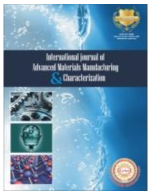

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Reflection and Transmission of S_o Lamb Mode in A Metal-Composite Adhesive Joint

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ABSTRACT

In the present paper reflection and transmission of the fundamental symmetric Lamb mode (S_o), and the mode converted Lamb mode (A_o) at 200 kHz in a metal (aluminium)-composite (glass fiber/epoxy) adhesive joint is presented. When S_o mode is employed for detection of disbond in a metal-composite adhesive joint, the mode can be excited either on the composite end or metal end. When S_o Lamb mode excited on either end is incident on an adhesive joint, it undergoes reflection and transmission and propagates as S_oS_o mode in both the metal and composite parts. Moreover, S_o mode undergoes mode conversion to A_o and this mode propagates as S_oA_o mode along with the S_oS_o mode. Amplitudes of the S_oS_o and the S_oA_o modes propagating in the metal and the composite parts depend on the orientation of adhesive and also the end from which the incident mode is excited. From numerical simulations it is found that the amplitude of reflected S_oS_o, S_oA_o and transmitted S_oA_o modes attain maximum values when the orientation of adhesive is 60^0 and the transmitted S_oS_o mode attains minimum value at the same angle. Moreover, the trend in variation in the amplitudes of the reflected and transmitted S_oS_o and S_oA_o modes is nearly same

Introduction

Significant progress in the development of high temperature materials for application in the aerospace, energy, material processing and many other fields are expected during the twenty first century. The properties required in materials for high temperature applications are high melting point, strong resistance to creep, thermal shock, oxidation and corrosion. Advanced composite materials can meet these demands. High performance composites are currently being used in the marine, automotive, aerospace and defense industries (1).
The technology which is driven by recent advances and techniques with the aim of continuous/real-time and automated surveillance of the overall integrity of structures through consideration of working condition updates and structural ageing is known as Structural Health Monitoring (SHM). More particular SHM is 'the nondestructive and continuous monitoring characteristics using an array of sensors related to the fitness of an engineered component as it operates, so as to diagnose the onset of anomalous structural behavior and it involves measuring and evaluating the state properties and relating these to defined performance parameters [1].

In order to reduce the weight of space vehicles which results in less specific fuel consumption, aerospace industries shift from heavy metal like steel to light metals like aluminum and composite as composites are having high specific strength, high specific stiffness and low weight. Several challenges have been faced with this change in materials, in finding the suitable method to join these structures. The resistance spot welding is conventional method of joining metal which is fast, versatile and suited for high volume production. Welding aluminum and composite is more difficult than metal due to higher melting point of surface oxide layer than the parent metal [2]. Welding process is more prone to cracking and high capital cost. On other hand the traditional mechanical fastened or riveted joint, which usually result in cutting of fibers and hence the introduction of stress concentrations, both of which reduce structural integrity.
To overcome these problems the manufacturers use adhesives to join the metal composite structure. Adhesives are now common in non-structural applications like fixing windscreen, trim and

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vibration damping as they exhibit many advances over conventional joining process. Some advantages are - improved fatigue and impact performance, increased joint tensional stiffness and vibration damping, more uniform stress distribution over length, easy to join complex shapes and dissimilar material, low cost etc. The major disadvantage of adhesive joint is low peel strength. Defects in adhesive joint occur either at the adhered-adhesive interface or within the adhesive layer itself. The adhesive strength at the interface between the adhesive and adherend layers is critical to the overall joint strength [2].

Lamb wave is also known as a plate wave and it exists in a thin plate-like medium, guided by the free upper and lower surfaces. Infinite wave modes are available in a plate like structure, and their propagation characteristics vary with entry angle, frequency and structural geometry. The guided Lamb wave is widely acknowledged as one of the most encouraging tools for inspecting integrity of plate by identifying damage quantitatively [3].

Developed and published in 1917 by Horace Lamb, Lamb wave is studied intensively since 1980s. During the late 1980's and early 1990's work began on the application of Lamb waves to composite materials. Research conducted at NASA by Saravanos demonstrated, both analytically and experimentally, the possibility of detecting delamination in composite beams using Lamb waves [3]. The most successful work to date of using Lamb waves for damage detection has been performed by two separate groups at Imperial College. Since the mid-1990's, Cawley's group has been working to optimize the generation of directional Lamb waves. Ramadas et al. [7] studied numerically and experimentally interaction of Lamb wave mode with metallic beam containing semi-infinite crack. Ramadas et al. [8] presented the propagation of the anti-symmetric fundamental Lamb mode (A_0) in a composite laminate containing a semi-infinite delamination through numerical simulations and experimental studies.
We can obtain the general description of Lamb waves in an isotropic and homogeneous plate with free upper and lower surfaces by applying appropriate boundary conditions in a general wave equation [2] described in a form of Cartesian tensor notation.

$$\frac{\tan(qh)}{\tan(ph)} = \frac{4k^2 qp\mu}{(\lambda k^2+\lambda p^2+2\mu p^2)(k^2-q^2)} \quad (1)$$

Where 2h is the thickness of the plate, λ is the lame's constant, μ is the modulus of rigidity, $p^2 = \frac{\omega^2}{C_L{}^2}$, $q^2 = \frac{\omega^2}{C_T{}^2}$ and $K = \frac{2\pi}{\lambda_{wave}}$, ω and λ_{wave} are the wave number, circular frequency and wavelength of the wave, respectively. C_L and C_T are the velocities of longitudinal and transverse/shear modes [1].
Further the equation (1) is split in to two parts as symmetric and anti-symmetric properties, indicating that Lamb wave in plate consist of symmetric and anti-symmetric modes [2].

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2 qp}{(k^2-q^2)^2} \text{For Symmetric modes} \quad (2a)$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(k^2-q^2)^2}{4k^2 qp} \text{For ant symmetric mode} \quad (2b)$$

Above equations are known as the *Rayleigh-Lamb equations* [1].

The symbols S_i and A_i (i= 0, 1 . . .) stand for the symmetric and anti-symmetric Lamb modes respectively, with the subscript being the order and in particular $S_o$and $A_o$being the lowest-order symmetric and anti-symmetric Lamb modes respectively. S_o modes predominantly have radial in-plane displacement of particles and are often called as compressional showing thickness bulging and contracting while $A_o$modes have mostly out-of-plane displacement, is known as flexural, presenting constant-thickness flexing [2]. Under the same excitation condition, the magnitude of S_i modes (in-plane motion) is normally smaller than that of A_i modes.

In the majority of studies the $S_o$mode is selected for damage identification as it has some advantages in distinction to the $A_o$mode; lower attenuation, faster propagation velocity, lower dispersion in the low frequency range, benefiting signal interpretation.

In this paper, numerical modeling on propagation and interaction of the fundamental symmetric Lamb mode (S_o), excited on composite end and metal end, with adhesive joint has been presented. Reflection and transmission characteristics of S_o mode and mode converted S_o mode propagating through adhesive joint have been discussed. In section 2, details of modeling and excitation of the fundamental symmetric Lamb mode (S_o) is described. In section 3, analysis of signals captured at different locations has been discussed. Result and discussion has been presented in section 4 followed by conclusions in the fifth section.

FEM details and excitation of the s_o lamb modes

Lamb waves are dispersive, and their velocities are dependent on wave frequency and plate thickness. The graphic depiction of solutions of the dispersion equations is called the dispersion curves. Figure. 1 shows the dispersion curve plotted between phase velocity and excitation frequency [4]. Dispersion curves are used to describe and predict the relationship among frequency, phase/group velocity and thickness. At any given frequency, there exist a minimum of two modes of propagation. In this work, the excitation of $S_o$mode at 200 kHz frequency on metal end and composite end has been delineated.

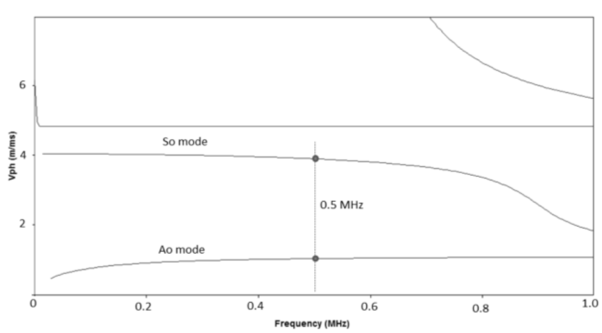


Figure.1. Dispersion curves [5]

FE Model

A Uni-Directional (UD) Glass Fiber Reinforced Plastic (GFRP) composite is joined to aluminum metal by adhesive material. Specifications of the model used for numerical simulations are shown in Figure. 2. Here, θ gives the orientation of the adhesive with respect to horizontal axis. The ply stacking sequence in the composite laminate was Uni-Directional (UD) with the thickness of each ply 0.33 mm and there were eight plies ($[0_8]$) so the total thickness of the laminate worked out to be 2.64

mm. The adhesive material with thickness 0.25 mm was used to join the 300 mm composite and the metal of the same length. The total length of the model was 600.25 mm. Properties of the materials used for numerical modeling are listed in Table 1.

Table.1.Material properties

Composite (GFRP)					
E_{11}(GPa)	44.68	υ_{11}	0.280	G_{11}(GPa)	2.54
E_{12}(GPa)	06.90	υ_{12}	0.355	G_{12}(GPa)	2.54
E_{13}(GPa)	06.90	υ_{13}	0.280	G_{13}(GPa)	2.54

Aluminum		Adhesive	
E(GPa)	70	E(GPa)	2.50
υ	0.35	υ	0.30
ρ (kg/m^3)	2700	ρ (kg/m^3)	1200

In the present work two excitation cases (a) excitation on the composite end and (b) excitation on the metal end have been attempted. In the cases (a) and (b) the excitation was given at x = 0 (composite end) and at x = 600.25 mm (metal end), respectively. Receivers were positioned at x = 150 mm, and 450 mm to capture in-plane and out-of-plane displacement time histories. Simulations were carried out for various orientations of the adhesive from 90^0 to 1 in 20 at a step of 15^0 i.e. 90^0, 75^0, 60^0, 45^0, 30^0, 15^0, 1 in 20 at 200 kHz excitation frequency.

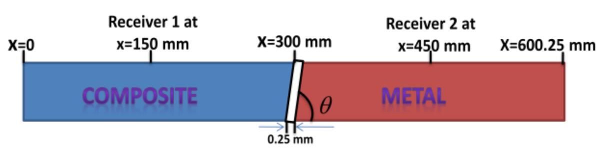


Figure. 2. Geometry of FEM model

To characterize exactly the Lamb wave scattering due to damage, a fine finite element mesh is required. It has been demonstrated that at least 10 nodes per wavelength of the Lamb wave can guarantee good accuracy [6].The time step for dynamic simulations must be less than the ratio of the minimum distance of any two adjoining nodes to the maximum wave velocity (often the velocity of the S_o mode) [1]. Based on this, the size of element selected across the thickness and along the length and time step were 0.165 mm and 0.25 mm 50 ns, respectively. The group (V_g) velocity of A_o and S_o modes in 2.64 mm thick composite and aluminium plates at 200 kHz are listed in Table 2.

Table.2. Velocity of the fundamental Lamb wave mode

Material	S_oMode(m/s)		A_oModem/s)	
	V_g	V_p	V_g	V_p
Composite(GFRP)	4762		1150	
Metal(Aluminium)	5376		2910	

Excitation of So mode

In finite element model, in-plane and out-of-plane displacement pattern shown in Figure. 3was applied on nodes across the thickness of the composite end to excite the symmetric Lamb mode [6].

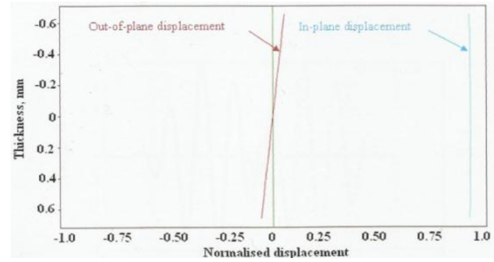


Figure. 3. Displacement pattern across thickness of the model to excite $S_o$mode at 200 kHz [7]

The locations of nodes generated at x= 0 during meshing are shown in Figure. 5.

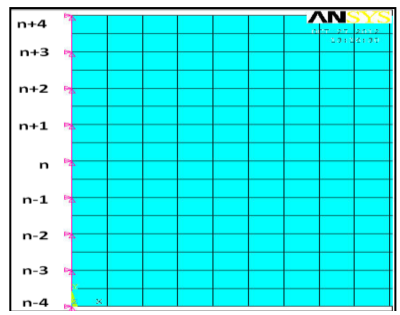


Figure. 4. Locations of nodesacross the thickness of the composite end at excitation location.

Constraint equations have been used to couple the Degree-of-Freedom (DoF) between various nodal points as shown in Figure. 4. Node number at (0, 1.32 mm) was denoted by n. Following are the constraint equations to input in-plane and out-of-plane displacements respectively, across the thickness of the composite laminate to generate S_o mode at 200 kHz frequency.

Out of plane displacement

$$1.3427\ (n)\ u_x - 1.34305\ (n+1)\ u_x = 0$$
$$1.3417\ (n)\ u_x - 1.34305\ (n+2)\ u_x = 0$$
$$1.3400\ (n)\ u_x - 1.34305\ (n+3)\ u_x = 0$$
$$1.3377\ (n)\ u_x - 1.34305\ (n+4)\ u_x = 0$$

$$(n+1)\ u_x - (n-1)\ u_x = 0$$
$$(n+2)\ u_x - (n-2)\ u_x = 0$$
$$(n+3)\ u_x - (n-3)\ u_x = 0$$
$$(n+4)\ u_x - (n-4)\ u_x = 0$$

In plane displacement

$$0.0202\ (n)\ u_y + 1.34305\ (n+1)\ u_x = 0$$
$$0.0402\ (n)\ u_y + 1.34305\ (n+2)\ u_x = 0$$
$$0.0600\ (n)\ u_y + 1.34305\ (n+3)\ u_x = 0$$
$$0.0794\ (n)\ u_y + 1.34305\ (n+4)\ u_x = 0$$

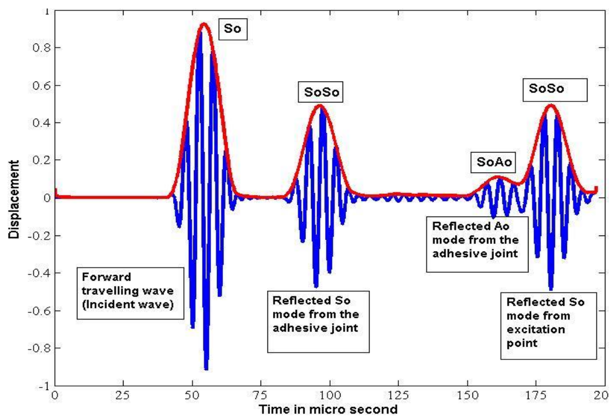
$$(n+1)\ u_y + (n-1)\ u_y = 0$$
$$(n+2)\ u_y + (n-2)\ u_y = 0$$
$$(n+3)\ u_y + (n-3)\ u_y = 0$$
$$(n+4)\ u_y + (n-4)\ u_y = 0$$

$$0\ (n)u_x+(n)\ u_y = 0$$

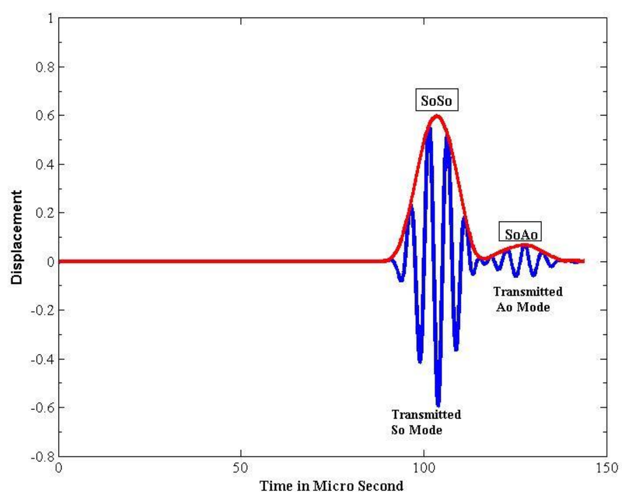
Numerical simulations were carried out for 200 kHz frequency of excitation. The excitation pulse was having five cycles modulated using Hanning Window function [6]. When the excitation was given at node, *n*, the other nodes across the thickness will also undergo deformation as a function of time

Data analysis

Figure. 5 shows in-plane displacement component time histories at *x* = 200 mm and 450 mm when the orientation of the adhesive was 60^0.



(a)



(b)

Figure. 5. In-plane displacement time histories a) at x = 200 mm b) 450 mm, for an angle θ = 60^0

Hilbert Transform (HT) was carried out on each signal, captured at *x* = 150 mm and 450 mm [6]. The peak of HT was taken as the representative time of arrival or Time-of-Flight (ToF) of that wave group. Further, the ToF of the Lamb mode was estimated using group velocity obtained from characteristic equation. The comparison of arrival times of various wave groups from A-scans and analytical estimates is tabulated in Table.3 for 200 kHz excitation frequency.

Table.3. Wave arrival times in micro second at 200 kHz.

Receiver location (mm)	Mode	Estimated time in (μ s)	A-scan Time in(μs)	Error (%)
x =150 mm	S_o	44.000	44.000	0.00
	S_oS_o	106.99	106.80	0.17
	S_oA_o	206.40	205.00	0.67
	S_o	180.39	180.45	0.03
x = 450 mm	S_oS_o	103.40	103.55	0.14
	S_oA_o	127.04	127.76	0.57

The arrival times from numerical modeling and that estimated using group velocity were approximately equal. In addition to this, Fourier Transform (FT) of the receiver signals captured at receivers was carried out. The peak of amplitude of each signal was at its central frequency of excitation, which was 200 kHz.

Reflection and transmission factors are calculated as the ratio of the amplitude of the reflected wave group to the amplitude of incident wave group and the ratio of the transmitted wave group to the incident wave group, respectively for all adhesive joint angles. Figures 6 and 7 show the variation in reflection, transmission factors of S_oS_o and S_oA_o modes, respectively.

Result and Discussion

The reflection and transmission of the fundamental symmetric Lamb mode (S_o), and the mode converted Lamb mode when propagating through a metal-composite adhesive joint was studied through numerical simulations. Two excitation cases – excitation on the composite end and excitation on the metal end were considered. For the joint angle 90^0, the incident S_o mode at the joint undergoes reflection and transmission and propagates as S_oS_o mode. Any joint angle other than 90^0, the incident S_o mode generates A_o which propagates as S_oA_o mode in the metal and composite. When the joint angle is 90^0 no traces of propagation of the mode converted S_o mode (S_oA_o mode) was found. This is because of the fact that the adhesive is located symmetrically with respect to the mid-plane of the joint. The scattered (reflected and transmitted) Lamb waves captured on the composite side and metal side are shown in Figures 5(a) and 5(b), respectively.

Figure 6 shows the variation in amplitude, expressed in terms of reflection and transmission factors, of the reflected and transmitted modes S_oS_o with respect to the orientation of the adhesive. Initially, reflection factor increases with increase in the orientation and reaches a maximum value, in both the excitation cases when the orientation is 60^o as shown in Figure 6(a). With further increase in the orientation, the reflection factor shows a decreasing trend. It has reduced from 0.49 to 0.47 when the orientation has increased from 60^0 to 90^0. However, the magnitude of rate (here 'rate' means with respect to the orientation of the adhesive) of decrease in reflection factor of S_oS_o mode is less for $\theta > 60^0$ when compared to the magnitude of rate of increase for $\theta < 60^0$ as shown in Figure 6(a).

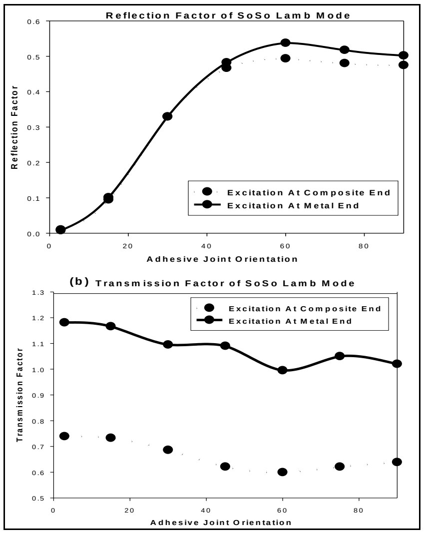


Figure. 6. The variation of a) Reflection factor b) Transmission Factor, for SoSo mode

Variation in transmission factor of S_oS_o mode with the orientation

is shown Figure 6(b). It is clear that the nature of variation in transmission factors of S_oS_o mode in both the cases of excitation is almost same. When the excitation was on the metal end, the amplitude of the transmitted S_oS_o mode was varying from 1.2 to 1, whereas, the amplitude of its counterpart varies from 0.75 to 0.6 when the excitation was given on the composite end. Variation in transmission factor of S_oS_o mode is negligible when compared to its variation in transmission factor.
However, the transmission factors in both the excitation cases reached minimum values when the excitation was 60^0 as shown in Figure 6(b). From this analysis it is also inferred that the composite part transmits higher amplitude wave group compared to that transmitted in the aluminium part.

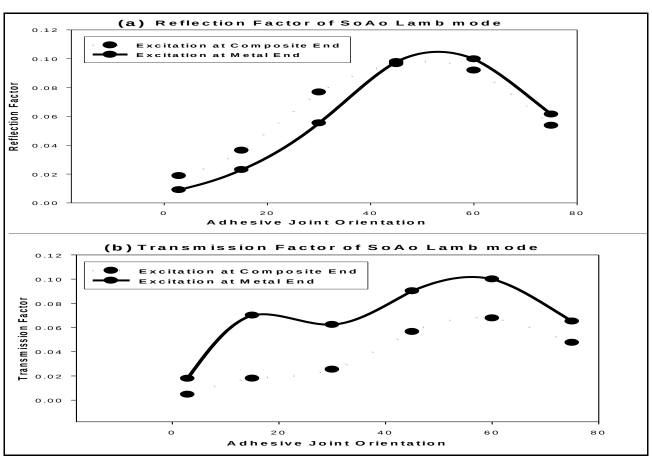


Figure. 7. The variation of a) Reflection factor b) Transmission Factor, for SoAo mode

Figure 7 shows the variation in amplitude of the reflected and transmitted mode converted Lamb mode i.e. S_oA_o. The amplitude of these modes is in the range of 2% to 11% of the incident S_o mode amplitude. Similar to the reflection factor of S_oS_o mode, the reflection factor of S_oA_o mode also increases with increase in the orientation and attains a maximum value at 60^0 (approx) orientation in both the excitation cases. Further increase in the orientation results in reduction in the reflection factor as shown in Figure 7(a). The rateof decrease in amplitude of the reflected S_oA_o mode is higher than S_oS_o mode when the orientation is more than 60^0. An interesting phenomenon is observed in case of the transmission of S_oA_o mode as shown in Figure 7(b). Transmission factor is found to be more when the excitation was on the metal end than that on the composite end. Similar to the reflection factor, the range of amplitude of the transmitted S_oA_o mode is in the range of 2% to 11% of the incident S_o mode amplitude.

Conclusion

Detailed numerical simulations on propagation of the fundamental symmetric fundamental Lamb mode through a metal-composite adhesive joint revealed that during the interaction of S_o mode with the adhesive generates A_o mode if the orientation of adhesive is other than 90^0. This is observed in both the excitation cases. When the excitation is on the metal end the amplitude of the transmitted S_oS_o mode is 1.6 (approx) times than its counterpart when the excitation is on the composite end. Therefore, it is recommended to deploy the transmitter and receiver on metal part and composite part, respectively while carrying out experiments to detect defects in metal-composite adhesive joint. It is also observed that amplitudes of the reflected S_oS_o, S_oA_o and transmitted S_oS_o mode attain maximum and that of the transmitted S_oS_o mode attains minimum when the orientation of adhesive is 60^0.

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