Lamb wave propagation simulation in smart composite structures

Dulip Samaratunga and Ratneshwar Jha

Department of Mechanical and Aeronautical Engineering
Clarkson University, Potsdam, NY 13699

Abstract: Abaqus/Standard simulation of Lamb waves in smart composite plates is investigated for detecting delamination type damage. Composite plates typical of aerospace structures are used and a PZT actuator is surface bonded to excite Lamb waves. Abaqus model of composite plate uses layered solid elements. Piezoelectric (PZT-5H) actuator is modeled using piezoelectric elements that have both displacement and electric potential degrees of freedom. Perfect bonding between composite plate and PZT actuator is assumed. Simulation results obtained with appropriate level of structural damping are correlated with experimental measurements. The effect of delamination size on the structural response is studied. It is shown that the size and the location of delamination can be quantified using Lamb wave measurements.

1. Introduction

Composite materials are widely used in industries such as aerospace and automobiles due to the specific advantages over traditional metals such as superior strength/stiffness to weight ratio, corrosion resistance and improved fatigue life. One of the main reasons restricting increased usage of composites is that the damage mechanisms are not well understood. One particular damage mechanism, namely delamination, can be initiated by loading, impact, or manufacturing defects. The delamination lengths can reach critical levels before visual inspection. Currently available non-destructive evaluation (NDE) methods are expensive in time and cost. Some of them are impractical in many cases such as in service aircraft testing and space structures. Lamb waves (fundamental symmetric and asymmetric modes) have shown particular promise for damage diagnosis of composite structures (Banerjee et al., 2007; Lestari et al., 2004; Raghavan et al., 2007). The fundamental idea behind Lamb wave propagation based diagnostics is that different types of damages interact differently with waves. Therefore features of the signals; for instance measured time history of the propagated wave, the traveling time, speed reduction, and wave attenuation parameters, are extracted and used as the damage identification variables. Further processing of the measured signals (e.g., using Wavelet transform, Hilbert-Huang transform, etc.) helps damage recognition.

The incident Lamb waves depend on the excitation signal parameters (pulse shape, amplitude, frequency and number of cycles to be sent during each pulse period) and may have significant impact on damage detection. Published papers discuss the effects of actuation pulse parameters in a general way, but specifics are seldom reported. Kessler, (2002) considered the actuation pulse parameters, but presented results for 15 kHz 3.5 cycles input only. Several authors suggested higher frequencies, but Diamanti et al. (2007, 2010) considered frequencies below 50 kHz to be particularly sensitive for composite diagnostics. The fundamental anti-symmetric Lamb mode A_0

is generated at frequencies below 50 kHz which has much lower phase velocity than the symmetric S_0 mode and thus a smaller wavelength making it more sensitive to damage detection. Delamination sizes well below the wavelength of the propagating mode were successfully detected by Diamanti et al. (2007, 2010) At lower frequencies the attenuation is less and the signals can propagate at longer distances having detectable amplitude without the need for amplification. An investigation of excitation signal parameters on the detection of delamination in composite plates in low frequency range 10-50 kHz is reported (Jha et al., 2010). Here the experimental studies supported by numerical simulation shows the effect of varying input parameters on final damage detection. A different approach of identification of delamination in composite plates using damage force indicator and wavelet based spectral finite element method is presented in (Widana-Gamage et al., 2011).

This paper investigates Lamb wave based detection of delamination in composite plates. We use composite plates typical of aerospace applications and provide actuation using integrated piezoelectric transducer (PZT). Finite element model is developed in Abaqus to simulate PZT actuation and Lamb wave propagation in the plate. Numerical studies show good correlation with experimental results with appropriate level of structural damping. A scanning laser vibrometer is used for recording structural responses. The ability of Lamb wave to locate and quantify the delamination is also presented. The novelty of this work is that the Abaqus model simulates piezoelectric excitation and damping is estimated in the model comparing responses with experimental data.

2. Lamb waves in damage detection

Lamb waves are a type of ultrasonic waves that are guided between two parallel free surfaces, such as upper and lower surfaces of a plate, and are suitable for structural health monitoring applications since they travel long distances. Their motion can be symmetrical or anti-symmetrical with respect to the mid plane of the plate as shown in Figure 1. The symmetric and anti-symmetric modes resemble axial and flexural waves in beam/plate waveguides. In fact, symmetric Lamb waves behave similar to axial plate waves, whereas anti-symmetric Lamb waves behave similar to flexural plate waves at low frequencies (Giurgiutiu, 2008). Lamb wave based SHM techniques have been proven to provide information about damage type, severity and location. Lamb waves can be generated and captured with conformable piezoelectric actuators and sensors that require low power.

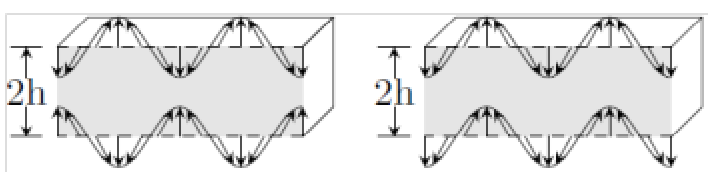


Figure 1. Lamb wave mode shapes; symmetric (left), anti-symmetric (right)

The actuation of Lamb wave using piezoelectric transducers (PZT) is reported in the literature (Valde´s et al., 2002). The application of Lamb wave techniques to identify the presence of damage in carbon fiber/epoxy specimens containing representative damage modes, including delamination, transverse cracks and through holes is reported in (Kessler et al., 2002). Based on the measured time history of the propagated wave, the traveling time, group speed reduction, and wave attenuation, parameters are extracted and used as the damage identification variables.

3. Abaqus model of composite plate with piezoelectric actuator

Abaqus model is developed to study Lamb wave propagation in carbon-fiber epoxy laminate. The AS4/3501-6 carbon-fiber epoxy laminate has dimensions of 250 x 126 x 1.25 mm (10 x 5 x 0.05 in) and consists of 8 cross-ply $[0/90]_{2S}$ layers. The plate is meshed with 15,750 solid (C3D8I) elements ensuring at least 10 nodes per wavelength (at 15 kHz of excitation frequency). The two lateral plate boundaries are restricted in all degrees of freedom as shown in Figure 2. In order to simulate the piezoelectric excitation similar to the experimental studies, piezoelectric (PZT-5H) actuator is modeled with 164 piezoelectric (C3D8E) elements. Perfect bonding between plate and PZT is assumed and an input of 30V is applied to PZT which has a shape of tone burst as shown in Figure 3. The mechanical properties of carbon-fiber pre-preg and PZT are provided in Table 1.

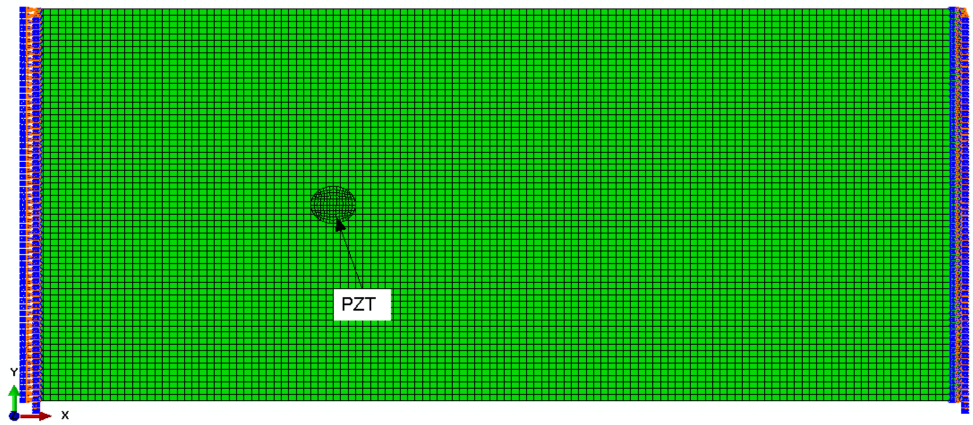


Figure 2. Finite element model of composite plate with surface bonded PZT actuator

Table 1. Material Properties

	AS4 3501-6	PZT
E_{11} (GPa)	147.0	60.61
E_{22} (GPa)	10.3	48.31
E_{33} (GPa)	10.3	60.61
G_{12} (GPa)	7.0	23.0
G_{13} (GPa)	3.2	23.5
G_{23} (GPa)	3.2	23.0
v_{12}	0.30	0.512
v_{13}	0.27	0.289
v_{23}	0.27	0.408
Density (kg/m^3)	1600	7500

Under small field conditions, the constitutive relations for a piezoelectric material are given by (IEEE Standard, 1987)

$$\begin{bmatrix} D \\ \varepsilon \end{bmatrix} = \begin{bmatrix} e^{\sigma} & d^{d} \\ d^{c} & s^{E} \end{bmatrix} \begin{bmatrix} E \\ \sigma \end{bmatrix} \tag{01}$$

where vector D of size (3x1) is the electric displacement (Coulomb/m^2), ε is the strain vector (6x1) (dimensionless), E is the applied electric field vector (3x1) (Volt/m) and σ is the stress vector (6x1) (N/m2). The piezoelectric constants are the dielectric permittivity e_{ij}^{σ} of size (3x3) (Farad/m), the piezoelectric coefficients d_{im}^{d} (3x6) and d_{jk}^{c} (6x3) (Coulomb/N or m/Volt), and the elastic compliance s_{km}^{E} of size (6×6)(m2/N). At 25 ^{0}C the piezoelectric coupling and dielectric permittivity properties for PZT-5H are given by,

$$d = \begin{bmatrix} 0 & 0 & 0 & 741 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 741 \\ -274 & 593 & -274 & 0 & 0 & 0 \end{bmatrix} 10^{-12}\, m/V$$

$$e^{\sigma} = \begin{bmatrix} 1.505 & 0 & 0 \\ 0 & 1.301 & 0 \\ 0 & 0 & 1.505 \end{bmatrix} 10^{-8}\, F/m$$

The electrical potential applied to the PZT actuator has the shape of a tone burst obtained by windowing a sinusoidal wave with a Hanning window (Figure 3). The dynamic analysis is performed using Abaqus/Standard direct solver. The fixed step increment is taken as 1μs. Solutions are obtained for 3.5 cycles tone burst input with carrier frequency of 15 kHz. Out of plane velocity responses are recorded at designated sensor locations.

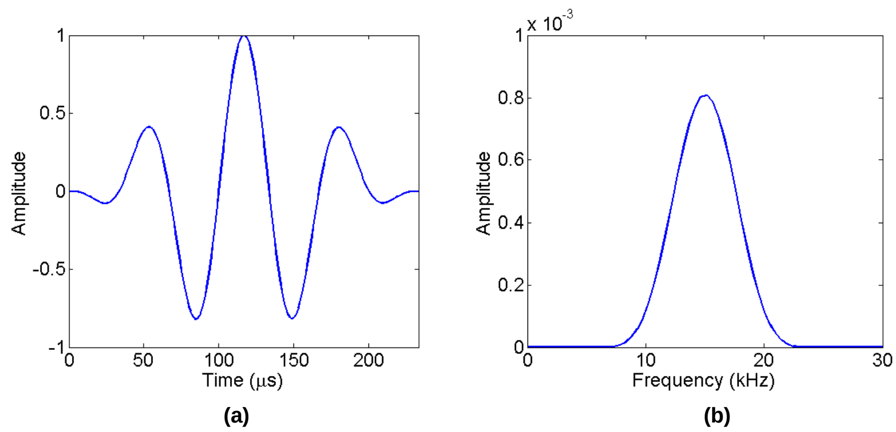
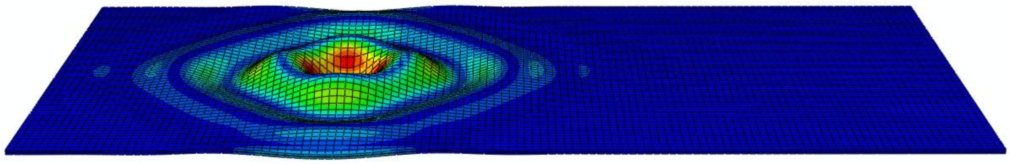
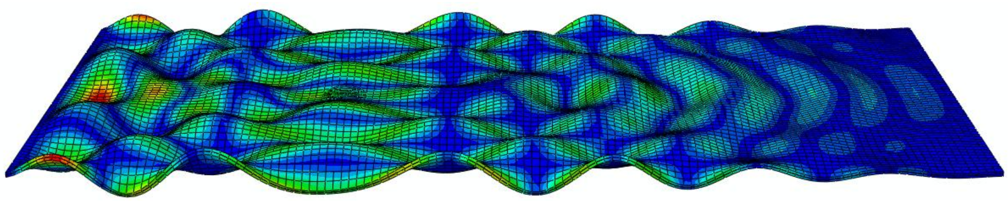


Figure 3. (a) 15k, 3.5 cycles tone burst in time (b) and in frequency

Figure 4 shows out of plane velocity field for healthy plate at different time instants. Once the circular PZT is actuated the tone burst is propagated radially outward through the structure. The speed of travelling wave is described by the Lamb wave dispersion curves. The figure also shows the directional variation of group velocity which is at its highest in X and Y directions. Since the laminate is symmetric cross-ply, it has the highest stiffness in X and Y directions.



100 µs



220 µs

Figure 4. Lamb wave propagation and scattering at different time instants

3.1 Structural damping

Structural damping has a significant effect on wave propagation, including initial amplitude and attenuation. Rayleigh linear damping model available in Abaqus/Standard is used to introduce damping to the plate. In Rayleigh damping model, it is assumed that damping is a linear combination of mass and stiffness matrices.

$$[C] = \alpha[M] + \beta[K] \tag{02}$$

where α and β are user defined constants. For a given mode *i* the fraction of critical damping, ξ_i, can be expressed in terms of the damping factors α and β as:

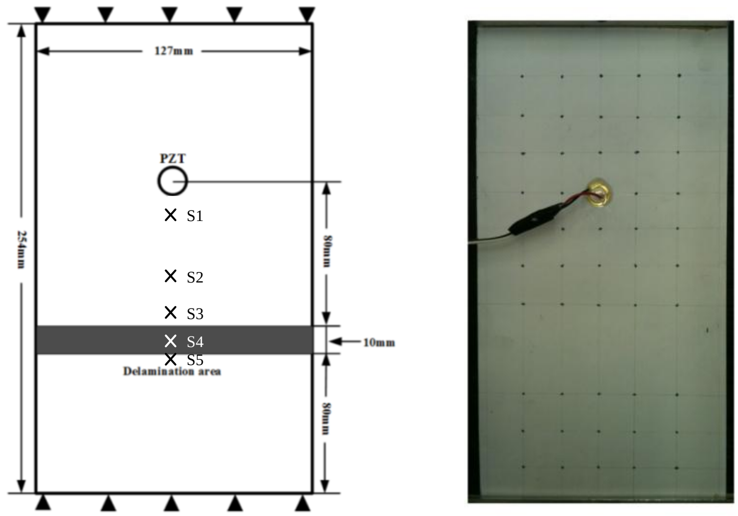
$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \tag{03}$$

where ω_i is the natural frequency of a mode. This implies the mass proportional damping parameter, α, damps the lower frequencies and the stiffness proportional damping, β, damps the higher frequencies. In our studies, the values for α and β are determined to be 0 and 4×10^{-7} by comparing with experimental data.

4. Experimental Investigations

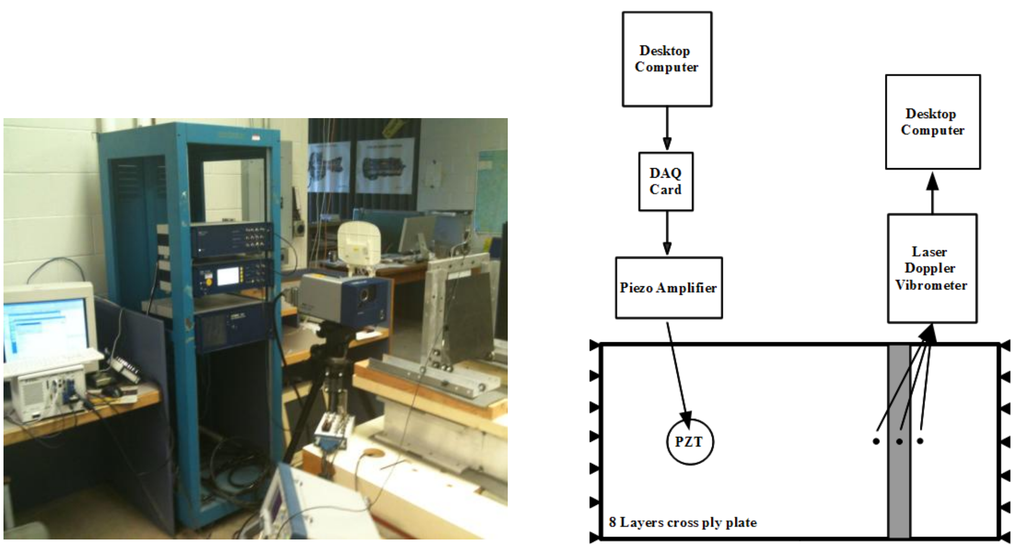
The composite plate used in experimental studies was fabricated from AS4/3501-6 pre-preg using vacuum bagging and oven curing technique. A schematic of composite plate with sensor locations is shown in Figure 5-a. Hi-temp mold release wax from Partall was applied between 4^{th} and 5^{th} layers to make the delamination in the plate. The piezoelectric actuator (diameter 13.5 mm and thickness 0.22 mm) was affixed onto the composite plate using epoxy as shown in Figure 5-b. A

National Instruments PXI 6339 and a BNC-2110 board were used to generate signals and a QuickPack® power amplifier was used to amplify the actuation signal. Tone burst excitations at 15 kHz and 3.5 cycle (Figure 3) was used to generate A_0 Lamb waves.



(a) (b)

Figure 5. (a) AS4/3501-6 pre-preg cross ply composite plate schematic diagram with delamination area (b) healthy composite plate with PZT actuator



(a) (b)

Figure 6. (a) Experimental setup (b) Schematic diagram

Tone burst type input was selected due to its ability to travel longer distances without much dispersion even in highly dispersive mediums like composites. A Scanning Laser Doppler Vibrometer (SLV) was employed to acquire the signals at designated sensor locations. The experimental set up is shown in Figure 6.

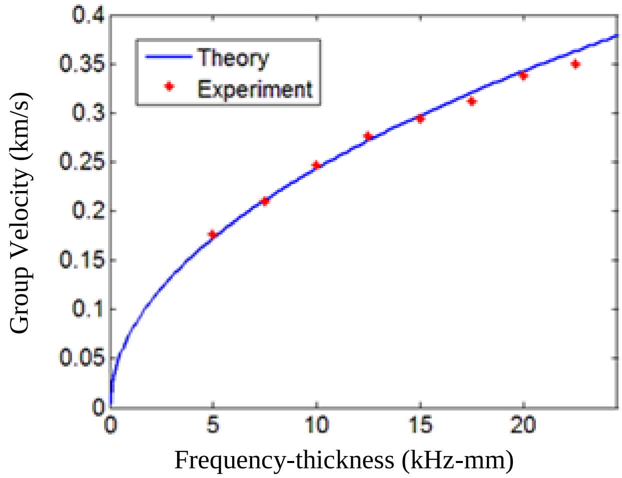


Figure 7. Lamb wave A_0 mode velocity comparison

The comparison of measured group velocities at different frequencies with analytical solution is shown in Figure 7 (Kim, 2011). The experimentally measured group velocities match well with the fundamental anti-symmetric mode (A_0) of analytical solution confirming that the excited signals are Lamb wave A_0 mode. Comparison of out of plane velocities in healthy FE and experimental responses at sensor location S_3 is shown in Figure 8. The time histories are normalized with the signal recorded at S_1 (sensor location close to the PZT) in each case to minimize the effect of differences in actuator attachment to the plate since experimental plate may not have perfectly bonded PZT.

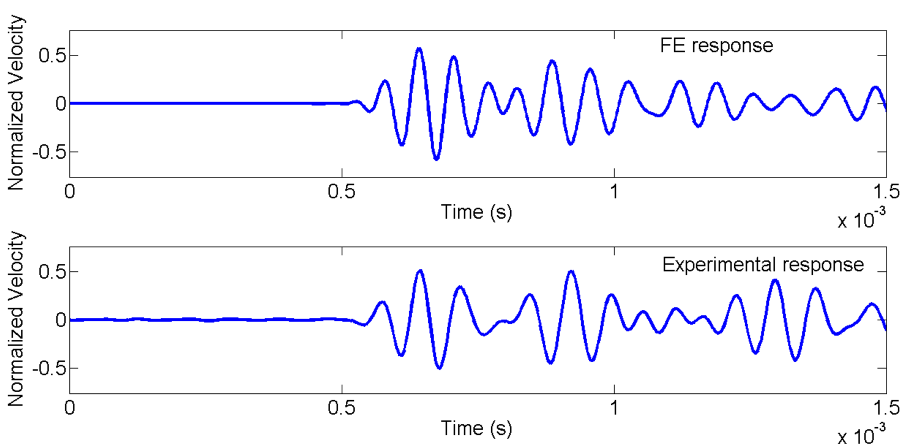


Figure 8. FE and Experimental response comparison at sensor location S_3

It is observed that Abaqus responses match well with experimental result for the first two wave packets. Subsequent responses show some deviations possibly due to the differences between FE and experimental conditions such as boundary and damping. Since the first few wave packets contain most important information for damage detection, the FE analysis with PZT modeling and damping values will be used in future for simulations with other input excitations.

5. Delamination analysis with Abaqus/Standard

A large plate is used for delamination simulations to avoid difficulty in data interpretation due to boundary reflections. The dimensions of the plate for delamination analysis are 500 x 500 x 10 mm having ten AS4/3501 unidirectional laminas bonded together. A delamination between the 5^{th} and the 6^{th} layers of the laminate is introduced by disconnecting nodes in the region of interest. Figure 9 shows the Abaqus model with delamination in the middle of the plate (highlighted in red in the figure). A 20kHz, 3.5 cycles tone burst excitation is given at the center of left edge of the plate. The input has a Gaussian distribution in space along *Y* direction. The plate is fixed all along the right hand side boundary. Since the problem is symmetric around *Y*=0 line, only a half of plate is modeled to save computational time. The cantilever type plate meshed with layered shell elements (S9R5) is analyzed for different delamination widths along *X* dimension. There is sufficient number of nodes (>10) to capture high frequency modes with the given excitation frequency. Abaqus/Standard direct solver is used for solving and problem.

Figure 10 shows the response measured at the tip (excitation point) of the plate with and without delamination. The first wave packet is the incident wave and the second large wave packet is the reflection from the fixed boundary which arrives 585μs after the excitation.

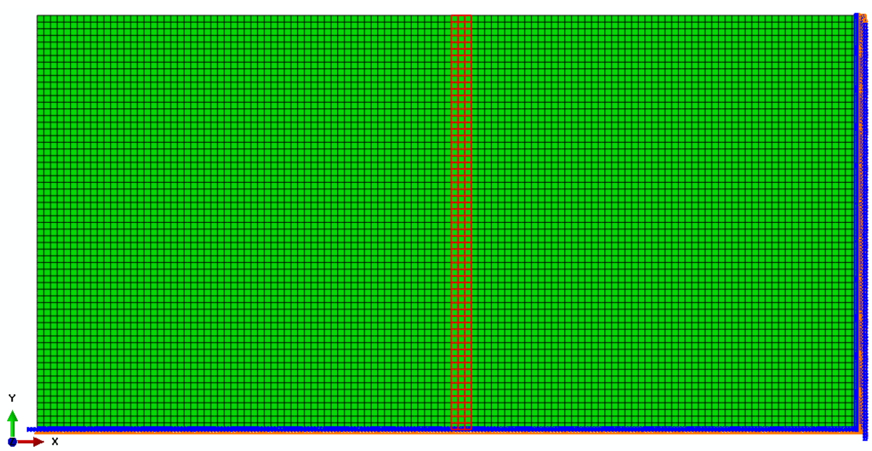


Figure 9. Finite element model of composite plate with delamination area is in red

The group velocity of the Lamb wave mode for this excitation is calculated as 1709 m/s. In the damaged plate response, there is an additional reflection which reaches the plate tip 293μs after the excitation. The distance to the reflected boundary can be calculated by multiplying the group velocity by the time it takes to arrive at the tip which is determined to be 0.500 m. This is two times the distance to the delamination boundary and therefore it can be concluded that the additional reflection appearing in the response of damaged plate is caused by the delamination.

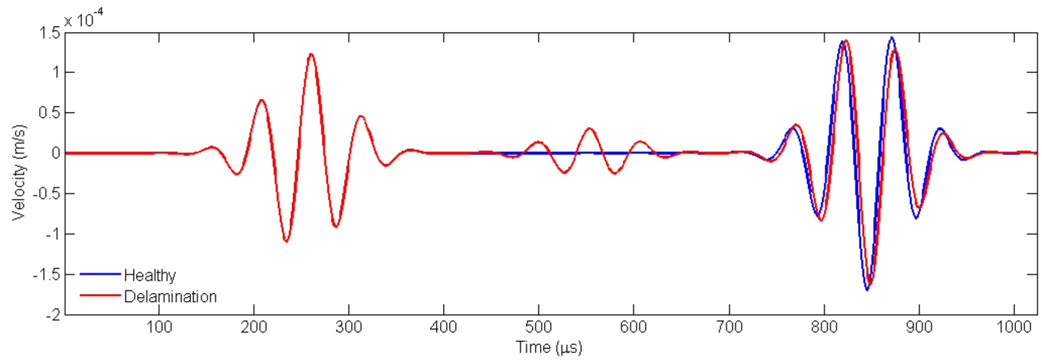


Figure 10. Response at the tip of the plate

Next, an analysis of damaged plate responses for different delamination sizes is presented. Figure 11 shows the responses measured at the tip of damaged plate with three different delamination widths, namely 12, 20, and 28 mm. It is observed that the reflections due to all three delaminations arrive at the same time. Therefore this reflection can be used to locate the damage. However, it is not very straight forward to conclude the severity (or size) of the delamination based on the reflected wave from the delamination. Amplitude of the reflected wave is reduced and it appeared more dispersed as the width of the delamination increases.

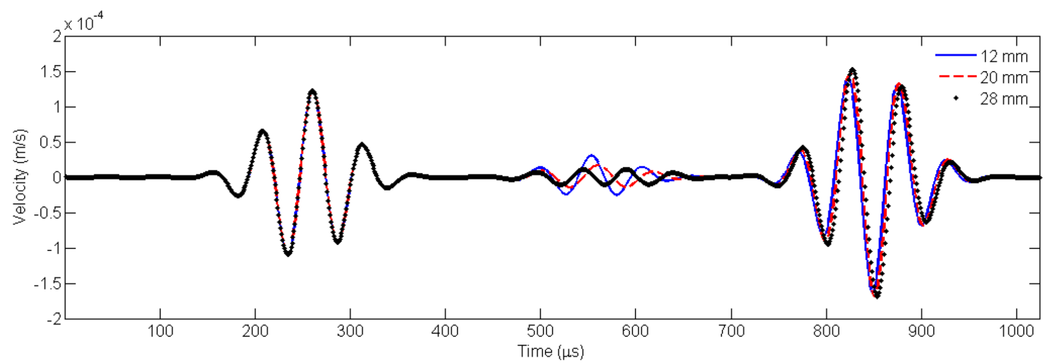


Figure 11. Response of damaged plate for different delamination sizes

However, the wave reflected from fixed boundary contains useful information for assessing the damages severity. The time it takes for the reflected wave to arrive at the excitation point is increased as the delamination width increases. This can be explained with the help of group velocity. The incident Lamb wave propagates along the pate at a velocity which is a function of plate thickness. Once the wave enters the delaminated region which has smaller thickness the wave speed is reduced. Therefore wider the delamination area it has to pass through, longer the time taken to come back to the excitation point. As the delamination size increases, a consistent delay of reflected wave arrival time is observed (Table 2).

Table 2. Arrival times and delay of fixed boundary reflection

Plate Condition	Arrival time of reflected wave (μs)	Delay with respect to healthy plate (μs)
Healthy	585	0
12 mm delamination	589	4
20 mm delamination	591	6
28 mm delamination	594	9

6. Conclusions

This study has presented the application of Abaqus/Standard simulation of Lamb waves for detection of delamination in composite plates. We used composite plates typical of aerospace applications and provided excitation using integrated PZT actuator. Piezoelectric (PZT-5H) actuator was modeled in Abaqus using piezoelectric elements that have both displacement and electric potential degrees of freedom. A scanning laser vibrometer was used for recording structural responses in experimental studies. Numerical studies showed good correlation of plate responses with experimental results with appropriate level of structural damping. The novelty of this work is that the Abaqus model simulates piezoelectric excitation and damping was estimated in the model comparing responses with experimental data. Abaqus model of composite plate with delamination used layered shell elements. It was shown that the reflection from the delamination can be used to locate the damage. The delamination size was correlated to arrival time lag of reflected wave from the fixed boundary.

7. Acknowledgement

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