Core-Skin Disbond Detection in a Composite Sandwich Panel Using Guided Ultrasonic Waves

Advanced composite materials are being increasingly used in state-of-the-art aircraft and aerospace structures due to their many desirable properties. However, such composite materials are highly susceptible to developing internal damage. Thus, safe operation of such structures requires a comprehensive program of effective nondestructive inspection and maintenance of their critical load bearing components before the defects grow and become unstable, resulting in failure of the entire structure. Ultrasonic guided wave-based methods have the potential to significantly improve current inspection techniques for large plate-like structural components due to the waves' large propagation range and sensitivity to defects in their propagation path. The application of guided waves for non-destructive evaluation (NDE) of real structures, however, requires a thorough understanding of the characteristics of guided waves in composite structures in the presence and absence of any defects. In this paper, the interaction of guided waves with a core–skin disbond in a composite sandwich panel is studied using a semi-analytical method, numerical simulations, and laboratory experiments. It is shown that the disbond causes complex mode conversion at its leading and trailing edges. The theoretical findings are verified with laboratory experiments, and the applicability of the proposed pitch–catch setup for NDE of complex composite structures for damage detection is discussed. [DOI: 10.1115/1.4037544]

1 Introduction

In state-of-the-art aircraft and aerospace structures, advanced composite materials are commonly used due to their many desirable properties. For example, honeycomb composite panels, in which thin carbon fiber-reinforced skins (CFRP) are bonded with adhesives to an very lightweight honeycomb core, are often used in aircraft and aerospace structures due to their high strength-to-weight ratio. However, in spite of their many advantages, such composite materials are susceptible to hidden defects that may occur at any time during manufacturing or service of the structure. The bond between the core and the skin may degrade over time, compromising the safety of the entire structure [1]. Many current methods for the detection and characterization of such hidden defects are time consuming, costly, or require partial disassembly of the structure [2]. Ultrasonic guided waves offer an attractive, cost-effective method for inspecting large structures. This is due to the fact that guided waves can propagate long distances and are strongly affected by defects in their propagation path. However, these waves are also affected by other geometrical features in the structure, such as stiffeners. For the successful application of wave-based methods in defect detection and characterization, the quantitative features of these interactions need to be well-understood [3–6].

The need for model-based studies is widely recognized in the nondestructive evaluation (NDE) and structural health monitoring communities and a great deal of work has been carried out using a variety of models. Many of these studies are focused on the propagation characteristics of guided waves in plates without defects. The general features of elastic waves propagating in isotropic and anisotropic solids have been investigated in detail [7–10]. However, the literature on the response of anisotropic and multilayered composite plates to subsurface defects that are representative of fatigue or impact damage is relatively sparse. The exact solution of three-dimensional problems, consisting of multilayered laminates subjected to various types of surface loads, has been given by Mal and Lih [11] and Lih and Mal [12]. Recently, a semi-analytical method has been developed to solve a variety of such problems [13]. Shkerdin and Glorieux [14] used an analytical method to study Lamb mode conversion at delaminations in plates, focusing on the influence of the size and location of the delamination on the scattering coefficients. Chakrapani and Dayal [15] studied Rayleigh to Lamb mode conversion in a laminate numerically and experimentally, and proposed that the size and location of the delamination can be identified through a comprehensive analysis of the wave signals. A similar study has been performed by Tian et al. [16] using a frequency-wavenumber domain analysis approach. However, almost no studies on the interaction of guided waves propagating in thick sandwich panels with disbands or delaminations are available in the literature to date. This is particularly true for studies on the dependence of scattering coefficients on the frequency and modes of the incident wave using methods that will be applicable to real-world problems.

In this paper, a comprehensive approach is used to study the interaction of ultrasonic guided waves with delamination-like defects in a thick honeycomb sandwich panel. Following the results of preliminary research by the authors on this problem [17–19], the basic features of guided wave interaction with defects are studied, in particular the mode conversion at the leading and trailing edge of the damage located at a depth that is much smaller than the plate thickness. In this case, the segment above the crack acts as a newly formed waveguide for Lamb waves. In this region, “wave trapping” occurs under certain conditions, i.e., only low transmission to other waves occurs at the trailing edge of the crack [6,19]. Depending on the excitation frequency and thickness of the core of the sandwich panel, it is shown that the segment below the defect also acts as a waveguide for either Lamb or Rayleigh-like waves. The wave and finite element (WFE) method [20] is used to investigate dispersion characteristics. This technique has been successfully applied to various kinds of waveguides, such as coupled cylinders [21], curved panels [22] as well as sandwich panels with an isotropic foam core [23] or poroelastic core [24], respectively. Generally, scattering at defects is investigated through a number of different methods. If the discontinuity lies in

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a cross-sectional plane of the waveguide, e.g., for cracks perpendicular to the axial direction, the modal decomposition method can be applied [6,25,26]. For more complex damage geometries, a combination of finite element (FE) and boundary element techniques is suitable (e.g., see Ref. [27]). In this paper, transient numerical simulations are utilized to study wave scattering effects. Assuming a sparse array of transducers, results from the numerical simulations are compared to those obtained from laboratory experiments. It is shown that core–skin disbonds can be detected using this guided ultrasonic wave-based approach.

The paper is organized as follows: In Sec. 2, the investigated problem is explained in detail, including fundamental information on guided ultrasonic wave propagation and scattering. In Sec. 3, the semi-analytical, numerical, and experimental methods to address this problem are presented. Results from simulations are presented in Sec. 4: dispersion results are discussed in Sec. 4.1, transient simulations in Sec. 4.2, and experimental results in Sec. 4.3, respectively. Concluding remarks are given in Sec. 5.

2 Problem of Investigation

The considered problem in this work is to find disbonds and delaminations in a thick sandwich panel. Guided ultrasonic waves are assumed to be excited and measured through surface mounted transducers, as shown in Fig. 1. When the induced guided waves encounter a disbond between the face sheet and the core of a three-layer sandwich panel, wave scattering occurs. Depending on the excitation frequency, the sandwich panel itself acts as waveguide for Lamb waves, and the separated layers also allow for Lamb wave propagation. However, at higher frequency, most of the wave energy is localized near the surface, and Rayleigh-like waves are induced. Such waves split at disbonds into Lamb waves that propagate in the face sheet, and Rayleigh-like or Lamb waves that propagate in the core–skin segment below the disbond. Similarly, reflection and transmission at the trailing edge occur. Such disbonds often occur in aircraft composite components after impacts with foreign objects. Note, the surface mounted transducers could be replaced by embedded piezoelectric patches in new components for continuous monitoring.

![Fig. 1 Disbond detection in composite sandwich panels using guided ultrasonic waves](image)

The specific honeycomb sandwich panel considered in this paper consists of two woven CFRP face sheets and an aluminum honeycomb core. The honeycomb core with a thickness of 12.7 mm has a regular hexagonal cell structure, as shown in Fig. 2(a). Due to the relatively low frequencies considered in this analysis, the CFRP skins and the honeycomb core are regarded as an equivalent homogeneous and transversely isotropic material with their symmetry axes normal to the surface (x3-axis). Approximate effective elastic properties of the two materials are determined using a mixture theory [28], and the results are summarized in Table 1. The effective properties of the laminate have been verified through destructive and nondestructive (wave propagation) experiments [29].

The propagation characteristics of guided ultrasonic waves for such complex materials can be studied through semi-analytical methods. In this paper, the WFE method [20] is applied to determine all relevant dispersion properties for the pristine and damaged stages. Through a time-of-flight analysis, wave signals from numerical simulations and laboratory experiments can be evaluated. Further details are presented in Secs. 3 and 4. Following the common nomenclature, Rayleigh-like waves are denoted by R, the antisymmetric waves are labeled A, and symmetric waves are labeled S with sequential numbering \(m, n = 0, 1, 2, \ldots\) respectively. The scattered waves are denoted by their current wave type as well as their propagation history with the most recent wave type being at the end of the sequence. Additionally, the current propagation direction is denoted by \(\leftarrow\) for left (toward \(-\infty\)) and by \(\rightarrow\) for right (toward \(+\infty\)) propagating waves, respectively.

The scattering of ultrasonic waves at discontinuities, such as the leading and trailing edges of disbonds, can be expressed in terms of scattering coefficients. Reflection coefficients \(s_{\text{refl},i}\) and transmission coefficients \(s_{\text{trans},i}\) describe the ratio of reflected to incident and transmitted to incident wave amplitudes, respectively, i.e.,

\[
s_{\text{refl},i} = \frac{a_{\text{refl},i}}{a_{\text{inc}}} \quad \text{and} \quad s_{\text{trans},i} = \frac{a_{\text{trans},i}}{a_{\text{inc}}}
\]

In this paper, the scattering of ultrasonic waves is investigated through the analysis of transient FE simulations, as described in Sec. 3.

3 Semi-Analytical, Numerical, and Experimental Methods

A detailed dispersion analysis for the investigated honeycomb sandwich panel is performed through the application of the WFE method. While the velocity of guided Lamb waves in multilayered sandwich panels can be obtained from its theoretical model using the global matrix method, developed by Mal [30], the WFE approach offers a more effective tool for determining dispersion

![Fig. 2 Composition of the sandwich panel: woven CFRP face sheets on top and bottom, and an aluminum honeycomb core with a cell “diagram” of about 5 mm: (a) honeycomb composite sandwich panel and (b) panel with disbond](image)
curves in more complex structures. In this paper, only propagating waves are considered because of their relevance to nondestructive testing (NDT) applications (for a detailed review of the method applied to composite materials, the reader is referred to the literature [24,31,32]). Here, only a summary of the most important aspects of the WFE method is presented. The WFE method combines FE modeling and theoretical wave propagation analysis. In the FE modeling process, only one segment of the waveguide (segment thickness \( h \), number \( s \)) is considered. With \( \varepsilon = \text{e}^{i \omega} \) and the wavenumber \( k \), the guided waves undergo the phase shifts \( u_{f_{s}}^{s+1} = i u_{f_{s}}^{s} \) and \( f_{L}^{s+1} = i f_{L}^{s} \) while traveling through this waveguide segment. In the end, the method yields an eigenvalue problem of the form

\[
T \left[ \begin{array}{c} u_{f_{s}} \\ f_{L}^{s} \end{array} \right] = \lambda \left[ \begin{array}{c} u_{f_{s}} \\ f_{L}^{s} \end{array} \right] \tag{2}
\]

Once the eigenvalues of Eq. (2) are determined, the wavenumbers \( k \) can be calculated from the following equation:

\[
k = -\frac{i}{h} \ln(\lambda) \tag{3}
\]

where \( \ln(\lambda) \) is the complex logarithm. The corresponding phase velocities \( c_p \) and group velocities \( c_g \) can then be determined from the well-known relations \( c_p = (\partial \omega / \partial k) \) and \( c_g = (\partial \omega / \partial \omega) \), respectively. However, in order to avoid difficulties in numerical differentiation, the group velocities are instead calculated via the energy transport velocity formula [33]. Various results in the form of dispersion curves and mode shapes for the problem at hand are presented in Sec. 4.1.

In order to investigate wave scattering at disbonds, as described in Sec. 2, transient finite element simulations are carried out. For the considered honeycomb sandwich panel, two-dimensional plane-strain models are created in the software package ABAQUS, as shown in Fig. 3. The edges of the model are traction free except for the point of attack of the force \( F \) as well as a fixed boundary on the right end to eliminate rigid body motion. For the mesh, four-node bilinear elements (CPE4R) are used with a spatial resolution of about 0.25 mm, which is more than ten times smaller than the smallest wavelength of the propagating ultrasonic waves. In order to calculate the transient response to a concentrated force input \( F_0 \), ABAQUS’ explicit time integration with a fixed time step of 20 ns is used, and simulations are conducted up to 160 \( \mu \)s. The excitation signal is a three-cycle sinusoidal tone burst enclosed in a Hamming window (also called Hanning window). Models with and without a defect are created. In the model with a damage, a zero volume disbonds is introduced \( 2H \) below the top surface, i.e., at the interface between the skin and core, as shown in Fig. 3. The leading edge of the defect is 50 mm away from the force input, and the disbond is 50 mm long. It has been shown in the previous research that the stress singularity at the tips of the disbonds has negligible effect on the waves in the far field [19]. The response is determined at virtual receivers 1, 2, and 3. The results from the transient FE simulations are presented in Sec. 4.2.

Laboratory experiments are carried out using a pitch–catch ultrasonic system that is augmented by a fixture for the accurate placement of the actuating and sensing transducers in repeated tests. With this fixture, a large array of transducers can be simulated with a small number of surface-mounted sources and receivers. The waves are induced and recorded by a pair of identical broadband piezoelectric transducers (Digital Wave B-225), as shown in Fig. 4. An ultrasound gel couplant (Sonotech) is used to improve the transmission of ultrasound. Five-cycle sinusoidal, windowed tone bursts are produced by an arbitrary waveform generator (NI 5402) and are used as the input to the source transducer. A signal conditioner (Digital Wave FM-1) is used to boost and filter the received signals. The input and received signals are digitized and recorded with an oscilloscope (Agilent 54624A). An average over multiple identical measurements is taken in order to increase the signal-to-noise ratio. In the middle of the panel, a disbonds is simulated through the insertion of a release film during the bonding of the top skin and core. The resulting disbondsed area is approximately \( 5 \times 4 \) cm\(^2\). The results from the laboratory experiments are presented in Sec. 4.3.

4 Results

In this section, results from dispersion and wave scattering analyses are presented. In Sec. 4.1, a detailed analysis of the dispersion characteristics of the guided waves is presented. The results from transient FE simulations for the wave scattering at the leading and trailing edge of a disbonds in a sandwich panel are presented in Sec. 4.2. Numerical findings are verified through laboratory experiments, and the results are presented in Sec. 4.3.

4.1 Dispersion. In order to investigate wave scattering at a discontinuity in any waveguide, the dispersion behavior of guided ultrasonic waves in the undamaged and damaged states of the structural component have to be well-understood. Recently, the authors have performed detailed analyses of the dispersion in CFRP sheets and sandwich panels [29,31]. A summary of the latest results is presented here in the context of the wave scattering phenomena.

First, the dispersion behavior of Lamb waves in an undamaged honeycomb sandwich panel, as described in Sec. 2, is presented. The material and geometrical parameters of skins and core are given in Table 1. In Fig. 5, the determined phase and group velocities are shown up to a frequency of 250 kHz. Because of the relatively large thickness of the sandwich panel, higher-order modes appear already at relatively low frequencies. For example, the second antisymmetric wave has a cutoff frequency of about 25 kHz. Hence, signal processing for damage detection is expected to be complex due to the propagation of several modes at higher frequencies that are typically used for NDE. Moreover, one point around \( f = 64 \) kHz is of particular interest since the fundamental symmetric wave \( S_0 \) becomes a nonpropagating wave at this frequency. At higher frequencies, the mode reappears as a propagating wave. Note that the dispersion characteristics of the \( A_0 \) mode have been verified through experiments [29], and the findings are denoted by \( x \) in Fig. 6. In addition to the dispersion curves, the mode shapes of the waves are determined through the application of the WFE method. For both the \( S_0 \) and \( A_0 \) waves, the corresponding mode shapes (displacement fields) are shown in Fig. 6. It can be seen that due to the significant differences in elastic properties of the skin and core materials, the mode shapes are quite different from those found for homogeneous isotropic or
quasi-isotropic plates. Nonetheless, the symmetry and antisymmetry of the modes can be clearly seen from Fig. 6.

If a disbond between one of the CFRP skins and the honeycomb core of a sandwich panel occurs (see Fig. 2(b)), the skin will function as a separate waveguide for Lamb waves. Hence, wave propagation in the woven CFRP face sheet is studied separately. With the material and geometrical parameters given in Table 1, the WFE method is applied assuming transverse isotropy in the woven composite. Note that the analytical solutions for this woven CFRP plate can also be found in the literature [29]. In Fig. 7, the determined dispersion curves for the CFRP face sheet are shown in the same frequency range up to 250 kHz. The group velocity of the antisymmetric wave has been experimentally validated at various frequencies. The results are marked by in Fig. 7. It can be seen that higher-order modes are not present in the considered frequency range. Furthermore, the group velocity of the first symmetric wave at, for example, 100 kHz is much higher than that in the undamaged sandwich panel. Hence, the part of the energy that is propagating as a symmetric wave in the separated face sheet will propagate with much higher velocity, and in turn, will allow for the detection of such damages using ultrasonic NDT. The first antisymmetric wave, on the other hand, propagates at about the same group velocity as in the sandwich panel at this frequency.

In a next step, the honeycomb core is studied together with one CFRP facesheet, which form the segment of the waveguide below a disbond (cf. Fig. 2(b)). The analysis is conducted using identical material and geometrical parameters as for the undamaged sandwich panel (see Table 1). The resulting phase and group velocities are shown in Fig. 8 for frequencies up to 250 kHz. It should be first noted that due to the asymmetry in the waveguide, standard classification into symmetric and antisymmetric Lamb waves is not possible. Compared to the intact sandwich panel, the dispersion characteristics in this waveguide segment show similar overall behavior. However, velocities are different to some extend and higher order modes appear at higher frequencies. While the symmetric wave in the separated woven CFRP face sheet above the disbond differs throughout the entire frequency range, here, clear differences in wave propagation can only be found in certain frequency ranges, in particular for lower frequencies. Hence, the success of ultrasonic NDT of sandwich panels to detect disbonds will strongly depend on the excitation frequency.

A summary of the most relevant group velocities for the analysis of FE simulations and laboratory experiments is given in Table 2. At 50 kHz, the fundamental antisymmetric waves in the damaged region are faster than the antisymmetric wave in the pristine sandwich panel. For 200 kHz excitation frequency, the wave above the defect is faster, while the one propagating below is slower than the one propagating in the pristine panel.

4.2 Wave Scattering. In addition to the investigation of the dispersion behavior in the intact sandwich panel and in the damaged region, in this section, the wave scattering at the leading and trailing edges of the disbond is investigated. To this end, transient numerical simulations are conducted using the FE software ABAQUS, as presented in Sec. 3.
A detailed analysis of these wave scattering phenomena is described in the following. The incident waves are recorded at \( x_1 = 25 \) mm, and are shown in Fig. 11 for both \( f = 50 \) kHz and \( f = 200 \) kHz. In these plots, the signals recorded for the healthy sandwich panel are shown as solid gray lines, and those recorded for the damaged sandwich panel are shown as red dashed lines. The wave amplitudes are normalized with respect to the maximum value of the wave signal recorded in the pristine state. Theoretically predicted arrival times of the corresponding waves are denoted by dotted vertical lines, which are in excellent agreement with the values found from the numerical simulations. As can be seen from Fig. 11(b), virtually no reflection occurs at the leading edge of the disbond, and only the incident waves can be observed, which are identical for both pristine and damaged cases.

In Fig. 12, the wave signals recorded at \( x_1 = 75 \) mm and \( x_1 = 125 \) mm, respectively, are shown for an excitation frequency of \( f = 200 \) kHz. It can be seen that above the damage at \( x_1 = 75 \) mm, the recorded signals differ significantly, and damage detection would be easily possible, i.e., the \( A_0 A_0^b \rightarrow \) wave (damaged) and \( A_0 \rightarrow \) wave (pristine) exhibit significant differences in amplitude and phase. In addition, the signal at the location past the defect, recorded at \( x_1 = 125 \) mm, is also modified due to wave scattering at the defect. In particular, the amplitude is reduced, and due to altered wave velocities in the damaged region, the wave packet arrives slightly earlier than in the pristine state. In both locations, a small \( S_0 \rightarrow \) can be seen to arrive slightly before the \( A_0 \rightarrow \) in the pristine state. This \( S_0 \rightarrow \) is always generated from surface-mounted transducers, however, due to the waves’ small amplitudes and temporal separation from the main wave, these waves are not studied in this work. It can also be seen from Fig. 12 that the maximum amplitudes of the wave signals recorded for the undamaged sandwich panel reduce with increasing travel distance.

In Fig. 9, the wave scattering of an incident Lamb wave at a disbond for \( f = 50 \) kHz is depicted. Time snapshots of the displacement fields (vertical direction) near the damaged region are shown at \( t = 49 \) μs and \( t = 89 \) μs, respectively. It can be seen that the \( A_0 \rightarrow \) incident wave splits into mostly an antisymmetric wave \( A_0 A_0^b \rightarrow \) propagating in the CFRP face sheet above the disbond, as well as an antisymmetric-like wave \( A_0 A_0^b \rightarrow \) below. As explained in Sec. 4.1, these waves have different propagation velocities, and it can be seen that the wave propagating above the defect is slightly faster than the one propagating below.

Another effect that cannot be seen from analyzing dispersion curves alone is shown in the following. If the excitation frequency is increased to \( f = 200 \) kHz, more and more of the wave energy is localized near the surface, as shown in Fig. 10. Snapshots of the displacement fields (vertical direction) near the damaged region are shown at \( t = 35 \) μs and \( t = 50 \) μs, respectively. A Rayleigh-like wave \( R \rightarrow \) splits at the leading edge of the disbond into an antisymmetric wave \( RA_0^b \rightarrow \) propagating above the defect, and a Rayleigh-like \( RR^b \rightarrow \) wave below. Again, due to differences in the propagation velocities, these waves will reach the trailing edge at different times.

### Table 2: Group velocities of the fundamental antisymmetric waves for a pristine and damaged sandwich panel

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>( A_0 \rightarrow ) (pristine) (m/s)</th>
<th>( A_0 A_0^b \rightarrow ) (above) (m/s)</th>
<th>( A_0 A_0^b \rightarrow ) (below) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1333</td>
<td>1385</td>
<td>1379</td>
</tr>
<tr>
<td>200</td>
<td>1519</td>
<td>1535</td>
<td>1506</td>
</tr>
</tbody>
</table>

### Fig. 8: Dispersion curves for the waveguide composed of the honeycomb core and one of the CFRP face sheets of the sandwich panel. Note, due to the asymmetry of the waveguide, standard classification into symmetric and antisymmetric waves is not possible: (a) phase velocity and (b) group velocity.

### Fig. 9: Wave scattering of an incident Lamb wave at the leading edge of a disbond in a composite sandwich panel for \( f = 50 \) kHz (FE simulations): (a) incident wave, \( t = 49 \) μs and (b) waves scattered at leading edge, \( t = 89 \) μs.

### Fig. 10: Wave scattering of an incident Lamb wave at the leading edge of a disbond in a composite sandwich panel for \( f = 200 \) kHz (FE simulations): (a) incident wave, \( t = 35 \) μs and (b) waves scattered at leading edge, \( t = 54 \) μs.
due to dispersion effects [34]. At $x_1 = 75$ mm, the maximum amplitude is reduced to 94.2%, and at $x_1 = 125$ mm to 86.0%, respectively. Hence, a direct evaluation of the scattering coefficients is not possible.

These effects are also very prominent if the excitation frequency is increased to $f = 200$ kHz. The recorded signals at the same locations above ($x_1 = 75$ mm) and after the damage ($x_1 = 125$ mm) are shown in Fig. 13. While the amplitudes of the wave signal recorded above and after the defect are not altered significantly compared to the corresponding waves in the undamaged case, a phase shift can clearly be found between the $A_0 \rightarrow$ wave (damaged) and $R \rightarrow$ waves (pristine), respectively. Hence, from an NDT perspective, the 200 kHz case will also be recognizable by an automated damage detection algorithm. It should also be noted that the maximum amplitude of the wave that is recorded after the damage is higher for the corresponding wave in the pristine case.

A comparison of all conducted transient FE simulations is presented in Fig. 14. Note that the time signals for $f = 100$ kHz and $f = 150$ kHz are omitted for the sake of brevity. In addition to the maximum amplitude of the envelope functions after the defect, the peak arrival time is recorded as well. For the damaged cases, findings from the signal analyses are compared with the theoretical peak arrival times of the waves for $f = 50$ kHz and $f = 200$ kHz, respectively. From Fig. 14(b), it can be seen that dispersion effects distort the wave packets and theoretically predicted arrival times
are slightly different from the ones observed in transient FE simulations. Even though no damping has been modeled, from Fig. 14(a), it can also be seen that dispersion effects lower the amplitudes of the propagating waves in the pristine state. Due to the slight differences in propagation velocities in the damage region, constructive or destructive interference can occur which might lead a decrease or increase in the maximum amplitude compared to the corresponding pristine case. The interference can be correlated with the involved wavelength in relation to the length and depth of the defect. Similar observations have been made in earlier researches [16,25].

4.3 Experimental Verification. In this section, the numerical results are compared to those obtained from laboratory experiments as described in Sec. 3.

The recorded wave signals for \( f = 50 \) kHz are shown in Fig. 15 for the receiver located above the damage (at \( x_1 = 110 \) mm) and after the damage (at \( x_1 = 170 \) mm). Note that the signals are not filtered in any way after the recording through the oscilloscope. Time ranges in the subsequent plots are chosen differently for reasons of clarity only. Observations from the experiments are very similar to those from the FE simulations. Above the damage, the wave is experiencing a significant phase shift. After the damage, a
more subtle change compared to the pristine case can be observed. It can also be observed at both locations that the wave amplitude is significantly reduced compared to the incident wave to whose amplitude the signal have been normalized. This is due to the additional material damping in the sandwich panel. Theoretical predictions of the arrival times of the corresponding waves are again in excellent agreement with the experimental findings. As in the numerical simulations, a second frequency, $f = 200$ kHz, is analyzed in detail for the laboratory experiments. The recorded measurement signals are shown in Fig. 16 for a receiver located above the damage (at $x_1 = 110$ mm) and after the damage (at $x_1 = 170$ mm), respectively. The increased complexity in the signals indicates that multiple waves are induced in the experiment, and signal processing is more involved than for the numerical simulations. For example, a wave of significant amplitude arrives before the main wave packet in the pristine case. This wave is also scattered at the leading edge of the damage, which is why it cannot be seen in the signal for the damaged case. Furthermore, similar phase shifts of the main wave packet can be seen in both signals as well as a significant reduction in amplitude due to the scattering of waves at the damage. While the theoretically predicted arrival times in the pristine and damaged case are very similar, denoted by vertical dotted lines located above the damage (at $x_1 = 11$ cm) and to about 10% at $x_1 = 17$ cm.

5 Conclusion

Through a detailed dispersion analysis, it has been shown that the segments above and below a disbond in a honeycomb sandwich panel guide ultrasonic waves with different characteristics as the undamaged panel. For example, the $S_0$ wave in the CFRP skin propagates at very high velocity, while the $A_0$ wave propagates at only slightly different velocity as the counterpart in the sandwich panel. The asymmetric waveguide below the disbond does not allow for symmetric and antisymmetric guided waves. However, the group velocities of possible guided waves are still very similar to those in the intact sandwich panel. Theoretically predicted arrival times are found to be in excellent agreement with numerical and experimental findings. Furthermore, it has been shown that induced ultrasonic guided waves from surface-mounted transducers strongly depend on the excitation frequency. The results from transient FE simulations revealed a concentration of wave energy near the surface, giving rise to Rayleigh-like waves at higher frequencies. While a defect at the bottom of the sandwich panel would likely not be detected with this Rayleigh-like wave, most damages occur near the outside surfaces due to impacts with foreign objects. However, in a case a damage is suspected in the lower region of the sandwich panel, a lower excitation frequency can be utilized. Most importantly, the scattering of the induced waves at the trailing and leading edges of the disbond can be detected by surface-mounted transducers. It has been shown that above the defect, wave signals are significantly different from those recorded for a sandwich panel in pristine state. In addition, record-ings from transducers after the defect also reveal a difference in the signals, both in arrival time and amplitude. Observations from numerical simulations have been found to be in excellent agreement with laboratory experiments. Even though significant material damping was present in the experiments, a clear distinction between pristine and damaged states is possible. Hence, the detection of a hidden core–skin disbond in complex anisotropic structural components is possible through guided ultrasonic waves that are induced by surface-mounted transducers.

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References


