The Effect of Temperature on Guided Wave Signal Characeeristics in a Honeycomb Composite Sandwich Structure with Disbond and Delamination

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ABSTRACT

Researchers developing guided wave (GW) based structural health monitoring (SHM) techniques frequently utilize amplitude and group velocity variations to detect and localize damage. However, external factors such as temperature and moisture can affect these features. To address this, a coordinated numerical and experimental study was conducted to investigate GW propagation characteristics in honeycomb composite sandwich structures (HCSS) with two types of damage: disbond and delamination, across a temperature range of $0°$ to $90°$ C. Computationally efficient two-dimensional (2D) numerical models were developed using COMSOL Multiphysics that takes into account a variety of temperature-related phenomena, such as thermal stresses and changes in the material properties of honeycomb sandwich and piezoelectric wafer transducers (PZTs). The amplitude and group velocity of the fundamental anti-symmetric (A0) mode are found to increase with disbond and decrease with delamination. Additionally, the normalised amplitude of the A0 mode linearly decreased with increasing temperature for both healthy and damaged cases. Given the A0 mode's wide usage for damage detection, an adjustment equation for amplitude and group velocity with temperature change is proposed.

INTRODUCTION

The applications and usage of HCSS is progressively increasing in a variety of lightweight engineering structures like aerospace and wind turbine blades due to their high strength-to-weight ratio. The occurrence of concealed faults such as disbond, core crush, and delamination in the HCSS, which might compromise the structure's safety, is a serious limitation restricting the use of HCSS. Employing the amplitude and group velocity of the guided wave modes, many researchers [1, 2] were successful in identify-

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ing and localising these defects. Variations in the signal features such as amplitude and phase are expected to occur when the HCSS is exposed to changing operating and environmental conditions such as temperature, moisture, vibration, and load [3]. As a result, knowing the influence of temperature on the amplitude and group velocity of guided wave modes is critical for developing a dependable SHM system.

Several investigations have explored the effect of temperature on the propagation of GWs in composite panels and have observed that temperature exerts influence over the amplitude and group velocity of the signals. Sikdar *et al* [4] performed research on the impact of temperature fluctuations on GW modes in a bonded composite structure (BCS) featuring a disbond, as well as a sandwich structure with a core-core joint debond. They observed that as the temperature increased, both the amplitude and group velocity of lamb wave modes decreased.

Previous literature indicates a scarcity of research concerning the influence of temperature on GW modes in HCSS. Additionally, there is a lack of robust numerical models capable of accurately simulating GW propagation in an HCSS under varying temperature conditions for healthy and damaged cases. Hence, the motivation behind this study is to examine how temperature affects the amplitude and group velocity of GW modes in an HCSS, considering both healthy and damaged regions such as disbond and delamination. Experimental investigations were conducted on an HCSS specimen, and a 2D numerical model was developed using COMSOL Multiphysics. Extensive analyses have been performed on the effect of temperature on the characteristics of the primary antisymmetric mode (A0 mode). Finally, a temperature compensation equation has been proposed for the normalised amplitude and group velocity of the A0 mode.

EXPERIMENTAL SETUP

Experimental studies on HCSS were performed using a thermal chamber manufactured by ARC lab (Figure 1 (Left)). The HCSS specimen, measuring 1 m x 1.2 m, was made by sandwiching two composite face sheets with a 12.7 mm thick aluminum honeycomb core between them. The face sheets consisted of six layers, each 0.125 mm thick, arranged in the following orientation: [0, +60, -60, -60, +60, 0]. These face sheets were individually cured and bonded to the core using film adhesive. The influence of temperature variations on GW signals was investigated for three scenarios: the healthy case, as well as the presence of two damages—disbond and delamination. The disbond was created by removing the film adhesive within a 30 mm x 30 mm region between the core and face sheet. On the other hand, the delamination was introduced between the second and third layers of the face sheet adjacent to the core by inserting a thin layer of Teflon release film measuring 30 mm x 30 mm.

The HCSS specimen, including disbond and delamination damages, was monitored using a network of eight PZTs as shown in Figure 1 (Right). The actuation and sensing of signals were facilitated by an Xilinx Artix®7 FPGA board, which was connected to the PZTs using a cable. To determine the maximum amplitude response of the PZTs on the HCSS, a narrow band signal modulated by a hanning window was employed and a frequency response plot was generated within the range of 50 to 140 kHz. The bonded surface PZTs exhibited a peak response at 90 kHz (Figure 3 (Left)). However, in this

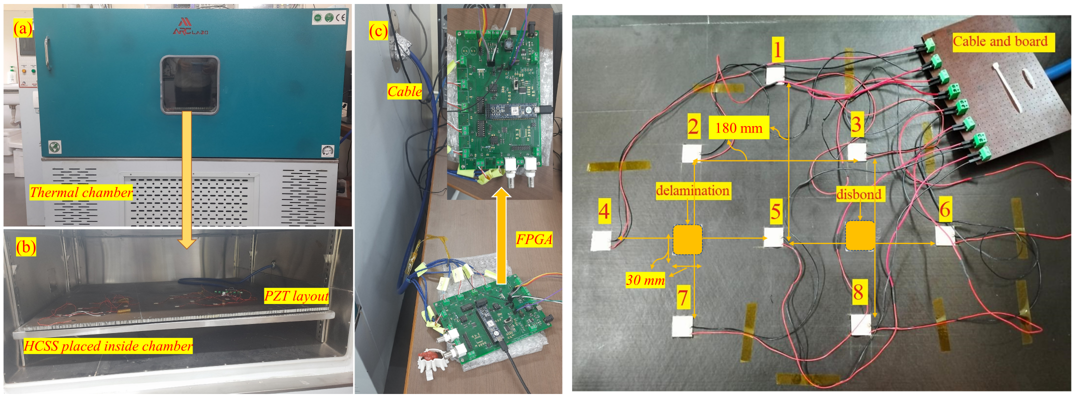

Figure 1. Experimental set-up used for thermal studies on HCSS(left),Figure showing PZT layout used and location of damages(right)

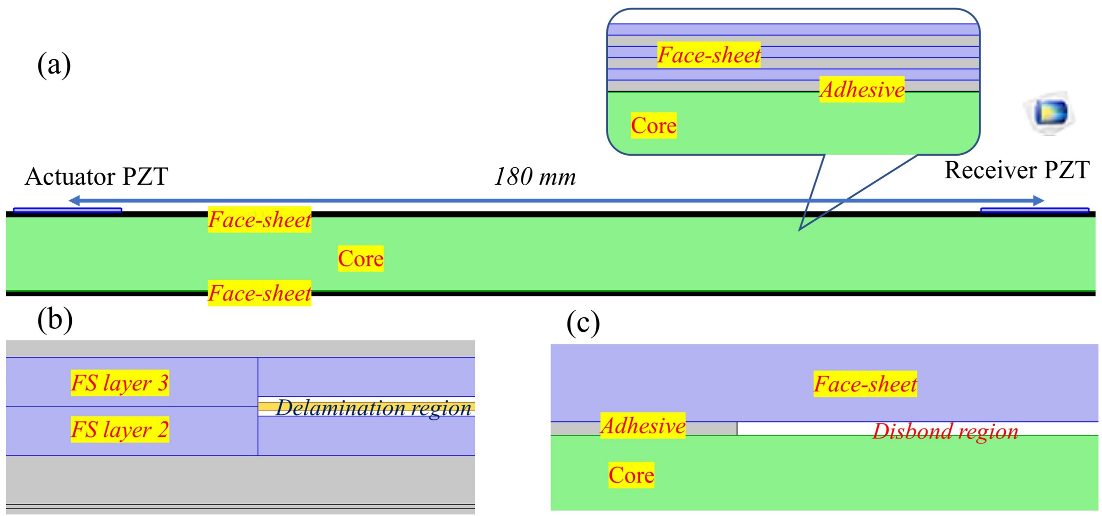

Figure 2. Numerical model developed using COMSOL (a) Section of HCSS with PZTs, Zoomed view of (b) delamination region, (c) disbond region

study, an actuation frequency of 75 kHz was selected to ensure better separation between the generated modes and to achieve sufficient response amplitude for the conducted investigations.

FE MODELLING OF HCSS WITH TEMPERATURE

COMSOL Multiphysics (version 5.5), was utilized for the FE simulations in this study. Given the dimensions of the HCSS used in our experimental investigation (1000 mm x 1200 mm x 14.2 mm), constructing a computationally efficient 3D model would require a significant number of degrees of freedom and substantial RAM resources. As a result, to mitigate computational demands, we opted for a 2D model. This decision was justified by the fact that all GW propagation paths in our study were straight lines, thereby allowing for accurate representation within a 2D simulation framework.

The 2D HCSS specimen used in the simulation had dimensions of 1200 mm × 14.2

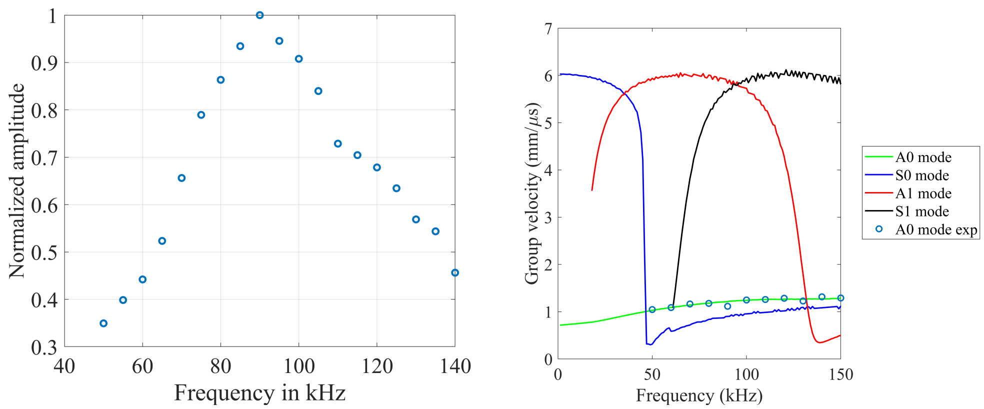

Figure 3. Calibration curve for frequency modulation (Left), Group velocity dispersion curves (Right)

mm. It consisted of a 12.7 mm thick aluminum honeycomb core (1200 mm × 12.7 mm) sandwiched between two composite face sheets. The face sheets were composed of six individual unidirectional layers. Two PZTs, measuring 20 mm × 0.7 mm, were attached to the surface of the HCSS at a center-to-center distance of 180 mm (Figure 2(a)). Both damages were positioned at a distance of 75 mm from the actuator and receiver PZTs, precisely in the center of the propagation path. Zoomed views of these damages are depicted in Figure 2(b) and (c), respectively. The temperature-dependent material properties of each layer in the HCSS are determined using the Chamis relation, while the temperature-dependent material properties of the PZTs are calculated using equations developed by Surajit *et al* [5]. The multi-physics simulation model involves two study steps. A stationary step is utilized to account for the effect of temperature on the HCSS, while a time-dependent step is employed for the propagation of guided waves through the HCSS. To ensure convergence of the stationary study, a gradual temperature change is implemented rather than an abrupt increase. The temperature is incrementally adjusted from room temperature to the desired temperature using tiny increments. The incremental change, denoted as i, ranges from 0 to 1 in increments of 0.01. This gradual temperature change is represented by the equation:

$$T_{DT} = T_{RT} + \delta T \times i \tag{1}$$

Here, T_{DT} represents the desired temperature, T_{RT} is the room temperature, δT is the temperature difference between the two states, and i represents the incremental change.

RESULTS AND DISCUSSIONS

Characteristics of GW Propagation at Room Temperature

The dispersion curves for the HCSS used in this study, were derived in previous work [6] and are shown in Figure 3 (Right).In this work, the A0 mode was chosen for investigation due to its smaller wavelength and higher sensitivity to defects present in the HCSS. To understand the influence of damage on GW propagation, the output response signals from the healthy and damaged examples are compared. The GW output

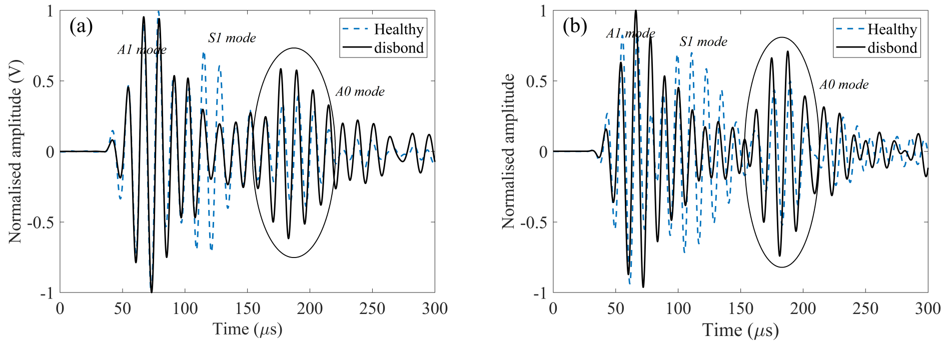

Figure 4. Plots showing Comparison of Healthy and disbond GW signals: (a) Experimental results (b) Numerical simulation results

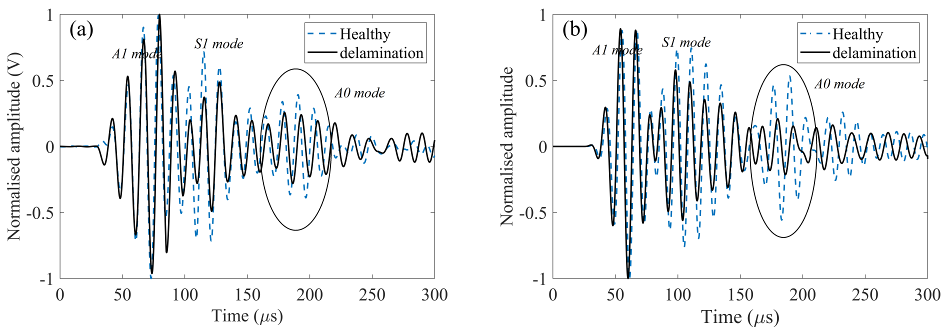

Figure 5. Plots showing Comparison of Healthy and delamination GW signals: (a) Experimental results (b) Numerical simulation results

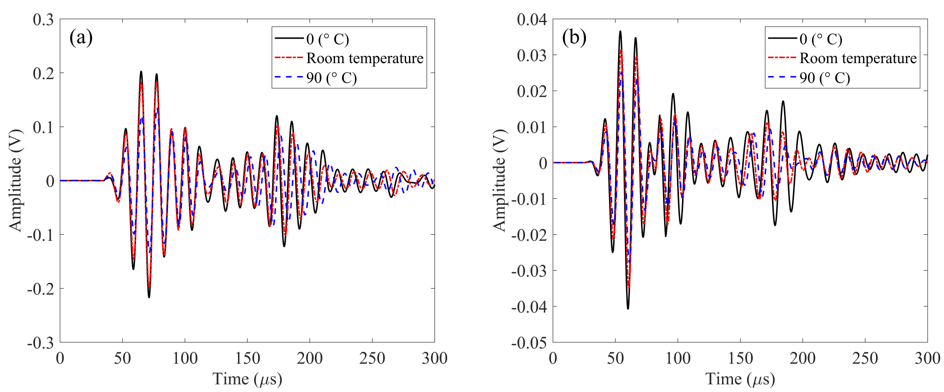

Figure 6. Plots showing the effect of temperature on GW signals: (a) Experimental results (b) Numerical simulation results

responses obtained from an experimental investigation and FE simulations for the disbond and healthy instances are shown in Figure 4. The figures show that the amplitude and group velocity of the primary anti-symmetric mode increase in the presence of disbond. Several authors [1, 7] attributed this increase in amplitude and group velocity of the A0 mode seen in the presence of disbond to the leaky lamb wave phenomenon. The fact that the A0 mode travels quicker in the face-sheet (due to greater stiffness) may

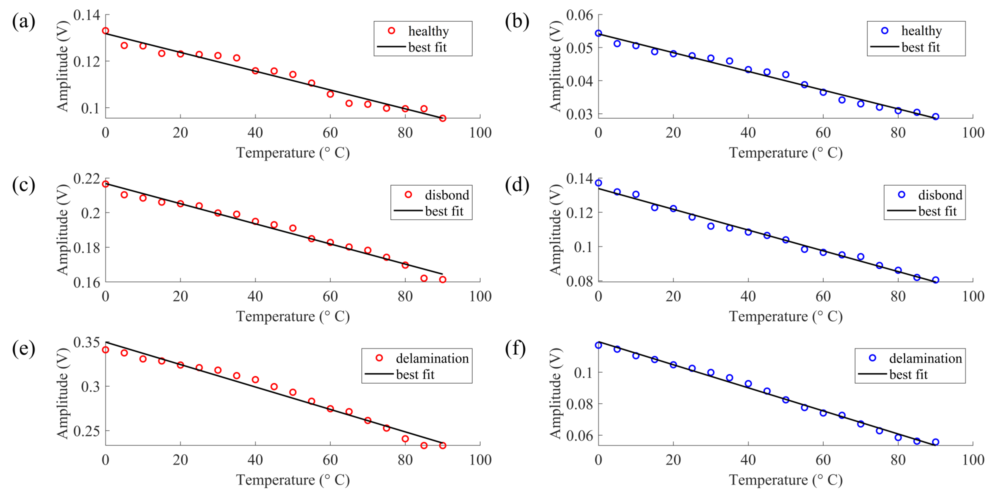

Figure 7. Variation of amplitude with temperature: (a, c, e) A1 mode and (b, d, f) A0 mode for healthy, disbond and delamination respectively

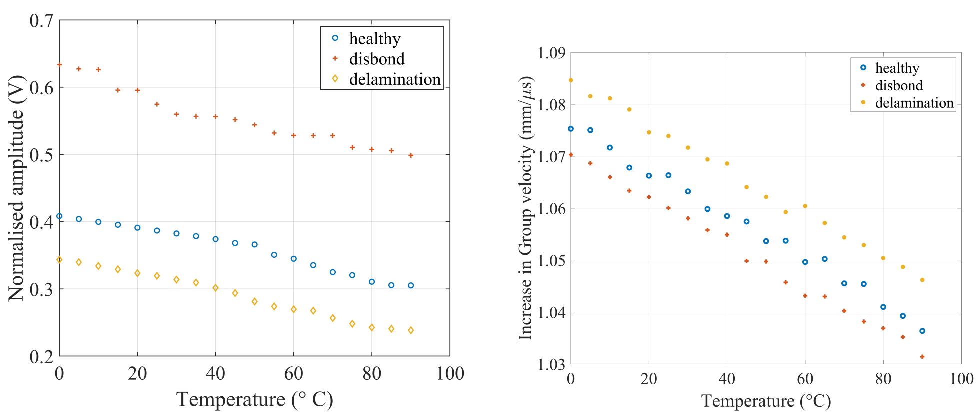

Figure 8. Variation in normalised amplitude with temperature for healthy, disbond and delamination (left), Variation of A0 mode group velocity with temperature for healthy, disbond and delamination (Right).

possibly account for the increase in the group velocity of the A0 mode [1].

When comparing the GW output response signals between healthy and delamination regions, the amplitude and group velocity of the A0 mode decrease, as illustrated in Figure 5. Wave trapping on top of the delaminated zone, as well as energy absorption in the layers between the face sheet and the Teflon release film, may explain the decrease in amplitude and group velocity of the A0 mode.

Variation of GW Amplitude and group velocity with Temperature

The GW response signals acquired from experimental and numerical investigations for the path that traverses a disbond zone with variation in temperature is shown in Figure 6. The findings reveal that when the temperature rises, the amplitude of the output response signals decreases across all GW modes and the arrival time slows down. Figure

7 depicts the fluctuation of amplitude of A1 mode and A0 mode versus temperature rise for paths traversing through the three cases investigated, and it can be seen that there is an almost linear reduction in amplitude with temperature increase.

Figure 8 (left) shows the normalised amplitude plots for the three cases considered: healthy, disbond, and delamination. It is worth noting that a linear drop in amplitude is seen in all three scenarios. When comparing the damaged region to the healthy region, it is imperative to remember that the amplitudes must be compared at the same temperature. Failure to do so might lead to false damage detection.

A temperature increase from 0^o to 90^o C delays the arrival time of the A1 mode by just 1 µs in all scenarios studied, but the arrival time of the A0 mode is delayed by roughly 6 µs. Temperature has a significant influence on the amplitude of the A1 mode but not on the group velocity. Because temperature has little impact on A1 mode group velocity, only variations in the A0 mode are shown. The variation in group velocity of the A0 mode with temperature is seen in Figure 8 (Right). Because the drop is comparable in all the three scenarios , the difference in group velocity can only be utilized to identify damage at the same temperature.

Amplitude and Group Velocity Correction Equation For The A0 mode

It is clear from the preceding discussions that amplitude and group velocity correction with temperature variation is required for a reliable and robust SHM of HCSS. All the three plots in Figure 8 (left) are employed for determining the amplitude correction equation. For each of the three scenarios considered, a polynomial of one degree was used to fit the data. Because the slope of the three equations are so near to each other, an average slope of the three examples is utilized, which is roughly -0.00133. The following is the suggested equation for calculating normalised amplitude A_T at any temperature 'T':

$$A_T = A_{RT} + 0.00133 * (RT - T) \tag{2}$$

Where A_{RT} is the amplitude of output sensor signal at room temperature and RT is the temperature at room temperature. Similar equation can be derived for the group velocity GV_T of the A0 mode at any temperature 'T':

$$GV_T = GV_{RT} + 0.0004223 * (RT - T) \tag{3}$$

Where GV_{RT} is the group velocity of the A0 mode at room temperature. Given that researchers often utilize A0 mode to identify and localize defects in an HCSS, these equations may be employed to determine amplitude and group velocity at any temperature 'T', as long as we know the values at ambient temperature. The slope of the linear equations suggested above may vary depending on a variety of parameters such as the HCSS material's properties and the frequency of investigation. An analogous linear relationship may be derived for a specific HCSS, thus developing an efficient and reliable SHM system.

CONCLUSIONS

Using coordinated FE simulations and experimental investigations,this study explored the effect of temperature on guided wave propagation in an HCSS, considering a healthy structure and two types of damages (disbond and delamination). Temperatures ranging from 0^o to 90^o C were studied, and output responses were obtained for every 5^o C variation in temperature. The objective was to understand how amplitude and group velocity change with temperature, as these parameters are commonly used for SHM of HCSS. The results showed that disbond increased the primary anti-symmetric mode's amplitude and group velocity, while delamination decreased them. Both amplitude and group velocity decreased with temperature, with the A0 mode being more affected. Normalised A0 mode amplitude was used for detecting disbond and delamination in an HCSS, and this parameter was studied with variation in temperature, and it was observed that this feature is effective even with changes in temperature. The study proposed an amplitude correction equation with temperature for the anti-symmetric mode, which is widely used for defect detection. The findings contribute to the development of a robust SHM system for HCSS under varying temperature conditions.

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