

ACOUSTIC EMISSION – THE SENTRY FUNCTION

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1. Introduction

The acoustic emission (AE) technique has been used for decades to detect damage onset and propagation in different kind of materials [1]. The more complex microstructure of the material, the more information can be derived from the AE signal [2].

Solid mechanics experimentalist are familiar with the acoustic emission produced by the material during the loading phase, which sometimes can be heard simply by naked ears.

In fact, during a material test or in general when a component is subject to external loads, a rapid stress redistribution can occur due to permanent and irreversible phenomena, caused by damage mechanisms.

During this redistribution, part of the strain energy stored in the material is released in the form of heat and of elastic waves that propagate in the material until they reach the free surface. These transient elastic waves are commonly detected as acoustic waves.

Some acoustic emission can be also produced by mechanisms different from damage (such as sliding and friction of two surfaces in contact) and this must be taken into account. The elastic waves propagating at the component surfaces are detected by means of piezoelectric devices that convert the mechanical signal into an electrical one.

Even if the AE physical principle is very simple and immediate, the use of this technique is not so straightforward because the acoustic wave propagation in solids is quite complicated. Multiple waves that propagate with different velocities, reflection, refraction, dispersion, and attenuation, may affect the measured signal.

Nevertheless some advantages with respect to other nondestructive testing techniques can be found in the possibility to monitor a large volume of material by means of few sensors able to locate the damage by triangulation and to make it continuous during real life service. In reality, the acoustic emission is produced within the material itself once loaded at a level that produces some form of damage. In this sense, it is not strictly a non destructive testing method since it is based on

passive monitoring of acoustic energy released by the material or structure itself while under load.

Mechanical information and AE information can be analyzed separately to determine damage in the structure. However, when one is taken into account and the other is omitted a comprehensive damage characterization cannot be taken out.

In this paper some possible application of a recently defined function [3,4] called Sentry (SF), to the damage identification and residual strength determination in the case of composite laminates, is shown.

2. Definition of the Sentry Function

In order to perform a deeper analysis of the laminate behavior, a function that combines both the mechanical and acoustic energy information is employed. This function is expressed in terms of the logarithm of the ratio between the strain energy (E_s) and the acoustic energy (E_a), where x is the test driving variable (usually displacement or strain).

$$f(x) = \text{Ln} \left[\frac{E_s(x)}{E_a(x)} \right]$$

The function $f(x)$ is divided into five distinct areas: an increasing function $PI(x)$, a sudden drop function $PII(x)$, a constant function $PIII(x)$ a decreasing function $PIV(x)$ and a some times a Bottom-up function $BU(x)$. Each region represents a specific stage in the damage process (Fig. 1).

The sentry function, type PI , represents the strain energy storing phase when it is increasing. During the test the ability of the material to store energy reaches its limits and the AE cumulative energy significantly increases due to damage progression hence the slope of the $PI(x)$ function decreases.

During the damage process when a major failure takes place in the material the stored mechanical energy is suddenly released producing a ratio of this energy as acoustic waves. This is shown by the abrupt drop in the function $f(x)$ that is described by the type II function, $PII(x)$.

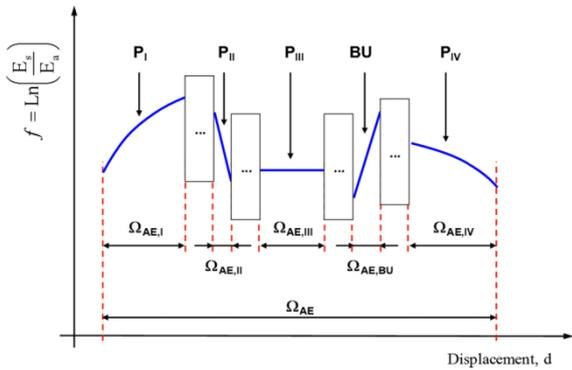


Fig. 1: a) tool for application, b) deformation zone with strain gauges

After each major failure, type II function, the slope of the next PI(x) function decreases, until the material largely loses its ability to store mechanical energy. At this stage the slope of the function reaches zero or below zero, type III or IV function.

The 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.

3. Damage identification

The function defined in the previous paragraph was named ‘‘Sentry’’ for its capability of highlighting important damage events.

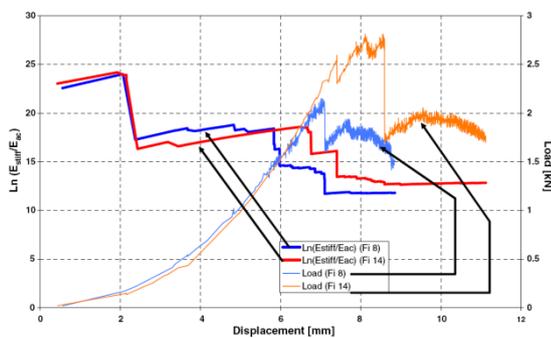


Fig. 2: Sentry function in the case of transversal indentation of a composite laminate

In Fig.2 it is shown the first application [3] to composite laminates. Different lay-ups show different sentry functions.

Fig. 3 and Fig 4. show a more recent application [5] to composite tubes loaded in torsion after an accidental impact.

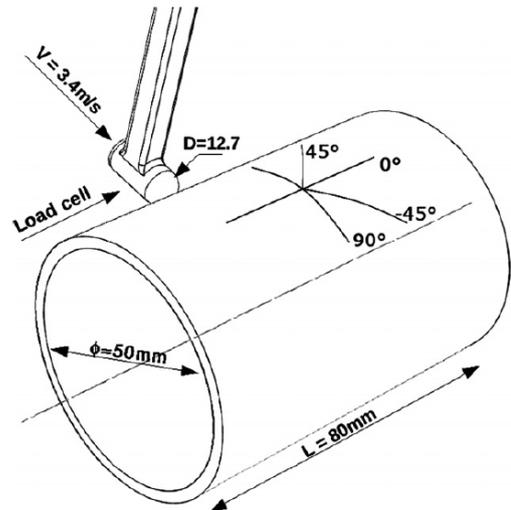


Fig. 3: Application of the SF to a composite tube under impact then loaded in torsion

In this case the shape and composition of the SF depend from the lay-up and also from the impact event characteristics.

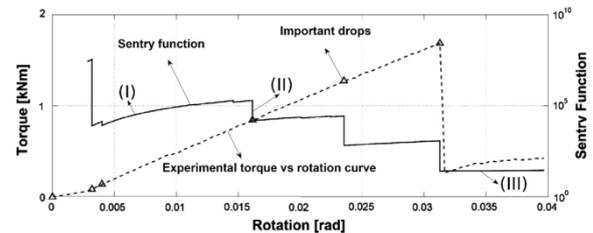


Fig. 4: SF as a function of the angle of torsion in the case of composite tubes

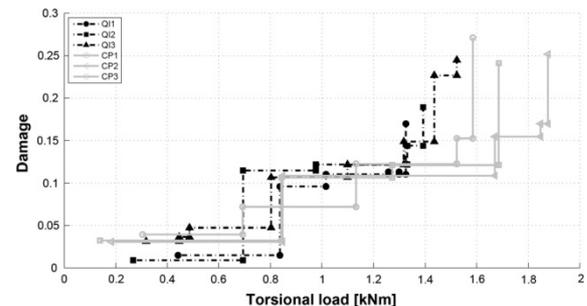


Fig. 5: SF as a function of the angle of torsion in the case of composite tubes

A completely different application has been done by the group of the Amirkabir University [6,7]. They used the Sentry function for the characterization of inter-laminar properties of CFRP by means of DCB specimens shown in Fig. 5. In particular in [6] the SF was utilized to detect initiation of delamination and to distinguish different kinds of damages in different regions in mode I delamination test. This approach simply discerns the behaviour of the material in different

stages of initiation. The damage mechanisms have been verified using SEM images.

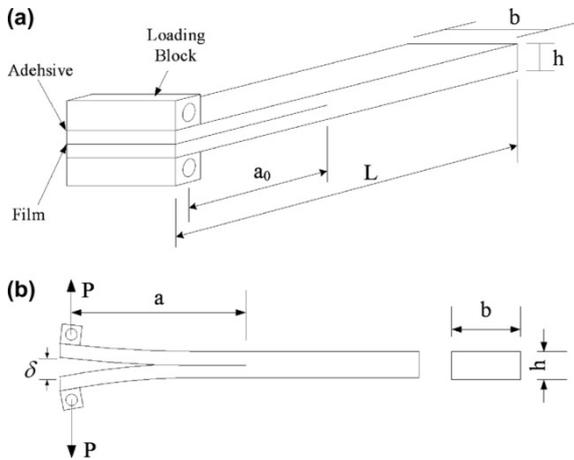


Fig. 6: DCB specimens for the characterization of the inter-laminar properties in CFRP

On the other hand in [7] the Integral of the SF was used, as explained in the following paragraph.

4. Residual strength determination

From the consideration that the SF is linked to damage processes it is was supposed that the integral of SF, called $Int(f)$, over the acoustic emission domain (in terms of the test driving variable) was related in same way to the residual strength or to the resistance to crack propagation.

$$Int(f) = \int_{\Omega_{AE}} f(x) dx$$

In [4] Minak & Zucchelli derived a phenomenological relation between the static residual strength in traction for different lay-ups and the $Int(f)$ for transversally indented laminates, that is shown in Fig. 7.

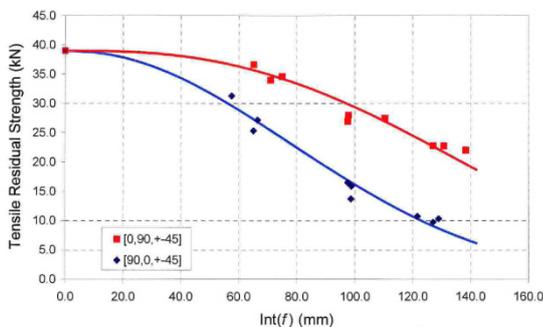


Fig. 7: Relation between residual tensile strength and $INT(f)$ for two different lay-ups

By means of that relation they and Morelli [8] found that it is possible to pool the results

regarding the tensile fatigue life for damaged and undamaged specimens (Fig. 8)

This was done referring the load levels to the residual tensile strenght derived from Fig.7 rather than to the tensile strength of the undamaged specimens.

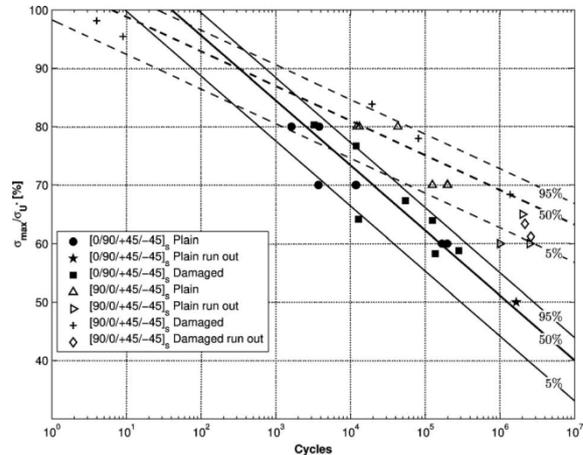


Fig. 8: Pooling of tensile fatigue life of damaged and undamaged specimens by means of $Int(f)$

As said before, Oskuei et al. [7] showed that, for DCB specimens (Fig. 6) based on values of SF it was possible to predict the test stage at which a delamination propagation becomes visible under an opening load condition. Furthermore, it was possible to highlight a bi-linear relation (see Fig. 9) between the cumulative strain energy release rate (GICUM) and $Int(f)$. The transition point in the bi-linear

relation enabled the estimation of the critical strain release rate (G_{IC}) value. The G_{IC} obtained by this approach was then compared to the values obtained by both ASTM D5528 standard test method and Ndiaye approaches.

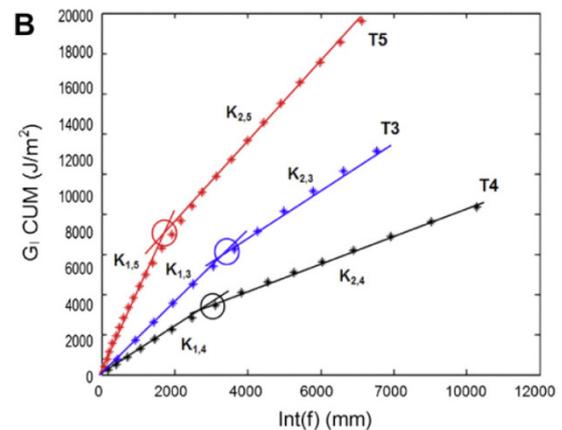


Fig. 9: Bilinear relation between GICUM and $Int(f)$

G_{IC} calculated from the SF method is in good agreement with the results obtained from the

ASTM D5528 method (5% max Load) (Fig.10). Moreover it can be also noted that the standard deviation related to the results obtained by the new method are smaller than the ones obtained applying the ASTM D5528 methods. It can thus be concluded that the Sentry function is another alternative method for calculating G_{Ic} directly from acoustic emission data.

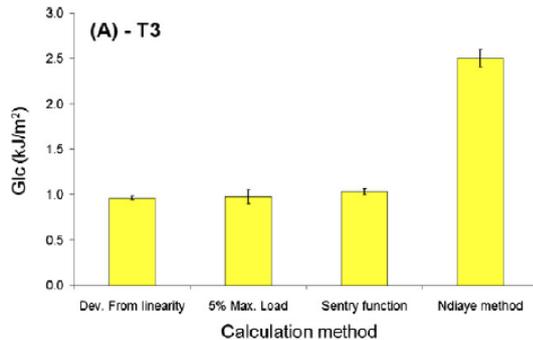


Fig. 10: Estimation of G_{Ic}

5. Conclusion

In this paper the capabilities of the Sentry function and of its integral in different case studies regarding the mechanical behaviour of composite laminates are shown.

Young researchers who want to use the method exposed to solve their problems, or who already did it, may feel free to contact the author or DR. Andrea Zucchelli (a.zucchelli@unibo.it) for support or discussion.

Acknowledgements: The author thanks DR. Andrea Zucchelli who is the first inventor of the method shown in this paper.

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