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Materials Today: Proceedings XX (2016) XXX–XXX

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PMME 2016

Characterization of residual strength in transversely loaded glass-polyester composites by acoustic emission and sentry function☆

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Abstract

This paper addresses damage evolution in composite materials by using acoustic emission (AE) as a non-destructive testing method to evaluate residual strength of specimens. Two composite samples at different lay-ups (Unidirectional and Cross-ply) were used in this investigation. The three-point bending test was applied on composite samples transversely while damage progression was monitored by means of acoustic emission technique. The test was stopped at three different damage levels, one (Low) corresponding to the load value of 10% before maximum load, the second (Medium) corresponding to the first load drop in the load-displacement curve and the third (High) to the complete failure of the specimen. Depend on loading level, the damage value was variant as it caused different residual strength that was related to acoustic emission signals activities. To find this relationship, firstly, the tensile test was carried out on damaged samples to evaluate the residual strength of them. Secondly, a method based on a special purpose function, called Sentry function, which is defined as the logarithm of the ratio between mechanical energy and acoustic energy, was applied to find out the relationship between the tensile residual strength and acoustic emission activates. Results show that the measurement of the strain energy in specimens and of the acoustic emission energy released by fracture events made it possible to estimate the amount of induced damage and can be effective in residual strength estimation and damage evolution.

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

Keywords: composite materials; trassverse load; residual strength; acoustic emission; sentry function

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1. Introduction

Glass-Fiber Reinforced (GFR) composite materials have wide application in variety of industries because of their high strength-to-weight and stiffness-to-weight ratios. But these materials can be easily damaged by loads transversely applied on them. During transverse loading of composite materials, different damage mechanisms depend on loading level can be activated. From results of numerous experiments on composite structures, it can be found that there are mainly four types of failure modes under transverse loading conditions [1-3]. These modes of failure for composites in either three-point or four-point bending are: (i) matrix cracking, (ii) Delamination, (iii) debonding, and (iv) fiber breakage. Damage due to transverse loads from low velocity impact and indentation can degrade residual strength of composites [4-6]. Therefore, besides the behavior of the material subjected to impact, an issue of great interest is the evaluation of the post-impact resistance characteristic of GFR composite materials.

Many different investigations on residual strength computation of composite materials under a variety of loading conditions and materials have been proposed in the literature. Most of these approaches refer to residual strength after fatigue [7-9] and post-impact [10-12] of materials by focusing on deterministic theories that predict strength degradation to compare with experimental data. On account of the relative complexity of the architecture of composite materials and their failure patterns in comparison with those of monotonic materials, Non-Destructive Evaluation (NDE) methods are more highly desirable than others for the inspection and characterization of such materials. Some researchers implemented Non-Destructive Testing (NDT) techniques to evaluate failure progression during loading to find its relationship with the residual strength of materials [13-16]. Among NDT methods Acoustic Emission (AE) is more useful in damage characterization. The ability to monitor dynamically in real time provides acoustic emission monitoring with a significant advantage over other non-destructive testing methods. Also, predominant failure evolution and damage classification with acoustic emissions is the way to find damage mechanism in composites [3, 4, 17, 18].

From the above discussion of various publications, it is clear that for any particular composite specimens, failure modes with different test configurations and geometry could be characterized. However, conclusions above only focus on the crack initiation, formation and propagation during static tests, relatively little work has been published describing damage evolution at different loading levels by AE, which is important to detect residual life or the age of structures.

In this paper, the main objective was to predict damage evolution in glass /polyester composite materials by using acoustic emission (AE) as a non-destructive testing technique in order to estimate the residual life of specimen. Acoustic emission method was used on samples that were under the three-point bending test to monitor induced damage. The test was carried out at different loading levels. Depend on loading level, the damage value was variant as it caused different residual strength that was related to acoustic emission signals activities. In this way, the tensile test carried out on damaged samples to evaluate the residual strength of them. Then, a method based on a special purpose function, called Sentry Function, was applied to find out the relationship between the tensile residual strength and acoustic emission activates.

2. Experimental procedure

2.1. Material preparation

The experimental work was carried out on the polyester resin reinforced by the E-glass unidirectional and cross ply fiber with the density of 1.12 g/cm3, 500 g/m2 and 600 g/m2, respectively. Laminates were provided by hand lay-up with compression molding. Rectangular plates of cross glass fiber/polyester composite with dimensions 200 mm × 50 mm × 5 mm were manufactured in the lab. The cross ply specimen [0, 90]s and the unidirectional specimen [0]s were used as for testing.

2.2. Testing Procedure and AE Equipment

The specimens were placed in a 3–point testing fixture with a span length of 150 mm and they were loaded at the center: hardened steel wedge with a nose radius of 5 mm were indented in the top center point of the specimens by means of a ball screw type universal testing machine equipped with a 5 kN load cell. Specimens were loaded monotonically in control of displacement and the head speed was of 2 mm/min. The applied compression loads versus displacement were stored digitally. Tests were stopped at three different damage levels, one (Low) corresponding to the load value of 10% before maximum load, the second (Medium) corresponding to the first load drop in the load-displacement curve and the third (High) to the complete failure of the specimen. During the test, AE events have been monitored by a Physical Acoustic Corporation (PAC) PCI-2 device and a maximum sampling rate of 40 MHz was used to record AE events. AE sensor, called PICO, was a broadband, resonant-type, and single-crystal piezoelectric transducer from PAC company. The resonance frequency and the optimum operating range of the sensor were 513.28 kHz and 100–750 kHz, respectively.

3. Sentry function

The Sentry function is defined as the logarithm of the ratio between mechanical and acoustic energies and it can be formulated as follows[18]:

$$f(x) = Ln\left(\frac{E_s(x)}{E_a(x)}\right) \tag{1}$$

The function f is defined over displacement domain where the acoustic energy E_a is non-zero (see Fig. 1, ΩAE). Depending on the material damaging process, the resulting f can assume any combination of the five trends as shown in Fig. 1. From the physical point of view, parts of f characterized by an increasing trend, type I, represent the strain energy storing phases. When a significant internal material failure occurs, there is an instantaneous release of the stored energy that produces an AE event with high energy content. This fact is highlighted by the sudden drops of the function f that can be described by type II functions: $P_{II}(x)$. The constant behavior of f, described by P_{III}, is due to a progressive strain energy storing phase that is superimposed on an equivalent energy release due to material damage progression. The subsequent Bottom-Up (BU) trend indicates that a strengthening event induced an instantaneous energy storing capability in the material. Such an event can be related to hardening effects, self-healing effects or, as in the case of the present study, it can be related to fiber bridging effects during delamination. The decreasing behavior of f, type P_{IV}, is related to the fact that the AE activity is greater than the material strain energy storing capability: the damage has reached a maximum and the material has no resources to sustain the loadResults and discussion

Results obtained from 3-point bending tests are explained in two main sections: in the first section, mechanical trends and AE parameters such as amplitude and energy are reported. The second section contains the application of Sentry function to evaluate the residual strength of specimens.

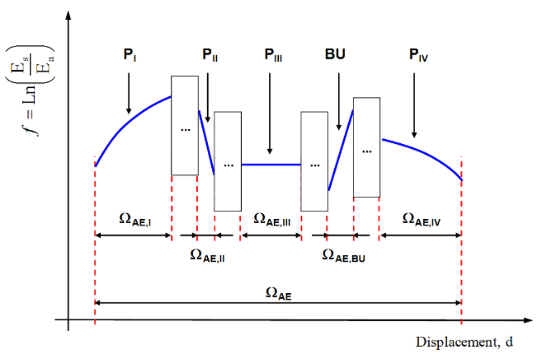

Fig. 1. The basic functions PI , PII , PIII and PIV, used to describe the function f.

3.1. Transverse loading tests and acoustic emission behavior

Fig. 2 indicates some of the most related information obtained from the mechanical behavior of specimens during 3- point testing. It can be seen that after the maximum load, the nonlinearity is significant, which is related to different stacking sequence of each specimen. For both of samples, there is a load oscillation, which shows the progressive damage process initiation. Due to the stacking sequence of cross-ply laminate, main failure mechanisms are the matrix rupture and delamination, which reduce the global stiffness of the structure. Despite cross-ply lay-up, for the unidirectional lay-up, fiber breakage is more dominant failure mechanism.

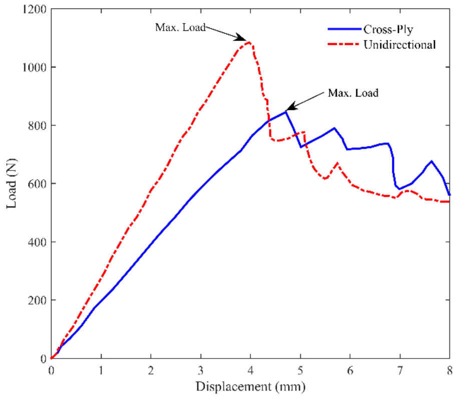

Fig. 2. Comparison of load-displacement diagram for unidirectional and cross-ply laminates.

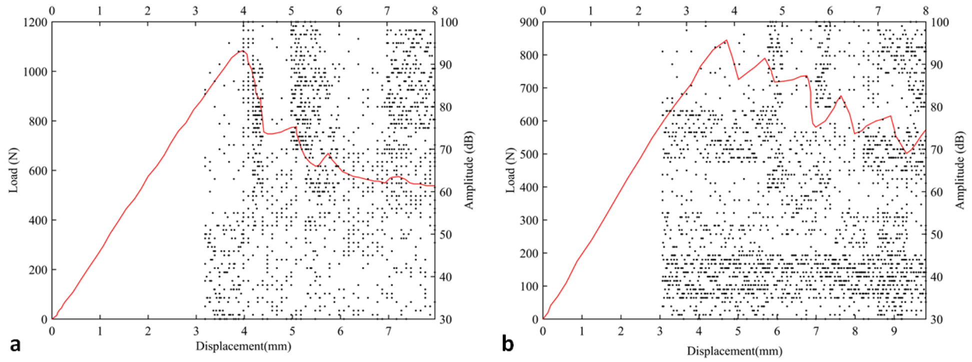

Fig. 3. Acoustic emission amplitude distribution during transverse loading for a) Unidirectional b) Cross-ply composite.

Amplitude and energy as AE signal features have been considered for damage mechanism evaluation during the loading [1-3]. In Fig. 3, AE amplitude is plotted with respect to the load-displacement curve. AE amplitude of signals during loading has been widely distributed because of different damage mechanisms activation. During three-point loading of specimens, various distributions of AE amplitudes were received. Fig. 3 indicates AE amplitude for both specimens during loading. From Fig. 3, for unidirectional samples, one can note the presence of three distributions. A principal distribution with amplitudes ranging from approximately 80 to 95 dB can be attributed to fiber breakages. The second distribution ranging from 35 to 45 dB is related to the matrix cracking and the last one is distributed between 45 to 65 dB and resulted from debonding between matrix and fibers [3, 19]. For cross-ply samples, AE amplitude began with low values i.e. matrix cracking and continued to end of the test. In the second order, delamination occurred in cross–ply samples at amplitude that ranged from 65 to 75 dB and at higher amplitudes, fiber breakages appeared.

3.2. The Sentry function application

The Sentry function is defined as the logarithm of the ratio between the Strain Energy and the cumulative acoustic energy as indicated in Equation 1. The strain energy is mechanical energy determined by using the load-displacement diagram, and the cumulative AE energy is considered as the summation of AE event energy. In Fig. 4 load-displacement plot and its relation with AE events energy have been shown. Also in Fig. 4 three different loading levels are reported.

Besides the analysis of AE information, it is interesting to relate AE diagrams to the mechanical response of the laminate. Based on Equation 1 and AE energy reported in Fig. 4, Sentry function trends for both samples, i.e. unidirectional and cross-ply laminates obtained and are shown in Fig.5.a and 5.b, respectively. In this figure, for all specimens, Sentry function diagram has some drops (PII trend), but some of them are dominant compared with other drops. This is due to the fact that a considerable internal material damage initiated, which causes an instantaneous release of the strain energy (stored energy in load-displacement diagram) that generates an AE event with high energy content. This fact is observable by the sudden drop of f(x) function.

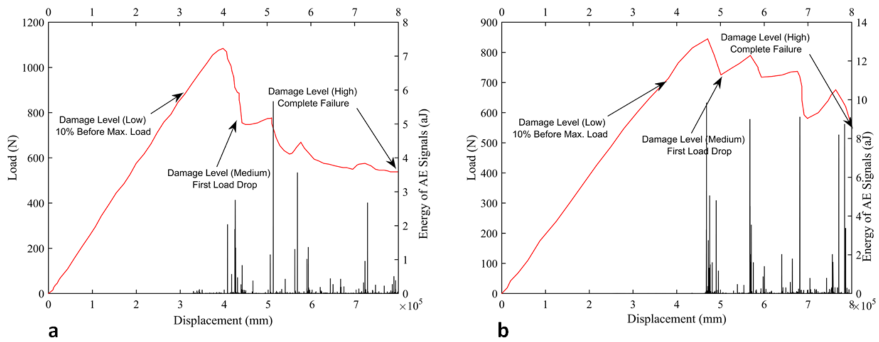

Fig. 4. Load and AE energy versus displacement a) unidirectional specimen, b) cross-ply specimen.

3.3. Residual Tensile strength

Tensile testing was used on specimens, which was obtained from quasi-static 3-point bending test at different loading levels, to evaluate the related residual strength of samples. The critical load reduction in damaged specimens can be come back to previous loading history of specimens during transverse loading. For highly damaged specimens, the load reduction is significantly higher than to low damaged or virgin specimens.

In order to take into account the material damage, it is necessary to evaluate all events that cause loss of structural integrity. Since the function f amplifies most important material damage events and it is able to consider at the same time the strain energy storing capability and the released internal energy, its integral was utilized as a damage indicator.

The relation between the values of Int (f) measured during the transverse loading phase and the residual tensile strength σ_c of damaged specimens at each loading level can follow us to find the reduction in load carrying by each specimen. This relation depends on the severity of induced damage with respect to the transverse loading.

In Fig. 6 critical load for all specimens are obtained and are plotted versus integration of Sentry function. It can be seen that for low damaged specimens, the value of integration of Sentry function is lower than for the high damaged one. In the other hand, because of more activity of specimens during high level loading, a lot of damage mechanisms activated and more AE signals obtained. In this case, more AE signals can be affected the value of Sentry function and will increase the value of integration of Sentry function, respectively.

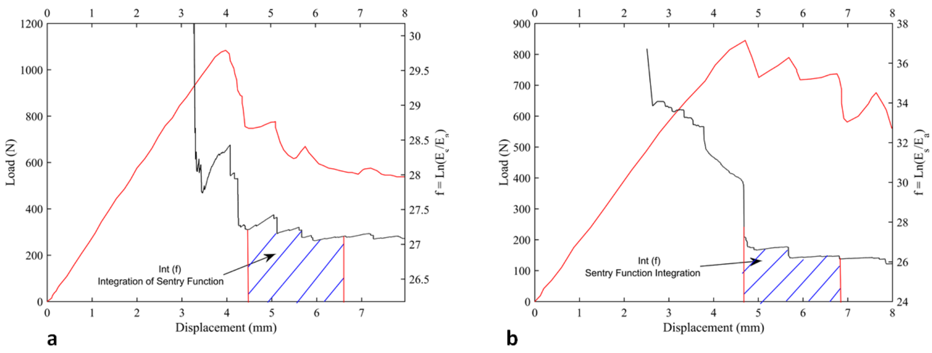

Fig. 5. Sentry function trends a) unidirectional specimen, b) cross-ply specimen.

In particular, it is evident that there is a negative relation between the residual tensile strength and values of the f integrate, confirming that the variable Int (f) is a reliable instrument to evaluate the material damage during the indentation process. To represent mathematically the relations between the residual tensile strength of composites and the damage indicator a continuous relation was considered having the following form:

$$\mathrm{Re}\,sidual = A.(\mathrm{int}(f))^{B} + C \qquad (2)$$

where the constant C is related to the ultimate load of the virgin material, and the constant A and B can be obtained by means of a linear regression based on the experimental data. Implementing the model in Equation 2 to the experimental data it was estimated following values for the coefficient of the continuous model:

For Unidirectional: A= -0.006784, B=1.683, C= 48 kN
For Cross-ply: A= -0.05437 , B= 1.181 , C= 27 kN

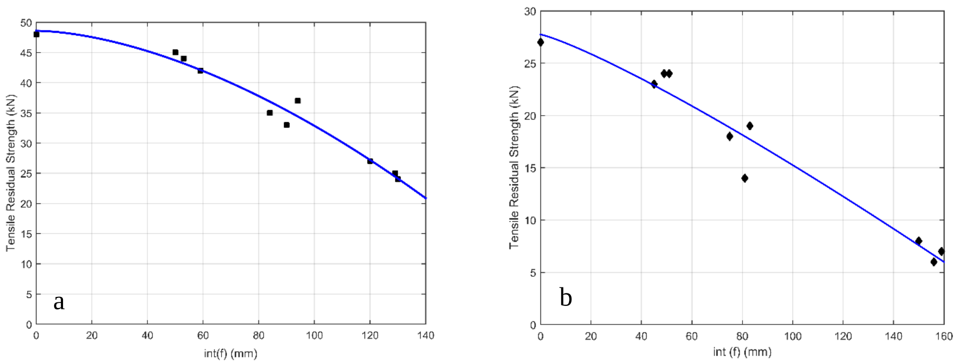

Fig. 6. Tensile residual strength versus integrate of the function f and correlation model for a) the unidirectional damaged laminate b) the cross-ply damaged laminate.

In Fig. 6, mathematical continuous models implementing the previous coefficient are represented by means of the continuous line showing a good fit.

4. Conclusions

The main purpose of this study was to investigate the efficiency of AE to evaluate the residual strength of composite materials. In this way, a function of the acoustic emission and of the strain energy i.e. Sentry function was introduced and its application to evaluate the tensile residual strength of composites was illustrated. In this case, Sentry function allowed to single out important material failure and to calculate corresponding damage values. Also, the residual tensile strength was related to the integral of the Sentry function over the acoustic domain defined in the transversal load test. Results show that AE method is a useful tool for monitoring damage progression during loading of materials. Also, this technique can find the relation between severities of damages with the recorded AE data. In the other hand, more AE activity can be related to more damage mechanism and cause to reduce load carrying capacity of materials.

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