Within-the-Bond Strategy for In-Situ Inspection of Composite Bonded Joints Using Piezoceramics

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ABSTRACT

In the present study, attention is paid to the implementation of a piezoceramic based structural health monitoring (SHM) system on a composite bonded and riveted lap-joint. The structure is composed of an aluminum plate riveted to a titanium spar which is itself bonded to a CFRP laminate structure. The bonding is ensured by double sided adhesive that is prone to degradation with improper installation or when submitted to extreme strains. Inspection within the bond is proposed in order to avoid complex reflection patterns induced by the rivets and optimal configuration is derived for the specific application. The novelty of the resent approach resides in the development of an optimal SHM configuration for within-the-bond inspection of complex joints in terms of mode, frequency, transducer array configuration and metrics to be monitored. Theoretical propagation and through-the-thickness strain distribution are first studied in order to determine damage sensitivity with respect to mode and frequency of the generated guided wave. It is shown that A0 mode appears as the best candidate for generation of large shear strains in the bond line. The optimal configuration of the system in terms of piezoceramic size, shape and inter-unit spacing is then validated using Finite Element Modeling (FEM) in 2D and 3D. The advantages of both approaches are discussed with respect to the bond complexity. Experimental validation of propagation characteristics is conducted using Laser Doppler Vibrometer (LDV) in order to validate theoretical and numerical assumptions and pitch-and-catch measurements are then proposed with rectangular piezoceramics in order to validate the efficient detection of the damage and accurate estimation of its size. It is shown that disbond size from 5mm to 20mm can be accurately determined by measuring A0 mode attenuation.

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INTRODUCTION

Adhesive bonding of aerospace primary structures is intensively used on current aircraft projects as a direct alternative to riveting [1]. Classical Non-Destructive Testing (NDT) of bonded structures includes detection of the bonding layer thickness using conventional ultrasonic techniques. A built-in Structural Health Monitoring (SHM) approach would be most desirable for this application, since the associated costs would be reduced by substituting the current schedule-based maintenance approach by condition-based maintenance [2]. Among the various techniques available, a SHM system based on Lamb wave propagation with piezoelectric transducers seems to be a cost-effective method for a quick and continuous inspection of metallic assemblies [3] and composite laminates [4]. In the case of bonded joints monitoring, it appears from previous studies that two strategies using guided waves propagation can be employed [5].

On the one hand, across-the-bond strategies have been employed in previous studies for simple joint structures, such as lap-shear metallic joints [6,7]. In that case, complex mode conversion can be observed when propagating through the bond [6] and it has been shown that disbonds severity can be quantified by measuring the attenuation associated to A0 mode [7]. For more complex structures, such as composite wing to spar joints, this approach has been successfully used and monitoring of bond condition has been realized by estimating the attenuation associated with S0 and A1 modes [5]. However, this approach remains limited since geometrical aspects, such as rivets or complex mode conversion, must be taken into account in order to compare different propagation paths. On the other hand, within-the-bond strategies offer the advantage of using the bond line as a waveguide, such that the influence of geometrical features located out of the bonded region can be minimized. In that case, the guided wave propagation within the bond is often approximated as propagation in two infinite bonded layers. This assumption allows deriving analytical models [8,9] and damage detection can be performed either by monitoring changes in phase velocity [10], in the wavenumber versus frequency [12] or by monitoring the attenuation. More recently, a study including the effect of joint geometry has been presented [5] using a within-the-bond approach in pitch-catch configuration. Measurement of RMS signal amplitude exhibits strong sensitivity to the bonding condition, such that attenuation of A1 and S0 modes appears as a potential candidate for bond inspection within the bond.

In the present study, attention is paid to the implementation of a piezoceramic based SHM system on a composite bonded and riveted lap-joint. Within-the-bond inspection is proposed in order to avoid complex diffraction patterns induced by the rivets. The novelty of the present approach resides in the development of a methodology in order to design a SHM system configuration for complex joints inspection in terms of mode, frequency, transducer array configuration and metrics to be monitored. Requirements are studied using analytical and numerical approaches using 2D and 3D Finite Elements Models (FEM) are discussed and validated experimentally on a representative coupon with inserted synthetic damages.

PROBLEM STATEMENT

In the present study, a bonded joint between an aluminum plate and CFRP plate is considered using a titanium (Ti) plate as presented in Fig. 1. The CFRP plate is made of 7 plies organized in $[+45/-45/0/90]_T$ layup configuration and the bond line is 25.4 mm thick, oriented in the 8.3° direction. The bonding is ensured by double sided adhesive (FM 300 by Cytec). The aim is to monitor the disbond occurring at the CFRP plate / titanium spar interface using guided waves generated by piezoceramic transducers. The objective of the present work is to propose a within-the-bond transducer configuration for pitch-catch detection of disbonds, and thus to determine the methodology to obtain an effective configuration for the SHM system in terms of:

- Guided waves sensitivity to the damage: mode and frequency selection,
- Metric extraction: detection and quantification of the disbond size,
- Transducer configuration: sensor and actuator size, shape and localization.

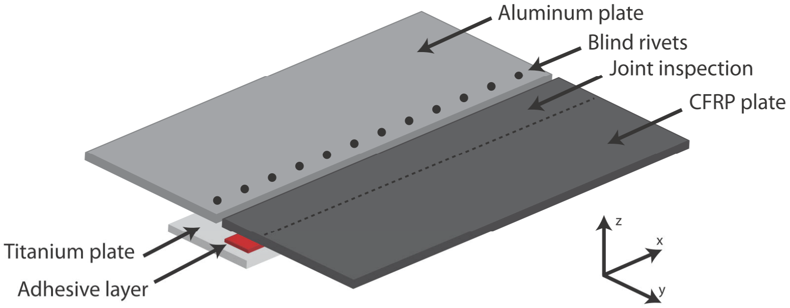

Figure 1: Schematic view of the considered bonded joint.

GUIDED WAVE SENSITIVITY TO THE DAMAGE

Dispersion Curves

The first step in the sensitivity analysis is to detail the propagation characteristics based on dispersion analysis. For this purpose, multi-layer dispersion curves are computed using the transfer matrix method [11] in the bond line (in the 8.3° direction). Damping is inserted in the model as an imaginary part determined as a percentage of the Young's modulus in order to compute attenuation coefficients associated with each mode (in Np/m). Fig. 2 represents the phase velocity and attenuation curves associated to the propagating modes in the bond direction below 700 kHz.

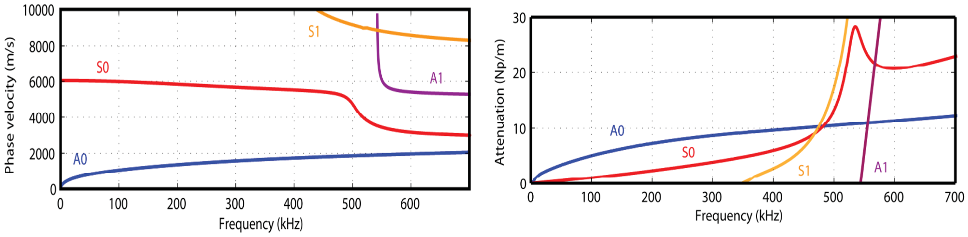

Figure 2: Phase velocity (left) and attenuation curves (right) in the bond direction.

Mode Profile in the Thickness of the Bond

In order to determine the proper mode and frequency range for inspection, the distribution of stresses along the thickness direction is analyzed. For this purpose, the cross-sectional distribution of shear stresses (σ_{xz}) is computed using the transfer matrix method [11]. Typical through-the-thickness shear stress profiles obtained at 100, 300, 500 and 700 kHz are represented in Fig. 3. In this figure, it appears that the normalized shear stress related to A0 mode are larger than for S0 mode in the adhesive region for frequencies below 300 kHz. However, around 500 kHz, S1 mode also generates large stresses in the bonding layer, but the associate wavelength is large (above 30 mm), such that its sensitivity to small damages is not guaranteed. A refined shear stress analysis (not presented here for clarity) confirms that A0 mode appears as a potential candidate for damage detection around 150 kHz.

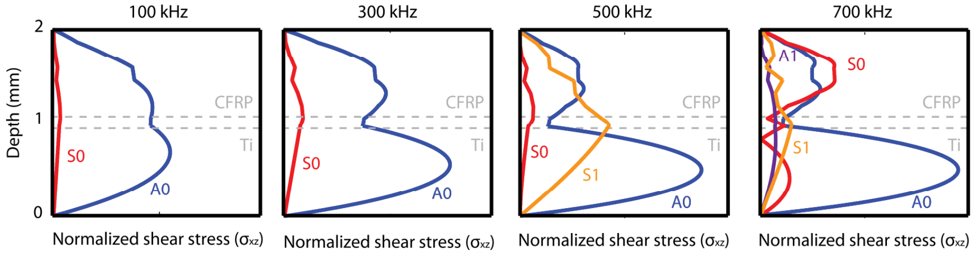

Figure 3: Shear stress distribution in the thickness direction from 100 to 700 kHz.

SYSTEM CONFIGURATION FOR DISBOND DETECTION

Numerical Model Definition

In order to extract a metric for detection and quantification of the damage and propose a configuration for the SHM system, FEM is proposed. For this purpose, a numerical software (COMSOL 4.2) is used to simulate the dynamic response of the plate and the interaction of guided waves with artificial disbonds. The area of interest is 480 mm long as presented in Fig. 4 and includes the 7 separated anisotropic CFRP plies with respective orientations, the adhesive layer, titanium plate, PZT transducers and absorbing regions. The simulations are performed in the frequency domain (harmonic excitation) in order to consider the loss factor in the viscoelastic materials. An absorbing layer (160 mm long) is modeled around the area of interest to ensure an infinite plate condition by adding an imaginary part to the elastic constants that increases with respect to the propagation distance [13].

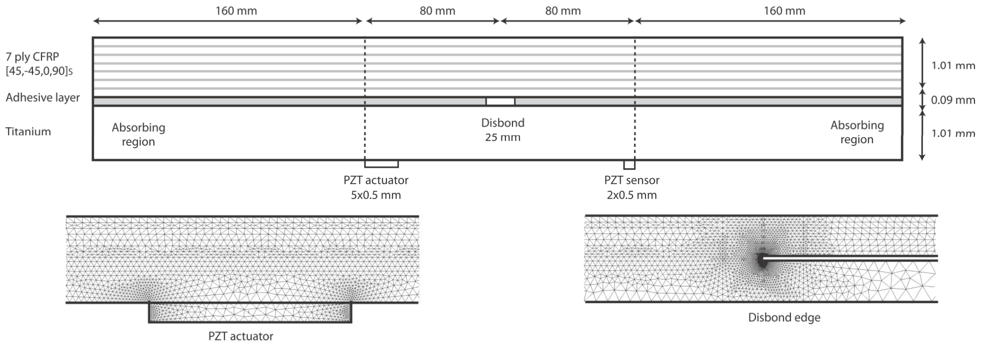

Figure 4: Definition of the geometry (top) and description of mesh refinement around PZT and disbond edges (bottom) used for 2-D FEM.

The damage is simulated by considering two different bonding conditions for a given length of 25 mm corresponding to the inspection requirement. The first condition corresponds to a total disbond of the targeted area, modeled by totally removing adhesive layer. The second condition consists in modeling the damaged area as an adhesive layer with the same mechanical properties except that the damping of the targeted area is increased from 1 % to 10 %.

Metric Extraction

In order to determine a metric and its robustness, pitch-catch simulations are presented for the two models for the disbond using a 3.5 cycles burst at 150 kHz. In each case, the time-domain signals obtained without damage are compared to the damaged case in Fig. 5. Signals envelopes and differences are represented in order to describe the damage influence. As predicted theoretically, S0 mode is not sensitive to the damage for the two investigated disbond models. However, A0 mode exhibits a relatively strong sensitivity to the damage, independently of the considered damage model.

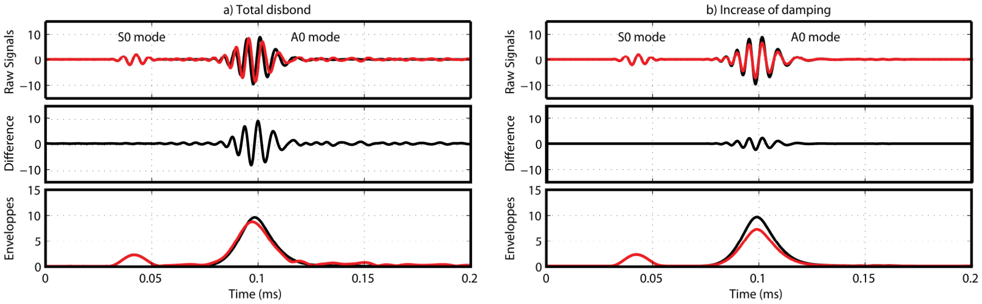

Figure 5: Pitch-Catch signals obtained in FEM in the case of total disbond (left) or considering a local increase of damping at the damage.

In the case of increase of damping in the damaged area, a decrease of 25% of A0 mode amplitude is observed in the raw signals and also using envelope extraction. In the case of a total disbond, a decrease of 10% of A0 amplitude is combined with a small delay. In that case, observation of A0 mode envelope allows precise detection of the disbond. Moreover, stationary waves in the disbond area due to multiple reflections at the disbond edges [12] can be observed, leading to echoes in the time signals between 0.12 and 0.15 ms.

EXPERIMENTAL SETUP AND VALIDATION

Experimental setup

For experimental investigation, a coupon structure has been manufactured as presented in Fig. 6. For this structure, four different zones are defined, namely undamaged, sub-critical damage (12.5mm), critical damaged(25mm) and over-critical damaged (37.5mm). Simulated damages are inserted using two hemispherical Teflon tapes between adhesive and titanium spar in order to simulate a realistic geometry of disbond. Those damages have been controlled after manufacturing using conventional immersion ultrasonic imaging (UT C-Scan) at 10 MHz.

From analytical and numerical calculations, a rectangular piezoceramics appears as the best choice for generation of plane wavefronts for A0 mode around 150 kHz. Sensors have been micro-machined on the same piezoceramics than the one used for actuator in order to form compact sensor and actuator units of thickness 1 mm as indicated in Fig. 6. Actuator dimensions of 5 x 21 mm and sensor size of 2 x 21 mm have been used as indicated in the numerical section. The input signals are generated using a HP 33120A generator with a sampling frequency of 10 MHz and amplified by a voltage amplifier (Produitson UA-8400). The acquisition of signals is performed using a LabVIEW interface with a high impedance (1 MΩ) National Instruments PCI-5105 12 bits acquisition board. The recorded signal length is 1 ms and the sampling frequency is fixed at 60 MHz. All measurements are averaged 100 times in order to increase the SNR.

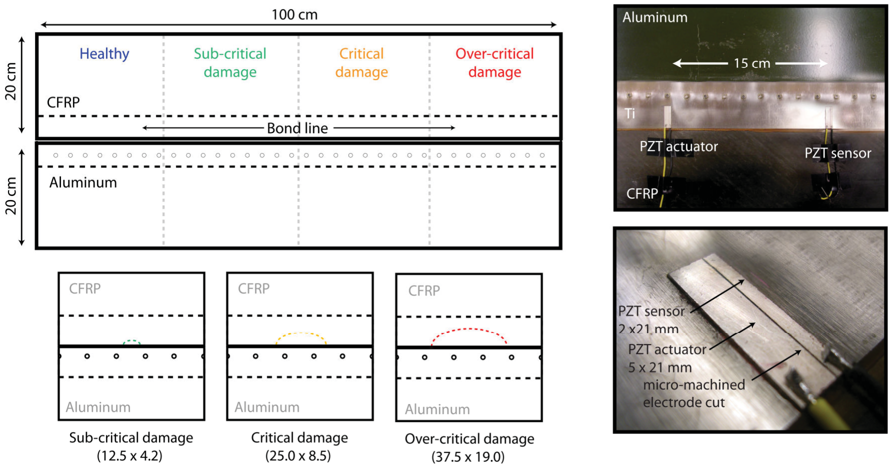

Figure 6: Schematic view (left) and photography (right) of the experimental setup used for pitch-catch detection using rectangular piezoceramics.

Pitch-Catch measurements

In this section, results of damage detection using rectangular piezoceramics as actuator and sensor are proposed using pitch-catch configuration within the bond. In this case, the compact micro-machined actuator/sensor units described in Fig. 6 are used and a sensor to actuator separation distance of 150 mm has been chosen, as presented in Fig. 5 in order to obtain a good mode separation and acceptable signal amplitude. Fig. 7 represents the measured sensor voltage and associated signal envelopes computed using Hilbert transform for an input signal defined as a 3.5-cycles Hanning windowed burst at 150 kHz. Results are represented in the undamaged region (blue) and for the 3 damage sizes, respectively 12.5 mm (green), 25 mm (orange) and 37.5 mm (red). In the undamaged case, both S0 and A0 modes are observed around 40 µs and 100 µs respectively. Secondary wave packets are visible around 55 µs and 80 µs and are independent on the damage severity. Since those waves are not observed in the 2D numerical model, their origin can be attributed to a reflection of S0 mode either at the joint edges or at the rivets.

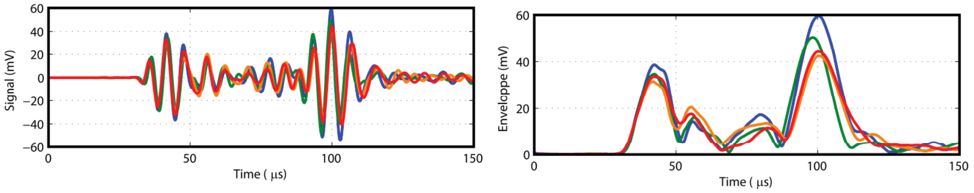

Figure 7: Measured sensor sensor voltage (left) and corresponding envelope (right) in pitch and catch configuration at 150 kHz for undamaged signal (blue) and damaged of 12.5 mm (green), 25 mm (orange) and 37.5 mm (red).

In Fig. 7 , it appears that both A0 and S0 modes are affected by the presence of the damage and variations up to 20 % in S0 mode amplitude and a decrease of 30 % for A0 mode are observed when increasing the damage size. According to the 2D numerical model, S0 mode amplitude should not be affected by the presence of a damage. However, experimental trends show that S0 mode is affected by the presence of the disbond, and this effect could be attributed to wave diffraction when entering and exiting the disbond edges which are not parallel to the generated wavefronts. In that case, this geometrical effect should also be expected for the A0 mode, such that the mode amplitude ratio between A0 and S0 modes can be proposed as a robust metric that only describes the attenuation of A0 mode when propagating through the disbonded area.

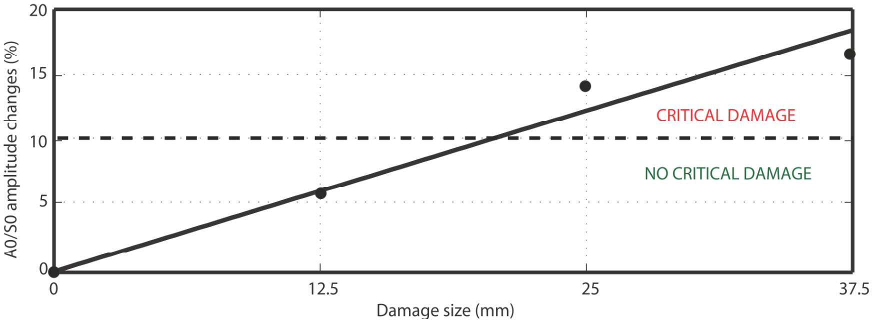

Figure 8: Evolution of the A0 to S0 amplitude ratio with respect to the damage size. The threshold for detection of critical damage is represented in black.

Fig.8 represents the evolution of the ratio between A0 and S0 mode amplitude for the three damage sizes. A linear tendency can be observed, such that the measured amplitude ratios are within ± 3% with respect to a linear approximation. From numerical analysis, a decrease of 25 % of A0 mode amplitude should be observed for 25 mm damage. However, in the present experimental setup, a decrease of only 15 % is measured. This observation could be attributed to the fact that the 25 mm damage size is measured at the base of the semi-elliptical inserted Teflon tape, such that the average damage size is lower. Moreover, results of the ultrasonic C-Scan indicated that the effective disbonded area did not cover the whole area of the Teflon tape and insertion of adhesive or prepreg epoxy between the two Teflon foils during curing could be the reason.

CONCLUSION

In this paper, a methodology is proposed for an optimal SHM configuration for detection of disbond in composite bonded joint is proposed. Selection of optimal mode and frequency range for inspection is based on theoretical dispersion analysis and stress distribution through the thickness. 2D and 3D FEM allow validating the metrics to be used and the optimal transducer configuration. Damage detection using rectangular piezoceramics in pitch-catch configuration within the bond is presented and a metric based on the ratio of amplitude between A0 and S0 modes at 150 kHz is proposed for damage size quantification.

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