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Detection of symmetric delamination using Time of Flight

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ABSTRACT: A feasibility study on detection of symmetric delamination size in a quasi isotropic laminate, $[0/+45/-45/90]_s$, using Time of Flight (ToF) of Lamb waves has been carried out through numerical modeling. Numerical simulations have been carried out using conventional Finite Element Method (FEM) on three delamination lengths of 40mm, 50mm and 60mm. In the numerical model, ply wise modeling was adopted. Delamination was modeled by de-merging the nodes at that location. Based on the interaction of the incident Lamb mode with delamination, an expression was derived, which gives the size delamination from ToF of Lamb waves. The ToFs of incident Lamb mode and mode converted Lamb mode on the transmitted side have been found from numerical simulations. These arrival times were used in the derived expression to find out the delamination size. The predicted delamination sizes were found to be matching closely with actual delamination size.

1 INTRODUCTION

The composite materials offer many advantages such as high specific strength, modulus, and corrosion resistance over metals. Because of these properties composite materials are being used for civilian and military applications. Damages in composites are critical than in metals. Delamination is one of the damages which occur because of weak interlaminar shear and out of plane tensile strengths. Delamination reduces stiffness of structure, especially in compression.

Lamb waves also known as guided waves propagate in the sagittal plane in a traction free plate. Lamb waves can propagate long distances in plate-like and cylindrical structures, have through-thickness displacements/stresses, and provides information along the line-of-sight. Hence, these waves can be used for Non-destructive Evaluation (NDE) as well as Structural Health Monitoring (SHM) of delamination damage in composite laminated structures. Lamb waves are dispersive; viz. velocity depends on frequency-thickness product.

Depending on the relationship between the displacement profiles with thickness, the modes are classified into symmetric (S_n) and anti-symmetric (A_n) modes. The specific order (represented by the subscript 'n') of these two modes types depends on the excitation frequency and thickness of an isotropic plate. However, in an anisotropic plate, it also depends on the direction of propagation. When a Lamb wave mode encounters defects in its path of propagation, the wave reflects, scatters and mode converts into other mode types. Hence, in the received signal one may find other modes in addition to the excited mode. It is difficult to separate various modes from the received signal. It is not easy to characterize the defect using Lamb wave, since the received signals are very complex. By selecting the excitation frequency in less dispersive region, where only the two primary Lamb modes, S_o (primary symmetric) and A_o (primary anti-

symmetric) exist, the complexity of signal can be reduced to some extent. Numerical simulations help greatly to understand the interactions of guided waves with various defects in composite plates.

Guo et. al. (1993) studied the interaction of Lamb waves with delaminations in a cross-ply composite laminate. Investigations were carried out on delaminations using S_o mode in pulse-echo configuration. Delaminations were introduced at various interfaces between the plies. When S_o mode encounters a delamination in its propagation path, a reflected wave was shown to be generated. It was found that, when shear stress is zero at that interface, no wave reflection takes place. Tan et. al. (1995), Birt (1998) and Bourasseau et. al. (2000) detected delamination on carbon fiber reinforced plastic laminates and foam core sandwich structures. Attenuation of transmitted Lamb wave was used for detection of delaminations. The proposed technique was simple, but, to quantitatively evaluate delaminations using change in wave forms is difficult.

Hayashi et. al. (2002) found, in pulse-echo mode, multiple reflections when a Lamb wave encounters a delamination. Numerical simulations were carried out on a cross-ply laminate using S_o and A_o modes. Palacz et. al. (2005) numerically analysed, using spectral finite element technique, propagation of flexural-shear coupled wave in a delaminated multilayered composite beam. It was found that when the delamination length grows reflections from the first and second tip of delamination appear. Ip (2004) proposed an active diagnostic system works in pulse-echo mode for asymmetric delamination detection. Kesavan et. al (2006) demonstrated detection of disbonds in T – joints using artificial neural network technique (ANN). T – Joint was manufactured using components fabricated through various techniques. Three different sizes of damages of sizes 30, 60 and 90 mm were introduced. They detected the damages using strains. Karthikeyan et. al. (2009) studied mode conversions of Lamb wave when encounters a symmetric delamination.

In this work, we carried out a feasibility study to characterize the size of central delamination in a quasi-isotropic carbon/epoxy laminate using Time of Flight (ToF) of Lamb wave. An expression, which gives the delamination size, was derived based on the wave interaction with the damage.

2 MODELING AND PROPAGATION OF GUIDED WAVES

Finite element (FE) technique has been used, for simulating the Lamb wave propagation in composite laminate. The specifications laminate, shown in Figure 1, are, 2 mm thick, 800 mm length.

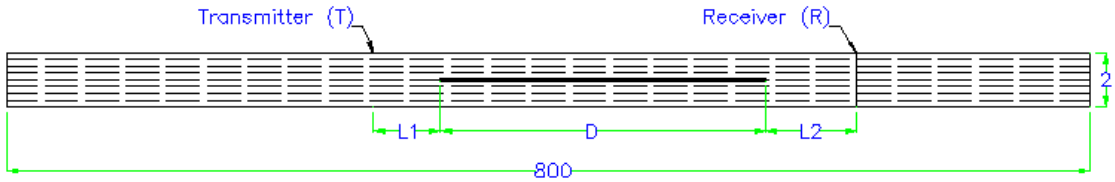

Figure1, Specification of model

The material was carbon/epoxy, properties of which are shown in Table 1.

Table 1, Material properties of Carbon/epoxy laminate

Material	E_{11} (GPa)	E_{22} (GPa)	υ_{13}	υ_{23}	G_{13} (GPa)	ρ kg/m^3
Carbon/Epoxy	128.49	6.98	0.288	0.55	3.52	1700

The lay up used was quasi-isotropic $[0/+45/-45/90]_s$. The thickness of each lamina was 0.25 mm. In FE model, each lamina has been modeled, its orientation and properties were attributed. The element selected was a two dimensional eight node serendipity element, with four corner nodes and four mid side nodes. This element has two translatory degrees of freedom at each node. The size of element was 0.5 mm, with an aspect ratio of unity. It was assumed that plane strain condition exists and there was no damping. The delamination length has been modeled by de-merging the nodes, which is like zero volume delamination, at that location as shown in Figure 2. The location of delamination was symmetric, which was in between 90^o layers.

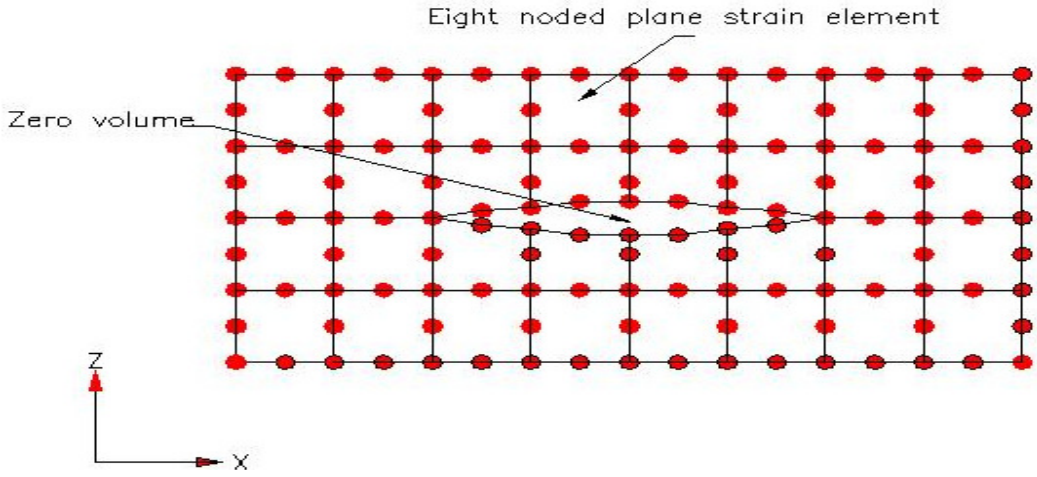

Figure 2, Modeling of delamination

The mode of excitation has been selected as primary anti-symmetric Lamb mode, A_o. The excitation frequency, 200 kHz, was selected in such a way that only primary Lamb modes exist at that frequency. The excitation pulse was a sinusoidal tone burst with seven cycles. Anti-symmetric Lamb mode was excited by giving displacements in out of plane direction. The distance between transmitter (T) and receiver (R) has been fixed as 70 mm. The defect was assumed to be in between the transmitter and receiver.

Numerical simulations have been carried out on three different delamination lengths, 40, 50 and 60 mm. For 50 mm delamination length, A-scan obtained at receiver (R) is shown in Figure 3. Karhikeyan et. al. (2009) studied that when A_o mode encounters a symmetric delamination, it generates a new mode, S_o, which is confined only to sub-laminates. Because of this mode conversion there appears a new mode, $A_oS_oA_o$ before $A_oA_oA_o$ mode, in through transmission mode shown in Figure 3.

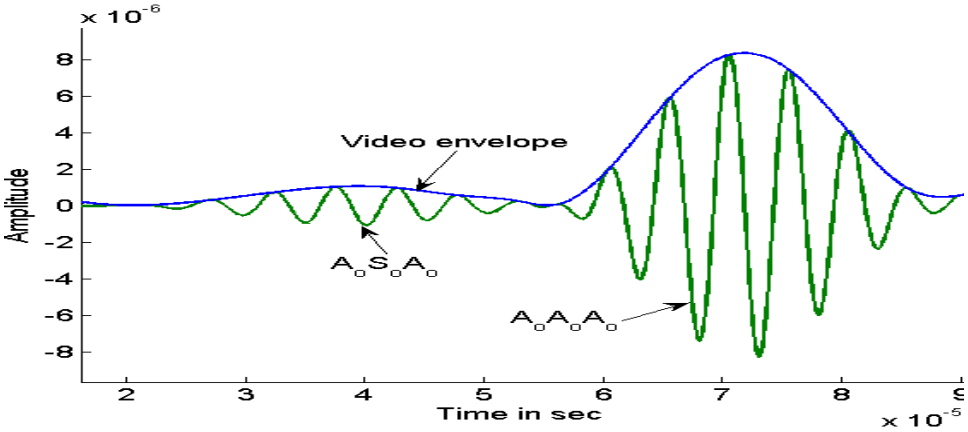

Figure 3, A-scan at receiver for 50 mm delamination

3 DELAMINATION LENGTH

The locations of transmitter and receiver are shown in Figure 1. The length of delamination is 'D', distance between transmitter and receiver is 'L'. Let L_1 and L_2 denote distances between transmitter and entrance of delamination, and exit of delamination and receiver respectively. Let V_{Aom} and V_{Aos} are group velocities of A_o mode in the main and sub-laminates respectively. V_{So} is the group velocity of S_o mode in the sub-laminate.

Assume that the first wave group, $A_oS_oA_o$, as shown in Figure 3 arrives the receiver (R) at 't_1' and second wave group, $A_oA_oA_o$, at 't_2' time. From distance, time and velocity relations, the following two relations can be derived.

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

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

Eliminate terms in the brackets from both the equations. The following expression can be obtained.

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

For the selected quasi-isotropic laminate, the sub-laminate lay up for symmetric delamination is [0/+45/-45/90]. The group velocities of A_o and S_o modes, obtained from numerical simulations, in sub-laminates are 1202 m/s and 4981 m/s respectively. For a known sub-laminate, these velocities are constant and independent of the delamination length. The term in the brackets in equation (3) is assumed to be a constant, which is equal to '1/C'. For the above A_o and S_o mode velocities, 'C' is equal to 1584. 32 m/s.

From equation (3), for a given delamination interface, that is, for a constant 'C', the delamination length is directly proportional to the difference in arrival times of $A_oA_oA_o$ and $A_oS_oA_o$ wave groups.

$$D = C(t_2 - t_1) = C\Delta t = (1584.32)\Delta t \quad (4)$$

If the difference in the arrival times is known, the delamination length can be found using equation (4).
This expression doesn't require the baseline data from a healthy specimen.

A video envelope has been fitted over each signal as shown in Figure 3. The peak of this envelope of each wave group has been taken as the representative arrival time of that particular wave group.

4 RESULTS AND DISCUSSION

The proposed method for detection of delamination size, which has been expressed in the form of an equation (4), was applied for three different cases of delamination lengths, 40, 50 and 60 mm. A-scans for 40 and 60 mm delamination lengths is shown in Figure 4.

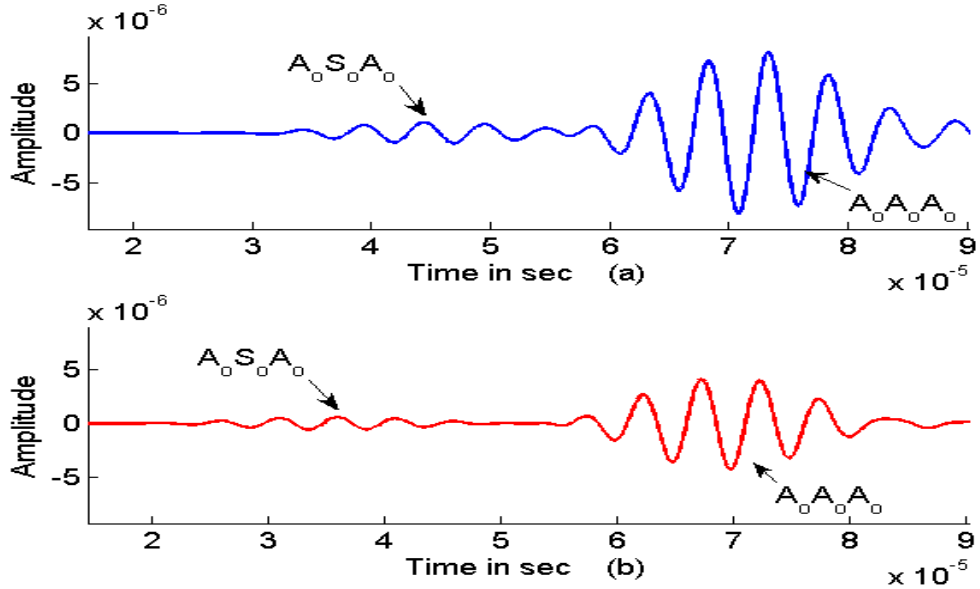

Figure 4, A-scans (a) delamination length 40 mm, (b) delamination length 60 mm

For each A-scan a video envelop has been fitted over each signal and the arrival time differences of $A_oA_oA_o$ and $A_oS_oA_o$ wave groups were computed. The delamination length has been computed using equation (4) from the difference in arrival times. The results have been shown in Table 2.

Table 2, Estimated delamination length

Actual length in	$\Delta t = t_2 - t_1$ in μs	Estimated length using equation (4)

mm		
40	27.65	43.8
50	33.74	53.4
60	38.20	60.5

From equation (4), estimation of delamination length depends on accuracy of group velocities and difference in arrival times. For a given group velocities, for e.g in the present case, if there is an error of 1 μs in the difference of arrival time, it gives an error of 1.58 mm in delamination length. So, the proposed technique based on ToF is very much sensitive to arrival times of the wave groups.

5 CONCLUSIONS

A feasibility study based on ToF to detect symmetric delaminations in a quasi-isotropic beam has been studied. An expression has been derived which gives the delamination size. From the expression, it is found that the delamination length is directly proportional to difference in arrival times of first two wave groups, $A_oS_oA_o$ and $A_oA_oA_o$, at the receiver. The technique has been applied for three different delamination lengths, 40, 50 and 60 mm. The predicted delamination lengths were found to be in good agreement with the actual lengths. This technique doesn't require baseline data from a healthy specimen.

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