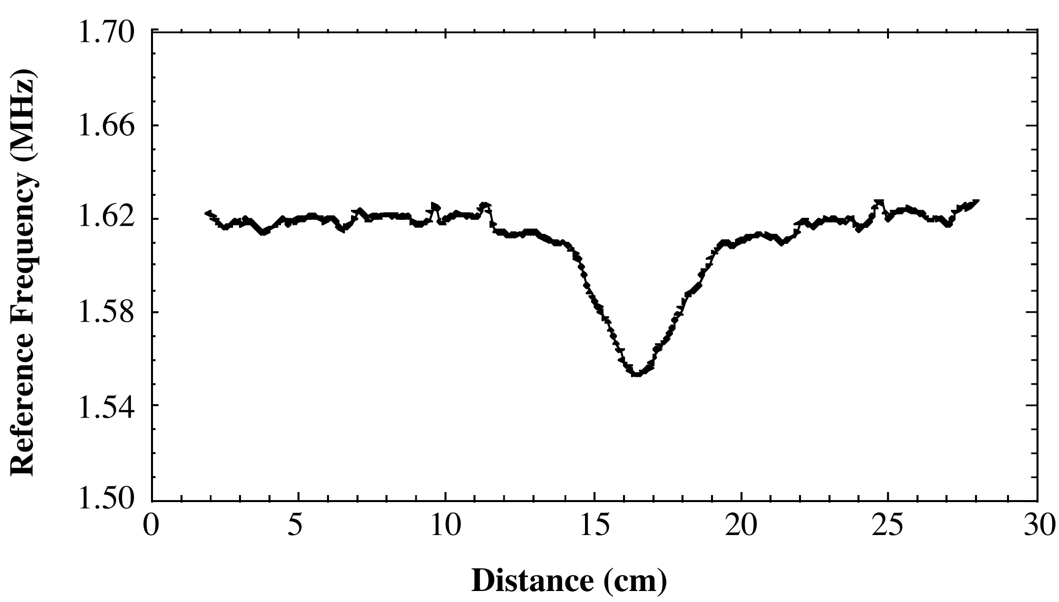

Figure 6. Curve shown is the variation of time-of-flight as a function of transducers' location. A decreased reference frequency represents the longer time-of-flight caused by a disbond.

disbond in the wave propagation path, and the magnitude of change is proportional to the dimension of disbond in the direction of propagation. For this specimen, disbond causes longer time-of-flight, which indicates a slower wave velocity. The small kinks appeared in the relatively flat portion of the curve are found to locate at edges of rivet columns, and are ascribed to the interference effect of waves.

DISCUSSION

With the described measurements and results, it is demonstrated that Lamb wave has promising potential for detection of disbonds, at least, in a two-layered structure. Although most of the tests were done on laboratory-fabricated specimens, field test on aircraft panel also showed reasonably good results. One of the advantage of utilizing Lamb wave is its capability of assessing the condition of layered structure over a long path length. The provided results are the integrated information of its path. If detailed information at each locations between the transducers is not crucial for an assessment, then this is an approach much more efficient than conventional point-by-point ultrasonic measurements. Especially for a specimen geometry, such as that of a lap joint, a one-dimensional scan should provide the necessary information for disbond evaluation. Otherwise, a second scan in the other dimension can be performed and would give the exact location of disbond.

Disbond detection for structures having more than two layers has not been tested intensively yet. In theory, if Lamb wave can be generated in a multi-layered structure, a disbond occurred in any one of the interfaces should be able to be detected. However, in this case, the wave energy distribution may become an intriguing problem and eventually determine what modes can be generated with measurable amplitudes, because the particle displacement is a function of depth from the surface and this property of Lamb wave may become critical when media thickness is not much smaller than the wavelength.

In summary, it is feasible using Lamb wave for a large area disbond assessment. Relatively simple amplitude and time-of-flight measurements on lap joint type structures have demonstrated this capability although there are many improvements can be done in terms of increasing the inspection speed and setup for the measurements.

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REFERENCES

1. D. C. Worlton, J. Appl. Phys., 32, 967 (1961)
2. T. R. Meeker, and A. H. Meitzler, in Physical Acoustics, vol. I, part A, 111, edited by R. N. Thurston (Academic Press, Inc. 1964)
3. K. J. Sun and D. Kishoni, IEEE 1991 Ultrasonics Symposium Proceedings, 859 (1991)
4. K. J. Sun and P.H. Johnston, IEEE 1992 Ultrasonics Symposium Proceedings, 763 (1992)
5. J. S. Heyman and E. J. Chern, Journal of Testing and Evaluation, vol. 10, No. 5, 202 (1982)