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Bondline Boundary Assessment of Cohesive Bonded Solid Woven Carbon Fiber Composites Using Advanced Diagnostic Methods

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Abstract. Composites are multilayered, anisotropic materials both on the microscopic and macroscopic scale. They are commonly made by curing weaves stacked in predefined layers and then are bonded to another composite or a metallic structure. The sequence of stacking composite layers is a function of manufacturing capabilities and design parameters. Ply layups can be produced manually or with mechanized machinery. Defects such as resin starvation, foreign material, improper surface preparation or disbonds within the composite or at the bond interface have a degrading effect on the final product performance. Resins contained in the composite's matrix help maintain the structural integrity of the ply and allows structural loads to be transferred between each layer. The condition of a bond can only be ensured with an inspection method that detects and characterizes the properties of the composite and composite-to-metal interface. This paper explores advanced diagnostic methods to evaluate the composite material and adhesive bondline as well as documents wave scattering through the composite interfaces. In addition to investigating traditional contact and immersion techniques, phased array techniques will be discussed. Finally, a summary of the detection and analysis techniques developed to identify disbonds are presented.

Introduction

Carbon fibre reinforced laminated composites are anisotropic materials composed of several plys, or layers, of carbon fibre fabric surrounded by a polymeric matrix. The orientation of each ply in the laminated composite directly affects the properties of the final, as-processed part. Manufacturing methods include wet lay-up and vacuum assisted resin transfer method (VARTM); however, the use of carbon fibre fabric pre-impregnated with resin (also called pre-preg) in combination with an autoclave is one of the more common of the manufacturing methods. Defects, such as fibre misalignment and voids, negatively impact the quality and strength of the part. When designing the part, the presence of such defects should be considered for a variety of locations, sizes and geometries. For example, a spherical void in the middle of the part would likely affect the strength of the part differently compared to an elliptical void near the edge of the part.

Although the fibres within a laminated composite provide the majority of the strength, the polymer matrix bonding the plys together is what maintains the structural integrity of the laminate as a whole. Furthermore, the polymer matrix can serve as an adhesive when co-curing another structure to the laminated composite. In general, the two main approaches to manufacturing a fibre reinforced laminated composite are pre-cure and co-cure. When using a pre-cure method, the laminate is cured and then bonded to the other assembly. The co-cure technique involves curing the composite laminate directly onto the next part of the assembly. When the laminate is fully cured, the entire assembly is complete because the polymer matrix served as the binding agent between the two materials. One example, which is used in this study, is a carbon fibre reinforced laminated composite co-cured to an aluminium plate. Both of these methods can produce defects within the part, such as porosity within the polymer matrix and voids at the bondline. Also, the mismatch in the coefficient of thermal expansion between the fibres, polymer matrix and aluminium can also produce undesirable defects or discontinuities [1].

The bondline between a laminated composite and a metallic structure needs to be evaluated post-assembly to ensure its quality. The method used to evaluate the bond must be able to identify and characterize the properties of the interface between the composite and the metallic structure. Several ultrasonic methods have been developed for the characterization of composites and bonds, but the accuracy and reliability of these methods are hampered by the attenuation and scatter experienced by the ultrasound wave as it travels through the orthotropic, nonhomogeneous composite laminate that sits between the probe and the composite-to-metal interface.

Ultrasonic techniques are important inspection methods to consider when developing and evaluating new composite designs. These techniques are capable of identifying and characterizing defects within the assembly and measuring sound velocities. Using the measured sound velocities, the material constants associated with the composite can then be calculated [2]. To assist with the inspection process and guarantee a good quality part, the reinforcement material (in this case carbon fibre fabric) needs to be laid flat during the manufacturing process to avoid the formation of wrinkles within the part. The presence of wrinkles within the material traps air within the part, which affects the properties and quality of the final part. To reduce the number of voids within the part, the composite laminate should remain under vacuum throughout the elevated temperature and pressure cure cycle [1]. As the temperature in the autoclave increases, the viscosity of the resin matrix decreases and the void pressure remains high. When the resin matrix reaches its minimum viscosity, the autoclave pressure is applied to remove the voids. If the autoclave pressure were applied prior to the minimum viscosity, the voids would be trapped within the matrix. Throughout the cure cycle, the resin matrix experiences three different stages. First, the matrix is in the free fluid migration stage where it is heated to its glass transition temperature and is in liquid form. Next, the matrix enters the polymerization stage. In this stage, the autoclave pressure is introduced and the resin matrix begins curing and forming linked chains. As the links form, they begin linking between the plys creating a three dimensional matrix around the reinforcing material. This linking between the ply layers is also referred to as cross-linking and takes place in the third stage called the hardening stage.

1. Wave Scattering Theory

A variety of ultrasound methods using preselected incident angles have been developed for the inspection of composite materials [2-5]. Ultrasonic spectroscopy is used to optimize the inspection techniques for characterizing the bondline between two materials. The elastic wave passes through the material and the complex structure of the fibre reinforced laminated composite. The amount of scatter experienced by the wave is dependent on both the frequency and the mode conversion type. Characterization of the bondline can be affected by other factors, such as surface texture of the composite (may have random or periodic roughness), ply orientation, concentrated areas of the resin matrix, and the thickness of the fibre reinforced laminated composite. As the ultrasound wave approaches the bondline between two dissimilar materials, in this case the interface between the composite laminate and aluminium, the frequency contains details related to the evaluation of the bond. The acoustic scatter's dependence on the incident angle is characterized by the longitudinal, shear and surface waves. The fibres within the laminates used in this study are assumed to be perfectly bonded to the resin matrix.

Wave scatter theory is based on elastic isotropic materials. This theory applies well to metals where the material is considered homogeneous. For example, the lattice structure of aluminium scatters a sound wave according to the size and orientation of the grains within the material. The amount of signal absorption is related to the metal's thermal conductivity. Composite laminates, which are anisotropic, are different from the isotropic metals when it comes to how they interact with the ultrasound wave. Both the wave scatter and attenuation within a composite laminate are dependent on the orientation of each ply within the laminate. The signal absorption due to the composite laminate is related to the viscosity of the resin matrix and its relation to the adhesive bonds. In addition to the material being inspected, the frequency of the probe also affects the wave scattering and attenuation. In general, the peak of wave scattering is assumed to occur at the interface between two materials. The thickness of the composite laminate and the attenuation experienced by the acoustic wave as it travels to the composite-to-metal bondline are key components when considering wave scatter in this study. The acoustic impedance mismatch between the composite laminate and the aluminium is highlighted as the probe frequency is increased. When the porosity volume fraction is between 0.2 and 0.4 percent, Reynolds and Wilkinson [6] found that it is directly proportional to the attenuation slope. When a compression wave travels through a composite material, the points within the composite experiencing compression also experience an increase in temperature. The rate at which the heat spreads outward from this area is related to the composite's emissivity. The signal absorption experienced within the resin matrix is proportional to the probe frequency squared [7].

2. Velocity Dispersion

The wave velocity measured through dispersive materials is dependent on the chosen probe frequency. In dispersive materials, such as carbon fibre composites, the phase velocity is not the same as the group velocity. The phase velocity (v_p) represents the time it takes a sinusoidal wave to travel through the material at a specific frequency, and the group velocity (v_g) represents the time it takes the peak amplitude of an ultrasonic signal to travel through the material. Equation 1 shows how to relate the phase velocity to the group velocity via the material's dispersive properties [8].

$$v_g = v_p + f \frac{\delta v_p}{\delta f} \quad (1)$$

A variety of ultrasonic methods have been developed for inspecting a metal-to-composite bondline [9-11]. Studies have shown that the strength of the bondline is dependent on the cohesive strength of the resin matrix as well as the adhesive strength of bond between the metal component and the polymer [12-15]. When evaluating a composite-to-metal bondline from the composite side, the time delay of the ultrasound signal is different for these two acoustic paths. Proper placement of the receiving probe produces the best results.

3. Sample Design

Aluminium stock (6.35 mm) was machined with two steps (5.41 and 4.57 mm). These dimensions will allow for a 4, 8 and 12 ply laminate, respectively, to be placed on top of the aluminium and still maintain a near flat surface on both sides of the test specimen. The flat surface on both sides allows for a similar inspection surface when evaluating a composite-to-metal bondline and a metal-to-composite bondline.

Two samples were inspected during this study. Both samples used eight-harness satin woven carbon fibre material as the reinforcement material in the laminate. The first sample was manufactured using the co-cure method described in an earlier section of this paper and had dimensions of 10.16 cm by 30.48 cm. The second sample was manufactured using a pre-cure method, which allowed different types of bonding or coupling materials to be studied. Figure 1 has a diagram of the side view of the test sample and an image of the end of the sample, which highlights the wave-like texture of the carbon fibre material.

Fig. 1. Specimens are constructed of carbon fiber reinforced plastic (CFRP) [4 ply $[0/90]_{2}]_{s}$ 8 ply $[0/90]_{4}]_{s}$ and 12 ply $[0/90]_{6}]_{s}$ preimpregnated 8 harness-satin weave with UF3352 TCR™ Resin

4. Bondline Detection with Conventional Ultrasonics

An ultrasonic probe emits an acoustic wave, the frequency of which is chosen based on the application, into the sample being inspected. The signal's backwall echo is then used for evaluating the material's response to the input acoustic wave. For example, the presence of cracks, voids and pores affect the signal's travel path by varying the amplitude and phase of the echo. The acoustic wavefront propagates through the material of interest by exerting stress on surrounding particles in the sample. The elastic properties of the sample, in this case a carbon fibre reinforced laminated composite, restrict this motion at the atomic level. The stresses exerted on the atoms by the acoustic wave causes the atoms to move, and as the atoms move, the wave continues to propagate through the thickness of the sample as a plane wave. The majority of ultrasound inspections using a contact transducer method have an incident angle that is normal relative to the sample surface, and in that configuration, the anisotropic nature of the material may be neglected.

When inspecting carbon fibre reinforced laminated composites, there are two primary ultrasound methods that may be used: through transmission and pulse echo. The through transmission technique captures the signal loss after the wave has travelled through the thickness of the sample. The pulse echo method is used to identify variations in the backwall signal, variations in signal amplitude and differences in time of flight measurements between different points in the inspection area. Selection of the appropriate probe frequency is important when inspecting carbon fibre reinforced laminated composites. Since the fibres within the material scatter the acoustic wave and the resin matrix tends to absorb the wave, high frequency probes, such as 15 MHz, will only be able to inspect thin composite laminates, whereas a lower frequency probe, such as 5 MHz will be able to inspect a thicker composite laminate.

During the inspection, an ultrasonic pulse (a longitudinal wave) exits the probe and enters the sample surface. The wave front propagates through the part until it approaches a different acoustic medium (void, crack or bondline), and a reflective wave is returned toward the probe where it is collected. The signal is then amplified and shown to the user on a display screen. Usually an inspection area is of interest rather than a single point, and the results for the area can be raster-scanned and shown to the user. By evaluating the results for area of interest, the user can identify differences in the signal, which can then be used to locate defects or bondlines in the part.

When evaluating a bondline, the refraction and mode conversion of the wave at non-perpendicular interfaces can be challenging to evaluate. While the acoustic pressure wave propagates through the first material, it encounters a material boundary (the bondline). At the bondline, part of the acoustic wave reflects back toward the probe, a portion of the wave is reflected away from the probe and a portion of the wave is transmitted into the second material. Snell's Law is the fundamental equation that describes this wave separation at an interface between two materials. Figures 2 and 5 include diagrams of the configuration used with the contact transducer method. Figure 2 has the probe in contact with the aluminium side while Figure 5 has the probe in contact with the composite side. Figures 3 and 6 include typical A-scans and power spectral density plots that would be observed while inspecting unbonded locations, and Figures 4 and 7 present the A-scans and power spectral density plots for a bonded location.

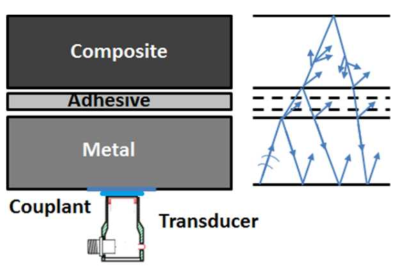

Fig. 2. Typical acoustic wave scatter through metal and composite material.

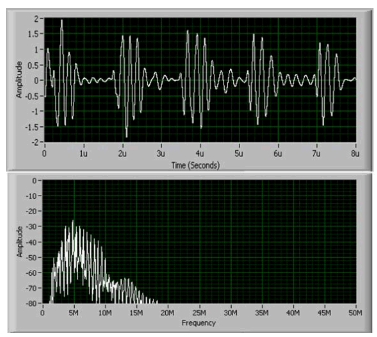

Fig. 3. The response of a 5 MHz probe (metal composite contact only, no adhesive couplant).

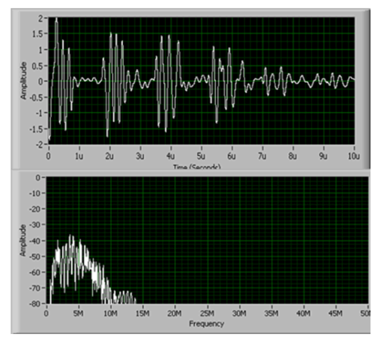

Fig. 4. The response of a 5 MHz probe (metal, adhesive couplant and composite contact).

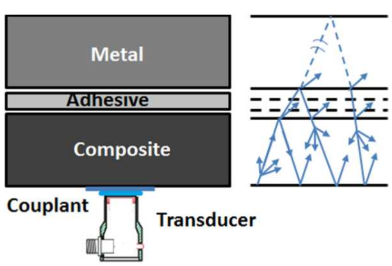

Fig. 5. Typical acoustic wave scatter through composite and metal.

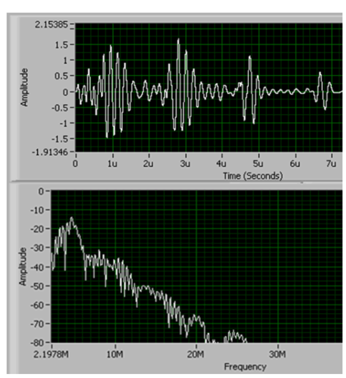

Fig. 6. The response of a 5 MHz probe on an unbonded composite (composite metal contact only, no adhesive couplant).

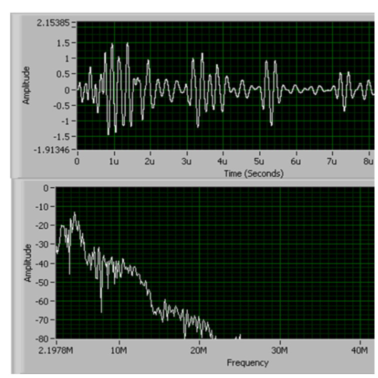

Fig. 7. The response of a 5 MHz probe on a bonded composite (composite, adhesive couplant and metal contact).

Bondline Detection Using Immersion and Advanced Diagnostic Techniques

5.1 Immersion Technique

While using an immersion technique, both the sample and the probe are placed in a container filled with water, and the water acts as a couplant between the probe and the sample surface. This configuration also allows for improved mobility of the probe while performing a C-scan inspection while simultaneously keeping the probe acoustically coupled to the part at all times. One of the disadvantages of using an immersion technique is the sample may be submerged for an extended period of time and may begin absorbing water. In this study, a pulse-echo technique was performed to capture the intensity of the scattered acoustic wave signal as the probe is moved across the inspection area. The high incidence angle allows the reflection from the interface to become diffuse and attenuated. When the wave passes through the bondline between the two materials its amplitude decreases, and this loss in signal energy may be attributed to both geometric effects (beam spread) and intrinsic effects (interactions between the wave and the material). The results obtained from the inspection of the aluminium-to-composite interface and the composite-to-aluminium interface are presented in Figures 8 and 9, respectively. Both of these figures include an A, B and C-scan obtained from the inspection results, and the A-scan coincides with the point highlighted by the intersecting red lines in the C-scan.

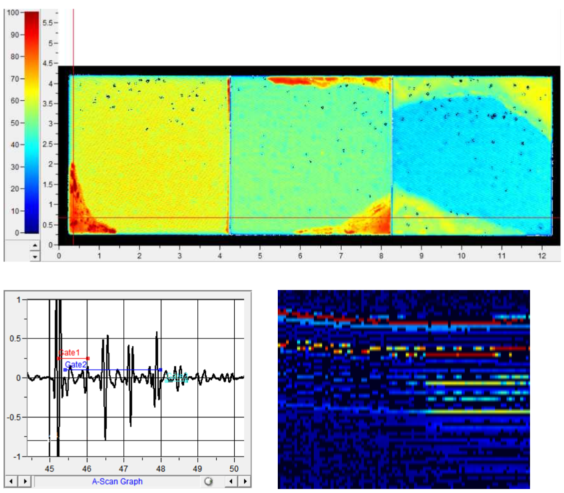

Fig. 8. C-scan, A-scan and B-scan displays of the aluminium to composite interface disbond.

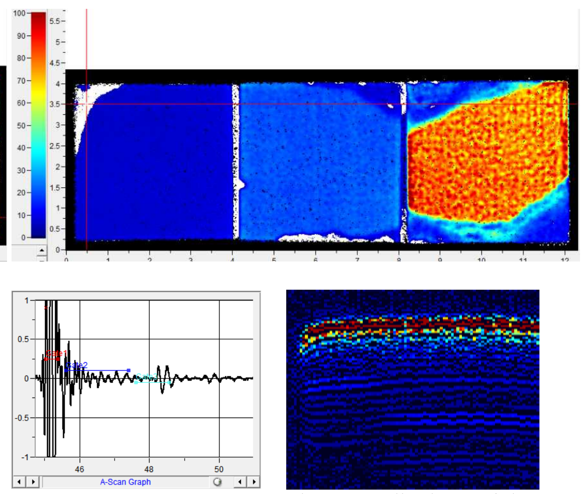

Fig. 9. C-scan, A-scan and B-scan displays of the composite to aluminium interface disbond.

5.2 Phased Array Technique

Phased array (PA) probes are comprised of many small piezoelectric elements embedded into a polymer base material. Each ultrasonic element is individually wired (connector, time delay circuit, and A/D converter) and is acoustically isolated from the other elements. The elements can then be pulsed in groups with pre-calculated time delays for each element (phasing). These individual delays can be tracked and measured for each element or a group of elements. This delay also allows the ultrasonic beam to be steered and focused. This steering permits multiple beam components to combine with each other and form a single wave front traveling out of the probe in the desired direction. The A-scan signal height is usually the grading criteria for bondline acceptance. While using phased array technology, the inspector must pay attention not only to the presented A-scan display, but the inspector must also review the entire data set before determining if the bondline is acceptable. This is due to the fact that only one aperture (group of defined elements) can be displayed (A-scan format) on the screen at a time.

One advantage of a phased array probe is that the data can be corrected for an intended refracted angle. The sectorial scan has the ability to move the acoustic beam along the axis of the array without any probe movement from the inspector. The beam movement is performed by the ultrasonic instrument time circuit for the active elements. Wave fronts will then combine (constructive and destructive interference) into a single primary inspection wave that reflects off cracks, discontinuities, back walls, and other material boundaries. The major difference in phased array and conventional ultrasonics is the final screen presentation. Figures 10 and 11 display a screen snap shot of a good and bad bondline, respectively.

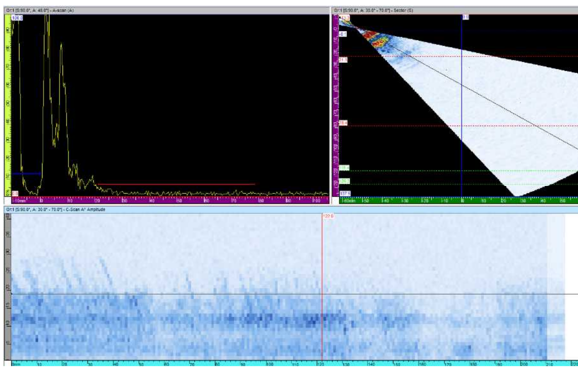

Figure 10. A-scan, S-scan and C-scan display of an aluminium-to-composite bonded interface.

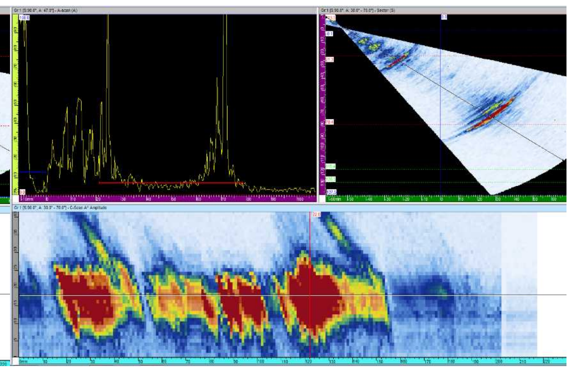

Figure 11. A-scan, S-scan and C-scan display of an aluminium-to-unbonded composite interface.

6. Data Analysis to Characterize Bondline

A lower probe frequency assists in eliminating a large amount of signal attenuation within the composite laminate material. A through transmission method is usually applied in situations requiring identification of delaminations, voids and regions of resin that are not fully cured. Although these types of defects negatively impact the signal attenuation, the factors inherent to the laminate that most effect the signal attenuation are the surface roughness and the weave pattern of the reinforcing material used in the laminate.

Results from this study indicate that the time of flight data is the most helpful when detecting the quality of the bondline in these samples. The accuracy associated with the inspection of the bondline interface relies on the consistency of the ultrasonic signal and the observed differences in the measured velocity between a purely bonded and an unbonded sample. For optimal results, an A-scan of a bonded region is used as a reference comparison when evaluating all other signals in a data set. Amplitude comparisons between the reference signal and each of the remaining signals are most common. Within the composite laminate, the difference between the individual ply layers contributes the most to the variations in the elastic properties of the sample, and areas of non-uniform resin are typical sources of variations in the ultrasound signal.

7. Conclusions

The scattering of an ultrasound signal at the bondline between a composite laminate and an aluminium plate was evaluated using a variety of non-destructive testing techniques including contact, immersion and phased array methodologies. When the fibre reinforced laminated composite is adequately thin (less than eight plys), these acoustic wave techniques are capable of characterizing the bondline between the two materials. Adhesive bonds between the metal and the composite laminate can be identified using both conventional and advanced ultrasonic techniques. In this study, a comparison was made between the pulse-echo signal at the interface when the acoustic wave experienced a metal-to-composite path as well as a composite-to-metal path.

Although the methods described in this study are able to identify many of the common discontinuities in composite laminates, the reliability of the inspection is dependent on the material properties and the surface roughness of the sample. When inspecting a composite laminate, the significance of signal attenuation must be understood.

Relating the strength of a bond to the ultrasonic signal is challenging since the strength of the bond is a structural parameter rather than a physical property. The objective of the methods used in this study was not to identify the weakest area of a bondline. Rather, the objective was to develop an improved understanding of the characteristics associated with adhesively bonded interfaces via ultrasonic inspection methods in an effort to improve the safety and reliability of designs involving a composite laminate bonded to a metal.

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