Chapter 34
Damage Characterisation in Composite Laminates Using Vibro-Acoustic Technique

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Abstract The need to characterise in-service damage in composite structures is increasingly becoming important as composites find higher utilisation in wind turbines, aerospace, automotive, marine, among others. This paper investigates the feasibility of simplifying the conventional acousto-ultrasonic technique set-up for quick and economic one-sided in-service inspection of composite structures. Acousto-ultrasonic technique refers to the approach of using ultrasonic transducer for local excitation while sensing the material response with an acoustic emission sensor. However, this involves transducers with several auxiliaries. The approach proposed herewith, referred to as vibro-acoustic testing, involves a low level of vibration impact excitation and acoustic emission sensing for damage characterisation. To test the robustness of this approach, first, a quasi-static test was carried out to impute low-velocity impact damage on three groups of test samples with different ply stacking sequences. Next, the vibro-acoustic testing was performed on all test samples with the acoustic emission response for the samples acquired. Using the acoustic emission test sample response for all groups, the stress wave factor was determined using the peak voltage stress wave factor method. The stress wave factor results showed an inverse correlation between the level of impact damage and stress wave factor across all the test sample groups. This corresponds with what has been reported in literature for acousto-ultrasonic technique; thus demonstrating the robustness of the proposed vibro-acoustic set-up. Structural health monitoring, impact damage, acousto-ultrasonic testing, non-destructive testing.

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I. Mporas et al. (eds.), *Energy and Sustainable Futures*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-030-63916-7_34

34.1 Introduction

Composite materials are increasingly been used in various industries such as energy, automotive, aerospace, marine, to mention but a few, as critical structural elements. This increasing use of composite materials necessitates the need for characterising in-service damage. Composite is formed by the combination of two materials with different physical and chemical properties. They are used for structural applications due to their light weight, high specific strength/stiffness and good resistance to a corrosive environment. Damage to composite structures can be invisible to the naked eye and non-destructive testing (NDT) techniques such as ultrasound, pulsed thermography and acoustic emission are often used to detect faults, such as delamination, matrix cracking, fibre-matrix de-bonding, fibre breakage and matrix porosity [1–3].

More also, for the past few decades, accurate characterisation of damage in fibre-based composites has been an area of active research [3–5]. Advancing this goal, this paper investigates the characterisation of impact damage in fibre reinforced polymer (FRP) composites by using a variant of acousto-ultrasonic technique (AUT).

Creating a viable procedure for damage characterisation that generally works for various fibre-based composites has proven to be challenging, because of the anisotropic nature of fibre-based composites. Moreover, impact response to composite structures can cause damage such as delamination, matrix cracking and de-bonding in the laminate.

AUT was first proposed by Alex Vary as an NDT technique for evaluating the inter-laminar shear strength of fibre composites [6]. AUT combines acoustic emission (AE) methodology and ultrasonic simulation of stress waves. In order to quantify variations in the mechanical properties, Vary proposed a measurement parameter called the stress wave factor (SWF). SWF is a descriptive parameter that correlates with the material properties of composite materials. Contrary to traditional acoustic emission technique that requires the material to be under stress, AUT does not.

In recent times, AUT has found application in the following areas for NDT of composite structures: damage detection and severity quantification [7], material property correlation of fibre-based composites [8] and naturally occurring composites [9].

Importantly, this paper addresses a different yet important question, “can the set-up for AUT be simplified for quick and economic one-sided in-service composite structure inspection?” To answer this question, a variant set-up of AUT is proposed and explored. This approach involves a low level vibration impact excitation and acoustic emission sensing for damage characterisation in composite structures.

34.2 Experimental

34.2.1 Sample Preparation

The test samples were made from an epoxy impregnated carbon fibre laminates (prepreg) with stacking sequence, as shown in Table 34.1. Hand lay-up method was used to prepare the test samples, in addition to autoclave curing to improve their mechanical properties. The curing cycle in the autoclave involved temperature ramp-up stage from ambient of 20 to 121 °C at a rate of 1 °C/min, followed by a dwell stage to maintain the temperature constant at 121 °C for two hours; and then ramp-down stage, with temperature being reduced to ambient temperature of 20 °C. The internal pressure of the autoclave was maintained at 106 kPa for the entire temperature cycling operation.

34.2.2 Testing

34.2.2.1 Low Velocity Impact Damage (Quasi-static Testing)

Composite laminate structures are very prone to low-velocity impact damage. Although, the effects of low-velocity impact damage are barely visible on the laminate surfaces, there can be extensive sub-surface damage in the form of matrix cracking, delamination and fibre failure, leading to a reduction in residual strength after an impact [10].

To experimentally simulate the effects of low-velocity impact damage in the test samples, a low-velocity impact experiment was performed on a Tinius Olsen Model 25ST Universal Benchtop Tester, as shown in Fig. 34.1, with the test samples in Table 34.1. The set-up consists of a hemispherical indenter with diameter of 25.4 mm and four toggle clamps attached to a steel plate with an open middle slot to enable

Table 34.1 Test Sample stacking sequence

Test Sample	Material	Stacking sequence	Dimensions (mm)	Laminate type	Number of samples
A	FibreDUX 6268C-HTA 12 K	$[90/\pm 45/0]_s$	150 × 135 × 2	Quasi-Isotropic	4
B	FibreDUX 6268C-HTA 12 K	$[90/0/\pm 45]_s$	150 × 135 × 2	Quasi-Isotropic	4
C	FibreDUX 6268C-HTA 12 K	[90/0]2s	150 × 135 × 2	Quasi-Isotropic	4

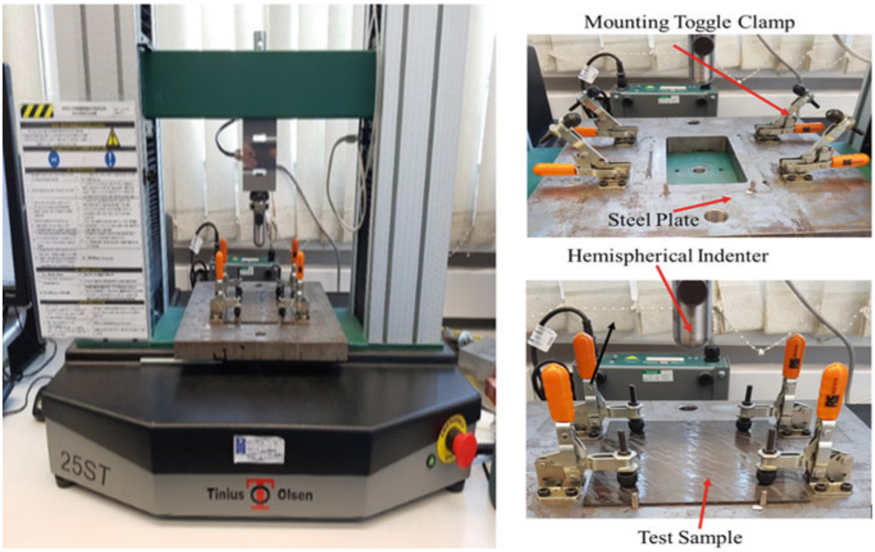

Fig. 34.1 Low velocity impact test set-up

the impacted zone to deform or fracture during the impact testing. The test samples were designated with numbers 0–3, where 0 represented non-impacted samples and other 3 samples were impacted with a velocity of 2 mm/s with increasing maximum impact forces of 2.00, 2.25 and 2.50 kN, respectively.

34.2.2.2 Vibro-Acoustic Testing

The conventional AUT set-up consists of two piezoelectric transducers, as shown in Fig. 34.2. The transmitting transducer is an ultrasonic emitter, while the receiving transducer is an AE sensor [11].

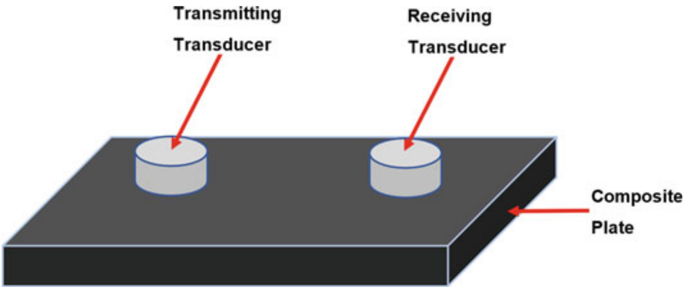

Fig. 34.2 Conventional AUT set-up

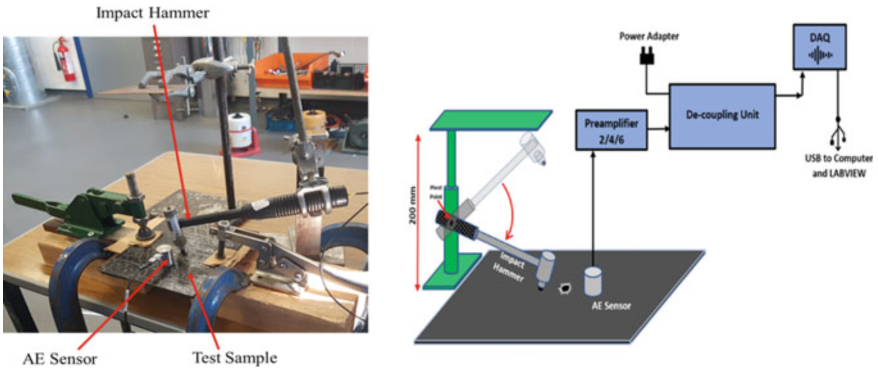

Fig. 34.3 Vibro-Acoustic test set-up

In order to explore the feasibility of simplifying the conventional AUT set-up for quick and cost effective one-sided in-service inspection of composite structures, a vibro-acoustic set-up shown in Fig. 34.3 is proposed. It consists of an impact hammer clamped to a rig with a pivot mechanism and a stopper of maximum height of 200 mm to ensure a repeatable low energy level excitation; nearly 59 N. R15α AE sensor from Physical Acoustics has a resonant frequency of 150 kHz, was coupled to a 2/4/6 preamplifier with a gain of 60 dB selected. Impact hammer of model 086-B02 from PCB Piezotronics was used. The NI USB-6361 data acquisition system from National Instruments with maximum sampling frequency of 2 MHz was also used. Total sample acquisition time of 30 s with excitation occurring after 10 s. To ensure the test samples did not move while being excited, they are held down with one toggle clamp on either side with cardboard-patches to prevent damage. For repeatability and also to minimise signal attenuation by the composite test samples, the AE sensor was placed approximately 20 mm from the impact zone, while the hammer hit was done approximately 15 mm from the impact zone. This sensor spacing (30–50 mm) corresponds with what has been reported to minimise the effect of signal attenuation [7, 8].

34.3 Results and Discussion

In an AUT domain, a commonly used approach for characterising a damage in fibre reinforced composite laminate is by calculating the stress wave factor (SWF). SWF quantifies the attenuation of the material to the induced stress wave. A low SWF corresponds to a region with higher attenuation, due to sub-surface damage and a relatively high SWF indicates a region of lower attenuation.

SWF can be determined with any of the following methods: peak voltage SWF method, ringdown SWF method, weighted ringdown SWF method and energy integral SWF method [12]. Each method for SWF resulted to different values for the parameter. For this investigation, the peak voltage method was applied. The peak voltage SWF method which assumed an inverse relationship between the peak-voltage and signal attenuation, due to damage in material is represented as Eq. (34.1).

$$SWF = V_{max} \tag{34.1}$$

where V_{max} is the peak voltage.

Figures 34.4 and 34.5 show the time domain AE response and SWF analysis from the vibro-acoustic tests.

Figure 34.4 depicts the time domain response of the AE signal and a trend can be observed: the peak induced test sample response from the excitation was significantly reduced, showing difference between the unimpacted samples (A0, B0 and C0) and the impacted samples (A1–A3, B1–B3 and C1-C3). Figure 34.5 shows a significant reduction in SWF between the unimpacted samples (A0, B0 and C0) and (A1, B1 and C1), which was subjected to 2 kN quasi-static load. This response suggests damage progression in the composite laminates. However, in Fig. 34.5, there was only a minor difference in SWF between (A2, B2, C2) and (A3, B3 and C3), at these points there were already significant fibre breakage and matrix cracking present in the impacted area. The result obtained agree with similar published ones [7].

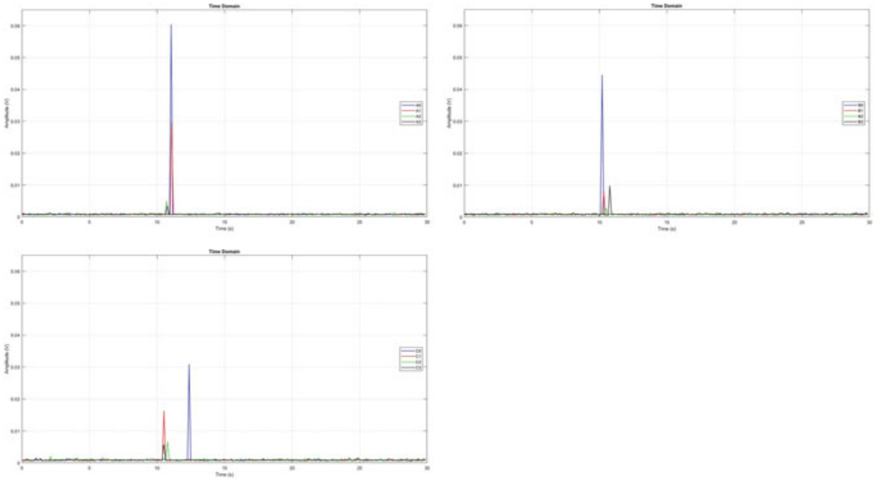

Fig. 34.4 Time domain AE response for test samples A(0–3), B(0–3) and C(0–3)

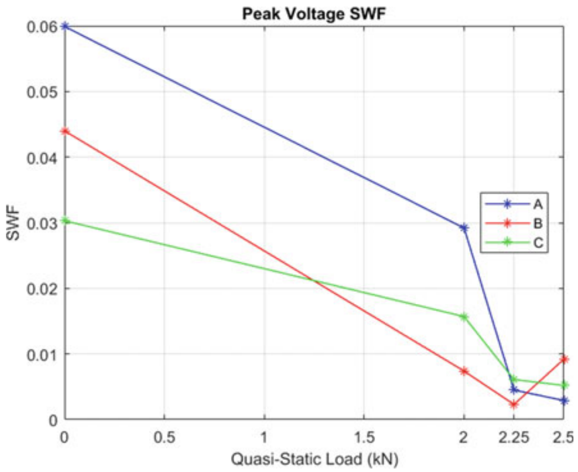

Fig. 34.5 Peak voltage SWF analysis for test samples A(0–3), B(0–3) and C(0–3)

34.4 Conclusions

This investigation explored the feasibility of simplifying the conventional set-up of AUT testing for quick and economic one-sided composite laminate inspection. Hence, the following inferences have been deduced from the study.

- The vibro-acoustic set-up proposed is viable and robust for damage detection and characterisation in fibre reinforced polymer composite laminate.
- Furthermore, the SWF analysis plot showed an inverse correlation relationship between the level of impact damage and SWF across all the test sample groups. This agrees with what has been reported in the literature for AUT [7].

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