STUDIA UNIVERSITATIS BABEȘ-BOLYAI
Engineering 66(1) 2021 DOI:10.24193/subbeng.2021.1.4

Acoustic emission as a valuable technique used for monitoring polymer failures

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Abstract. *In the paper, acoustic emission (AE) system was presented as a method that can be used to monitor polymer material failures. Samples fabricated of two aluminum profiles bonded together with a thick layer of cured epoxy resin were subjected to fracture tests. Epidian 53 epoxy resin cured with Z1 curing agent as well as Epidian 5 epoxy resin cured with PAC curing agent were selected as adhesives. Acoustic emission parameters were acquired during Double Cantilever Beam (DCB) tests. The frequencies of elastic waves released during failure were then analyzed using both Fast Fourier Transformation (FFT) and Wavelet Transformation (WT) for the two materials.*

Keywords*: acoustic emission, DCB test, epoxy resin, wavelets, Wavelet Transformation*

1. Introduction

Polymers consisting of epoxy resins are nowadays widely used especially as a fiber reinforced polymer (FRP) composites' matrices but also as adhesives and coatings in many branches of contemporary engineering e.g. automotive industry, aerospace industry, marine industry and electronics. Besides their excellent chemical and corrosion resistance, high tolerance to different environmental conditions [1] and adhesive properties [2], epoxy resins are classified as brittle materials with low crack propagation resistance and weak fracture toughness [3]. Thus, it is important to examine the mechanical behavior of these materials as well as to detect failures that may occur just at their origin to prevent further damages.

Acoustic emission (AE) is described as a useful technique applied for health monitoring [4, 5] and failure detection [6–8]. The term "acoustic" seems to be a little bit misleading because human ear is not able to hear the frequencies which are referred to this technique, with a range of 100 kHz – 1 MHz [6]. This method let to classify material defects with relation to appropriate ranges of signal frequencies. The main AE advantage is that it gives the opportunity to indicate damage onset just while the propagation initiates [9, 10] whereas other traditional methods allow to notice material failures until as they are much more advanced. Most commonly occurring material defects can be correlated with specific frequencies of the elastic waves [5–8, 11–14]. However, the frequency ranges depend on the materials. In addition, various matrices can generate various AE signals while cracking [9] as well as ply geometry and orientation of fibers and matrices can also affect the emission [15]. Thus, it is crucial to deeply analyze the behavior of particular materials before AE can be successfully used for defect recognition and health monitoring.

Typical AE system consists of piezoelectric sensors, preamplifier, A/D card and a PC equipped with a dedicated software [6, 12]. Data registered by AE sensors are hits and counts in classical approach. Today, however the AE systems enable much more sophisticated analysis of the registered elastic waves: not only energy or amplitude of the signal can be derived, but also FFT and wavelet analyses [13, 15]. In order to make it possible to distinguish different types of damage processes based on signal analysis it is essential to categorize the collected signals into clusters. It can be obtained using K-means method [5, 16, 17] based on calculating Euclidean distances.

So far, many AE researches have been already conducted on matrix-fiber effect appearing in various material types. Different defects were classified such as matrix cracking, matrix-fiber debonding, delamination, fiber breakage or fiber pull out and assigned to AE frequencies [5–8, 11–14]. Moreover, some additional examinations were done on fibers separated from matrices to confirm the range of frequency for fiber breakage [13]. It was also proved by AE that higher number of hits was registered in case of samples without self-healing capability than in case of samples with self-healing capability which was caused by constantly matrix repairing [5]. Furthermore, the number of hits can be also correlated with the course of stress-strain curve [13] and in-plane shear modulus [15].

Based on the open literature the different ranges of frequencies of acoustic waves emitted during failure can be correlated with appropriate types of damages appeared inside testing materials. Following groups of AE frequencies were distinguished for CFRP composites: 0–50 kHz, 50–150 kHz, 200–300 kHz, 400–500 kHz and 500–600 kHz, which could be referred to matrix cracking, delamination, debonding and fiber failure or fiber pull out, respectively [14]; for GFRP composites: 140–250 kHz, 250–350 kHz and 350–450 kHz, which corresponded to matrix cracking, debonding and fiber breakages, respectively [11]; 0–150 kHz, 150–400 kHz and 400–550 kHz, which could be attributed to matrix cracking, interface failures and fiber breakage, respectively [5]; 60–150 kHz, 200–300 kHz and 400–500 kHz, which were associated with matrix cracking, delamination and fiber cracking, respectively [6]; 63.1 kHz, 129.5 kHz and 213.3 kHz, which were connected to matrix cracking (without fiber bridging or fiber pull out), delamination (with fiber pull out) and fiber breakage, respectively [12]; for hybrid CFRP/GFRP composites: 50–160 kHz, 150–300 kHz, 300–400 kHz and 400–600 kHz, which corresponded to matrix cracking, interface failure, fiber pull out and fiber breakage, respectively [13]. As it can be noticed, for each material the failure classification looks similar referring to raising frequency. The lowest frequencies corresponded to intra-ply cracking, whereas the highest ones were reserved for fiber breakages and fiber bridging. Furthermore, medium frequencies were related to interlaminar cleavage. However, frequency ranges might vary in each case depending on different types of composites and specimens preparation, also among the same type e.g. GFRPs. Moreover, different types of damages occurring inside breaking specimens could be referred to different ranges of elastic waves amplitudes. As described in [7] following ranges were distinguished: 40–50 dB, 45–60 dB, 65–80 dB, which corresponded to matrix micro-cracking, fiber/matrix debonding and fiber pull out, respectively. Hence, it can be inferred that raising amplitudes corresponded to material failures in a similar way that they corresponded to raising frequencies.

Analysis of acoustic emission waveforms is based on applying signal analysis tools such as Fast Fourier Transformation (FFT) and Wavelet Transformation (WT). Acoustic emission systems are equipped with a specialized frequency analysis computer software which helps to interpret the results using both FFT and WT, providing particular information on acoustic wave propagation, as well as damage mechanisms and their origin. However, it is worth to notice that WT has some advantages over FFT. The most important of them is that this method of analysis let to obtain more accurate results as it is localized not only in frequency as FFT, but also in time. Hence, additional information is given on when in time a specific frequency occurs [18, 19], which makes WT a valuable mathematical tool helping to deeply examine signal structure [20]. Because of that, WT can help with analyzing complicated issues that are unable to resolve using FFT only [16].

Signals are represented in WT as a linear combination of wavelets [18] which have limited duration and are located where concerned [21]. While FFT bases on wave analysis, WT focuses on wavelet which is explained as a “small wave”, having its energy focused in time [17]. Thus, it gives the ability to conduct simultaneous time and frequency analysis using appropriate mathematical solutions. One of the most significant wavelets property is that they are smooth which means that they are the best basis for representing signals consisting of freely many singularities. This means that function of n derivatives can be represented by a wavelet that is n times continuously differentiable. In case when not enough information is given about a signal, using wavelets is a good choice for classifying different varieties of functions because wavelets have the unconditional basis property, described additionally as a near-optimal property. Likewise, nonlinear thresholding and coefficient vector truncation are both optimal in case of signal recovery, statistical estimation and data compression. Moreover, WT is computationally less expensive than FFT and can be easily adopted to inhomogeneous functions [17].

Generally, WT is a transformation similar to FFT because both of them are based on the operation of multiplying the signal function $f(t)$ by transformation kernel. The difference is that FFT uses periodic sine and cosine functions representing defined frequency whereas WT’s transformation kernel bases on wavelets. The using of WT requires that only one elementary wavelet is applied, defined as a mother wavelet. In order to decompose the signal, mother wavelet copies are used. They come into being due to mother wavelet scaling and relocating, according to formula (1) where *t* is time or space coordinate and *b* is mother wavelet relocation in time or space domain. Thus, Continuous Wavelet Transformation can be calculated as the integral of signal function multiplied by wavelet function, using the formula (2) which may be also expressed as (3). Function $\overline{\psi_{a,b}}$ is defined as a complex wavelet function coupled to $\psi_{a,b}$ [22].

$$\psi_{a,b} = \frac{1}{\sqrt{|a|}} \psi\left(\frac{t-b}{a}\right) \tag{1}$$

$$W_{f(a,b)} = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} f(t) \cdot \overline{\psi\left(\frac{t-b}{a}\right)} dt = \left\langle f(t), \psi_{a,b} \right\rangle \tag{2}$$

$$\left\langle f, \psi_{a,b} \right\rangle = \int_{t \in R} f(t) \cdot \overline{\psi_{a,b}}\, dt \tag{3}$$

After substitution $a = \frac{1}{2^j}$ and $b = \frac{k}{2^j}$, k, j ϵ C to formula (1) a new wavelet family is created which is a basis of Discrete Wavelet Transformation expressed by formula (4).

$$W_{f(j,k)} = 2^{j/2} \int_{-\infty}^{+\infty} f(t) \cdot \overline{\psi(2^j t - k)}\, dt = \left\langle f(t), \psi_{j,k} \right\rangle \tag{4}$$

Furthermore, it should be emphasized that the same signal can be interpreted in a different way depending on the basis wavelet that has been chosen. Hence, selecting the appropriate basis wavelet plays an important role in whole analysis process. Different wavelets can be used as a basis for computation, including Haar wavelet, Morlet wavelet, Meyer wavelet, Mexican Hat wavelet [21].

Application areas of WT include: harmonic analysis; numerical solutions; mathematical problems; signal processing e.g. medical, biomedical, seismic, geophysical; image processing e.g. medical, biomedical; fractals and chaotic systems; radaring; automatic target recognition [16, 17]. Moreover, since middle 90s it has been also applied for cutting the noise from audio files [23].

2. Methods and materials

In the paper AE was used to monitor polymer failures during Double Cantilever Beam (DCB) test, which was conducted in accordance with ASTM D5528-13 Standard. DCB is a mode I fracture test [24]. In this case, failure is caused due to a load attached in perpendicular direction to a specimen surface [25]. The schematic view of a specimen with dimensions indicated is shown in Fig. 1.

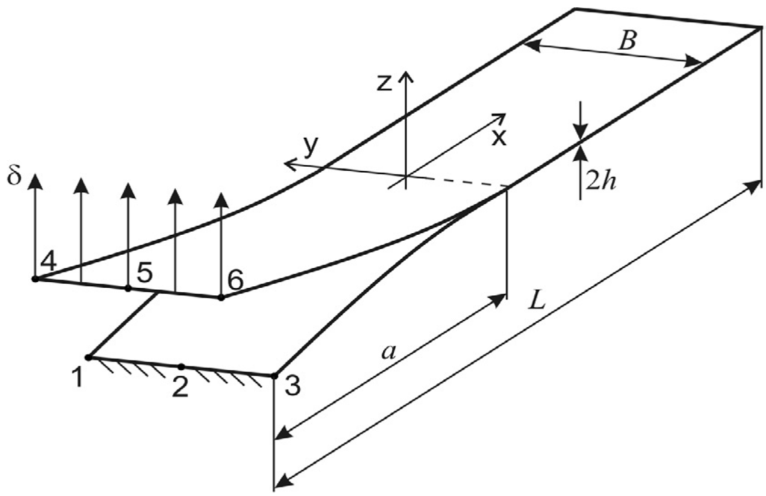

Figure 1. Schematic view of DCB specimen [25].

Samples with following dimensions (according to Fig. 1) were used: length L = 210 mm, pre-crack length a = 65 mm, width B = 25 mm, thickness 2h = 8 mm. Specimens were fabricated of two aluminum profiles thick on 2 mm and a polymer layer thick on 4 mm. Polymer layer was made of cured epoxy resin, wherein two kinds of epoxy resins as well as two kinds of curing agents were used to produce the specimens at ambient conditions by bending the appropriate amounts of the ingredients. Materials' details are given in Table 1.

Table 1. Cured epoxy resins prepared for testing

Material symbol	Material designation	Epoxy resin	Curing agent	The amount of curing agent added expressed as a % of a total weight of resin
I	E53/Z1/100:10	Epidian 53	Z1	10
II	E5/PAC/100:60	Epidian 5	PAC	60

In order to prepare DCB samples a silicone form was used with recesses 210 mm x 25 mm x 8 mm. To obtain the appropriate length and thickness of cured epoxies, rectangular aluminum pieces thick on 4mm were used to set a distance between profiles, as shown in Fig 2. After curing and 3-day acclimatization the pieces were removed. Subsequently, notches deep on 20-30 mm were cut in the middle of polymer layer.

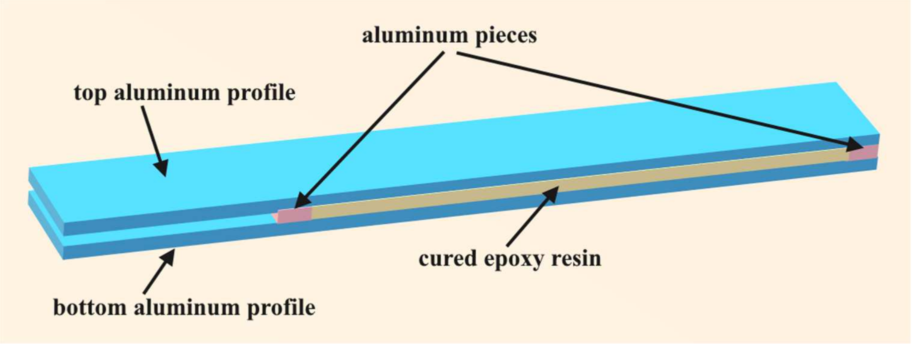

Figure 2. The model of DCB sample taken out of the form.

The samples were then subjected to DCB tests using the Autograph AGS-X 5kN universal testing machine. The photo presenting a loaded specimen is shown in Fig. 3.

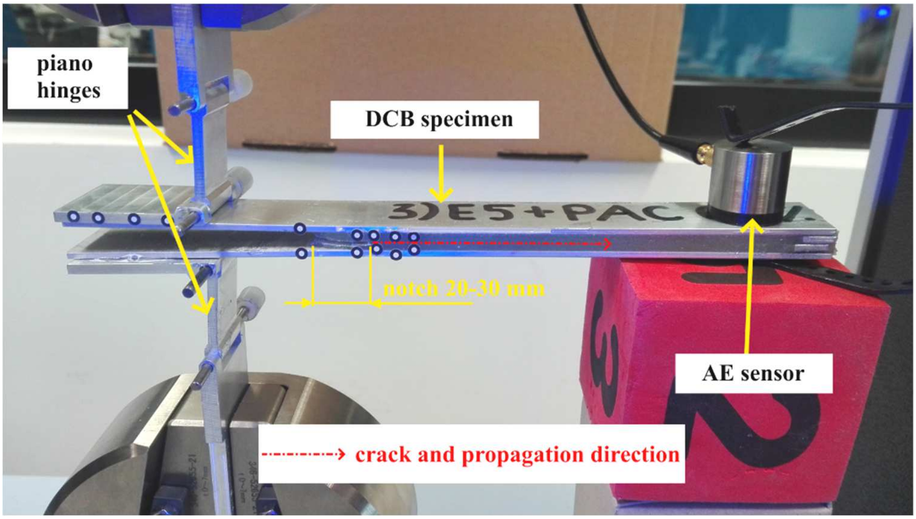

Figure 3. View of a loaded specimen during DCB test.

Firstly, piano hinges were bonded to each specimen. Secondly, DCB samples were loaded quasi-statically at vertical speed equal to 1 mm/min. During DCB test, acoustic emission system AMSY-5 was used to register acoustic emission parameters. AE sensor was placed in 30 mm distance from specimen's end. The acquired data was collected on computer's hard drive. Finally, dedicated software was applied to conduct the analysis.

3. Results and discussion

During DCB tests AE parameters such as frequencies (f_{AE}), hits, counts, amplitudes, as well as forces and corresponding energies were registered by AE system. In Fig. 4 mean values of frequency were plotted for the two tested specimen types. As it can be seen mean value of frequency was equal to 117.5 kHz and 45 kHz for material I and material II, respectively. Thus, the frequency for material II was over 60% lower than for material I. This proves that AE frequency registered during fracture depends on material type.

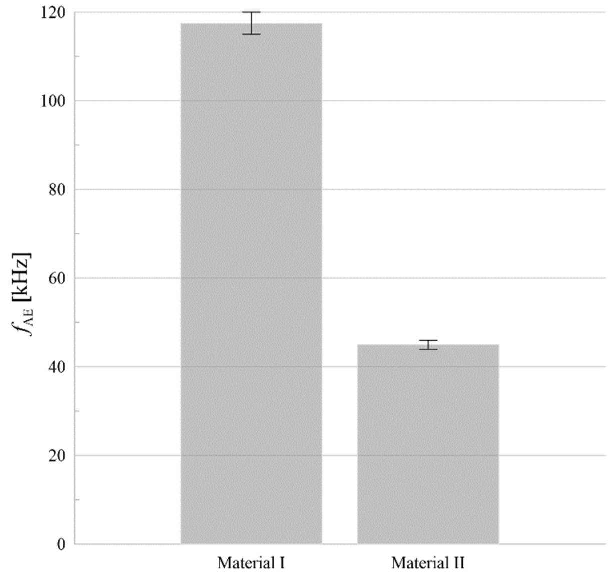

Figure 4. Mean values of acoustic emission frequency for the two tested materials.

Moreover, wavelet analysis tool was applied to determine the time range when AE frequency occurred. One specimen for material I and II was selected to prepare visualization based on wavelets, as presented in Fig. 5. This way of results presentation uses a contour diagram in which WT coefficients are indicated by color map.

As it can be noticed the measurement points with the highest intensity of WT coefficients may be simply localized in both frequency and time and peak frequencies obtained from FFT analysis correspond well with the results of WT. In Fig. 5a and 5c color map of WT coefficients is shown for material I and II, respectively. Furthermore, in Fig. 5b and 5d the respective FFT plots are given. In the case of both materials the mean value of frequency 117.5 kHz and 45 kHz is related with the highest intensity of WT coefficients presented in Fig. 5a and 5c and is localized in the time range of 55-60 μs and 30-35 μs, respectively. To summarize, emission of elastic waves was more intense in case of material I, because the higher AE frequency was registered as well as the signal duration was longer, over 80 μs and over 50 μs in case of material I and II, respectively. However, a time duration was relatively low in both cases.

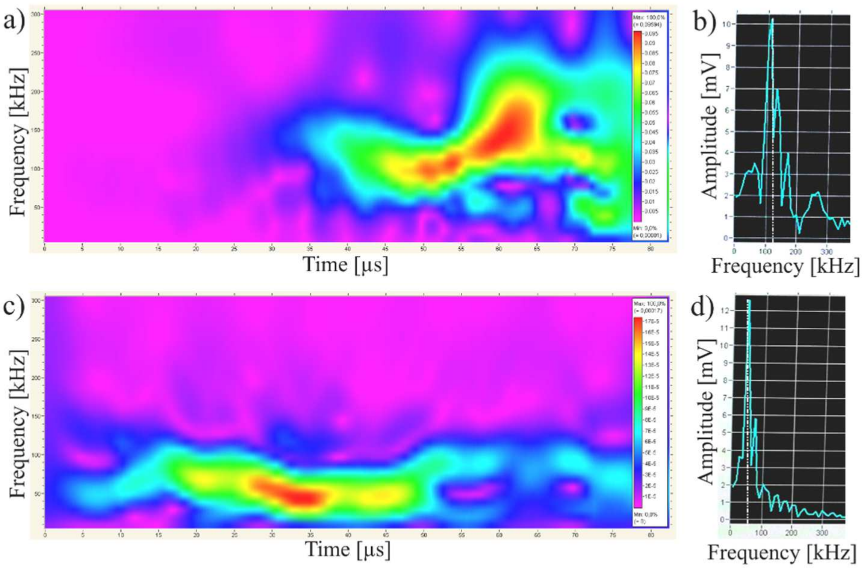

Figure 5. Contour maps of WT coefficients: a) material I; c) material II and respective FFT plots: b) material I; d) material II

For the purpose of this research the AE frequency was only analyzed although other AE parameters were also registered during the tests. It would be interesting to conduct deeper analysis of the problem with additional relation to number of hits, counts, acoustic energy, as well as force. This will be the objective of further research.

4. Conclusion

Based on the experimental analysis it can be concluded that:

1) It was proved that acoustic emission may be successfully used for monitoring failures in case of both selected materials: Epidian 53 epoxy resin cured with Z1 curing agent (marked as material I) as well as Epidian 5 epoxy resin cured with PAC curing agent (marked as material II).

2) According to the results mean values of AE frequency registered during failure for the two tested materials varied depending on material type.

3) DCB test can be applied not only to laminates and adhesively bonded parts but also to analyze the behavior of cracking appeared inside the thick adhesive layer.

4) Wavelet analysis is a promising tool which helps to examine AE signal in detail regarding time, frequency and WT coefficients.

Acknowledgment. This paper was financially supported by the Ministerial Research Project No. DEC-2016/21/B/ST8/03160 financed by the National Science Centre, Poland.

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