Acoustic Emission Sensing of Structures

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Abstract—**This paper presents some experimental results concerning the acoustic emission (AE) of different material structures, submissive at mechanical tests. Acoustic emission signals were prevailed by AE sensor, fixed on the material surface by an electroacoustic material. The AE piezoelectric sensor realizes the mechanical to electrical energy conversion, and the output signal is displayed on the memory digital oscilloscope. By signal analysis in time and frequency one can get the attenuation coefficients, delaminating, voids, defects, into material, revealing important information about the material structure behavior at mechanical stresses. Also, we can determine the moments when the material could be cracked or irreversibly deteriorated. Therefore, one can detect the maximum acoustic emissions and predict the material failure. Experimental works provided information concerning the AE response of different type of materials (aluminum, brass and concrete) under mechanical strengths, in order to predict their behavior at maximum strengths. The information could be applied for complex construction structures, in order to prevent their breaking risks.**

Keywords-acoustic emission; AE; sensor.

I. INTRODUCTION

A critical issue in practical structural strength state monitoring is related to the capability of proper sensing systems integrated within the host structures to detect, identify, and localize damage generation, such as cracks and potential problem areas in metal pressure boundary applications while other types of Nondestructive techniques are used to provide acceptance or rejection criteria [1]. To this aim, many techniques have been proposed involving dynamic measurements such as: modal analysis, acoustic emission, and ultrasonics [2].

Acoustic Emission techniques have been used in the field for the testing of metal and composite pressure vessels and piping. Nondestructive techniques were not accepted long time for the testing of bridges, and other components of the infrastructure because of two primary reasons: the difficulty in separating valid signals from extraneous noise and the inability of the AE technique to determine the size of the crack [1].

It results in the need for the development of advanced and effective inspection techniques. Thus, AE techniques draw a great attention to diagnostic applications and in material testing.

Acoustic Emission inspection is a powerful aid to materials testing and the study of deformation, fracture and corrosion. It gives an immediate indication of the response and behavior of materials under stress, intimately connected with strength, damage, fracture and failure [3].

Acoustic emissions (AEs) are the stress waves produced by the sudden internal stress redistribution of the materials caused by the changes in the internal structure. Possible causes of the internal-structure changes are crack initiation and growth, crack opening and closure, dislocation movement, twinning, and phase transformation in monolithic materials and fiber breakage and fiber-matrix debonding in composites. Most of the sources of AEs are damage-related, the detection of these emissions are commonly used to predict material failure. The Acoustic Emission method can be successfully applied for monitor the integrity of piping systems, and to aid in maintenance planning.

AE technology involves the use of ultrasonic transducers (20 kHz - 1 MHz) to listen for the sounds of failure occurring in materials and structures. Crack growth due to fatigue, hydrogen embrittlement, stress corrosion, and creep can be detected and located by the use of AE technology. In addition high pressure leaks can also be detected and located. AE technology is also finding wide application in the nondestructive testing for structural integrity of composite materials and structures made from composite materials. Fiber breakage, matrix cracking, and delaminating are three mechanisms that can produce AE signals when stress is applied to the material or structure.

AE sensors typically consist of a piezoelectric element on a ceramic plate inside a metal case with an electrical contact on top, insulated by epoxy. The shape, dimensions and mass of most commercial AE sensors make them unsuitable for integration into composites. In spite of extensive work with thin PVDF films (e.g. [4], [5], and [6]) there are to the best of our knowledge no commercial PVDF AE sensors available. AFCs present a number of advantages in comparison with conventional AE sensors: (1) light weight, (2) flexibility (adaptable to curved surfaces), (3) anisotropic sensitivity, and (4) potential for integration into composites due to their low thickness (about 300 µm) and compatibility with polymer-matrix laminate and related manufacturing processes. Ultrasound wave propagation in materials is presented in [7].

II. USUAL AE APPLIED TECHNIQUES

Acoustic Emission (AE) techniques have been studied in civil engineering for a long time. The techniques are recently going to be more and more applied to practical applications and to be standardized in the codes. This is because the increase of aging structures and disastrous damages due to recent earthquakes urgently demand for maintenance and retrofit of civil structures in service for example.

Crack initiation can be determined by the appearance of the AE signal at low stretch stress levels. After the crack advent, the AE signals around the zero stress were thought to be caused by crack-face grinding when the cracks were closed.

2.1 Wireless Monitoring Techniques Based on MEMS

Existing monitoring systems use traditional wired sensor technologies and several other devices that are time consuming to install and relatively expensive (compared to the value of the structure). Typically they are using a large number of sensors (i. e. more than ten) which are connected through long cables and will therefore be installed only on a few structures. A wireless monitoring system with MEMS (Micro-Electro-Mechanical-Systems) could reduce these costs significantly [8]. MEMS are small integrated devices or systems combining electrical and mechanical components that could be produced. The principle of such a system is shown in the scheme given in Figure 1.

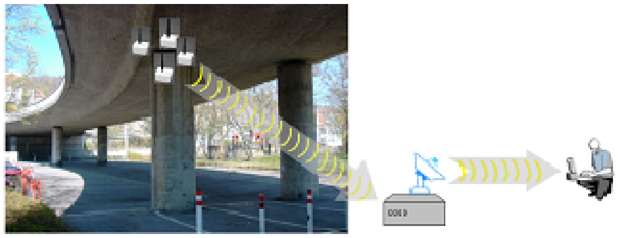

Figure 1. Scheme for wireless sensing of structures using radio frequency transmission techniques and MEMS [8].

2.2 Motes

Monitoring systems equipped with MEMS sensors and wireless communication can reduce the costs to a small percentage of conventional monitoring systems, and will increase its field of application. For instance, due to the detailed information of the structural behavior of bridges obtained from the monitoring system, maintenance costs could also be reduced, since inspection methods can be applied more efficiently [9].

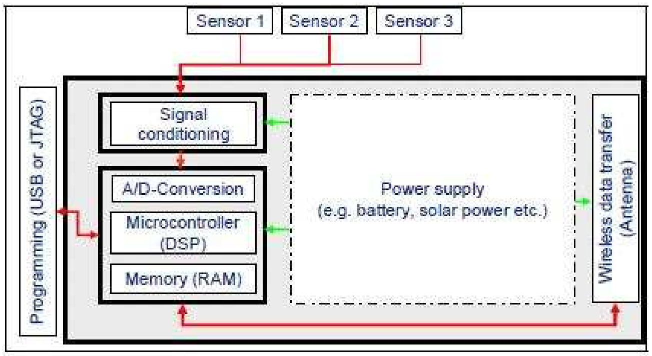

Figure 2. Principle of MEMS based *mote*; Concept of the sensor and processing board [9].

III. AE SIGNALS DURING TENSILE TESTING

Acoustic-emission activities have been shown to relate to different stages of tensile tests of materials Figure 1 presents the cumulative AE count, AE count rate, and stress versus strain relationship during a tensile test [10]. The cumulative AE count is the sum of the count of all AE events. The AE count rate is the time derivative of the AE cumulative count. The beginning portion of the linear elastic region is very quiet (i.e., low count rates and cumulative counts) or is associated with an incubation stage. The AE activity reaches its peak in the second stage right before yielding occurs. After the material yields, the AE activity decreases, but is still detectable until the material fails.

3D-Localization of acoustic emission events is a powerful tool in quantitative AE techniques. It is the basis of advanced signal interpretation and the discrimination between signal and noise. Signal-based procedures, such as: accurate 3D localization of damage sources, solutions for fault plane orientation, and moment tensor inversion, are described with respect to applications in civil engineering. More quantitative analysis of the signals is based on a 3D localization of AE sources (hypocenters) and the recordings obtained from a sensor network. For instance, using moment tensor inversion methods, the radiation pattern of acoustic emission sources and the seismic moment (as an equivalent to the emitted energy), as well as the type (Mode I, Mode II, and mixed modes) and orientation of the cracks, can be determined [11].

Fatigue tests are usually long-term experiments. A great amount of signals, including the noises from the load-chain, are detected by the sensitive AE sensors during fatigue testing. According to the time sequence for the guard and main sensors to receive the signals, the signals originating from outside the test section can be detected and discarded. Crack initiation was determined by the first appearance of the AE signal at low stress levels. This stage has a steady-state dislocation motion that will eventually result in microvoids and initiate microcracks. The third stage is an AE-active stage. In this stage, cracks start to grow and propagate. Many of the AE signals in the third stage can come from the crack-tip plastic deformation, fracture of hard inclusions, microcrack coalescence, transgranular cleavage, and fracture along grain boundaries.

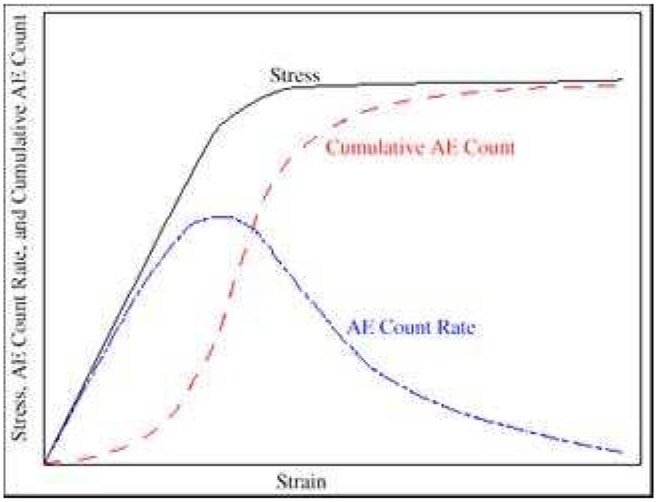

Figure 3. A tensile stress-strain curve and AE signals [10].

As example [10], the maximum stress was 644.8 MPa with a ratio of 0.05, where:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{1}$$

$\sigma_{\min}$ and $\sigma_{\max}$ are the applied minimum and maximum stresses, respectively. The frequency was 5 Hz initially to study crack-initiation behavior.

Tabel 1 presents the main mechanical and thermal properties of some construction materials.

TABLE I. MECHANICAL AND THERMAL PROPERTIES OF DIFFRENT CONSTRUCTION MATERIALS

Material	*Longitudinal elasticity module, E, daN/cm²*	*Transversal elasticity module G, daN/cm²*	*Poisson Coefficient μ*	*Thermal Dilatation Coefficient α_t*
Soft steel	$(2.0\text{-}2.15)\cdot 10^6$	$(7.8\text{-}8.5)\cdot 10^5$	0.24-0.28	$12\cdot 10^{-6}$
Hard steel	$(2.0\text{-}2.2)\cdot 10^6$	$8.5\cdot 10^5$	0.25-0.29	$11.7\cdot 10^{-6}$
White wrought iron	$(1.0\text{-}0.6)\cdot 10^6$	$4.5\cdot 10^5$	0.23-0.27	$10\cdot 10^{-6}$
Tin	$0.2\cdot 10^6$	$0.7\cdot 10^5$	0.42	$26.7\cdot 10^{-6}$
Copper	$(1.1\text{-}1.3)\cdot 10^6$	$4.9\cdot 10^5$	-	$16.5\cdot 10^{-6}$
Bronze	$1.1\cdot 10^6$	-	-	$17.5\cdot 10^{-6}$
Brass	$(0.8\text{-}1.0)\cdot 10^6$	$(3.5\text{-}3.7)\cdot 10^5$	0.32-0.42	$18.4\cdot 10^{-6}$
Brick	$(0.027\text{-}0.03)\cdot 10^6$	-	-	-
Concrete strength 100-200 daN/cm²	$(0.15\text{-}0.23)\cdot 10^6$	-	0.16-0.18	$(8.8\text{-}0.4)\cdot 10^{-6}$
Concrete	$(0.18\text{-}0.43)\cdot 10^6$	-	-	$10\cdot 10^{-6}$

IV. THEORY

The acoustic emission (AE) signal can be divided into successive type signal and sporadic type signal. This type of AE signals are analyzed through the signal processor in the form of variables such as the existence of a signal generation or the shape of signal etc. excepting the signal of special case. Therefore, in the signal processor, the critical voltage is set up for the signal processing, and the acoustic emission would be regarded to be generated if it exceeds the critical voltage.

As shown in Figure 4, the displacement of one point x in the external domain by the surface traction or the body force (volume stress) at the micro area is expressed as follows using the Green function [12].

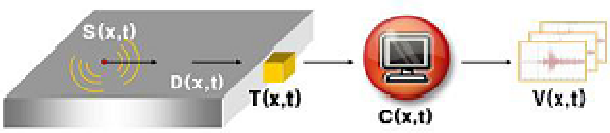

Figure 4. Transfer function [12].

$$\begin{aligned} u_i(x,t) &= \int dx' \int G_{ij,k'}(x,x',t-t')\Delta\sigma_{jk}(x',t')dt' \\ &- \int dS'_{k'} \int G_{ij,k'}(x,x',t-t')\Delta t_{jk}(x',t')dt' \end{aligned} \tag{2}$$

It is usually called transfer function. This function consists of many sub transfer functions as follows.

$$G(x,t) = D(x,t) * T(x,t) * C(x,t) \tag{3}$$

It can express as the convolution integral of each transfer functions by the mold (D), the converter (T) and computer (C).

On the other hand, the output V (x, t) that is to be visibly recognized is expressed as a function of G and S as follows.

$$V(x,t) = G(x,t) * S(x,t) \tag{4}$$

As remark, the direction of force is applied vertical to the surface of the test piece.

V. EXPERIMENTAL WORK

The experimental works were made by an original set-up, composed by: FPZ 10 Universal Testing Machine, Fritz Heckert, Germany (Figure 5), an AE piezoelectric sensor (200 kHz bandwidth), and TDS 3034B, Tektronix memory digital oscilloscope for the sensor output displaying.

The metallic samples (aluminum and brass pipes) were fasten into the mechanical testing machine at both ends, the piezoelectric sensor was fixed on the sample surface by mediation of Vaseline medium for a maximum electroacoustic coupling between the sensor and sample.

The metallic samples were precisely stretched by the mechanical testing machine till their breaking. The AE signals from the sensor output were continuous displayed and memorized on the oscilloscope.

Figure 5. FPZ 10 Universal mechanical testing machine.

Figure 6 presents the AE sensor catch on the sample surface. The AE piezoelectric sensor realizes the mechanical - electrical conversion, revealing the AE signals from the metallic samples, submissive at mechanical stretches by the testing machine.

Figure 6. AE sensor is fixed with a spring instead of the dead weight used for the tests.

The main technical characteristics of some AE piezoelectric sensors are presented into the Table 2

TABLE II. PROPERTIES OF SOME AE PIEZOELECTRIC SENSORS

Properties	*AE sensor characteristics*
Outer dimension	Diameter: 20.5 mm x 14 mm
Effective sensing area	Around 230 mm^2
Total mass (g)	12
Piezoelectric mass (g)	5 – 6
Capacitance (pF)	350
Piezoelectric charge coefficient d_{31} (10^{-12} m/V)	-150
Frequency range (kHz)	100 - 450

Figure 7 presents the aluminum pipe structure after its breaking produced by the stretch procedure.

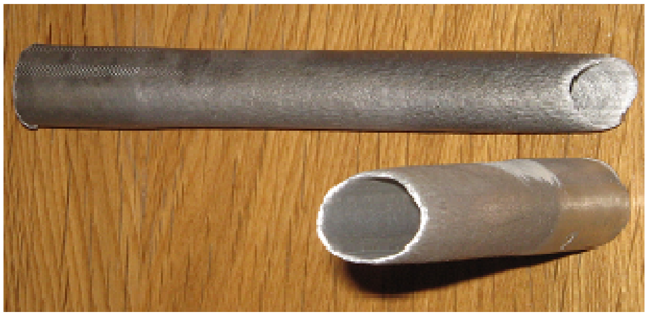

Figure 7. Broken aluminum pipe after stretching.

Figure 8 presents the prevailed AE signals from the sensor output in the breaking moment of aluminum pipe at the maximum stretch.

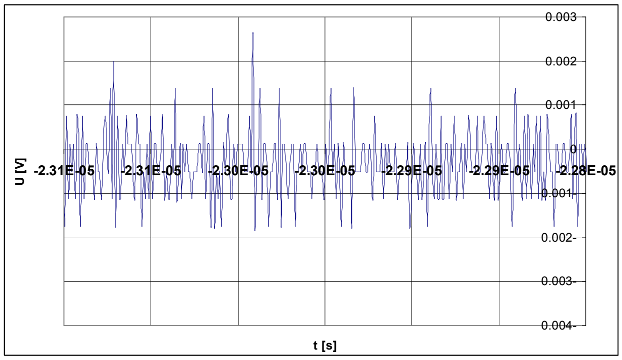

Figure 8. AE time spectra for aluminum pipe (ϕ 20x150 mm, and thickness 1mm).

Figure 9 presents a brass pipe structure after its breaking produced by the stretch procedure.

Figure 9. Brass pipe after stretch cracking (ϕ10x150 mm and 0.5 mm thickness).

Figures 10 and 11 present prevailed AE signals by the sensor in the breaking moment of the brass pipe at the maximum stretch. Therefore, one can detect these emissions and predict the material failure.

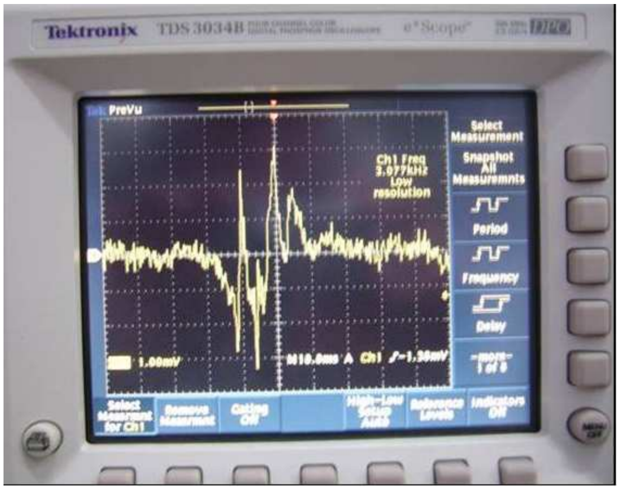

Figure 10. AE time spectra for brass pipe at mechanical stretch, at the oscilloscope display.

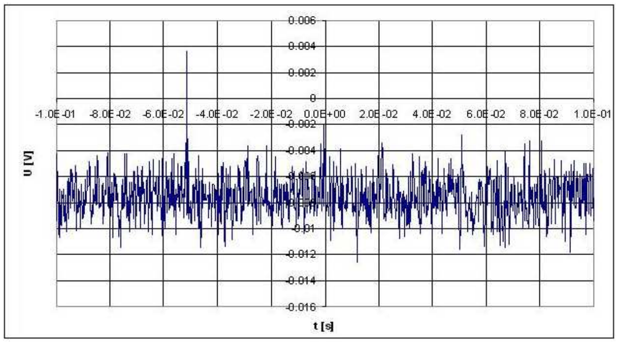

Figure 11. Detailed AE time spectra for brass pipe at mechanical stretch.

Figure 12 presents the AE signals prevailed by the sensor in the breaking moment of concrete sample at the maximum stretch. Therefore, one can detect these acoustic emissions and predict the material failure.

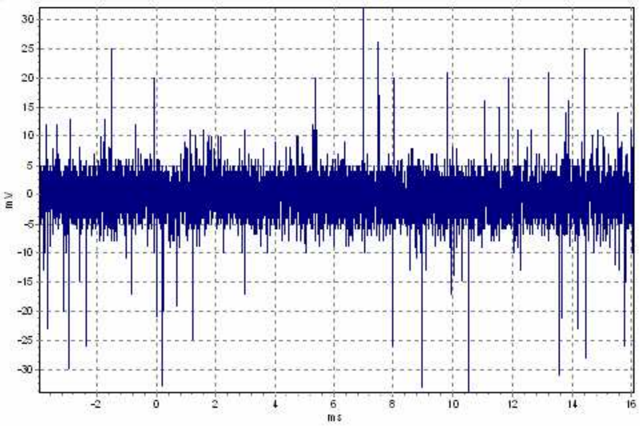

Figure 12. AE signals from a concrete sample at breaking point at mechanical stretch.

Crack initiation was determined by the appearance of the AE signal at low stretch stress levels. After the crack initiated, the AE signals around the zero stress were thought to be caused by crack-face grinding when the cracks were closed.

Further, the AE signals cached by the sensor could be stocked on the digital memory oscilloscope and then analyzed in time and frequency, in order to determine the relevant material structure characteristics, such as: the attenuation coefficients, delaminating, voids, defects, etc.

Also, by signal graphic representation analysis in time and frequency can be determined the attenuation coefficient of the pulse into material. In the literature we can find specific tables with experimental material parameter values for different type of metallic samples and structures.

By studding the AE signals, one can detect the acoustic emissions and predict the material failure. Each material type, structure and geometry has particular AE impress. As result, specific base data could be made and applied for complex structures, and architectures such as: metallic beams, crossbeam, bridges, buildings, etc.

VI. CONCLUSION

By these experimental works one can determine practical information concerning the AE response of different type of materials (aluminum, brass and concrete) at mechanical strength and predict their behavior and maximum strengths.

The AE signals prevailed by the sensor in the breaking moment of samples at the maximum stretch, could offer important data, in order to detect the AE emissions, predict the material failure and cracks initiation into material.

In the future research it is provided to realize a large data base, concerning the various materials samples behavior at mechanical stretches and their AE signals analysis (shape, amplitude, frequency, bandwidth, etc.). So, it can obtain practical information about AE of monitories complex construction structures, such as: bridges, containers fulfilled with liquids, etc., in order to prevent the possible risks and catastrophes, their breaking due to hostile environmental (shocks, long time vibrations, bending, temperature differences, etc.).

ACKNOWLEDGMENT

This work was supported in part by the National Authority for Scientific Research (ANCS), the Executive Agency for Higher Education and RDI Funding (UEFISCDI) and the Romanian National Centre of Programs Management (CNMP).

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ISBN: 978-1-61208-145-8