Delamination Size Detection using Time of Flight of Anti-symmetric (A_o) and Mode Converted A_o mode of Guided Lamb Waves

C. RAMADAS,[1,2,*] M. JANARDHAN PADIYAR,[1] KRISHNAN BALASUBRAMANIAM,[1] MAKARAND JOSHI[2] AND C. V. KRISHNAMURTHY[1]

[1]Centre for Nondestructive Evaluation and Department of Mechanical Engineering

Indian Institute of Technology Madras, Chennai – 600 036, India

[2]Composite Research Center, R & D E (E), Dighi, Pune – 411 015, India

ABSTRACT: In this article an attempt has been made to quantitatively assess the extent of delamination in composite laminates, using time-of-flight of fundamental Lamb wave modes, without recourse to baseline data from a healthy structure. An expression has been derived to determine the delamination size, from group velocities of primary Lamb modes in the sub-laminates and time-of-flight of transmitted A_o signal and mode converted A_o signal, which is generated when A_o mode propagates through a delamination. The effectiveness of the expression, when group velocities of primary Lamb modes in the main laminate were used, has been verified through numerical simulations carried out on a quasi-isotropic glass/epoxy laminate with various delamination interfaces. The effectiveness of the expression has also been verified experimentally, on two GFRP cross-ply laminates of [0/90/0] lay-up with 40 mm and 50 mm delamination sizes, using air coupled ultrasonic transducers. The predicted delamination sizes were found to be in good agreement with the actual delamination sizes. Using the proposed technique absolute identification of delamination is possible. A supplementary equation for determining the minimum length of delamination has also been derived and presented in the article.

Key Words: Lamb wave, delamination, time of flight, air-coupled ultrasonic transducers.

INTRODUCTION

THE main reasons for extensive use of fiber-reinforced plastic (FRP) composite materials in aerospace, military and civilian structural applications are high specific strength, modulus, corrosion resistance and excellent fatigue performance. The most important damages in composites are matrix cracking, fiber breakage, delamination and fiber-matrix interface debonding. The reasons for delaminations in composites can be attributed to the weak interlaminar shear strength and the low out-of-plane tensile strength compared to in-plane strength. Accidental impacts by tools or any other hard objects during maintenance and repair can cause delamination in addition to operational hazards. Of the various types of damage, delamination in particular causes a significant reduction in compressive strength and stiffness.

The delaminations are sub-surface damages, which can not be detected through visual inspection and hence ultrasonic non-destructive testing (NDT) methods have to be used to locate these damages. The conventional ultrasonic C-scan method is a point-by-point inspection that is tedious and time consuming. Further, conventional NDT methods are difficult to use for the inspection of inaccessible portions of structures.

Lamb waves are guided by the geometrical boundaries to propagate long distances along the contours of the specimen. These waves provide information about integrity of the medium along the path. Hence, these waves can be used for NDT as well as structural health monitoring (SHM) of composite laminated structures.

Use of ultrasonic elastic waves for damage detection in composite structures started in 1990s. Guo and Cawley (1993) studied the interaction of S_o mode with delaminations in a cross-ply composite laminate. When S_o mode encountered a delamination in its propagation path, a reflected wave was shown to be generated. It was found that, when shear stress is zero at the delamination interface, no wave reflection takes place. It was proposed to use multiple tests, each with a different Lamb mode for inspection of delaminations. Ip and Mai (2004)

*Author to whom correspondence should be addressed.
E-mail: rd_mech@yahoo.co.in
Figures 1–4 appear in color online: http://jim.sagepub.com

1045-389X/10/08 0817–9 $10.00/0 DOI: 10.1177/1045389X10367836

proposed an active diagnostic system that works in pulse-echo mode. This diagnostic system does not require baseline data for locating the edge of an asymmetric delamination from a reference point in the composite beam. Primary anti-symmetric Lamb mode (A_o), which was excited using a surface mounted piezoelectric patch, was used. Accelerometer was used for monitoring the response of the beam. Continuous wavelet transform using Gabor wavelet was applied to decompose the received signal from accelerometer. The location of the delamination edge was found using time-of-flight (TOF) of the reflected wave group. Toyama and Takatsubo (2004) proposed an inspection technique using symmetric Lamb mode (S_o) to detect impact induced delamination in composite laminates. This technique requires two line scans. Change in wave velocity and amplitude due to delamination, were the criteria used for damage detection. Su and Ye (2004) established a Lamb wave based quantitative identification scheme for delamination in CF/EP composite structures using artificial neural network (ANN). An intelligent signal processing and pattern recognition (ISPPR) package was developed to perform the identification, in which a multi-layer ANN supervised by error back propagation (BP) was trained using spectrographic characteristics extracted from acquired Lamb wave signals. Duflo et. al. (2007) characterized the defects in the bonding of carbon epoxy composite laminates using Lamb waves. Air coupled transducers were used to obtain C-scan images of the transmitted signal when the plate was moving between two air coupled transducers. Contact transducer and laser interferometer was used for studying Lamb wave propagation through the defect. The size and flaw area were estimated.

Some studies were conducted (Toyama et al., 2002; Dayal and Kinra, 1991; Tang and Henneke II, 1989; Seale et al., 1998) to detect damage in composite laminates by making use of Lamb wave method. These studies mainly focused on evaluation of damage based on changes in Lamb wave velocity due to a reduction in the stiffness of laminate. Guo and Cawley (1994), and Valdes and Soutis (2002), determined the location of delamination using the arrival time of Lamb wave reflected at the delamination edge.

Karthikeyan et al. (2009) and Ramadas et al. (2009) studied the interaction of primary anti-symmetric Lamb mode with symmetric delaminations, both numerically and experimentally, using non-contact ultrasonic transducers. It was found that when A_o mode interacts with a symmetric delamination, it generates a new mode, S_o, which is confined only to the sub-laminates, that is, the delaminated region, and can be detected in the main laminate through the mode converted A_o mode when the S_o mode interacts with the exit portion of the delamination.

Hayashi and Kawashima (2002) used strip element method, proposed by Liu and Achenbach (1994) and Liu et al. (1999), and numerically simulated Lamb wave propagation in delaminated region in a cross-ply laminate. Palacz et al. (2005) numerically analyzed, using spectral finite element technique, propagation of flexural-shear coupled wave in a delaminated multi-layered composite beam. It was found that when the delamination grows reflections from the first and second tip of delamination appear.

It is evident from the above literature that for detection of delamination in composite structure, baseline data from the healthy region is required. In this article a strategy for detection of the extent of delamination without recourse to baseline data from a healthy structure has been developed. This strategy has been implemented on a numerically simulated quasi-isotropic glass/epoxy laminate, with lay up $[0/\pm45/90]_s$, with various delamination interfaces. The technique has been verified experimentally on asymmetrically delaminated cross-ply laminates. In the first part of this article, an expression has been derived based on the interaction of primary Lamb modes with delamination. In the second part, numerical simulations on a quasi-isotropic laminate with four different interface delaminations have been carried out to check the effectiveness of the derived expression. In the third part, experimental verification was conducted using non-contact ultrasonic transducers (NCU) (Bhardwaj, 2001) on cross-ply laminates [0/90/0] with 40 mm and 50 mm delamination sizes. The derived expression was used to estimate the sizes of delamination created in cross-ply laminates. The estimates were found to be in accord with the actual sizes of delaminations.

EXPRESSION FOR DELAMINATION LENGTH

It was shown (Karthikeyan et al., 2009; Ramadas et al., 2009) that when A_o mode is incident on the entrance of delamination (E) in Figure 1(a), it splits into two A_o modes, and propagates independently in each sub-laminate as A_oA_o wave groups. This wave group, A_oA_o, reaches the exit of delamination (X), interacts with it and transmits in the main laminate as $A_oA_oA_o$ wave group. During the interaction of A_o mode with 'E', it generates S_o mode, which propagates as A_oS_o wave group in the sub-laminates. This wave group interacts with 'X', gets converted to A_o mode and propagates in the main laminate as $A_oS_oA_o$ wave group. Since S_o mode travels faster than A_o mode, $A_oS_oA_o$ wave group always appears before the $A_oA_oA_o$ wave group at the receiver location.

The locations of transmitter and receiver are shown in Figure 1(b). The length of delamination and distance between transmitter and receiver are 'D' and 'L' ($=L_1 + L_2 + D$), respectively. L_1 and L_2 denote distances

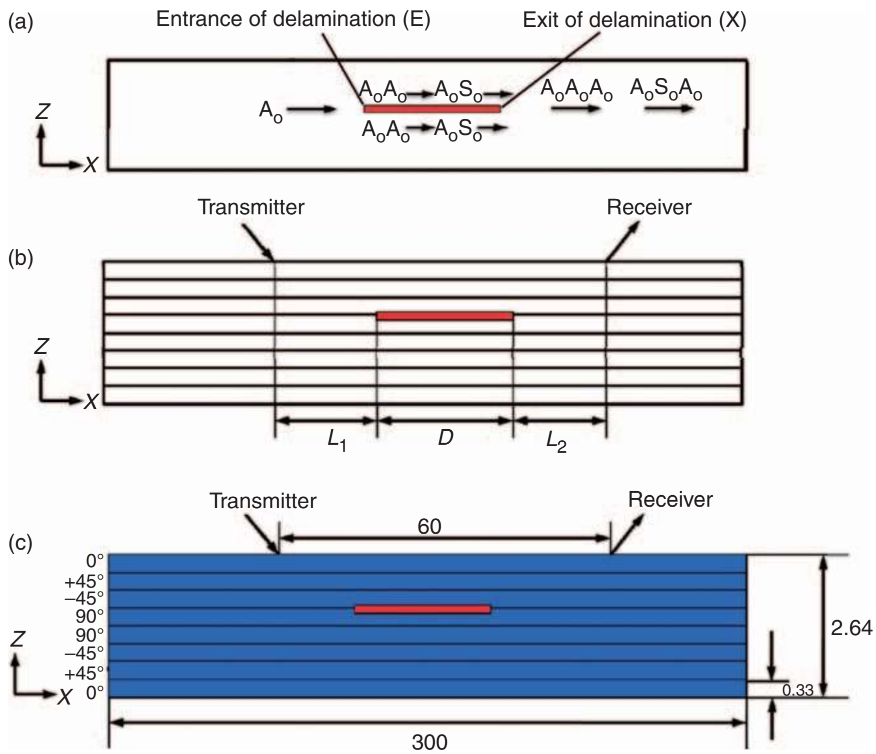

Figure 1. *(a) Schematic of Lamb mode propagation through delamination, (b) locations of transmitter and receiver, (c) specifications of quasi-isotropic laminate.*

between transmitter and entrance of delamination, and between exit of delamination and the receiver respectively. The group speeds of A_o mode in the main and the sub-laminates are V_{Aom} and V_{Aos} respectively. The group speed of S_o mode in sub-laminate is V_{Sos}.

Let t_1 and t_2 be the arrival times of the first wave group, $A_oS_oA_o$, and the second wave group, $A_oA_oA_o$ respectively, recorded by the receiver (R) at distance L from transmitter (T), as shown in Figure 1(b). From distance, time and velocity relations, the following two expressions can be derived:

$$t_1 = \frac{L_1}{V_{Aom}} + \frac{D}{V_{Sos}} + \frac{L_2}{V_{Aom}} = \left(\frac{L_1 + L_2}{V_{Aom}}\right) + \frac{D}{V_{Sos}}, \quad (1)$$

$$t_2 = \frac{L_1}{V_{Aom}} + \frac{D}{V_{Aos}} + \frac{L_2}{V_{Aom}} = \left(\frac{L_1 + L_2}{V_{Aom}}\right) + \frac{D}{V_{Aos}}. \quad (2)$$

Eliminating terms in brackets from both the expressions, the following expression is obtained:

$$t_2 - t_1 = D\left(\frac{1}{V_{Aos}} - \frac{1}{V_{Sos}}\right). \quad (3)$$

The above expression is an original contribution of the authors, which was derived based on the interaction of guided waves with a delamination. For estimation of the size of delamination in a composite laminate, using expression (3), the difference in arrival times of $A_oS_oA_o$ and $A_oA_oA_o$ wave groups at the receiver and group velocities of A_o and S_o modes in the sub-laminates are required. Delamination divides the main laminate into two sub-laminates. In the sub-laminates, the wave groups A_oA_o and A_oS_o modes propagate independently. Since the lay up in each sub-laminate is different, the group velocities of A_o and S_o modes will also be different in the sub-laminates. In the active diagnostic for detection of delamination edge, proposed by Ip and Mai (2004), the change in group velocity of Lamb mode in the sub-laminates was not considered. The group velocity of Lamb mode in the sub-laminate was assumed to be equal to that in the main laminate.

In practice, since the interface of delamination is not known, the group velocities of A_o and S_o modes in the sub-laminates are not known. Expression (3) requires the group velocities of primary Lamb modes in the sub-laminates. One of the ways to approximate size of delamination is by considering the velocities of Lamb modes in the main laminate instead of those in the sub-laminates. The effectiveness of the expression (3) when replaced with the group velocities of the primary Lamb modes in the main laminate has been verified on quasi-isotropic laminate through numerical simulations and on cross-ply laminate through experiments.

VERIFICATION THROUGH NUMERICAL SIMULATIONS

Numerical simulations have been carried out using commercial FEM software, ANSYS, on a glass/epoxy quasi-isotropic laminate with a fixed delamination size of 50 mm, but at four different locations across the thickness. There are eight plies with a lay up sequence of $[0/\pm45/90]_s$. The specifications of laminate are shown in Figure 1(c). Thickness of each ply and total laminate thickness are 0.33 mm and 2.64 mm respectively. The length of the laminate is 300 mm. The properties of glass/epoxy lamina are shown in Table 1. In numerical model, each ply has been modeled and their properties assigned. The central frequency of excitation and number of cycles were 200 kHz and seven, respectively. The excitation pulse was a tone burst modulated with Hanning window. The mode of excitation was A_o. The element used for modeling is an eight node plane strain element with two translational degrees of freedom at each node. The size of element was 0.33 mm in thickness direction and 0.25 mm in length direction. Attenuation was not considered in numerical modeling. Delamination is modeled by de-merging the nodes at delamination (Guo and Cawley, 1993). Since A_o mode has predominant out-of-plane displacement, it was generated by giving the excitation in *z*-direction. The separation distance between the transmitter and receiver is 60 mm as shown in Figure 1(c).

Initially, numerical modeling was carried out on the quasi-isotropic laminate with zero delamination length. A-scan obtained in this case is shown in Figure 2(a). In this A-scan, there was only one wave group, that is, A_o. Four delaminations of 50 mm size have been modeled separately, at various ply interfaces, in the numerical model. The delamination locations are between plies (i) [0] and [+45] (ii) [+45] and [−45] (iii) [−45] and [90] (iv) [90] and [90]. Since we are interested in A_o mode, only out-of-plane displacement history was captured. A-scans obtained at all four of the afore-mentioned locations, are shown in Figure 2. When a delamination was introduced in the laminate, there are two wave groups in the received signals. The first and second wave groups shown in Figure 2(b)–(e) are $A_oS_oA_o$ and $A_oA_oA_o$ modes, respectively. Group velocities of A_o and S_o modes in the quasi-isotropic main laminate are 1136.8 and 2551.3 m/s, respectively, as obtained from DISPERSE (Imperial College, 2003). The arrival time of each wave group is worked out by taking the peak of envelope fitted over each signal. Based on arrival times of wave groups and group velocities of primary Lamb modes in the main laminate, the delamination sizes have been predicted and are shown in Table 2.

VERIFICATION THROUGH EXPERIMENTS

Fabrication of Specimen

Experiments were carried out on cross-ply laminates. Two glass/epoxy laminates of [0/90/0] lay up, with delamination interface between [0] and [90] plies were fabricated using resin film infusion (RFI) technique. The thickness of each ply was 0.33 mm. In each laminate there are three plies (two zero plies and one ninety ply), so the thickness of each laminate is 0.99 mm. The fabrication technique for [0/90/0] laminate with 50 mm delamination length with delamination interface between [0] and [90] plies has been described below.

A glass / epoxy cross-ply laminate of 0.99 mm thickness with [0/90/0] lay up was prepared using RFI technique. A resin film was sandwiched between two plies. Such sandwiches were placed one above the other till the desired thickness was reached. A brass strip of 0.05 mm thick, 50 mm width (delamination length) and 100 mm length (80 mm length was kept inside the laminate, remaining 20 mm was projecting out) was inserted between 90 and 0 degree plies from one of the sides of the laminate. The brass strip was coated with poly vinyl alcohol (PVA) for easy removal from the laminate after curing. Sufficient bleeder was used to absorb any excess resin. A vacuum bag was placed on the top and sealed with a sealant tape. A thermocouple was placed on the top of the job to continuously monitor the temperature during curing. The job was heated at a rate of 2°C/min up to 80°C, soaked for 30 min followed by heating to 120°C and soaked for 60 min. After completion of heating cycle, the job was allowed to cool to room temperature. The brass strip was removed by subjecting to four point bending. Thus a delamination of 50 mm length was created in the laminate. The laminate was cut into length and width of 400 mm and 300 mm respectively. The lamina properties of this laminate are given in Table 1.

The same fabrication technique (RFI) as described above was used for making laminate of [0/90/0] lay up with 40 mm delamination size. Delaminations introduced in two laminates of [0/90/0] lay up, divided each laminate into two sub-laminates, [0/90] and [0], at the delamination region.

Table 1. Material properties.

Material	E_{11} (GPa)	E_{22} (GPa)	υ_{13}	υ_{23}	G_{13} (GPa)	ρ (kg/m^3)
Glass/epoxy	44.68	6.90	0.280	0.355	2.54	1990

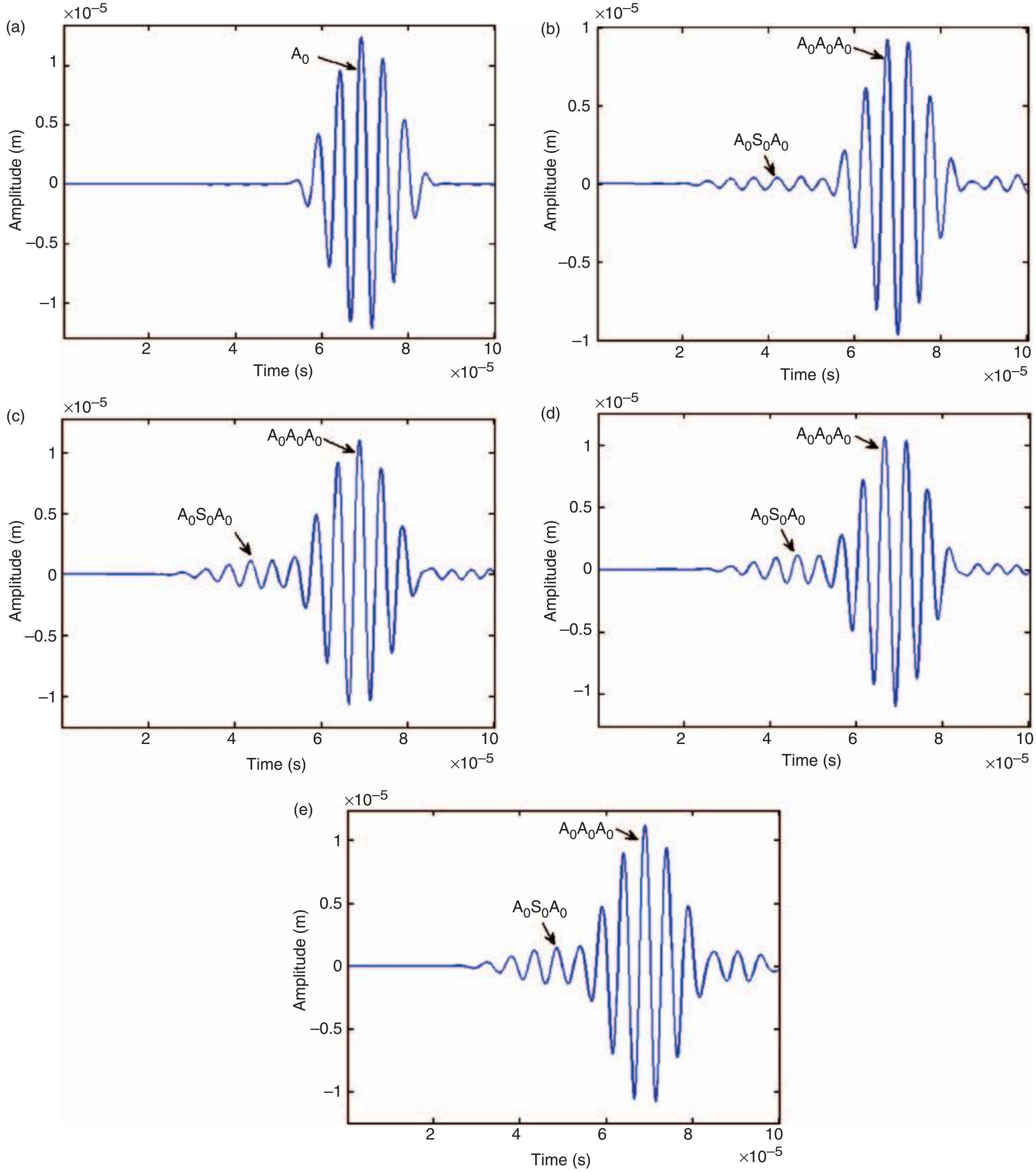

Figure 2. *A-scans from numerical simulations on $[0/\pm45/90]_s$ laminate: (a) with no delamination (intact), (b) with delamination interface between plies 0, +45, (c) +45, −45, (d) −45, 90, and (e) 90, 90.*

Experimental Set Up

The schematic experimental set up as shown in Figure 3, consists of a signal generator, power amplifier, 100 MHz A/D card, signal conditioner and a desktop computer. The probes used were non-contact ultrasonic (NCU) transducers with central frequency of 200 kHz, provided by Ultran Group, USA. Probe holding fixtures were fabricated to hold NCU probes attached to the scanner. The angle of the probe with respect to the vertical was adjusted as 21° (approximately), which is required for generation of A_o mode in the laminate. Pitch-catch

Table 2. Arrival times of wave groups and predicted delamination sizes in quasi-isotropic laminate. Actual delamination size was 50 mm.

Delamination interface	Arrival time of wave group $A_oS_oA_o$ t_1 μs	Arrival time of wave group $A_oA_oA_o$ t_2 μs	$\Delta t = t_1 - t_2$ μs	Predicted size using main laminate group velocities (mm)	Predicted size using sub-laminate group velocities (mm)
[0] and [+45]	47.8	69.8	22.0	45.1	46.9
[+45] and [−45]	46.4	68.6	22.2	45.5	47.5
[−45] and [90]	46.6	68.8	22.2	45.5	47.7
[90] and [90]	47.5	69.4	21.9	44.9	44.1

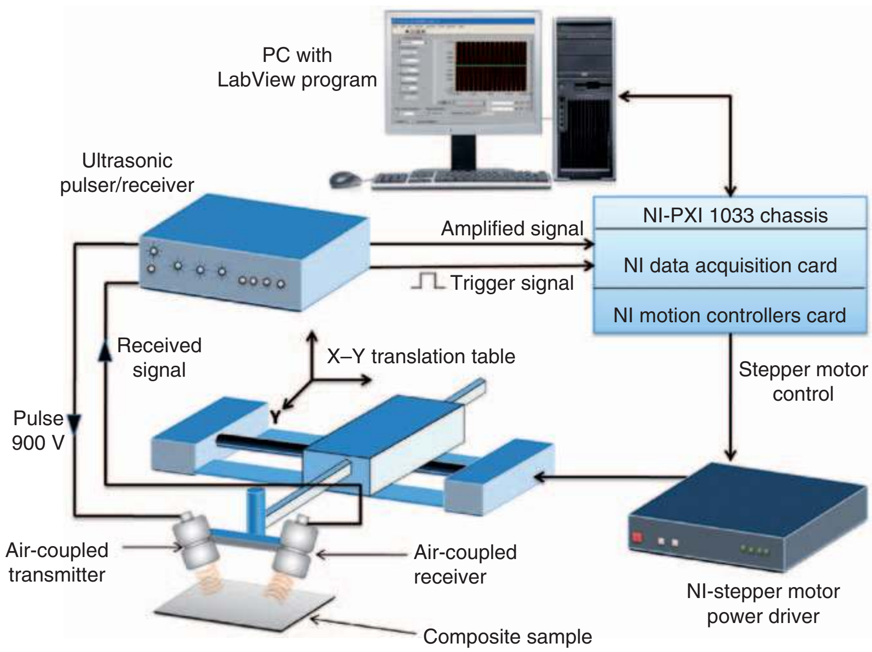

***Figure 3.** Schematic of experimental set up.*

arrangement was employed and a probe separation (distance between the middle of the incident and receiver ultrasonic beams on the test sample) of 60 mm was maintained for the experiments conducted on both the specimen with different delamination lengths. The excitation pulse was a tone burst modulated with Hanning window. The number of cycles in the excitation pulse was seven, which corresponds to 35 μs.

A-scans from Experiments

The advantage of using NCUs is that a good A-scan can be obtained even with presence of small waviness on the laminate. In this study, the fundamental anti-symmetric Lamb mode (A_o) was chosen due to its smaller wavelength compared to S_o mode wavelength at a given frequency and excitability using NCUs. A-scans obtained for delaminations of 50 mm and 40 mm lengths located between the transmitter and receiver are presented in Figure 4. In both A-scans, $A_oS_oA_o$ mode is present.

For prediction of delamination sizes, A_o and S_o mode velocities are required. In this case, the group velocities are taken as those in the main laminate. The group velocities of A_o and S_o modes in the main laminate, obtained from DISPERSE, are 1149 and 3982 m/s, respectively. The peak of the video envelope, shown in Figure 4, was taken as the representative time of arrival of the wave group at the receiver. The predicted delamination sizes from arrival times and group velocities from the main laminate are shown in Table 3.

RESULTS AND DISCUSSION

When A_o mode interacts with the delamination in a composite laminate, there are two wave groups, $A_oS_oA_o$ and $A_oA_oA_o$, in the received signal. Based on the interaction of A_o mode with the delaminations, expression (3) has been derived, which estimates the size of delamination. This expression requires the group velocities of A_o and S_o modes in the sub-laminates and difference in arrival times of wave groups $A_oS_oA_o$ and $A_oA_oA_o$ at the receiver. From expression (3) it is clear that the length of

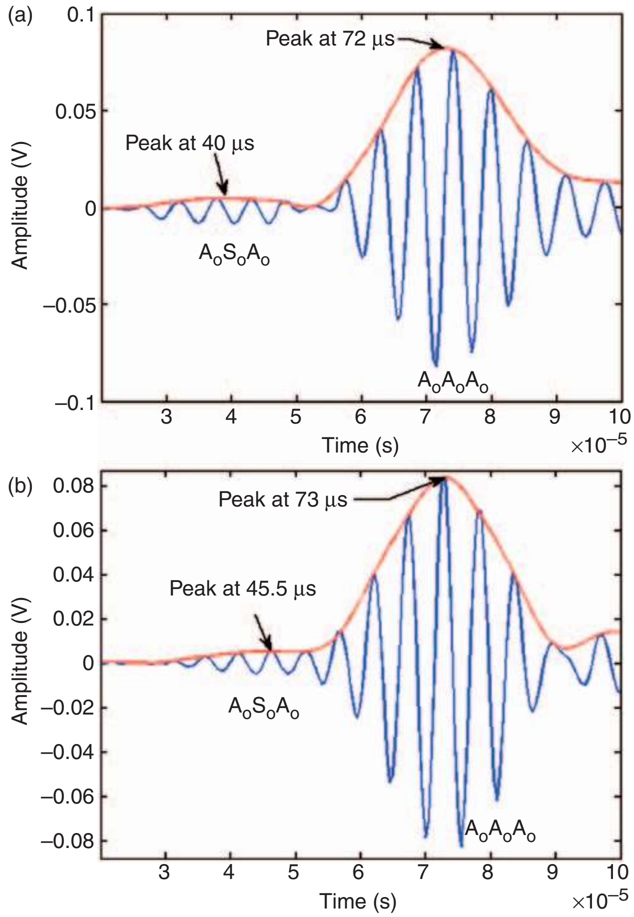

Figure 4. *A-scans of [0/90/0] laminate: (a) 50 mm delamination and (b) 40 mm delamination.*

delamination is directly proportional to the difference in arrival times of both wave groups. For estimating the length of delamination, the locations of transmitter and receiver with respect to the entrance and the exit of delamination, L_1 and L_2 respectively, are not required. If delamination length is more, the wave groups will have more separation time, that is, Δt will be higher. For smaller delamination length, there will be interference between these two wave groups. The most important aspect of the present study is that there is no need of a reference from the healthy structure to ascertain the extent of delamination, that is, to say the arrival time of A_o mode at the receiver in a healthy laminate is not required.

Equation (3) holds good for any case and size of delamination located across the thickness of laminate, as long as it satisfies Equation (4) referred to hereunder. If 'T' is the duration of one cycle ($T = 1/f$, where, 'f' is central frequency of excitation) and if there are 'n' number of cycles in the excitation pulse, then the total duration of excitation pulse $= nT$. The peaks of wave groups, $A_oS_oA_o$ and $A_oA_oA_o$, can clearly be identified if the difference in arrival times is greater than or equal to '$nT/2$'. Based on this premise the following inequality can be written:

$$\begin{aligned} t_2 - t_1 &\geq \frac{nT}{2} \\ D\left(\frac{1}{V_{Aos}} - \frac{1}{V_{Sos}}\right) &\geq \frac{nT}{2} \\ D &\geq \frac{nT}{2}\left(\frac{V_{Sos}V_{Aos}}{V_{Sos} - V_{Aos}}\right) \\ D_{\min} &= \frac{n}{2f}\left(\frac{V_{Sos}V_{Aos}}{V_{Sos} - V_{Aos}}\right). \end{aligned} \tag{4}$$

As per Equation (4), the minimum delamination length that can be found using this technique depends on duration of excitation (number of cycles), frequency of excitation and velocities of A_o and S_o modes. On substitution of the excitation frequency, number of cycles and A_o and S_o group velocities of quasi-isotropic and cross-ply laminates in Equation (4), the minimum delamination sizes work out to 35.8 and 28.2 mm, respectively.

The number of cycles and excitation frequency should be selected in such a way that dispersion is minimal. Techniques to separate out the $A_oS_oA_o$ and $A_oA_oA_o$ wave groups may be adopted, when there is interference between them. In this study, the distance between the transmitter and receiver was 60 mm. This distance may also be increased. In such a case, the amplitude of the wave groups will reduce due to damping effects, but the difference in arrival times of $A_oA_oA_o$ and $A_oS_oA_o$ wave groups, does not change. It is possible to use $A_oS_oS_o$ mode, except when the delamination is in a symmetric location. In such a case the $A_oS_oS_o$ mode does not propagate in the main laminate. Amplitude of $A_oS_oS_o$ is lower than $A_oS_oA_o$ mode. $A_oS_oS_o$ mode can be detected, if in-plane displacement time history is taken. In the present work, we are capturing only out-of-plane displacement, which corresponds to A_o mode.

Wave groups A_oA_o propagate independently in both the sub-laminates from entrance to exit of delamination, undergo interference at the exit, and then propagate as a single wave group. Same phenomenon happens with A_oS_o wave group also. In quasi-isotropic laminate, when the delamination was in the interface of [0] and [+45] plies, the sub-laminates were [0] and [+45/−45/90/90/−45/+45/0]. S_o mode velocity depends on in-plane stiffness in the direction of propagation. Since [0] ply has higher in-plane stiffness, S_o mode velocity is higher in this ply. S_o mode group velocities in these sub-laminates are 4767 and 2432.1 m/s, respectively. The variations of S_o mode velocity from the main laminate to the sub-laminates [0] (thin sub-laminate) and [+45/−45/90$_2$/−45/+45/0] (thick sub-laminate) are 86% and 4.6%, respectively. A_oS_o wave group in thin sub-laminate propagates faster and reaches the

Table 3. Arrival times of wave groups and predicted delamination sizes in cross-ply laminate.

Laminate	Actual delamination length in mm	Arrival time of wave group $A_oS_oA_o$ t_1 μs	Arrival time of wave group $A_oA_oA_o$ t_2 μs	$\Delta t = t_1 - t_2$ μs	Predicted size
[0/90/0]	50	40.0	72.0	32.0	51.6
	40	45.5	73.0	27.5	44.4

Table 4. Group velocities of A_o and S_o modes in various thick sub-laminates and their percentage variations with respect to group velocities of A_o (1136.8 m/s) and S_o (2551.3 m/s) modes in the main laminate.

Delamination interface	Thick sub-laminate lay up	A_o mode group velocity	Percentage variation	S_o mode group velocity	Percentage variation
[0] and [+45]	[+45/−45/90_2/−45/+45/0]	1135.8	0.0	2430.5	4.7
[+45] and [−45]	[−45/90_2/−45/+45/0]	1139.1	0.2	2433.5	4.6
[−45] and [90]	[90_2/−45/+45/0]	1141.9	0.4	2434.1	4.5
[90] and [90]	[90/−45/+45/0]	1143.0	0.5	2643.1	5.3

exit of delamination earlier than the one propagating in the thicker sub-laminate. A_oS_o wave groups from both the sub-laminates undergo interference at the exit of delamination and propagate as a single wave group in the main laminate. In the received signal, the peak of $A_oS_oA_o$ wave group occurs at 47.8 μs. If the amplitude of wave group A_oS_o is higher in [0] sub-laminate then the peak should occur at 37 μs (approximately). This analysis indicates that the amplitudes of wave groups propagating from the sub-laminates [0] and [+45/−45/90/90/−45/+45/0] to the main laminate are different. Since the peak corresponds to the wave group A_oS_o propagating in the sub-laminate, [+45/−45/90/90/−45/+45/0], it is more appropriate to use the group velocity of S_o mode (2432.1 m/s) in this sub-laminate, for prediction of delamination size. Group velocity of S_o mode in the main laminate is 2551.38 m/s, which is 4.9% higher than that in [+45/−45/90/90/−45/+45/0] sub-laminate.

Even when the delamination interface was between other plies, a similar trend of robust transmission of wave groups from the thick sub-laminate to the main laminate has been observed. The arrival time of $A_oS_oA_o$ wave group at the receiver for various delamination interfaces as shown in Table 2, has been found to correspond with the arrival times of $A_oS_oA_o$ wave group propagating in the thick sub-laminate.

The group velocities of A_o and S_o modes, worked out from numerical simulations, in the thick sub-laminates formed for various delamination interfaces, are comparable with group velocities in the main laminates with a maximum variation of 5.3% in case of S_o mode when the delamination is symmetric, as shown in Table 4. The variations in A_o mode velocities from the main laminate and the thick sub-laminates are negligible. The predicted delamination sizes in quasi-isotropic laminate, when group velocities of the main laminate and sub-laminates were employed in expression (3), are listed in Table 2. The predictions made in both cases are in good agreement with the actual values. The S_o mode group velocity in [0/+45/−45/90] sub-laminate was estimated on the basis of numerical simulations. A minor deviation in this estimation may have resulted in a slight mismatch in the estimation of delamination size.

From this discussion, it can be concluded that a good approximation of delamination size can be made if the main laminate group velocities are used in expression (3) instead of the sub-laminate group velocities, which are not known in practice.

In Figure 4(a) and (b), the experimental A-scans of laminates with 50 mm and 40 mm delamination lengths are shown. The arrival times of wave groups $A_oS_oA_o$ and $A_oA_oA_o$ for various delamination lengths and delamination sizes predicted using expression (3), have been shown in Table 3. The group velocities of primary Lamb modes in the main laminate were used in expression (3) for prediction of delamination sizes. The predicted delaminations sizes are in good agreement with the actual values. The maximum error is 11% in the prediction of 40 mm delamination size.

However, it is clear that an approximate delamination size can be predicted without baseline or healthy region data and using A_o and S_o mode velocities in the main laminate.

CONCLUSIONS

An attempt has been made to predict the size of delamination using time of flight of mode converted wave group, $A_oS_oA_o$, and transmitted wave group, $A_oA_oA_o$, at the receiver in pitch catch mode without requiring the baseline/healthy data. An expression, which gives the size of symmetric and asymmetric delaminations, located in between the transmitter and receiver, has been derived based on the interaction of wave groups with entrance and exit of delamination. This expression requires group velocities of primary Lamb modes in the sub-laminates. Instead of using primary Lamb mode group velocities in the sub-laminates, group velocities in the main laminate were used. The effectiveness of the expression has been verified on numerically simulated delaminations in a quasi-isotropic laminate. Experimental verification was also carried out on two cross-ply laminates with 40 mm and 50 mm delamination sizes. Experiments were carried out, using NCUs, to find out the arrival times of wave groups, $A_oS_oA_o$ and $A_oA_oA_o$, in each laminate. The arrival times from experiments and group velocities from DISPERSE were used in the derived expression to determine the delamination sizes. The predicted delamination sizes were found to be in good agreement with the actual values. A supplementary expression was also derived for determining the minimum detectable length of delamination. The advantage of the proposed technique is that the baseline or reference data from a healthy specimen is not required for the prediction of delamination size.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help rendered by Dr. Rahul Harshe, Mr. Vinod Durai Swamy for specimen fabrication, and Mr. K. Ranjith for characterization, from R&DE (E). The authors also thank Dr. Mahesh Bharadwaj and the Ultran Group for their generous donation of the NCU probes. The authors thank ADA, Bangalore for partial funding of the work.

REFERENCES

Bhardwaj, M.C. 2001. "Non-Contact Ultrasound - The Final Frontier in Non-destructive Analysis," In: Biderman, A. (ed.), *Encyclopedia of Smart Materials*, John Wiley & Sons, New York.

Dayal, V. and Kinra, V.K. 1991. "Leaky Lamb Waves in Anisotropic Plate. II: Nondestructive Evaluation of Matrix Cracks in Fiber Reinforced Composites," *J. Acou. Soc. Am.*, 89:1590–1598.

Duflo, H., Morvan, B. and Izbicki, J.L. 2007. "Interaction of Lamb Waves on Bonded Composite Plates with Defects," *J. Compos. Struct.*, 79:229–233.

Guo, N. and Cawley, P. 1993. "The Interaction of Lamb Waves with Delaminations in Composite Laminates," *J. Acoust. Soc. Am.*, 94:2240–2246.

Guo, N. and Cawley, P. 1994. "Lamb Wave Reflection for the Quick Nondestructive Evaluation of Large Composite Laminates," *Mater. Eval.*, 52:404–411.

Hayashi, T. and Kawashima, K. 2002. "Multiple Reflections of Lamb Waves at a Delamination," *Ultrasonics*, 40:193–197.

Imperial College, London, UK. 2003. Disperse version 2.0.16b.

Ip, H.K. and Mai, W.Y. 2004. "Delamination Detection in Smart Composite Beams using Lamb Waves," *J. Smart Mater. Struct.*, 13:544–551.

Karthikeyan, P., Ramadas, C., Bhardwaj, M.C. and Krishnan Balasubramaniam. 2009. "Non-Contact Ultrasound Based Guided Lamb Waves for Composite Structure Inspection: Some Interesting Observations," In: Thompson, D. and Chimenti, D.E. (eds), *AIP Conference Proceedings, Rev. of Prog. QNDE Vol. 28 1096, 928*, New York.

Liu, G.R. and Achenbach, J.D. 1994. "Strip Element Method for Stress Analysis of Anisotropic Linear Elastic Solids," *J. Appl. Mech.*, 61:270–277.

Liu, G.R., Xi, Z.C., Lam, K.Y. and Shang, H.M. 1999. "A Strip Element Method for Analyzing Wave Scattering by a Crack in an Immersed Composite Laminate," *J. Appl. Mech.*, 66:898.

Palacz, M., Krawczuk, M. and Ostachowicz, W. 2005. "The Spectral Finite Element Model for Analysis of Flexural-shear Coupled Wave Propagation. Part: 2 Delaminated Multilayer Composite Beam," *J. Compos. Struct.*, 68:45–51.

Ramadas, C., Balasubramaniam, K., Joshi, M. and Krishnamurthy, C.V. 2009. "Interaction of Primary Anti-symmetric Lamb Mode with Symmetric Delaminations: Numerical and Experimental Studies," *J. Smart Mater. Struct.*, 18, DOI: 10.1088/0964/-1726/18/8/085011.

Seale, M.D., Smith, B.T. and Prosser, W.H. 1998. "Lamb Wave Assessment of Fatigue and Thermal Damage in Composites," *J. Acou. Soc. Am.*, 103:2416–2424.

Su, Z. and Ye, L. 2004. "Lamb Wave Based Quantitative Identification of Delamination in CF/EP Composite Structures using Artificial Neural Algorithm," *J. Compos. Struct.*, 66:627–637.

Tang, B. and Henneke II, E.G. 1989. "Lamb Wave Monitoring of Axial Stiffness Reduction of Laminated Composite Plates," *Mater. Eval.*, 47:928–934.

Toyama, N., Okabe, T., Takeda, N. and Kishi, T. 2002. "Effect of Transverse Cracks on Lamb Wave Velocity in CFRP Cross-ply Laminates," *J. Mater. Sci. Lett.*, 21:271–273.

Toyama, N. and Takatsubo, J. 2004. "Lamb Wave Method for Quick Inspection of Impact-induced Delamination in Composite Laminates," *Compo. Sci. and Tech.*, 64:1293–1300.

Valdes, S.H.D. and Soutis, C. 2002. "Real-time Non-destructive Evaluation of Fiber Composite Laminates using Low Frequency Lamb Waves," *J. Acou. Soc. Am.*, 11:2026–2033.