Effects of Honeycomb Core on Acoustic Emission Wave Propagation in Glass Fibre Composite Plates

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Abstract
The objective of this article is to study in detail the acoustic emission wave propagation in a complex sandwich structure panel by utilising artificial Hsu-Nielsen acoustic emission sources. The sandwich panel consists of aluminium honeycomb core placed between two unidirectional glass fibre laminated plates. In order to study the effects of a bonded honeycomb core, artificial acoustic emission sources were generated on the top of a glass fibre laminated plate alone, at different angles relative to the fibre direction then repeated on the sandwich panel to find the change in (i) attenuations, (ii) wave velocities and (iii) frequencies of propagating acoustic emission waves. The attenuation of the waves increases after bonding the honeycomb in some directions. As an example, in direction 30^{o}, the attenuation coefficient increases significantly from 5.252 dB/m to 10.27 dB/m whereas in 15^{o} the change is small from 5.256 dB/m to 5.994 dB/m. On the other hand, the average velocity of acoustic emission in the plate has increased from 3527.02 m/s to 3836.85 m/s after bonding the honeycomb. However, in some other directions such as 0^{o} direction, the average velocity has significantly reduced from 4028.41 m/s in the fibre glass laminated plate to 3637.36 m/s. Finally, wavelet transformation has been carried out on the waves in all directions and it is found that the active frequencies in the glass fibre laminated plate and the sandwich panel are in range from 30 kHz to 130 kHz. The results show that the presence of a bonder honeycomb core contributes significantly in changing to the acoustic emission propagation characteristics in the laminated glass fibre plates.

Keywords: Acoustic emission; Honeycomb Composite; Lamb wave; Wave attenuation; Wave directional velocity; Wave propagation

1. Introduction
As the interest for light weight with high stiffness materials is expanding in wind energy industry, the use of honeycomb sandwich structure panel becomes important for wind turbine blades. Honeycomb composite structure is a special class of composite materials that have become popular for aerostructures due to their outstanding mechanical properties such as tailorable stiffness and light weight. A sandwich panel is a combination of composite structural components, consisting of two thin stiff plates with a core material in between. As a result, a sandwich panel can be implemented in

different wind turbine blade designs, especially at "near root'' area where there are severe bending stresses. However, a primary concern of the honeycomb composite structure is to characterise the failure modes and defect initiation within the composite material during testing and operating as well. Acoustic Emission (AE) is increasingly being recognised as a viable structural health monitoring (SHM) technique, not only in defect detection but also in defect localisation. AE is the mechanical perturbation that occurs in the elastic medium due to the sudden release of strain energy in a material under loading[1]. In this technique, piezoelectric sensors are placed over the test area of interest using an acoustic couplant, such as grease, which acts to ensure good transmissivity between the sensor and the structure. The surface waves that are generated as a result of defect's energy release in the test area, cause the piezoelectric sensors to produce a voltage and hence a signal output can be displayed using a suitable data acquisition system and subject to post-processing. However, a major concern with this technique is the understanding nature of the elastic wave motion in the structure. For infinite surface bounded with two boundaries, usually a Lamb wave[2] is the dominant wave. Lamb waves are characterised by two distinctive wave modes; an extensional S_o mode and a flexural A_o mode. The S_o mode typically propagates at higher frequencies and velocities than the A_o mode. Although the wave characteristics are the same in all directions for isotropic materials, in anisotropic (e.g. orthotropic) fibre reinforced composite, the wave has directional characteristics (i.e. wave characteristics are different in various axes)[3]. Most studies in the field of AE in composites have only focused on composite or metallic plates. So far, however, there has been little discussion about the AE wave behaviour in honeycomb composite structure. For instance, Sikdar et al [4], have used acoustics emissions testing in analysis of honeycomb sandwich structure for defects localisation using analytical, numerical and experimental analyses. They have proposed different sensor-arrays (circular, rectangular, and zigzag) and induced artificial AE using Hsu-Nielsen sources. They found that the zigzag sensor array has the lowest source localisation error (i.e. ±6 mm). Baid et al [5], have conducted analytical, numerical and experimental analyses for studying wave dispersion in three different materials; aluminum, carbon fibre woven laminate and aluminum honeycomb sandwiched between two carbon fibre composite plates. They found that the phase velocity of S_o drops dramatically in case of adding aluminum honeycomb between two carbon fibre faces. However, it has not yet been investigated the effects of the honeycomb contact area with top and bottom glass fibre laminated plates. The paper at hands presents a detailed study on AE wave characteristics in sandwich panel of orthotropic glass fibre composite plates and aluminium honeycomb core using artificial AE sources. This study is done through the following steps:

- Comparing the attenuation coeficients of the fibre glass laminated plate before and after bonding the honeycomb core.
- Comparing the velocities of the arrival AE waves the fibre glass laminated plate before and after bonding the honeycomb core.
- Wavelet transformation analyses of the fibre glass laminated plate and the sandwich panel to characterise the active frequencies.

2. Materials and Methods

2.1 Specimen manufacturing

The specimen used for this investigation consisted of honeycomb aluminum core sandwiched between two unidirectional glass fibre composite faces. The glass fibre top and bottom plates consisted of 5 laminates each $[0^o /90^o]_{5s}$ and total thickness is 2.5 mm per plate and the honeycomb core height was 10 mm. Further details on the specimen structure design and optimisation is provided in the study of Abdulaziz et al [6]. The glass fibre plate was manufactured by vacuum resin infusion technique. Ten spiral wound plastic tubes were placed equidistant on a nylon peel ply. Furthermore, vacuum pressure drop test was carried out to inspect leakage and ensure the gum tape sealing quality. The vacuum pressure was -1010 mbar inside the plate after the epoxy resin infusion. Then, the plate was left for curing in room temperature for 24 hours. The plate's length and breadth were trimmed to 820×820 mm with tolerance (±5mm) by using band saw machine. Figure 1 presents the manufacturing process of the composite plate.

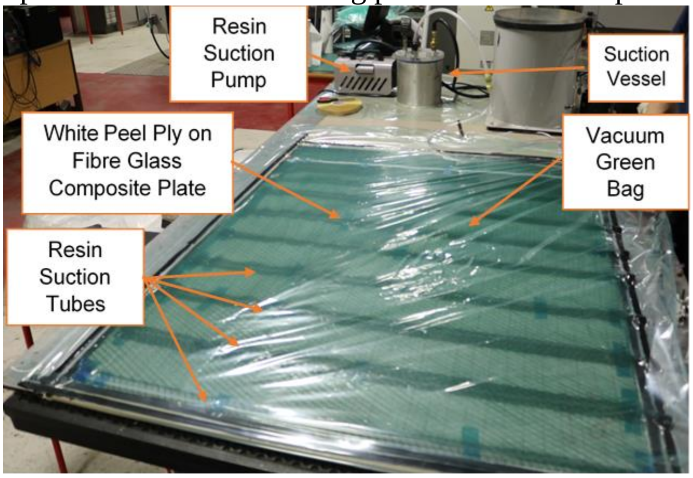

Figure 1. Glass fibre manufacturing by vacuum resin infusion process

Afterwards, the specimen was inspected using ultrasonic phased array to find out manufacturing defects before using it. The first specimen was defective due to the high suction pressure and poor infusion regions. The high vacuum pressure compressed down the spiral tubes on the glass fibre plate. Figure 2 shows the ultrasonic scanning result.

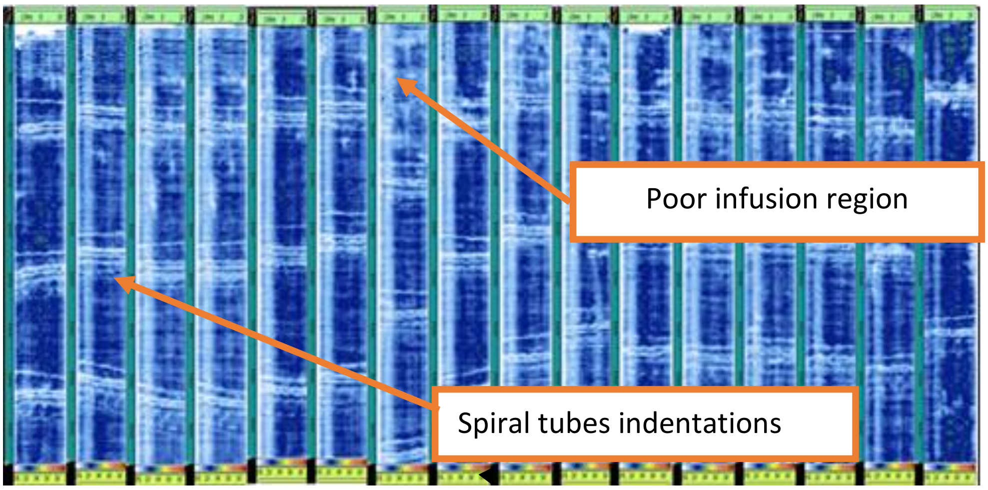

Figure 2. Phased array scanning of first glass fibre plate

These problems have been avoided in other specimens by using proper suction pressure of -1002 mbar and avoiding high suction pressures. Further, double mesh has been placed under each spiral tube to act as a cushion while infusion. To avoid the bad infusion region, each spiral tube was pre-tensioned in order that the epoxy could flow evenly and smoothly.

2.2 AE Test Apparatus

The laminated glass fibre plate was simply supported on two rigid aluminum supports. Figure 3 presents a schematic drawing of the AE test apparatus. Two wide band differential AE sensors (WD sensor from Mistras Ltd) were used; one (S_1) was fixed in the centre using silicon and another (S2) was placed 100 mm apart from the central sensor using grease as the acoustic couplant. The WD sensor has a wide range of operating frequencies, with a rated operating range of 100 kHz to 1000 kHz. The sensors were attached to pre-amplifiers and the gain was selected to be 40 dB. After that, the output BNC cables from the pre-amplifiers are fixed to a Mistras Ltd AEWin based PCI-2, 4 channel acquisition system. The sampling frequency was 5 MHz and maximum frequency of the signal band was 1 MHz which satisfied Shannon's theorem (e.g. max frequency $\leq 0.5 \times$ sampling frequency).

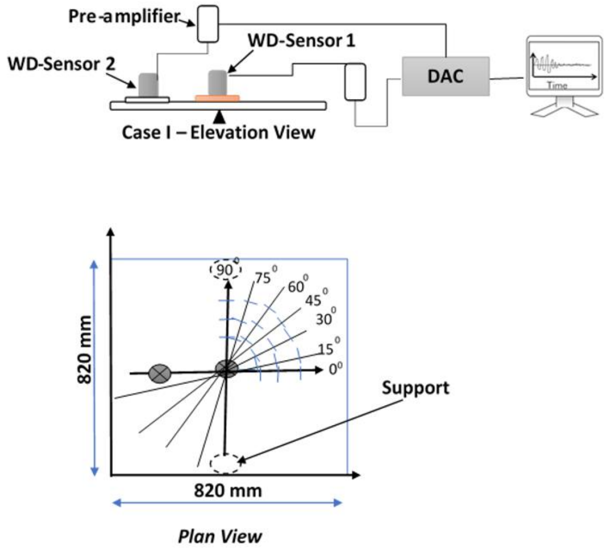

Figure 3. Schematic drawing of test apparatus

Furthermore, on the top right-hand quarter of the fibre glass laminated plate, angular lines were drawn to cover the area from 0^{o} to 90^{o} with interval 15^{o} with tolerance range [$\pm 1^{o}$]. For each direction, artificial AE sources were generated at distances of 50, 100, 150, 200, 250, and 300 mm from the central sensor; in order to improve the reliability of the result, five events were generated at each distance so that an average could be obtained. The experimental setup is presented in figure 4. This has been carried out on the glass fibre laminated plate alone (i.e. case I) and after fixing the honeycomb core between the plates (i.e. case II). It is worth mentioning that this panel is designed with such large surface area in order to obtain a guided AE wave with relatively low reflections.

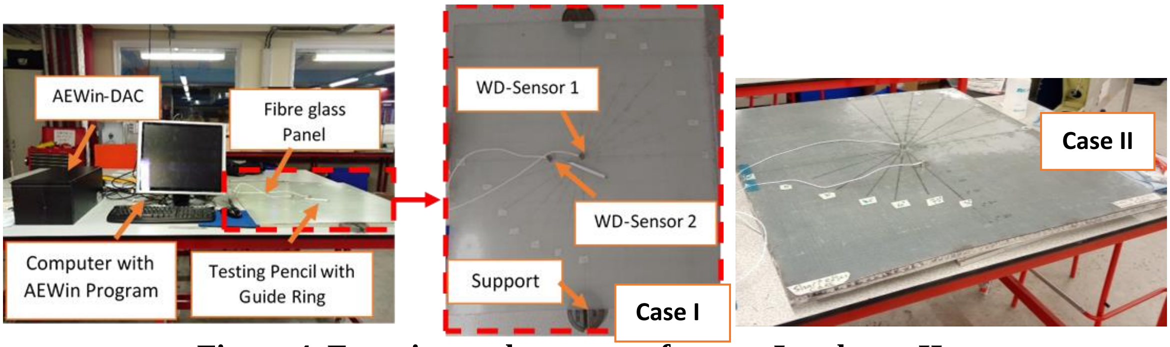

Figure 4. Experimental test setup for case I and case II

The timing parameters HLT, PDT, and HDT were 300, 100, and 200 µs respectively and the threshold level was 40 dB.

2.3 AE Results and Discussions

Ultrasonic wave speed and its attenuation during propagation in solid elastic media are important parameters that can be used for understanding the AE wave nature[7]. The following section explains the effects of honeycomb on AE wave propagation in the glass fibre laminated plate.

2.3.1 Attenuation Characteristics

AE wave propagation is affected not only by the material elastic properties but also by the geometry of the structure (e.g. holes, stiffeners, fibre alignment etc.) and the type of surrounding media (e.g. water, air, etc.). Therefore, wave attenuation study is worthwhile to ensure that AE sensors can be positioned appropriately on large honeycomb sandwich structures such as wind turbine blades. As aforementioned in section 2.2, the artificial AE sources were generated in different angles from 0^o to 90^o with interval 15^o on the glass fibre laminated plate and the sandwich panel as well. The average maximum signal amplitude was documented for each point and each angle, thus the attenuation curves shown in figure 5 were plotted. It should be acknowledged that the maximum signal amplitude in each instance was the amplitude of the A_o Lamb wave mode, so Figure 5 equated to the attenuation of the A_o Lamb wave mode. Further, the kind of wave propagating in the sandwich panel is still ongoing study to confirm whether it is Lamb wave or another kind.

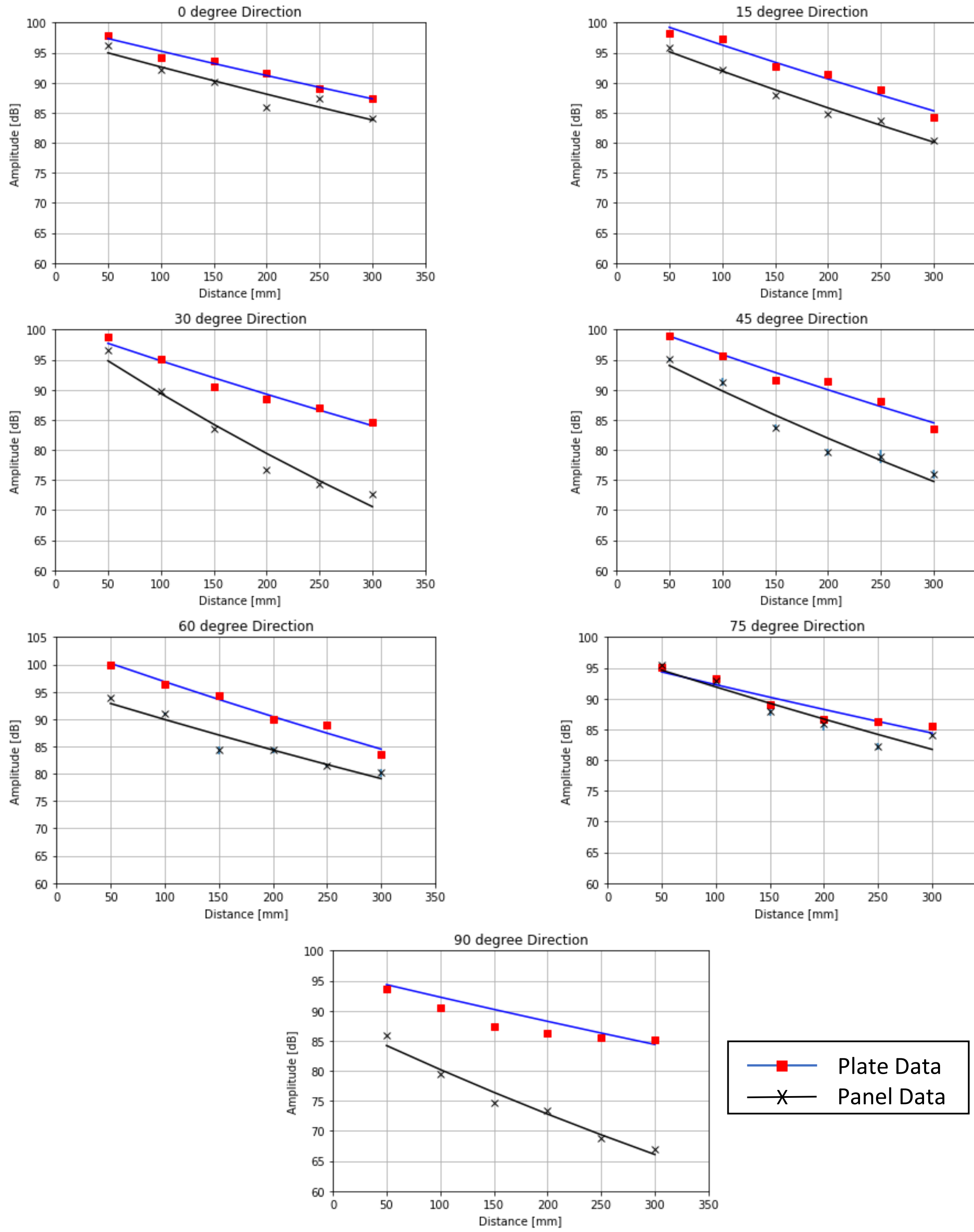

Figure 5. Attenuation curves of AE waves propagations in different directions

The results presented in figure 5 show how the attenuations of AE waves in different directions have changed after bonding the aluminum honeycomb with the top/bottom glass fibre laminated plates. In all instances, the amplitude of the signal in the sandwich panel was lower than that in the glass fibre laminated plate for the same propagation distance. It can also be seen that in most instances the gradient of the data for the sandwich panel is steeper than that for the plate, indicating that the rate of attenuation is greater. In order to quantify the attenuation, an exponential curve fitting function was applied to each set of data. According to Miller[8], the wave amplitude decay rate can be expressed as presented in Eq.1.

$$A = A_o e^{-\alpha x} \qquad \text{……. (1)}$$

where A: wave amplitude at sensor,
α: the coefficient of attenuation and must be positive,
A_o: the source amplitude at the start of the transient wave
x: the distance between wave source and the sensor.
The wave propagation has been attenuated dramatically in specific directions and slightly in other ones. Table 1 compares the attenuations coefficients in different directions in fibre glass laminated plate and the sandwich panel. Overall, the most significant increase in the attenuation coefficients can be seen in the 30^o direction and in the 90^o direction. The glass fibre laminated plate attenuation factor in 30^o direction is 5.25 dB/m and increased to 10.27 dB/m after bonding the aluminium honeycomb while in 90^o direction, it is 3.88 dB/m in glass fibre laminated plate and increased to 8.43 dB/m in the sandwich panel.

Table 1. The attenuation coefficients in different angles for glass fibre laminated plate and sandwich panel

Angle	0^o	15^o	30^o	45^o	60^o	75^o	90^o
α_{plate} (Np/m)	0.435	0.604	0.603	0.630	0.681	0.446	0.446
α_{panel} (Np/m)	0.500	0.688	1.180	0.917	0.640	0.585	0.969
α_{plate} dB/m	3.785	5.256	5.252	5.483	5.929	3.880	3.880
α_{panel} dB/m	4.357	5.994	10.27	7.984	5.575	5.097	8.435

2.3.2 Wave Velocities

It is necessary to know the velocity of AE waves to locate sources using the traditional time of arrival technique. As with the attenuation study, the wave velocities were calculated for the glass fibre laminated plate alone, for different propagation angles, then re-examined after bonding the aluminium honeycomb core.

As aforementioned in the introduction, usually two fundamental modes are associated with Lamb waves travelling in thin plates; asymmetrical flexural A_o and symmetrical extensional S_o modes. However, for the purpose of defect location determination, the S_o mode velocity is the most useful since it is the first arrival wave mode.

Thus, S_o mode velocity was measured in different directions from 0^o to 90^o with intervals of 15^o on the glass fibre laminated plate to understand how the wave group velocity varies with direction. For reducing velocity determination errors, accurate arrival time estimation is important. Therefore, S_o wave time of arrival (TOA) is estimated with using Akaike Information Criteria (AIC) picker. AIC picker determines the difference in a signal entropy before and after each data point until finding the minimum value of the largest difference and can efficiently separate various events in time domain data [10]. Eq.2 describes the AIC picker function, at sample (n) in time series of n_{sample} length, AIC compares dependent dataset (i.e. y axis data) until finding sample (n) which represents the sample at which the difference becomes the greatest.

$$AIC(n) = n \times \log(variance(y(1{:}n))) + (n_{sample} - n - 1) \times (\log(variance\ (n+1{:}\ sample))) \quad ...(2)$$

Figure 6 presents a flow chart of the overall programme for calculating S_o velocities.

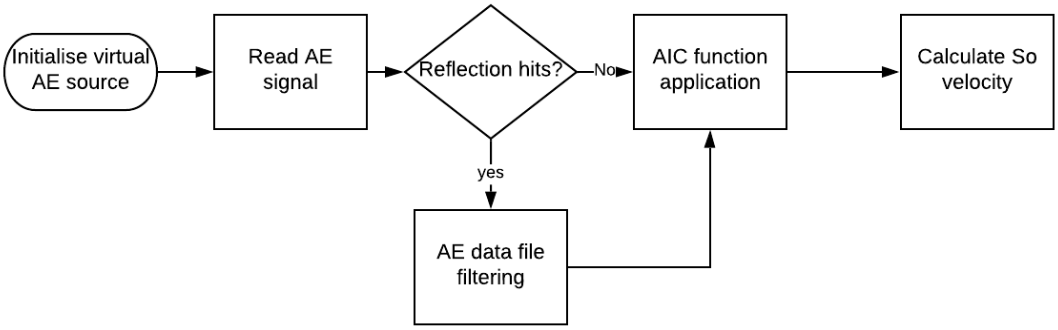

Figure 6. Flow chart of the AE analysis

An example of the use of the AIC for the determination of the arrival time of the wave is shown in Figure 7 for both the glass fibre laminated plate and the sandwich panel. As shown previously in Figure 3, the signal is recorded first by sensor S1 and then by sensor S2 which was placed 100 mm behind it, thus the velocity can be calculated by determining the difference in TOA between the sensors across this known distance.

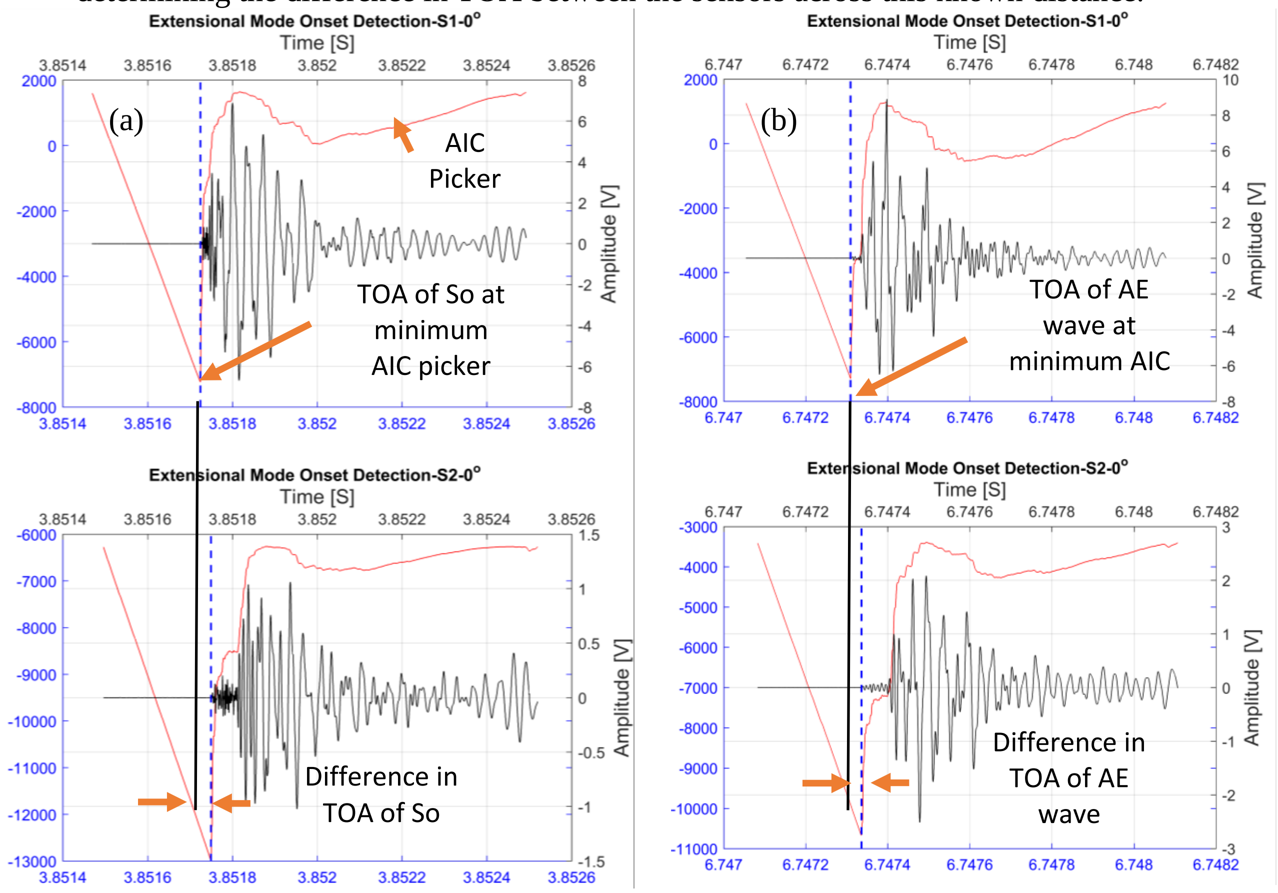

Figure 7. Time of arrival difference between sensor 1 and sensor 2 in 0° direction for (a) glass fibre laminated plate and (b) sandwich panel

The velocities of the first arriving AE waves have been computed and plotted as shown in figure 8. Interestingly, the velocities of arrival AE waves have been changed significantly in some directions.

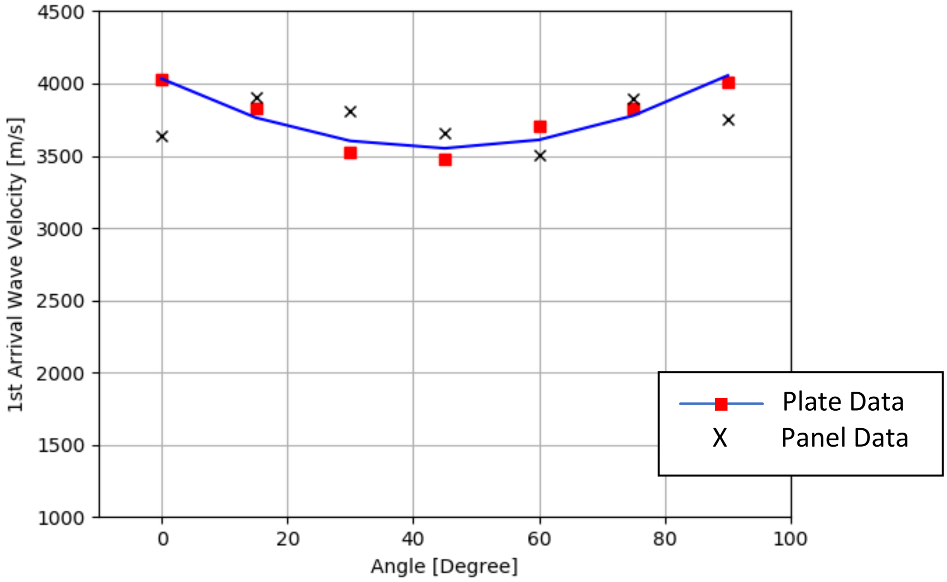

Figure 8. Velocities of arrival waves in glass fibre and sandwich panel

Further, during the average AE wave velocity calculation, the quartile analysis has been performed in order to control the data quality by removing the outlier data points. Furthermore, the standard error has been computed for each velocity sample to measure how far the sample mean of the data is likely to be from the true mean.

Table 2 summarises the AE wave velocities in the glass fibre and the sandwich panel with the corresponding standard error. Moreover, the percent change is calculated for all velocities.

Table 2. First arrival waveforms velocities in glass fibre plate and sandwich panel

Direction	Glass fibre Plate (m/s)	Sandwich Panel (m/s)	Percent Change (Wave velocity in Plate - Wave velocity in Panel)/(Wave velocity in Plate) %
0^o	4028.41 (±9.64)	3637.36 (±33.97)	9.70
15^o	3829.46 (±15.5)	3927.22 (±8.28)	-2
30^o	3527.02 (±16.22)	3836.85 (±21.68)	-7.87
45^o	3472.01 (±10.35)	3658.42 (±10.43)	-5.37
60^o	3700.92 (±10.22)	3509.49 (±25.94)	5.17
75^o	3828.95 (±16.2)	3892.76 (±15.42)	-1.66
90^o	4005.07 (±15.76)	3752.15 (±9.02)	6.41

The considerable changes in velocities are in 0^o direction, 30^o, 45^o, 60^o and 90^o. On the other hand, slight changes are in 15^{o}and 75^o.

2.3.3 Wavelet Transformation

As a result of fast Fourier transform (FFT)'s inability to provide a time-dependence of the signal frequency spectrum, the wavelet transform (WT) has been performed on the AE signals in 0^o direction at 50 mm. This is in order to find the active frequencies in the glass fibre laminated plate and the sandwich panel.

Figure 9 presents the wavelet transformation for AE wave in the (a) glass fibre laminated plate and (b) sandwich panel.

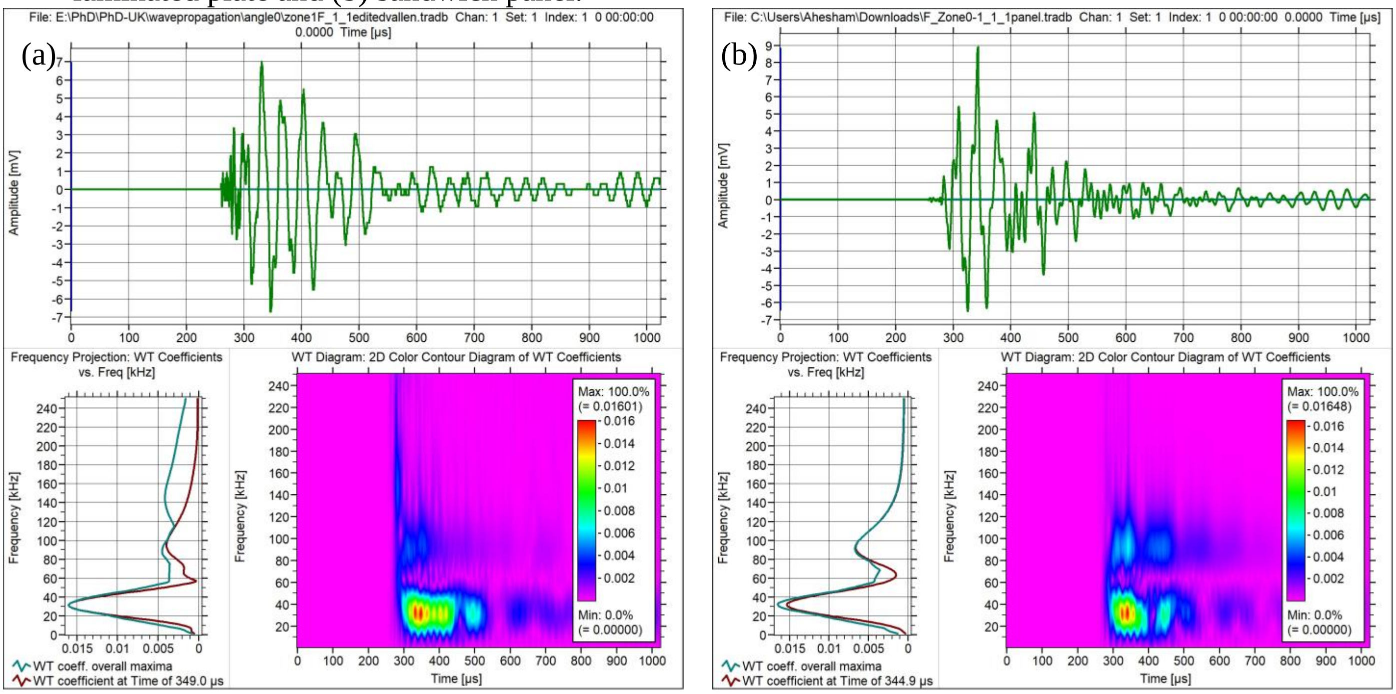

Figure 9. Wavelet Transformation a) glass fibre laminated plate, b) sandwich panel

The wavelet transformations show that frequencies between 30 kHz to 130 kHz are active in both. It can be concluded the low frequency wave component of 30 kHz and high frequency component at 100 kHz are dominant. This shows that a Lamb wave could found in both glass fibre laminated plate and the sandwich panel. Since this Lamb wave can be trapped and occurred only in the glass fibre plate or can be in the whole panel, it should be investigating the transmitted wave from top plate to the bottom plate through the honeycomb core by applying forced harmonic wave using a piezoelectric transducer.

3. Conclusions

To conclude, this paper provides a detailed study on AE wave propagation in thin glass fibre plate and honeycomb sandwich panel as well. The empirical attenuation coefficients have significantly increased after bonding the honeycomb core between the thin glass fibre laminated plates in some directions and slightly in other directions. The highest attenuation coefficients after bonding the honeycomb are 10.27, 7.984 and 8.435 dB/m observed at 30^o, 45^o and 90^o, respectively. However, the attenuation curves in all directions were steeper. Furthermore, the AE waveforms velocities have been computed based on TOAs that were estimated accurately using Akaike Information Criterion AIC to eliminate the triggering errors. It is found that the velocities were behaving in a 2nd degree polynomials manner in case of thin glass fibre laminated plate. After bonding the honeycomb, the velocities have been changed significantly in 0^o, 30^o and 90^o. For the 0^o, the AE wave velocity in the glass fibre laminated plate is 4028.41 m/s whereas in the sandwich panel it becomes 3637.36 m/s. On the other hand, the wave velocities have been slightly changed in 15^o and 75^o with percent change -2% and -1.66%, respectively. Furthermore, the wavelet transformation has been carried out on the AE waves in all directions, and results show that the frequencies 30 kHz to 130 kHz are dominant in both fibre glass laminated plate and the sandwich panel. As a result, Future research should be on investigating of the transmitted wave from top plate to the bottom plate through the honeycomb core by applying forced harmonic wave using a piezoelectric transducer to confirm whether a Lamb wave is still in the sandwich panel or another AE wave form. Also, it is worth to estimate the energy transfer from top plate to bottom plate through the honeycomb surfaces to find the total energy drop.

Acknowledgements

This research is carried out within the PhD project entitled *"Investigation of Honeycomb Composite Structure for Wind Turbine Blades with Acoustics Emissions Damage Assessment"* funded by Newton-Mosharafa Fund in Egypt, I.D: (*NMJ 3/18*). Many thanks to Frederic Purcell in Cardiff University, Weam Sherin in Bristol University, and Ahmed Ali in Huawei Technologies, Ltd, for the technical discussions and advice in the digital signal processing.

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