Detection of Disbond in a Honeycomb Composite Sandwich Structure Using Ultrasonic Guided Waves and Bonded PZT Sensors
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Abstract. "Honeycomb Composite Sandwich Structure" (HCSS), is widely used to form major structural components of aerospace, marine and automotive vehicles due to its high strength to weight ratio and high energy-absorption capabilities. In service, the bond between the honeycomb core and skin may degrade with aging and continuous cyclic loadings leading to separation of the load bearing skin from the honeycomb core (called "disbonds"), and compromising the safety of the structure. Guided wave techniques have the potential to provide information on the presence of disbond since they can travel long distance and interact with localized defects. In this study, a baseline free technique has been developed for health monitoring of HCSS plates using ultrasonic guided Lamb waves and embedded piezoelectric transducer (PZT) wafer array. The PZT wafers were arranged in a grid manner on the top surface of the HCSS plate in which one of the PZT wafer acts as a transmitter and the other wafers act as receivers. A five cycle sine pulse modulated by Hanning window is transmitted and the effect of disbond on the response signal interrogated first. The directional group velocities in the HCSS plate are obtained for both primary symmetric (S0) and antisymmetric (A0) modes. A baseline free damage index algorithm is developed by taking into account the time-frequency information of the received signals. Damage index (DI) maps are plotted using the experimentally obtained time response data to detect the location of disbond region in the HCSS plate. The DI maps clearly show the higher values of DI at disbond location with high degree of accuracy.

Introduction
The importance of structural health monitoring (SHM) to enhance the reliability and reduce the life-cycle costs of present and futurity infrastructure is widely acknowledged. Lamb-wave-based SHM methodologies have been widely reported to be sensitive to small damage, convenient and efficient in detecting fatigue cracks in metallic structures, disbonds and delaminations in composite structures and for the assessment of structural repairs [1,2,3]. Apart from the essential requirement that SHM systems must be reliable, two important desired features are graphical representation and quantitative evaluation of damage. In the literature, different methods have been developed to provide a graphical representation of damage. Wang et al [4] presented an imaging method based on the time-reversal concept for damage detection and the method was experimentally verified using an aluminum plate. Zhao et al [5] developed a reconstruction algorithm for probabilistic inspection of defects (RAPID) for damage detection in an aircraft wing using ultrasonic guided waves. A defect distribution probability map is constructed to locate the damage and to monitor its growth. The method was verified using an aircraft wing made from aluminum alloys and coated with paint. Michaels and Michaels [6] applied time shift averaging algorithms to differential Lamb wave signals filtered at multiple frequencies. A set of images corresponding to each center frequency are then generated and combined to form an image for locating the damage. An experimental verification was carried out using an aluminum plate. Su et al [7] proposed an imaging method for damage detection using Lamb waves. Probability densities of damage occurrence are calculated based on time-of-flight analysis of scatter waves and superimposed to form an image of the damaged composite laminate. Giurgiu and Bao [8] used embedded ultrasonic structural radar and phased array beam forming techniques for damage detection. Experimental studies were carried out on metallic structures to illustrate and verify the method. Sundararaman et al [9] employed
beam formers consisting of sparse phased array transducers to characterize damage in homogeneous and heterogeneous structures. Olson et al [10] applied beam forming and an array of piezoelectric transducers to detect damage and an experimental study using an aluminum plate was used to verify the method. Ng and Veidt [11] investigated the application of the beam forming method to detect and locate damage in composite laminates by accounting for the angular dependence of the group velocity. They introduced a graphical representation that not only pinpoints the location of damage but reconstructs a possible damage area which provides quantitative information for any required remedial work.

This paper presents the application of Lamb waves to inspect disbond in HCSS plate. The proposed methodology employs a network of transducers that are used to sequentially scan the structure before and after the presence of disbond by transmitting and receiving Lamb wave pulses. A damage localization image is reconstructed by analyzing the cross-correlation of the scatter signal envelope with the excitation pulse envelope for each transducer pair. A potential damage area is then reconstructed by superimposing the image observed from each actuator and sensor signal path. The experimental case studies employ the arrangement of surface bonded PZT wafers in a grid manner on the top surface of the HCSS plate in which one of the PZT wafer acts as a transmitter and the other wafers are act as receivers. A five cycle sine pulse modulated by Hanning window was transmitted and the effect of disbond has been investigated by means of response collected along three sections located at different locations. Further study was done by dividing the grid arrangement of PZT wafers into three zones and each zone is analyzed by collecting response at receivers. Prior to application of algorithm, the directional group velocities in the HCSS plate were obtained for both primary symmetric (S0) and primary antisymmetric (A0) modes. A damage index is defined at every point of the HCSS plate by taking into account the Hilbert transformation of the raw time signal. Damage index (DI) maps are generated to detect location of disbond in the HCSS plate. The DI maps clearly show higher values of DI at disbond location with high degree of accuracy.

**Damage Index**

In order to perform a base line free damage detection of the HCSS, a damage detection algorithm is developed. A damage index (DI) is defined by taking into account the Hilbert transformed data rather than the raw time-domain signal data. Based on the time verses Hilbert transformation coefficient (HTC) information of received signals, the DI is defined at any point P(x, y) within the transducer grid on the plate as follows:

\[
\text{DI}(x, y) = \sum_{m=1}^{4} \sum_{n=1}^{4} \int_{t_1}^{t_2} (\text{HTC})^2 \, dt \quad (2.1)
\]

where,

- HTC = Hilbert transform coefficient of the received signal corresponding to the excitation signal frequency at any time. Suffix ‘m’ represents transmitter and ‘n’ represents receiver. Say if we consider data from 1-2 path then it refers to data received in transducer - 2 when transducer-1 acts as transmitter (m is always not equal to n).
- \( t_1 = \frac{d_1}{c_s} + \frac{d_2}{a_s} = \) Time required for the wave to travel from the \( m^{th} \) transmitter to the \( n^{th} \) receiver
- \( d_1 = \) distance between the source and the point P
- \( d_2 = \) distance between the point P and the receiver
- \( c_s = \) group velocity of the S0 mode
- \( a_s = \) group velocity of A0 mode
- \( t_2 = t_1 + t_s \)
\( t_s = a \) fixed bandwidth of the received signal assuming non-dispersive guided wave mode in the
response signal.
It can be seen that the damage index is defined in such a way that it typically represents that energy
content of the received signal matched in time at any point \( P(x, y) \).

**Health Monitoring of HCSS Plate**

The honeycomb composite sandwich plate used in this study consists of two skins at top and
bottom, which are being bonded to core by means of adhesive layer. Each skin consist of seven
layers in which fibres arranged as +0/90, 35, -35, 0, -35, +35, +0/90. Core is made up of Al5056,
which is in hexagonal shape with cell size of 1/16 inches. Core cell extends to depth of 12mm with
material density of 32 kg/m\(^3\). Bond between skin and core is achieved by means of foaming
adhesive product Hexcel 212-Na. The protection film was removed to mount the PZT sensors.

![Honeycomb composite sandwich plate](image)

**Experimental Set-up.** Surface-bonded PZT wafers, SP-5H (20x20x0.4mm), are mounted on the
surface of HCSS plate (600 x 450 x 13.5 mm) to actuate lamb waves. The schematic and
experimental arrangement of National Instrument (NI) data acquisition set-up is shown in Fig. 2.

![Schematic and experimental arrangement of NI set-up](image)
An arbitrary signal generator and oscilloscope are embedded in NI-instrument and a five-cycle sine pulse modulated with Hanning window is transmitted into plate by means of FGEN Soft Front Panel, and SCOPE Soft Front Panel is employed to collect Lamb wave signals and also a voltage amplifier is used to increase the amplitude of the transmitted signal as shown in Fig. 2(b). Initially two piezoelectric transducers mounted on surface such that spacing between them is equal to 200 mm which is as shown in Fig. 3(a). Among two transducers one acts as transmitter and other will be receiver. To identify the optimal frequency of excitation, Lamb waves with different central frequencies ranging from 0.05MHz-0.230MHz were evaluated experimentally by applying a five-cycle sine pulse modulated with Hanning window. To know the efficiency of the PZTs at different frequencies, frequency vs. response graph was plotted as shown in Fig. 3(b).

![Transducers spaced at 0.2 m](image)

Fig. 3, (a) Experimental set-up for frequency modulation, (b) frequency modulation curve

**Study of disbond effect:** To study the effect of disbond four sections of Piezo electric transducers are arranged such that each section consist of two transducers separated at a distance of 200mm. Section 1-2 and 5-6 are located on either side of centre of plate where as section 3-4 is located at centre of plate as shown in Fig. 4. FGEN Soft Front Panel is applied to produce a five-cycle sine pulse modulated with Hanning window at a frequency of 175 kHz. The response along every section is analyzed to know effect of disbond. When transmitted primary symmetric mode (S0) interacts with disbond, results in generation of new primary anti symmetric mode are observed. It can be clearly noticed the effect of disbond from response of 1-2, 3-4 and 5-6 as shown in Fig. 5, Fig. 6 and Fig. 7, respectively.

![HCSS plate with PZT wafers located along three sections](image)

Fig. 4, HCSS plate with PZT wafers located along three sections; (a) schematic, (b) experimental.
After analyzing these responses now it is required to do a further analysis, which is done by considering three set of transducer network. To do the same, sections 1-2, 3-4 are considered as one transducer network whereas sections 3-4, 5-6 are considered as other transducer network. In addition to these two networks one more network of transducers 3-4, 7-8 is also considered. The schematic and experimental representation of three transducer networks and different paths in transducer network is shown in Fig. 8. Response collected along paths 1-2 (without disbond zone) and 1-5 (with disbond zone) is as shown in Fig. 9, which clearly shows the effect of disbond. Response collected along paths 2-1 and 2-3 is also shown in Fig. 10, where the effect of disbond is absent.

After performing a number of studies it is clear that disbond is located in zone-2 and zone-3 whereas, zone-1 is free from disbond. So in order to locate exact location of disbond, a damage detection algorithm is proposed. Prior to application of the damage detection algorithm, it is required to know the velocity of primary symmetric (S0) and primary anti-symmetric (A0) mode in
all directions. Arrangement of PZT wafers with respect to location of known disbond region is shown in Fig. 4, which are implemented to collect the response by considering one of transducer as transmitter and others will be receivers. The collected responses are processed to obtain group velocity maps for both primary symmetric and primary anti-symmetric mode as shown in Fig. 11.

Results and Discussions

The damage detection algorithm discussed earlier is such that, it is capable of locating damage only if, the damage is located inside network of transducers. Transducer network 1-2-3-4 is considered as zone-1 in which damage is not present. The transducer network 1-2-5-6 is considered as zone-2 in which damage is located to near to transducer pair 5-6. Transducer network 3-4-7-8 is considered as zone-3 in which damage is located at center of transducer network. When the transmitter is excited with a tone-burst signal, guided waves are generated which travel through the honeycomb composite. If there is any discontinuity on the propagation path of the wave, reflection will occur, resulting in higher values of Hilbert transform coefficients (HTC) in the received signals. All the Hilbert transformations (HTs) are calculated. Typical signal recorded at receiver with disbond (sec. 5-6) and without disbond (sec. 1-2) is shown in Fig. 12. The direct pass and the reflected A0 modes from the disbond slits are clearly identified.
Damage Index (DI) Maps. The received signals are processed in two steps: first, Hilbert transformation is done on the raw signal data; second, the direct pass and edge reflection are discarded from the Hilbert transformed signal based on the group velocities of the propagating modes. However, edge reflections can be accommodated if the edges of the plate are considered as damage features. Thus, the processed signals are used to calculate DI at different points on the plate. As the dimension of the honeycomb composite is 600x450x13.5mm, a grid of 60x45 nodes are created to represent the plate in a reduced scale where 1 unit is equivalent to 10 mm. Each node is assumed to be a damage location, \( P(x, y) \) and the DI is calculated as per Eq. 1. The algorithms are implemented in MATLAB and the DI maps are plotted in Fig. 13, for zone-1, Fig. 14, for zone-2, and Fig. 15, for zone-3 for the identification of disbond. For all three different zones binary figures are also plotted to locate - the disbond. From the damage index maps it is clear that Zone –1 is free of disbond whereas Zone-2 and Zone-3 contain the disbond. The disbond location can be clearly identified either from Zone-2 or Zone-3 damage index maps.

Fig. 14, (a) DI map in case of Zone-2, (b) Binary figure shows exact location of disband.

Fig. 15, (a) DI map in case of Zone-3, (b) Binary figure shows exact location of disbond.
Conclusions

A baseline free damage detection algorithm is developed for detection of disbond in HCCS structure using bonded PZT transducers. The efficiency of the PZT transducers is studied through frequency tuning. While the PZT transducers predominately excite the S0 mode, it is observed that the amplitude of the A0 mode of the transmitted Lamb wave signals when it interacts with the disbond. This information along with direction group velocities is utilized for developing the damage index algorithm. It is shown that the damage index algorithm is able to locate the disbond inside the transducer network. It should be noted that the algorithm can utilize S0 mode (in the case of experimental data where PZT vibration is in radial direction induces dominant symmetric mode) as well as A0 mode (in the case of simulation data where the source vibrates in vertical direction inducing dominant anti symmetric mode) for damage detection purpose. Nevertheless, the presence of damage can be identified with a high degree of accuracy.

References