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Review Article

Advancements in Acoustic Emissions for Civil Structural Engineering Monitoring: A Research and Application Review

Stefi Zamsari[1], Mohamad Azim Mohammad Azmi[2*], Shahiron Shahidan[1], Sharifah Salwa MohdZuki[1], Nor Baizura Hamid[2], Mardiha Mokhtar[2], Khairi Supar[2], Nur Ilya Farhana Md Noh[3]

[1] *Faculty of Civil and Build Environment, Tun Hussein Onn University of Malaysia, Johor, Malaysia.*
[2] *Department of Civil Engineering, Center for Diploma Studies, Tun Hussein Onn University of Malaysia, Johor, Malaysia.*
[3] *School of Civil Engineering, College of Engineering, UiTM Shah Alam, Selangor, Malaysia.*

[*]Corresponding Author : azim@uthm.edu.my

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Abstract *- Structural Health Monitoring (SHM) is a technique used to assess the condition and integrity of a structure continuously or periodically, such as buildings, dams, aircraft, pipelines, bridges and more. The primary goal of SHM is to detect and identify any possible damage, deterioration or anomalies in the structure's material. One of the best tools for real-time monitoring systems is the Acoustic Emission (AE) technique. This technique is an effective tool for the assessment of anysystem without detriment to the material condition. In civil structures, concrete mainly carries high compressive strength, but in terms of tensile strength, it is very weak and, hence, cracks easily. Cracking is one of the common indications of distress, which has the greatest impact on the concrete structure and early symptoms of failure structure. In this concern, this paperaims to be a focused overview of the application of AE in civil structure monitoring. The main topic of this paper is previous research on AE in civil structure since many researchers have shown an increased interest in AE. Research on theAE technique continues today in the pursuit of enhancing the performance and condition of civil structures. It can be concluded that applying AE in civil structure monitoring enhances safety, reduces maintenance costs and ensures the long-term sustainability of the structure.*

Keywords *- Structural Health Monitoring (SHM), Acoustic Emission (AE), Civil structure, Cracking, Real-time monitoring.*

1. Introduction

Structural Health Monitoring (SHM) is a technology and process that is used to intermittent and uninterrupted assess the condition of the structure to detect and evaluate potential damage, defect or degradation. Consequently, SHM is becoming increasingly popular and widely acceptedin all engineering systems, such as civil engineering, mechanical engineering and aerospace. It involves the use of various sensors, data acquisition systems and analysistechniques to monitor the structural integrity of buildings,bridges, dams, pipelines, aerospace structures and other engineering assets. The dominant goal of SHM is to ensure the structural safety, reliability and longevity of these structures by detecting any anomalies early on, allowing for timely maintenance and repair. Currently, SHM is extensively used,especially in civil structures, for continuous real-time monitoring systems with cost-effectiveness. In civil engineering, SHM is particularly applicable for continuously monitoring and evaluating the health and performance of structural systems, especially in situations where the structure is exposed to significant loads or dynamic forces. By using SHM in such scenarios, the engineer can detect any early potential problem, which enables to take appropriate actions to ensure the safety and reliability of the structure. On the other hand, SHM involves monitoring and analyzing various parameters to evaluate how well the structure is functioning, which includes checking for signs of damage, deformation of cracks, or other problems that might affect the structure's performance. The selection of the best tools for SHM depends on various factors, including the specific application, the type ofstructure being monitored, the desired level of accuracy,budget constraints and other project-specific requirements. One of the best tools for real-time monitoring systems is Acoustic Emission (AE). This technique is an efficient tool for the assessment of any system without damaging thematerial condition. It also enables to detect the early of crack and possesses a very high sensitivity towards crackgrowth. Other than that, acoustic emission can be used to identify both tensile cracks and shear movements at critical zones within in order to detect cracks forming in concrete structures [1]. In the concrete structural element, concrete mainly carries high compressive stress, and shear, corrosive and weathering are essential, but in terms of tensile strength, it is very low and hence cracks easily. Concrete can deteriorate for various reasons, and the damage of the concrete often happens due to a combination of various factors such as temperature, structural design defects, environmental or material and the concrete casting procedure [2]. Cracking is one of the common indications ofdistress which has the greatest impact on the concrete structure and early symptoms of failure structure [3]. Pise et al. [4] identified that cracks can destroy the wall integrity and building artistry, influence the shape protection and reduce the sturdiness of concrete. Concrete cracks easily andcreate an easy path for the deleterious agents in saturation, freeze-thaw damages and steel corrosive [5].

Premature cracking is one of the major causes of concrete structure deterioration. Alam and Loukili [6] observed the patternand behaviors of micro and macro cracks in the concrete. Srimook [7] investigated thermal cracking in terms of cracking spacing and thermal crack width on reinforced concrete. Previous research findings into the cracking ofconcrete structures have been widely investigated because cracking is a complex phenomenon. It is important to understand that cracks that occur in the structure are normal,but an excessive number of cracks in the structure is not. Thatis why acoustic emission is a powerful technique to detect internal damage in the concrete structure [8]. This study highlights the important and new trends and the potential applying using AE on civil structures to enhance the performance and condition of the civil structure and also predict the behavior of structural material.

2. Literature Review

The concrete structure is faced with various forms in terms ofphysical, mechanical and chemical damage during their period due to factors such as aggregate expansion, fatigue loading, degradation, carbonation, and high loading of the structure. This interaction also affects structural integrity and condition. The implication of concrete damage needs early detection to prevent structural failure, ensure structural safety and also reduce cost maintenance.The above findings are consistent with the study by Khazanovich et al. [9], which mentioned that the detection of damage at early stages is very important for the rehabilitation ofthe structure before it has uncontrolled failure of the structure. One of the top tools that can used to overcomethis problem is Acoustic Emission (AE).

In recent years, several studies have focused on an important feature of AE research, which is its ability to identify an active source when actual data is available from one sensor to another sensor. AE is a method that enables to detection of cracks at an early stageand the evaluation of any system without breaking up the material condition. This method is very sensitive to crack growth and is found to be sufficiently sensitive to detect newly formed crack surfaces. Besides that, a small crack may alsobe detected in an area which difficult to reach. Ohtsu [10] described the AE method as having attracted much attention, which is related to the field of concrete engineering because it demands maintenance and evaluates structural integrity.

2.1. History of Acoustic Emission

In classical time acoustic emission was naturally used when observation was made related to the sound accompanying structural failure. AE was first discovered by J. Kaiser in Germany used scientific application. Research finding by Dahmene et al. [11] also point out towards J. Kaiser which used electronic instrumentation to detect the clear sound produced by deformation on the metallic specimen in the early 1950's. Joseph Kaiser, also known as J. Kaiser, successfully published a thesis in PhD about the inevitable phenomena of AE. The discover of an irreversibility phenomenon known as 'The Kaiser Effect' came as a result of his discovery. In AE testing, the Kaiser effect is commonly utilized to provide information on the prior maximum stress on the structural material. In recent years, there has been an increasing amount of research about AE which improved the AE instrumentation. Many researchers have shown an increased interest in AE, such as Schofield in 1952, who studied the effect of the energy produced by the AE method on structure when stress is applied to it [12]. Dahmene et al. [11] also discovered that Tatro improved the instrumentation and interpret the source of AE during plastic deformation in the middle of 1950. Although many studies have been done and chosen AE for its promising practical application, the capability is still limited.

The application of AE in civil engineering, especially in structural building, began in the 1970s when Fetis and Cube researched how concretematerials respond to AE behavior. According to Ziehl et al.[15] AE was used early 1980s as a formalized structural evaluation method. The use of AE in engineering fields is the determine information about the previous maximum stress on the structural material. Essentially, the analysis primarily focused on a small scale of specimens. However, it is worth nothing that a number of researchers have begun to investigate their research on the frequency of AE on concrete materials. Nowadays, the application of AE technology in the evaluation of industrial components such as material and composite has become more common due to historical development. AE application has also been used in other fields such as industrial process, aerospace, structural engineering and others. Today, in terms of the technique's potential effectiveness, AE has been verified to be a reliable, non-destructive method which includes periodic and continuous monitoring of structural conditions in detecting critical or bad effects such as cracks and the detection of impending fatigue failure in engineering structure. As highlighted by Pinal- Moctezuma et al. [12] stated that AE is the most powerful tools to detect, locate or assess damage for a wide range of applications. Figure 1 illustrates the AE system setup [16].

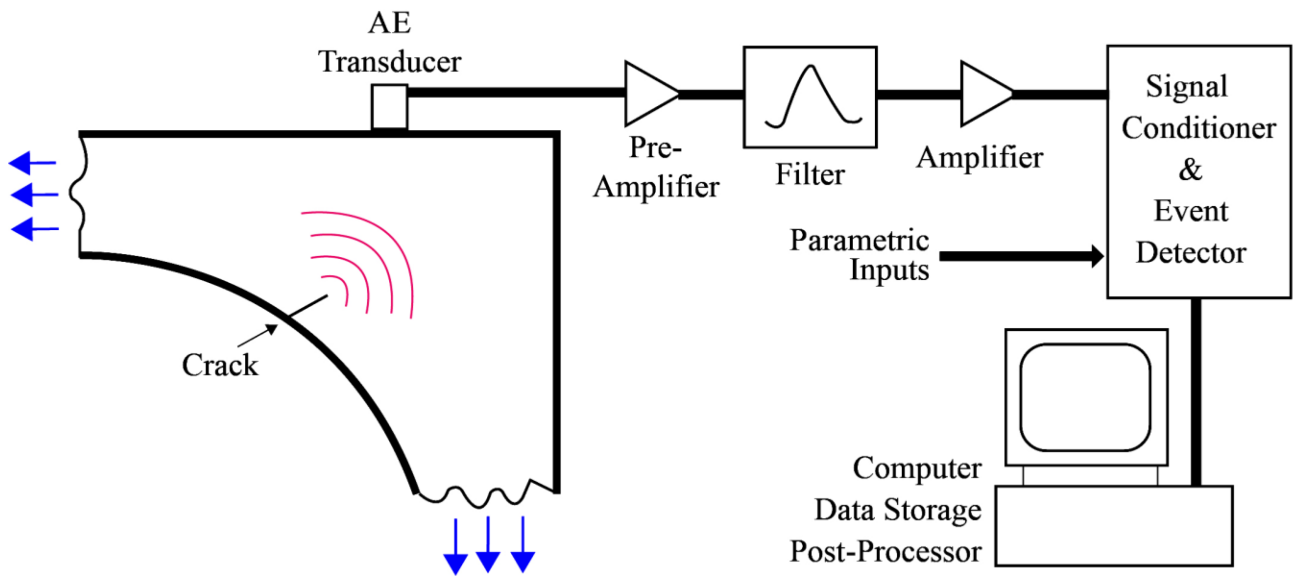


Fig. 1 AE setup system

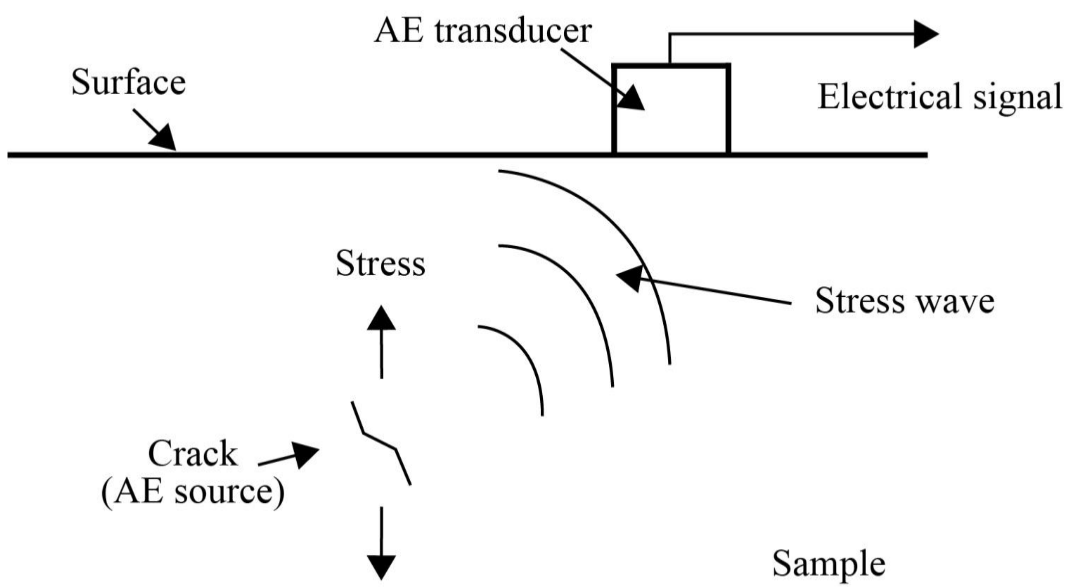


Fig. 2 Principle of AE detection [17]

2.2. Principle of Acoustic Emission

Acoustic emission is a short-term flexible wave caused by the rapid arrival of continuity in material as a result of flexible deformation and break propagation due to external and internal forces applied to the material. When a sample is subjected to external or internal pressure, strain energy is discharged and spreads inside the material as a flexible wave, causing vibration on the sample's surface. When the vibration spreads to the AE sensors coupled to the samples, the elastic deformation created in the chip produces electric charges that appear at the surface and render an electric fieldthat can be observed. The vibration on the sample surface is thus converted into an electrical sign, which is then enhanced, handled and displayed on appropriate instruments, as shown in Figure 2.

The AE technique basically listens for the energy emitted within the object and is the most commonly used on structure operations because it provides appropriate loading for the propagation of flaws and triggering AE. Table 1 presents the material that can be measured using the AE method.

Table 1. The material in which AE was measured

Materials
Metals
Fiberglass
Wood
Plastics
Ceramics
Rocks and Geology Materials
Composite

Table 2. The comparison of AE compared to other NDT methods

Acoustic Emission	Other NDT method
Detect movement	Detect geometric form of detecting.
Requires stress	Do not require stress.
Each loading is unique	Inspection is directly repeatable.
More material sensitive	Less material sensitive.
Less geometry sensitive	More geometry sensitive.
Less intrusive on plant process	More intrusive on-plan process.
Requires access only at sensor	Requires access to the whole area of inspection.

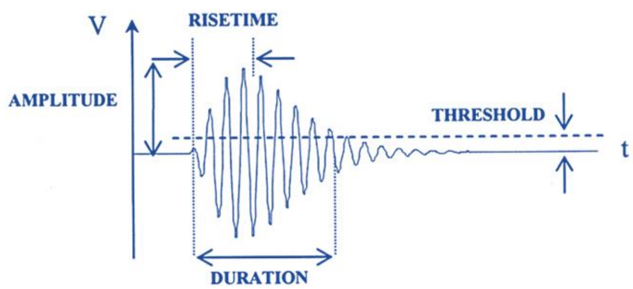


Fig. 3 The electrical signal of acoustic emission [19]

AE is also classified as a Non-Destructive Test (NDT) method. Although AE is classified as NDT, this method is distant from other NDT methods in two ways. First, the signal's original. The AE signal is generated by the material itself and not by an external source.

Another research by Gholizadeh [18] also mentioned that the AE method listens tothe sound made by the energy released by the object instead of supplying the energy to the object. Second, AE detects movements and deals with the dynamics process in the material.This ability to differentiate between stagnant and developingfaults is important. Table 2 shows the comparison characteristics of the AE method and other NDT methods.

2.3. Basic Acoustic Emission Parameter

In general, AE is the physical phenomenon consisting of the generation of the elastic wave in a material when subjected to stress and due to the changes in its deformation or stress fields [19]. AE is also classified as the NDT method. In NDT, elastic waves are produced in the concrete, and these waves can be detected accounting for defects existence or present damage in the concrete material. The author also stated that the main objective of AE is to provide valid information to detect a possible failure and to evaluate the level of damage in the concrete material. Figure 3 shows the signal of AE. Guzmán et al. [19] evaluated the mechanical behaviors of the reinforced concrete beams using AE in a four-bending test. The author also found that the AE test allows one to determine a kind of stress and the zone where major occurs.

In the experimental, the final results are according to the value of b-values, in which the value is increased up to 55% where the prevailing micro cracking in the beam and where the macro cracking is present. So, this work showed that using three methods, which are b-value, medium frequency (RA), and load information can be obtained. This is very important to determine the damage to structural material. Further research is required with a large variety of leading protocols and materials in fields of civil engineering, especially in the civil structure, in order to draw a quantitative and statically evaluated conclusion.

2.4. Acoustic Emission Detail in Composites

The characteristics of the Acoustic Emission (AE) waves emitted by a source which related to the dynamic of crack propagation. Ghadarah et al. [28] mentioned that the way a crack grows influences the sound waves it produces. Both the characteristics of the material and the loading circumstances have an impact on this relationship. The speed at which a crack propagates is not solely dependent on the applied load but also on the inherent properties of the material itself. For example, different materials may exhibit different rates of crack propagation under the same loading conditions. This variation in crack growth speed contributes to the specific frequency bandwidth of the acoustic emission signal produced.

Research by Ren et al. [29] investigated the effect of loading parameters on crack growth speed in fiber-reinforced composites. They found that variation in loading rate and direction influenced the dynamics of crack propagation, which in turn affected the characteristics of AE signals. In addition, the failure mode (how the material fails) and orientation of the AE sources (such as cracks or defects) within the composite material create a unique radiation pattern of acoustic emission.

Research by Li et al. [30] examined the radiation pattern of AE signal in rock specimens subjected to different loading conditions. They observed that the orientation of crack planes and the mode of failure (e.g., shear, tensile) influenced the distribution of the AE signal around the source. There are differing opinions or findings regarding the intensity of the AE signal. Figure 4 shows an overview of the acoustic emission details according to the author's opinion [28].

2.5. The Signal Shaping Chain

The process of signal shaping involves four key links: the sources (where the signal originates), the propagation of the wave (how the signal travels from its sources to the sensor), the sensor (which detects the signal) and the signal-conditioning electronics (which process the detected signal).

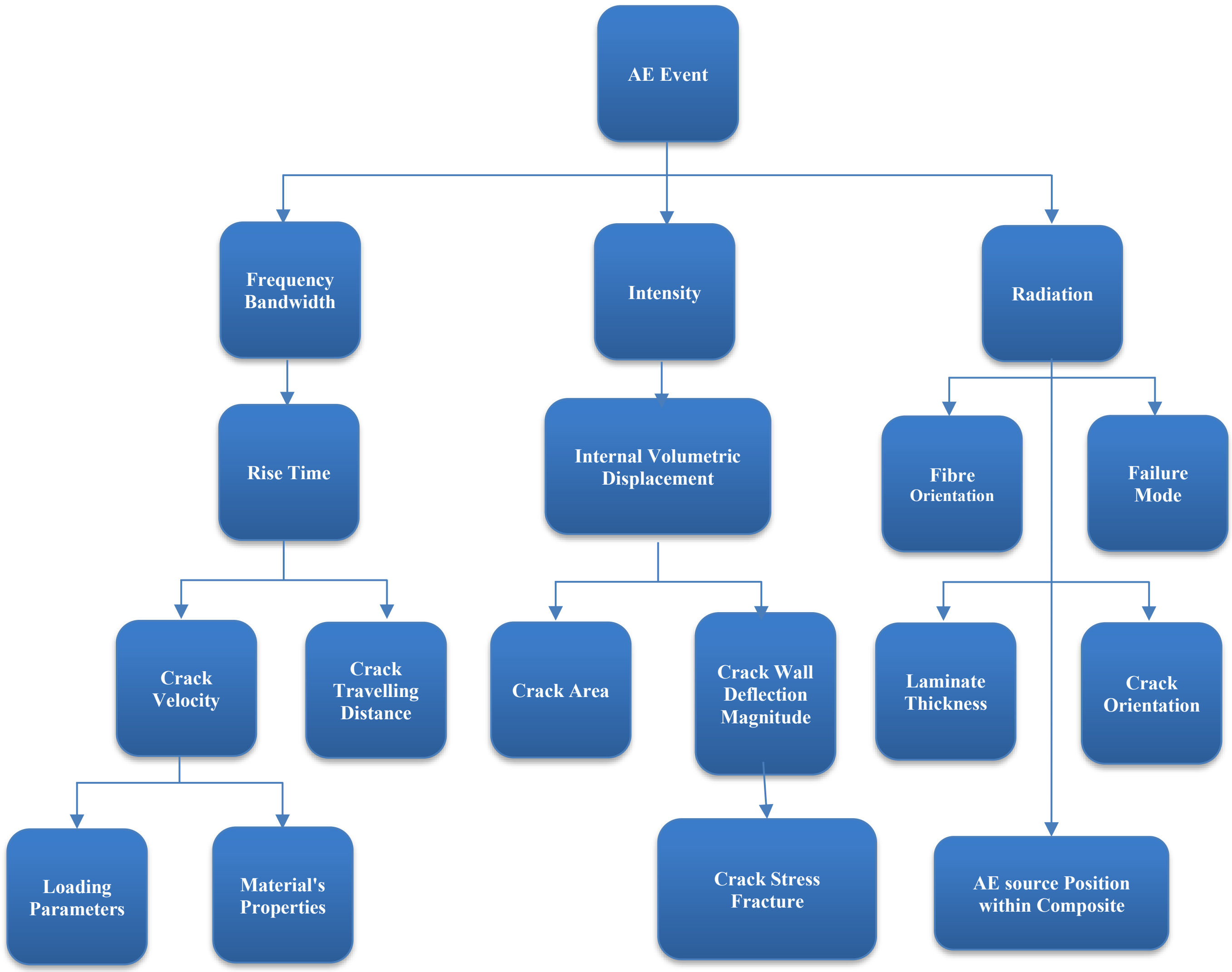


Fig. 4 An overview of the acoustic emission detail [28]

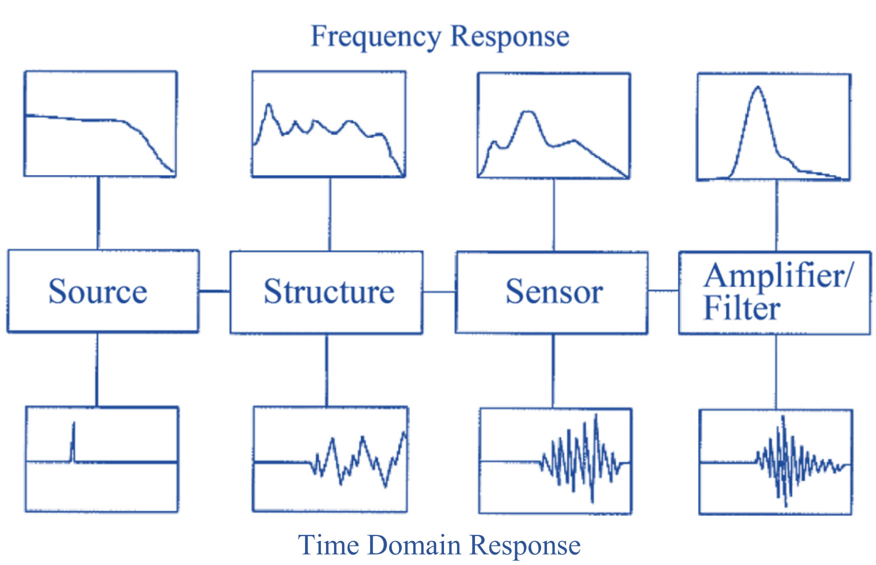


Fig. 5 The signal-shaping chain

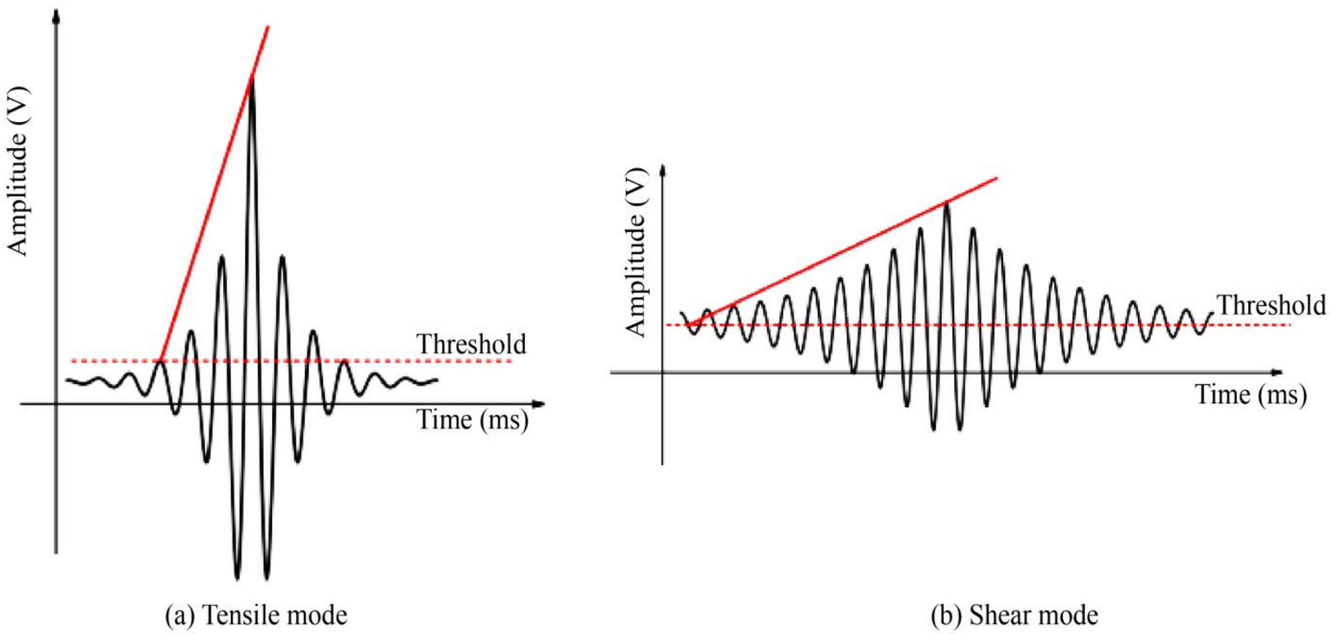


Fig. 6 AE waveform modes for tensile cracks and shear cracks [32]

Figure 5 shows the signal shaping chain. Each of these links plays a crucial role in determining the size and shape of the measured signal. It is essential to understand that the final signal can undergo significant transformations in both size and shape compared to the original motion at the sources. One critical aspect to consider when discussing the signal shaping chain is the frequency content. Every signal can be broken down into its constituent sine wave frequency content. This concept is central to Fourier analysis, which stands as one of the most powerful tools in the realm of signal processing science and technology. Through Fourier analysis, it gains insights into the fundamental frequency components that constitute a signal, enabling it to understand and manipulate signals more effectively.

3. Crack Pattern Based on Acoustic Emission

AE data acquisition system can measure various parameters such as count (frequency), rise time, energy, duration time and amplitude of acoustic emission events. These parameters are crucial for characterizing and analyzing the damage processes accusing within a material or structure. As highlighted by Md Nor et al. [31] mentioned that are five types of analyses can be performed, for example RA value, intensity analyses, b-value, relaxation ratio and calm ratio.

All the analyses mentioned above can be used to determine the type of crack and crack zone. Average frequency (AF) versus RA value analyses is one of the methods that can classify the cracks into tensile cracks and shear cracks. Figure 6 shows the AE waveform mode for tensile cracks and shear cracks, while Figure 7 shows the classification of tensile cracks and shear cracks by the RA-AF analysis method.

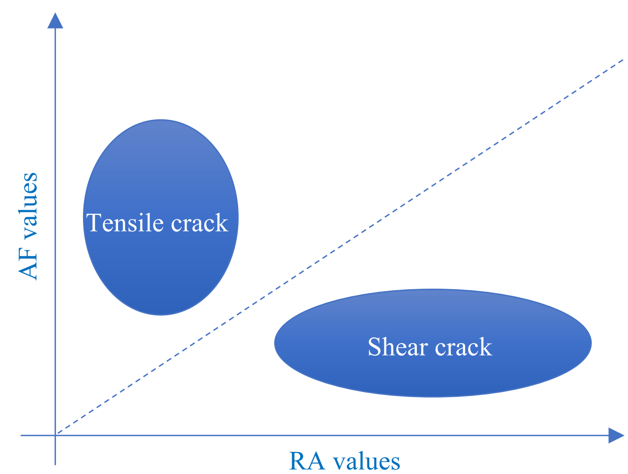


Fig. 7 Classification of tensile cracks and shear cracks by RA-AF analysis method [32]

Research findings by Liu et al. [13] point towards the correlation analysis between AF and RA to figure out the cracking mode of concrete beams. Figure 8 shows the correlation diagram of AF and RA in the bending deformation of concrete beams under various conditions. The author used the Average Frequency (AF) and the ratio of rise time to amplitude (RA) to determine the cracking mode of concrete beams under various conditions. Figure 9 a) N (represent concrete beam without sensor), b) S0 (concrete beam embedded with a sensor on a smooth surface), c) S1 (concrete embedded with a sensor on the surface with low density) and d) S2 (concrete beam embedded with a sensor on the surface with high density). The final results show that all the concrete beams are mainly tensile cracks supported by shear cracks.

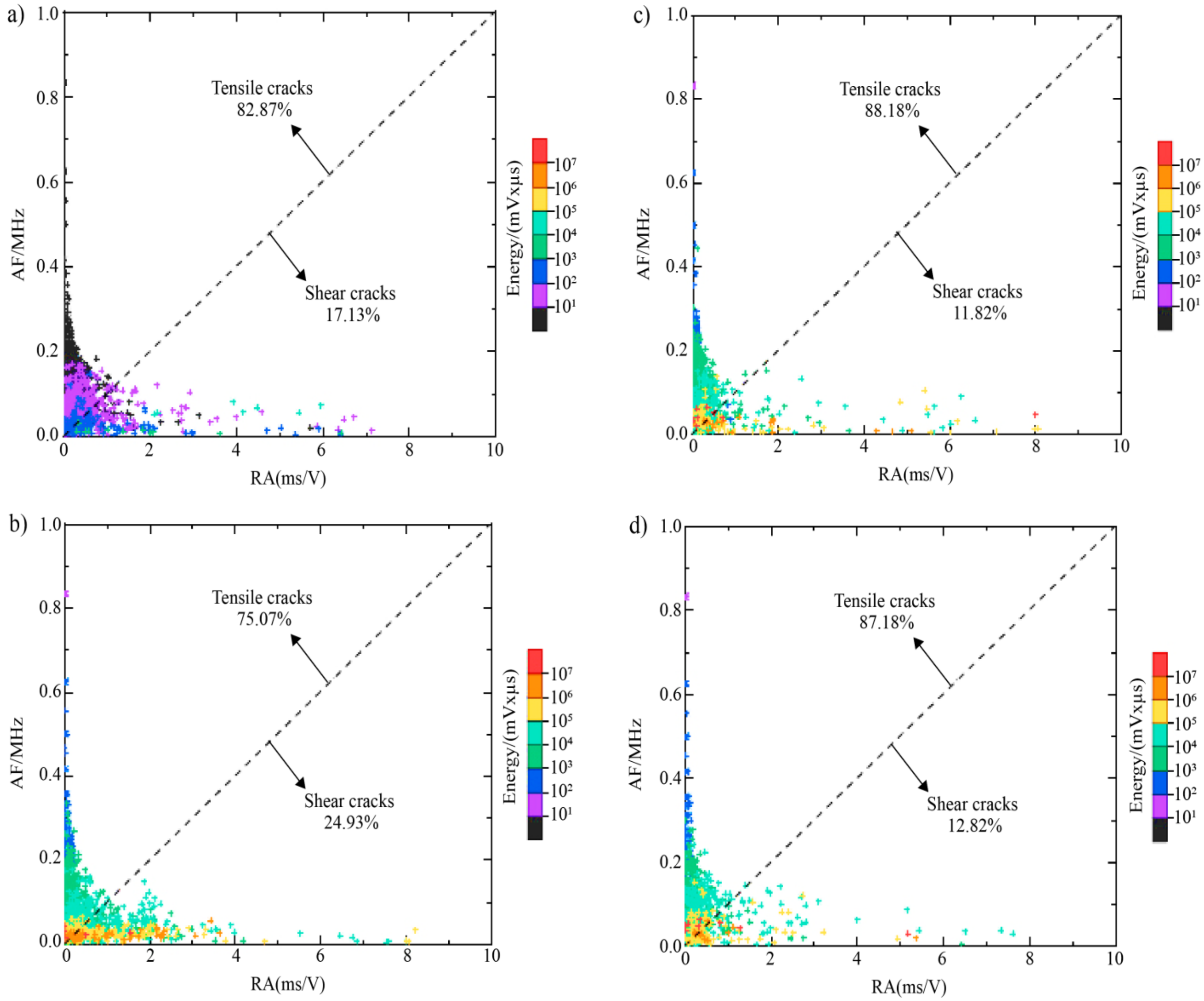
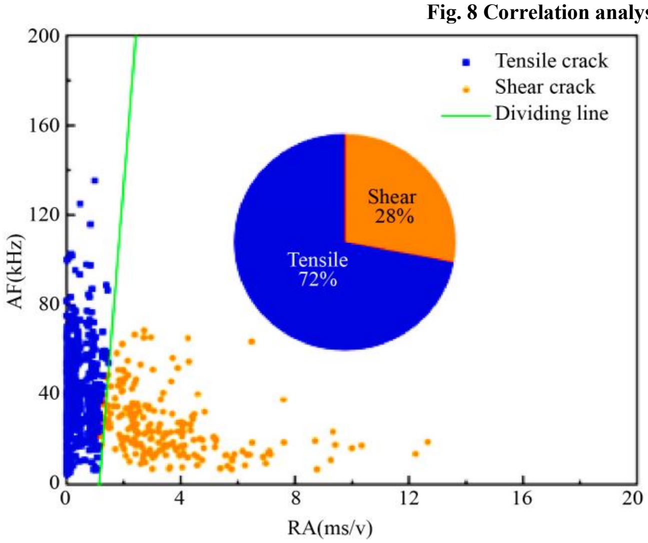
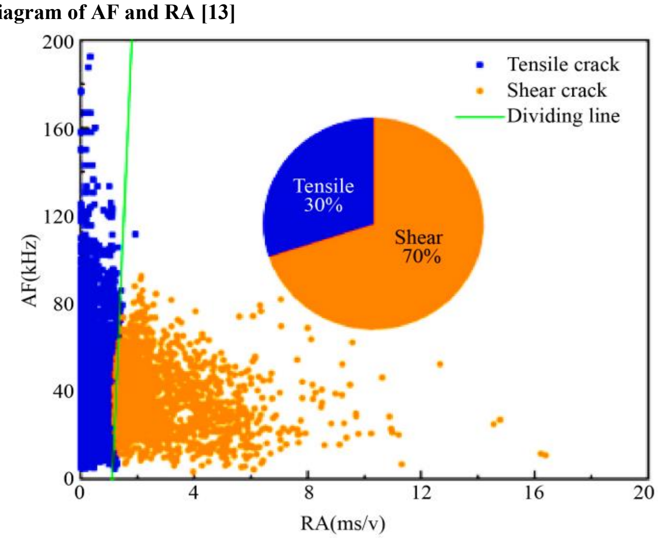


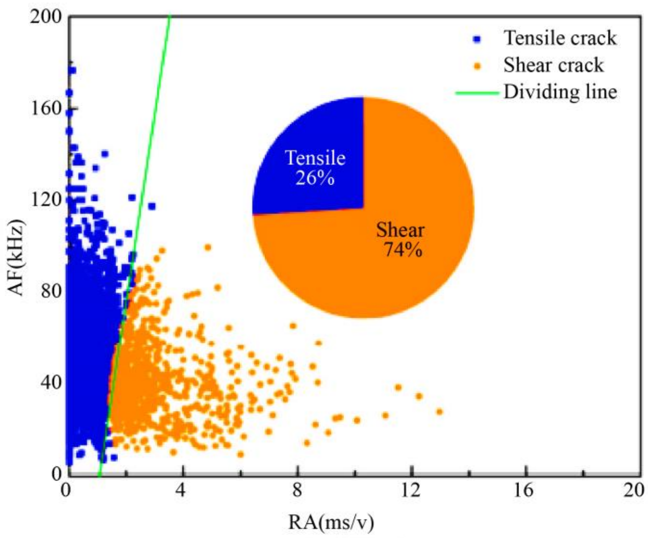
Fig. 8 Correlation analysis diagram of AF and RA [13]



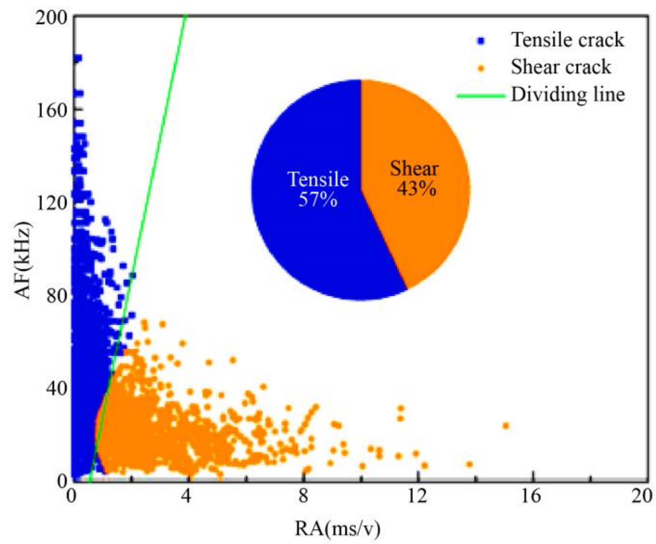
a) MSC



b) GFRMSC-CIL13



c) BFRMSC-CIL13



d) SFRMSC-CIL13

Fig. 9 Analysis of RA and AF for MSC with different types of fiber [14]

Table 3. Previous research on acoustic emission in concrete monitoring

Ref	Aim	Outcomes
[20]	Early-stage assessment of the concrete structure.	AE can classify the type of cracking as micro-cracks in the cement paste (Class 1) and the formation of micro-cracks on the concrete (Class 3).
[21]	Examine the mechanical behavior of sandwich composite material under static and dynamic loadings and assess the damage.	In both types of sandwich material, the AE can identify and characterize local damage in the 4-point bending.
[22]	AE is used to detect and locate the early stages of corrosive and micro cracks as well as to classify different types of cracks in maintenance priorities.	Corrosion, micro-cracks and propagation can be detected by using AE.
[23]	To identify the damage of characteristics in composite material.	AE is strongly related to cumulative damage and additional tensile step loading, whereas specific indices are sensitive to the cracking mode (matric cracking delamination)
[1]	Cracks classification in terms of location, crack types and orientation sing the simplified green for moment sensor (SiGMA).	Develop a crack model with three types of cracks which are tensile, mixed mode and shear.
[24]	AE technique is used to detect defects and damage in reinforced concrete beams and masonry structures.	A fractural or multiscale methodology is used to predict the damage assessment and time structure collapse based on fracture mechanics concepts.
[25]	AE identification amplitude assessment and recommend the b-value analysis	The findings were in good agreement with the progression of the fracture process in a concrete structure.
[26]	AE is used to monitor the crack propagation of unjacketed and BFRP-jacketed concrete cylinders.	Three damage stages of the BFRP-jacketed cylinder were defined.
[27]	AE is used to monitor the concrete fracturing process and the relationship between concrete damage.	The concrete bridges operate safely without disastrous damage.

The above finding is consistent with the study by Jiao et al. [14] examined RA and AF for classifying the fracture mode of Manufactured Sand Concrete (MSC) with a different type of fibers (steel fiber, basalt fiber and glass fiber). Figure 9 shows an analysis of RA and AF for MSC with different types of fiber. Based on the results, both GFRMSC-CIL13 (30%) and BFRMSC-CIL13 (26%) showed less tensile cracks than MSC (72%). Parametric analysis of RA and AF to determine fracture mode (tensile and shear cracks) shows that the addition of fiber can decrease the tensile cracks. The authors concluded that the addition of fibers could suppress the micro cracking.

4. Acoustic Emission Application on Concrete Monitoring

Structural safety monitoring is very suggestive, particularly in concrete structures where material condition assessment can prevent a big-scale failure structure and also aids in terms of safety and economic management of the structure. AE is one of the most widely used for real-time non-destructive monitoring. This AE technique is highlysensitive to crack growth and is able to detect cracks at anearly stage. It is appropriate for the study of structural integrity as it is able to provide continuous monitoring on a big scale of damage mechanisms in real time.

Table 3 briefly summarizes previous research that investigated the acoustic method in concrete monitoring. From the summary in Table 3, it is obvious that the AE approach has been used to detect early damage in concrete, such as first cracking that occurs due to loading or corrosion.

In recent years, there has been an increasing amount of research in AE because the application of this technique has shown improvements. According to the table above, the majority of the improvements have been made to the material and geometry structure. These analysis methods arethe most important consideration when evaluating AE data parameters for identifying damage classification in concrete structures.

5. Conclusion

The application of Acoustic Emission (AE) in civil structure monitoring is a valuable and effective approach to ensure the safety, reliability and longevity of critical infrastructure. AE offer several significant advantages that contribute to the comprehensive assessment and real-time monitoring of civilstructures, which makes it a popular non-destructive testing method in the field of structural health monitoring.

By continuously assessing the structural health and identifying potential issues early on, AE contributes to the sustainable and reliable operation of the civil structure, ensuring the well-being and safety of communities and infrastructure assets.

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