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Acoustic structural health monitoring of composite materials : Damage identification and evaluation in cross ply laminates using acoustic emission and ultrasonics

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ABSTRACT

The characterisation of the damage state of composite structures is often performed using the acoustic behaviour of the composite system. This behaviour is expected to change significantly as the damage is accumulating in the composite. It is indisputable that different damage mechanisms are activated within the composite laminate during loading scenario. These "damage entities" are acting in different space and time scales within the service life of the structure and may be interdependent. It has been argued that different damage mechanisms attribute distinct acoustic behaviour to the composite system. Loading of cross-ply laminates in particular leads to the accumulation of distinct damage mechanisms, such as matrix cracking, delamination between successive plies and fibre rupture at the final stage of loading. As highlighted in this work, the acoustic emission activity is directly linked to the structural health state of the laminate. At the same time, significant changes on the wave propagation characteristics are reported and correlated to damage accumulation in the composite laminate. In the case of cross ply laminates, experimental tests and numerical simulations indicate that, typical to the presence of transverse cracking and/or delamination, is the increase of the pulse velocity and the transmission efficiency of a propagated ultrasonic wave, an indication that the intact longitudinal plies act as wave guides, as the transverse ply deteriorates. Further to transverse cracking and delamination, the accumulation of longitudinal fibre breaks becomes dominant causing the catastrophic failure of the composite and is expected to be directly linked to the acoustic behaviour of the composite, as the stiffness loss results to the velocity decrease of the propagated wave. In view of the above, the scope of the current work is to assess the efficiency of acoustic emission and ultrasonic transmission as a combined methodology for the assessment of the introduced damage and furthermore as a structural health monitoring tool.

0. Introduction

The failure of laminated composite materials typically includes a sequence of mechanisms which are triggered successively. The first expression of damage is the matrix cracking vertical to the load direction at early loading stages, which is known as transverse or interlaminar cracking. These cracks act as stress concentration points on the interphase between the 90° and 0° plies. When load continues to increase, and due to the differential compliance of the on- and off-axis plies, delaminations start to evolve from these points. Delaminations may well continue to develop after the transverse cracking becomes saturated, while the final failure of the material comes with the rupture of the longitudinal fibre plies. The load at which the different mechanisms are activated as well as eventual failure occurs, depends on the plies' mechanical properties and the interlaminar shear strength [1,2].

The knowledge of the damage propagation mechanisms can aid towards the improvement of the design of composite structures. Real time monitoring of the structural integrity of composites is critical for assessing the performance of the structure as damage accumulates. Acoustic methods in their passive (Acoustic Emission, AE) and active (ultrasonic testing, UT) form can provide crucial information for both purposes [3–7].

The Acoustic Emission (AE) technique has been employed in numerous applications for damage characterisation of composite materials. Suitable sensors are placed on the surface in order to record the transient waves (hits) generated by damage initiation and propagation inside the material. Moreover, AE has been successfully applied in cross ply composites in order to separate the acoustic activity of various damage modes in a cross ply composite [3]. Further study of the waveforms may provide in depth insight of the fracture process. The source of the AE activity is closely

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connected to the mode of fracture [8]. The benefit of classification of the cracking mode is twofold. Since the time sequence of the mechanisms is known (transverse cracking–delaminations–fibre rupture), classifications enable to evaluate the remaining life for the structural component and act as a warning against final failure [9]. Additionally, it is possible to tailor the properties of the constituent phases and their interface using proper design or materials so as to optimise the resistance against the specific failure modes. In the engineering field, the shape of the AE waveforms is reported to be characteristic of the fracture mode. Shear events are characterised by longer Rise Time (RT, time delay between the first threshold crossing and the maximum peak) and usually lower peak amplitude (A, voltage of the largest cycle) than tensile events [10–12]. This is examined by the RA value which is defined as the ratio of the RT (expressed in μs) to the waveform Amplitude, A (expressed in V, see Fig. 1) [8]. It has been shown that lower RA values, indicate tensile nature of fracture events [8,10–12]. Another technique that has been used for structural integrity monitoring is UT. Pulse velocity has been correlated to damage and strength offering rough but valuable information because the damage condition influences the mechanical properties and hence wave speed [13,14]. In the present case, the above mentioned techniques are both used to study the fracture behaviour of composite cross-ply laminates. Incremental step loading as well as tension–tension fatigue until final failure of the materials were employed for the purposes of this study. In the case of incremental tensile loading, matrix cracking develops gradually until saturation, while in the case of fatigue, matrix cracking is expected to reach a level directly dependent on the applied stress while the shear interlaminar stresses favour delaminations at the 0/90 interface which evolve during cyclic loading.

1. Experimental

The cross-ply laminates were fabricated by hand layup with a sequence $[0°_4/90°_4]_s$, resulting in a number of 16 plies with total specimen thickness of 2 mm. The UD 220 g/m^2 (Aero) unidirectional glass fibre fabric was impregnated using the HT2 epoxy resin/hardener matrix system (mixing ratio 100:48) manufactured by R&G Faserverbundwerkstoffe GmbH Composite Technology. A 250 × 250 mm^2 laminate was manufactured and was allowed to cure for 24 h at room temperature. Tensile specimens were subsequently cut according to the ASTM D3039 standard, at a width of 20 mm each.

The tensile specimens were loaded in load controlled tension, in a step loading mode. The loading spectrum was a saw-tooth spectrum formed from a sequence of triangular loading/unloading steps. A rate 5 kN/min was employed for both loading and unloading. The maximum load was incremented by 4 kN at each consecutive step. The step loading continued until the tensile failure of the specimen. All tensile tests were performed using an Instron Universal Testing Machine equipped with hydraulic gripping system, under load control, at controlled environmental conditions of 25 °C and 70% relative humidity. Tension–tension fatigue ($R = 0.1$, frequency = 5 Hz) was applied on the same standard specimens on levels of 50%, 60% and 70% of the ultimate tensile strength of the material which was determined by quasi static tensile testing (ASTM D3039).

For the purpose of the AE monitoring, two wide band AE sensors (Pico, Physical Acoustics Corp., PAC) were attached on the same side of the specimen. Electron wax was applied between the sensor and the specimen to enhance acoustic coupling, while it offered the necessary support to the sensors during the experiment. The specific sensors were chosen over other AE transducers mainly due to their spectral response. They are sensitive to frequencies from 50 kHz up to approximately 800 kHz, with maximum sensitivity at 500 kHz. Therefore, they can capture a wide range of different sources. The distance between the two receivers was 70 mm. A snapshot of the experimental setup is seen in Fig. 2.

For the purposes of ultrasonic measurements during fatigue, an acoustic emission sensor (R15, PAC) was also employed as a pulser. The pulser was attached to the specimen as seen in Fig. 2. A tone burst of 10 electric cycles of 200 kHz every 10 s was fed to the transducer by a wave generator (AFG3102, Tektronix) and the response of the sensors was recorded. The setup was employed for transmission and pulse velocity measurements.

Finally, wave propagation simulations were performed using the Wave 2000™ software which employs a finite difference algorithm for the calculation of the propagated modes. Materials were considered elastic without viscosity components. The structure consisted of three distinct layers, the top and bottom of which are the longitudinal plies of thickness 0.5 mm each. The mechanical properties used in the specific indicative case, were: Young's modulus, $E = 50$ GPa, and Poisson's ratio, $\nu = 0.3$, which corresponds to the experimentally measured velocity 3100 m/s for the pristine laminate and the manufacturer's quoted density of 1.4 g cm^{-3} The centre layer of 1 mm thickness is the transverse layer. Its Young's modulus in the propagation direction was set to 5 GPa, with the same Poisson's ratio or one tenth of the Young's modulus of the 0° direction as is typical in unidirectional glass fibre reinforced composites. The geometry was initially tested in its intact form to obtain the reference of crack-free structure. In order to simulate damage, another material was imported in the modelling. In this case, for simplicity, properties of air were assigned (pulse velocity of 3300 m/s and density 1.2 kg/m^3). Matrix cracking was simulated by vertical inclusions of 0.2 mm thickness vertical to the middle layer. Delaminations were simulated by horizontal inclusions of 0.2 mm between the successive layers. The "pulser" introduced a tone burst of 10 cycles of 200 kHz of vertical displacement, while the receivers recorded the average displacement on their whole length, which was captured by the two "receivers" positioned at 20 and 90 mm respectively away from the "pulser".

2. Results and discussion

2.1. Mechanical testing results

The typical monotonic tensile stress/strain curve for the studied cross ply laminate is depicted in Fig. 3. The curve is typical of cross

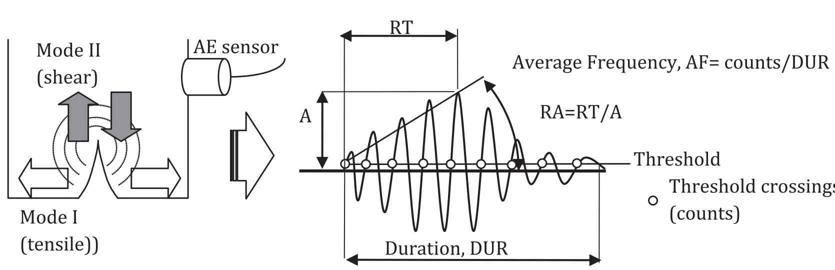

Fig. 1. Typical AE waveform with basic parameters.

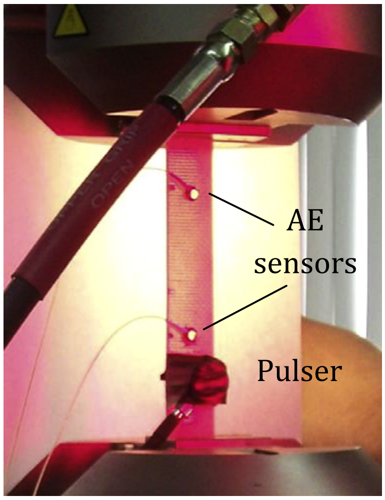

Fig. 2. Setup for Ultrasonic and Acoustic Emission measurements.

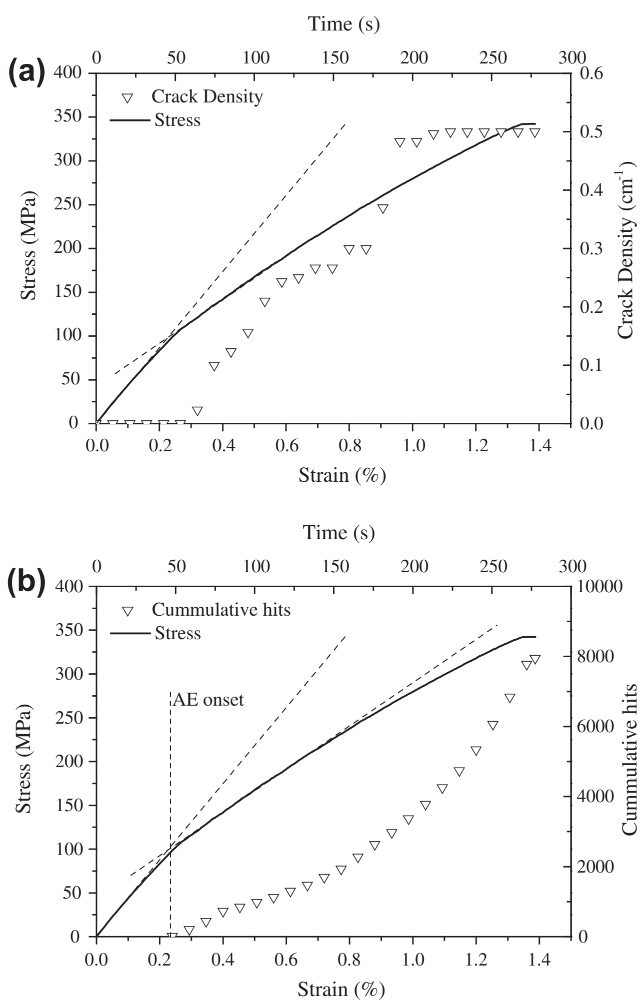

Fig. 3. Tensile stress/crack density (a) and tensile stress/AE hits (b) curves vs. strain and time for the studied cross ply composite.

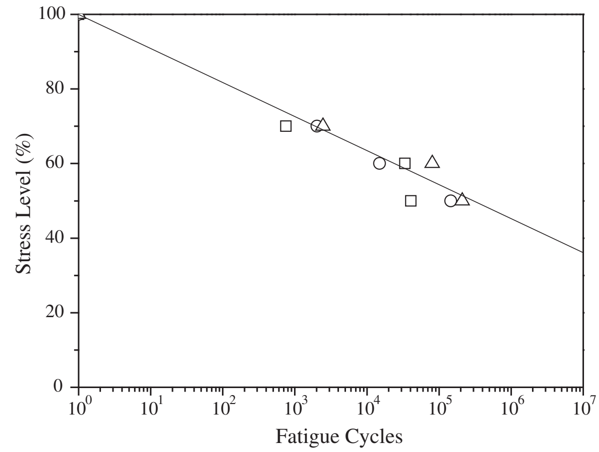

Fig. 4. *S*/*N* curve for the studied cross ply composite laminate.

ply configurations, exhibiting an initial linear part, prior to any damage. There is a notable change in the slope as transverse cracking initiates, as can be seen in Fig. 3. As has been previously assessed [3], the onset of transverse cracking has been verified both optically and acoustically (Fig. 3b), as irreversible damage coincides with recording of acoustic emission activity and has been identified to coincide with the divergence from linearity of the stress strain curve. The overall static strength of the studied system was measured to be 339 ± 13 MPa.

The *S*/*N* curve for all tested laminates is shown in Fig. 4. The specimens exhibited consistent behaviour in fatigue with reasonable experimental scatter. As the purpose of this study involved the investigation of the distinct damage mechanisms, stress levels were chosen so that they were within the stress range between the onset and the saturation of transverse cracking, which for the studied system was between 30% and 80% of the ultimate static tensile strength [3].

2.2. AE results from loading steps

Fig. 5 shows a typical case of load and cumulative AE activity. As the loading cycles become more intense, the AE activity increases considerably. From the negligible number of hits during the first loading cycle, the activity reaches more than 15,000 hits at the final cycle.

The increase is reasonable since as the load increases, matrix cracks accumulate while delaminations are triggered and propagate at the 0°/90° interface. The cumulative number of hits correlates well to the load sustained by the composite at each cycle, as shown in Fig. 6, where all data for three different specimens tested under the same conditions are depicted. As is obvious, the strong correlation implies that the cumulative activity may well be used as an indicator of the load that has been applied to the material. This phenomenological correlation is particularly important as (i) it allows estimation of the load based on simple observation even if there is no physical insight about the mechanisms behind the AE activity and (ii) it establishes the direct relation of the acoustic activity to loading history and consequently cumulative damage.

The in-depth study of the AE data reveals that specific parameters may also provide useful correlations with a view to understanding damage mechanisms. The AE energy (MARSE, Measured Area under the Rectified Signal Envelope) is considered proportional to the energy released at the fracture incidents and has been used in similar studies [3,11]. Fig. 7 shows the correlation plot between AE energy and the maximum load at each cycle. The AE energy is normalised to the value of the first step for each specimen. The correlation is satisfactory, reaching a R^2 value of approximately 0.9. The reduction in average energy is indicative that the fracture energy is distributed to many more hits as the loading continues, resulting to lower average energy for each signal. It can also be postulated that lower energy dissipation mechanisms become

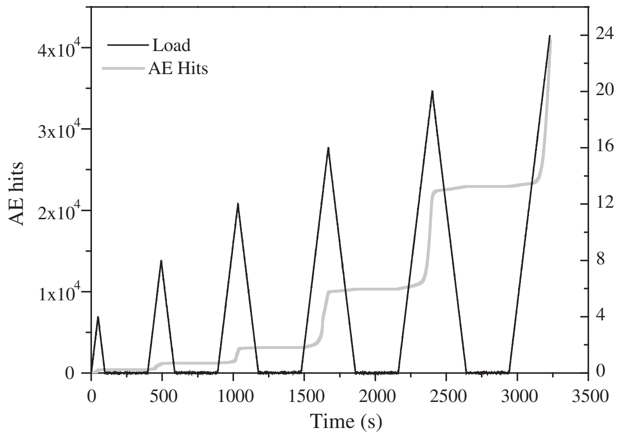

Fig. 5. Load and cumulative AE history.

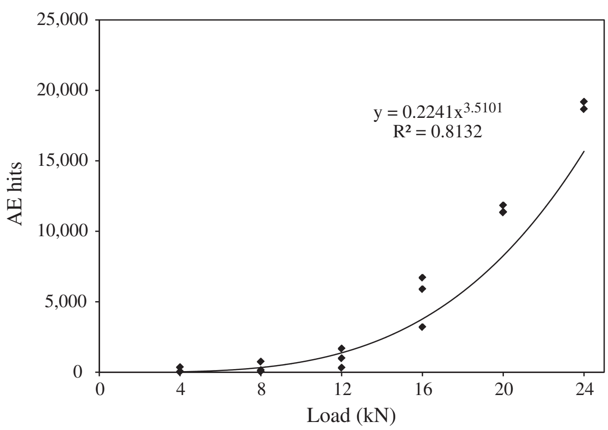

Fig. 6. AE activity vs. maximum load of each cycle.

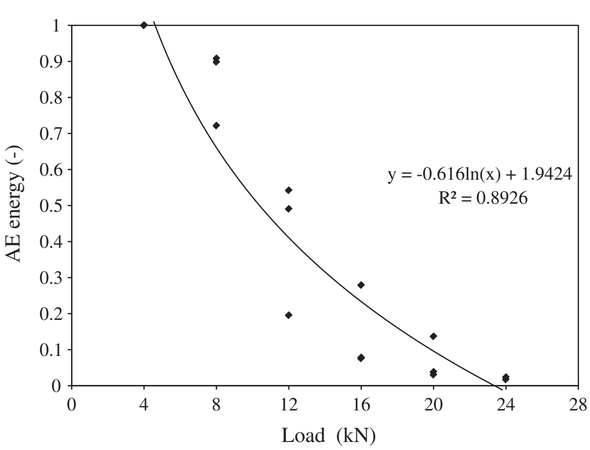

Fig. 7. Average AE energy vs. maximum load of each cycle.

dominant such as delaminations which emit lower energy than the matrix cracking events in this material [3].

As mentioned above, the shape of the waveform reveals information on the source crack motion that resulted in the corresponding signal. The initial slope of the waveform is directly relevant to the damage process [15] and is expressed by the rising angle of the signal (RA = Rise Time/Amp). In general, a shift from low to high RA values indicates transition from the tensile mode of crack to shear in different materials like concrete, rock and composites [8,10–12]. Alternatively, as is mentioned in literature [10,11], the "grade" or the inverse of RA is employed. In the case of step loading, as the load was monotonically increasing during each step, the RA was shifting to higher values (see Fig. 8a). The RA curve is presented as the moving average of the last 400 hits. This increase is considered indicative of the gradually increasing population of delamination events, which "replace" the matrix cracking [15]. After reaching the maximum load of each step, the RA value rapidly returns to approximately the initial values. Each successive step exhibits higher RA values and at the final step, while the material is approaching final failure, RA exhibits an explosive increase surpassing 10,000 μs/V (see Fig. 8a). The mean RA value for each loading step is shown in Fig. 8b. As can be seen, the load and the mean RA strongly correlate. Summarising, the load history and consequently all induced damage mechanisms, leave a distinct signature on the acoustic emission behaviour on the number of the incidences as well as the qualitative characteristics of the acquired waveforms; monitoring of the AE parameters may provide valuable information in the respect to the load induced damage of the composite as structural health monitoring indices, or provide early warning of the forthcoming failure.

2.3. Wave propagation measurements

As shown in Fig. 2, for wave propagation measurements, the two AE sensors are combined with another transducer acting as a pulser, in order to conduct wave velocity and transmission measurements during fatigue loading. The wave velocity was measured by the delay between the first detectable disturbance between the waveforms of the two transducers. This is usually referred to as pulse velocity and in most cases corresponds to the longitudinal

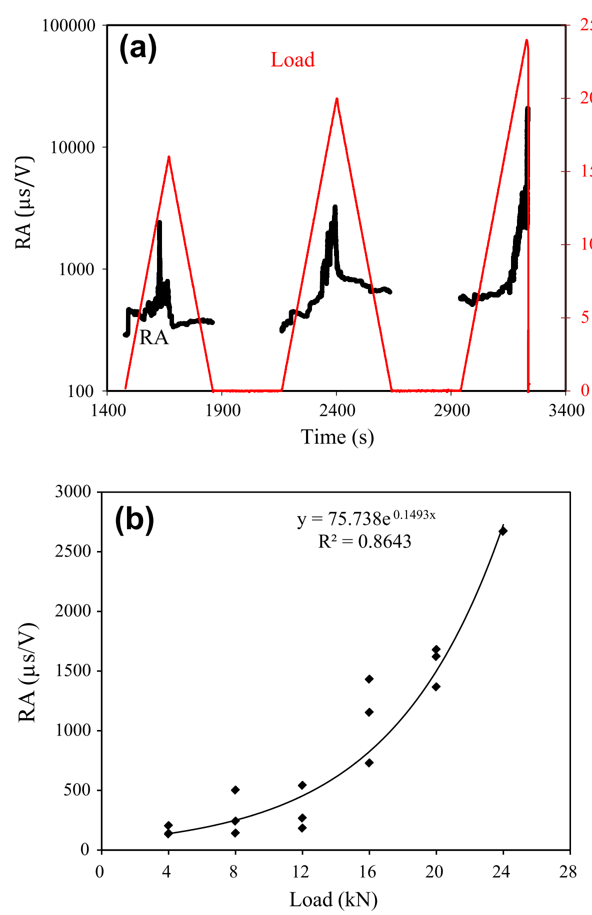

Fig. 8. (a) Load and RA value history for the three last steps, (b) RA vs. maximum load of each cycle.

waves. Pulse velocity is generally correlated to the health status of the material, as it is indicative of its elastic response [16,17].

Fig. 9a is showing the typical behaviour at 60% load level for the measured pulse velocity of the studied system. The curves belong to three different specimens and include approximately 40 measurements, which are adequate to show the transient shifts of velocity.

All specimens in the virgin state, exhibit the same velocity (approximately 3100 m/s) since they are cut from the same laminate before the onset of loading. It is noteworthy that immediately after load application all specimens exhibit a considerable increase in the pulse velocity of the order of up to 10%. The behaviour of the pulse velocity in this material, differs considerably from the behaviour in bulk materials, where any type of cracking results in reduction of wave propagation parameters like velocity and transmission [16,17]. However, in the case of cross-ply laminates, due to their specific geometry and structure, some type of damage temporarily increases the apparent transmission. Therefore, wave measurements on the surface of the plate may well offer an indication of the degree of delaminations, by the temporary increase of pulse velocity. Transmission, as measured by the amplitude difference between the two receivers has also shown to increase in a similar recent study [15].

More analytically, the characteristic behaviour of all studied systems can be described to follow three distinct stages; at first there is a notable increase in the pulse velocity of the system.

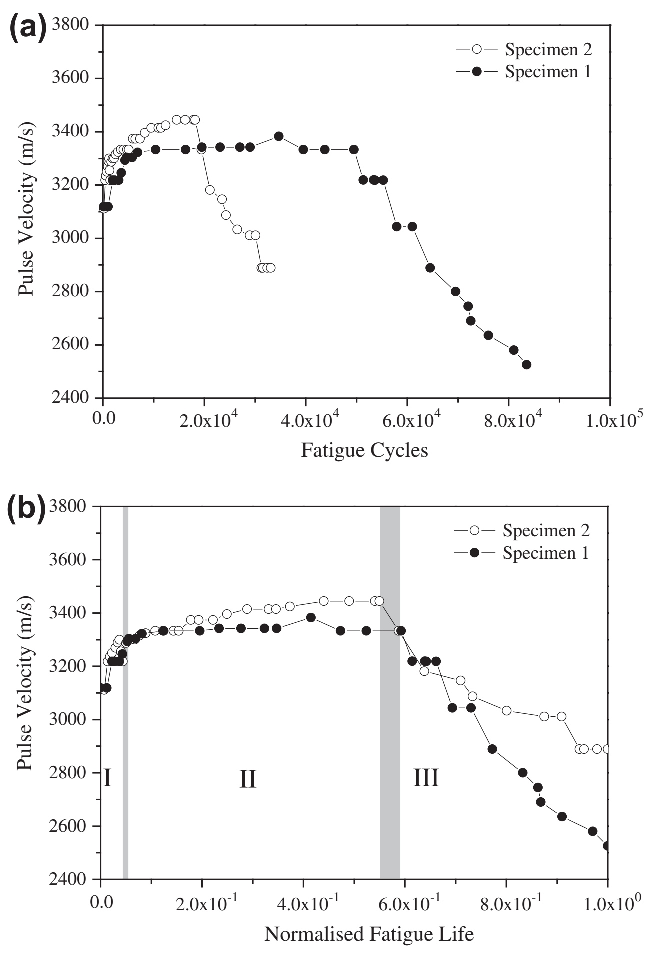

Fig. 9. Pulse velocity measured on the surface along the axis of the cross-ply specimen vs. (a) number of cycles and (b) life fraction under fatigue loading for 60% stress level, where stages I, II and III denote the transverse cracking, the delamination propagation and the longitudinal fibre rupture respectively.

Following the rapid initial velocity increase, the pulse velocity tends to stabilize asymptotically to a value which may correspond to a damage saturation stage. The final stage corresponds to a notable singularity of the curve which marks the onset of decreasing velocity until failure.

Fig. 9b shows the history of pulse velocity as a function of fatigue life fraction. Since the fatigue lives for the specimens were quite different (from 14,000 cycles to 80,000), the horizontal axis is presented normalised to the ultimate fatigue life of each specimen for conformity. The initial rapid increase may be directly attributed to the accumulation of transverse cracking and the onset of delamination; the following asymptotic behaviour is attributed to delamination propagation as transverse cracking is expected to be less prone to fatigue loading than delamination propagation. These damage entities lead to the isolation of the propagated wave to the outer 0° layers. The stiffer outer layer (in the wave propagation direction) is therefore acting as a waveguide, and the wave propagates faster as the isolated unidirectional waveguide is considerably stiffer than the initial cross ply material. Since the loading cycles fluctuate around the mean amplitude, the transverse cracking is expected to rapidly reach a maximum value directly related to the stress level. At all transverse crack sites, delaminations initiate and propagate with further fatigue loading. These delaminations are responsible for the isolation of the outer layers. Pulse velocity increases until after half the fatigue life, which indicates that until then, the longitudinal ply becomes progressively detached from the middle layer, or else delaminations are still active. As is noteworthy, the pulse velocity reaches a plateau before what can be seen as a discontinuity in the velocity/number of cycles curve (Fig. 9b). At 60% or 70% of the ultimate life, the velocity starts to decrease and just before the termination of the experiment it exhibits a decrease of 6–11% compared to the initial value. This can be attributed to extensive damage that occurs on the longitudinal plies at the last stage of the composite's life. This does not directly mean that no further delaminations take place, but that failure of longitudinal fibres accumulates rapidly resulting to stiffness loss with the subsequent velocity decrease. as the longitudinal fibre breakage is the primary damage mechanism which will lead to the final failure. What is even more interesting, the damage entity attributed to longitudinal fibre breaks seems to possess a distinct signature which is directly related to the life time of the specimen and not to the load level as in all cases seems to mark the onset of catastrophic failure. These remarks exhibit the potential of the employment of the aforementioned methodology as a structural health monitoring method for the early warning of catastrophic failure.

According to the aforementioned analysis, the extend of this plateau is directly relevant to the extent of delaminations the laminate can withstand before the final failure mechanism is activated and becomes dominant and is directly relevant to the damage tolerance of the composite.

2.4. Numerical simulations

In order to shed light on the propagation mechanisms, as well as to interpret wave measurement in a realistic way, good knowledge of wave propagation in laminated materials is necessary. These materials are inherently anisotropic and their anisotropy is increased by possible damage in the form of cracks and delaminations. Moreover, these materials are inherently inhomogeneous, and the scale of their inhomogeneity changes with the scale of service induced damage. Numerical simulations help in this direction and have been used in several cases for better understanding of ultrasonic results, mainly concerning damage content [18,19]. Simulations for this study were conducted with commercially available software [20]. The fundamental equation governing the

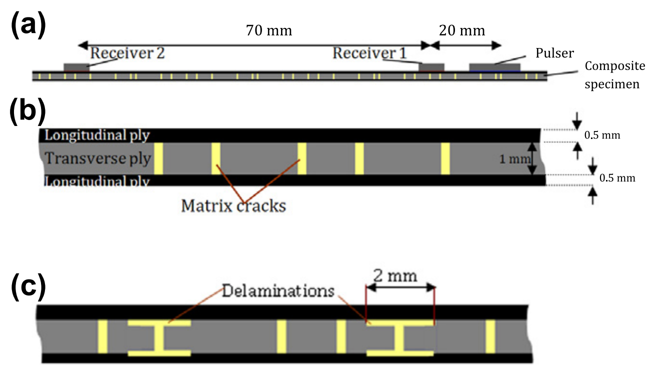

Fig. 10. (a) Geometric model for the simulations, close up showing simulation of (b) matrix cracking and (c) delaminations.

two-dimensional propagation of elastic waves in a perfectly elastic medium, ignoring viscous losses is seen below:

$$\rho \frac{\partial^2 u}{\partial t^2} = \mu \nabla^2 u + (\lambda + \mu) \nabla \nabla \cdot u \quad (1)$$

where $u = u(x,y,t)$ is the m vector, ρ is the mass density, λ and μ are the first and second Lame constants respectively, while t is time. The software operates by solving the above equation based on a method of finite differences. Eq. (1) is solved with respect to the boundary conditions of the object, which include the input source that has pre-defined time-dependent displacements at a given location and a set of initial conditions [21]. For heterogeneous media like the one studied herein, propagation in each distinct homogeneous phase is solved according to Eq. (1), while the continuity conditions for stresses and strains must be satisfied on the interfaces [21].

The three layer structure which was employed for the simulation purposes can be seen in Fig. 10a. As mentioned earlier, two are the major types of damage in this material. Firstly, the matrix cracking which was simulated by vertical inclusions of 0.2 mm thickness vertical to the middle layer (see Fig. 10b), whereas delaminations were simulated by horizontal inclusions of 0.2 mm between the successive layers, as seen in Fig. 10c. Wave parameters were measured for different numbers of vertical cracks from 0 to more than 200 in an arbitrary arrangement. Typical waveforms collected at the two transducers can be seen in Fig. 11a and b for two different crack populations. In the first case where the transverse layer includes only 12 cracks, the 2nd receiver records only a small percentage of the amplitude of the 1st, while in the case of Fig. 11b where there are 144 cracks in the transverse layer, the waveform amplitude captured by the 2nd receiver is visibly increased. At the same time, as the number of total matrix cracks increased, the velocity captured by the 2nd receiver is strongly influenced rising by more than 13% (Fig. 12a). This shows that as the number of cracks increases, the successive layers tend to be isolated and wave propagation takes place only on the top layer. This trend is even clearer for simulated delaminations. In the extreme case of total debonding between the layers, the ultrasonic energy propagates solely on the top layer. The measured pulse velocity increases asymptotically to the value of the top layer, see Fig. 12b. The length of the de-bonded surface in each delamination was considered to be 2 mm as shown in Fig. 10c, while the

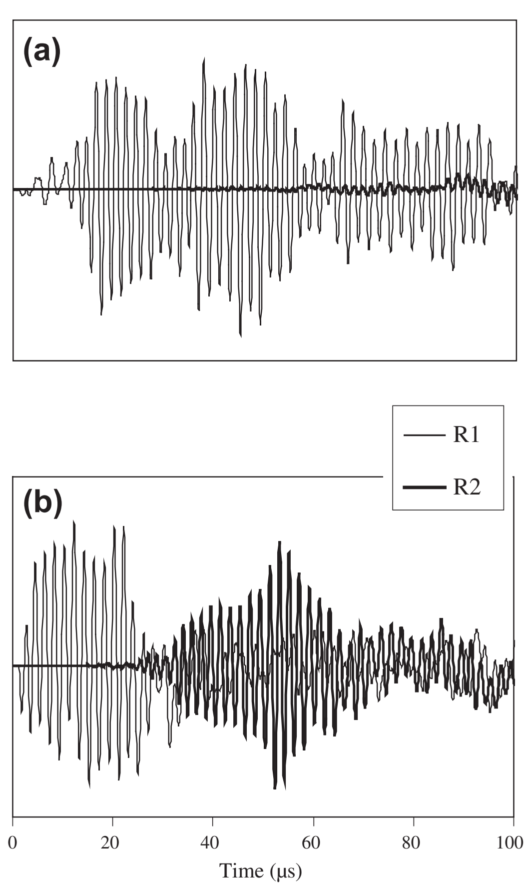

Fig. 11. Simulated waveforms of the two receivers for: (a) 12 and (b) 144 vertical matrix cracks.

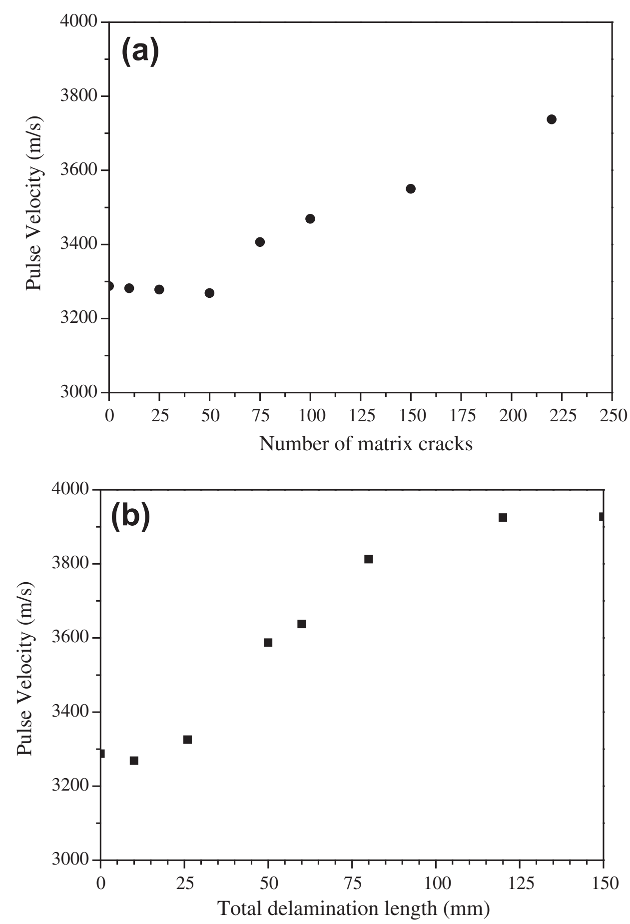

Fig. 12. Pulse velocity vs. matrix cracks (a) pulse velocity vs. total delaminated length (b).

total delaminated length was adjusted by the number of individual delaminations.

The specific arrangements of cracks and delaminations are some of the infinite possible cases that can actually occur and by using other sequence of cracks (distance between cracks and delaminations, length of delaminations) the results may be different. However, comparisons between the different cases are valid showing the eventual increase of wave transmission with accumulation of damage. The time step for the simulation is 0.06095 μs meaning that a cycle of 200 kHz (duration of 5 μs) is represented by more than 80 points which is more than adequate for numerical simulations [18]. However, although the space resolution of 0.5 mm is much finer than the longitudinal wavelength (approximately 11 mm), it is comparable to the geometry thickness, requiring simulations on a finer mesh. However, this is not expected to affect the conclusion that the debonding between layers, as well as matrix cracking may actually increase wave velocity, as was observed in the experimental measurements presented above, trend which is in contrast to what usually happens in bulk, homogeneous materials.

3. Conclusions

In the present study, the acoustic and ultrasonic behaviour of cross ply laminates under loading is examined. Acoustic emission activity is strongly correlated to the damage accumulation in incremental tensile step loading, while specific indices exhibit sensitivity to the cracking mode (matrix cracking or delamination). Specifically the average energy of the AE signals decreases as damage shifts from matrix cracking to delaminations, while the RA value, parameter that has been extensively used to characterise the damage mode in materials, suggests a certain shift from mode I (tensile) to mode II (shear). Unlike isotropic homogeneous materials, these composites exhibit an increase in wave transmission and pulse velocity when they suffer excessive cracking and debonding between layers, as is measured from surface measurements during tension fatigue. Numerical simulations were conducted in order to enlighten the propagation mechanisms in such complicated media. Results show that due to the specific geometry of laminates, damage actually isolates the distinct layers, making the top stiff layer to increasingly act as a waveguide while damage is being accumulated, giving an estimate on the extent of delaminations. It is concluded that study of ultrasonic readings and acoustic emission parameters can be used to characterise the structural health of composites in real time.

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