

A review of the application of acoustic emission technique in engineering

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Abstract. The use of acoustic emission (AE) technique for detecting and monitoring damages and the progress on damages in different structures is widely used and has earned a reputation as one of the most reliable and well-established technique in non-destructive testing (NDT). Acoustic Emission is a very efficient and effective technology used for fracture behavior and fatigue detection in metals, fiberglass, wood, composites, ceramics, concrete and plastics. It can also be used for detecting faults and pressure leaks in vessels, tanks, pipes, as well as for monitoring the progression of corrosion in welding. This paper reviews major research developments over the past few years in application of acoustic emission in numerous engineering fields, including manufacturing, civil, aerospace and material engineering.

Keywords: application of AE; acoustic emission; non-destructive testing; NDT applications

1. Introduction

Acoustic emission is one of the new introductions to the Non-Destructive Evaluation (NDE) industry. It was introduced to address the limitations of previous NDE technologies on applications or to cut down financial costs of evaluation. The need to evaluate AE's suitability for use in engineering applications was instigated by some new groups of researchers from Japan, Europe and the USA in the late 1970s and early 1980s (Barber 2006). The definition of AE as given by ASTM E1316 (2014) is "The class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material, or the transient wave(s) so generated". Acoustic emission or stress wave emission as it is often called describes the acoustic stress waves that emerged as a result of a rapid release of energy because of the microstructural changes that occur in materials (Musa 2002).

AE is a very efficient and effective technology used for fracture behavior and fatigue detection in metals, fiberglass, wood, composites, ceramics, concrete and plastics (Huang *et al.* 1998). It can also be used for detecting faults and pressure leaks in vessels, tanks, pipes, as well as for

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monitoring the progression of corrosion and welding (Boehnlein *et al.* 2004). In order to address the challenges posed by audible sounds, which were reported by researchers particularly in the 1990s to occur during AE material deformation investigations, led to the advent of the technological era (Jackson *et al.* 1998). This brought about several advances particularly in the areas of rapid measurement instrumentation in AE. For example, advanced digital instruments can now be used to digitize and store large numbers of high speed digital waveform signals of AE (Holford *et al.* 2009).

2. Inspection requirements

Common instruments used in AE include preamplifiers, amplifiers, filters, sensors and other data collection, analysis and storage equipment like computers, oscilloscopes and voltmeters (NDT 2012, Pollock 1989). Preamplifiers are used for the prevention of loss of signal and to reduce the interference from noise while the piezoelectric sensors are used for the conversion of mechanical AE waves into electrical voltages (PAC 2005). The overall objective of the measurement is to determine the various AE parameters such as the frequency range (controlled by filters) that exist in the system by observing and measuring the performance of AE amplifiers and sensors. These are very useful mechanisms for environmental noise discrimination and for identifying deterioration through the measurement of parameters such as event, count, energy-moment, maximum amplitude, hit, energy, arrival-time difference, RMS (root mean square) voltage, rise time, spectrum, frequency and duration (Grosse *et al.* 2008).

3. Overview on acoustic emission waveform parameters

In the 1950s and '60s researchers investigated the essentials of AE, established instrumentation particularly for AE, and considered the AE behavior of numerous resources. AE was starting to be recognized for its exclusive competences as a NDT technique intended for checking dynamic procedures. In the 1970s, studies were carried out to develop more synchronized and directed through the construction of the working groups, and its usage as an NDT process continued to increase for industrial applications. During the 1980s, the computer developed as a basic component for both instrumentation, data examination, and nowadays it has flashed a resurgence of chances intended for study and improvement. Nowadays, waveform-based AE investigation is typical and there is a change in AE accomplishments through more importance on uses than on study (Drouillard 1996).

Two types of analysis can be considered by AE. One is under time domain waveform which is related to basic parameter in a time domain of testing and the second is frequency domain waveform which considers the signal parameters with upcoming recorded frequency under testing. The extensively used signal measurement parameters in AE signal examination are counts, duration, amplitude, rise time, and the measured area under the corrected signal envelope that is also called relative energy as shown in Fig. 1.

Amplitude: It is represented with A and shows the highest peak of the voltage signal. This is identical significant characteristic since it openly controls how much the AE event is detectable. Amplitude of the AE signal is immediately related to the magnitude of the source and varies over a wide range from micro volts to volts. According to Unnþórsson (2013), the amplitudes of AE are

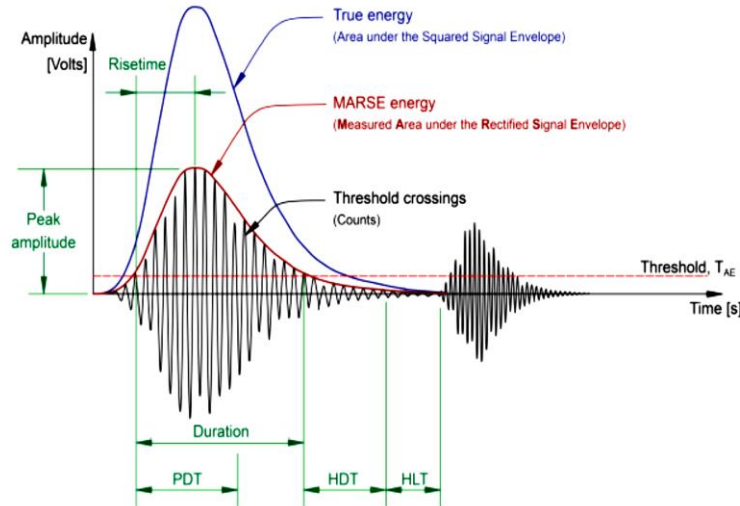


Fig. 1 Acoustic emission events recorded by using definition (Unnþórsson 2013)

usually mentioned in decibel scales. For example $1 \mu\text{V}$ at the transducer is defined as 0 dB, $10 \mu\text{V}$ as 20 dB, and $100 \mu\text{V}$ as 40 dB.

Counts: Counts commonly are presented by N . When the amplitude of the signal is larger than the threshold, the number of pulses emitted by measurement circuitry is defined as N . Counts strongly rely on the AE properties and reverberant nature of the sensor and specimen material.

Hits: When a signal exceeds the threshold consequently a system channel accumulates data, this signal is known as the hit and describes an AE event. The number of events or hits per time determines the event rate. Both number of hits and number of counts determines the quantity of an AE activity.

Duration, D: The time interval between a signal trigger and the time it reduces below the threshold value is known as the duration of the signal.

MARSE Energy: Measured Area of the Rectified Signal Envelope is known as MARSE and sometimes represented by E and referred to as energy counts. This area is the zone below the envelope of the signal which is rectified and measured from the sensor. Energy is preferred over counts since it is sensitive to amplitude as well as duration, and it relies fewer on the threshold location and functioning frequency.

Absolute (true) energy also is resulting from squared voltage signal divided by reference resistance of $10 \text{ k}\Omega$ over the time duration of acoustic emission waveform packet. According to (PAC 2005), this parameter indicates the true energy of an AE event from transient signals or of certain data rate interval of continuous AE signals. The absolute energy of a detected AE burst signal commonly expressed in atto-joules ($1 \text{ aJ} = 10^{-18} \text{ J}$) and values can be mentioned in logarithmic scales (dB, decibels) (ASTM E1316). The energy is defined as

$$E_t = \frac{1}{2} \int_{t_1}^{t_2} \phi_+^2(t) dt - \frac{1}{2} \int_{t_1}^{t_2} \phi_-^2(t) dt \quad (1)$$

Rise time: Rise time is presented by R and defines the time interval between the maximum amplitude of the burst signal and the first threshold crossing. This parameter is frequently used when time dependent processes such as vibration or dynamic loading are involved.

Threshold: Threshold is a kind of set up parameter which is used for the elimination of electronic background noises. Its main objective is to eliminate as much background noise as it can. However, a balance should be struck so that the threshold does not also eliminate signals that are weak but useful given that background noises are characterized by low amplitude.

To run proper AE monitoring, certain parameters of the data acquisition systems need to be set according to the testing material and the existing noise level. These parameters which are categorized as control parameters can be mentioned as Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lock out Time (HLT) that are timing parameters of the signal acquisition process and contain material specific values. PDT identifies the signal peak for rise time and peak amplitude measurements. HDT quantifies a signal to be accounted as one hit and appropriate HLT setting ensures the ability to discard the spurious signal decay measurements.

3. Application of AE in engineering

Several industries such as power generation, refineries, structures (cranes, bridges, etc.), pipelines, aircraft, etc., make use of AE for nondestructive testing in their operations. Since its advent in Germany in the 1950s, AE has been very widely applied especially in the areas of quality control in manufacturing operations and process monitoring. AE systems are also very useful applications of composite structures like advanced aerospace materials, reinforced plastics and fiberglass and can also be employed in research applications and quality control in manufacturing operations (Li 2002).

3.1 Manufacturing

Dornfeld (1992) noted that although AE was initially intended for non-destructive testing of structures, today it has been widely applied as a technique for monitoring manufacturing processes because of its sensitivity to process parameters. Several researchers have looked into the various challenges faced in monitoring manufacturing processes such as Dornfeld *et al.* (2003), Haber *et al.* (2004), Jemielniak and Arrazola (2008), but focused mainly on sensor techniques and how they fit into future manufacturing requirements. Likewise, Chen and Li (2007) investigated the AE signals of wavelet analysis for tool condition monitoring, while, Sun and Tang (2002) used wavelet transform modulus maxima to monitor operating bearings in order to identify any abrupt changes that may occur in the signals of the vibration. Teti *et al.* (2010) conducted a very detailed review on sensor technology and the techniques employed for processing data in automated machine by using several sensors of varying levels of applicability based on the phenomenon type, precision level or control parameter requiring measurement so as to capture the necessary information on the manufacturing process (Lee *et al.* 2006). Fig. 2 shows an update of a related diagram from the aforementioned review paper (Dornfeld *et al.* 2003), and the diagrams of other sensors based on their class and applicability at both control parameter type and level of precision (beginning from the conventional scale edging downwards to the level of ultra-precision material removal at the ordinate scale) (Dornfeld *et al.* 2003, Lee *et al.* 2006).

The use of AE as a monitoring technique for machining operations comes with a lot of advantages, one of which is its ability to discriminate between environmental noise and machine vibrations from those of AE signals due to high frequency range and sensitivity of AE signals, thus preventing it from interfering with the cutting operation (Govekar *et al.* 2000). This characteristic

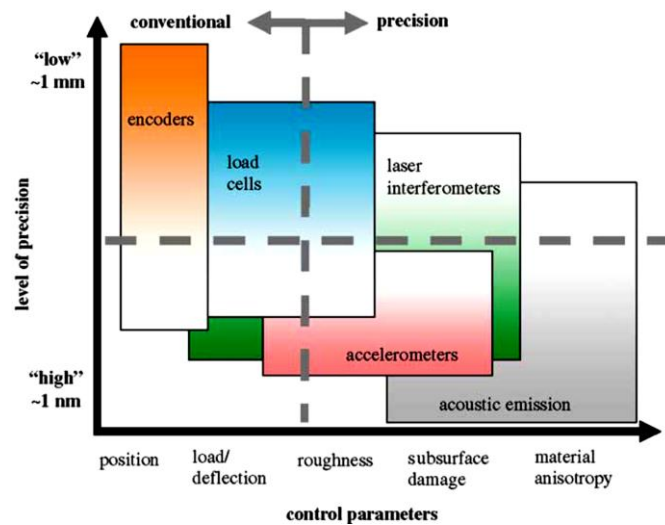


Fig. 2 Sensor application vs. level of precision and control (Dornfeld *et al.* 2003)

has made AE signal one of the most preferred tools used for process monitoring. The resulting AE signal continuously generated due to friction between the tool and work piece provides rich information regarding the cutting process. Different techniques and methodologies exist for monitoring of wears in tools used in welding (Suresha and Rajaprakash 2009, Zeng *et al.* 2006), turning (Jemielniak *et al.* 2011, Sharma *et al.* 2008), forming (Hao *et al.* 2000), milling (Mathew *et al.* 2008, Marinescu *et al.* 2008), grinding (Jayakumar *et al.* 2005), drilling (Arul *et al.* 2007, Velayudham *et al.* 2005).

3.2 Civil

Another method used for the procedure of implementing a damage characterization strategy for maintenance purposes in engineering structures is structural health monitoring (SHM) (Brown *et al.* 2010). SHM employs AE technique in detecting early cracks in structures. It relies on the high frequency ultrasonic waves generated energy that is rapidly emitted from a material, right from the initial to growth progression of cracks. This AE technique makes it possible to monitor structures in real-time, thereby making it enabling the immediate detection of signals caused by cracks as soon it occurs (Kaphle 2012). The two basic types of AE monitoring strategies which can be applied are local and global monitoring strategies. Global monitoring strategy aids in the assessment of the whole integrity of the structure, whereas the local monitoring strategy is concerned with a particular damage area (Carlos *et al.* 2000).

The wide applicability of AE technique is evident in several metal piping system evaluations and fibreglass reinforced plastics (FRP) (Ai *et al.* 2010, Oliveira *et al.* 2008), concrete bridges (Golaski *et al.* 2002), premature crack detection, fatigue crack development monitoring and the correlation of crack development with AE activity in steel parts (Keshtgar *et al.* 2013, Yu *et al.* 2011, Yu *et al.* 2011). A detailed discussion on AE fracture in metals is presented by (Ono 2011), while cracking in concrete is well discussed by (Kishi *et al.* 2000).

Most common long-term assessment conditions due to damages experienced on concrete bridges are reinforcement corrosion and its associated cracks. Several research centers such as

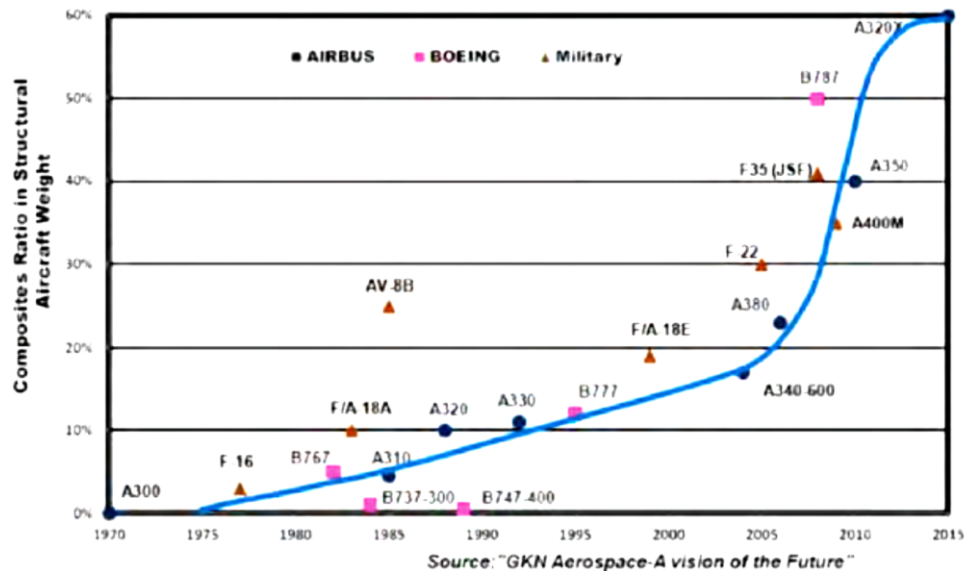


Fig. 3 Composites ratio in structural aircraft weight during last decade in commercial and military aircraft (Ono and Gallego 2012)

highway agencies and universities are seeking ways through which AE can be implemented on concrete bridges (Watson *et al.* 2005). Vogel *et al.* (2006) discussed the processes involved in pre-stressed concrete bridges. They found that the use of AE for new crack monitoring was very significant as most concrete structures do not exhibit any sign of cracks at their initial stage of their service life. Recent findings on AE activities include Reiterer *et al.* (2000), who used a wedge-splitting configuration to determine a crack's uniform growth in both soft and hard woods by investigating the emission features resulting from mode I fracture in the plane normal to the radial direction. Aicher *et al.* (2001) looked at the damage caused in softwood generated by tension from loading specimens in a plane normal to the tangential direction.

3.3 Aerospace

The application of AE took center stage after it was employed in developing reinforced glass-fiber composite rocket motorcases that were used in 1962 for Polaris A3 circa. It was also used to test Apollo lunar module propellant tanks and various aerospace applications. AE variations were first noted by Aerojet engineers, who identified different emissions from fiber failures, interlaminar failures and resin failures (Green *et al.* 1964, Green 2006), thus leading to the modification of the manufacturing processes for example, shear stress could be reduced by modifying the design such that the geometrical inflection points are eliminated (Asakawa *et al.* 1965).

The use and significance of composite structural components is on the increase particularly in commercial aircrafts such as (B787, Airbus A380, F35, Typhoon) due to the superior strength features they have over metallic properties. The applications of AE real-time monitoring in mechanical tests are evident in the traditional polymer composites, which are reinforced with fibers (Park *et al.* 2004), glass (Benevolenski and Karger-Kocsis 2001, Margueres *et al.* 2000), or

carbon (Mizutani *et al.* 2000). These studies employed classical NDT application analyzed at various stages with sound progressive analysis with the goal of accepting or rejecting the stress material to the measurement and localization of accumulated damage.

Pawar and Ganguli (2007) did a comprehensive review of various techniques used in helicopter rotors. Pullin *et al.* (2010) determined the distinct correlation between AE and crack growth and also used TRL5 (technology readiness level of five) to detect landing gears fractures in AE. Takeda (2008) did a study on monitoring damages with small-diameter optical fiber sensors and structural health monitoring of composite structures. AE was monitored with Full Scale Aircraft Structure Test Evaluation and Research (FASTER) in several honeycomb sandwich composites curved fuselage panes, with different scenario of damage, placed in Atlantic City (US). Fiber-Bragg grating (FBG) sensors and combined with piezoelectric actuators for Lamb wave inspection of carbon fiber reinforced plastic (CFRP) structures by Leone *et al.* (2008). Several recent studies on NDT in aircraft manufacturing can also be found in Giurgiutiu *et al.* (2003), Roach (2008), Schnars and Henrich (2006), Speckmann and Henrich (2004), Ullmann *et al.* (2010).

There are several difficulties faced in using composite components by NDE/NDT during the manufacturing process, flight conditions, SHM, and service inspections. Several tests have been carried out in laboratories on large composite components especially in the last decades for aircraft structures (Ono and Gallego 2012). The increased and varying application of composites in various military and commercial aircrafts is shown in Fig. 3.

3.4 Material engineering

3.4.1 Composite

AE originates from stress waves generated as a result of the growth or movement that takes place in solid defects. AE, unlike other techniques which can only detect geometrical discontinuities, detects fiber breakage movement, delamination (debonding of neighbouring plies) in laminated composite plates, matrix cracking and fiber pull-out (Diamanti and Soutis 2010). Majority of AE is caused by the rubbing or friction that takes place between damaged components in the composite. Some studies have looked into the potential application of AE technique in assessing the impact of the damage (Aymerich and Staszewski 2010), and understanding the behavior of the fracture of composite materials (Pappas and Kostopoulos 2001). AE was used by Szabó *et al.* (2004) to monitor the single-edge notched tensile (SENT) samples (notch length 10 mm) in polypropylene/polyamide (PP/PA) blends (with different concentration of PA: 0, 10, 20, 30, 40 and 50 wt%) reinforced by short basalt fiber (De Groot *et al.* 1995) at various contents (0, 10 and 20 wt%). Shen *et al.* (2002) proposed a model to explain the relationship between AE signals and force that generates deformation in plastics.

Other researches have looked into the application of AE technique for damage evolution analysis and failure detection methods in traditional polymer composites reinforced with glass (Oskoue and Ahmadi 2010), aramid fibres (Caneva *et al.* 2008, Claudio Caneva *et al.* 2007), or carbon (Chen and Liu 2008, Liu *et al.* 2012). Nevertheless, there are not many studies on damage mechanisms in composites reinforced with natural fibers in AE such as kenaf, hemp, flax and jute (Anuar *et al.* 2007, Czigány *et al.* 2005, Dogossy and Czigány 2006, Kocsis and Czigany 2007, Szabó *et al.* 2004). The use of AE method to investigate the behavior of fracture and failure in biodegradable jute fabric reinforced thermoplastic polyester composites was carried out by Acha *et al.* (2006). While the correlation that exists between AE amplitude, elongation and cumulative hits, and elongation on wood flour filled polypropylene composites was shown by Dányádi *et al.*

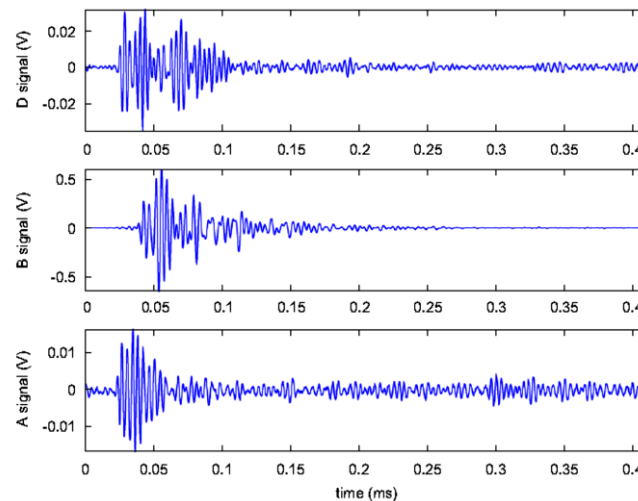


Fig. 4 AE signals of $[\pm_62]_{12}$ cross-ply composite: matrix cracking (A signal), fiber-matrix debonding (B signal) and delamination (D signal) (Marec *et al.* 2008)

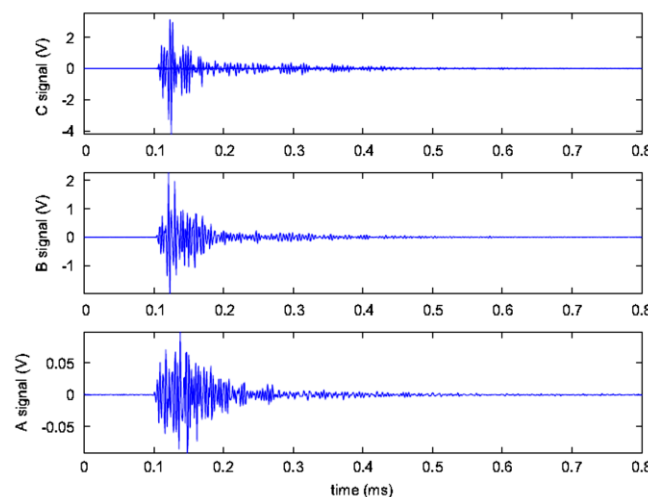


Fig. 5 AE signals of SMC composite: matrix cracking (A signal), fiber-matrix debonding (B signal) and fiber failure (C signal) (Marec *et al.* 2008)

(2006). Romhányi *et al.* (2003) used AE to monitor and identify the sequence of failure mode that occurred in flax fiber reinforced composites during a tensile test. Their study revealed the possibility of identifying, during the failure of a composite, the AE amplitudes released by the flax fibers, despite the fact the previous values are lowered due to the damping effects of the matrix. Marec *et al.* (2008) investigated the local damage of composite materials based on the acoustic emission signal analysis. The results clearly identified the damage mechanisms in various composite materials: cross-ply composites and sheet molding compound (SMC) under tensile tests. This study also indicated the time evolution of damage mechanisms in these materials till the global failure and identified the most critical damage mechanisms. Matrix cracking and fiber-

matrix debonding occur with delamination for the cross-ply composite material. In the SMC composite, matrix cracking, fiber matrix debonding, and fiber failure were observed. The identified A, B and D signals for the cross-ply composite and A, B and C for the SMC composite are presented in Figs. 4 and 5.

3.4.2 Metal

The signals generated from AE are subject to both dispersion and attenuation due to the elasticity of the waves. Majority of the studies carried out in this domain with regards to monitoring AE in metals are mostly focused on specimens with thin plate geometries (Aggelis and Matikas 2012, Sedlak *et al.* 2009). However, by definition, propagation in thin plates is dispersive (Brepta *et al.* 1996, Rose 2004), because of the varying phase velocities at which different frequencies are propagated. According to Brown *et al.* (2010) there are four-point bending in which AE amplitudes correlate to stress in composite metal specimens. Dang Hoang *et al.* (2010) showed the relationship that exists between the duration of AE energy and the failures in a central bolt-connected aluminum plates. In a similar study, the relationship between the count rates in AE events and crack propagation rates in steel and welded steel compact tension (CT) specimens under fatigue was studied by Roberts and Talebzadeh (2003). Aggelis *et al.* (2011) found that some parameters like rise angle (RA), duration and rise time are very sensitive to the rate of crack propagation and are useful in the characterization of the transition to shear failure from in CT specimens under fatigue. Also Boschetto and Quadrini (2011) found that when metal powder is dropped in a controlled manner on a metal plate, the number of waveform counts was seen to be indicative to particle diameter. Furthermore, the study conducted by Han *et al.* (2011) on fatigue properties in a micro-alloyed steel and welds and AE characterization of fractographic and micro-structural observations reveal that AE can be used as a monitoring mechanism for damage caused by fatigue in structures due to its sensitivity to changes that occur within the fracture mode. Fig. 6 shows the relationships between the AE counts rates (dC/dN) and stress intensity factor ranges (ΔK) for different specimens. The AE counts rates increased in a linear relationship with the increase in ΔK on the log-log axes. Moreover, higher AE counts rates were also observed in the welded specimens than in the base metal specimens. In addition, the slopes of the lines for the

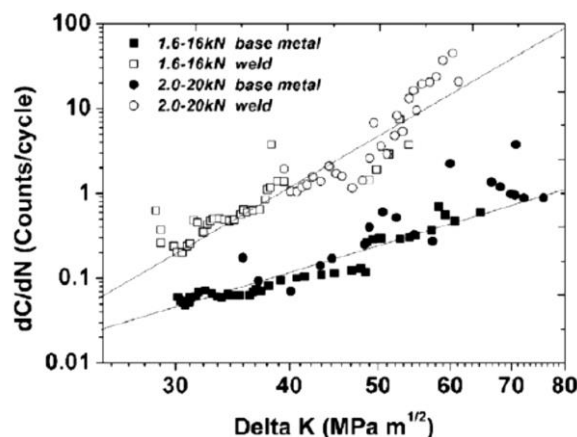


Fig. 6 Relationships between crack growth rates and AE counts rates with ΔK for the base metal and weld under the peak loads of 16 kN and 20 kN (Han *et al.* 2011)

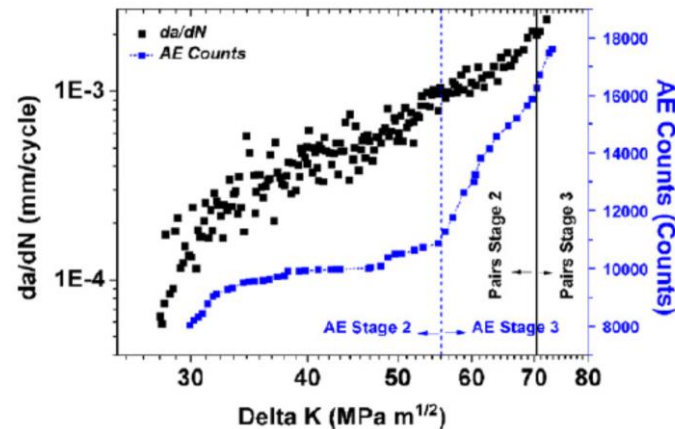


Fig. 7 Comparison of the LEFM and AE transitions (Han *et al.* 2011)

welded specimens were higher than the base metal specimens, also suggesting that the weld generated more AE signals during fatigue crack propagation. It was known that the stable and unstable crack propagations are generally identified by different slopes in the log-log plot of da/dN versus ΔK in the classical linear elastic fracture mechanics (LEFM). Fig. 7 shows for a base metal specimen, when the AE transition occurs at $\Delta K = 56 \text{ MPa m}^{1/2}$, there is no change in the linear relationship between da/dN and ΔK on the double logarithmic axes. Until $\Delta K = 70 \text{ MPa m}^{1/2}$, an unapparent change in the slope is observed. Thus, the AE stage transition precedes the unstable crack propagation defined by LEFM.

3.4.3 Concrete

Structural safety monitoring is very significant especially in concrete structures where early material condition assessment can help prevent large-scale failure and also aids in the safe and economic management of the structures. AE is one of the most widely used techniques employed for real time non-destructive monitoring. The methodology behind the AE technique is measurement and recording of the elastic waves emitted during crack propagation incidences by transducers that are kept on the material surface (Ohtsu and Uddin 2008).

In a study carried out by Ohno and Ohtsu (2010), two types of crack methods were investigated using AE technique to classify cracks in concrete by applying the RA value and average frequency parameters. The results from the laboratory investigation showed that concrete cracking were more powerful because of the metal reinforcing bar corrosion (Ohtsu and Tomoda 2008). Also, discriminations were observed between the pull-out that occurred when bending the fiber reinforced concrete and matrix cracking (Soulioti *et al.* 2009). Several studies have also used the boundary element method (BEM) and AE measurements to carry out both experimental and numerical investigations on the mechanism associated with corrosion-induced cracks in concretes (Ohtsu and Uddin 2008, Uddin *et al.* 2006). An estimation of the level of damage experienced in concrete structures can be easily obtained by measuring the maximum AE signal amplitude and the total number of AE hits (Ohtsu 2006), whereas the source of AE localization as a result of the micro-cracks can be estimated by computing the differences in the time it takes for each AE waveform to arrive at the AE sensor (McLaskey and Glaser 2007). Aggelis (2011) studied the AE monitoring of different types of concrete during bending. The investigation showed AE parameters

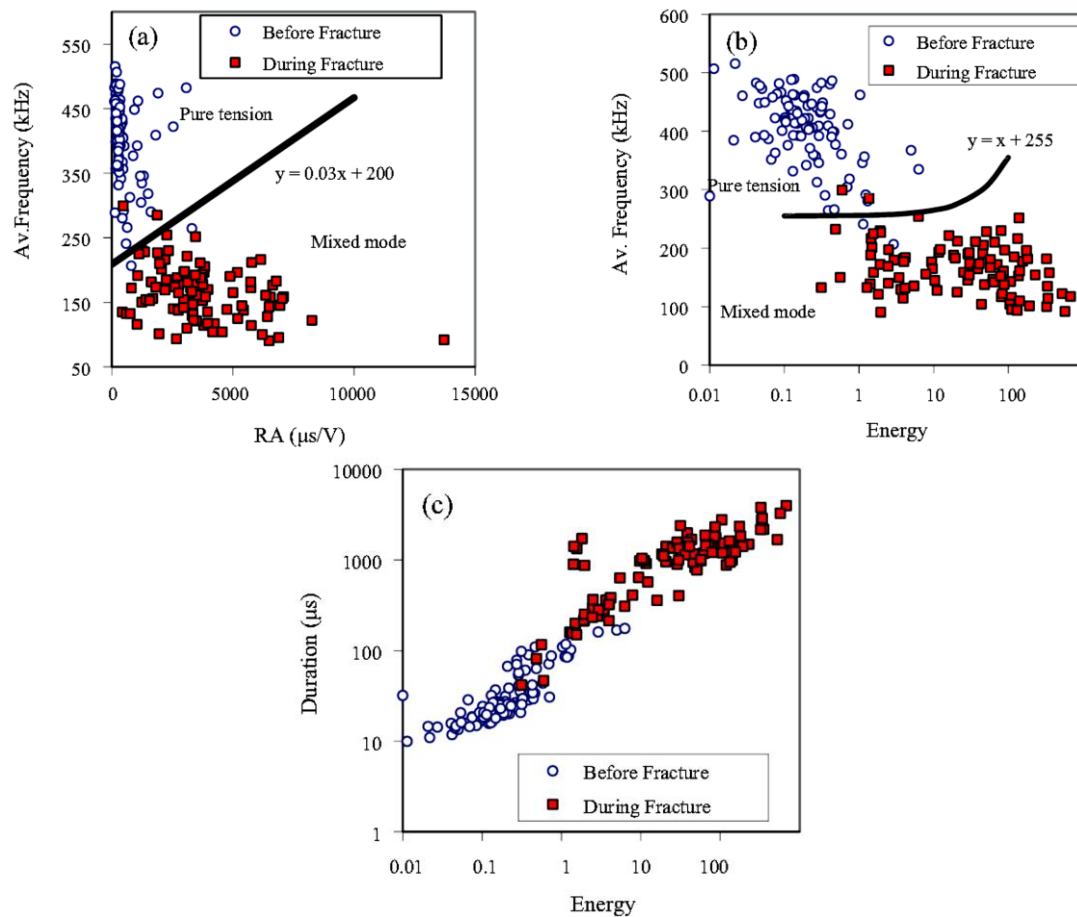


Fig. 8 Correlation plots between (a) AF and RA, (b) AF and AE energy, and (c) duration and AE energy (Aggelis 2011)

as a simple classification scheme between different modes of fracture in concrete. Fig. 8 illustrates the correlation plots between AE parameters in before fracturing and after. Fig. 8(a) shows the average frequency (AF) vs. RA for different fracture stages for all specimens. There is a very strong discrimination between the different stages based on these two AE parameters. Only a number of few dots are overlapping, allowing a robust classification by one straight line. When the AF of a signal is higher than $0.03 \cdot \text{RA} + 200$, the crack can be securely classified to the tensile mode. Fig. 8(b) shows the corresponding correlation plot between AF and AE energy. The classification based on these two parameters is also strong, indicating that when the AF of a signal is higher than the energy (ENE)+255 the crack is tensile. Another parameter showing high sensitivity to the fracture pattern is AE duration (DUR). Its correlation vs. energy is depicted in Fig. 8(c), which shows a few more overlaps between micro-cracking and macro-fracture with pull out but still exhibits high classification potential.

3.4.4 Rock

As of today, AE technique has been employed in several studies in evaluating the processes of

failure in different engineered materials, rock and concrete types, and is being widely applied in the field of geoscience and material science (Michlmayr *et al.* 2012). AE is undoubtedly a very powerful nondestructive technique used for the detection of elastic waves emitted from crack initiations, growth, and coalescence. These AE signals generated from these emissions yield several kinds of useful information about the AE induced-sources through evaluation of the characteristics of the fracture sources and waveform or parametric analysis (Shiotani 2006). Recent studies also show how AE technique have been employed in the investigation of fractures caused as a result of pore pressure changes and fluid injection (Mayr *et al.* 2011, Stanchits *et al.* 2011). Several studies have also applied AE technique in the study of rock stability. Aker *et al.* (2014) used AE technique to study on the effects of triaxial stress on shear and tensile experienced in a standalone sample of around horizontal borehole and observed that a relationship exists between the macroscopic sample deformation based on the AE event rate and the deviatoric and isotropic percentage of the seismic moment tensors component based on the expected failures mechanisms. Mori *et al.* (2004) employed AE in the study of AE characteristics and electromagnetic emission activities on granite samples by testing repeated loading and taking their respective AE measurements in order to determine the Kaiser Effect in rock sample.

4. A comparison of the AE technique and other NDT

AE monitors components continuously via structural health monitoring tool starting from the qualification phase through the testing phase, to the eventual periodic replacement of that component. AE utilizes the energy generated from within the defected structure for its operation and does not require any external energy source. This makes it a passive technology (Kaphle 2012).

Through the use of AE technique, structures can be monitored in real time given that signals are emitted immediately when a crack occurs. These signals can also be analyzed in real time using AE technique to generate constant information regarding the nature of the crack or energy source. Besides its primary role of monitoring specific structure locations, AE can also be employed for monitoring complete structures or large areas if its number of sensors is increased. This makes it a global or semi-global monitoring technique. AE differs from other non-destructive techniques that source signals from external sources like ultrasonic in that its signal is internally sourced from the material itself (Vallen 2002). The ability of AE to detect movements unlike the detection of geometrical discontinuities that exist by other techniques makes it superior to these techniques

Table 1 Comparison of AE characteristics with other methods (Kaphle 2012)

Acoustic emission	Other methods
Detects movement of defect	Detect geometric form of defect
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 plant process
Requires access only at sensors	Requires access to whole area of inspection
Main problems noise related	Main problems geometry related

(Kaphle 2012). A summary of the comparison of AE and other inspection methods, highlighting their major differences, is presented in Table 1.

Some researchers used AE with another NDT method such as ultrasound, thermography, digital image and etc, as tools for detecting the onset damage and crack growth in materials. Kurz *et al.* (2005) used ultrasound signals and acoustic emissions based on the Akaike Information Criterion (AIC). The AIC picker was then compared to an acoustic onset detection algorithm based on Hinkley criterion. Manual picks were also performed for reference values. Both automatic onset detection algorithms were applied to ultrasound signals and acoustic emission for monitoring the hardening of the concrete during the pull out test. The AIC-picker produced reliable results for ultrasound signals with small deviation from manual picking between 2% and 4%. Concerning acoustic emission, only 10% of the events resulted in a mislocation vector greater than 5 mm, which can approve that the AIC-picker is a reliable tool for automatic onset detection of different signals.

Aggelis *et al.* (2009) used AE and ultrasound for monitoring damage characterization of reinforced concrete beams at different levels of loading. Ultrasound pulse velocity measurement obtained transient three dimensional tomographic reconstruction of the internal structure at different loading. Results showed that the AE technique and velocity tomography can be useful tools for finding the failure progress of concrete. Figs. 9 and 10 show the location of actual cracks obtained by AE events and ultrasonic pulse. Small cracks that cannot influence pulse velocity can be identified by AE as they propagate. On the other hand, inactive cracks those show no AE activity influence ultrasonic pulse velocity (UPV) and can be detected. Therefor AE and UPV can work complementary to each other.

According to Fig. 9(b), AE event shows two-layer composite specimen that 89% of loading to maximum loading was applied; the aggregation of number of event near the edge of the diagonal crack developing from the left is obvious. Other events near the smaller crack propagating vertically towards the top surface can also be seen. The final fracture pattern was similar to the one

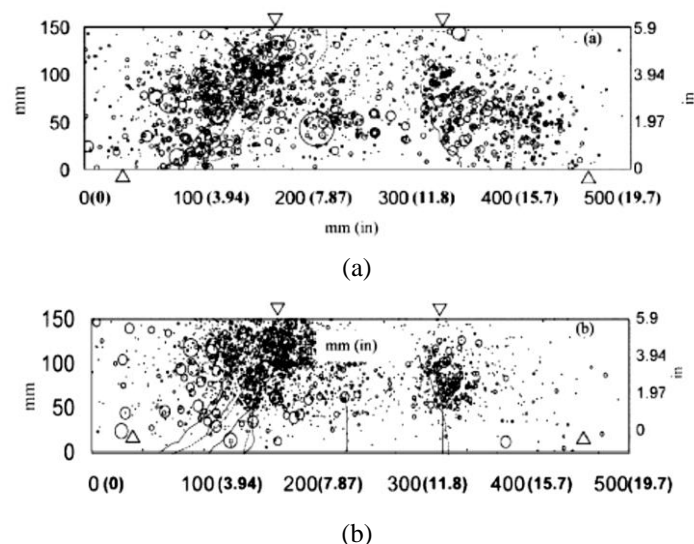


Fig. 9 Location of AE events and actual pattern of cracks for (a) plain concrete at third loading (b) composite specimen at fifth loading (Aggelis *et al.* 2009)

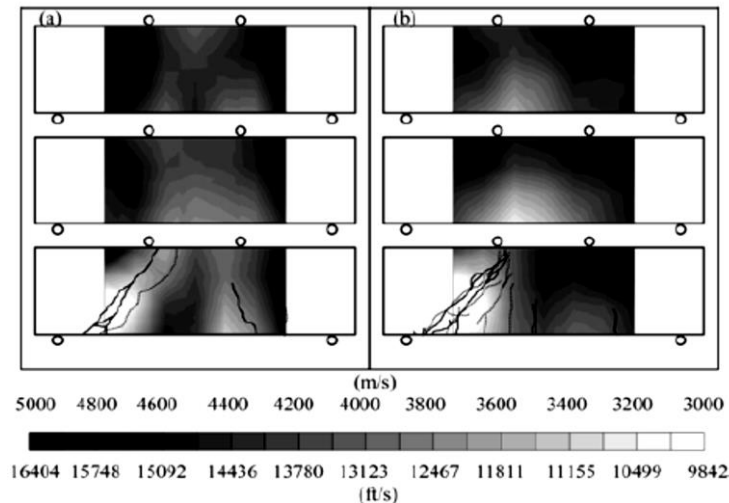


Fig. 10 Velocity tomography of central cross section of: (a) plain concrete; and (b) two-layer specimen for different loading stages (Aggelis *et al.* 2009)

of plain concrete (development of diagonal cracks from the bottom to the top surface).

Tomography results based on the pulse velocity are depicted in Fig. 10. The top graphs shows the intact condition that the velocity of the material was more than 4000 m/s, and the next two to the last two loading stages for the central cross section of the specimens that pulse velocity decreased to 3000 m/s at the zone where the diagonal macroscopic cracks developed.

Naderi *et al.* (2012) presented experimental approach for characterizing dissipated thermal energy and damage evolution in a woven glass/epoxy (G10/FR4) laminate by using infrared thermography and AE. A fraction of the input mechanical energy was converted to thermal energy, which resulted in an increasing the specimen temperature, during cyclic loading. Thermal energy was estimated by analyzing surface temperature. Infrared thermography was used to assess the temperature evolution and various damage states; and AE was utilized to certify the thermography results in characterizing the reduction progression. The results showed similar evolutionary response revealing the existence of degradation stages. Using calculated dissipated thermal energy (DTE), a damage growth model was developed that appropriately characterizes the three damage phases during fatigue process of glass/epoxy.

A real-time crack growth measurements in composites using combined NDE techniques infrared thermography (IRT) and AE was conducted by Dassios *et al.* (2014). Glass-ceramic matrix composites were loaded under cyclic tension with unloading-reloading loops under the compact tension (CT) specimen configuration. During the test, the front side of specimen was monitored by infrared thermographic camera and back side of specimen AE sensor was mounted. Fig. 11 shows thermographs collected at indicative successive stages of crack growth and Fig. 12 represents the time history of the cumulative received AE energy, along with load-line crack opening displacement (COD). In Fig. 11 warmer colors correspond to higher damage accumulation as opposed to colder colors. Violet color, corresponding to the maximum temperature, is attributed to crack growth. Fig. 13(e), collected just before composite failure, represents the maximum damage span on the specimen. Fig. 11(f) shows damage zone and its evolution with time during composite fracture. In Fig. 12, AE energy increased as the strain was reaching the peak of each

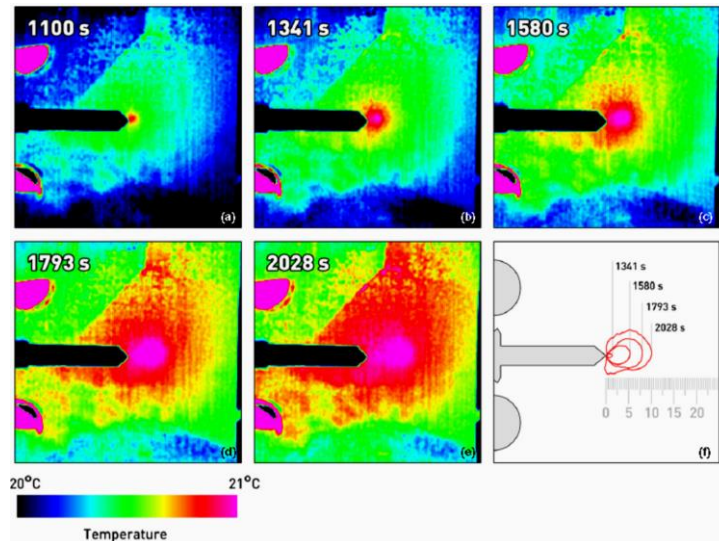


Fig. 11 Indicative thermographs showing crack growth and extent of damage during composite fracture (Dassios *et al.* 2014)

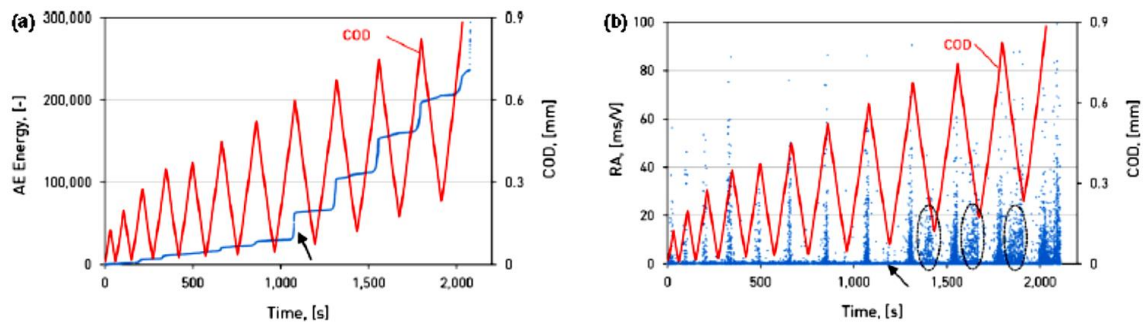


Fig. 12 (a) Cumulative acoustic emission (AE) energy history and (b) RA of entire AE signal population (Dassios *et al.* 2014)

cycle, an observation indicating increased damage accumulation within this specific regime. Fig. 12(b) shows the RA values for the entire population of AE signals; RA increased with strain within each cycle, while low RA values are seen at the descending part of load-line COD.

In this study, AE was particularly successful in closely following the actual crack growth measured by IRT, an observation that brings out the potential of the technique for quantitative measurements.

Aggelis *et al.* (2013) used AE for monitoring of the fracture behavior of externally reinforced concrete beams under bending. The monitoring was complemented by Digital Image Correlation (DIC) for assessing a clear depiction of the surface strain field and its transient changes according to stress redistribution which occurs after fracture moments. AE parameters provided information on the damage mechanisms, while DIC was used to measure the results by the obtained strain fields and their fluctuations. The complementary information supplied by DIC helped to minimize the assumptions in the interpretation of the AE trends in relation to the responsible damage

mechanisms by revealing the fluctuation of the surface strain fields. Results showed that AE were thus benchmarked and certain trends reliably attributed to specific processes and the mechanical performance of the different reinforcing materials on the beams. Moreover Rouchier *et al.* (2013) developed a methodology for monitoring and detection of damage and fracture in fibre reinforced mortar materials by energetic renovation. DIC and AE monitoring were simultaneously performed during tensile loading. All ranges of cracks were obtained by DIC, from microscopic to macroscopic, and an image processing procedure was conducted as to quantify their evolution in the course of the degradation of the samples. The comparison of these measurements with the acoustic activity of the material showed a fair match in terms of quantification and localisation of damage. It was shown that after such a calibration procedure, AE monitoring can be autonomously used for the characterisation of damage and fractures at larger scales.

5. Conclusions

The AE technique has been found to be a very effective method for monitoring and detecting fracture and failure of materials. AE is an NDT method that allows acoustic energy emitted from material due to mechanical or physical change, to be detected without any energy input. It is a very efficient method for fatigue detection and for understanding the behaviors of fractures in wood, metals, concrete, ceramics, composites, fiberglass and plastics. AE and NDT were used to follow the fracture behavior of different types of materials. This showed the reliability of the techniques, which can be used in large structures. AE yields detailed information regarding the origin and development of flaws experienced by a component under stress or that is subjected to continuous or repetitive stress. The main distinction between other NDT methods and AE method of NDT is in their passive nature unlike the other NDT methods that mostly active. Lastly, AE method of NDT can help prevent repair- and damage-related costs as it detects faults at an early stage.

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