The interaction of Rayleigh waves with delaminations in composite laminates

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Abstract
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Detection of in-plane fiber waviness in composite laminates using guided Lamb modes
The interaction of Rayleigh waves with delaminations in composite laminates

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In the present work, the interaction of Rayleigh waves with a delamination in a fiber reinforced composite plate was analyzed. Rayleigh waves, upon interacting with delamination mode, convert into Lamb waves in the delamination zone. These guided Lamb modes have the capability to mode convert back into Rayleigh modes when they interact with the edge of the delamination. A unidirectional glass/epoxy laminate with a delamination of known size was fabricated and tested using air-coupled ultrasonics. Finite element models were developed to understand the mode conversions occurring at various sections of the delamination. Particle displacements along with numerical and experimental velocities were considered to identify each mode. Conclusions were drawn based on the velocity analysis.

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I. INTRODUCTION

Damage detection and characterization in composite materials have been widely explored. Different techniques have been proposed for different types of defects. One of the most important defects that occur in composite laminates is delamination. A delamination in a thick laminate (thickness >30 mm) is generally difficult to detect. Detection using conventional ultrasonics becomes difficult due to attenuation at high frequencies, and usage of guided Lamb modes becomes difficult due to the thickness of the laminate. Rayleigh waves seem to be very effective in detecting sub-surface defects and convenient for wave propagation in thick composite laminates. The limitation of using Rayleigh waves is their sensitivity, which is on the order of the wavelength of the signal. This makes it possible only to detect surface, sub-surface defects.

Extensive analyses in-terms of acoustic wave interaction with delamination have been done using guided Lamb waves. Some of the primary work in the field of stress wave interactions with delaminations was performed by Auld and Tan who predicted the reflection of Lamb modes from vertical delaminations. Later, Rokhlin studied the Lamb mode diffraction in different delaminations placed at the midplane. Guo and Cawley have published work on the interaction of the fundamental S0 Lamb mode with delamination in a cross-ply laminate at different depths. Various researchers have explained the interaction using theoretical and numerical models. Ramadas et al. showed the mode conversions which occur when the fundamental anti-symmetric and symmetric modes interact with delamination using finite element techniques. Further, Shkerdin and Glorieux used the modal decomposition technique to show the various Lamb mode conversions in a plate with delamination. Instead of using the fundamental mode interaction, they managed to create models for multi-mode interactions in the laminate. Special attention was given for Lamb waves converting into Rayleigh waves and vice versa. Li and Achenbach investigated the interaction of Rayleigh waves with a disbond normal to the free surface. By modeling the interphase layer with extension and shear springs, they were able to obtain a solution using the boundary element method. The transmission and reflection coefficient of Rayleigh wave was investigated for both surface breaking and subsurface disbonds.

The present paper deals with studying the interaction of a Rayleigh wave with delamination. The primary Rayleigh wave upon interacting with the leading edge of the delamination, mode converts into the fundamental Lamb modes. The Lamb mode interacts with the trailing edge of the delamination to reconvert back into a Rayleigh wave. Finite element models were used to capture this phenomenon and unidirectional glass/epoxy laminate with delamination was fabricated to validate the theoretical models. The sample was designed so that only the fundamental Lamb mode can be excited in the delamination. This approach makes it easier for the experimental-theoretical correlation. Although, at first approach, the phenomenon looks direct and straightforward, it was observed that extensive mode conversions take place which can be captured and understood only by creating finite element models. For the considered excitation frequency, the wavelength (7.5 mm) of the Rayleigh wave is large enough that surface roughness of the sample does not affect its propagation.

II. EXPERIMENTAL DETAILS: SPECIMENS AND SETUP

All investigations were carried out on a 30 mm thick unidirectional glass/epoxy laminate. A delamination was formed by placing a sheet of release film of specific dimension between the second and third dry fiber layers. A vacuum assisted resin transfer (VARTM) infusion process was used to infuse the epoxy. Once the sample was completely cured, the release film was pulled out, creating a true delamination.
The delamination dimensions are 50 mm (L) × 50 mm (W) × 1.4 mm (T). The specific thickness of the delamination was chosen for generation of the fundamental Lamb modes, i.e., A0 and S0.

The experimental setup consists of a pair of Ultran® 200 kHz air coupled transducers excited by an Olympus 5077 pulser-receiver. An auxiliary amplifier supplies 40 dB of gain in addition to the 20 dB provided by the pulser-receiver, to increase the amplitude. A 300 V square wave pulse was used to excite the transducers at a pulse-repetition rate of 100 Hz. The signal was acquired through a 12 bit digitizer which digitizes and sends the data to a computer for processing. A better signal-noise ratio was obtained by performing summed averaging at 64 averages per waveform. A 3 axis X-Y-Z scanner was used to facilitate B-Scan capabilities. This is the single-sided B-Scan, where both the transducers are held on the same side of the laminate and moved simultaneously. A detailed description of the setup is shown in Fig. 1. The scanner was controlled by a motion controller which was interfaced with the data collection software on the computer. This enables plotting the time of flight vs distance traveled, with the amplitude in color scale.

### III. NUMERICAL MODEL

Numerical simulations of wave propagation were carried out using ANSYS® 13. A 120 layered half space was modeled to simulate Rayleigh wave propagation. The number of layers chosen to create the half-space depends on the wavelength of the Rayleigh wave (7.5 mm). Since no absorbing boundary conditions were used, bulk wave reflections from the bottom surface were minimized by modeling a very thick structure. Each layer was 0.7 mm thick and was assigned with orthotropic properties which are listed in Table I. Eight-node plain strain elements were chosen for the meshing, with no damping or attenuation effects. For a good convergence of the dynamic simulation, the mesh size should have at least ten elements per wavelength.11,12 The FE model had 3 elements through the thickness of each layer with element size across the thickness being 0.2334 mm and 0.328 mm along the length direction, which amounts to ~30 elements per wavelength of the Rayleigh wave in the thickness direction and ~23 elements in the wave propagation direction. A “zero volume” delamination was created between the second and third layer. This technique has been used before effectively with good results.5,6,13 The right side edge of the FE model was fixed and the top, left and bottom surfaces along with the delamination faces were attributed with traction-free boundary conditions as shown in Fig. 2. A linear, small displacement transient analysis was performed with a time step size of 200 nsec and the total time of simulation being 200 μsec. Time integration was carried out using Newmark’s time integration scheme14 and the FE problem

### TABLE I. Material properties of laminate and epoxy used for numerical modeling.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_x</td>
<td>44.68 GPa</td>
</tr>
<tr>
<td>E_y</td>
<td>6.90 GPa</td>
</tr>
<tr>
<td>E_z</td>
<td>6.90 GPa</td>
</tr>
<tr>
<td>ν_xy</td>
<td>0.280</td>
</tr>
<tr>
<td>ν_yz</td>
<td>0.355</td>
</tr>
<tr>
<td>ν_xz</td>
<td>0.280</td>
</tr>
<tr>
<td>G_xy</td>
<td>3.06 GPa</td>
</tr>
<tr>
<td>G_yz</td>
<td>3.33 GPa</td>
</tr>
<tr>
<td>G_xz</td>
<td>3.109 GPa</td>
</tr>
<tr>
<td>ρ</td>
<td>1990 Kg/m³</td>
</tr>
</tbody>
</table>
was solved using the direct sparse solver. Out-of-plane dis-
placement in the form of a 7 cycle, 200 kHz tone-burst with
Hanning window was used as the excitation source at the
transmitter node. Out-of-plane displacement was chosen as
the input to excite the fundamental anti-symmetric mode.
Similarly, out-of-plane and in-plane displacements were
extracted from the receiver node. No contact elements were
used to model the delamination, and the strain amplitudes
(\(\sim1 \times 10^{-6}\)) were 2–3 orders of magnitude lower than the
delamination opening (\(1 \times 10^{-4}\)), thus ensuring that they did not
cause any nonlinear interactions between the delamination
faces. Further, at each time step, the delamination faces were
monitored, and it was confirmed that there was no contact or
overlap of the nodes.

IV. RESULTS

Using the setup described in Sec. II, a preliminary B-
Scan was performed, which is shown in Fig. 1. A time of
flight shift, along with amplitude decrease was observed
when the transducers moved over the delamination region.
Although this signifies that detection of the delamination is
possible, it does not highlight the real physics behind the
interaction. To analyze this better, the entire laminate can be
divided into three sections as shown in Fig. 2 (cross sectional
view of the laminate with delamination). Section 1: Rayleigh
wave generation in defect free half-space. Section 2:
Delamination and the half-space below the delamination.
Section 3: half-space beyond the trailing edge of the delami-
nation. Each of these sections was analyzed both numerically
and experimentally. Although generation of longitudinal
waves and other modes at the edges of the delamination are
possible, this paper focuses solely on the Lamb and Rayleigh
waves that were generated.

To be consistent with some of the previous work\(^6\,13,15,16\)
and for clarity of presentation, each of the newly generated
modes has been given a different name. The primary excited
mode is mentioned first, and the subsequently generated
modes are listed from left to right. The mode under
consideration is the one which is mentioned last (right-
most). A subscript generally denotes the mode type,
although for Rayleigh waves it is simply used to distinguish
between Rayleigh modes in different sections. For example,
\(R_1A_0\) denotes the fundamental \(A_0\) mode generated from
the primary Rayleigh wave. This naming convention is consist-
ent with previous published work.\(^6\,13,15,16\)

A. Section 1

In this section, there is no delamination and hence
Rayleigh wave generation in half space is shown. This is
equivalent to Rayleigh wave propagation in a defect free
plate. The numerical and experimental A-Scans are shown in
Fig. 3. The transducers were experimentally optimized for
maximum amplitude at \(14^\circ\) from vertical for Rayleigh wave
generation. Since the transducers were close to the edge of
the laminate, reflections off the edge can be seen in the A-
Scan. Since only the modes which arrive first are considered,
any form of reflections can be neglected.

B. Section 2

The wave interaction in this section can be further di-
vided into two sections, i.e., Section 2.a—The delamination
section—and Section 2.b—The half space below the
delamination.

1. Section 2.a

The primary Rayleigh wave upon interaction with the
leading edge of delamination, converts into Lamb modes in
the delamination. The thickness of the delaminated portion
is such that it can sustain only a Lamb wave. The low fre-
quency of the signal and the thickness of the delamination
can only support the fundamental modes, \(A_0\) and \(S_0\). Since
the delamination is only 50 mm long, these modes further
experience reflection and transmission at the trailing edge.
Figure 4 shows the mode converted \(A_0\) and \(S_0\) which are
denoted as \(R_1A_0\) and \(R_1S_0\). The numerical excitation is a 7
cycle Hanning window tone burst, hence the entire disturbance or wave packet is denoted by the specific mode. In Fig. 4(a), R1A0 is denoted by the larger wave packet and R1S0 which has small out-of-plane component, is identified by the smaller disturbance traveling in the front. To illustrate this phenomenon better, out-of-plane (Uy) and in-plane (Ux) displacements have been plotted together in Fig. 5. The difference between R1A0 and R1S0 is more apparent in the figure. The data shown in Fig. 5 were collected closer toward the leading edge of the delamination and hence are different compared to Fig. 4(a). To identify the mode type, numerical displacement profiles were obtained. A displacement profile plots the displacement as a function of depth or thickness. Figures 6(a) and 6(b) shows the displacement profile for R1S0 and R1A0 extracted at 54.2 μsec and 74.6 μsec, respectively. These are consistent with the fundamental Lamb mode displacement patterns. Since the generated R1A0 and R1S0 travel at different speeds compared to R1, the receiver angle has to be changed to $18^\circ/C_1$ for R1A0 and $5^\circ/C_1$ for R1S0 for optimum signal amplitude. These angles were theoretically verified which will be shown later.

2. **Section 2.b**

The Rayleigh wave generated in section 1, interacts with the lower half space and produces another Rayleigh wave which travels along the lower half-space surface. Only numerical results can be obtained in this section due to the difficulty in experimentally measuring the waves. A numerical A-Scan of R1R2 is shown in Fig. 7(a). To confirm the mode type, out-of-plane (Uy) and in-plane (Ux) displacement profiles, normalized to one wavelength were extracted at 70.5 μsec and plotted in Fig. 7(b). The mode shape is consistent with Rayleigh wave displacement pattern.

C. **Section 3**

The half-space following the delamination can only support a Rayleigh wave. Hence, the Lamb modes experience reflection and transmission at the trailing edge of the delamination resulting in R1A0 converting completely into a Rayleigh wave; R1A0R4. Since R1S0 has a very small out-of-plane component as seen in Fig. 6(a), its mode conversion efficiency is very low for the given delamination thickness and hence does not mode convert into a Rayleigh wave. On the other hand R1A0 has a higher out-of-plane component and has higher conversion efficiency and will be converted into a Rayleigh wave (R1A0R4). A mode conversion analysis in terms of conversion efficiency was
performed by Shkerdin and Glorieux, and the abovementioned mode conversions are consistent with their analysis.

Furthermore, $R_1R_2$ which was generated in Section 2.b, interacts with the trailing edge of the delamination and due to displacement continuity, converts into another Rayleigh wave; $R_1R_2R_3$. This newly generated $R_1R_2R_3$ can be seen in the A-Scan shown in Fig. 8. At this location, the receiver angle was again changed to $14^\circ$ to efficiently receive the mode converted Rayleigh waves.

Figure 9 shows a schematic summary of all the mode conversions occurring when the Rayleigh wave travels across the delamination. When a Rayleigh or Lamb mode interacts with a delamination, based on the transmission and reflection coefficients, part of the energy will be transmitted and part of it will be reflected. At each section, the reflected energy will also undergo mode conversions resulting in new Rayleigh and Lamb modes. For simplicity’s sake, and lack of space, none of the reflected modes are considered in this work.

V. DISCUSSIONS

Numerical and experimental velocity measurements were carried out to confirm the findings. Individual A-Scans at different locations were extracted from the numerical model. Similarly individual A-Scans were collected at different spatial locations on the sample. For velocity analysis, the waveform overlap technique was used to determine the time-of-flight difference. Observed numerical and experimental velocities of different modes are summarized in Table II. A comparison between absolute time of flight values measured in experiments and numerical simulation will not be valid since there is no air path included in numerical simulation. The presence of air path increases the time of flight values.
found experimentally. Hence a velocity comparison instead of a time of flight comparison is considered here.

In general a 10% error between experimental and numerical velocities can be observed in Table II. Although a more accurate model with material properties closer to the experimentally obtained properties is possible, it was found that the values in Table I were sufficiently accurate to predict the interactions and validate them with experimentally measured responses. The significant observation to be noted in Table II is that the velocities of R1, R1R2, and R1A0R4 and R1R2R3 are very close, both in the experimental and numerical data. This shows that all these modes are Rayleigh waves and, hence, travel at similar speed. Although their absolute values are off by 10%, the trend or pattern of each of these modes is retained in experimental and numerically simulated data, which confirms that these are Rayleigh modes.

Analytical dispersion curves were obtained to confirm the Lamb wave velocities. Developing dispersion curves in orthotropic laminates have been explored extensively in the past.18–22 The dispersion curves presented in this work were developed using equations worked out by Dayal and Kinra.19 The dispersion curves plotted using the material properties listed in Table I are shown in Fig. 10(a). The velocity determined from the dispersion curve for 0.14 MHz-mm for A0 mode is 1200 m/s. This value is consistent with the experimentally determined velocity values for R1A0. It also matches well with the numerically simulated R1A0 value of 1230 m/s. The velocity of R1S0 mode, which was determined experimentally matches with the S0 mode velocity obtained from the dispersion curve. As a further confirmation of the Lamb modes, an excitation angle vs frequency-half plate thickness curve was plotted as shown in Fig. 10(b). For the given laminate, at 0.14 MHz-mm, the excitation angles for A0 and S0 are 4° and 19°. This matches with the experimentally observed excitation angles mentioned earlier.

From Table II, it is observed that the velocity of R1R2 is higher than the velocity of R1A0. Hence when these modes interact with the end of the delamination, they both convert into respective Rayleigh waves, but their arrival times are different. This can be seen clearly in the experimental and numerical A-Scan shown in Figs. 8(a) and 8(b). R1R2 arrives earlier at the trailing edge compared to R1A0, and once they convert into R1R2R3 and R1A0R4, they travel at the same speed. The time of flight difference between R1R2R3 and R1A0R4 obtained numerically and experimentally was 11 µs and 10.2 µs, respectively.

![FIG. 8. (Color online) (a) Numerical A-Scan extracted from Section 3 showing the mode converted Rayleigh modes R1A0R4 and R1R2R3 from the anti-symmetric Lamb mode from section 2.a and the Rayleigh wave from section 2.b. (b) Experimentally measured response for Section 3.](image-url)

![FIG. 9. An overview of the different mode conversions that take place when the Rayleigh wave interacts with a delamination.](image-url)

<table>
<thead>
<tr>
<th>Mode Name</th>
<th>Section</th>
<th>Experimental Velocity m/s</th>
<th>Numerical Velocity m/s</th>
<th>Analytical Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>1</td>
<td>1590 ± 10</td>
<td>1740 ± 7</td>
<td>-</td>
</tr>
<tr>
<td>R1A0</td>
<td>2.a</td>
<td>1210 ± 22</td>
<td>1230 ± 17</td>
<td>1200 ± 8</td>
</tr>
<tr>
<td>R1S0</td>
<td>2.a</td>
<td>5290 ± 15</td>
<td>-</td>
<td>4990 ± 8</td>
</tr>
<tr>
<td>R1R2</td>
<td>2.b</td>
<td>-</td>
<td>1700 ± 43</td>
<td>-</td>
</tr>
<tr>
<td>R1R2R3</td>
<td>3</td>
<td>1550 ± 12</td>
<td>1770 ± 43</td>
<td>-</td>
</tr>
<tr>
<td>R1A0R4</td>
<td>3</td>
<td>1550 ± 12</td>
<td>1770 ± 43</td>
<td>-</td>
</tr>
</tbody>
</table>
One of the important applications of this detailed analysis is the determination of delamination depth or delamination thickness. By performing a velocity analysis similar to what is shown here, one can determine the depth or thickness of the delamination by using the experimental velocity of the Lamb mode in the delamination and finding the corresponding frequency-thickness value from the dispersion curve. Knowing the frequency of excitation, one can easily calculate the thickness of the delamination. Because of the lack of space and to maintain coherency of the work, the delamination thickness measurement is not presented here and will be published elsewhere.

VI. CONCLUSIONS

The main objective of this paper was to study the Rayleigh wave interaction with a delamination. A preliminary B-Scan showed amplitude and velocity changes over the delamination. A finite element model was developed to understand the mode conversions. The numerical model was validated by fabricating a composite sample with known delamination size and tested using air-coupled ultrasonics. It was observed that the primary Rayleigh mode ($R_1$) upon interacting with the leading edge of the delamination undergoes a mode conversion into anti-symmetric Lamb mode ($R_1A_0$) and symmetric Lamb mode ($R_1S_0$) in the delamination and a new Rayleigh mode ($R_1R_2$) in the lower half-space. The Lamb mode $R_1A_0$ interacts with the trailing edge of the delamination and mode converts into $R_1A_0R_4$, while the $R_1S_0$ mode does not mode convert. $R_1R_2$ interacts with the edge of the delamination and converts into $R_1R_2R_3$, which arrives faster than $R_1A_0R_4$. All the described mode conversions were supported with experimental and numerical evidence. Further, a possible technique to determine the thickness of the delamination has also been described. Future work in the same area includes model assisted, multi-mode analysis for delamination thickness measurement. This work can also be extended for cross-ply and quasi-isotropic layup, where the Lamb mode velocities change based on the layer orientation of the delamination. The effect of delamination size, i.e., length and width on the different mode generation will also be explored.

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