International Journal on Advances in Systems and Measurements, vol 16 no 1 & 2, year 2023, http://www.iariajournals.org/systems_and_measurements/

Acoustic Emission Sensing of Materials and Structures at Mechanical Strengths

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Abstract—**Acoustic Emission (AE) sensing is used in the field for the testing of metal, composite and structures, as non-destructive techniques. The AE technique allows determining the size of the cracks, damages, fractures and failures into materials. 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 fibre breakage and fibre-matrix debonding in composites. AE technology involves the use of ultrasonic transducers to listen for the sounds of failure occurring in materials and structures. Monitoring the stability of construction structures, by AE techniques get involve detecting the onset and evolution of stress-induced cracks and preventing the structural failures.**

Keywords-Acoustic Emission (AE); Acoustic Emission technique (AET); Non-Destructive Testing (NDT); Structural Health Monitoring (SHM); Polyvinylidene fluoride (PVDF).

I. INTRODUCTION

Acoustic Emission (AE) techniques have attracted attention to the diagnostic applications, material testing and study of deformation, fracture and corrosion, because they give an immediate indication of the response and behavior of materials under stresses, intimately connected with strength, damage, fracture and failure. AE technology involves the use of ultrasonic sensors (20 kHz - 1 MHz) to listen to the sounds of failure occurring in materials and structures [1], [2].

The roughest localization method is guessing the source origin using the “first hit” technique. The sensor which detects an AE first defines a radius or a half sphere, respectively, in which the signal originated. For instance, this can be done for some cases in combination with other techniques or knowledge to “localize” the source of failures.

Fibre breakage, matrix cracking, and delaminating are three mechanisms that can produce AE signals when stress is applied to the material or structure. Most of the sources of AEs are damage-related to the detection of these emissions.

The continuous research evolution in this field may be useful for a targeted diagnosis of the corrosion-induced damage severity and the recognition of corrosion sources through the AE online inspection and monitoring [3]. Also, integrated with additional information, such as metallography, AE technique can provide a valid tool for identifying specific features related to crack initiation and propagation mechanisms.

AE technology uses ultrasonic transducers in the frequency range (20 kHz - 1 MHz) to detect sounds emitted by defects that occur in materials and structures, which are subjected to mechanical pressure or temperature variations.

Determining the degree of degradation of mechanical properties and the residual life of metal structures under complex dynamic deformation demands has various applications related to bending, static and dynamic tensile loads and defect initiation processes [4].

In case of metal structures, fatigue failure occurs due to cyclic stress from operating conditions. The main mechanisms of failure occur from mechanical fatigue or thermal fatigue, such as: mechanical fatigue failure is due to cyclic stresses and thermal fatigue failure is due to cyclic temperature changes. The tipping point for failure is when the material fails at loads lower than the yield strength of the material. The acoustic emission as a monitoring tool has capabilities to detect fatigue crack initiation and propagation in mooring chains [5].

Structural Health Monitoring (SHM) allows the early detection of potential damages resulting from the natural deterioration of structural materials and the optimization of decisions over maintenance, repair, and reconstruction of the bridge asset [6].

The structure of this paper is organized as follow: Section II describes the Acoustic Emission sensors. Section III describes the Acoustic emission monitoring methods. The conclusions and acknowledgment close the article.

II. ACOUSTIC EMISSION SENSORS

The future market for electronic devices will focus on miniaturized flexible electronic devices with low power consumption. The development of piezoelectric films with excellent piezoelectric responses and low coercive voltages would therefore be advantageous [7]. Acoustic emission sensors are usual piezoelectric receiver transducer, having as active elements discs made by piezoceramic lead titanate zirconate (PZT), lead titanate (PT), barium titanate (BP) [8], PVDF materials, copolymers, and composites. Piezoelectric materials are among the most important new materials in this century because of their excellent performances.

Polyvinylidene fluoride (PVDF), also known as polyvinylidene difluoride and PVF2, is part of the fluoropolymers family, a group of specialized, versatile polymeric materials with distinct properties that result from the strong bond between their carbon atoms and fluorine atoms and the fluorine shielding of the carbon backbone. PVDF is a polymer with pyroelectric and piezoelectric properties and is used in the manufacturing of diverse high-purity, high-strength, and high-chemical-resistance products for applications in electrical, electronic, biomedical, construction, etc.; PVDF has a similar structure to poly (tetrafluoro-ethylene) PTFE, except that the hydrogen atoms are only replaced by fluorine on every alternate carbon [9].

Piezoceramic-based AE sensors measure the acoustic emissions and are sensitive to the flexural wave motion (vertical motion to the surface). The acoustic emissions due to impact hammering, fatal failure, large disturbances, and glass fracture had a high-amplitude vertical component of wave motion, detected by AE sensors. Attempts were made to capture the in-plane component of the wave motion using fiber-Bragg grating sensors. Coupled piezoelectric film strain sensors, monolithic piezoceramic patches were used to measure the acoustic waves [10]. The schematic of the cross-section of a typical commercial AE sensor is shown in Figure 2. It has several components inside a steel housing. It has a backing plate, PZT material, electrodes, and damping material inside the housing. The top electrode of the PZT material is connected to the center conductor of the connector and the bottom electrode is grounded to the housing. A bonding agent is used to connect the AE sensor to the host structure [10]. Piezoelectric elements inside the sensor convert this pressure into current, which then converted to a voltage signal**.**

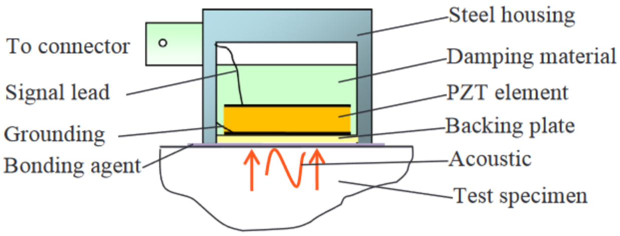

Figure 1. Cross-section of a typical commercial AE sensor which measures out-of-plane wave motion [10].

Figure 2. Image of an AE sensor

Figure 1 presents a cross-section of a typical commercial AE typical commercial AE sensor which measures out-of-plane wave motion [10], and Figure 2 is the image of a usual AE sensor.

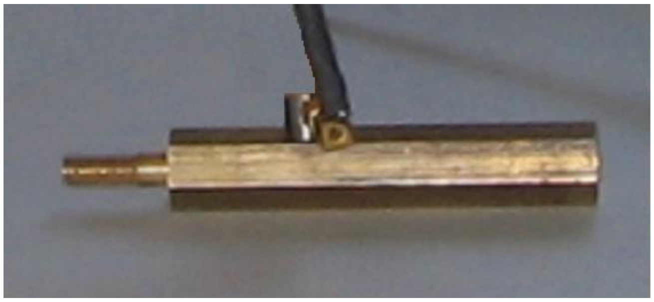

Figure 3. AE sensor placed on a metal bar

As an application, a piezoceramic AE sensor was fixed on the surface of a metal bar by means of a silicone Vaseline-type coupling material (Figure 3), which ensures the maximum coupled transmission coefficient of the acoustic elastic waves at the piezoelectric element of the sensor.

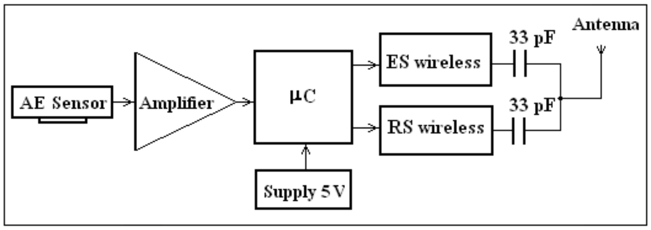

Figure 4. Block diagram of a module with acoustic emission sensor (SEA) [11].

More sophisticated devices were constructed as intelligent modules with AE sensor (SEA), used to pick up the acoustic emission signals. For example, an intelligent module with AE sensor (MSEA) is composed by: Acoustic emission sensor (SEA), Wireless transmitter (ES), Wireless receiver (RS), Stabilized voltage source with battery, Amplifier, PIC 18F452 microcontroller (µC) (Figure 4) [11].

III. ACOUSTIC EMISSION MONITORING METHODS

A. *Non-Destructive Evaluation Techniques*

For historical buildings, Non-Destructive Evaluation (NDE) techniques are used for several purposes: (1) detecting hidden structural elements, such as floor structures, arches and piers; (2) determining masonry characteristics, mapping the heterogeneity of the materials used in the walls (e.g., use of different bricks during the life of a building); (3) evaluating the extent of the mechanical damage in cracked structures; (4) detecting voids and flaws; (5) determining moisture content and rising by capillary action; (6) detecting surface decay phenomena; and (7) evaluating the mechanical and physical properties of mortar and brick, or stone [12]. The choice of a technique for controlling and monitoring reinforced concrete or masonry structures is strictly correlated with the kind of structure to be analyzed and the data to be extracted.

A general approach for AE data analysis, which will be followed here is stepwise: (a) evaluating AE activity, e.g., the rate or cumulative number of selected AE hits or located events and noting their correlation with time or applied load; (b) evaluating AE intensity, e.g., the burst signal peak amplitude, burst signal energy, or continuous signal parameters and their behavior with load; (c) AE source location, if more than one AE sensor has been used, e.g., spatial or spatial-temporal clustering of AE event sources; and finally (d) looking for indications of different damage mechanisms, e.g., from AE intensity or waveform analysis [13].

Delamination behaviour of composites is a standard reference for all those researching laminated composites and using them in such diverse applications as microelectronics, aerospace, marine, automotive and civil engineering. In AE small amounts of elastic energy are released within a structure by a mechanical mechanism. Such energy release may arise from a variety of mechanisms, such as crack tip advance, plastic deformation, or other mechanical behaviour like friction and rubbing. This energy radiates from its point of release, known as the source, in all directions, propagating as an elastic wave [14]. The nature of this technique means that a source mechanism must be active (i.e., damage must be growing) in order for it to be detected, making it ideal for in-service structural health monitoring (SHM) and non-destructive testing (NDT).

AE monitoring appears to be a promising technique that can be used for bridge inspection to quantify the condition of steel-reinforced concrete, where corrosion is occurring, and where repair is needed.

Material study is another field of acoustic emission application. Particularly, acoustic emission is used for studies of:

- Environmental cracking including stress corrosion cracking, hydrogen embrittlement.
- Fatigue and creep crack growth.
- Material properties including material ductility or embrittlement, inclusions content.
- Plastic deformation development.
- Phase transformation, and many other.

B. Acoustic Emission Testing Methods

Acoustic emission is a very versatile, non-invasive way to gather information about a material or structure. Acoustic Emission Testing (AET) can be applied to inspect and monitor pipelines, pressure vessels, storage tanks, bridges, aircraft, and bucket trucks, and a variety of composite and ceramic components. It is also used in process control applications such as monitoring welding processes. Acoustic Emission Testing is a non-destructive testing method that "listens" for transient elastic-waves generated due to a rapid release of strain energy caused by a structural alteration in a solid material.

Piping inspection is another common application, and Acoustic Emission is used efficiently and fast for detection of cracks, corrosion damage and leaks. There are multiple advantages of the method in case of piping inspection.

For example, in case of buried or insulated pipelines (Figure 5), there is no need to open the entire surface of the pipe but just a small opening for installation of sensors, while a distance between sensors can be from few meters to 100 meters. Acoustic emission testing is applied also for inspection of high pressure and temperature piping systems during their normal operation.

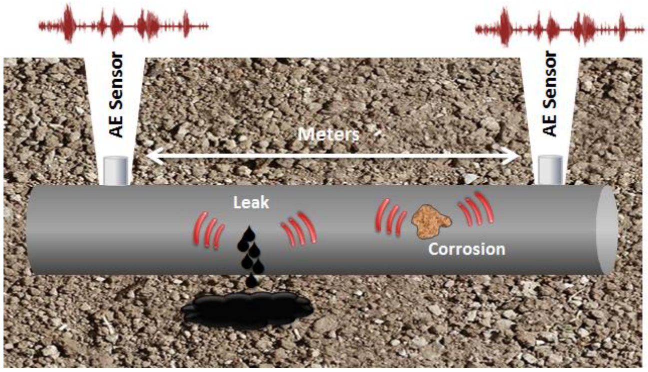

Figure 5. AE sources related to corrosion development and a leak in an underground pipeline.

As example, inspections of concrete and reinforced concrete bridges are applications where acoustic emission is used for detection of cracks, other concrete flaws, rebar corrosion, failure of cables and other. The method allows an overall inspection of a structure and long-term condition monitoring when it is necessary providing important information for bridge maintenance.

An elastic wave is a combination of longitudinal, transverse, and reflected waves, with a broadband frequency range from kHz to MHz. The AE is a phenomenon in which transient elastic waves are generated by rapid release waves, and a monitoring system requires a source and crack propagation or a tendon failure (Figure 6) [6].

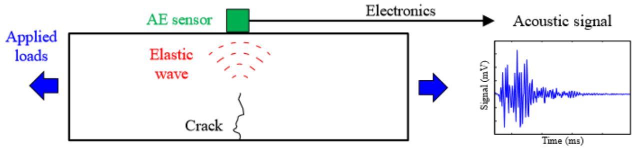

Figure 6. Working principle of an AE monitoring system [6].

The evaluation by AE monitoring of the complex mechanisms acting during stress corrosion crack (SCC) is still far from a clear, well accepted interpretation [3]. SCC is one of the most critical corrosion types and can also cause premature failures of structural components and should not be neglected in damage risk managements.

Monitoring a structure by means of the AE technique makes it possible to detect the onset and evolution of stress-induced cracks. Crack opening, in fact, is accompanied by the emission of elastic waves that propagate within the bulk of the material (Figure 7) [3].

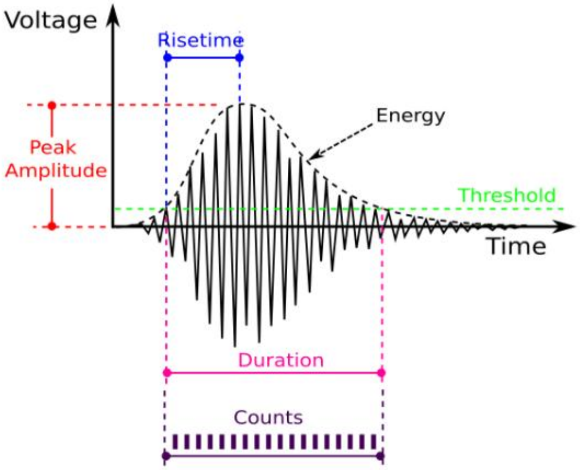

Figure 7. Schematic of an Acoustic Emission event and related parameters [3].

These waves can be captured and recorded by transducers applied to the surface of the structural elements [12]. The signal identified by the transducer (Figure 8) is preamplified and transformed into electric voltage; it is then filtered to eliminate unwanted frequencies, such as the vibrations caused by the mechanical instrumentation, which are generally lower than 100 kHz. In the Ring-Down Counting method, the signal is analyzed by a threshold measuring unit, which counts the oscillations exceeding a certain voltage value.

Non-destructive techniques were not accepted for long time for the testing bridges and other components of the infrastructures, because of inability of AE technique to determine the size of cracks [15].

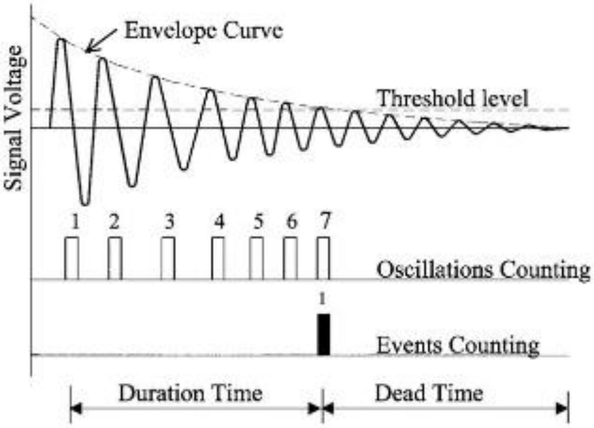

Figure 8. Counting methods in AE technique [12].

For example, one of the major issues in offshore equipment design is preventing the accumulation of fatigue damage over a long period of time.

A full-scale fatigue test rig and the monitoring setup were arranged to perform the AE measurements [5]. The chain failure most likely occurs at the point of the intrados (the lower or inner curve of an arch) (KT point) and crown positions, due to higher localized stresses in these areas (Figure 9). Four sensors were used on links and a water-based couplant was used to facilitate the transmission of the sound signal between the transducer and the link's surface. Also, each sensor was equipped with an integrated 34 dB pre-amplification.

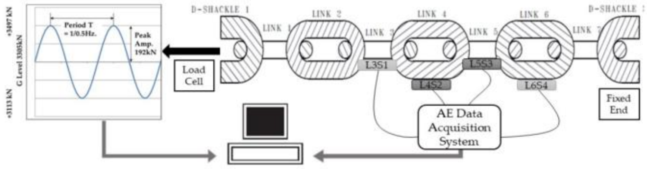

Figure 9. Test rig illustration: the chain is fixed at one end (right) and the loading (strain) is applied at the other end (left) [5].

After careful evaluation of the different AE signal features and all possible correlations, it appears that the frequency content of the AE signals is the most promising parameter. An increase of the average frequency is observed with the growth of the crack in the chain [5].

AE sensor manufacturers typically provide a sensitivity curve based on face-to-face calibration. This calibration procedure has been treated as proprietary information and described only inadequately. Calibration curves are usually in reference to the reference level of 1 V/μbar, but this reference remains undefined [16].

AE technique (AET) has found applications in monitoring the health of aerospace structures because sensors can be attached in easily accessed areas that are remotely located from damage prone sites. AET has been used in laboratory structural tests, as well as in flight test applications.

By signal graphic representation analysis in time and frequency can be determined the attenuation coefficient of the pulse into material. Figure 10 shows an aluminum pipe structure subjected to the mechanical stretching after its rupture [17].

Figure 10. Broken aluminium pipe at maximum mechanical stretch [17].

Figure 11 presents prevailed AE signals by the sensor in the breaking moment of aluminium pipe at the maximum stretch. Therefore, one can detect these emissions and predict the moment of material failure, and causing damage to the overall structure.

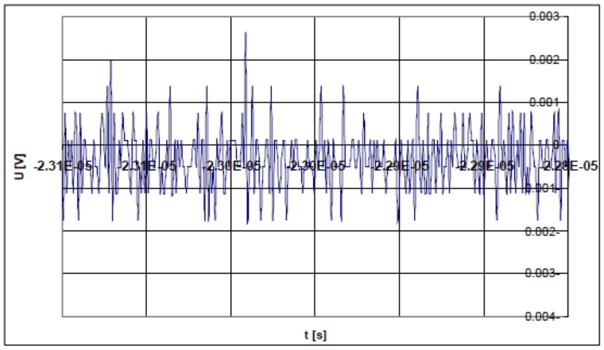

Figure 11. AE time spectrum for aluminium pipe (ϕ20x150 mm, and thickness 1 mm) subjected to the mechanical stretching [17].

The use of the phenomenon of acoustic emission during deformations of tension and bending makes it possible to predict the onset of critically dangerous states of loss of working capacity of metal structures.

The Acoustic Emission Technique (AET) is one of the non-destructive methods usually implemented to investigate the damage onset, damage evolution, and damage location in civil engineering structure [18].

Investigating the performance of acoustic emission (AE) technique on material deterioration of masonry is subjected to uniaxial monotonic and cyclic tensile loadings [19]. The basic acoustic emission (AE) counting, considering the cumulative or averaged number of AE hits or AE energy, proves the capacity of AET for damage assessment in masonry. Auto Sensor Test (AST) is carried out preliminarily to ensure no variation of sensor sensitivity.

In the case of localization AE events at a minimum error, an experimental set-up with four AE sensors, formed into a three-dimensional space is placed at the four corners of specimen, near the expected initial crack, each sensor placed about 2 cm from the stone edge (Figure 12) [19] .

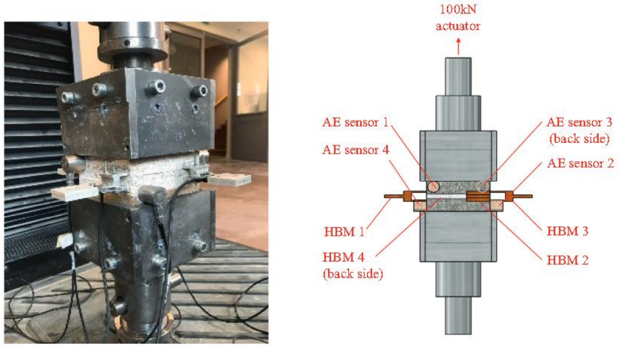

Figure 12. Experimental setup and instrumentations [19].

Experimental tests reveal that the signal durations represent a dominant parameter which can distinguish the signal from micro crack to macro crack, based on the correlation between the evolution of AE energy and fracture energy. Also, the scale effect should be considered, according to [20], as the mechanical analysis of masonry specimen under tensile loading is concentrated in the mesoscale, while the emission is received in a micro scale, more fundamental research is needed to uncover this relation at microscale.

Average Frequency (AF) is defined as the ratio between the number of counts and duration of an AE waveform. It basically determines the number of threshold crossings per unit time of an AE waveform [21].

$$\text{Average Frequency (AF) [in kHz]} = \text{Counts/Duration} \qquad (1)$$

where "Counts" indicates the number of times the signal amplitude exceeds the fixed threshold over the entire duration of the AE waveform, and *RA value* of an AE waveform is defined as the ratio between the rise time and amplitude:

$$\text{RA [in } \mu\text{s/V]} = \text{Rise time/Amplitude} \qquad (2)$$

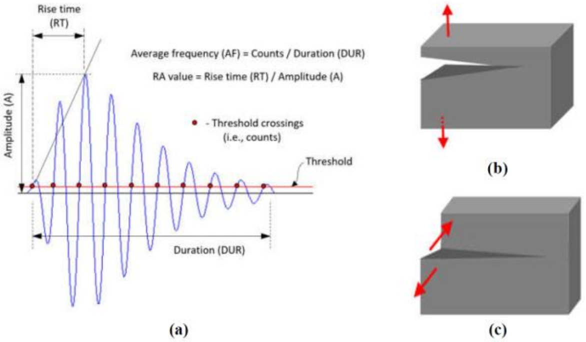

Figure 13. Schematic representation of (**a**) an AE signal and some important AE parameters, (**b**) tensile crack, and (**c**) shear crack [21].

AE waveforms generated due to tensile cracks (Figure 13) have shorter rise time, tensile-type cracks usually generate AE signals with lower *RA values* and higher AF, and in the case of shear-type cracks, the AE waveforms are longer, *RA values* are relatively higher, and AF is lower.

Various features, such as, amplitude, rise time, counts, duration, energy, number of hits, etc. [21] of the acoustic emission signals can be analyse and monitored the progressive damage of the samples under the four-point bending test.

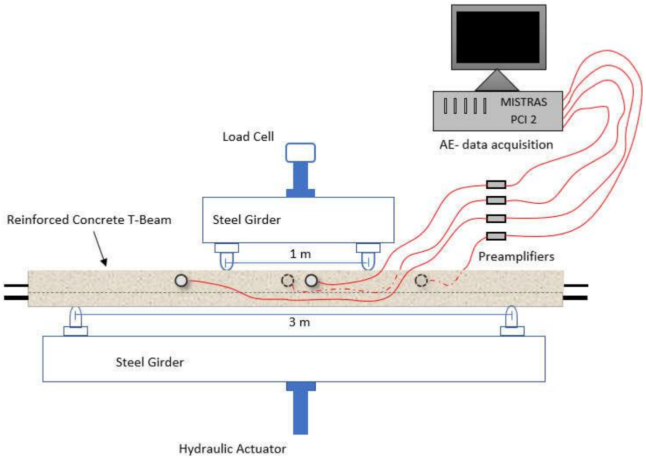

Figure 14. Reinforced concrete T-beam subjected to four-point bending and acoustic monitoring [21].

Much more, AE activity evolves as function of the applied load, where amplitudes of the involved AE hits become higher in the case of a major crack, and the cumulative number of hits can be considered as a global parameter, which can be sensitive to the mechanical test conditions for instance the load rate. The evolution of the cumulative hits per unit time is constant for each mechanical test and the evolution of the cumulative hits per unit time is proportional to the loading rate, where the highest value is for the loading rate corresponding to 4 mm/s, which creates the shortest nonlinear zone.

In order to classify the AE data, machine learning methods type supervised and unsupervised are employed.

Guo et al. present experimental quasi-static splitting tensile tests corresponding to a strain rate of $\sim 2\times10-6$ s^{-1} using a Shimadzu universal testing machine. Each cylindrical specimen is placed on the lower loading platen with its axis parallel to the platen, and the upper loading platen was set to move downwards at a speed of 0.2 mm/min to compress the specimen (Figure 15) [22].

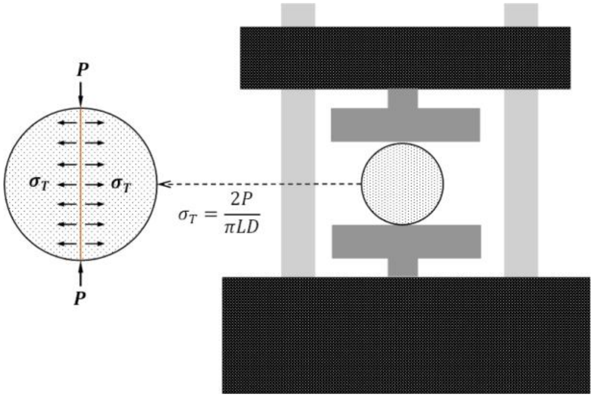

Figure 15. Experimental arrangement for quasi-static splitting tensile tests [22].

It is useful to verify, for the length scale studied, whether a homogeneous-linear-elastic analysis yields reasonable estimates of stress and deformation. Using elastic analysis one can determine material tensile stresses ($\mathcal{E}$) derived at 0^0, 45^0 and 90^0 [22], and the theoretical values are compared with those measured by the strain gauges (Figure 16).

Concrete is heterogeneous at the meso-scale, comprising a mortar matrix with randomly distributed coarse aggregate particles, and is able to display a small degree of plasticity.

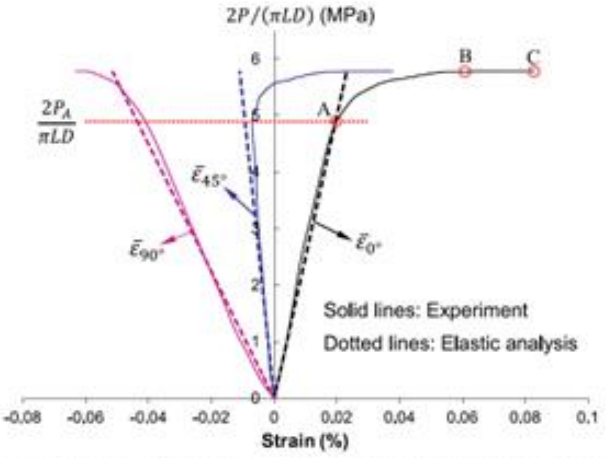

Figure 16. Variation of tensile stress at specimen centre ($2P/(\pi LD)$) with average strain in three directions (0°, 45° and 90°), for a splitting test on a C80 specimen – comparison of experimental results with theoretical predictions based on elastic analysis [22].

A monitoring system can analyse parameters like count, hit, event, rise time, duration, peak amplitude, energy, RMS (root mean square), voltage, frequency spectrum, arrival – time difference, etc. Considering AE measurement in concrete, one can use the standard ISO 16836 / 2019[23]. A measuring system with a digital-signal processor includes the following main elements: (S) - AE sensor, (Pa) - pre-amplifier, (Ma) - main amplifier and (Bf) - band-pass filter.

The AE localization algorithms are based on the distance travelled by the emitted waves. Their value can be achieved by multiplying arrival time to the propagation speed in the specific medium. The speed of the P-wave in a structure is closely related to the travel path.

Localization of AE sources in different structures can be done by using one or more AE sensors and representation in 1D linear, 2D planar and 3D localization technique (Figure 17) [24].

Single-sensor approaches are based on modal acoustic emission (MAE), which requires identification of the arrival time of extensional and flexural wave modes.

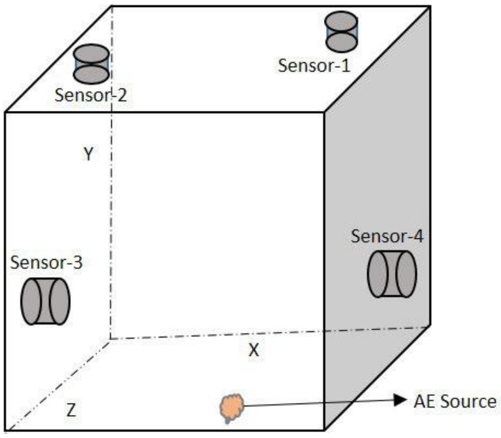

Figure 17. Localization of AE sources in 3-D structures [24].

Since the velocities for both modes are different, it is possible to calculate the distance traveled by the propagation of the wave modes if the respective velocities are known. The implementation of MAE has several associated problems, such as wave reflections and the separation of multiple AE events [24].

The attenuation of the extension wave is measured to appreciate its applicability in the long-range localization of sources. Time reversal technique and the artificial neural network are used in the literature for the AE localization problem. The convolutional neural network is more stable in allowing more information rich inputs in the frequency domain.

Triangulation method for AE source localization relies on the identification of precise arrival times and the knowledge of an appropriate propagation velocity.

The experimental works can determine practical information concerning the AE response of different materials and structures at mechanical strength and predict their behaviour and maximum strengths.

As novelty, monitoring the stability of important construction structures, by AE technique makes possible to detect the onset and evolution of stress-induced cracks and prevent the structural failures. Also, AETs investigate the damage onset, damage evolution, and damage location in civil engineering structure, material deterioration of masonry.

IV. CONCLUSION

The acoustic emission techniques are well applied for the identification, characterization, and localization of deformations in civil engineering structures. Numerous localization techniques, i. e. Structural Health Monitoring, Modal Acoustic Emission, Neural Networks, Beamforming, and Triangulation methods with or without prior knowledge of wave velocity can detect into material structure the fatigue cracks, delaminations, corrosions, etc.

Monitoring structures by AE techniques could detect the onset and evolution of stress-induced cracks into materials (metals, non-metals, composites) and the crack opening is accompanied by the acoustic emission of elastic waves that propagate within the bulk of the materials and structures. These waves (AE) can be captured and recorded by transducers, type AE sensors, applied to the surface of the structural elements and provide the material behavior at mechanical stresses, fatigue and vibrations.

Crack initiation into material is determined by the appearance of the AE signal at low stretch stress levels. After the crack initiated, the AE signals around the zero stress could be the cause by crack-face grinding when the cracks are closed. By experimental works one can determine practical information concerning the strength of different type of materials, their mechanical limits at different stretch values. More, it can obtain practical information about AE of monitories complex construction structures, such as: bridges, containers fulfilled with liquids, etc., in order to prevent their possible breaking due to hostile environmental (shocks, long time vibrations, bending, temperature differences, etc.).

The internal stress redistribution of the materials caused by the changes in the internal structure can be predicted by the monitoring the acoustic emissions of the stress waves generated by the structures.

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. A number of challenges related to accurate localization and classification of sources still remain, which must be addressed in order to exploit the full potential of the AE technique.

ACKNOWLEDGMENT

This work was supported by the Romanian Ministry of Research, Innovation and Digitalization (MRID) for:1) Core Program PN 18N/2019 and PN 23 05 No. 11N /2023, and 2) Program I – Development of the National R & D System, Subprogram 1.2 Institutional Performance-Projects for Excellence Financing in RDI, contr.18PFE/2021.

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