TO THE DETECTION OF BONDLINE FLAWS IN RUBBER/METAL LAMINATES

A COMPARISON OF THE SENSITIVITY OF TRANSVERSE AND LAMB WAVES

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INTRODUCTION

The use of adhesively-bonded structures is prevalent throughout the Navy since watertight rubber-to-metal bonds are required on many undersea systems including sonar transducers and electrical cables. In addition, adhesive bonds are used to transfer loads between rubber and metal adherends for limited structural applications. However, in each case the principal function of the adhesive bond is to provide watertight integrity for the bonded components in the hostile ocean environment where corrosion is of major concern.

Unfortunately, reliable rubber-to-metal bonds are difficult to make and to maintain in service. During manufacture, contamination of the material surfaces to be bonded often occurs and latent defects (potential disbonds) are in essence built into the structures. During service, these latent defects can grow under load and cause water leaks, as well as degrade mechanical integrity. Thus, the problem is how does one determine that a satisfactory adhesive bond has been produced initially and that the bond maintains the desired properties during a structure's lifetime?

The nondestructive evaluation (NDE) of adhesive bonds to determine initial quality, as well as forecast reliable performance, is difficult at best. Conventional NDE approaches such as normal incidence pulse-echo ultrasonics cannot discriminate poorly-bonded from well-bonded areas. The acoustic impedance between commonly used rubbers and steel is not much different than that between water and steel. Thus, the reflection coefficients at the interface are approximately the same in both cases.

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What are needed are more sensitive NDE techniques that can detect manufacturing defects and service-induced flaws with high reliability - defects and flaws which are insidious in their nature. For example, a manufacturing "unbond" can be so tightly closed that the rubber is in intimate contact with the steel but no significant bond strength exists.

To address the problem of inspecting rubber/metal adhesive bonds from the point of view of determining bond quality, new ultrasonic NDE techniques based on propagation of ultrasonic guided waves in elastic layered media are being investigated, especially the application of Lamb (plate) waves and bulk transverse (shear) waves. Lamb waves have the advantage that they generate both shear and longitudinal stresses, and their behavior depends on material properties as well as boundary conditions. This paper compares the sensitivity of Lamb waves to that of transverse shear waves for adhesive bond flaw detection and characterization in rubber/metal laminates.

EXPERIMENTS

Description of the Methods

Thin plates on the order of 0.01 in. to 0.25 in. support the excitation of Lamb waves within the range of frequencies from 1.0 to 10.0 MHz commonly used in ultrasonic NDE. Physically, Lamb waves are vertically polarized travelling plate waves [1]. They may be excited under immersion conditions (e.g., in water) by external compressional waves impinging on the surface of a plate at an oblique incidence angle. Mode conversion occurs, and transverse and/or longitudinal waves are created in the plate. These waves undergo refraction and reflections at the plate boundaries and interference (constructive and destructive) within the plate to yield the Lamb or plate waves. If the relative acoustic impedance of the surrounding medium is similar to that of the plate, the plate will "leak" or radiate energy into the medium (water) that can be detected as a longitudinal wave. Lamb wave phase velocity and Snell's law determine the angle of radiation.

The modal pattern established in the plate depends on the driving frequency, the angle of incidence, the plate thickness, and, if there is more than one layer in the plate, the acoustic characteristics of the interfacial boundaries. For fixed geometry and fixed frequency, the modes excited will depend on the characteristics and nature of the boundaries. This dependence is the basis for evaluating rubber-to-metal bonds using leaky Lamb waves.

At incidence angles greater than the first but less than the second critical angle, bulk shear waves can be generated in the plate by mode conversion. For sufficiently thick plates (on the order of the wavelength of sound in the plate), these waves propagate as bulk waves that can be observed in the surrounding medium as discreet signals. The effect of acoustic impedance mismatch, as measured by the varying reflection coefficients at interfaces in a layered plate, enables transverse waves to be indicators of bond flaws in rubber-to-metal bonds.

Parameters Investigated

In this work, various thicknesses of steel plates (1/16, 1/8 and 1/4 in.) were investigated for a constant rubber thickness of 1/8 in. Surface preparation prior to bonding was also varied; for example, the surfaces were sanded or not sanded, were coated with adhesive or not coated, and were contaminated (with mold release) or not contaminated. A standard method of bonding neoprene rubber to the prepared steel plates was used as described previously [2]. Frequencies of 0.5, 1.0 and 5.0 MHz were used at incidence angles of 20° (> first critical angle in steel) and 30° (> second critical angle in steel). Specimens of the type shown in Fig. 1 were used for both the Lamb wave and the shear wave experiments. Note on the left side of Fig. 1, that approximately one third of the specimen had no rubber bonded to it. This is the "bare" area that had subtly different surface preparation, i.e., bare but sanded and bare but not sanded.

Instrumentation

The experimental set up is shown in Fig. 2. A Data Precision Model 2020 Polynomial Waveform Synthesizer was used with a Data Precision Model 6000 Waveform Analyzer as the basic means of generating and receiving ultrasonic signals of the desired wave shape and duration, e.g., tone bursts. An ENI Model 240L RF Power Amplifier provided high voltage to the transducers. Harisonic immersion transducers (0.5, 1.0 and 5.0 MHz) were used in matched pairs for generating and receiving ultrasonic signals. The transducers were mounted in a pitch-catch arrangement on a Compumotor-based scanner described elsewhere [3]. Finally, an H-P 82315A "Vectra" PC-308 Computer/Controller with an H-P 7475A six-pen color plotter was used to control the scanning and to acquire, analyse and display the data. The software used with the Vectra was developed in-house.

EXPERIMENTAL RESULTS

Selected results of the experiments designed to compare the relative sensitivities of transverse waves and Lamb waves to the detection of bondline flaws in adhesively-bonded rubber/metal laminates are presented in this section. In addition to the two incidence angles (20° and 30°) used, the separation distance between transducers (as measured at the center of each transducer face) and the lift-off of the transducers above the specimen (as measured from the centers of each transducer face to the specimen) were varied as required to improve resolution of the mode-converted transverse and Lamb waves. The steel side of the specimen always faced the transducers.

Figure 3 compares the results of transverse wave and Lamb wave inspections on a 1/16 in. thick steel plate with 1/8 in. of neoprene rubber bonded in the pattern shown in Fig. 1 using 1.0 MHz transducers and tone-burst excitation. The transducer separation distances and the lift-offs were as indicated in Fig. 3. Note that at 1.0 MHz, the plate thickness of 1/16 in. is much less than the wavelength of sound in the plate and bulk shear waves are not established. Thus, the two methods give essentially the same results because of the quasi-plate wave behavior in both cases.

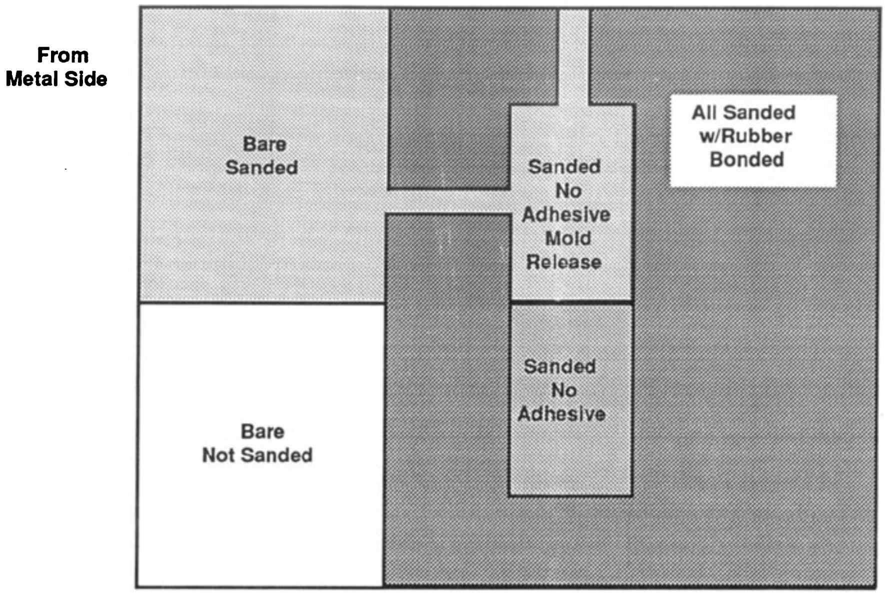


Fig. 1 Specimens

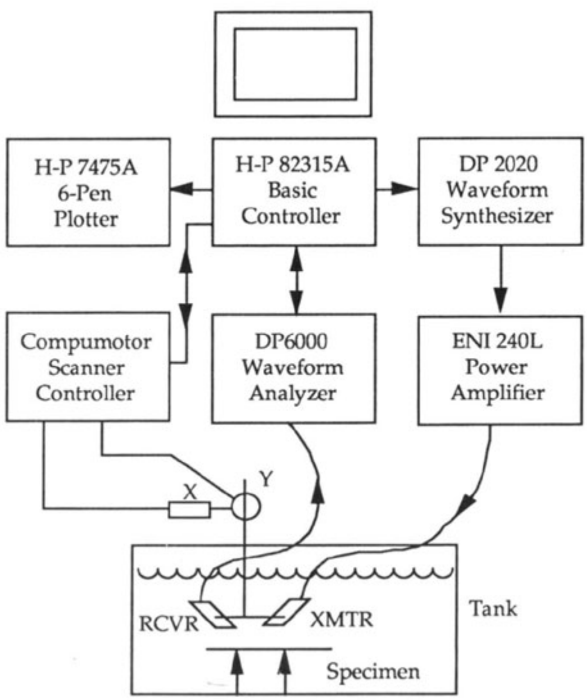
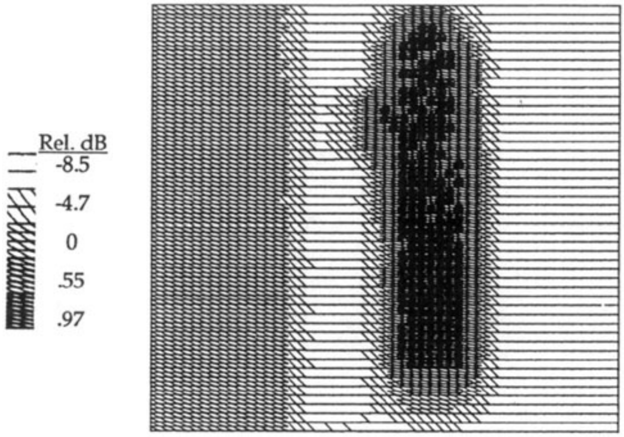
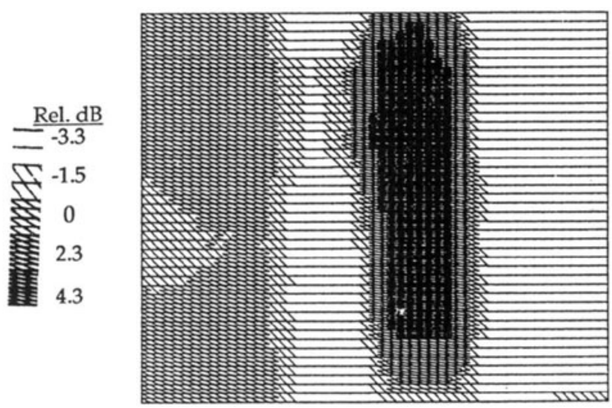


Fig. 2 Block Diagram of Instrumentation



a. 20° Incidence, 0.88 in. Separation, 0.05 in. Lift-Off

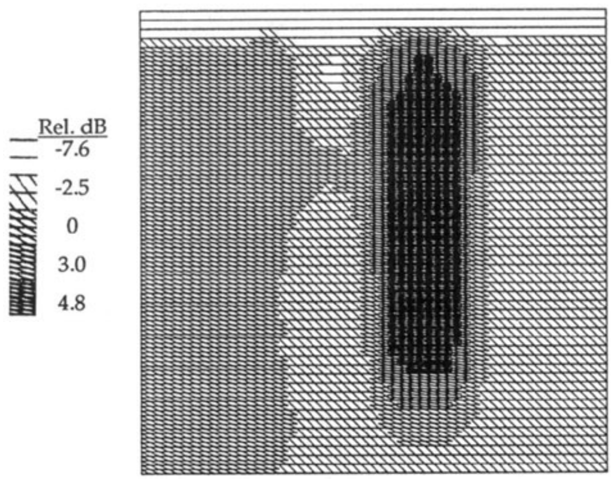


b. 30° Incidence, 1.40 in. Separation, 0.01 in. Lift-Off

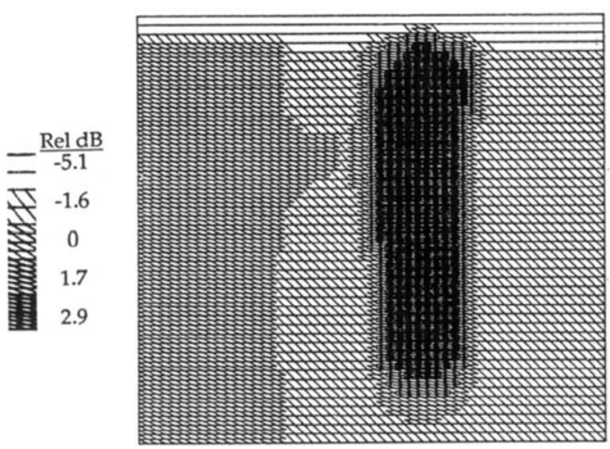
Fig. 3 Comparison of Transverse Shear Wave and Leaky Lamb Wave Results on 1/16 in. Steel Plate (1/8 in. Rubber Layer)

Figure 4 shows results similar to those above but for a steel plate thickness of 1/8 in., rubber thickness of 1/8 in. and a frequency of 1.0 MHz. As in the case of the 1/16 in. thick plate at 1.0 MHz, the 1/8 in. plate thickness is less than the wavelength of sound in steel. Bulk shear waves are not established and again the waves propagate as quasi-plate waves.

For the case where the wavelength in steel is on the order of the plate thickness, i.e., 1 MHz and 1/4 in. thickness, the results are shown in Fig. 5. In this case the transverse shear wave gives the higher sensitivity (better image) of the bondline flaws shown previously in Fig. 1.

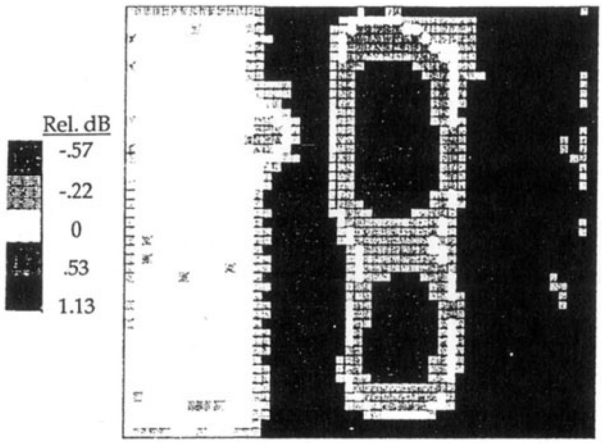


a. 20° Incidence, 0.88 in. Separation, 0.03 in. Lift-Off

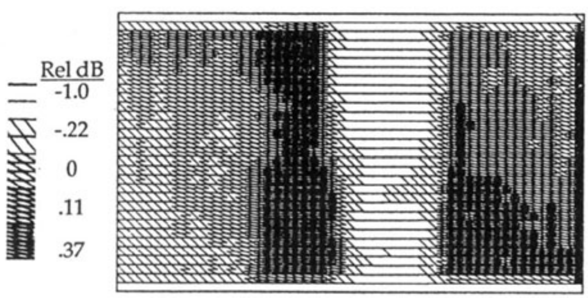


b. 30° Incidence, 1.30 in. Separation, 0.01 in. Lift-Off

Fig. 4 Comparison of Transverse Shear Wave and Leaky Lamb Wave Results on 1/8 in. Steel Plate (1/8 in. Rubber Layer)



a. 20° Incidence, 1.88 in. Separation, 1.23 in. Lift-Off



b. 30° Incidence, 2.86 in. Separation, 0.01 in. Lift-Off

Fig. 5 Comparison of Transverse Shear Wave and Leaky Lamb Wave Results on 1/4 in. Steel Plate (1/8 in. Rubber Layer)

CONCLUDING REMARKS

From the results of this investigation, it is concluded that:

- For thin substrates less than the wavelenth (e.g., 1/16 in. and 1/8 in. at 1 MHz), the results of transverse shear wave and leaky Lamb wave measurements are essentially the same. This is attributed to the quasi-plate wave behavior in both cases, i.e., the steel layer is so thin compared to wavelength, that bulk shear waves are not established.

- For thicker substrates less than the wavelength (e.g., 1/4 in. at 1 MHz), the transverse shear wave method provides higher sensitivity to bondline flaws of the type used in this investigation.

- Both transverse shear and Lamb guided waves provide excellent sensitivity compared to conventional pulse-echo methods employing only longitudinal waves.

ACKNOWLEDGEMENT

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3. C.M. Teller, et al., J. Adhes., in press.