Lamb wave–based detection of a controlled disbond in a lap joint

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Abstract
Lap joints are widely used across many critical structures such as aircraft and bridges. Lamb waves have long been proposed to monitor lap joints against defects such as disbonds. However, there are many challenges which must be answered to make use of Lamb wave technology. Frequency selection is often overlooked, and many authors will select a single frequency without knowing if other frequencies will result in better sensitivity. Another challenge is the features (mode conversion, attenuation, reflection) associated with damage are also inherent in a lap joint. This sharing of features can lead to confusion (false positive/negative) depending on the chosen damage detection strategy. Furthermore, almost all proposed methods require a baseline reading of the structure in its flawless state. Relying on a baseline reading can result in false positives due to shifts in sensor outputs caused by ageing and inconsistent environmental conditions. Instead of a baseline, this article proposes a technique which uses strategically positioned sensors to detect Lamb wave modes generated only in the presence of a disbond. The technique is first developed using a numerical study and then verified with an experimental study. Several frequencies are trialled and detailed in this article which shed light on the ideal frequency selection when using this method.

Keywords
Lamb wave, lap joint, disbond, modal analysis, detection

Introduction
Established bulk wave methods are able to identify most delaminations (i.e. kissing bonds excepted) within structures; however, they can only inspect a single point at a time. In order to cover an area, repeated single point scans are performed resulting in what is known as a C-scan as demonstrated by Wood et al.² and also later in this article. This is often done in an immersion tank and requires costly and large hardware. The appeal of Lamb waves comes from their ability to travel across and inspect large areas in plate structures using sensors which are low cost and small.

Most publications involving Lamb waves use a lead zirconate titanate (PZT) transducer to excite Lamb waves. The propagating Lamb wave perturbations are typically received with either another PZT transducer or a laser vibrometer (LV). A PZT transducer has a small footprint which allows it to be embedded in a fixed location for structural health monitoring (SMH).³,⁴ A LV is costly and large, constraining its use to laboratory studies. However, the LV can detect Lamb waves without contact which allows thousands of points to be recorded on a plate to offer a complete picture of the wavefront.⁵ This provides enough spatial data to perform dispersive analysis via methods such as two-dimensional fast Fourier transform (2D FFT).⁶ Recent developments⁷ show fibre Bragg grating (FBG) sensors as a promising alternative to LV for measuring Lamb waves. FBG sensors allow a distributed sensor array to be embedded in a single strand of fibre making it possible to obtain multipoint measurements without the size and expense of LV.⁸ The miniaturisation potential for FBGs has been demonstrated by Murayama et al.,⁹ where FBGs were embedded into a bond line to provide strain data.

Damage detection using Lamb waves is usually performed using pitch-catch or pulse-echo methods.¹⁰ In a

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pitch-catch arrangement, a transmitter excites Lamb waves towards an inspection area with a receiver placed in the shadow cast by that area. A pulse-echo arrangement has the transmitter and receiver placed on the same side such that an echo will result from the wave reflecting off the damage. When both these methods are used on a realistic structure such as a lap joint, it is often difficult to discriminate which disturbances occur from the joint and which occur from the presence of damage. In fact, Lowe et al. showed that many of the phenomena associated with damage (attenuation, mode conversion, reflection) can be also associated with a lap joint. As a result, authors often resort to taking baseline readings when the structure is undamaged. Cuc and Giurgiutiu tested a pulse-echo method to detect disbonds on a lap joint structure after recording a baseline at first. Their method required subjective (human-interpreted) comparison of the time–amplitude history to identify an echo belonging to a disbond. Sensors which were known to be away from the disbond were used as a baseline and exhibited lower amplitudes. Sun and Johnston similarly reported amplitude reductions as the pitch-catch path was placed across a disbond in a lap joint structure. Similarly, Nagy et al. presented work using leaky guided interface waves to identify disbonds. The received frequency spectrum was compared against that of a good bond resulting in observable differences for a poor bond, porous bond and kissing bond. Ha et al. showed that Lamb wave’s features such as phase and amplitude can be shifted from a baseline reading by elevating the temperature of an aluminium specimen with adhesive film. Consequently, damage detection by contrasting against baseline readings may work well in the laboratory; however, a false positive can occur from ageing sensors and environmental conditions in the real world. Salamone et al. also presented a pitch-catch strategy to identify disbonds in a lap joint structure. Autoregressive (AR) models were used which could reliably discriminate undamaged areas from disbonded ones as well as determine the size of the disbond. However, this method still requires a baseline in the form of a ‘training database’. Fasel and Todd extended this work with AR modelling and tested several frequencies from 100 to 350 kHz and found that 300 kHz produced optimal sensitivity to disbonds.

The ability to capture and characterise the underlying scattering mechanism may remove the need for a baseline measurement. To achieve this, the methodology must be able to clearly identify the presence of the wave mode that is scattered by the damage or defect. This article will focus on testing this claim with a set of numerical and experimental studies on identifying the disbond on a bonded lap joint. The aim is to show that the presence of a disbond can be determined from the scattered wave field by the disbond without the need for any pre-determined baseline.

This study first presents a numerical study to form and test methodologies based on distributed sensing and 2D FFT analyses to detect a disbond within a lap joint. The methodologies were then verified experimentally. Before and after the introduction of the disbond, scanning LV was used to record propagating Lamb waves across the entire plate. The data from LV were then processed according to the methods learned in the numerical study to identify a disbond.

Numerical prediction

The numerical work will be used to develop a methodology for disbond detection which will be later verified with experimental data. The focus here is to determine if one can utilise the scattered wave field to identify the presence of a disbond. An ability to do this will pave the way for a disbond detection technique that is not reliant on baseline measurement.

The model features two pieces of 1.6-mm-thick aluminium plates, the base plate has planar dimensions of 205 mm × 130 mm and the doubler measures 90 mm × 130 mm. The FM300-2K adhesive was modelled by Ong et al. was used to define the material properties for the FM300-2K adhesive. The resulting model is shown in Figure 1 with the addition of a damped boundary to reduce edge reflections. The damped boundary uses the same tetrahedral solid elements and is a 10-mm extension of the plate material on each edge with the material damping coefficient set to 0.5. The 3D model was created and meshed with tetrahedral elements in UGS Femap and solved with NASTRAN’s transient dynamic solver. Out of plane displacement from the top surface was output from the solution to match the experimental data which will be presented later. The time step was set to 0.04 µs and mesh size to 0.6 mm to provide adequate temporal and spatial resolution. The highest wave speed in this study is approximately 5400 m/s for S0 at 200 kHz; hence, these parameters satisfy the courant stability criteria for travelling waves

\[
\frac{C \Delta t}{\Delta x} < 1
\]

where C is the wave speed, \( \Delta t \) is the time step and \( \Delta x \) is the linear element size.
A 10-mm diameter, 1-mm thick PZT transducer was modelled as a solid disc protruding from the plate. A time-varying radial force was applied to the circumferential face of the disc simulating the expansion and contraction of a PZT transducer. This method of simulating a PZT transducer is advocated and described further in detail in Rajic et al.\textsuperscript{22} Similar approximations which utilise a time-varying in-plane force have proven to be a close match to experimental in several other studies.\textsuperscript{23–26} The time-varying forcing function is identical to the input functions used to excite the PZT transducers in later experimental studies. It consists of Hanning-windowed sinusoids ranging from 200 to 600 kHz. The −3-db bandwidth is approximately 100 kHz for all frequencies. This is kept constant by keeping the Hanning window as close as possible to 20 μs while maintaining an integer number of cycles.

Two models were created, one flawless and one with a section of adhesive removed to approximate a disbond. For brevity, the approximated disbond will be referred to as the disbond throughout the article. The removed adhesive was semicircular in shape with a diameter of 50 mm and the centre of the semicircle positioned on the doubler’s edge and +50 mm in the Y-direction relative to the PZT transducer as shown in Figure 1. The location and size of this disbond were set to match the experimental study after it was measured by ultrasonic C-scan to be presented later.

The wave field incident on the bonded doubler comprises S\textsubscript{0} and A\textsubscript{0} modes within the 200–600-kHz range. Given that the group velocities of these modes are vastly different at the aforementioned frequencies of interest, we are able to separately investigate the effects of the disbond on the individual incident wave modes using the following time-gating schemes:

1. Effects of disbond on the incident S\textsubscript{0} mode (25 μs < t < 40 μs);

2. Effects of disbond on the incident A\textsubscript{0} mode (25 μs < t < 40 μs).

**Effects of disbond on the incident S\textsubscript{0} mode (25 μs < t < 40 μs)**

Displacement snapshots at t ≤ 25 μs have been omitted for brevity. At t = 25 μs, the incident S\textsubscript{0} will only just reach the doubler. The end of the time period (t = 40 μs) was chosen to exclude the incident A\textsubscript{0} from the doubler. Displacement field snapshots at t = 40 μs are shown in Figure 2. Figure 2(a) shows that, at t = 40 μs, the incident A\textsubscript{0} mode has only arrived at the edge of the doubler. Therefore, the time period (25 μs < t < 40 μs) can be used to investigate the scattering of the incident S\textsubscript{0} mode as it propagates over the doubler. Figure 2(c) shows that a mode converted A\textsubscript{0} (MC-A\textsubscript{0}) is observed to have been scattered from incident S\textsubscript{0} when it propagated over the doubler. In order to confirm these modes, 2D FFTs have been performed in line with the radial wavefront originating from the PZT as marked by line RD (doubler) and RB (base plate) in Figure 2(d) and presented in Figure 3. For brevity, the datasets for all frequencies have been summed into a single plot for each line. Figure 3(a) shows that the PZT is generating A\textsubscript{0} and S\textsubscript{0} modes across all frequencies on the base plate. Upon arrival at the doubler, Figure 3(b) shows A\textsubscript{0} and S\textsubscript{0} still present with some mode conversion into A\textsubscript{1} when the frequency is 500 kHz and higher.

The results presented in Figure 2 are shown in flawless and disbonded pairs in order of ascending excitation frequency. The side-by-side presentation enables the effects from the disbond on the Lamb waves to be studied. Upon reviewing the animation of the displacement field in 0.1 μs steps, it was found that the boundaries of the disbond causes reflections resulting in waves propagating inwards from the disbond’s edge as illustrated by the red line in Figure 2(d). As a result, a proportion of the Lamb wave energy is trapped within the disbonded region similar to the trapping of energy observed in a partial depth hole as previously reported by Ong et al.\textsuperscript{27} This is possible because the S\textsubscript{0} wave travels at high speed in the base material under the disbond without interacting with the doubler until reaching the disbond’s semicircular boundary. The remaining proportion of the Lamb wave energy is refracted by the edge of the semicircular disbond as indicated by the blue line in Figure 2(d).

The MC-A\textsubscript{0} wavefront is visibly distorted in the vicinity of the disbond for excitation frequencies between 200 and 500 kHz. At these frequencies, the disbond refracts MC-A\textsubscript{0} waves into the doubler as indicated by the blue line on Figure 2(d). At 600 kHz, the Lamb

![Figure 1. Reduced lap joint specimen used in the numerical model.](image-url)
waves in the area surrounding the disbond show minimal influence from the disbond, and the waves almost resemble those when the plate is flawless. This highlights the need for careful selection of excitation frequency to detect disbonds. It is hypothesised that this is due to the shear lag effect of the adhesive layer being more prominent at higher frequencies due to the shorter oscillation period. This would have two effects; first, it would be a reduced transferral of wave energy to the doubler from the base plate and second, it would soften the edge of the disbond. However, it is not possible to verify this without further research.

The disbond identification methodology starts with a series of spectral analyses which were performed using the displacement-time data along line 1 marked in Figure 2(c) and located on the doubler. 2D FFTs were calculated along this line resulting in the plots shown in Figure 4. Line 1 is located on the doubler 2 mm from the edge to capture waves originating from incident $S_0$ which are refracted into the doubler by the delamination. It is possible to target these damage-induced waves because line 1 is deliberately oriented perpendicular to the incident wave at the start of the line and $55^\circ$ to the incident wave at the end of the line.
Consequently, it is expected to yield a very low wavenumber (close to zero) when the plate is undamaged as no waves are expected to travel in the direction of line 1. However, in the presence of a disbond, as shown in Figure 4, the 2D FFT conducted along line 1 will yield a wavenumber that is associated with the MC-A0 mode. Another benefit of this methodology is the incident wave data included in line 1. This can be used to normalise the data such that variations in source amplitude in practical applications can be overcome for baseline-free identification of the MC-A0 mode.

When the driving frequency is at 300 and 400 kHz a strong indication of the disbond is observed along line 1 (Figure 4(c) to (f)). Figure 4(c) to (f) shows that the MC-A0 mode is strong and can only exist when the disbond is present to redirect the waves parallel to line 1. In order to quantify the difference in MC-A0 amplitude caused by the disbond, the peak amplitudes were measured from the 2D FFT and summarised in Figure 5. The results show quantitatively that there is a clear distinction between flawless and disbonded specimens at 300–400 kHz.

Effects of disbond on the incident A0 mode (50 μs < t < 60 μs)

Displacement field snapshots at 60 μs after actuation are shown in Figure 6. This time period was chosen to include the incident A0 propagating into the doubler. The data are harder to interpret over this interval because the incident S0 has already propagated through, and reflections from the plate edge are more severe. This section will highlight the need for frequency analyses to discriminate wave energy associated with a disbond.

The incident A0 has negligible distortion when it propagates over the bonded doubler when compared to MC-A0 (see Figure 2(c)) because the phase velocity change across the doubler is small hence minimising refraction according to Snell’s law. This is illustrated in Figure 6(a) where the wavefront of the incident A0 mode has a higher intensity which allows it to be differentiated from the other modes. The A0 mode within this time period appears to be most sensitive in the 300- to 500-kHz region. As shown and labelled in Figure 6(f), the reflected A0 waves are emanating from the location of the disbond. The disbond is essentially acting like a point source. While this is not very clear in Figure 6(d) and (f), the following analysis will highlight these phenomena.

The reflected waves originating from the disbond is highlighted using a 2D FFT analysis along line 2 which is located on the host structure (see Figure 6(d)). Line 2 is positioned 2 mm from the edge of the doubler to capture waves reflected from the delamination back into the host structure upon the arrival of incident A0. This analysis makes it possible to distinguish waves originating from the disbond from all other waves. The approach is similar to that described in the previous section; line 2 is aligned such that only waves originating from the disbond will propagate parallelly and register a wavenumber corresponding to A0. The results from the 2D FFT analysis along line 2 are shown in Figure 7. As expected, an A0 mode is recorded by the 2D FFT only when the disbond is present in the plate. This occurs at all frequencies in the range of 200–600 kHz making it a potentially robust indicator that remains to be tested by experiment. As in the previous section, the A0 amplitude was quantified resulting in Figure 8 which suggests that 400 kHz provides the greatest contrast for identifying a disbond.

The numerical investigation demonstrates the potential of using a 2D FFT of the time series data collected along a line parallel to the edge of the doubler (line 2). The distortion of the incident S0 by the doubler will lead to the appearance of the MC-A0 when the data on
the doubler is analysed. This can be accompanied by similar analysis using data along a line parallel to the edge of doubler on the parent substrate. In the latter case, the reflection of the $A_0$ mode by presence of the disbond is used as a detection tool. These findings will be substantiated with the experimental work in the following section.

**Experimental work**

**Test specimen – lap joint**

The lap joint specimen was created from aircraft grade 7075 aluminium alloy plates to replicate the scenario presented in the numerical study. This specimen will be used to provide experimental verification of the findings.
from the numerical study. In order to match the numerical model, the relative positioning of the disbond and PZT transducer was made identical to the numerical study. The base plate measured 500 mm × 240 mm × 1.6 mm and had a doubler bonded to the centre measuring 100 mm × 240 mm × 1.6 mm as shown in Figure 9. The doubler was bonded with FM300-2K film epoxy adhesive made by Cytec. The specimen size was increased from the numerical model to avoid reflections from the plate edges and also to provide the opportunity to introduce multiple disbonds.

Two PZT transducers were bonded to the plate in order to actuate Lamb waves. PZT P1 was placed in

Figure 5. Amplitude of $A_0$ along line 1.

Figure 6. Displacement field at 60 μs: (a) 200 kHz, flawless; (b) 200 kHz, disboded; (c) 300 kHz, flawless; (d) 300 kHz, disboded; (e) 400 kHz, flawless; (f) 400 kHz, disboded; (g) 500 kHz, flawless; (h) 500 kHz, disboded; (i) 600 kHz, flawless and (j) 600 kHz, disboded.
the centre of the doubler plate, while PZT P2 was placed in the centre of the right side as shown in Figure 9. Both PZT transducers were identically installed, consisting of Ferroperm Pz27 Ø10-mm × 1-mm-thick PZT discs. Each PZT transducer was bonded with electrically conductive adhesive to provide an electrical connection to the bottom face as well as mechanical adhesion to the plate. An electrical wire was soldered onto the centre of the exposed face of the PZT transducer. A power amplifier (Krohn-Hite Model 7602) was used to drive the PZT transducer where the voltage applied across the disc was set to 50 V peak-to-peak.

Figure 7. 2D FFT along line 2: (a) 200 kHz, flawless; (b) 200 kHz, disbonded; (c) 300 kHz, flawless; (d) 300 kHz, disbonded; (e) 400 kHz, flawless; (f) 400 kHz, disbonded; (g) 500 kHz, flawless; (h) 500 kHz, disbonded; (i) 600 kHz, flawless and (j) 600 kHz, disbonded.
The drive signals consisted of Hanning-windowed sinu-
soids generated by a computer-controlled function gen-
erator (National Instruments PCI-5412) at a sampling
rate of 100 MHz. LV was used to measure the out of
plane displacement caused by Lamb waves propagating
over the test plate.5,28–33

The LV rig used in this study is identical to that
reported in Ong and Chiu.25,26 An approximate 50-
mm-diameter disbond was introduced into the specimen
as labelled in Figure 9. The method used to control the
disbond size will be discussed in the following section.

The main area of interest is between the PZTs P1 and
P2 where the disbond was to be introduced. Figure 9
shows the area of the test plate that was scanned by
LV. The specimen was first scanned in a flawless state.
After the disbond was introduced, the plate was lined
up on the LV rig and scanned again.

It was found that Lamb waves from the PZT P1
resulted in poor contrast between flawless and
disbonded states. This occurred because of several
reasons:

- For the same voltage input, lower amplitude Lamb
  waves occur on the doubler which adversely effects
  signal to noise ratio.
- A wavefront coming from the P1 encounters a
  convex-shaped disbond rather than the concave
  shape encountered by waves from P2. The convex-
  shaped disbond does not distort the wavefront as
  much in the context of this experiment.
- Waves originating from P1 on the doubler did not
  experience mode conversion as severe when propag-
  ating into the base plate when compared with
  waves originating from P2.

Consequently, the results presented in this article are
from Lamb waves generated at the PZT P2 location.
The PZT P2 was driven at excitation frequencies rang-
ing from 200 to 600 kHz in 100 kHz intervals.

**Creating a disbond along the adhesive bond line**
Considerable effort was put into the specimen fabrica-
tion in order to experimentally achieve a precisely
shaped disbond which could match that in the numeri-
cal model. The test specimen was designed and manu-
factured so that disbands could be introduced at precise
locations under the doubler. The various stages of man-
ufacture are summarised in Figure 10. Prior to bonding
the doubler, the host substrate was scoured at the loca-
tion where the doubler was to be bonded. The edge of
the scoured region and the semicircular region was
masked off as shown below using flash breaker tape. The latter served as ‘weak’ spots to create a disbond. The doubler was subsequently bonded using FM300-2K adhesive as previously mentioned, and the specimen was oven cured using standard procedures prescribed by the adhesive manufacturer. Upon curing, the flash breaker tape was removed so that there was no spew fillet along the edge of the doubler.

A hollow receptacle was then placed over one of the weak spots and filled with liquid nitrogen. The process was employed to render the adhesive layer into a brittle state so that it could be mechanically damaged without damaging the substrate or doubler. The concept is based on the fact that the adhesive has a much lower thermal conductivity than the aluminium plates. Once the liquid nitrogen boiled off, a chisel was used to damage the adhesive layer. The presence of the disbond was ascertained using a C-scan performed on the doubler, the result of which is shown in Figure 11. The disbond can be clearly observed and was measured to be 50-mm wide. The other artefacts are attributed to the PZT with the connecting wires as well as the adhesive that are used to bond the wires to the plate next to the PZT to act as a stress relief.

**Effects of disbond on the incident S\(_0\) mode**

\((25 \ \mu s < \tau < 40 \ \mu s)\)

In the numerical simulation, the disbond was modelled by the removal of the adhesive layer between the doubler and the parent substrate. However, during the experiment, the adhesive layer remained with the doubler although there was a clear disbond between the adhesive and the parent substrate (see Figure 11). In this respect, some discrepancies in the details between the numerical and experimental results were expected.

During the experiment, the test specimen was scanned using LV in the region marked on Figure 9. Figure 12 shows the displacement fields at \(t = 40 \ \mu s\) after actuation making it possible to make direct comparisons to the numerical prediction shown in Figure 2. The modes, wave speeds and timing of the wavefront arrival closely match those predicted numerically in Figure 2. The Lamb wave modes are also confirmed in Figure 13 to match those predicted numerically in Figure 3. This is highlighted by Figure 12(c) where the incident \(A_0, S_0\) and \(MC-A_0\) are easily identified because each occupy a different part of the plate due to their different group velocities. As in the numerical study, the separation of modes allows us to focus on \(S_0\) by setting a specific time window (25–40 \(\mu s\)). In Figures 12(b), 12(d) and 12(f), the disbond is seen to cause substantial distortion to the wavefront and trap energy in the disbond as predicted in the numerical results (see Figure 2). At the higher frequencies (500 and 600 kHz shown in Figure 12(h) and (j), respectively), no Lamb waves are observable in the disbonded area, and the disbond does not cause distortion to the wavefront. This is similar to the outcome predicted in numerical simulations. At 500 kHz, the disbond was predicted numerically to result in visible Lamb waves generated in the disbond and changes to the wavefront after passing through the disbond. This was not reflected in the experiment and is most likely...
attributed to the differences in modelling the disbond and a lack of damping in the numerical model resulting in residual errors.

Figure 14 shows the result from frequency analysis along line 1 marked in Figure 12(c). This line is located at the identical location on the doubler as that used in the numerical study allowing for direct comparison. The analysis of the data from that study along this line was previously shown to be able to discriminate waves which are scattered by the disbond. In the case of the experimental study, the 300-kHz excitation resulted in the greatest sensitivity to the disbond as Figure 14(d) shows much larger $A_0$ amplitude compared to Figure 14(c). Figure 15 shows a quantitative comparison of the
Figure 13. 2D FFTs on radial lines from PZT (experimental): (a) line RB and (b) line RD.

Figure 14. 2D FFTs along line 1 (on doubler): (a) 200 kHz, flawless; (b) 200 kHz, disbonded; (c) 300 kHz, flawless; (d) 300 kHz, disbonded; (e) 400 kHz, flawless; (f) 400 kHz, disbonded; (g) 500 kHz, flawless; (h) 500 kHz, disbonded; (i) 600 kHz, flawless and (j) 600 kHz, disbonded.
relative amplitudes of the $A_0$ mode for each frequency in the flawless and damaged specimen. The results show that a frequency analysis along line 1 can be used to identify the presence of a disbond if the excitation frequency is less than 600 kHz.

**Effects of disbond on the incident $A_0$ mode**

$(50 \mu s < t < 60 \mu s)$

Figure 16 shows the displacement field measured at time $t = 60 \mu s$. At this time instant, the image in Figure 16(a) shows the $A_0$ mode incident wave has propagated into the doubler. As predicted in the numerical

![Figure 15. $A_0$ amplitudes on doubler (25–40 $\mu$s).](image)

![Figure 16. Displacement field at $t = 60 \mu s$ showing passage of incident $A_0$ wave over the doubler: (a) 200 kHz, flawless; (b) 200 kHz, disbonded; (c) 300 kHz, flawless; (d) 300 kHz, disbonded; (e) 400 kHz, flawless; (f) 400 kHz, disbonded; (g) 500 kHz, flawless; (h) 500 kHz, disbonded; (i) 600 kHz, flawless and (j) 600 kHz, disbonded.](image)
model, Figure 16(a) to (f) shows point source behaviour of waves reflecting off the boundary of the disbonded area upon incident $A_0$ arriving. This effect is studied by analysing the data along line 2 as defined in Figure 16(c) to identify these waves originating from the disbond. Line 2 in this section is located on the host structure and is identical to ‘Line 2’ previously described in the numerical study. It should be noted that Figure 16(g) to (j) indicates that the disbond is not sensitive to the $A_0$ mode at excitation frequencies in the 500- to 600-kHz range.

The resulting amplitudes from 2D FFT analysis along line 2 are shown in Figure 17. The results corroborate the observations made in Figure 16 where only excitations in the 200- to 400-kHz frequency range resulted in reflected waves from the disbond. Figure 18
shows the amplitudes of the scattered $A_0$ obtained from the 2D FFT shown in Figure 15. The results indicate 400 kHz as the optimal frequency for detecting the disbond. At this frequency, the $A_0$ amplitude is 3.2 times larger with a disbond than it was when flawless.

**Conclusion**

The aim of this article was to show that the presence of a disbond could be determined from the scattered wave field by the disbond without the need for any predetermined baseline. This problem was addressed both numerically and experimentally. A numerical model was first created to investigate how scattered waves from a disbond could be discriminated from the scattered waves coming from the lap joint. It was found that the disbond caused noticeable reflection and refraction and mode conversion of the incident $S_0$ wave. These scattered waves travelled in a different direction to those present in the undamaged plate. As a result, they were detected and quantified using 2D FFT analysis to determine the presence of a disbond. In this instance, since redirection of the wavefront can only physically occur with a disbond, registration of a false positive result is highly unlikely. Once the incident $A_0$ mode reached the defect, it was shown that the disbond behaves like a point source. Similar to the occurrence with incident $S_0$, this wave propagated in directions substantially different from the waves in an undamaged scenario.

The disbond’s effect on the propagating Lamb waves was confirmed to occur in the experimental study in which the scenario presented in the numerical model was replicated, and its methodologies were employed. The same positioning of actuator and receiving lines (line 1 and line 2) were used and were able to identify the disbond at certain frequencies. During the numerical study, it was suggested that Lamb waves excited at 400 and 500 kHz were best suited to identifying the disbond. In the experimental study, it was found that 300- to 400-kHz excitations resulted in the strongest response from a disbond. The discrepancy between optimal frequency predicted numerically and that measured experimentally could potentially stem from key assumptions such as the complete removal of adhesive elements and the lack of damping in the numerical model. The optimal (300–400 kHz) experimental frequency range is in line with the findings by Fasel and Todd who examined an adhesive disbond between composite plates. This suggests there may be a link between adhesive disbond types of damage and the optimum frequency range to detect it. It also highlights the need to carefully select the excitation frequency as frequencies beyond 500 kHz, in the present case, resulted in less mode conversion, reflection and point source behaviour from a disbond. Having shown the importance of frequency with adhesive disbond type damage, this raises the question whether other defects (such as fatigue cracks) may have optimal frequencies for detection and may benefit from sweeping a range of frequencies.

The numerical and experimental works presented above show the ability to use the underlying scattering mechanism to identify the presence of a disbond in the adhesive layer of a bonded lap joint. By placing a distributed sensor parallel to the edge of the doubler, the presence of the disbond can clearly be identified by the appearance of a wave mode. Any incident, transmitted or reflected wave field in the undamaged state will return a wavenumber much lower in energy. This can potentially facilitate the development of a SHM methodology that is baseline free.

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