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DETECTION OF DISBONDS IN ADHESIVELY BONDED ALUMINUM PLATES USING LASER ULTRASOUND

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ABSTRACT

Adhesively bonded metals are increasingly used in aerospace and automotive industries. Critical, load-bearing elements are often reinforced using stiffeners bonded to the main structure.

Inspecting these parts remains challenging for modern non-destructive testing techniques. To some extent, high-frequency contact ultrasound probes can be used to detect defects between two plates. It appears, however, that the limited bandwidth of these systems cannot resolve multiple reflections and mode-conversions occurring at subsequent layers.

Laser ultrasound (LU), due to its broadband nature, has shown great potential in high-resolution imaging of carbon-reinforced composites. For a metal surface, however, excitation of longitudinal waves in the normal direction is inefficient. On the other hand, shear waves can be efficiently generated using laser absorption and used to image defects in metallic structures.

In this paper, we present the application of an LU system to detect damage in adhesively bonded aluminum plates. Laser-generated shear waves propagating into the structure at an oblique angle are back-reflected at discontinuities in the adhesive layer and detected on the surface. The distance between transmitter and receiver must be adjusted to maximize system sensitivity at a given depth. Here, we use finite difference (FD) simulations to optimize the measurement configuration.

Keywords: laser ultrasound, shear waves, adhesive bonds,

NOMENCLATURE

LU	laser ultrasound
FD	finite difference
US	ultrasound
TOF	time-of-flight

1. INTRODUCTION

Adhesively bonded multi-layer metal plates are commonly used in many industries, including nuclear energy, automotive and aerospace [1].

Porosity and voids in the adhesive layer can be detected using X-Ray radiography. This technique, however, requires double-sided access, is relatively slow, and cannot detect non-volumetric defects like delaminations. Therefore, conventional ultrasound remains the main modality to inspect these structures.

For typical aircraft components, 2 to 4 plates with 0.5 – 4 mm thickness are bonded to obtain the desired stiffness. For these structures, multiple wave reflections and mode-conversions at subsequent layers make pulse-echo signal interpretation extremely difficult. Therefore, through-transmission mode remains the standard procedure, even though it cannot provide in-depth resolution.

Many limitations of conventional ultrasonic testing have been overcame recently by laser ultrasound (LU). Laser pulses can generate broadband signals providing resolution much better than that of contact US probes. For composites, longitudinal waves reflected from subsequent plies can create images of quality comparable to X-ray computed tomography [2].

In metals, LU is limited because it cannot efficiently produce longitudinal waves in the normal direction without surface ablation. Therefore, common LU methods appropriate for composites do not directly translate to metals. Nevertheless, other wave modes can be generated by lasers in metals. Applications of laser-generated surface [3] shear [4] and Lamb waves [5] have been reported in the literature.

In this work, LU-based damage detection is tested in adhesively bonded aluminum plates. Laser-generated shear waves propagate at an oblique angle into the inspected structure. If a discontinuity lies along their propagation path, a reflected wave propagates to the surface where it can be detected. Knowing the wave generation angle and the depth of anticipated defects, the position of optical sensors can be adjusted to

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maximize system sensitivity. The optimal source-detector distance is selected based on multi-physics simulations of laser wave generation and propagation.

2. MATERIALS AND METHODS

2.1 Ultrasounds excitation: thermo-elastic region

For non-ablative laser excitation of shear waves, the LU system functions in the thermo-elastic regime. Elastic waves are generated from stresses induced by heating a small part of the material by light absorption [6]. These stresses are small enough to avoid damaging the sample.

For an isotropic material, the excitation mechanism in the thermo-elastic region (neglecting the heat produced by mechanical deformation, and the second derivative of the temperature T) is described by the following set of coupled differential equations [7]:

$$k\nabla^2 T = \rho c_V \dot{T} - \boldsymbol{q} \tag{1}$$

$$\mu\nabla^2 \boldsymbol{u} + (\lambda + \mu)\boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\boldsymbol{u}) = \rho\ddot{\boldsymbol{u}} + \beta\boldsymbol{\nabla}\mathrm{T} \tag{2}$$

where:
k – thermal conductivity
ρ – material density
c_V – constant volume specific heat
β – thermo-acoustic coupling constant: $\beta = (3\lambda + 2\mu)\alpha_T$
α_T – linear thermal expansion coefficient
λ, μ – Lame constants
$\boldsymbol{u}$ – displacement vector field
$\boldsymbol{q}$ – power density of heat source

Equation (1) defines thermal conductivity and thermal expansion due to the change of temperature T, and equation (2) describes propagating elastic waves excited by the thermal expansion $\beta\boldsymbol{\nabla}\mathrm{T}$.

2.2 Finite difference modelling

To obtain elastic displacements from the thermal source, Eq. (1)-(2) were implemented using a finite difference scheme within a 2-dimensional model, as presented in figure 1. A 40 mm wide, two-layered metal plate structure was modeled, with physical characteristics of the plates equivalent to aluminum ($\rho = 2700,\ E = 68.9\ MPa, \nu = 0.33$). The model was discretized in space using a rectangular 4.2 µm grid.

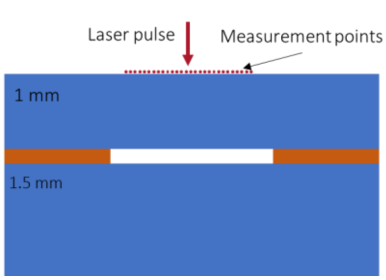

FIGURE 1: SCHEMATIC OF SIMULATED FD MODEL

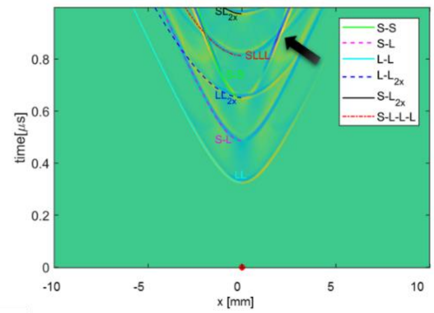

FIGURE 2: SPACE-TIME REPRESENTATION OF SIMULATED SIGNALS OBTAINED AS THE DIFFERENCE BETWEEN OUT-OF-PLANE RESPONSES FOR PRISTINE AND DAMAGED CASES. COMBINATION OF LABELS **L** AND S DENOTES REFLECTED OR MODE-CONVERTED LONGITUDINAL OR SHEAR WAVE RESPECTIVELY.

The time step was 0.5ns. The adhesive layer was modelled as a one-element thick layer with density of 1540 kg/m3, Young modulus of 3.5 GPa, and Poisson's ratio of 0.33.

A 15 nsec duration Gaussian laser pulse with spatial width of 150 µm was used. Two cases were calculated: first, perfect bonding between the plates; next, a 2 mm defect in the epoxy layer with physical characteristics equivalent to air. Out-of-plane displacements were acquired at a set of spatial locations indicated in figure 1.

To remove waves not altered by the defect, signals from both simulations were subtracted, producing the wavefield image in figure 2. This image shows parabolic shapes formed by waves reflected by the defect. Subsequent lines were successfully identified as reflections of shear (S) and longitudinal (L) waves. The area of the largest intensity is indicated in figure 2 by the black arrow. This point occurs at approximately 2 mm source-receiver distance and 0.9 µs time of flight (TOF), and corresponds to reflection of a shear wave.

2.3 Experimental setup

Experiments were carried out using the LU scanner described in detail in [8]. A schema of the setup is presented in figure 3. The laser beam was focused using a cylindrical lens to form a thin line on the sample surface. Based on the numerical simulation, the source-receiver distance was set to 2 mm. The inspected sample contained 3 aluminum plates (1, 1.5, and 3.5 mm thick) bonded using epoxy film. A 15x15 mm Teflon insert was placed between the first and second layers. The sample was fixed to a mechanical scanner and inspected over the defect area with 0.02 mm lateral resolution. Signals were spatially averaged using a 2D Gaussian window (15x15 point) and low pass filtered using a cut-off frequency of 9 MHz.

3. RESULTS AND DISCUSSION

An example of A-scans acquired over bonded and disbonded areas is presented in figure 4. The waveforms were normalized to the peak amplitude. These signals are very similar since not all wave modes were sensitive to the defect. Indeed, the largest peak corresponds to surface a wave, which is expected to remain constant over the inspected sample. For TOF equal to approx. 0.9 µs, the signal acquired over the defect has a significantly larger amplitude than the reference, in good accordance with simulations. To focus on signal differences related to the defect, the amplitude of all recorded signals corresponding to TOF equal to 0.9 µs was imaged in the form of a C-scan, as presented in figure 5. Clearly, the Teflon insert was successfully detected and imaged.

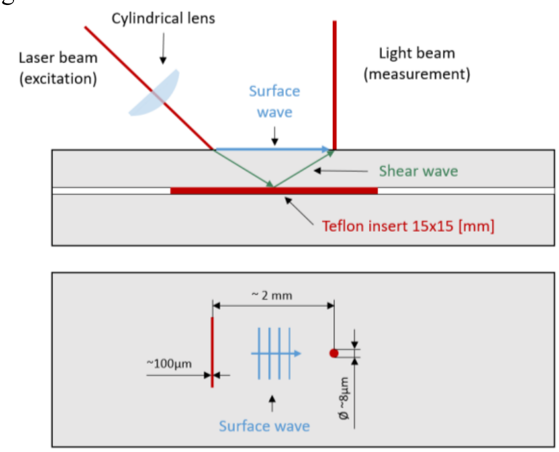

FIGURE 3: CROSS-SECTION AND TOP VIEW OF THE EXPERIMENTAL SETUP

4. CONCLUSION

Although longitudinal waves cannot be efficiently excited in metal plates with laser pulses in a non-ablative regime, these structures can be inspected using other wave modes. Here we demonstrated that adhesively bonded aluminum plates can be inspected using shear waves excited at an angle to the surface normal in the thermo-elastic regime. Because of the complex nature of acquired signals, identifying individual wave reflections in structures like the one inspected here can be difficult. However, the source-detector distance can be optimized using numerical simulations to maximize inspection sensitivity. We believe that the proposed method can be robust, fast, and highly sensitive in evaluating not only full disbonds, but also in quantitative control of plate adhesion.

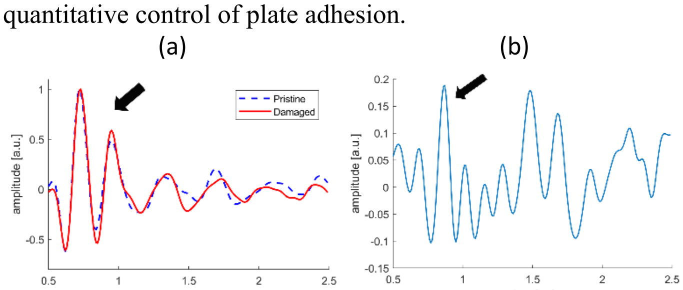

FIGURE 4: COMPARISION OF A-SCAN WAVEFORMS ACQUIRED OVER UNDAMAGED STUCTURE AND DEFECT (a); AND DIFFERENCE BETWEEN SIGNALS (b). ARROWS DENOTE SHEAR WAVE ARRIVAL.

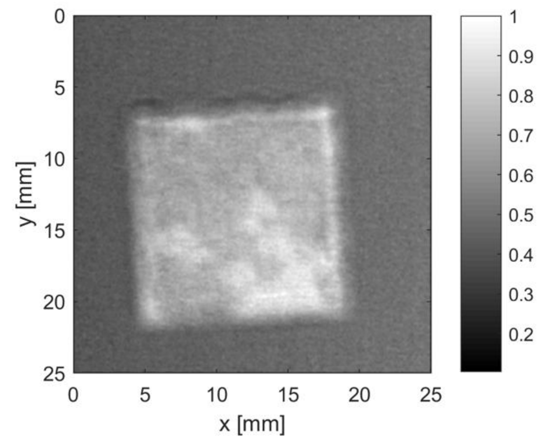

FIGURE 5: C-SCAN IMAGE PRESENTING AMPLITUDE OF THE RESPONSES ACQUIRED FOR TOF = 0.9 µs.

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