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Inspection of Adhesively Bonded Joints Using Ultrasonic Guided Waves

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Abstract

Adhesives are used to join some critical structural parts of aircraft, for example, the wing panel. The inspection of such joints, to detect degradation in the adhesive and the bond line is critical to ensure the operational safety of aircraft. Ultrasonic guided waves provide an effective tool for non-destructive inspection. Guided waves have a multi-modal nature which permits stress wave energy to be directed to any point in the structure and over a long distance. A theoretical study for understanding the ultrasonic guided wave propagation characteristics through an adhesively bonded lap joint can help us in the identification of physical features to guide inspection. With the use of a hybrid analytical method and a numerical approach, guided wave reflection and transmission through an adhesively bonded lap joint with interfacial and cohesive weakness was studied. The analytical method helps select a suitable guided wave mode and the numerical method provides a benchmark/visualization with which the experimental results can be compared.

Keywords: Adhesive bond, ultrasonic guided wave, guided wave reflection and transmission, joints

1. Introduction

Adhesive joints are used to join structural elements in aircraft. Compared to the conventional structural joining techniques such as bolting, riveting and welding, adhesive joints minimize stress concentration and fatigue problems. Adhesive joints are susceptible to environmental degradation and hence it is imperative to use methods of inspection which provide information on these structural joints. Ultrasonic non-destructive evaluation provides an attractive choice in this regard since the propagation of ultrasonic waves are dependent on the mechanical properties of the system.

As noted by Rose [1], the early literature on the inspection of adhesive joints is based on the use of ultrasonic bulk waves. One of the most prominent results in this context is the use of shear wave energy introduced using shear transducers or oblique insonification for detecting the cohesive or adhesive weakness in adhesive joints [2]. Since an ultrasonic guided wave is the result of interference between longitudinal and shear waves, it can introduce shear at the interfacial region in addition to being able to propagate longer distances [3-7].

A step-lap joint is one of the simplest adhesive joint configurations. It still involves transition from a single material waveguide to a layered structure and back to a single material waveguide even with isotropic materials. In order to understand the propagation of ultrasonic guided waves, geometric dispersion is studied. Researchers have studied the energy reflection and transmission at geometric transitions using the finite element method [5], a global-local finite element method [6] and semi-analytical approaches [7]. In our previous study [8], the sensitivity of reflection factor to the changes in adhesive material was noted. Since the reflected wave does not interrogate the entire length of adhesive, a transmission based approach is being considered in this paper.

In this study, an amplitude transmission factor, computed by normalizing the spectrum of the transmitted wave is used. A hybrid-analytical framework, based on the orthogonality of guided wave modes [9, 10] is used to calculate the energy amplitude transmission factor for a bonded joint with simulated adhesive and cohesive weaknesses. Numerical validation is performed using an explicit finite element solution implemented in ABAQUS, a commercial solver. The results from studies on an isotropic lap joint are presented in this paper.

2. Formulation of guided wave based approach for inspection of joints

Ultrasonic waves undergo multiple reflections and mode conversions within waveguides like a plate. Interference among these waves results in the formation of guided waves possessing unique geometric dispersion phenomena, or variation in wave velocity as a function of frequency, characteristic to the waveguide [1].

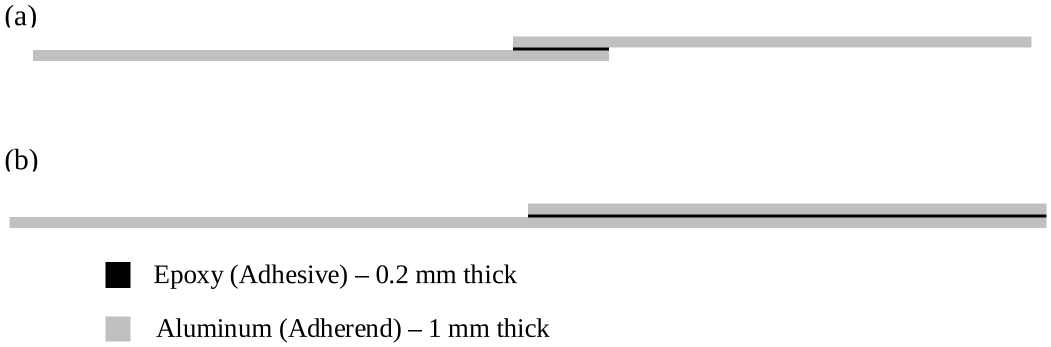

Figure 1. Geometry of (a) an actual adhesive step-lap joint and (b) a step-lap joint used in this study.

The figure 1(a) shows the geometry of an adhesive step-lap joint. A step-lap joint involves a transition from a single layer structure (aluminum) to a three layer structure (aluminum-epoxy-aluminum) and back to a single layer structure (aluminum). In this study, we are considering an infinitely long overlap length in the adhesive joint, as shown in figure 1(b), to understand the excitation of guided waves within a three layered structure from a single layer structure. The lap-joint considered here has a geometry transition from a 1 mm thick aluminum plate to a bonded structure comprised of two 1 mm thick aluminum plates bonded with an epoxy, as shown in figure 1(b).

In order to efficiently transfer energy across the geometric transition, a region of maximum overlap between the superposed dispersion curves (Figure 2) was considered. For the waveguide dimensions specified in figure 1, in the frequency range of 350 kHz, there is good overlap between the dispersion curves of the aluminum and epoxy bonded aluminum structures. Hence, we use a frequency range centered at 350 kHz for this study.

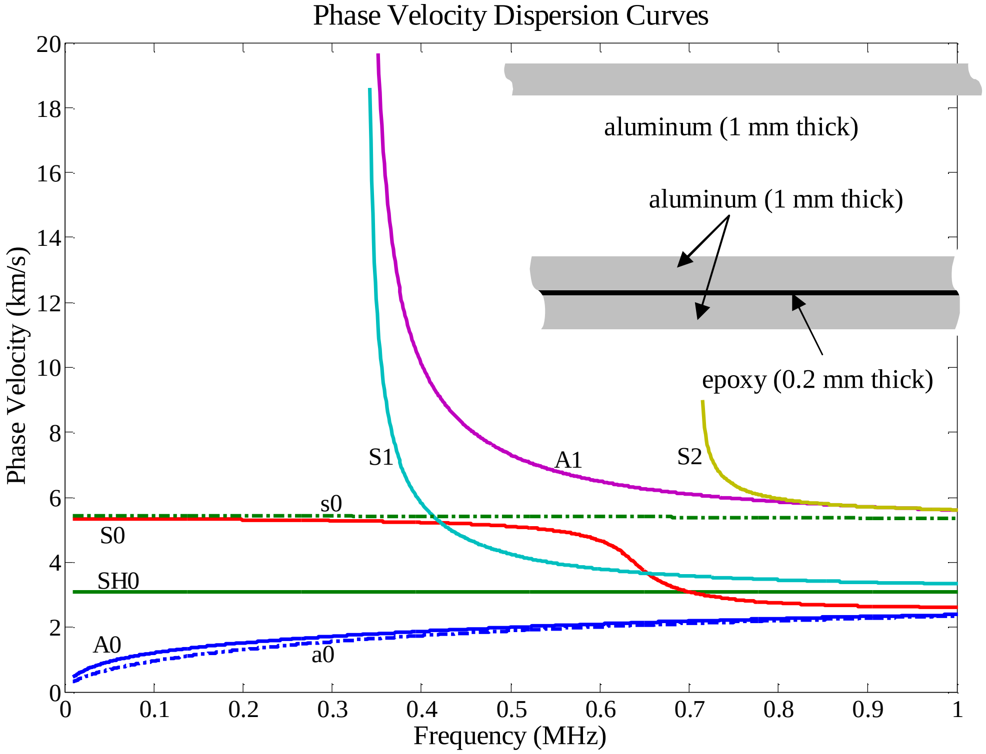

Figure 2. Dispersion curves for a 1 mm thick aluminum plate (dashed line) and for a bonded aluminum (1 mm)-epoxy (0.2 mm)-aluminum plate (1 mm) (solid line) superimposed. The guided wave modes are shown labeled with smaller case for those of aluminum and upper case for bonded aluminum.

Two approaches used to study the guided wave energy reflection/transmission across the geometry transition in a step lap joint are briefly described in the following sections.

2.1 Hybrid Analytical Method

A hybrid-analytical method [8, 10] was developed to study the effect of change in geometry and material on the ultrasonic guided wave propagation in an adhesively bonded joint. The hybrid-analytical framework considers a 2D plane strain problem. The procedure adopted for solution is described as:

a) Eigen-solutions for a waveguide provide the phase velocity of the wave modes – both propagating and evanescent, that can exist at a given frequency.
b) Using the principle of orthogonality of guided wave modes, a normal mode expansion (NME) is carried out to express the displacements in terms of all the possible modes existing in both the aluminum plate and the lap joint geometry. The coefficients for the wave modes in the NME are the unknowns to be determined.
c) A single wave incidence is simulated by imposing the appropriate wave structure (or cross-sectional displacement distribution) at the geometry transition. A solution for the unknown coefficients is obtained by imposing the stress and displacement continuity at the geometry transition.
d) The energy partition between the guided wave modes is made possible by using the

NME coefficients. An energy conservation based check ensures the convergence of the solution.

2.2 Finite Element Method

In order to numerically simulate the wave propagation across an adhesively bonded joint, a 2-D plane strain model of the joint (figure 1(b)) was made using ABAQUS, a commercial Finite Element (FE) package. The geometry was discretized using continuum plane strain elements with a linear dimension equaling a tenth of the wavelength of the dominant wave mode in the waveguide. An explicit time marching algorithm available in ABAQUS was used to obtain the solution to the wave propagation problem. The s0 wave mode at 350 kHz was excited within the aluminum layer by using input displacement matching the wave-structure of the mode. A three cycle Hanning windowed input pulse was used for the displacement.

Figure 3 shows the snapshots of the s0 mode propagation through the aluminum layer into the epoxy bonded aluminum joint, obtained from FE solution. The reflected and transmitted modes can be clearly seen in figure 3. The reflected modes being separated in time are identified individually. The transmitted modes cannot be distinguished from the snapshot. In order to identify the transmitted modes from the FE solution, some signal processing techniques have been applied.

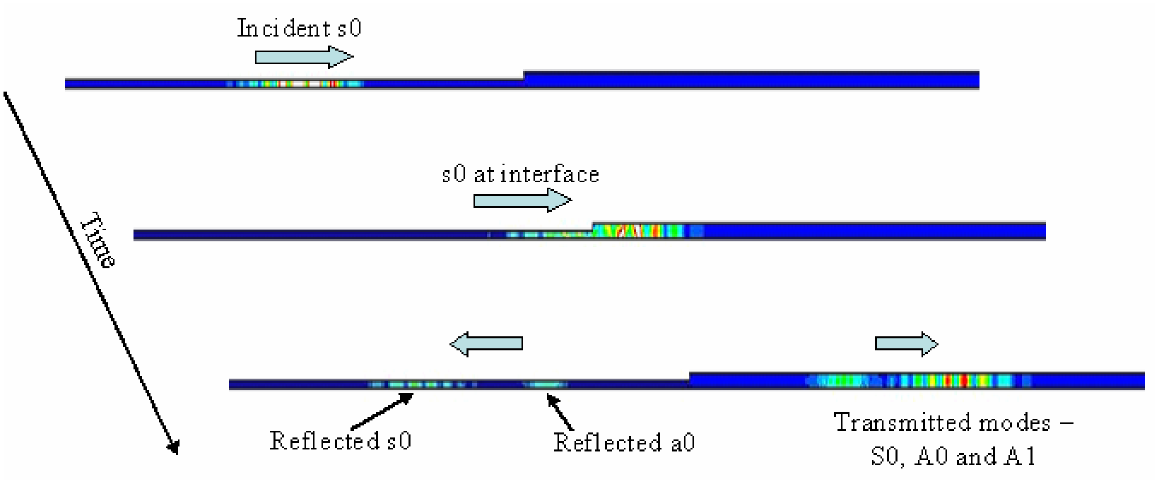

Figure 3. Snapshots of the propagation of the s0 mode through the aluminum layer into the epoxy bonded aluminum joint, obtained from finite element solution. The guided wave modes reflected from the geometric transition from aluminum to epoxy bonded aluminum, are separated in time and identified in the figure. The transmitted modes overlap and hence are not identified separately.

3. Case study results

In this paper, we are reporting the effect of a cohesive weakness i.e. weakness in the adhesive (epoxy) layer, and adhesive interfacial weakness on the energy transmitted across an adhesive joint. Cohesive weakness in the adhesive material is simulated by reducing the bulk longitudinal and shear wave velocities, separately and also together. Reduction in the bulk wave velocity causes a reduction in the elastic stiffness values of the material. In order to simulate interfacial weakness, the adhesive layer was modeled as a three layered medium with the properties of the thin top and bottom layers modified to represent strong and a weak interface. The interfacial layer properties were varied in the same manner as done for the cohesive weakness case.

A quantity called the amplitude transmission factor is defined to quantify the effect of cohesive degradation in the adhesive on the propagation of ultrasonic energy. Amplitude transmission factor is calculated by dividing the frequency spectra of the transmitted part of the wave with that of the incident part of the wave. Figure 4 shows a comparison of the amplitude transmission factors for the symmetric wave mode obtained from the hybrid-analytical method and the solution obtained using the FE method under similar loading conditions. In both cases an s0 wave is simulated to be incident on the geometry transition region. In the FE method, a displacement is specified at an end of the aluminum plate, away from the overlap portion, such that it matches the in-plane displacement of the s0 mode.

It can be seen from figure 4 that a reduction in the shear modulus by 10% shifts the transmission factor minima to the left. A much larger shift can be observed for the case of reduction in shear modulus by 20%. The case of adhesive interfacial weakness also shifts the minima of transmission factor to lower frequency. The shift is lower than the case of 10% reduction in the properties of the entire adhesive layer. It was observed that a reduction in the longitudinal velocity produces only a small amplitude change to the minima of transmission factor, and hence it was omitted from the plot in figure 4. This additionally reinforces the importance of shear waves in monitoring the adhesive quality.

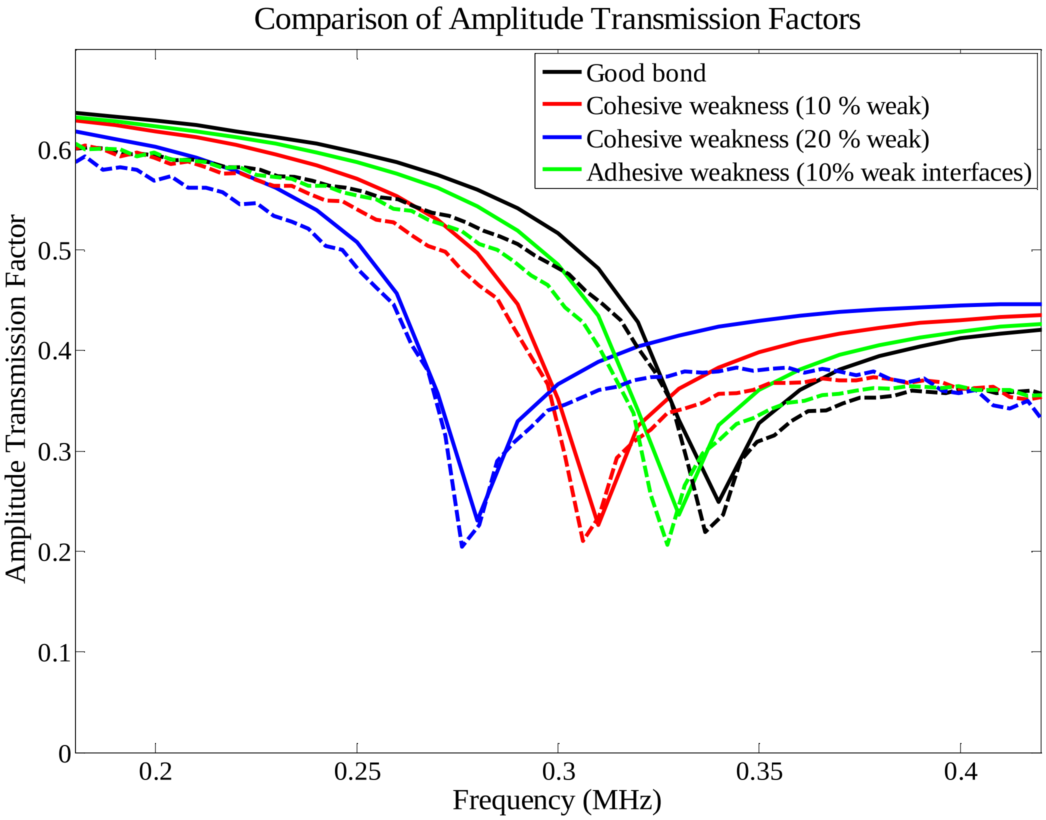

Figure 4. Amplitude transmission factors for symmetric wave mode (s0) incidence, calculated for different cases of adhesive joint. The solid lines are from the hybrid-analytical method and dashed lines from the finite element method. Spectral shifts clearly indicate bonding degradation.

4. Conclusions

The hybrid-analytical method and the finite element method were applied to determine the amplitude transmission factors for adhesive joints with simulated cohesive and adhesive weaknesses. It was found that cohesive weakness simulated using reduction in the wave velocities produces a shift in the spectral minima of the transmitted wave. A similar trend was observed in the case of adhesive interfacial weakness. Both the hybrid-analytical method and the finite element method agreed well on this trend. The hybrid analytical method solves the problem at every single frequency. This makes it an ideal tool for finding the optimal frequency for inspection. The FE method would agree more closely to the actual experiments since it uses a finite bandwidth incident pulse.

Acknowledgements

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