9th European Workshop on Structural Health Monitoring
July 10-13, 2018, Manchester, United Kingdom

Ultrasonic Inspection of Bonded Metal Laminates Using Internal Shear-mode Piezoelectric Transducers

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Abstract

Ultrasonic techniques in structural health monitoring have shown great potential in the detection, location, characterization, and quantification of damage in simple and complex structures. Research to date has primarily employed Lead Zirconate Titanate (PZT) piezoelectric transducers to actuate and sense ultrasonic waves using direct (d33) and transverse (d31) piezoelectric properties. There has been significantly less work exploring the use of shear mode (d15) piezoelectric transducers in ultrasonic and SHM applications.

Researchers at the University of Wisconsin - Milwaukee have recently been investigating the use of shear-mode Lead Zirconate Titanate transducers embedded within adhesively bonded metal structures to inspect for damage and bond-line defects. Shear-mode piezoelectric transducers have been found to generate unique and complex wave actuation in these laminate structures with multiple modes of actuation in the different components of the structures. The shear-mode piezoelectric transducers also provide an inherent hardware based processing of the sensed signals that has been found to be potentially beneficial in interpreting complex signals for detecting a variety of structural defects.

This paper and presentation will review recent work performed at the University of Wisconsin - Milwaukee employing shear-mode piezoelectric transducers embedded within laminate structures for ultrasonic actuation, sensing, and damage detection. It will also present finite element simulation and experimental validation of the results.

1. Introduction

Structural health monitoring (SHM) based on ultrasonic wave propagation has received a lot of attention in recent years because of its potential to improve safety and reduce maintenance costs in engineering structures like aircraft and bridges. SHM systems enable real time inspection of structures with minimal effort. These systems are based on a permanently mounted set of sensors to detect damage and structural state. Ultrasonic systems have received particular attention because they only require a sparse array of sensors distributed across the structure. Waveform analysis has demonstrated the ability to detect, localize, characterize, and quantify multiple forms of damage in structures. However, there are still many challenges that hinder wider application of SHM such as high up front cost, and limited capabilities to inspect complex structures including joints [1], [2]. Adhesively bonded joints are used extensively in construction and repair, and increasingly replacing mechanical fasteners like rivets and machine screws for bonding metallic materials and non-metallic materials together. Bond lines provide both an opportunity for placement of piezoelectric transducers and a challenge in monitoring the structure, including the adhesive which is susceptible to multiple types of defects such as cracks, voids, disbonds, delaminations, and kissing bonds. Therefore, inspection of adhesively bonded structures is of great interest.

Ultrasonic SHM regularly uses Lead Zirconate Titanate (PZT) piezoelectric transducers permanently mounted onto structures due to their strong piezoelectric material properties [3]. Typically, PZTs are polarized and actuated with electric fields aligned in the same direction, creating aligned (d_{33}) and perpendicular deformations (d_{31}). However, many piezoelectric materials, including PZT, can be actuated in a shear mode which could have stronger piezoelectric properties than the axial modes. Shear actuation at resonant frequencies has been widely used in timekeeping, however, there has been relatively little exploration of using shear-mode piezoelectric transducers to actuate and sense ultrasonic waves. Studies that have addressed wave propagation from shear actuated piezoelectric elements mounted on the surface of a structure was performed by some researchers [4]–[6]. Kamal and Giurgiutiu [4] have studied shear horizontal (SH) waves excited with shear-mode piezoelectric transducers attached to the surface of aluminum plates. Diaz Valdes and Soutis [7] also found the A_0 with a low excitation frequency range (<100 kHz) producing promising results for detection of delaminations in a composite beam using surface-mounted rectangular d_{31} piezoelectric transducers. Similarly, Osmont et al. [6] used low-frequency A_0 Lamb waves to detect and locate damage in a foam core of a sandwich plate with round d_{31} piezoelectric transducers mounted on the surface.

Zhuang et al. [8] and Dugnani et al. [9] investigated the feasibility of embedding piezoelectric sensors into adhesive bond joints and monitoring their electromechanical (EM) impedance in order to inspect the bond-line integrity. While these techniques have demonstrated the ability to detect defects in adhesive joints, they are limited by the fact that EM impedance methods are only sensitive to the region adjacent to a transducer.

This paper will review recent work performed at The University of Wisconsin - Milwaukee employing shear-mode piezoelectric transducers embedded within laminate structures for ultrasonic actuation, sensing, and damage detection. It will also present finite element simulation and experimental validation of the results.

2. Shear-mode PZTs Embedded in the Bond-line of Laminated Structure

Fundamental understanding of guided waves generated and sensed by embedded shear-mode PZTs in laminated structures is necessary to accurately model their behavior. Thus, simulation and experimental studies were performed exploring the waveform generation and propagation resulting from actuation of the shear-mode piezoelectric transducer embedded in the bond-line between two 6061 aluminum sheets bonded together with Hysol EA9394 epoxy. Two shear-mode PZTs were embedded in the adhesive layer in pitch-catch orientation.

2.1 3-D Finite Element Simulation

The multilayered structure was initially modeled in ANSYS 17.0 multiphysics to simulate the propagation of ultrasonic waves emitted from a shear-mode PZT piezoelectric actuator embedded in the bond-line. A multilayered structure consisting of two 6061 aluminum substrates bonded together with a layer of EA9394 adhesive was modeled. The adhesive layer has a Young's modulus of 4.237 GPa, Poisson's ratio of

0.45, and density of 1360 kg/m^3 [10]. The structural and electromechanical material properties of a piezoelectric transducer polarized in x_1-direction given in IEEE standard format [11] were used to define the elasticity matrix, the piezoelectric stress coupling constants, and the permittivity matrix as shown in Eq.(1).

$$
\begin{aligned}
&[c]=\begin{bmatrix} 110.9 & 75.1 & 75.1 & 0 & 0 & 0 \\ 75.1 & 120.4 & 75.2 & 0 & 0 & 0 \\ 75.1 & 75.2 & 120.4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 22.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 21.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 21.1 \end{bmatrix} GPa \\
&[e]=\begin{bmatrix} 15.784 & 0 & 0 \\ -5.351 & 0 & 0 \\ -5.351 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 12.295 \\ 0 & 12.295 & 0 \end{bmatrix} \frac{C}{m^2} \qquad \left[\varepsilon^T\right]=\varepsilon_o \begin{bmatrix} 1581 & 0 & 0 \\ 0 & 1851 & 0 \\ 0 & 0 & 1851 \end{bmatrix}
\end{aligned}
\tag{1}
$$

In Eq.(1), ε_o is the vacuum permittivity and has a value of 8.854 $\mu F/m$.

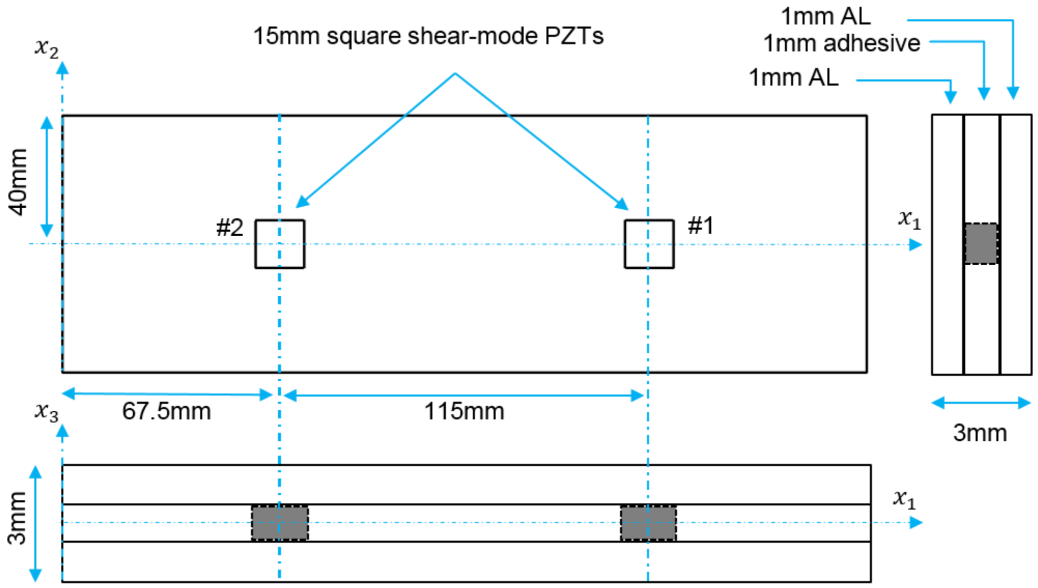

Figure 1: Schematic diagram of an aluminum multilayered structure with two shear-mode PZT transducers placed in the bond-line.

The overall geometry is shown in Figure 1 with two shear-mode PZTs embedded in the adhesive layer arranged in pitch-catch orientation. To model the electromechanical behavior of the shear-mode PZTs, 3-D multiphysics analysis was performed using a 20-node coupled-field solid element, SOLID226. The aluminum plates and the adhesive layer were meshed with a structural solid element, SOLID185. More details on modeling adhesive joints are available in ANSYS17.0 documentation [12]. A 5-peak Hanning-windowed tone burst signal with a center frequency of 30 kHz was used to actuate PZT1.

In Figure 2, the distribution of elastic wave propagation in the adhesive layer from the actuator to the sensor is displayed at two-time instances. It can be observed that the shear-mode actuator creates waves which predominantly propagate in two opposite directions. In the simulation results in Figure 2, each wave appears as a semicircle with different magnitudes traveling and spreading in a conic shape from the source actuator. It is also worth noting from Figure 2 there is almost complete absence of the antisymmetric shear waves in the transverse direction (x_2-axis) with respect to the source.

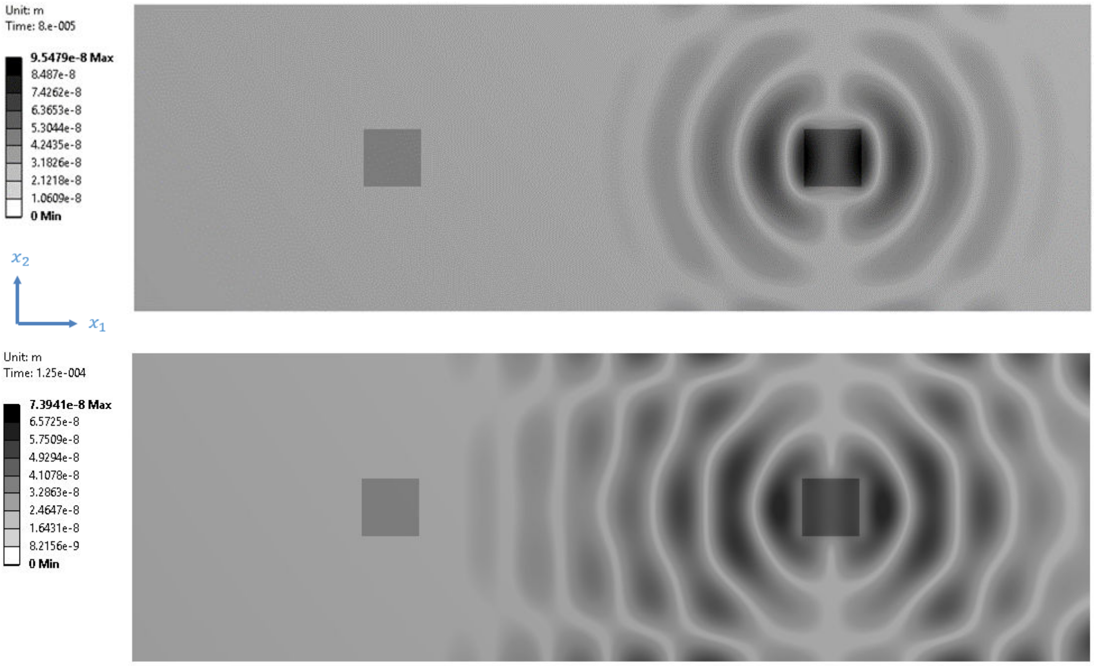

Figure 2: Full-field view of elastic wave propagation in the bond-line at 80μsec and 125μsec.

2.2 Experimental Testing

To validate the FE approach, a laminated specimen was created with the same geometry and materials that were modeled. Two 6061 aluminum sheets were machined to 250 x 80 x 1 mm in size. The PZTs were adhered to one aluminum sheet that would serve as a common ground using Chemtroncs Circuitworks CW2400 conductive epoxy which was cured at room temperature for 24 hours [13]. 30 AWG magnet wire was used for the leads and adhered to the individual terminals of the PZTs using the same conductive epoxy. The aluminum sheet with shear-mode PZTs and wiring are shown in Figure 3. Hysol EA 9394 was then used to bond the aluminum sheets together [10]. This epoxy also served as an insulator protecting the hot terminals of the PZTs from shorting against the second aluminum plate. The final assembly was cured at 66C for one hour.

A fully prepared sample is shown in Figure 4. A factor in selecting this design layout was the desire to avoid overlapping signals due to reflections.

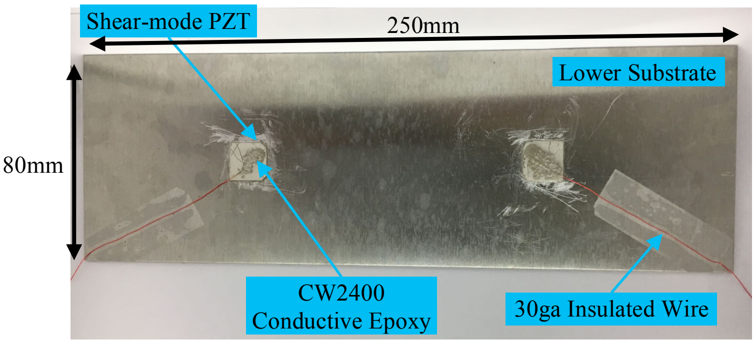

Figure 3: Partially prepared sample, two shear-mode PZT transducers mounted on an aluminum sheet.

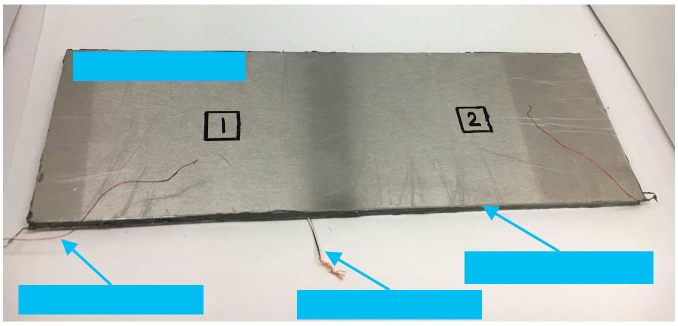

Figure 4: Fully prepared sample.

The actuating transducer, labeled as PZT1 in Figure 4, was connected to a KEYSIGHT 33500B Series waveform generator with a Krohn-Hite 7602M Wideband Amplifier to boost the applied voltage. Both of the shear-mode PZT transducers were connected to a Tektronix MDO3014 Mixed Domain Oscilloscope to simultaneously record voltage signals across the actuator and the sensor. The full setup is shown in Figure 5. The specimen was tested in pitch-catch orientation by 5-peak tone burst signal. In the next section, the results of the experiment and the FE simulation were compared to validate the FE simulation's accuracy in modeling wave propagation in the laminate structure actuated and sensed by shear-mode PZTs embedded in the bond-line.

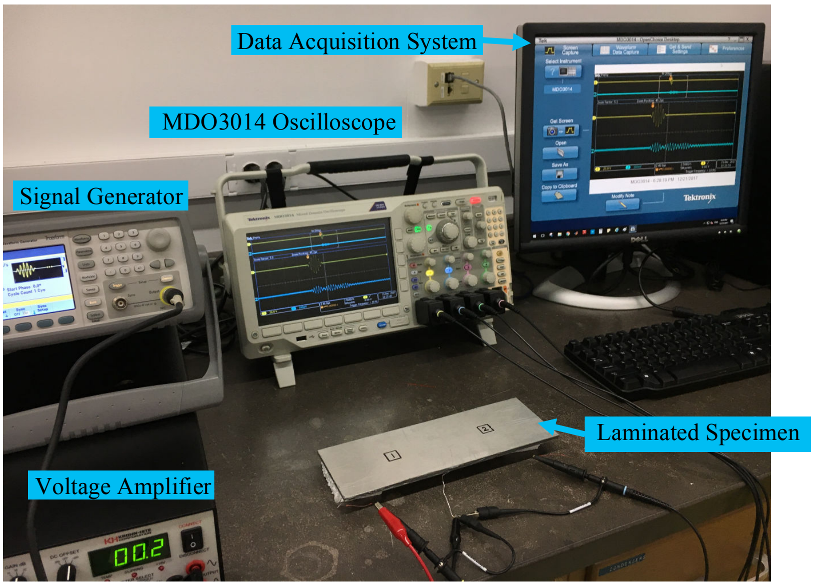

Figure 5: Experimental setup for testing a multilayered specimen.

2.3 Model Validation

The experimental signals collected from the specimens were de-noised using Discrete Wavelet Transform using MatLab's *wden* function to improve the signal to noise ratio. Furthermore, the Short Time Fourier Transform was also implemented to perform time-frequency analysis on the collected numerical and experimental signals using MatLab's *spectrogram* function.

Comparison of experimentally acquired and simulated waveforms sensed after propagation are shown in Figure 6. The specimen was tested with 5-peak tone burst signal modulated with Hanning window with a center frequency of 30 kHz. In Figure 6a, the actuation signal in time domain and time-frequency domain are plotted. Similar plots of the propagated and received signal from experiment and FE shown in Figure 6b and Figure 6c indicate that the overall behavior of wave propagation is in a good match especially with respect to the magnitude and frequency of the first wave packet. The time-frequency response also indicates that the actuation wave packet has widened in shape but has maintained its frequency range. This was expected because shear waves at low actuation frequency are highly dispersive. A 2-D FE analysis of the laminate structure was conducted by following the same procedure discussed in Section 2.1 in order to be validated for the damage detection analyses. The results are shown in Figure 6d and also show a good match to experimental results.

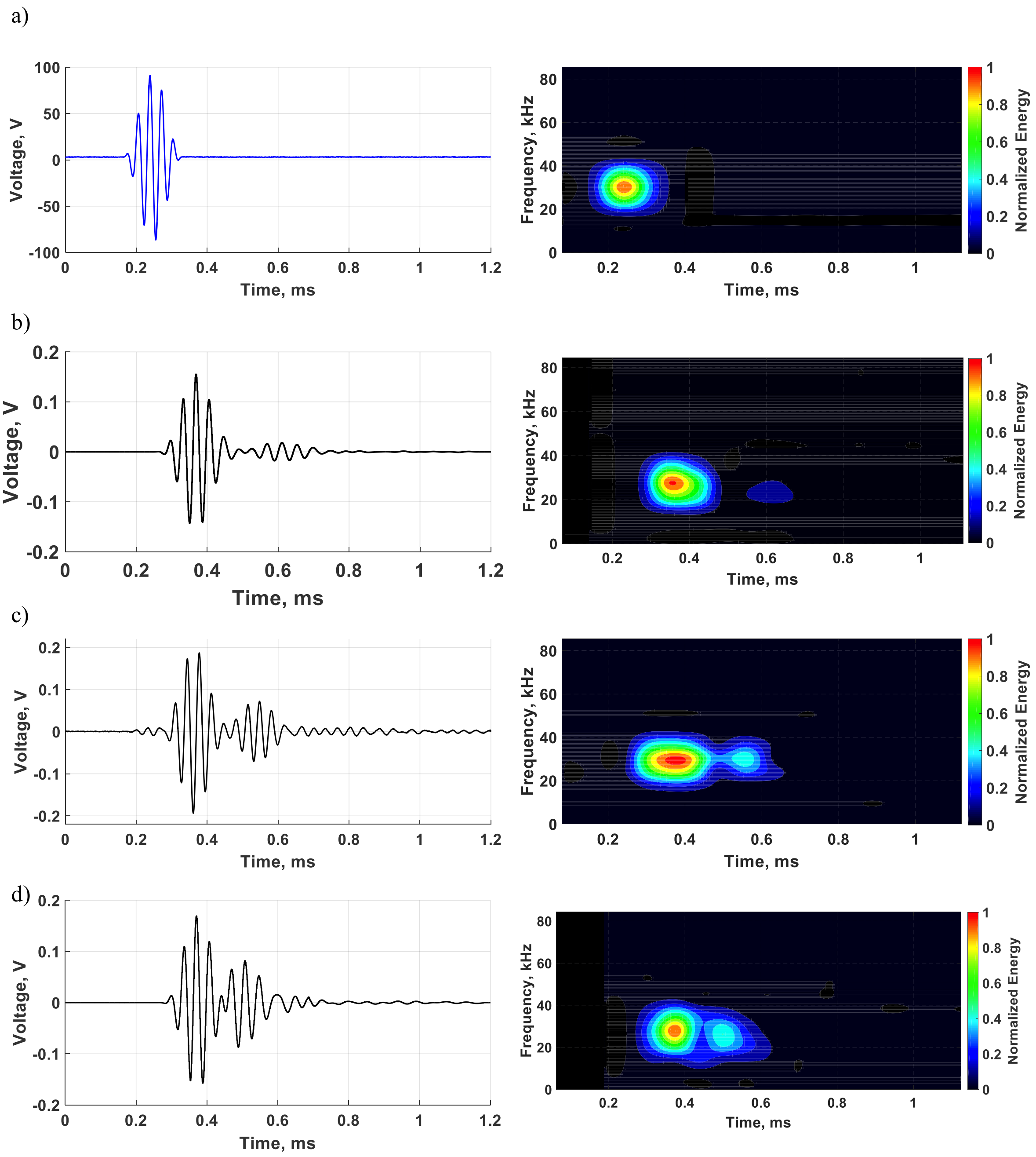

Figure 6: Pitch-catch method of a multilayered structure with shear-mode actuation: a) 5-peak Hanning-windowed tone burst signal at 30 kHz currier frequency; b) waveform response from 3-D multiphysics analysis; c) waveform response from experiment; d) waveform response from 2-D multiphysics analysis.

From 3-D multiphysics analysis, it was observed that even though only shear waves were actuated in the bond-line, the fundamental symmetric and antisymmetric modes could coexist in the metallic plates due to mode conversion. Therefore, the adhesive layer is mainly excited with shear waves while the aluminum substrates can have both modes simultaneously propagating in the media. The adhesive layer could also carry symmetric wave modes, produced due to wave interference and mode conversion resulting from geometric discontinuity and introduced material discontinuity in the model. Shear-mode PZT however largely capture antisymmetric wave modes in the media offering a valuable merit by performing a hardware based form of signal processing which can significantly reduce the complexity of computational signal processing and enhancing the process of damage detection.

3. Damage Detection Analysis

3.1 Damage Modeling

The modeling procedure discussed in Section 2.1 was followed herein to simulate the 2-D multilayered structure with adhesive joint defects. In Figure 1, the structure was modeled with no damage to obtain a baseline signal for comparison with damage state. Four damage cases including void, vertical crack, disbond, and kissing bond introduced in the bond-line were considered to study the influence of joint defects on shear waves.

The joint defects simulated herein were located at 50 mm from the transducers. To simulate a disbond in the adhesive joint, a group of contact elements at interface region was defined to allow joint separation. The disbond at the interface region is 10 mm long. Mode-I crack (opening crack) was also considered in this study through the application of infinite friction on a group of contact elements in the bond-line creating a vertical crack with rough contact. The crack was made through the thickness of the adhesive layer. A common damage in adhesive joins is void which was simulated by removing a group of structural elements creating 0.5 x 5 mm void at the center of the bond-line. Another common adhesive joint defect is kissing bond. Several techniques have been introduced in the literature to simulate kissing bonds [9], [14], [15]. In this analysis, a kissing bond was simulated in the interface joint through a reduction in material stiffness of the adhesive elements. A group of elements at the interface region have material stiffness reduced by 50%.

3.2 Analysis of Damage Detection

In all damage cases, the actuation signal was kept the same for comparison study. The 5-peak tone burst signal shown in Figure 6a was emitted from a shear-mode PZT transducer. The baseline signal with no damage being introduced in the bondline was plotted as a pristine state (pristine signal) in Figure 7. Similarly, the signal of a damage state was denoted by damage signal in the waveform plots. Damage index (DI) based on the root mean square deviation method was also calculated for each damage case as follows [16],

$$DI = \sqrt{\sum_{i=1}^{N} (X_i - x_i)^2 \Big/ \sum_{i=1}^{N} x_i^2} \tag{2}$$

In Eq.(2), X_i is the pristine state at the i^{th} measurement point, x_i is the damaged state at the i^{th} measurement point. This value indicates the sensitivity of shear waves propagating in the bondline to various damage characteristics. Damage index (DI) was included in the plots. The scatter signal which was determined by calculating the difference between the pristine signal and the damage signal was also displayed in Figure 7.

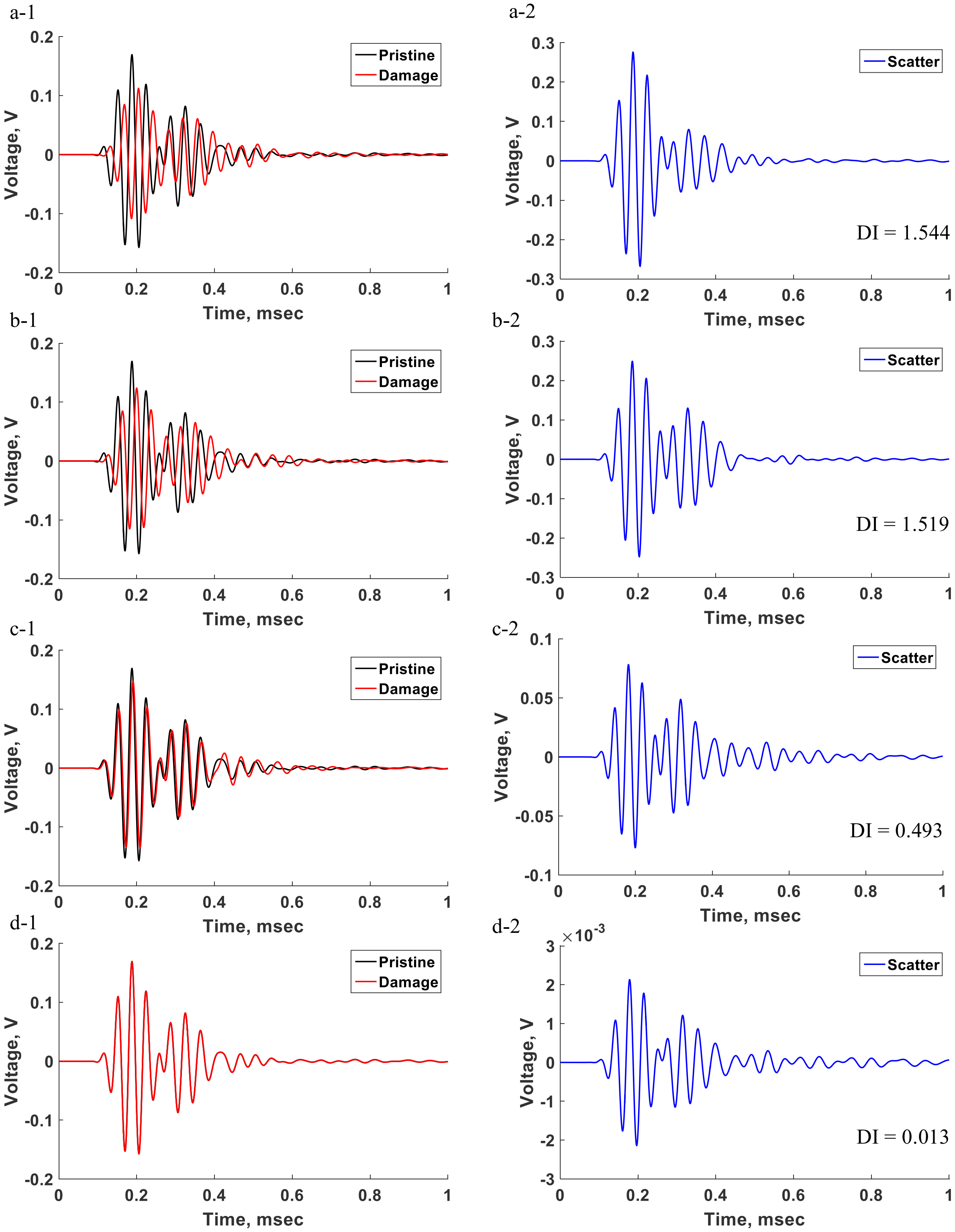

Figure 7: Comparison of waveforms between pristine state and damage state of a multilayered structure excited with 5-peak actuation signal at 30 kHz: a) disbond; b) vertical crack; c) void; d) kissing bond.

A common trend can be observed from the results that shear waves are sensitive to all investigated types of damage discussed herein but at various levels. In Figure 7a, shear waves exhibit higher sensitivity to disbond causing phase shift and magnitude attenuation. Similar behavior was also observed with a vertical crack in Figure 7b with a damage index relatively high. One common behavior between disbond and vertical crack which has contributed to higher sensitivity is the capability of shear waves to open and close the crack under the influence of shear forces. The shear waves however show less sensitivity to the center void as can be seen in Figure 7c. Because shear waves exhibit flexural particle motion with minimal displacement at the neutral axis. In Figure 7d, kissing bond which is the most challenging type of damage to detect indicated very little sensitivity to shear waves suggesting the kissing bond is undetectable at the given damage and actuation characteristics. Also, a simulation of kissing bond with cohesive zone model is expected to produce more accurate representation than simply reducing the material stiffness. This model allows a joint separation when stresses induced by shear waves exceed the joint strength of a kissing bond resulting in higher distortion in received signals.

4. Summary and Conclusions

A double-layer aluminum structure with two shear-mode PZTs embedded in the bond-line was considered to study the propagation of ultrasonic waves using 3-D multiphysics model and experimental work. A laminated specimen was prepared and tested to validate the multiphysics FE modeling procedure. The FE and experimental results were found comparable. The results indicated that shear-mode PZT sensors offer a valuable merit by largely capturing antisymmetric wave modes in the adhesive. The elimination of symmetric modes in received signals could reduce the complexity of signal processing.

This study also investigated the influence of damage on the propagation of shear waves in the bondline by considering four damage cases including void, vertical crack, disbond, and kissing bond. The damage index was also calculated for each damage case to quantify the sensitivity of shear waves to certain damage characteristics. It was observed that shear waves were sensitive to all investigated types of damage but at different levels. Shear waves were found to exhibit high sensitivity to disbonds and vertical cracks. Voids were expected to show a varying sensitivity based on their characteristics and location within the adhesive layer. However, kissing bonds were found the most challenging type of joint defect to detect with very little sensitivity to shear waves.

The results presented in this paper provide a promising inspection method to detect defects in bonded joints by using shear waves induced by embedded shear-mode PZTs to detect defects in bonded joints. Future work will seek to investigate more aspects of using shear-mode PZTs for damage detection in real-life adhesively bonded structures such as size of PZT transducers, geometry of substrates, characteristics of actuation signals, signal processing methods, and environmental conditions. These factors are expected to have significant influence on the sensitivity of shear waves to joint defects.

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