Quantitative assessment of damage in composites by implementing acousto-ultrasonics technique

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Abstract: This study focused on quantitative damage severity assessment in composite materials using Acousto-Ultrasonics (AU), an in-service and active non-destructive inspection technique in which Lamb waves are communicated through a damaged zone. This was done by activating a signal onto the composite material surface and acquiring the received waves after their interactions with the damage. It relied on early research that presented a series of stress wave factors (SWFs) derived from the frequency-domain of the AU data, as quantitative identifiers of the received signal. Although, the SWFs have previously been proven to determine the understanding of the spatial arrangements of the impact damage, the degree or severity of the damage inside the impact damage area has not been assessed. Therefore, the current research was a step in the right way toward that aim. AU waves were generated via a laminate with increasing concentrations of ply faults, across longitudinal length. The stress wave factors were first examined for an undamaged composite, and the SWFs were then connected with the fault concentration. The significance of the found linkages and the possible futures of quantitative assessment of the degree of damage by such relationships were examined. The stress wave factors showed clear and consistent patterns, as the fault concentration increased. With a rise in fault density, an element measuring the energy content of the waves significantly changed with R- sq(adj) = 91.33% and almost linearly, and provided a robust measurable trend, while other parameter exhibited lesser shifts with R- sq(adj) = 51.86%. The result obtained from the presented work provided a base to cost-effective and in- service measure to early detection of catastrophic failures in composite structures, including the wind turbine blades for renewable and sustainable energy generation.

Keywords: Acousto-ultrasonics, non-destructive evaluation, wave propagation, wave dispersion, stress wave factor.

1. Introduction

In spite of the fact that polymer composites are finding increasing uses in a diverse selection of constructions, there is always the possibility that its overall safe functionality might be compromised in specific circumstances. If somehow the boundaries for the commencement of damage or flaws are surpassed, this is the primary cause of unanticipated damage occurring in confined places, including such after an impact or in the stress concentration locations. These conditions include either of above cases. If the localised damage cannot be identified and proceeds to uncontrolled development of successive damage, ultimately malfunctions are probable to occur. These failures might be caused by a variety of factors. In order to give resistance to the accumulation of damage, steps are taken while the structural engineering phase. Nevertheless, in several circumstances, cost-effective design requires the implementation of structural health monitoring (SHM) procedures, while the structure is in operation. Although, appreciated works have been achieved in the area of SHM, a study [1] drew a conclusion that one of the most significant obstacles is making the shift from research to practice. Linking in-service monitoring of laminated composites to the status of a material in the localised damage zones is one of the obstacles that must be overcome. In order to overcome this challenge, this work proposed a damage severity assessment that was based on stress wave factors obtained by an AU approach.

2. Theory of structural health monitoring based on acousto-ultrasonics

Many investigations of guided waves in damaged composite materials [2,3] have been reported, but very few have focused on in-service damage detection and quantification. The quantitative approach should work for same-side assessment of a damaged composite material. With this in mind, the acousto-ultrasonics (AU) approach with pitch-catch setup was investigated. Fig. 1 shows this localised damage inspection arrangement. Preliminary research on the AU approach [4,5] used a stress wave factor to experimentally connect a performance measure assumed to represent the damage zone material condition with the acquired signal by introducing the stress wave factor (SWF). Such parameter, originally described in [4,6] primarily and updated subsequently [7] , counted maxima in the received signal employing some pre-specified constraints.

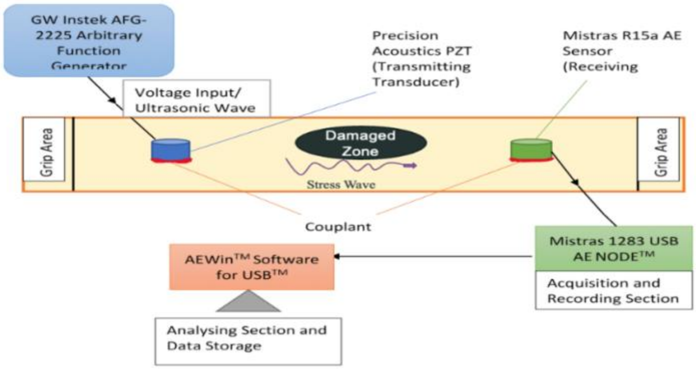

Fig. 1. Acousto- Ultrasonics approach with pitch- catch setup for detecting a faulty zone

Time and frequency domain relationships are quite well known for steady Gaussian random transmissions. For the fairness of explaining the new SWFs, a quick description of relevant theory is as follows [8].

Let (V_{avg}) be an average volage/ signal and can be expressed as:

$$x(t) = V_{avg} = \sum_{i=1}^{n} \frac{V_i}{n} \tag{1}$$

And
$$V_i^{\,u} = V_i - V_a \tag{2}$$

Where, (V_i) is the original voltage, (V_{avg}) is the average voltage and ($V_i^{\,u}$) is the unbiased voltage values.

The FFT of $x(t)$ or V_{avg} is needed to get the frequency domain descriptions [8] as shown:

$$W(f) = \int_{t_a}^{t_b} x(t) e^{-i\omega t} \tag{3}$$

Where, (f) is the frequency and (t) is the time of the signal; $\omega = 2\pi f$.

The inverse conversion done at t=0 provides:

$$x(0) = \int_{f_a}^{f_b} W(f) df \tag{4}$$

2.1 Acousto-ultrasonics components (SWFs)

Moment analysis was introduced to quantify AU components to get quantitative information from the Fourier transform [8]:

Generally, these can be calculated from the following:

$$M_s = \int_{f_a}^{f_b} W(f) f^s df \tag{5}$$

At $s = 0$:

$$M_0 = \int_{f_a}^{f_b} W(f) df \tag{6}$$

This graphically relates to the area under the power spectral density plot. Theoretically, it is the average square voltage and is the energy of the received signal. This value is stated as ($A1$):

$$A1 = M_0 \tag{7}$$

Next SWF is defined as:

$$A2 = \frac{M_1}{M_0} \tag{8}$$

Graphically, $A2$= Central Frequency.

Other SWFs are as follows:

$$A3 = \left(\frac{M_2}{M_0}\right)^{0.5}$$

$$A4 = \left(\frac{M_4}{M_2}\right)^{0.5}$$

$$A5 = \frac{A4}{A3} \tag{9}$$

The first two stress wave factors (Eqs 7-8) are the shape and location of the power spectrum and are the most important SWFs. Hence, in this study only these two were considered.

3. Experimental methodology

3.1 Material and mechanical testing

A carbon fibre reinforced polymer specimen of $[90_8]_s$ was fabricated using epoxy/resin system with hand-layup. The flexural test was performed according to the ASTM D790 standard. The test samples were tested on a 3-point bending equipment with a span to thickness ratio of 16. The test sample has length, width and height of 125, 25 and 2 mm, respectively. The Tinius and Olsen universal testing machine was used with a feed rate of 2.5 mm/min, as shown in Fig. 2. The sample was subjected to ten progressively higher fractions of load, using the ultimate flexural strength as a maximum baseline and was ultrasonic C-scanned at every step for the fault concentration measurement.

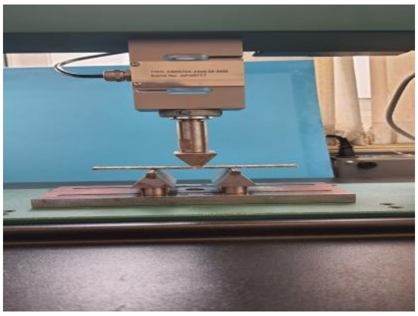

Fig. 2. Three- Point bending test

The sample was examined using AU technique at each of the higher stresses. The method for measuring and analysing AU was subsequently elucidated.

3.2 Acousto-ultrasonics testing

AU technique is premised on the idea that stress waves which have passed through a damage region and reacted with fractures emit acoustic energy. The American Society for Testing and Materials (ASTM) recognised the procedure by publishing “Acousto-Ultrasonic Assessment of Composites, Laminates and Bonded Joints” in 1992 and amended it in 2012 [7]. The Document describes pitch-catch, through-transmission and their variations as a sensor configuration.

3.2.1 Study for undamaged material

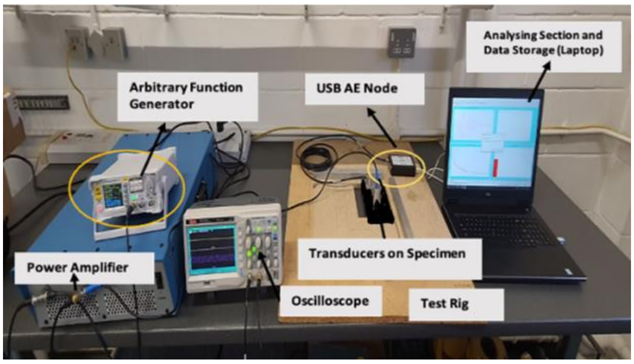

Fig. 3. Acousto ultrasonics experimental set-up.

As a transmitter and a receiver, respectively, an ultrasonic piezo-electronic transducer with a frequency of 1 MHz and a resonant-type AE transducer with a resonance frequency of 150

MHz were used and placed at a distance of 80 mm from each other. Wax was used to connect sensors to the plate. Throughout the experiment, a sensor-to-testing-plate contact pressure of 0.060 MPa was employed. An arbitrary function generator was used to transmit a 3-cycle sine wave tone burst manual signal to the ultrasonic transducer. This signal was sent to a 50-dB RF power amplifier to increase the transmission wave to 5 V. Fig. 3 shows the oscilloscope readings before and after the power amplifier.

Using AU Lamb wave theory, it was established that only the A_0 and S_0 modes transmitted in thin sheets under 1 MHz frequency [8]. Also, Because S_0 has a larger phase velocity at these frequencies, the front component of the output signal was S_0 wave phase. Thus, Fig. 4 depicts two pulse modes in a standard output signal and also the FFT/ frequency domain of the output signal.

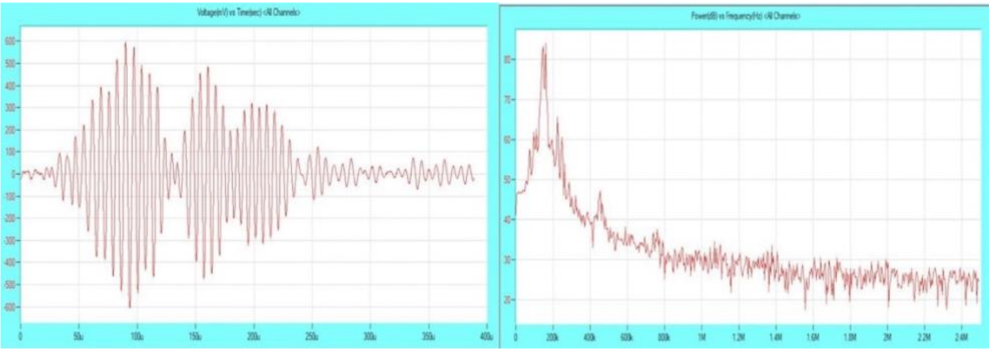

Fig. 4. Output signal in (a) time- domain (b) frequency- domain (FFT).

3.2.2 Study for damaged material

Section 3.1 describes how to induce different-concentration fractures in the laminate. The sample was transferred from the testing equipment and AU signals were received as similar with the unbroken laminate. Frequency-domain graphs for each faulted specimen evaluated the signals. Fig. 5 shows how these plots altered at two stress levels relative to zero load (undamaged sample).

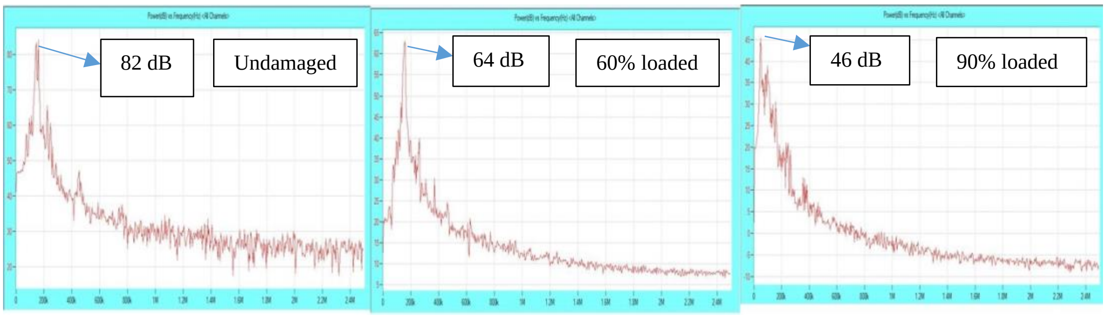

Fig.5. Frequency-domain plots of the initial (undamaged) sample compared with the loaded samples.

4. Results and discussion

Figs (6a) and (6b) depict that the suggested technique yielded significant trends in associations of SWFs and fault concentration. According to the in-service assessments, the existing non-destructive examination (NDE) can reveal damage existence and geometric extent, but not severity. SWF correlated with composite tensile strength [9]. This association was factual and not significant. Breakdown was tensile, compressive or shear strength. Before this final state, many failures happen from pre-existing degradation. The link across SWFs and fault concentration reflects material condition and external impulse response. Obviously, upon impact on a multi-layer composite, matrix cracking, fibre breakings, delamination and different crack densities across layer occurred. However, fault concentration was an integrative indicator of the flaws in the impacted zone, and similar to the SWF. It was related to the AU waves, which were associated with the faults across the same volume.

Due to the noticeable trend in the energy content, variations in the (*A1*) were predicted to measure the severity of damage (in this case, the fault concentration). In Fig. 6, the value of this component, derived using the signal's energy and normalised by its undamaged stage estimate, was displayed against the fault concentration. As shown in Fig. 6(a), there was a definite association.

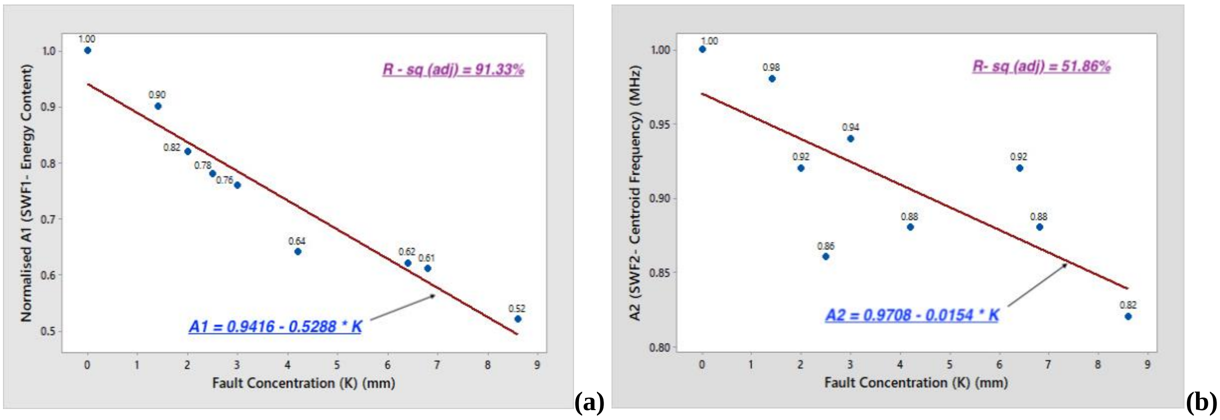

Fig. 6. Variation in (a) A1 and (b) A2, SWF associated with energy content and central frequency with fault concentration (K), respectively.

In actuality, the straight line in the illustration represents a linear connection that gives an indication of the damage severity (fault concentration). *A2* is a representation of the received wave centre frequency. A decrease in this frequency indicated that a few of the high frequency component of the wave was dispersed, due to contact with faults. Fig. 6(b) depicts the fluctuation of the (*A2*), as a function of fault concentration.

However, the entire decrease in central frequency (*A2*) from healthy to maximum fault concentration was a lower with R- sq(adj) = 51.86% when compared with the (*A1*) change with R- sq(adj) = 91.33%. Therefore, (*A1*) is a decent initial assessment of damage severity as per the R- sq(adj) analysis, whereas (*A2*) provides further information.

5. Conclusion

This research quantified damage severity in laminated composites, using AU technique. Frequency-domain analysis was performed on the intact composite material. When the composite had varying fault concentrations, the same power spectrum (frequency-domain) exhibited differential modifications that might be characterised by previously suggested stress wave parameters based on spectral moments. Both stress wave factors increased with fault concentration. An element describing the energy content (*A1*) of the waves exhibited a substantial and obviously quantifiable trend with the rise in fault, whereas the other factor (*A2*) showed a lower change and seemed to indicate secondary alterations in the received waves that had engaged with the flaws. This current study offers a cost-effective and in-service technique, using AU to identify severe breakdowns in composite structures, as applicable to the wind turbine blades. Further investigations with other SWFs may provide more and detailed insights on the damage severity, in the future work.

Acknowledgments

This research was funded by DTA3/H2020 as a part of COFUND programme with University of Hertfordshire through University Alliance Scheme.

References

[1] Farrar C., Worden K., (2007). An introduction to structural health monitoring, Philosophical Transactions of the Royal Society A, 365:303-315.

[2] Su Z., Ye L., Lu Y., (2006). Guided Lamb waves for identification of damage in composite structures: A review, Journal of Sound and Vibration, 295:753-780.

[3] Su Z., Ye L., (2009). Identification of Damage Using Lamb Waves, Springer London, London.

[4] Vary A., Bowles K., (1979). An ultrasonic-acoustic technique for nondestructive evaluation of fiber composite quality, Polymer Engineering and Science, 19:373-376.

[5] Kautz H., (2013). Ray propagation path analysis of acousto-ultrasonic signals in composites, NASA technical memorandum,1-19.

[6] Vary A., (1988). The Acousto-Ultrasonic Approach, Springer, Boston.

[7] ASTM E1495/E1495M : Standard Guide for Acousto-Ultrasonic Assessment of Composites, Laminates, and Bonded Joints n.d. https://global.ihs.com/doc_detail.cfm?document_name=ASTM E1495%2FE1495M&item_s_key=00592876 (accessed July 20, 2022).

[8] Kiernan M., Duke J., (1996). PC analysis of an acousto-ultrasonic signal, Materials evaluation, 46:1344-1352.

[9] Bajpai P., Singh I., (2020). Reinforced Polymer Composites: Processing, Characterization and Post Life Cycle Assessment, Wiley, London.