Application of interface guided waves for structural health monitoring of hybrid bonded joints

Mark Jahanbin
The Boeing Company

E-mail: mark.jahanbin@gmail.com

Abstract. The application of ultrasonic interface guided waves for the inspection of adhesively bonded joints is studied. A thin adhesive layer forms a bond line between the surfaces of distinct structural elements. This work demonstrates the formation of specific ultrasonic guided waves which are propagating on the boundaries of bonded joints and can be used for health monitoring of adhesive bonds. Interface waves are extremely sensitive to changes in elastic and plastic characteristics such as density and viscosity of the adhesive layer. Using finite element simulations, the changes in propagation of wave form, attenuation of leaky interface wave and Time of Flight (TOF) were observed and recorded as a baseline. Then the pervasive effect of bonding failure on these parameters are used for damage detection in adhesive bonded joints. The cohesive damages such as dis-bond and delamination are slowing down interface wave speed depending on size and location, and the adhesive properties also change the Time of Flight of propagating wave. The results of this study show that interface waves can be used to inspect adhesively bonded joints and, possibly, to determine the strength of the bond line and predict the failure mechanisms of bonded structures.

1. Introduction
Metallic–composite hybrid structures in aircraft are often joined using mechanical fasteners. The fasteners add weight, increase localized stress and damage the structure due to drilling, and also add labour and part inventory costs. Total elimination or reduction in the number of fasteners in hybrid joints can reduce cost and weight. Adhesive bonding is emerging as an alternative to mechanical fasteners for joining hybrid structures. Adhesive bonds are already inherent to composite materials at the laminate level where plies are co-cured together. The usage of adhesively bonded hybrid structures with customized mechanical properties and adaptive functional performance is gradually changing the traditional design concept, especially in aerospace structures.

While adhesive joining techniques offer numerous design advantages over conventional joining methods, there is a great reluctance to use adhesive bonding, because it is sensitive to process variables (surface treatment, cure cycle, etc.) and it is not feasible to reliably inspect once the bonding process is completed. The development of a non-destructive technique to assess the quality of a bond has long been recognized to be critical to the acceptance of adhesive bonding as a substitute for conventional fastening techniques in high-strength applications. Regulatory agencies demand the development of repeatable and reliable non-destructive inspection techniques to ensure the strength of the bonded joint [23, 24].

Historically, specific modes of ultrasonic waves, so called interface waves, were introduced by Rayleigh, Stoneley, and Scholte and primarily used in geology for geophysics phenomena such as seismic waves for earthquake measurements. These ultrasonic waves propagate in all directions away
from the excitation source or transducer but are primarily confined to the interface between two distinct media. One possible wave propagating along the interface between two solids is a Stoneley wave [1]. Interface Stoneley waves exist for certain combinations of isotropic media [2]. Claus and Kline first introduced the application of Stoneley-like guided ultrasonic waves for bond inspection [3-5]. Others used the surface and interface wave approach to study the bonding in solid media and adhesive joints [6-9]. Rose introduced a feature mapping approach for bonded joint with the concept of surface waves by usage of angle beam transducers introduced for non-destructive inspection [10] and later Rokhlin used the critical angle beam for assessment of interfacial properties [11]. Rose and Pilarski also introduced the mode conversion of interface wave to surface wave and bonded Lamb wave in weak joint [12]. Since the 1990s many researchers have used interface waves to characterize the quality of bonded joints but the problem of measurements for strength of the bond line remained unsolved [13-23]. Presently, there are no viable damage growth inspection methods in industry to evaluate the bond integrity of adhesively bonded structures and, moreover, certification requires assembly and component proof testing in which the results depend heavily on the coupon configuration.

The method used in this work is versatile and can be used to monitor the structural integrity of composite laminates and adhesively bonded joints in an in-situ manner and throughout the service life of the structure. It utilizes a guided wave mode to inspect the adhesive bond, regardless of topography and through-the-thickness structure of bonded sections.

The fundamentals of ultrasonic guided interface wave are briefly presented in the methodology section. Typical cohesive failure common to bonded joints such as dis-bond crack at free edge and delamination at first plies of the hybrid bonded joint has been explored by the authors [18-19]. In this study the numerical simulation of an adhesively bonded joint with aluminium and composite section is performed using finite element method. Finally, this model is used for different failure scenarios testing, associated with possible adhesion and cohesion damages in bonded joints

2. Methodology

Guided waves are acoustic waves that are guided by boundaries. Depending on the structural geometry, guided waves can either propagate between boundaries, which are known as plate waves (Lamb waves) or propagate on the surface of the object (surface-bonded waves or acoustic surface waves).

2.1. Modelling interface wave at hybrid joints

This section describes the modelling and finite element simulation of hybrid joints and interface wave at the bond line of composite–aluminium section. The benefit of FEM is that it provides the opportunity to understand the physics and possible implications of the results, before constructing the test coupons and experimental studies. The schematic of a hybrid bonded joint is shown in figure 1. The upper section of the model is metallic (aluminium) and the lower section is a laminated CFRP composite with the ply orientation in principal [0, 45, -45, 90, -45, 45, 0] degree orientations stacking sequence.

![Figure1 Schematic of hybrid structure [17](image)](image)

The interfacing bonded ply is called Inner Mould Line or IML and the farthest ply from the interface bond line is Outer Mould Line or OML. The orientation of IML is critical for determination of interface wave speed at the bond line. This configuration replicates situations in which metallic fittings are attached to the composite structure in wing fabrication or in repair circumstances where a composite
patch is used for metallic skin or repairing composite surface with metallic patch. This model also can be used to investigate the bonding condition of two composite sections by changing the metallic section to another laminated or honeycomb composite. In some applications to avoid corrosion between metals and CFRP, layers of different materials might be used at the interfaces, and for composite–composite hybrid interfaces, a layer of adhesive might be used; all can be simulated by introducing a third material or viscous properties of adhesives.

Each lamina in the composite laminate is a single ply with typical ply thickness of 0.2 mm. The interface waves decay away from the bond line so the orientation and thickness of other plies through the thickness of the composite section is not of interest. However, typically the 2nd and 3rd plies play an important role in the interlaminar buckling and delamination damage of the composite section.

The metallic section has dimensions 76.2 x 101.6 mm, while the composite section has dimensions 254 x 101.6 mm. The length of the bond-line is 101.6 mm at the interface of composite and metallic sections. Aluminium is the material used for the metallic section with elastic constants, $E = 69$ GPa, and Poisson’s ratio, $\nu = 0.3$, each ply of the unidirectional composite and has four elastic constants of $E_1 = 137.9$ GPa, $E_2 = 10.3$ GPa, $G_{12} = 6.2$ GPa, and $\nu = 0.34$.

ABAQUS finite element code was used for wave propagation simulation and analysis. Plane strain continuum shell elements were utilized. These elements include the effects of transverse shear deformation, which is critical for studying interface waves. The anisotropic section is built up by composite layup tools to form a balanced, symmetric laminate and all the unidirectional plies are meshed accordingly. A typical mesh had around 520,000 nodes and 520,000 linear quadrilateral two dimensional plane strain (PS4) elements. The model is constrained for translation and rotation at the two upper corners of the metallic section and the two lower corners of the composite section. An excitation source or actuator is placed on the composite section on one side, and a receiving sensor is placed on the other side of bond line. A Hanning-windowed, five-cycle burst of a sinusoidal signal was used as the pulse excitation signal. The initial forcing frequency was set at 1 MHz to model the interface wave. A 10 MHz excitation has also been used to investigate the influence of frequency on the damage identification process.

2.2. Bonded Joint mechanism

The high frequency of interface waves and independence from the through-thickness topology of the structures offers a promising wave mode for the detection of very small Interfacial defects. Dis-bonds and delaminations of hybrid interfaces and localized matrix defects or fibre fracture in laminated composites are among the critical failure modes of these structures. In prior work [19, 20] the application of interface waves for the detection of interlaminar and intralaminar defects in hybrid joints was demonstrated. In reality there is an adhesive layer in between the substrates and coatings that is referred to as the bond line, as shown in figure 2.

![Figure 2. Idealized adhesive bonded joint.](image)

The bonded load path is a chain of material and interfaces that form the adhesive bonded joint. The strength of the bond is determined by the weakest link in this chain. The interface wave frequency of this application can be optimized to the efficient wavelength as explained in reference [20] to cover the entire chain of the bond line such that it can capture any adhesive or cohesive degradation of the elements shown in figure 4. The interface wave travels on the bond line and damage can cause distortion in the path of the traveling waves. If the damage is due to failure of materials, coatings and adhesive, then the
bonding process is probably reliable, but if the failure is due to an anomaly in any of the four interfaces between substrates and coatings or between the coatings and the adhesive the bonding process is not reliable. The latter is the primary focus of the study presented in the following sections.

2.3. Numerical Simulation of Bonded Joint

The physics of interface wave propagation in hybrid structures is considered. The analytical Stoneley wave solution is used to determine the frequency of excitation for the interface. Stoneley-like waves form at the bond line of isotropic and anisotropic media and the mode conversion due to interfacial damages can be used for detection purposes. Numerical simulations have been performed using the Explicit Dynamic solver of the ABAQUS Finite Element code to predict the existence of interface waves and to define their propagation characteristics based on the mechanical properties of the bonded joint and adhesive layer. Interface wave propagation is simulated in the interfaces between laminated Carbon Fibre Reinforced Polymer (CFRP) and aluminium alloy 6061, with HYSOL EA 9394 adhesive in between. Table 1 lists the materials used in this simulation.

| Sections                  | Modulus: \( E, G \) (GPa) | Density, \( \rho \) (g/cm\(^3\)) | Poisson’s ratio, \( \nu \) |
|---------------------------|---------------------------|---------------------------------|-----------------------------|
| Composite ply (CFRP)      | \( E_1 = 137.90 \)        | 1.55                            | 0.34                        |
|                           | \( E_2 = 10.34 \)         |                                 |                             |
|                           | \( G_{12} = 6.89 \)       |                                 |                             |
| Adhesive HYSOL            | \( E = 3.72 \)            | 1.38                            | 0.40                        |
|                           | Viscosity of adhesive: \( 1 \times 10^{-6} \) kPa*s (1 centipoise) |

The Adhesive simulated in this modelling matches the low viscosity adhesive we are using for experimental validation. The adhesive Dexter Corporation’s Hysol EA-9394 is an amine-cured epoxy paste adhesive which can be cured at room temperature. The adhesive has density of 1.38 g/cc, a porosity of about 6% which makes it compatible for post peel ply application to CFRP composite. Hysol has glass transition temperature of 82°C and a coefficient of thermal expansion of approximately 60 x \( 10^{-6} \) oC\(^{-1} \) (between -30o C and 70o C).

Theoretical studies suggest that the interface waves propagate with speeds lower than the lowest speeds of bulk waves in the denser media. The finite element simulation shows that the velocities of the guided waves depend on the frequency of excitation, material orientation, and specific material properties at the interface boundary.

The properties and quality of the adhesive layer can change the velocity of the interface wave. For a hybrid bonded joint with the similar configuration, the approximate velocity of interface wave is about 3 mm/μs, with the assumption of a perfect bond without adhesive layer. The velocity of the interface wave increases due to the presence of the adhesive layer. The wave velocity is the function of surface coating interfaces and the density, viscosity and elastic–plastic deformation of the adhesive layer.

In this work, the reaction of the interface waves to the changes in the bonding interfaces at the bond line of an adhesively bonded joint is investigated. Previously it was shown that the velocity of interface waves decreases as the size of dis-bond cracks and delaminations at the bond line increase. In this study, the focus will be on interface degradation that depends on the bonding process. Therefore, the changes in all elements of the interface such as surface preparations, coating types and adhesive itself have been analysed to evaluate the detection characteristics of interface waves. This work demonstrates the cases in which interface waves are sensitive to bond defects and wave form distortion can be used to detect damage. The density and viscosity changes of interfaces also interfere with the normal wave behaviour. This study is in the most part focused on the interfacial damages to characterize the adhesion defects and predict the possibility of bond failure. Figure 3 (a) shows the wave form attenuation in the vicinity of an adhesive layer with pristine density and modulus properties, and figure 3 (b) shows the attenuation of the same wave form when it encounters a low viscosity adhesive with reduced stiffness.
The detection technique described in the next section, requires further assessment of the interface wave parameters such as reflection, attenuation, and energy dissipation.

![Figure 3](image)

**Figure 3.** (a) Pristine adhesive property – normal wave behaviour (b) Degraded adhesive property – anomalous wave behaviour

3. Damage modelling in adhesively bonded structure

The damage and failure of adhesively bonded joints is fuzzy and complex. It is important to identify and understand the nature and location of failure in a bonded joint and composites. The bonding process and compatibility of material selection with appropriate surface preparation and coatings are primary factors for constructing a good bond. Some other factors such as environmental effects, corrosion, heat damage, fluid ingress and contamination could be considered as secondary causes of failure of adhesive bonds.

In industry, these requirements for the bonded joint are critical to the adhesion failure because they affect bonding process reliability. Any other form of mode I, II, III and mixed fracture modes, which causes cohesive material failure are irrelevant to the bonding process. Hence damage modelling of the bonded joint is focused on the damage nucleation at surface–coating - adhesive interfaces and on the degradation of the adhesive layer itself. The bond region is resin-rich and the reduced stiffness and density of resin-rich area causes the wave velocity to decrease. If the changes in physical and chemical properties of adhesive cause thickness change, then the damage can be detected easily; because it will be visible in the form of skin pull-up, pull-down or wrinkles at the adhesively bonded joint.

The other factor contributing to the defects of adhesive bonds is cohesive failure which might happen separately, in conjunction with or in addition to adhesive failure. The failure at substrates, surface preparations or coating and adhesive itself, which are shown in figure 4, are all cohesive failures. These types of damages are not as much critical as the adhesive failure which are shown as interfaces between bonding chain in figure 4.

![Figure 4](image)

**Figure 4.** Cohesive Failure vs. Adhesive Failure

4. Results

In this section the results of numerical simulations for both adhesive and cohesive type of damages are presented. Damage was simulated in form of drack, delamination and also through adhesive layer
density reduction. Dis-bond of hybrid interfaces, delaminations, and localized matrix defects or fibre fracture in laminated composites are among the critical failure modes of hybrid structures.

For damage simulation, we introduce a dis-bond crack at one free edge of the bonded section (see figure 5) and monitor the disruption in the continuity of interface wave propagation to calculate the delay in time of flight (travel time of interface wave from actuator to receiver). Figure 6 shows the undamaged or perfectly bonded interface as well as some of the different lengths of dis-bond cracks that are considered for this simulation.

Both actuator and sensor are placed on the exposed surface of the composite section. Several different crack sizes are considered ranging from 2.54 mm to 25.4 mm for a 101 mm bond. Simulations were also performed for a pristine undamaged (UD) structure to provide the baseline. The travel time of the propagating wave from the actuator to the receiver is recorded. Wave motion in the x coordinate direction is perceived at a slightly different time than wave motion in the y-direction and hence these two travel times are differentiated. The nominal delay time of recorded displacement in y direction is about 1.5%. The results are presented in figure 7 for four crack simulations. As the size of damage increases the time of travel of the wave pulse increases. The interface wave is faster when the direction of wave propagation aligns with the composite ply direction (i.e. 0°) whereas 90° ply orientation causes the slowing of the interface wave. We observed nominal 5% delay in time of flight for recorded signals at sensor when the fibre orientation is perpendicular to the interface wave travel path on bond line. For both cases, the time of travel appears to be linear with the crack size.

Table 2 and figure 8 show the interface wave velocity change with decrease in density of the adhesive layer. Some factors that contribute to the attenuation of interface wave in degraded adhesive model are absorption and scattering of the wave. In reality, the pervasive effects of chemical and viscous effects are not linear, even though the numerical simulation represents a linear trend on interface wave propagation velocity.

For a typical SHM setup, the baseline is pristine or undamaged condition. Then, the most appropriate signal processing methods are used to detect damage by comparing signal voltage, energy dissipation, velocity, and time of flight, among others. The study reported in this paper did not elaborate on all of these methods and focused mostly on the time of flight, which corresponds to the velocity of wave and mode conversion in case of any damage at the bond line. The low-viscosity adhesive EA 9394 used for simulation and experiments is available with different densities and moduli of elasticity.
Usually, the reasons for adhesive characteristics deterioration are not purely physical, they may be caused by chemical or other factors, such as environmental, that can contribute to degradation of the adhesive bond. The debonding failure occurs in the plastic regime of the adhesive layer. The detection technique requires further assessment of the interface wave parameters such as reflection, attenuation, and energy dissipation. In this study, the extreme change of density magnitude has been used as the most efficient way to build up the model and to verify the effect of lowering the density or viscosity of the adhesive. There was no attempt to replicate effects of moisture/humidity, chemicals, temperature variation, vacuum, radiation, and many of the pre-post bonding effects, such as surface preparation. They may be studied in the future. This work was focused on demonstrating typical and common adhesive and cohesive failures in bonded joints.

This phenomenon is in good agreement with the general equation of wave velocity in solid media where \( V \propto \frac{E}{\rho}^{1/2} \) which confirms the reduction in density is a contributing factor to time of flight.

Table 2. Interface waves Time of Flight (TOF) between points with 101.6 mm distance

| Points | Density Change (g/cm³) | TOF (µs) |
|--------|------------------------|----------|
| UD     | \( \rho = 1.38 \)      | 14.89    |
| D1     | \( \rho = 0.70 \)      | 14.85    |
| D2     | \( \rho = 0.35 \)      | 14.79    |
| D3     | \( \rho = 0.17 \)      | 14.77    |
| D4     | \( \rho = 0.09 \)      | 14.65    |

Figure 7. Travel time for interface wave signal versus the disbond crack size

Figure 8. Change in time of flight of interface wave with adhesive density reduction
decrease or velocity increase. Another factor to characterize adhesive bond quality is the energy method and the measurement of the energy dissipated per unit volume by viscous effects, i.e., the EVDDEN factor, which is an output in finite element analysis. The interface energy is confined to the region near the boundary. The energy method is more reliable compared to the time-of-flight measurement and attenuation. For instance, TOF monitoring is tedious and needs very accurate instrumentation for small size test coupons. The measurement of attenuation might also not be preferred because it is difficult to consistently identify the attenuation due to leakage when there are other causes for loss of energy in measurement.

Previous studies have found that the distribution of the energy of the interface waves above and below the interface changes repeatedly with propagation distance due to interference between the two modes which have slightly different phase velocities. The pervasive effect of cohesive failure on interface wave is very similar to that demonstrated by the studies on dis-bonds and delaminations. The high frequency interface wave is typically effective within the range of bonding construction which is less than one wavelength. Hence, if there is any discontinuity in the pathway of the traveling wave, the wave behaviour, such as the time of flight, changes and the effects change linearly with the size and location of the discontinuity.

Figures 9 (a) and (b) shows the scattering of interface waves due to a cohesive damage crack at the free edge on the left. This dis-bond and delamination at the interface of the coating and the adhesive causes a Stoneley to Rayleigh wave mode conversion plate like Lamb wave formation at upper or lower bond of adhesive layer. Either case will change the slowness profile of the interface wave and reduction in wave form velocity.

The results of these modelling techniques and damage simulations might be of particular interest for the development of experimental test setups and the basic idea of actuator – sensor placement for a novel pitch–catch ultrasonic structural health monitoring system, designed for laminated and hybrid structures.

![Figure 9](image-url)

**Figure 9.** (a) Undamaged adhesive bond, (b) Damaged cohesive bond

5. Conclusion

This research is devoted to the use of a Structural Health Monitoring (SHM) system to assess the quality of adhesive bonds between two materials, by measuring the propagation of ultrasonic interface waves through the adhesive, guided by the physical interface between the materials and the adhesive. Anomalies in interface waves generated by an ultrasonic signal applied to the bonded materials are a mixture of wave effects resulting from differences in velocity, phase, and amplitude, originating from differences in material viscosity, density, thickness, continuity, and specifically differences at the physical boundaries between materials.

This research summarizes the results of investigating the following measurable aspects to differentiate good bonds from bad bonds. First, wave velocity (wave-front time-of-flight over a given distance) is measured. Second, wave attenuation (diminishing amplitude over a known distance due to absorption and scattering of the interface wave) and third, the wave energy dissipation (diminishing
amplitude integral over a known distance due to absorption and scattering of the interface wave). The results of this study may lead to the development of a repeatable and reliable inspection method for the assessment of adhesively bonded joints.

References
[1] Stoneley R 1924 Elastic waves at the surface of separation of two solids Proc. Roy. Soc. London A 106 416–28
[2] Scholte G 1947 The range of existence of Rayleigh and Stoneley waves Geophys. Suppl. MNRAS 5(5) 120–6
[3] Claus R O and Kline R A 1979 Adhesive bondline interrogation using Stoneley wave methods J Appl. Phys. 50(12) 8066–9
[4] Claus R O 1980 Optical Measurements of Ultrasonic Waves on Interfaces Between Bonded Solids IEEE Trans. Sonics Ultrasonics 27(3) 97–102.
[5] Claus R O 1980 Surface and near-surface defects in glass-to-glass bonds” Proc. SPIE Int. Soc. Opt. Eng. 250 38–44
[6] Kumar V and Murty G S 1982 Influence of External Pressure on Interfacial Wave Propagation at a Loosely Bonded Solid-Solid Interface” IEEE Trans. Sonics Ultrasonics 29(3) 138–42
[7] Rokhlin S I 1983 An ultrasonic bridge for the study of viscoelastic properties of thin interface films J. Acoust. Soc. Am. 73(5) 1619–23
[8] Kumar V 1983 Attenuation and velocity of waves propagating along a steel-steel interface J. Appl. Phys. 54(2) 1141–3.
[9] Yew C H 1984 Using ultrasonic SH waves to estimate the quality of adhesive bonds: A preliminary study J. Acoust. Soc. Am. 76(2) 525–31
[10] Rose J L, Nestleroth J B and Balasubramaniam K 1988 Utility of feature mapping in ultrasonic NDE Ultrasonics 26(3) 124–31.
[11] Wang W and Rokhlin S I 1991 Evaluation of interfacial properties in adhesive joints of aluminum alloys using angle-beam ultrasonic spectroscopy J. Adhes. Sci. Technol. 5(8) 647–66.
[12] Pilarski A and Rose J L 1992 Lamb wave mode selection concepts for interfacial weakness analysis J. Nondestr. Eval. 11 237–49
[13] Hsieh T M and Rosen M 1993 Ultrasonic leaky waves for non-destructive interface characterization Ultrasonics 31(1) 45–52
[14] Singher L, Segal Y, Segal E and Shamir J 1994 Considerations in bond strength evaluation by ultrasonic guided waves J. Acoust. Soc. Am. 96(4) 2497–505
[15] Lowe M J S and Cawley P 1994 The applicability of plate wave techniques for the inspection of adhesive and diffusion bonded joints J. Nondestr. Eval. 13(4) 185–200
[16] Singher L 1997 Bond strength measurement by ultrasonic guided waves Ultrasonics 35(4) 305–15
[17] Vine K, Cawley P and Kinloch A J 2001 The correlation of NDT measurements and toughness changes in adhesive joints during environmental attack J. Adhes. 77(2) 125–61
[18] Jahanbin M, Santhanam S and Ihn J-B 2016 Interface Waves in Hybrid Metal-Composite Structures ASME 2016 SMASIS2016-9007 1 V001T05A002
[19] Jahanbin M, Santhanam S, Ihn J-B, Bossi R and Cox A 2017 Application of Interface Waves for near surface damage detection in hybrid structures 10169-96_ProcSPIE_SS17-SSN08-35
[20] Wang H, Han Q-B and Qian M-L 2012 Leaky interface wave measurement at a solid-solid interface with laser ultrasonics Chinese Physics Letters 29.10.104304
[21] Qingbang H and Hao W 2014 Laser-induced interface waves at solid/solid interface AIP Conf. Proc. 1581(33) 437–43
[22] Cho H and Rokhlin S I 2015 Interface wave propagation and edge conversion at a low stiffness interphase layer between two solids: A numerical study Ultrasonics 62 213–22