Guided Lamb wave based multi-level disbond detection in a honeycomb composite sandwich structure
Shirsendu Sikdar¹, Sauvik Banerjee ²

¹,²Civil Engineering Department, Indian Institute of Technology Bombay; Mumbai-400076, India
Phone: +91-22-25767343, Fax: +91-22-2576 7302; e-mail: ¹shisu.iitkgp@gmail.com, ²sauvik@civil.iitb.ac.in

Abstract
The objective of this study is to detect hidden disbonds in a honeycomb composite sandwich structure (HCSS) using ultrasonic guided Lamb waves and bonded piezoelectric wafer transducers (PWTs). To achieve this, a combined theoretical, numerical and experimental study has been carried out to understand the guided wave (GW) propagation characteristics in HCSS. A fast and efficient global matrix based two dimensional (2D) semi-analytical model is used to study dispersion behaviors and transient response in a healthy HCSS under PWT-excitations. Finite element (FE) based numerical simulation of GW propagation in a disbonded HCSS is then carried out in ABAQUS. Experiments are then carried out in the laboratory to validate the numerical results. A good agreement is found among the theoretical, numerical and experimental results. A substantial amplification in the primary anti-symmetric mode (A0) is observed due to the presence of disbond. Eventually, based on these changes in modal amplitudes, the location and size of hidden disbond within the PWT-network is experimentally determined using a probability based damage detection algorithm. The study is further broadened for multiple disbond identification in HCSS, using pseudo-experimental signals.

Keywords: Honeycomb composite sandwich structure (HCSS), guided wave (GW), disbond, piezoelectric wafer transducer (PWT), group velocity

1. Introduction
HCSS is a special kind of composite structure in which, thin fiber reinforced composite skins are bonded to the top and bottom faces of relatively thick and substantially lightweight aluminum honeycomb core using adhesive. These novel materials are extensively used in aeronautic, aerospace and marine industries as a specialized lightweight construction material [1]. The higher strength-to-weight ratio makes it suitable for construction of some of the major structural components such as flight wings, fuselage, blades, etc. and the high energy-absorption capability makes it attractive for impact protection and mitigation related applications. Unfortunately, due to aging, repeating loading or an intensive load, the honeycomb core tends to induce debonding along the skin-core interface, jeopardizing the safety and integrity of the whole structure [2]. The in-situ inspection methods are the subjects of recent studies to overcome the limitations of the conventional, time-consuming and costly off-line non-destructive examinations, which require the disassembly of the large structures/sub-systems. Guided Lamb wave based inspection techniques have the potential to accurately detect such disbonds in composite structures [3,4,5,6]. The GW mode tuning plays a significant role in the non-destructive evaluation (NDE) and structural health monitoring (SHM) of composite structures employing piezoelectric transducers (PZTs) [7,8]. By using the piezoelectric actuators/sensor system, Su et al. [9,10] used the time of flight (TOF) calculation technique to triangulate the delaminations in composite laminates. The prestack-reverse migration technique was used by Wang and Yuan [11]. In this work, a linear PZT disk network was used to image the delaminations in composite structures. The wave propagation in honeycomb sandwich structures can be characterized as leaky GWs at sufficiently higher frequencies, owing to the striking acoustic impedance difference between the skin and core and the high core/skin thickness-ratios [12,13]. A significant amount of wave attenuation occurred due to the energy dissipation mechanism of GWs into the honeycomb core. The GW propagation through the debonded area of honeycomb sandwich structures, a substantial
increase in amplitude of the received output signal was noticed [6,14,15]. A global matrix method based solution of wave propagation problems for a multilayered anisotropic plate due to the time harmonic loadings was presented by Mal [16]. Wave propagation studies in laminated composite plate using the spectral finite element method and the first order laminated theory was presented in [17]. Dispersion characteristics of the propagating GW modes in a multilayered laminated composite plate subjected to transient surface excitations were studied using a global matrix method based simplified two-dimensional (2D) semi-analytical model [18]. A robust 2D semi-analytical model is established by Banerjee and Pol [19] for rapid calculations of the elasto-dynamic field in a laterally unbounded honeycomb composite sandwich plate, subjected to time-dependent transient surface excitation. The 2D semi-analytical model has shown the potential to accurately represent the theoretical output signal for the HCSS. Theoretical simulation of leaky Lamb waves in the composite skin was shown by Hay et al. [6]. The sensitivity analysis of various Lamb wave modes for the composite skin-Nomex core debonding was analyzed by the frequency sweeping. Qi et al. [20] compared the ultrasonic wave transmission energy for the specimen at normal conditions and the debonded specimen in order to identify the skin-core debonding in the honeycomb composite by using the leaky surface wave propagation. Nevertheless, the information for the quantitative assessment of debonding was not provided. The authors used clusters of sensor arrangements to accurately locate the skin-core debonding, though, no information was provided about the size of debonding. Recently, the probability analysis-based algorithms have been proposed, in order to image the corrosion and cracks in aircraft wings and composite laminates [21,22]. A three-dimensional numerical simulation and experimental study have been done by Song et al. [13] for damage detection. In the work, a signal difference coefficient (SDC) was used to represent the differential features of debonding. Recently, Sikdar et al. [23] has shown a damage detection technic based on the mode-conversion in the received signal, using the PWT actuator/sensor network for a HCSS plate, based on the experimental results. Though, there is a deficiency of a fast, systematic and efficient disbond detection technique for HCSS by using a sparse actuator-receiver network of PWTs.

In this research work, the dispersion curve and the baseline theoretical response of the HCSS is obtained, using a global matrix method based 2D semi-analytical model [19] to guide the numerical and experimental results. A 3D FE method based numerical simulation in ABAQUS is carried out, in order to simulate the disbond influences on GW propagation in the HCSS. Experimental studies are then conducted to verify the numerical simulation and for disbond detection. Eventually, based on changes in modal characteristics, the location and size of unknown disbonds within the PWT array are experimentally (for single disbond) and pseudo-experimentally (for multiple disbond) determined using an appropriate SDC algorithm. The differential features of disbond are represented by using an appropriate SDC. Probabilistic analysis of the differential features of the propagated GWs in the HCSS with and without disbond for each transmitter-receiver pair is conducted to form the disbond localization image at each frequency. By superimposing the images from each transmitter-receiver itinerary, an imaging area is reconstructed. The final image of the whole plate is obtained by using image fusion technique, demonstrating that the proposed approach is able to provide reliable quantitative information about the size and location of hidden disbonds in the HCSS.
2. Experimental setup

The HCSS sample plate (600mm × 450mm × 13.5mm) used in this study is comprised of an aluminum honeycomb core (12mm thick) embedded between two Graphite/Epoxy fiber reinforced composite (GFRC) skins (0.74mm thin) at the top and bottom. Each GFRC skin consists of seven composite layers, in which five unidirectional (UD) twill composite layers are present in-between two cross-ply (CP) layers. The disbond region (30mm × 30mm) between the skin-core interphase is generated during the manufacture of the sample HCSS plate. The detailed elastic properties of the HCSS are given in Table 1. Where, ‘\(E\)’ is the Young’s modulus, ‘\(G\)’ is the shear modulus, ‘\(\nu\)’ is the Poisson’s ratio, ‘\(t\)’ is the layer thickness and ‘\(\rho\)’ is the mass density.

Table 1: Elastic properties of the HCSS

<table>
<thead>
<tr>
<th>Material</th>
<th>(E_1) (GPa)</th>
<th>(E_2) (GPa)</th>
<th>(E_3) (GPa)</th>
<th>(G_{12}) (GPa)</th>
<th>(G_{23}) (GPa)</th>
<th>(G_{13}) (GPa)</th>
<th>(\nu_{12})</th>
<th>(\nu_{13})</th>
<th>(\nu_{23})</th>
<th>(\rho) (kg/m(^3))</th>
<th>(t) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD-lamina</td>
<td>60.212</td>
<td>60.212</td>
<td>10.252</td>
<td>18.20</td>
<td>3.611</td>
<td>3.611</td>
<td>0.20</td>
<td>0.03</td>
<td>0.03</td>
<td>142</td>
<td>0.08</td>
</tr>
<tr>
<td>CP-lamina</td>
<td>110.31</td>
<td>110.31</td>
<td>18.247</td>
<td>42.41</td>
<td>4.136</td>
<td>4.136</td>
<td>0.30</td>
<td>0.12</td>
<td>0.12</td>
<td>165</td>
<td>0.17</td>
</tr>
<tr>
<td>Soft-core</td>
<td>0.0804</td>
<td>0.0804</td>
<td>1.6121</td>
<td>0.0321</td>
<td>0.0964</td>
<td>0.0964</td>
<td>0.25</td>
<td>0.025</td>
<td>0.025</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>Adhesive</td>
<td>0.0486</td>
<td>0.0486</td>
<td>0.0486</td>
<td>0.0174</td>
<td>0.0174</td>
<td>0.0174</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>125</td>
<td>0.01</td>
</tr>
</tbody>
</table>

In order to verify the theoretical and numerical results, experiments are carried out on the HCSS sample plate using surface-bonded PWTs (20mm × 20mm × 0.4mm). The actuator/sensor PWTs are operated through an NI-instrument (PXI system), as clearly described in [24].

![Fig. 1: (a) Sample HCSS, (b) PWT arrangements on the HCSS against the disbond region and (c) 150kHz input signal](image)

A proper transducer arrangement is crucial for the success of GW based NDE of HCSS [15]. In Fig. 1(b), the schematic diagram of the PWT positions on the experimental plate is shown. It is useful to note that the disbond falls directly along the GW propagation path comprised of transducer pairs 5-6 and 1-8.

Selection of an appropriate driving frequency is essential for the success of GW-based SHM and NDE [25]. In order to counter the dispersive effects of the propagating GW signal, an optimum input signal for the available SP-5H PWTs is selected as 150kHz five–cycle sine pulse in a Hanning window (Fig. 1(c)) and used for the experiment and subsequent theoretical and numerical studies unless otherwise stated.
3. Theoretical modeling of HCSS

In order to study the dispersion characteristics and response of the healthy HCSS plate, a recently developed 2D semi-analytical theoretical model is considered. The schematic representation of the 2D semi-analytical model of the given HCSS for a horizontal surface excitation (representing the PWT loading behavior) is shown in Fig. 2.

![Fig. 2: 2D schematic representation of the layered HCSS](image)

A detailed formulation of 2D semi-analytical model for wave field calculations in HCSS can be found in Banerjee and Pol [19] and will not be repeated here for brevity. In this model, the horizontal surface displacement on the HCSS can be expressed in frequency-wavenumber domain in the form:

\[ \hat{u}_i = \frac{F(\xi_1, \omega)}{G(\xi_1, \omega)} \quad (2) \]

where, \( \omega \) and \( \xi_1 \) comes from the complicated matrix operation.

The group velocity-dispersion curves can be obtained from the given dispersion condition as:

\[ G(\xi_1, \omega) = 0 \quad (3) \]

The values of \( \xi_1 \) can be determined for a range of values of \( \omega \) and the corresponding group velocity-dispersion plots can be sought by using

\[ c_g = \frac{\delta \omega}{\delta \xi_1} \quad (4) \]

where \( c_g \) represent the group velocity of the propagating GW modes.

The solution for the horizontal surface displacement in the spatial domain can be obtained through

\[ \hat{u}_i(x_1, x_3, \omega) = \int_{-\infty}^{\infty} F(\xi, \omega) e^{i \xi x_3} d\xi \quad (5) \]

The integration in equation (5) can be solved by applying the Cauchy’s residue theorem [26] on the real roots of \( \xi_1(\xi_r, \text{where } r = 1 \text{ to } NR, \text{NR = no. of real roots}) \) as

\[ \hat{u}_i(x_1, x_3, \omega) = 2\pi i \sum_{r=1}^{NR} \frac{F(\xi_r, \omega)}{dG(\xi_r, \omega)} e^{i \xi_r x_3} \quad (6) \]

Finally, an inverse Fourier transform can be performed to the Eq. (6) to get the time-domain results.

4. Numerical Simulation

A 3D numerical simulation of PWT induced GW propagation in the HCSS with multiple disbond regions is carried out using FE based explicit and implicit codes in ABAQUS, in order to study the disbond effects on the propagating GW modes and to generate pseudo-experimental signals for the pseudo-experimental identification of multiple disbonds in a
single HCSS. In the explicit code, the HCSS sample plate is modeled, using the 8-noded ABAQUS C3D8R elements. The layer-wise element sizes in the HCSS are: GFRC skin: 5mm × 5mm × 0.05mm, adhesive: 5mm × 5mm × 0.01mm and aluminum core: 5mm × 5mm × 0.5mm. Then, in the implicit code eight-PWTs (actuator/receiver) are placed at a distance of 400mm on the top surface of the explicit-HCSS model (Fig. 3(a)). The PWTs comprises of two parts, one is the electrode part (at the bottom) and the other is the piezoelectric part (at the top), as shown in Fig. 3(b). The 8-noded standard C3D8E elements (1 mm × 1mm × 0.1 mm) are considered to model the electrode part. In which, zero voltage is assigned on both the top and bottom surface nodes. The 8-noded standard C3D8E linear piezoelectric brick elements (1 mm × 1mm × 0.13 mm) are selected for the piezoelectric part (piezo). This C3D8E element is capable to grasp the electro-mechanical coupling phenomenon, and the electrical voltage is the additional DOF in the coupling element. The selected input signal (voltage) applied at the nodes on the top surface of the transmitter-piezo, and zero voltage is applied at the bottom nodes of both the transmitter and receiver-piezo to model the grounding operation. The output voltage collected at the top surface of the receiver-piezo. In this study, the SP-5H piezoelectric wafer transducers (manufacturer: SPARKLER Ceramics Pvt. Ltd., India) are used [27]. Finally, the ABAQUS ‘Standard-Explicit Co-simulation’ option is implemented in order to create the link between explicit and implicit simulation [28].

Fig. 3: (a) Numerical model of HCSS with three disbond regions showing the PWT positions and (b) an enlarged view of the PWT

5. Results and discussions

5.1 Dispersion curves and baseline response: The theoretical frequency versus group velocity dispersion curve for the HCSS is theoretically obtained and presented in Fig. 4(a).

Fig. 4: (a) Theoretical group velocity-dispersion curve and the (b) comparison of baseline theoretical, numerical and experimental time-history responses for the HCSS
The dispersion plot clearly shows the existence of multiple propagating wave modes that correspond to the real roots of the Eq. (3). The steepest descent method is applied to draw out these roots [29]. The anti-symmetric modes are designated as A0, A1, A2, etc., while the symmetric modes are designated as S0, S1, S2, etc. [25]. The theoretical obtained output response is obtained for an actuator-receiver distance of 200mm on the healthy HCSS and compared with the numerical and experimental baseline responses, which shows a good agreement with the presence of six independent GW modes.

5.2 Study of disbond effect: The numerical and experimental output responses are obtained and compared for with and without disbond cases, in order to understand the disbond-effect on the propagating GWs (Fig. 5(a,b)). It is observed that due to the presence of disbond in the HCSS significantly amplifies the A0 mode amplitudes of the received signals for both numerical simulation as well as experiments.

![Graph](image1)

**Fig. 5:** Comparison of the with and without disbond signals from (a) numerical simulation, (b) laboratory experiment and the (c) WT of the experimental signals at (b)

5.3 Disbond detection algorithm: An SDC based disbond imaging algorithm is used [25], which uses the Wavelet transform (WT) [18] of the experimental sensor signals in the time-domain. The damage localization probability, \( D_d \), of any arbitrary position \((x, y)\), within the sensor network is expressed [22] as:

\[
D_d (x, y) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} D_{ij} (x, y) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} sdc_{ij} (x, y) \left[ \frac{\beta - A_{ij}(x, y)}{\beta - 1} \right]
\] (1)

where, \( D_{ij}(x,y) \) represent the damage distribution probability, measured from actuator-sensor pair: i-j and \( sdc_{ij}(x,y) \) is the signal different coefficient, which is the difference in amplitude area with disbond and without disbond for a particular GW mode. The SDC can be represented as:

\[
sdc_{ij} = \sqrt{\frac{\int_{t_1}^{t_2} (s^d - s^b)^2 \, dt}{\int_{t_1}^{t_2} [s^i]^2 \, dt}}
\] (2)

where, \( s^d \) and \( s^b \) are the GW signals correspond to the with disbond and without disbond, \( t_1 \) is the time of arrival for a particular wave mode and \( t_2 = (t_1 + \text{bandwidth of signal}) \), \( \left[ \frac{\beta - A_{ij}(x, y)}{\beta - 1} \right] \) is the spatial distribution function, which has contour in the shape of ellipse with a positive value, and
\[ A_j(x, y) = \begin{cases} p_j(x, y), & p_j(x, y) < \beta \\ \beta, & p_j(x, y) \geq \beta \end{cases} \]  

(3)

where, \( p_j(x, y) = \frac{\sqrt{(x-x_j)^2(y-y_j)^2} + \sqrt{(x-x_j)^2(y-y_j)^2}}{p_{ij}} \)  

(4)

where the \( \beta \) is a small scaling parameter that reduces the size of the disbond zone and it is independent of propagation velocity and \( P_{ij} \) is the distance between actuator ‘i’ and receiver ‘j’.

5.4 Disbond identification using experimental signals: The size and location of a hidden disbond region is identified using the WT of the A0 mode based experimental received signals (e.g. Fig. 5(c)) in the SDC algorithm. In this study, the 1-2 sensor configuration (path) is taken as baseline for 3-4, 5-6, and 7-8 sensor path, as the 1-2 path is considerably away from the disbond region (ref. Fig. 1(b)). Similarly, the sensor path: 2-7 is considered as baseline for the sensor path: 1-8. In order to obtain the SDC maps, the transformed A0 mode received signals are collected from the sensor configuration: 1-2, 3-4, 5-6, 7-8, 1-8 and 2-7, and applied as input to the SDC algorithm. The SDC maps are shown in Fig. 6, which represents the maximum damage intensity value close to the disbond location. A 3D representation of the disbond region corresponding to the SDC magnitudes is also shown in Fig. 6(c) for better understanding of the disbond effect on the SDC. It is expected that the availability of baseline data will significantly improve the disbond detection capability and possibly size it with some degree of confidence. However, it is observed that the algorithm is capable to identify the hidden disbond location using the A0 mode based signal with a minimum number of sensor paths available.

5.5 Multiple-disbond identification using pseudo-experimental signals: The pseudo experimental results are considered for multiple disbond identification due to the absence of experimental sample plate with multiple disbond zones. Towards this, a 3D numerical simulation of the HCSS with presence of three disbond zones (50 mm × 50 mm) is carried out in ABAQUS. In the PWT-network shown in Fig. 3(a), the ‘with disbond’ and ‘without disbond’ signals are collected from different receiver PWTs. The actual experimental system noise is considered, as shown in Fig. 7(a). A histogram (Fig. 7(b)) of the experimental-noise is obtained in MATLAB. The relationship between number of data and number of bins can be represented [30] as:  

\[ W = 1 + 3:3 \log_{10} (NS) \]  

(5)

where, \( W \) and \( NS \) are the number of bins and data points, respectively.
In the study, a 250µs noise with 748 data points is considered for generating the histogram, where the number of bins was obtained as 11. The normal distribution is fitted well to the histogram. Once, the noise is characterized, random numbers are generated based on the parameters (mean = 0.000519065 and variance = 2.18356e-05) of the distribution. The pseudo-experimental signals are then generated by adding this simulated noise to the numerically obtained signals.

The pseudo-experimental signals correspond to different actuator-sensor paths are applied in the SDC algorithm to examine the potential of the proposed NDE technique for multiple disbond identification in the HCSS. It is observed that the SDC-maps (Fig. 8) obtained by using the pseudo-experimental signals in the algorithm have shown the exact location and approximate size of the hidden disbond zones. Fig. 8(c) shows a 3D representation of the SDC map with prominent effects from the multiple disbond zones.

### 6. Conclusions

The GW propagation mechanism in the HCSS is multi-modal in nature. Existences of six independent GW modes (A0, S0, A1, S1, A2 and S2) are found in the received signals at 150kHz frequency. The presence of disbond in the HCSS leads to significant amplification of the A0 mode. The proposed SDC-algorithm based NDE technique is capable to experimentally identify the approximate size and exact location of hidden disbond region in the HCSS within an actuator/sensor network, using minimum number of sensor paths. The proposed technique has also shown its potential to efficiently identify multiple disbond.
regions in the HCSS, using the transformed pseudo-experimental signals.

References