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SHEAR ACTUATION OF PIEZOELECTRIC TRANSDUCERS EMBEDDED WITHIN LAMINATE STRUCTURES FOR DAMAGE DETECTION

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ABSTRACT

Structural bonding is increasingly supplementing and replacing mechanical fasteners because of the potential to reduce weight, part count, and assembly time in addition to the reduction in stress concentrations and ability to bond complex geometries that are not feasible with mechanical fasteners. Despite the advantages of structural bonding over mechanical fasteners, structural bonding is challenging to inspect and introduces new failure modes into structures.

Significant work on techniques for inspection of bond-lines has been performed. Ultrasonic techniques using externally mounted actuators and sensors have consistently found that shear waves and antisymmetric guided waves were the most sensitive to flaws in bond-lines. Recent work has also focused on using resonant frequencies and electromechanical impedance methods with internally embedded transducers to inspect bond-lines for damage.

This manuscript presents results from a recent study employing internally embedded (in the bond-line) shear-mode piezoelectric transducers to actuate and sense ultrasonic waves for damage detection. The use of wave propagation techniques has the advantage of providing a sensing capability along the entire path of wave propagation. Sensors were embedded into the bond-lines with the intent of maximizing the coupling between the shear-mode actuator and the structure's bond-line and to place the bond-line in shear through antisymmetric / flexural mode actuation which has been found to be sensitive to bond-line damage. Shear-mode sensing also provided a hardware-based filter of the propagated strain signal to simplify signal interpretation. A review of prior work, finite element simulation, and experimental validation is presented addressing wave propagation and sensitivity to different forms of damage in a laminate structure composed of two aluminium sheets bonded together with epoxy.

1. Introduction

1.1 Motivation

Adhesive bonding is increasingly replacing and supplementing mechanical fasteners due to its many benefits including reduced weight, part count, and assembly time in addition to a reduction in stress concentrations and the potential to create complex geometries[1].

1.2 Background

Many approaches have been explored to inspect for damage in bond-lines. Ultrasonic techniques have shown promise in detecting multiple types of defects and have the advantage of being able to scan large areas with small numbers of actuators and sensors based on changes that occur in signal transmission. Kundu et.al. experimentally inspected the sensitivity of various lamb wave modes to kissing bonds simulated by multiple glass plates pressed together. They adjusted the angle of actuators to induce specific lamb wave modes and found that the first antisymmetric mode was the most sensitive to joint defects, but sensitivity was also found to be limited to a specific range of phase velocities [2]. According to beam and plate bending theory, antisymmetric and flexural (bending) stresses are always accompanied by transverse shear stress [1, 3, 4]. Therefore, the finding that antisymmetric waves are sensitive to changes in the interface is consistent with inspecting the shear properties of the interface. Another study by Nagy employed a traditional C-Scan setup and inspected the sensitivity of differing ultrasonic wave propagation modes to intentionally induced bond-line damage. In this study, compression waves were found to be less sensitive to bond-line defects than shear waves [5]. Both of these studies found that inspection of shear properties was effective for finding changes and defects in bond-lines and interfaces.

Structural health monitoring (SHM) pursues the use of permanently mounted sensors to enable automated damage detection systems. This approach can create a paradigm shift in the lifecycle of engineered products with consideration in design, monitoring of manufacture, real time damage detection, modification of allowable performance envelopes, condition-based maintenance, prognostics, and determination of end of life.

To enable these goals, many SHM systems have pursued sensing systems internally embedded within laminate structures [6, 7]. Small scale hardware has been pursued to reduce parasitic effects like geometric accommodation, added weight, and reduced structural integrity [8 – 26]. Lead Zirconate Titanate (PZT) piezoelectric transducers are commonly used for actuation and sensing in ultrasonic SHM systems [27]. However, reducing the size of PZT actuators has the adverse effect of reducing their strength and reducing the strength of the strain signals they generate [28].

2. Objective

This paper presents recent work exploring the use of shear-mode piezoelectric transducers embedded into adhesive bond-lines for the detection of bond-line damage.

3. Approach

Shear-mode PZTs were internally embedded in the bond-line to directly actuate the adhesive structure of interest with the strongest piezoelectric actuation mode possible. Placing the actuators and sensors directly in contact with the bond-line structure of interest reduces potential shielding effects from the adherands. Additionally, the shear piezoelectric coefficient (d_{15}) of PZT-5A is multiple times greater than the transverse piezoelectric coefficient (d_{31}) that governs piezoelectric wafer active sensors (PWAS) commonly used in SHM or direct piezoelectric coefficient (d_{33}) employed by interdigitated transducers (IDT). Internally embedding the transducer also provided the transducer with structure to push against, other than its own mass, similar to the function of PWAS and IDTs enabling stronger actuation. Because of the coupling between bending and transverse shear, flexural or antisymmetric wave propagation was expected from this configuration.

The work presented herein is focused on the actuation mode of shear-mode PZTs coupled with a structure and the fundamental ability to detect damage in the bond-lines of simple laminate structures employing this actuation. Large devices and geometries were employed to simplify this initial exploration.

4. Major Tasks

An approach of simulation with experimental validation was pursued starting from the component level and building to the full structure with damage. First a FEM model of the shear-mode piezoceramic was created to inspect the deformation modes and natural frequencies. This FEM model was compared to analytically predicted natural frequencies and experimentally derived natural frequencies. Then a full laminate structure was simulated consisting of 2 aluminium layers bonded together with epoxy containing shear-mode piezoelectric elements in the bond-line. The sensor response to actuation was simulated and compared to a matching experimental specimen. Finally, the simulated structures were modified to incorporate multiple damage forms and simulated signal changes were inspected to characterize output signal sensitivity to different forms of damage.

4.1 Actuator

Analysis of the actuator was performed to provide a good understanding of its capabilities and function. This analysis included analytical calculation, full 3D finite element simulation, and experimental validation of the results based on a 15 x 15 x 1 mm APC-850 shear-mode PZT [29].

4.1.1 Analytical Result

The electromechanical impedance was analytically calculated to find the natural frequencies of the specimens. This analysis followed the methods presented by Mueller [30] and Kamal [31] and produced the results shown in Figure 2 with resonant frequencies listed in Table 1.

4.1.2 Simulation

A full 3D model was made to simulate actuation of the shear-mode PZT using SOLID226 coupled field elements in ANSYS 17.0. Actuation was performed from 10 kHz to 7 MHz. A convergence study was performed to identify the necessary number of through thickness elements. Modelling with 15 through thickness elements was found to produce a converged solution. The simulation calculated electromechanical impedances shown in Figure 2 with resonant frequencies listed in Table 1.

In addition to calculating the electromechanical impedance and natural frequencies, the deformation of the actuators was simulated and inspected. The low frequency and first two resonant frequency deformations of the shear-mode PZT are shown in Figure 1. This shows that the low frequency shear deformation represents a purer state of shear with larger shear deformation than occurred at the natural frequencies.

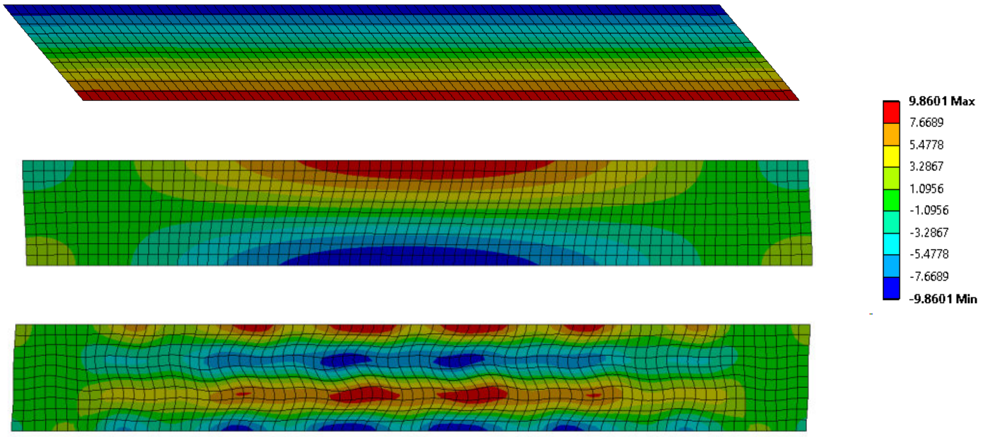

Figure 1 – Simulated actuation deformation of a shear-mode PZT at low frequency (top), the first natural frequency (middle) and second natural frequency (bottom).

4.1.3 Experiment

The prior results were confirmed by experimentally testing a specimen with a chirp signal sweeping from 10 kHz to 7 MHz and measuring the impedance. A 100 Ω resister was placed in series with the PZT to enable voltage measurement. A KEYSIGHT 33500B Series waveform generator created the signal and the output was measured using a Tektronix MDO3014 Mixed Domain Oscilloscope [32, 33]. The measured electromechanical impedance and resonant frequencies are shown in Figure 2 and Table 1 respectively.

4.1.4 Results

Comparison of the electromechanical impedance shown in Figure 2 and specific natural frequencies shown in Table 1 show a very close match of natural frequencies between analytical solution, simulation, and experiment, validating the simulation results.

Table 1. Natural frequencies for the first 3 modes of a shear PZT actuator.

Mode	#	1	2	3
Analytical calculation	MHz	0.879	3.028	5.092
Simulation	MHz	0.853	3.001	5.051
Experiment	MHz	0.888	3.139	5.637

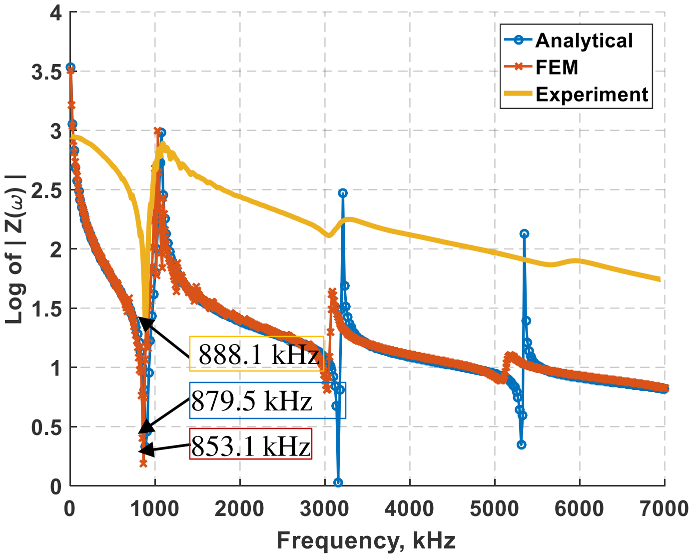

Figure 2 – Electromechanical impedance vs. frequency of a shear-mode PZT calculated analytically, simulated, and experimentally measured [34].

Based on this analysis, low frequency actuation was selected to produce shear in adhesive bond-lines using internally embedded shear-mode PZTs.

In sensing, shear-mode PZTs also provide a hardware signal filter as they are largely inert to normal deformations. This means that using a shear-mode PZT sensor will only produce signals due to experienced shear which can occur as transverse shear in bending. The shear-mode PZTs will be inert to axial deformations that do not produce shear.

4.2 Laminate Structure

A laminate test structure was modelled to inspect the wave propagation and sensed signal resulting from actuation of a shear-mode PZT embedded into the structure's bond-line. The structure, shown in Figure 3 consisted of two 6061-T6 aluminium plates measuring 250 x 80 x 1 mm each, bonded together with Hysol EA 9394 epoxy. To accommodate the PZTs, the bond-line was just over 1 mm thick. The shear-mode PZTs were separated by 100 mm and adhered to one of the aluminium plates using Circuit Works CW2400 conductive epoxy to serve as a common ground.

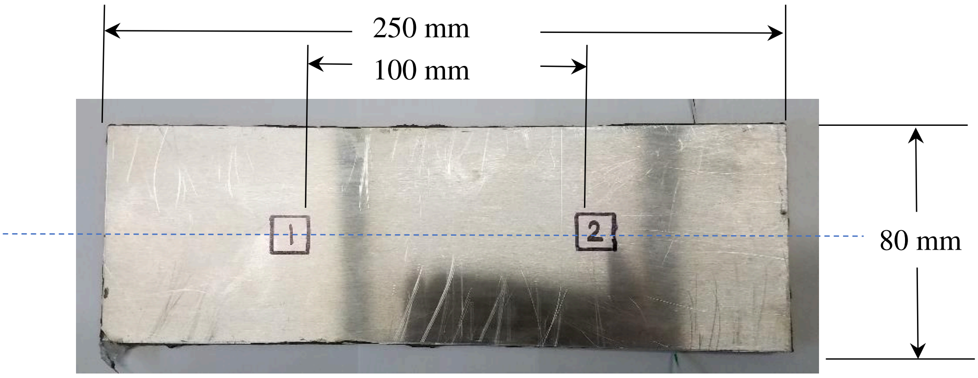

Figure 3 – Test specimen of 6061 aluminium plates bonded together with Hysol EA934 an internal PZT locations marked

4.2.1 Simulation

The full structure was modelled in 3D using ANSYS 17.0. The piezoelectric elements were again modelled with SOLID226 coupled field elements while the remainder of the structure was meshed with SOLID185 elements. The bottom corners of the structure were constrained from movement. Multiple actuations were simulated and compared, however all the work presented herein was as follows (unless stated otherwise): PZT 1 on the left was actuated with a 5 peak Hann windowed tone burst with a 30 kHz centre frequency. The simulated strain waves actuated were inspected as shown in Figure 4 and simulated signal created by the sensor recorded as shown in Figure 7.

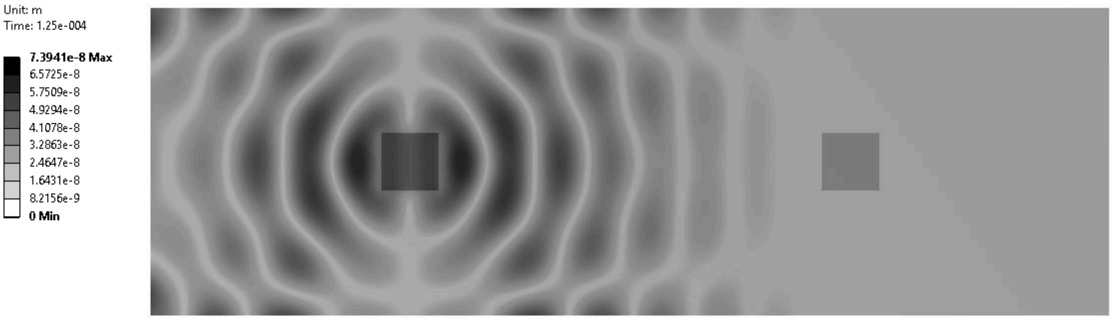

Figure 4 – 3D Simulated in plane motion of the top adhesive surface due to shear actuation at 300 kHz

Because of the computational time necessary to perform a full 3D simulation, a 2D simulation was also performed along the centreline of the structure shown by the dashed line in Figure 3. The PZTs were meshed with PLANE 223 elements and the remainder of the structure was meshed with PLANE 183 elements and again, the motion of the bottom corners of the structure were constrained. This provided information on the deformation through the thickness of the laminate structure as shown in Figure 5 and a reasonably accurate simulated signal shown in Figure 7 with drastically reduced computational time.

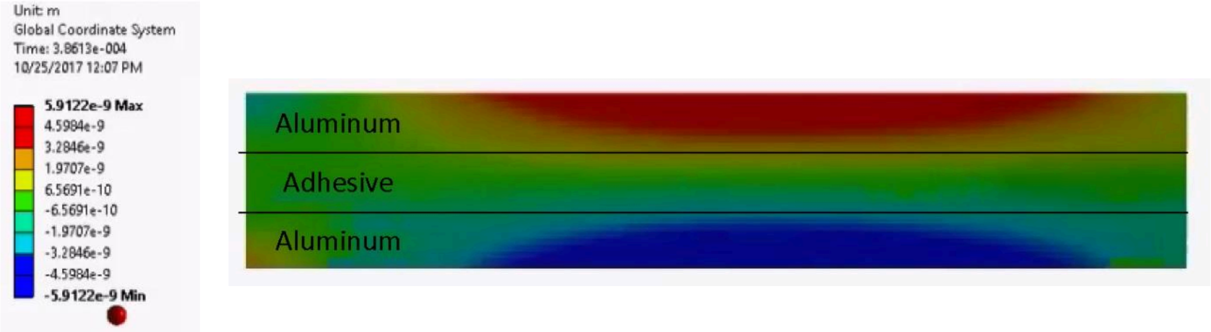

Figure 5 – Simulated strain profile from a 2D simulation along a cross section of the laminate structure

4.2.2 Experiment

Experiments were performed to collect real propagated signals from the structure in question. Samples were synthesised as described at the beginning of section 4.2 Laminate Structure. The specimens were connected to a Krohn Hite 7206M amplifier which amplified input signals from a KEYSIGHT 33500B Series waveform generator [32, 34]. The actuation and sensed signals were recorded using a Tektronix MDO3014 Oscilloscope [33]. The setup is shown in Figure 6. To verify the validity of the simulations, signals matching simulation actuations were input and the output signals recorded and then analysed in MatLAB. The results presented here are from a 5 peak Hann windowed tone burst centred at 30 kHz.

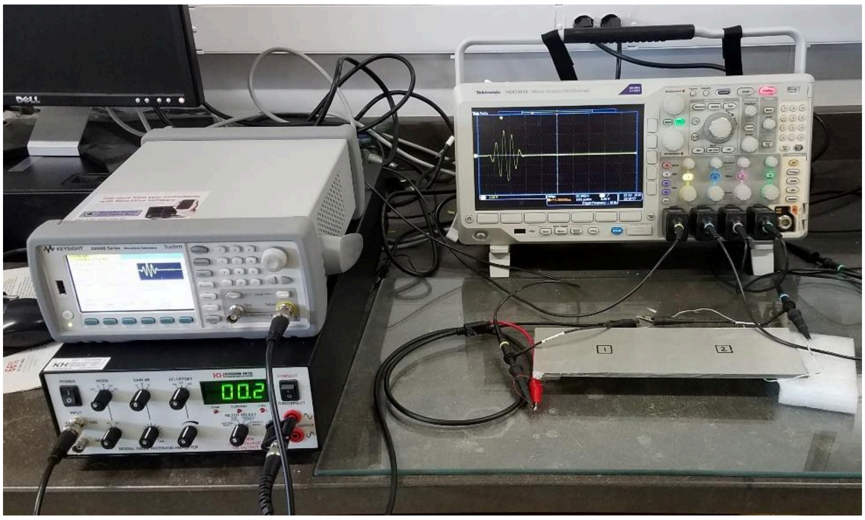

Figure 6 – Experimental setup including a KEYSIGHT 33500B Series waveform generator (top left), Krohn Hite 7206M amplifier (bottom left), Tektronix MDO3014 Oscilloscope (top right), and specimen (bottom right)

4.2.3 Analysis of Simulation Results

The experimentally measured and simulated sensor signals are shown in Figure 7. Comparing the first arrival, simulation matches experimental results very well in both time and form validating the simulations. The ability of the 2D model to accurately simulate the wave propagation with significantly lower computational time than the 3D model led to increased use of the 2D model for continued study.

The simulation results in Figure 5 with opposed tension and compression in the top and bottom of the structures suggests a dominant bending / flexural / antisymmetric wave propagation mode. Analysis of the time of flights in Figure 7 matches extremely well with a low frequency flexural wave propagation in this structure. This also corroborates the expectation that actuating shear in the middle of a beam/plate similar to transverse shear, will induce bending in a beam/plate structure.

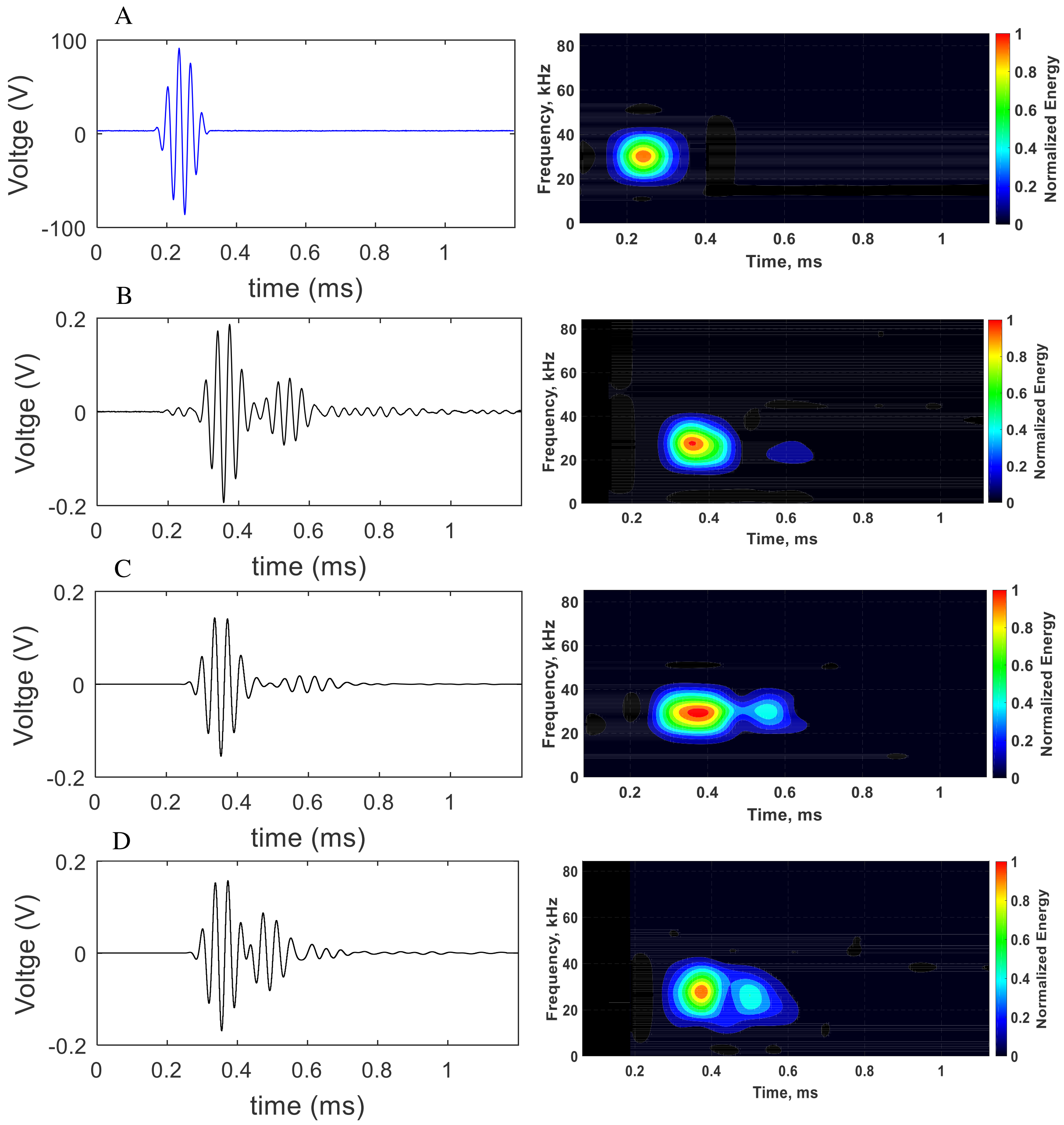

Figure 7 – Experimental and simulated signals actuated by a shear-mode PZT embedded into a bond-line, propagated through a laminate structure, and received by another shear-mode PZT embedded into the bond-line. A) actuation signal, B) experimentally recorded signal C) signal from 3D FEM model and D) signal from 2D FEM model[34].

4.3 Bond-line Damage Detection

Based on the previously presented results 2D FEM simulation was used to simulate the structural wave propagation and sensor response with multiple forms of bond-line damage included in the simulation. Voids, vertical cracks, disbonds (adhesive failure) and kissing bonds were modelled at the midpoint between the actuator and sensor. Voids were modelled at midline of the bond-line by removing structural elements representing a 0.5 x 5.0 mm area. Vertical cracks through the thickness were modelled by designating a group of contact elements with infinite roughness. Disbonds from the adherands were similarly modelled by designating a group of contact elements with a 10 mm length at the interface between the adhesive and aluminium structure. Kissing bonds were modelled by a 50% reduction in stiffness in a group of adhesive elements along a 10 mm length at the interface with the aluminium structure. The simulated signals from the ‘damaged’ states were compared to the signal from the pristine state and a root mean squared damage index was calculated according to equation (1).

$$DI = \sqrt{\frac{\sum_{i=1}^{n}(x_i - X_i)^2}{\sum_{i=1}^{n}(X_i)^2}} \tag{1}$$

Where DI is the damage index, n is the number of frequencies in the spectrum, X are the elements of the spectrum in the signal from a pristine specimen, and x is the elements in the spectrum from the test signal [27]. Overlaid signals from the pristine and various ‘damaged’ states, with calculated damage indexes are shown in Figure 8.

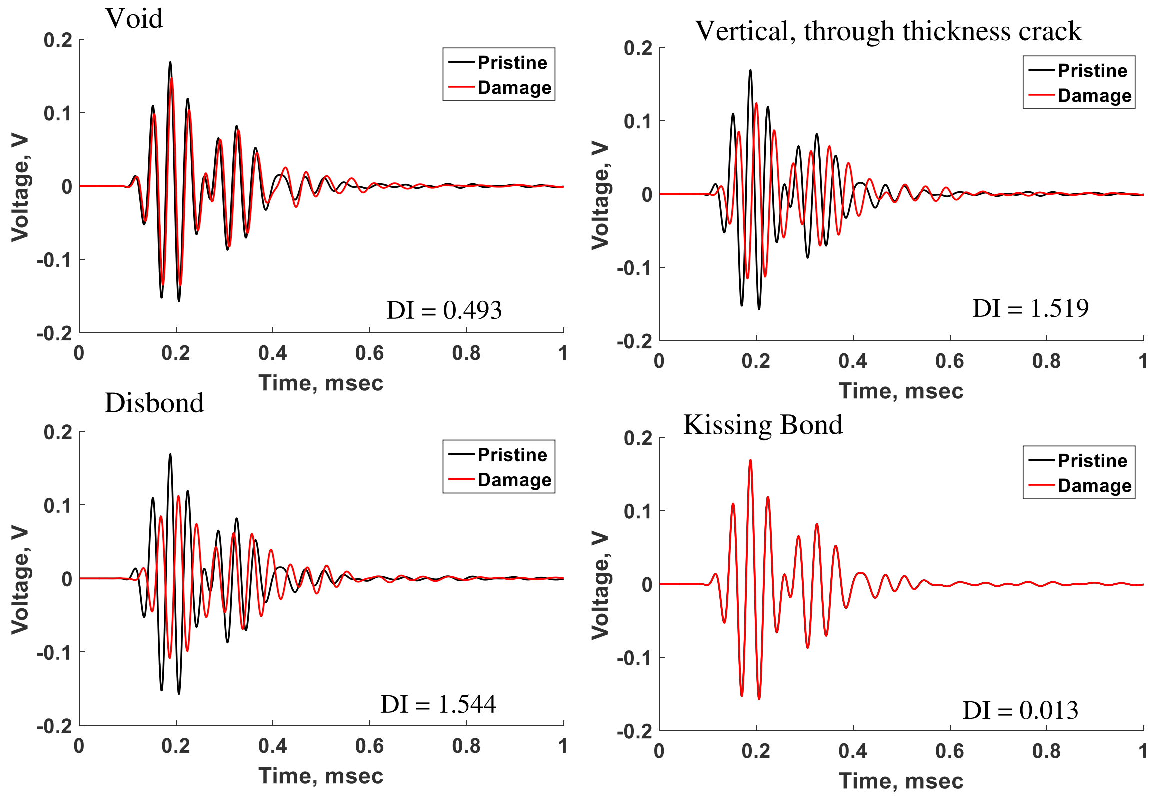

Figure 8 – Comparison of simulated signals propagated in pristine and damaged models using shear-mode PZTs as actuators and sensors embedded in the bond-line of an aluminium epoxy structure.

5. Results

From the simulation results it can be observed that ultrasonic waves actuated by shear-mode PZTs using a Hann windowed 5 peak tone burst at 30 kHz and sensed with another shear-mode PZT are highly sensitive to disbonds or adhesive failures, followed by through thickness cracks. Voids and kissing bonds did result in signal changes but they were small compared to the other forms of damage modelled.

Inspection over a range of frequencies found that lower frequencies generally produced larger damage indexes but with the same trend of sensitivities to differing damage types.

6. Discussion & Conclusion

Simulations were used to model the actuation deformation and natural frequencies of shear-mode PZT transducers and confirmed with analytical and experimental results. This information was used to design a novel system for inspecting bond-lines for damage, by placing the shear-mode PZT transducers into the bond-line to actuate the bond in shear. This took advantage of the strongest piezoelectric mode, coupled the transducer directly to the structure of interest, actuated flexural wave modes found to be sensitive to bond-line defects, and provided a hardware filter of the sensed signal.

2D and 3D models of a full laminate structure consisting of 2 aluminium layers bonded together with epoxy, containing shear-mode PZTs in the bond-line were created along with matching physical specimens. Shear PZTs were actuated to propagate ultrasonic waves and produce sensed signals in the simulations and experiment with very similar results validating the models. The models were inspected to understand the wave propagation.

Finally, various forms of damage were introduced into the model bond-lines, and the resulting signal changes evaluated. Across the four types of damage simulated, it was found that lower frequencies produced larger damage indexes and the signals were most sensitive to disbonds or adhesive failures, followed by through thickness cracks then voids and kissing bonds.

7. Vision and Future Work

The initial study presented herein was intended to demonstrate the feasibility of the approach of using shear-mode PZT actuators and sensors internally embedded in bond-lines to detect bond-line damage. To that end, further work is necessary to experimentally validate the simulated damage detection capabilities. Further work is also necessary to characterize the wave propagation modes, identify sensitivity to defects in the adherands, and differentiate damage types.

In the greater pursuit of SHM as embedded and automated systems, further study is also necessary to characterize signal strength produced by this application of shear-mode (d_{15}) PZT actuators and sensors both in comparison to and potentially paired with traditional (d_{31}) PWAS or (d_{33}) IDT transducers. E.g. are the strongest signals produced (with comparable size and applied power) by actuating and sensing using shear PZTs, PWASs, IDTs, or combinations thereof. This will allow for reduction in the parasitic effects of SHM hardware enabling system miniaturization and mass deployment.

Acknowledgement

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References

[1] Richard G. Budynas and J. Keith Nisbett, Shigley's Mechanical Engineering Design. New York: McGraw Hill, 2015.

[2] T. Kundu, A. Maji, T. Ghosh, and K. Maslov, "Detection of kissing bonds by Lamb waves," Ultrasonics, vol. 35, no. 8, pp. 573-580, January 1998.

[3] Robert D. Cook and Warren C. Young, Advanced Mechanics of Materials 2nd edition. Upper Saddle River, NJ: Prentice Hall, 1999.

[4] Robert. L. Norton, Machine Design: An Integrated Approach, fifth edition. Boston: Prentice Hall, 2014.

[5] Peter B. Nagy, "Ultrasonic detection of kissing bonds at adhesive interfaces," Journal of Adhesion Science and Technology , vol. 5, no. 8, pp. 619-630, 1991.

[6] Mark Lin and Fu-Kuo Chang, "The manufacture of composite structures with a built-in network of piezoceramics," Composite Science and Technology, vol. 62, no. 7-8, pp. 919-939, 2002.

[7] Christos Andreades and Andreades Ciampa, "CFRP Composites with Embedded PZT Transducers for Nonlinear Ultrasonic Inspection of Space Structures," in Proceedings of the European Workshop on Structural Health Monitoring, Manchester, England, 2018, p. 0133.

[8] Nathan Salowitz et al., "A vision on stretchable bio-inspired networks for intelligent structures," in Structural Health Monitoring 2013 - A Roadmap to Intelligent Structures, Stanford, 2013, pp. 35-44.

[9] Nathan Salowitz, Integration and Deployment of Thick Film Piezoelectric Actuators/Sensors on Organic Stretchable Substrates. Stanford, California, U.S.A., 2013.

[10] Nathan Salowitz, Yu-Hung Li, Sang-Jong Kim, Surajit Roy, and Fu-Kuo Chang, "Structural Health Monitoring of High Temperature Composites," in Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition, Denver, Colorado, U.S.A., 2011, Paper ID IMECE2001-64788.

[11] Nathan Salowitz, Giulia Lanzara, Zhiqiang Guo, James Rose, and Fu-Kuo Chang, "Design of planar electrodes for multifunctional piezoelectric sensors," in Structural Health Monitoring 2009: From System Intgration to Autonomous Systems, vol. 2, Stanford, CA, 2009, pp. 1080-1087.

[12] Nathan Salowitz, Sang-Jong Kim, Fotis Kopsaftopoulos, yu-Hung Li, and Fu-Kuo Chang, "Design and Analysis of Radially Polarized Screen Printed Piezoelectric Transducers," Journal of Intelligent Material Systems & Structures, p. Accepted, 2015.

[13] Nathan Salowitz et al., "Recent advancements and vision toward stretchable bio-inspired networks for intelligent structures," Structural Health Monitoring - An International Journal, vol. 13, no. 6, pp. 609-620, November 2014.

[14] Nathan Salowitz et al., "Development of a bio-inspired stretchable network for intelligent composites," in International Conference on Composite Materials, Jeju, South Korea, 2011, Paper ID AF1453.

[15] Nathan Salowitz et al., "Bio-inspired stretchable network-based intelligent composites," Journal of Composite Materials, vol. 47, no. 1, pp. 97-106, January 2013.

[16] Nathan Salowitz et al., "Screen Printed Piezoceramic Actuators/Sensors Microfabricated on Organic Films and Stretchable Networks," in Structural Health Monitoring 2013 - A Roadmap to Intelligent Structures, Stanford, CA, 2013, pp. 1543-1550.

[17] Nathan Salowitz et al., "Microfabricated Expandable Sensor Networks for Intelligent Sensing Materials," IEEE Sensors Journal, vol. 14, no. 7, pp. 2138-2144, 2014.

[18] Nathan Salowitz et al., "Bio-inspired intelligent sensing materials for fly-by-feel autonomous vehicles," in IEEE Sensors 2012, Taipei, Taiwan, 2012.

[19] Nathan Salowitz, "Stretchable sensors don't feel the strain," Nature Electronics, vol. 1, pp. 156-157, March 2018.

[20] Yu-Hung Li et al., "High temperature intelligent composites," in International Conference on Composite Materials, Jeju, South Korea, 2011, Paper ID AF2029.

[21] Giulia Lanzara, Nathan Salowitz, Zhiqiang Guo, and Fu-Kuo Chang, "A Spider-Web-Like Highly Expandable Sensor Network for Multifunctional Materials," Advanced Materials, vol. 22, no. 41, pp. 4643-4648, 2010.

[22] Giulia Lanzara, Zhiqiang Guo, Nathan Salowitz, and Fu-Kuo Chang, "Strain/Elongation Sensative Metal-Coated Polyimide Microwires for micro-scaled highly expandable sensor networks".

[23] Zhiqiang Guo et al., "Functionalization of stretchable networks with sensors and switches for composite materials," Structural Health Monitoring, 2017.

[24] Zhiqiang Guo et al., "Micro-Fabricated, Expandable Temperature Sensor Network for Macro-Scale Deployment in Composite Structures," in Proceedings of the 2011 IEEE Aerospace Conference, Big Sky, Montana, 2011, Paper ID 1648.

[25] Zhiqiang Guo et al., "Bio-Inspired Smart Skin Based on Expandable Network," in Structural Health Monitoring 2011 - Condition Based Maintenance and Intelligent Structures, Stanford, CA, 2011, pp. 1717-1724.

[26] Z. Guo et al., "Bio-Inspired Smart Skin Based on Expandable Network," in Proceedings of the 8th International workshop on Structural Health Monitoring, Condition-based Maintenance and Intelligent Structures, Stanford, CA, 2011, pp. 1717-1723.

[27] Victor Giurgiutiu, Structural Health Monitoring with Piezoelectric Wafer Active Sensors, 2nd ed. Boston, USA: Elsevier, 2014.

[28] Donald J. Leo, Engineering Analysis of Smaret Materials Systems. Hoboken, New Jersey, U.S.A.: John Wiley & Sons, 2007.

[29] American Piezoelectric Corperation. (2011, February) Properties of APC Piezoelectric Materials. [Online]. http://www.americanpiezo.com/materials/apc_properties.html

[30] V. Mueller and Q. M. Zhang, "Shear response of lead zirconate titanate piezoceramics," JOURNAL OF APPLIED PHYSICS, vol. 83, no. 7, pp. 3754 - 3761, April 1998.

[31] A. Kamal and V. Giurgiutiu, "Shear horizontal wave excitation and reception with shear horizontal piezoelectric wafer active sensor (SH-PWAS)," Smart Materials and Structures, vol. 23, pp. 1-17, July 2014.

[32] Keysight Technologies, "33500B Serise Waveform Generators," Data Sheet 2017.

[33] Tektronix, MDO 3000 Series Mixed Domain Oscilloscopes User Manual, 2016.

[34] Krohn-Hite, "Model 7600M/7602M Wideband Power Amplifiers," Data Sheet 2018.

[35] Hussain Altammar, Anoop Dhingra, and Nathan Salowitz, "Investigating the Feasibility of Ultrasonic Shear Actuation for Evaluation of Adhesive Joints in Multilayered Structures: FE Simulation," in American Society of Nondestructive Testing Annual Conference 2017, Nashville, TN, 2017.

[36] Hussain Altammar and Nathan Salowitz, "Ultrasonic Inspection of Bonded Metal Laminates Using Internal Shear-mode Piezoelectric Transducers," in Proceedings of the European Workshop on Structural Health Monitoring, Manchester, England, 2018.