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The main objective of the current work is to develop a practical nondestructive inspection methodology for a highly sound absorbing composite structural system consisting of polymeric and metallic materials. Due to constraints in geometrical shapes and thicknesses of the composite system used in this work, ultrasonic guided wave approach has been chosen. Since the polymer coatings have high damping properties, less energy is dissipated into the adjacent media in the presence of interface delaminations. Experimental measurements performed on a targeted composite system, whether it has an aluminum, carbon-fiber-composite, or steel outer casing, show promising results.

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Quantitative Diagnostics of Multilayered Composite Structures with Ultrasonic Guided Waves

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Abstract. The main objective of the current work is to develop a practical nondestructive inspection methodology for a highly sound absorbing composite structural system consisting of polymeric and metallic materials. Due to constraints in geometrical shapes and thicknesses of the composite system used in this work, ultrasonic guided wave approach has been chosen. Since the polymer coatings have high damping properties, less energy is dissipated into the adjacent media in the presence of interface delaminations. Experimental measurements performed on a targeted composite system, whether it has an aluminum, carbon-fiber-composite, or steel outer casing, show promising results.

INTRODUCTION

Aging infrastructure has a major impact on safety, increasing awareness of the need to assess damage severity. Technical machinery, systems and components, i.e. airplanes, cars, pumps, pipes in oil and chemical industry, are subject to varying cyclic service loading and environmental influences. Sometimes multilayered coatings are used requiring a high resolution inspection to confirm the presence of a defect such as a delamination and accurately locate and quantify its size [1]. Highly attenuating materials may significantly increase the inspection time while limiting defect observability. For several decades, guided waves have been recognized as having excellent potential for nondestructive inspection. However, the presence of viscoelastic coatings that are used for corrosion protection is one of the major obstacles for guided wave inspection [2].

A large number of researchers have been interested in the application of ultrasonic guided waves for nondestructive inspection of plate and tube-like multilayered structures [3, 4, 5, 6, 7, 8, 9, 10]. Guided waves are more and more used for ultrasonic nondestructive testing applications [11]. Compared to standard ultrasonic bulk waves, guided waves have the main advantage of insonifying large sections of tested structures, thus reducing the inspection time [12, 13]. Generally, guided waves propagate along the mid-surface of thin-wall shells and plates. They can travel at relatively large distances with very little amplitude loss and offer the advantage of large area scanning. However, guided waves inspection techniques can be complicated by the existence of many possible propagating modes and by the dispersive nature of the modes [14]. These propagation modes are characterized by a variable sound speed as a function of the frequency-thickness product. For example, Figure 1 shows the dispersion curves of guided waves propagating in an aluminum plate. In practical applications, it is generally desirable to excite a single propagating mode in order to simplify the interpretation of the received waveforms.

The main goal of this study was to investigate the feasibility of applying ultrasonic guided waves to detect internal delaminations inside multilayered composite structures. A secondary objective was to develop light, low profile interdigitated transducers (IDTs) for interrogating entire targeted sections of multilayered composite structures by selectively exciting only one mode of guided waves in these structures [15]. Being a less dispersive mode at low frequency-thickness, the symmetrical mode, S_0, was chosen for this application. For the symmetrical mode, the particle motion is perpendicular and symmetric to the mid-thickness plane. The zeroth order mode signals can carry more energy with less dissipation in most practical applications than the higher order mode signals.

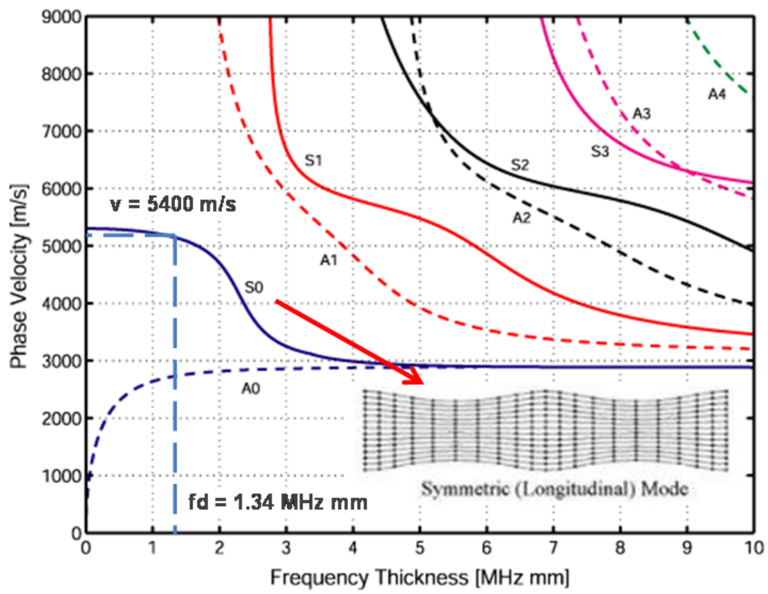


FIGURE 1. Dispersion curves of guided waves in aluminum plate.

TEST SPECIMENS

Three multilayered plate-like structures of 610 mm long and 300 mm wide were fabricated using aluminum (two plates) and carbon fiber as the external skin layer. Three successive layers of aluminum/carbon fiber, butyl rubber, and composite polymers were bonded to the external layer to form a composite multilayered structure (Figure 2). The outer skin aluminum plates were 6.25 mm thick and the multilayered structure was composed of aluminum/rubber /polymer layers. One-half (150 mm of its width) of one aluminum plate specimen was constructed without any seeded delaminations and it was considered as the control section. The carbon fiber laminate used for the carbon fiber composite test specimens was 2.5 mm thick and had an epoxy matrix with a symmetrical layup of 0˚/45˚/90˚ carbon fabric. The multilayered structure was formed as carbon fiber/rubber insulation/polymer layer. To simulate delaminations between layers, polyimide films of various sizes as shown in Figure 3 were seeded at both interfaces. The polyimide materials were chosen due to their high acoustic impedance as compared to the low impedance of the rubber layer.

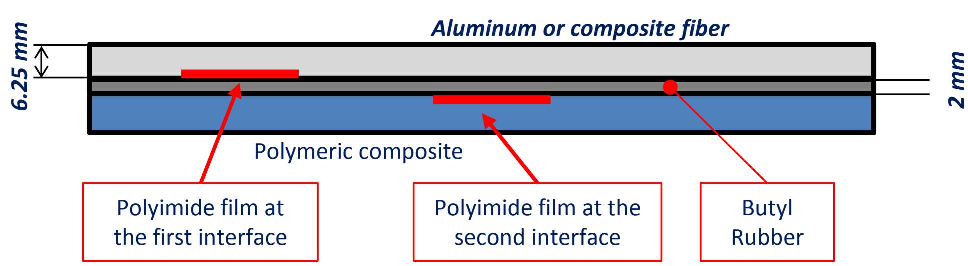


FIGURE 2. Side cross-sectional schematic view of composite multilayered structure of the plate/tube-like specimens used for the current investigation.

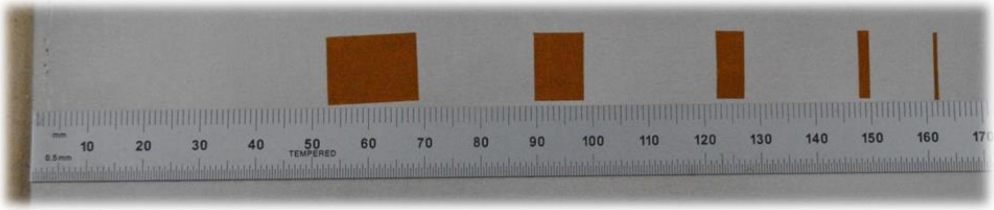


FIGURE 3. Polyimide films used as seeded delaminations in the first interface of the composite multilayered structure.

Two multilayered cylindrical half-tubes with aluminum and carbon fiber composite outer casings were prepared to be inspected in a similar way as in the plate case (Figure 4). The same type of polyimide films were seeded as simulated delaminations at the two bond line interfaces. The aluminum tube casing was 6.35 mm thick and the carbon fiber casing was 2.5 mm in thickness. Both tubes had an outer diameter of 203 mm and were 305 mm long.

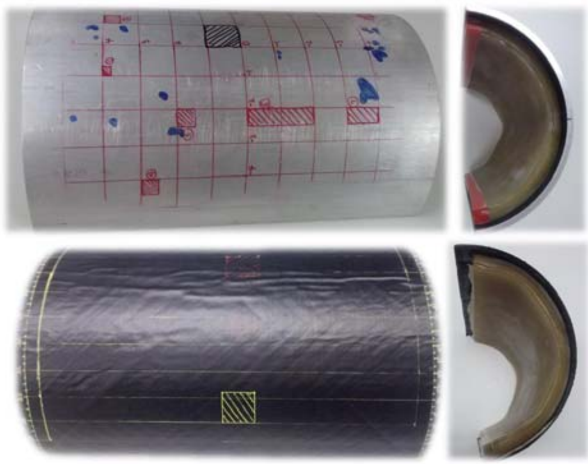


FIGURE 4. Ultrasonic guided wave measurements were performed on multilayered half-tube test specimens having an outer casing layer of aluminum and carbon fiber composite.

EXPERIMENTAL PROCEDURE

Ultrasonic measurements were performed initially on multilayered flat plate having aluminum and carbon fiber outer skin. Then these measurements were repeated on multilayered cylindrical half-tubes with the same aluminum and carbon fiber skin. The first symmetric mode S_0 of Lamb waves in plates and tubes was excited selectively by means of specially designed IDT sensors. These IDT sensors were fabricated from thin wafer of piezoelectric lead zirconate titanate (PZT) substrates by using a pulse laser micro-machining process to etch inter-digitated electrode patterns on the surface.

To confirm excitation of the first symmetric mode S_0 by the custom designed IDT sensors multiple velocity measurements were made for both aluminum plate and tube specimens (Figure 5). The measured value of the phase velocity, v_p, was 5,400 m/s for both plates and tubes. During the measurements, both transducers were coupled to the surface of specimen using a thin layer of acoustic coupling liquid. A sinusoidal waveform was used to launch a guided wave inside the structures since a large frequency content of a pulsed burst generated by a broadband transducer can travel at different velocities and consequently the pulse shape may change as the waves travel in the material. The excitation signal applied to the transmitter was a 12 cycles of sinusoidal toneburst with a frequency of 210 kHz. An improved image quality was obtained by enclosing the sinusoidal waveform into a Hanning window.

This approach seemed to suppress the sidelobes that may appear at the chosen excitation frequency. Typically, it is known that these sidelobes tend to excite multiple modes of guided waves causing undesirable wave interferences [14].

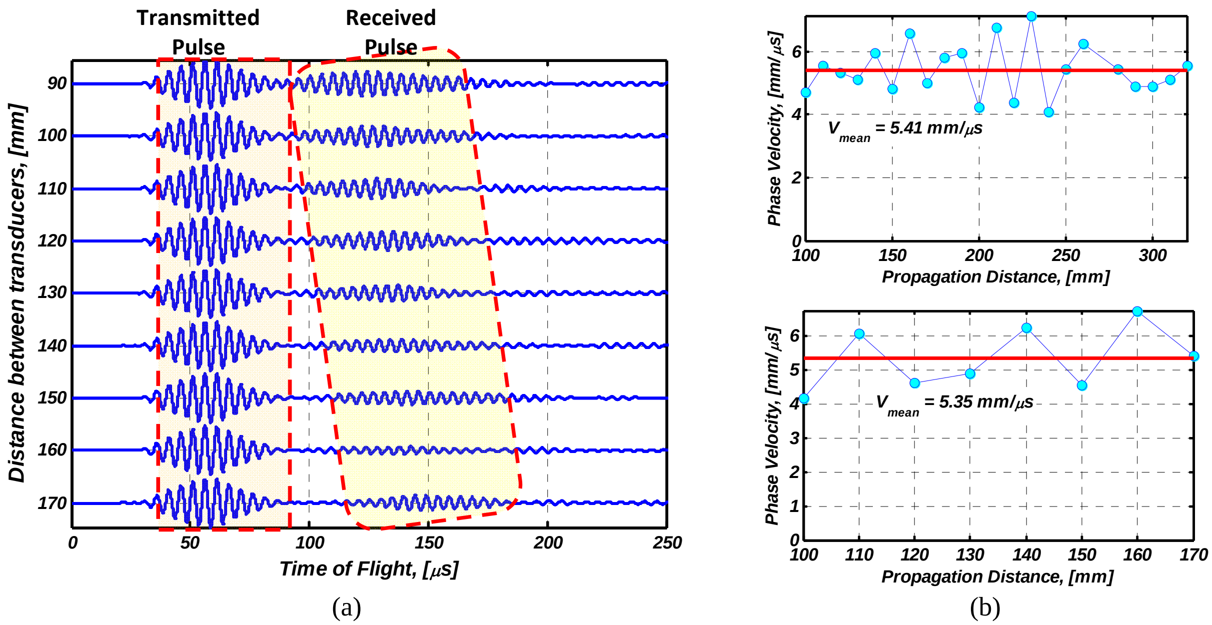


FIGURE 5. The first symmetric mode, S_0, was selectively excited both in aluminum plate and tube specimens. The phase velocity data was collected through multiple measurements, (a). The averaged velocities were 5,410 m/s for plate specimens, (b) top graph, and 5,350 m/s for tube specimens, (b) bottom graph.

Two different experimental setups were prepared: a bulky high-power amplifier based system and a compact portable pulser/receiver based system. For the first system, a programmable function generator was used to generate sinusoidal signals that were amplified using a 150-watt RF power amplifier before the signals sent to the transmitting transducer. Then, full traces of the received signals were filtered with a low-pass filter having a cutoff frequency of 0.5 MHz followed by waveform averaging on a digital oscilloscope before being processed on a computer. On the contrary, the second system shown in Figure 6 used a compact portable high-voltage pulser/receiver unit and a laptop computer for DAQ and data analysis. All test specimens were scanned by sliding the transmitter and receiver (pitch-catch) across the surface. The propagation distance was 500 mm for the plates and 180 mm for the half-tubes. In the case of half-tubes, the transducers were moved only along the circumferential direction.

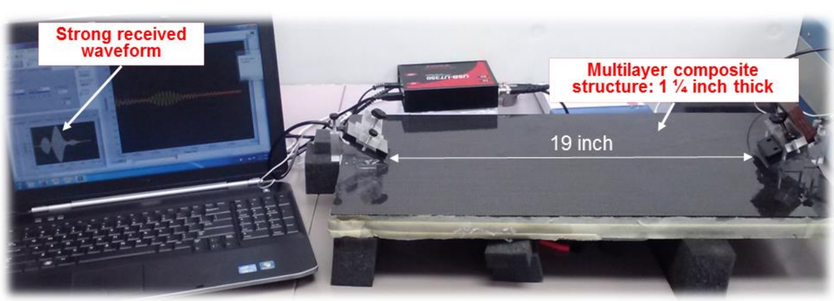


FIGURE 6. A portable ultrasonic scanning system was designed and tested successfully on multilayered structures including the ones with carbon fiber skin.

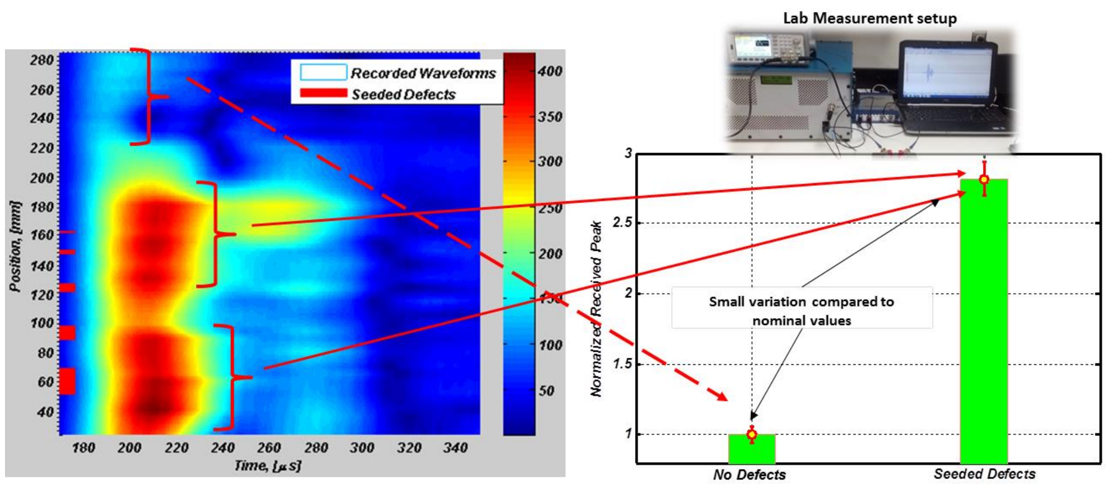
The portable ultrasonic system was used to track the scan position, collect ultrasonic data, analyze the results, and provide B-scan images in real time. The guided waves were launched from the outer surfaces of the test specimens by using acrylic coupling shoes. In this way, the guided wave energy was launched through the tip section of the shoe and subsequently propagating along the surface of the test specimen. Time domain signal processing was applied to analyze the received waveforms.

EXPERIMENTAL RESULTS

One way of detecting defects was thought to look for the presence of other modes in the received signal after launching single mode, S_0, signals into the test structure. In addition, due to the presence of a highly damping material such as butyl rubber, the material's sound absorbing characteristics was also thought to be a suitable indicator of internal delamination because the energy leaked into the rubber layer from the casing layer would not reflect back toward the casing. The loss of bonding between layers allows for less energy leakage into the interface layer of rubber and composite polymer layer, producing a stronger received signal. Thus, the energy of the received waveform would be quantitatively measurable based on the signal amplitude level. In this investigation, the sound energy was defined as the integral of the square of the recorded amplitude signal over the time interval of the received S_0 mode and described as

$$E = \int_{t_i}^{t_f} V(t)^2\, dt \quad , \tag{1}$$

where t_i and t_f are the beginning and the end of the time interval defining the received S_0 mode, and $V(t)$ is the recorded signal amplitude as a function of time. When defects are present, the received acoustic energy should be significantly larger (approx. three times larger) due to local acoustic impedance mismatch as shown in Figure 7 (b). The presence of the seeded delaminations can be easily identified from the high peaks of the waveform envelopes, which are represented in colored coded images in Figure 7 (a).



(a) (b)

FIGURE 7. The transmitted energy was almost three times higher in the presence of delaminations at the first interface of the aluminum multilayered composite structure.

B-scan images were obtained by 'stitching' together all the envelopes of the recorded waveforms. The internal delaminations seeded at both interfaces were observable based on the changes in the received sound energy. In the absence of delaminations, most of the input energy was absorbed into the successive rubber/composite polymer layers due to high damping properties of the rubber material and hence less energy was received as shown in Figure 7 (b).

The error bars show the variability of data over a range of ten repeated measurements. However, the B-scan data of both aluminum plates showed that the signatures of the defects were wide due to possible beam-spread and dispersion effects. It should be noted that the beam-spread is a diffraction phenomenon depending both on the width of the transducers and the excitation frequency. On the other hand, the wave dispersion is the tendency of ultrasonic signal to spread spatially and temporally during propagation [16].

While successfully demonstrating the presence of internal delaminations can be detected reliably by measuring changes in the energy of the received signals, it is estimated that the pitch-catch ultrasonic system developed for the current investigation can detect a delamination as small as 1 mm wide, the narrowest polyimide film shown in Figure 3. Similarly, in the half-tubes, small delaminations were also detectable in both aluminum and composite structures as indicated in Figure 8 and 9, respectively.

To inspect the carbon fiber composite structures, approximately four times more energy was required due to a higher attenuation property of the outer composite casing layer. Additionally, the received energy was four times lower than the aluminum multilayered plate case. The portable system was found to be effective for both aluminum and carbon fiber composite structures, even though the carbon fiber composite plate exhibited higher signal attenuation as depicted in Figure 10. Yet, both defects in the first and second bondline interfaces were successfully detected.

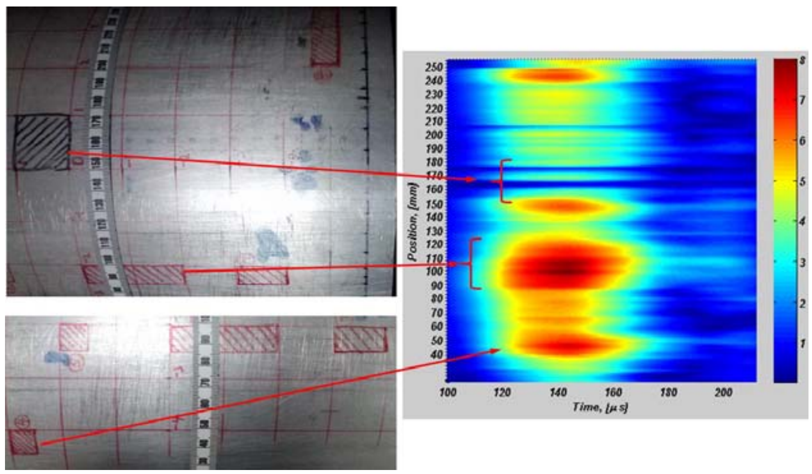


FIGURE 8. B-scan image of the multilayered aluminum half-tube structure demonstrates a strong ultrasonic energy transmission (red) in the presence of internal delaminations.

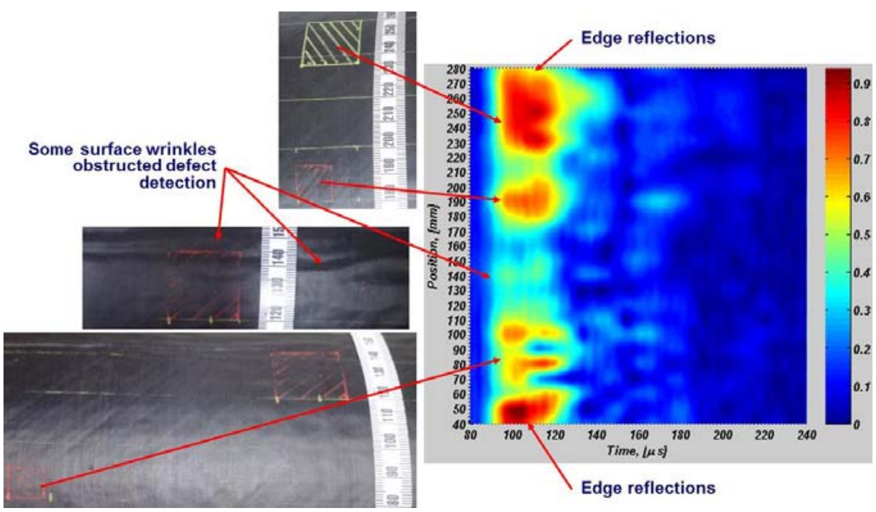


FIGURE 9. Multilayered half-tube structures of carbon fiber composite were successfully scanned to show indications of strong energy transmission where seeded delaminations were present.

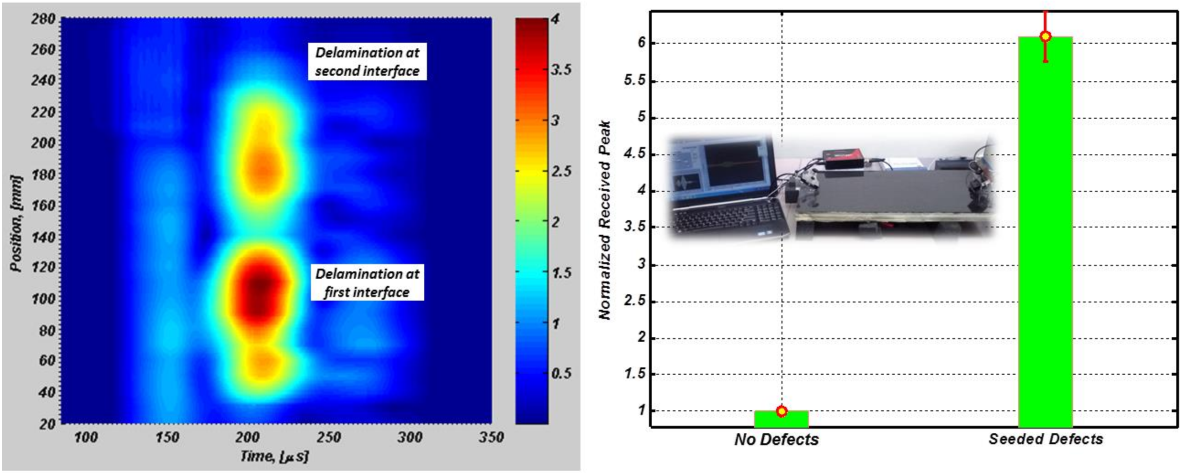


FIGURE 10. B-scan image indicating two delaminations seeded at the two interfaces of a multilayered plate with carbon fiber skin, which was scanned with the portable prototype inspection system developed during this investigation.

CONCLUSIONS AND FUTURE WORK

The presence of sound absorbing viscoelastic rubber-like materials in multilayered structures can cause significant challenges for conventional nondestructive inspection methods. During the current investigation, an ultrasonic guided wave based pitch-catch scanning system has been developed specifically to detect internal delaminations in plate- and tube-like multilayered composite structures. These guided waves were generated by incorporating IDT transducers along with a set of acoustic coupling shoes to accommodate both flat and non-flat surfaces.

It has been demonstrated from the current work that an ultrasonic guided wave approach can offer a potential inspection methodology by exciting a specific mode of Lamb waves that propagate through the layers of materials even in the presence of a highly damping material such as rubber. In principle, driven below the cut-off frequencies of the higher order Lamb modes, the first symmetric mode, S_0, can be excited selectively. From the measurements made on the changes in the received wave energy, internal delaminations artificially seeded between the internal structural layers were successfully detected during this investigation. It has been found that further studies are needed to investigate the effects of specimen geometry and operating frequency in terms of minimum detectable defect size quantification.

In conclusion, an IDT sensor based guided wave inspection methodology developed in this work is thought to have a high potential as a field deployable inspection tool for complex multilayered structures. Among many advantageous wave properties of guided waves, the attribute goes to the aspect that they can propagate long distances with minimum distortions and decays. From the current investigation, it is concluded that guided wave signals are sensitive enough to detect the presence of delaminations at the bond lines of multilayered structures. One of the additional future works can involve the development of a helical ultrasonic tomography procedure to improve the accuracy on defect sizing and localization.

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