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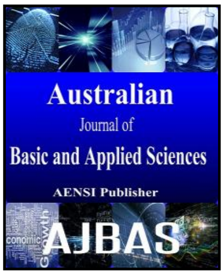

Exploiting the Wave Characteristics in Natural Fibre Reinforced Composites for Passive Damage Evaluation

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ABSTRACT

Background: Low-velocity impact damage has created a major concern in the design of structures made of composites material because such damage is mostly hidden inside the laminates and cannot be detected by naked eye**. Objective:** This study investigates the wave velocity characteristic of the woven natural fibre reinforced composite when impacts introduced onto the panel. It is based on a classical sensor triangulation methodology, combines with experimental strain wave velocity analysis. **Results:** As demonstrated in this study, the present dynamic response based procedure using smart sensors can be effectively used to assess the validity and capability of the strain characteristic in the natural fibre composite (NFC) sample.

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INTRODUCTION

In recent years, much research activities have been dedicated to natural fibre reinforced polymer composites because the requirement of environmental friendly materials. Natural fibre offer many advantages compared to synthetic fibre which make them attractive as reinforcement in composite materials. Natural fibre come from abundant and renewable resources which ensures a continuous fibre supply and significant material cost saving to the plastic industry. The most widely used natural fibre composite structures are laminates consisting of one or many fibre reinforced laminae that are bonded together to achieve the desirable structural properties and better performance over conventional materials. For example, in structural applications and infrastructure applications, natural fibre composites have been used to develop load-bearing elements such as beam, roof, multipurpose panel, water tanks and pedestrian bridge (Ticoalu *et al*. 2010). While in the automotive applications, kenaf and flax mixture has gone into package trays and door panel inserts for Saturn L3000s and European market Opel Vectras (Holbery and Houston, 2006). However, laminated composites often suffer significant internal damage when they are subjected to localized dynamic surface loads. The damage may involve delamination, matrix cracking and debonding as well as fibre breakage between the individual laminae (Islam and Craig, 1994, Ip and Mai, 2004). Such damage has been observed to occur even at relatively low impact speeds resulting in a severe loss in the load carrying capacity of the laminate.

Although it is clear that the damage is caused by the stresses which developed within the material, the precise nature of these stresses and their relationship particularly to the degree and mode of the damage are not clearly understood. This is particularly true in the dynamic case where the stresses are caused by strain waves whose propagation characteristics are strongly influenced by the inherent anisotropy and heterogeneity of the composite material. Recent investigation has demonstrated the use of sensor technologies in damage detection. Several techniques have been investigated for damage detection in composite materials such as Lamb Wave method (Degertakin and Khuri-Yakub, 1997, Kessler *et al.*,

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2002 and Diamanti *et al*., 2004), modal frequencies (Yang and Chiu, 1993, Zhang *et al*., 2004 and Choi and Stubbs, 2004), structural health monitoring (Mal *et al*., 2005, Sohn *et al*., 2008, Staszewski *et al*., 2009 and Diamanti and Soutis, 2010), artificial neural network (Vallabhaneni and Maity, 2011, Kudvat and Munirt, 1992, Leclerc *et al*., 2007 and Mahzan *et al*., 2010) and conventional non destructive testing (NDT) (Santulli, 2001, Sazonov *et al*.,2002, Ru 2006 and Igor *et al*., 2009). In general, there are two general approaches in damage detection, i.e. active and passive approach (Staszewski, 2009). The active approach is generally based on actuating and sensing of structures and includes such techniques as ultrasonic and Lamb waves techniques. In passive techniques the actuator transducers are not used. Here, a series of receiver sensors are used to obtain any perturbation caused by the damage such as Acoustic Emission (AE) technique.

For impact damage detection, sensors are employed to monitor the impact strain data. The energy of impacts is estimated, which could provide substantial information related to impact severity. These techniques have been employed to various types of synthetic reinforced composites. However, very limited findings have been reported available for information and data dealing with the impact damage for natural fibre reinforced composite (NFC). In active damage detection approaches, the uses of Lamb wave's techniques are of interest (Ru, 2006, Staszewski *et al*., 2009 and Diamanti and Soutis, 2010). This is due to the capability of stress wave to propagate in long distances. In general, Lamb Waves has demonstrated the capability in damage localization and characterizations. The propagation characteristics of Lamb waves, with emphasis on group velocity and characteristic wave curves, are investigated theoretically and experimentally. However, as an active approach, it requires an actuator as medium of implementation. On the other hand, AE is categorized as a passive approach since it does not employ actuators. De Rosa *et al*. (2009) have reviewed the application of AE for monitoring the mechanical behavior of natural fibre composites. It was found that the variability in natural fibre geometry and resistance of natural fibre composites to defect propagation create difficulties to AE techniques. AE techniques also have difficulty is estimating the wave propagation of damage due to the short distance, which subsequently require high accuracy of stress wave measurement. Recent studies by Staszewski *et al*. (2009) and Mahzan *et al*. (2010), have demonstrated the feasibility of manipulating the stress wave for passive damage detection approach. The results indicated that different materials produced different wave propagations depending on the configuration of the composites. Although, an immense number of techniques exist for the identification and location of damage in composite material, but a reliable damage detection procedure has yet been fully addressed and implemented, especially dealing with natural fibre reinforced composites. Hence, this paper attempts to investigate the behavior of wave velocity characteristic in natural fibre reinforced composite during impact events. The impact events on the composite structure eventually initiate the strain data, substantial for wave velocity identification.

1. Wave Velocity Characteristics:

Theoretically, during an impact event, the structure is deflected and produced strain waves that propagate outwards in all possible directions. For an isotropic material, it is expected that the wave propagation is identical in all possible direction. However, for a natural fibre reinforced composite, that categorized as an anisotropic material, the wave propagation is unknown. However, the wave velocity characteristics $V_i = f(a_i)$ can be estimated a priori for monitored composite structures using experimental analysis for all possible angles of wave propagation.

Figure 1 demonstrates the schematic arrangement for modified multilateration procedure, as reviewed in Staszewski *et al*. (2009) and Mahzan *et al*. (2010). Three different sensors, e.g. P_1, P_2 and P_3 were used to 'sense' the strain wave resulted from an impact event. Three different angles, e.g. α_1, α_2 and α_3 have been randomly selected for wave propagation directions. For every transducer Pi and assumed wave propagation angle, the distance di between the transducer and impact position can be calculated as

$$d_i = v_i t_i \quad (i=1,2,3) \tag{1}$$

where t_i and V_i are arrival times and velocities of the propagating strain waves, respectively. The arrival times can be estimated from the experimental strain data for all transducers.

2. Methodology:

2.1 Sample Preparation:

The investigation employs the woven pineapple fibre as the natural fibre and the epoxy as the resin matrix. The dimensions of the pineapple fibre composite boards were 300mm (L) × 300mm (W) and 2mm thickness. Figure 2 demonstrates the woven pineapple used in the investigation. The ratio between epoxy resin and hardener for this study was 2:1 by weight. Firstly, the release agent was laid up on the mould. Then, epoxy and hardener were mixed together based on the weight percentage to form a matrix. After that, the epoxy mixture was poured uniformly for the first layer on to the mould. Next, the first woven pineapple was added into the mould and another layer of epoxy was applied uniformly on the first layer of the woven pineapple fibre. The second layer of woven pineapple fibre is then applied and another layer of epoxy is uniformly applied on the woven pineapple fibre. The processes are repeated until six layers of epoxy and woven pineapple fibre are obtained. The mould is closed and the composite material was pressed uniformly in the hot press machine. After the composite fibre are fully dried, then it is separated from the mould.

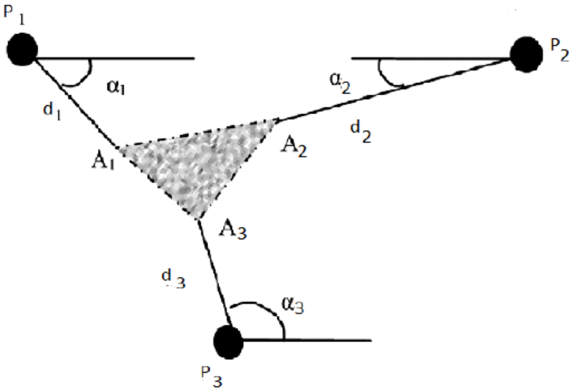

Fig. 1: Schematic sensor arrangement of modified triangulation for wave propagation direction procedure (Mahzan *et al*. 2010).

Fig. 2: Sample of woven pineapple fibre.

2.2 Experimental setup:

The test performed was the experimental analysis of passive impact strain waves for various wave propagation directions in the NFC structure. The objective was to obtain wave velocity characteristics based on the modified triangulation procedure, prescribed in Figure 1. An impact hammer, as used for modal testing, was applied to produce impacts on the natural fibre composite plate. The experiments were conducted on a laboratory, where the plate was positioned on foam without any mechanical constraints. A series of impacts were applied to the composite plate using an impact hammer at x = 50 mm and y = 230 mm, as shown in Figure 3. The *DEWEsoft* oscilloscope was used to capture and display all strain data from the impact events with a sampling frequency of 5 kHz.

Table 1: Sensors distances and calculated angle from impact location.

Sensor	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Distance (mm)	235	170	108	59	62	30	89	210	235	272	280	244
Angle (°)	10	20	30	65	120	200	250	280	300	310	325	340

Table 1 demonstrated the distances and calculated angles from impact points, depicted in Figure 3. For known distances between impact point and sensor positions, the wave velocity can be calculated, provided the arrival time was estimated. The time of arrival was estimated at the time which first maximum amplitude was obtained. Polynomial functions were then curve-fitted to the experimental data. A curve fitting procedure was applied to the experimental velocity characteristics. The Mean Square Error (MSE) was used to assess the performance of the functions used for curve fitting. The MSE was defined as

$$MSE(u) = \frac{100}{N\sigma_u^2}\sum_{i=1}^{N}(u_i - \hat{u}_i)^2 \tag{2}$$

where u_i are experimental data points,

$\widehat{u}_i$ are theoretical data points given by the functions used for curve fitting,

σ_u is the standard deviation of the experimental data and

N is the total number of points in the data sets used.

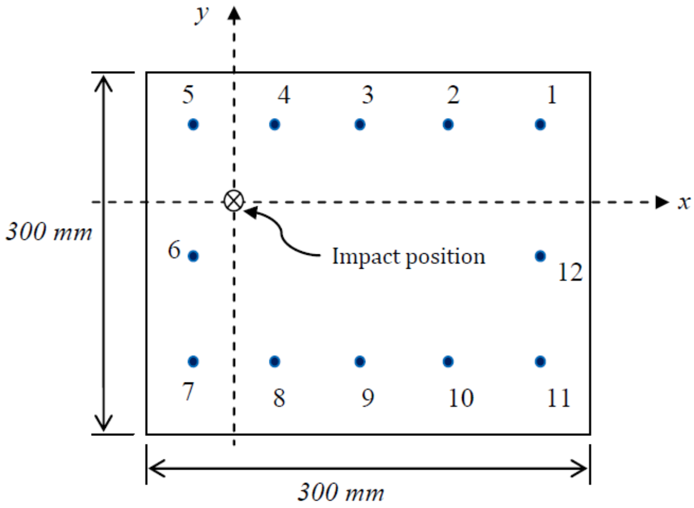

Fig. 3: Schematic diagram for sensor placement on the natural composite structure.

RESULTS AND DISCUSSION

A series of 30 low-velocities, low-energy impacts were performed at position indicated in Figure 3. The resulting strain waves of 2 s were acquired by sensors S1 until S12. The impact strain data were acquired using the *DEWEsoft* oscilloscope. The sampling frequency used was equal to 5 kHz. The strain data were stored on a PC's hard disc for further analysis. Figure 4 gives examples of impact strain data from sensors S2, S5, S6 and S12 in response to the impact at x = 50 mm and y = 230 mm. The time of arrival is almost found similar for all the sensors but the maximum amplitudes are different. Since the energy of a strain wave decays as it propagates away from the source of impact, the maximum amplitude of sensor S12 is lower than that of sensor S5 and S6. While S2 give the higher amplitude compared to S12 since it is nearer to the impact location.

Figure 5 demonstrates the experimental wave velocity characteristics obtained for the NFC composite, with the wave propagation angles between 0° and 180°. It was found that the velocity of propagating strain waves increased nonlinearly from approximately 12 m/s for 0° to 17 m/s for 45°, and then decreases nonlinearly to the value of 11 m/s for 90°. Similar pattern has been shown for angles between 90° to 180°. A curve fitting procedure was applied to the experimental velocity characteristics to obtain the curve fit with minimum error using the Eq. 2. Three different analytical functions, namely a fifth order polynomial, sixth order polynomial and seventh order polynomial were curved-fitted to the experimental data using MATLAB software. A summary of all the functions fitted to the experimental data together with the appropriate coefficients are given in Table 2.

Table 3 gives the summary of correlated error between the fitted curves and experimental velocity data or the MSE values. The results show that the best curve fit was obtained using the seventh order polynomial function since it produced the smallest MSE value 0.5104, whereas the worse curve fit was obtained using fifth order polynomial function with errors of 1.8074. Finally, the wave velocity characteristics for the 0° - 180° angle range were mirrored (due to the symmetry of the NFC panel layout) to produce the final characteristics for the 0°-360° angle range as demonstrated in Figure 6. From the figure, it was noticed that the highest velocity of strain wave propagates at the angle of 45°, 135°, 225° and 315°. These higher values obtain in accordance to woven fibre orientation, as expected.

4. Conclusion:

The wave velocity characteristics for a woven pineapple fibre reinforced composite has been developed using experimental impact strain data. The maximum values of wave propagation were obtained when the strain wave propagates through fibre directions. The mean error was obtained when 7th order polynomial equation was used with the value of 0.5104. The wave velocity characteristics provide substantial data *priori* to impact localization and characterizations. Understanding on the behavior and damage characteristics is vital to evaluate current condition and estimates their integrity for future application. Thus, a reliable signal processing evaluation enables application to various NFC users.

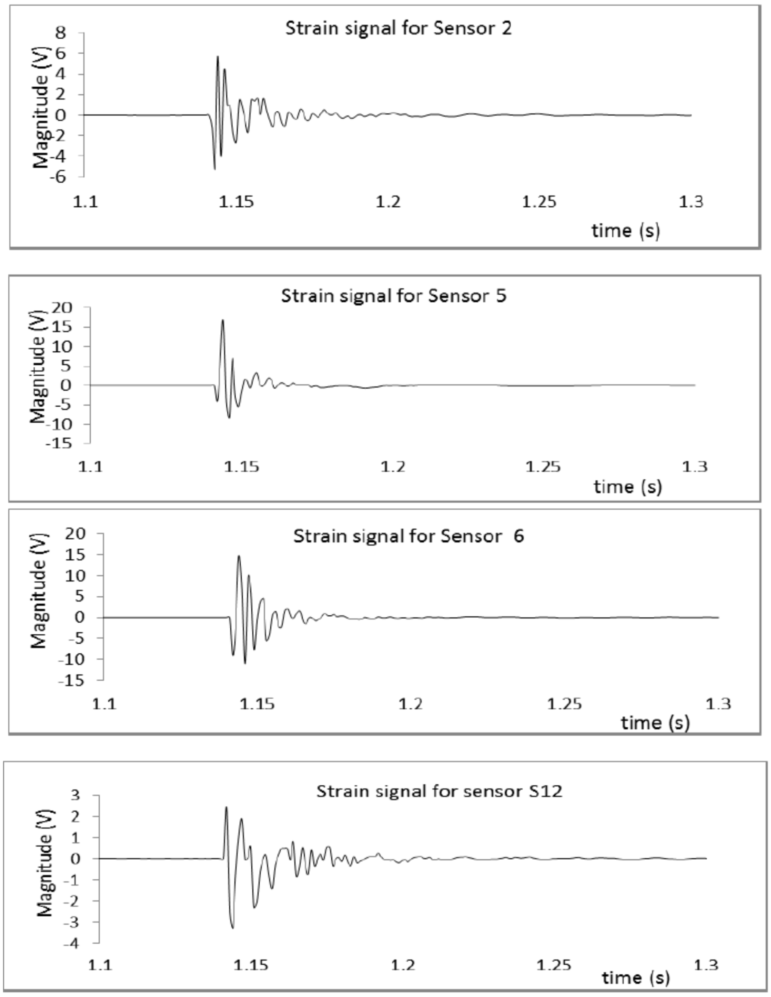

Fig. 4: Examples of strain wave signals produced from an impact at position (x = 50 mm, y = 230 mm) measured by (a) sensor 2, (b) sensor 5, (c) sensor 6, and (d) sensor 12.

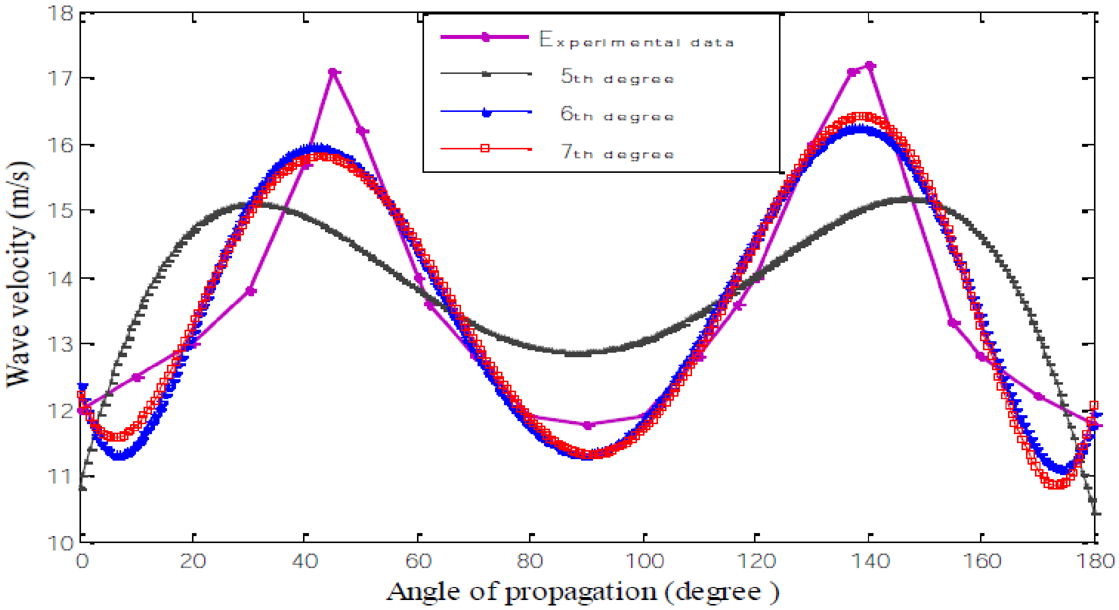

Fig. 5: Wave velocity characteristics for NFC panel produced for the 0° - 180° angle range.

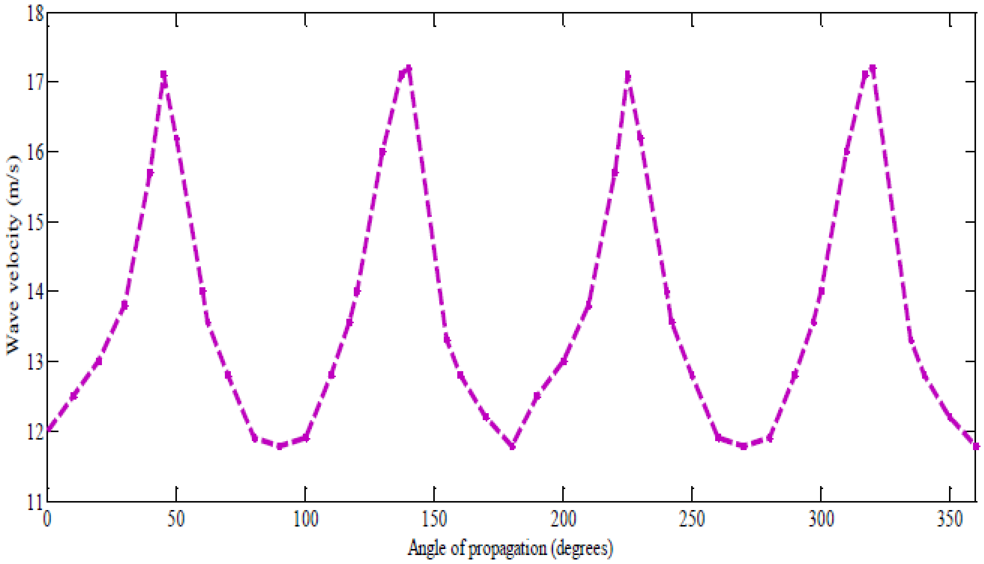

Fig. 6: Strain Wave velocity characteristics for 0° - 360° angle range.

Table 2: Analytical functions used for curve-fitting wave velocity characteristics.

F	Equation	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
1	$y = p_1x^5 + p_2x^4 + p_3x^3 + p_4x^2 + p_5x + p_6$	7.91e-11	-2.37e-7	7.73e-5	-8.58e-3	0.3371	10.831	-	-
2	$y = p_1x^6 + p_2x^5 + p_3x^4 + p_4x^3 + p_5x^2 + p_6x + p_7$	9.54e-11	-5.153e-8	1.03e-5	-9.13e-4	0.0341	-0.348	12.365	-
3	$y = p_1x^7 + p_2x^6 + p_3x^5 + p_4x^4 + p_5x^3 + p_6x^2 + p_7x + p_8$	2.71e-13	-7.51e-11	-9.3e-9	5.06e-6	-5.82e-4	0.0240	-0.234	12.228

Table 3: Correlation error between the fitted curves and experimental velocity data.

Function type	Correlation error
5th order polynomial	1.8074
6th order polynomial	0.5342
7th order polynomial	0.5104

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