

Time-frequency analysis of acoustic emission signals generated by the Glass Fibre Reinforced Polymer Composites during the tensile test

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Abstract. Fibre reinforced polymer composites are currently dominating in the composite materials market. The lack of detailed knowledge about their properties and behaviour in various conditions of exposure under load significantly limits the broad possibilities of application of these materials. Occurring and accumulation of defects in material during the exploitation of the construction lead to the changes of its technical condition. The necessity to control the condition of the composite is therefore justified. For this purpose, non-destructive method of acoustic emission can be applied. This article presents an example of application of acoustic emission method based on time analysis and time-frequency analysis for the evaluation of the progress of the destructive processes and the level of degradation of glass fibre reinforced composite tapes that were subject to tensile testing.

1. Introduction

A composite is a material consisting of two or more different materials: they are purposefully combined and they can be separated with the use of mechanical methods, distributed in a controlled manner in order to provide them with optimal properties, having properties that are unique and better than individual components. A continuous component of a composite is called a base or a matrix. Fibres or grains (particles) are embedded in the matrix, and they are called in accordance with their application: filler, reinforcement or reinforcing bar (rebar) [1].

Dynamically developing technology and constantly increasing needs and requirements of the industry force the development of new materials that would cut the production costs and that would be simultaneously characterised by better physical and/or chemical properties than traditional materials. Thanks to the increasing level of knowledge about the relationships that occur between the production technology, chemical composition of the components used for the production, and the structure and properties of the finished products, numerous new alloys, plastics and ceramic materials have been developed over the last two decades [2], [3].

Searching for new materials, thanks to the desired properties achieved during their production, intended for specific industrial applications, has led to rapid development of research on the widely understood issue of materials engineering, namely composite materials. Moreover, the progress in the methods of non-destructive tests related to composites, both at the stage of prefabrication and the diagnostics of load-bearing structures, conduces dissemination of this material in applications in construction [4], [5].



Unique properties of polymer composites are appreciated by more and more recipients. The improvement of safety and economics of usage is the main motive of their increasing application in the industry. Many branches of industry are currently using the constantly widening family of composite materials, among these industries there are: construction industry, automotive, trail, aviation or arms industries [6], [7], [8].

Mechanical degradation of polymer composites, which is caused by prolonged permanent loads, is connected with the changes of the material structure that are local or that include the whole volume of the element's body. These changes are in the form of various types of discontinuity, including: debonding, matrix and fibres cracks and delamination [9], [10], [11].

For composites testing, a method of acoustic emission is useful. This method consists in recording elastic waves resulting from changes on micro- or macro-structural level of the material as a result of imposing external stimulus (load, the activity of external environment, etc.) in real time. AE method is a developing and widely applied diagnostic, non-destructive testing method (NDT) [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22].

2. Materials and methods

2.1. Materials

Glass fibre reinforced composite tapes with cross-sections of 12x3 mm were the subject of the test. Test was carried out with the use of Zwick-Roell testing machine located at Kielce University of Technology. Tensile speed was 0.2 mm/min. The test included determining the tensile strength, indicating percentage elongation at rupture and determining modulus of elasticity.

The samples of the tapes for testing were prepared through double-sided sticking of bevelled sections of aluminium flat with the use of epoxy glue (Figure 1).

For the acquisition of acoustic emission signals, Vallen AMSY-5 measuring apparatus was used. Two broadband sensors were used, and they were mounted with a clamp on the central part of the sample. A layer of resin was applied on the surface of the contact. The accuracy of the working of apparatus was checked before carrying out the proper measurement. In the vicinity of each sensor, signals for testing the efficiency of the sensors and the correctness of their mounting were initiated. The source of those signals was graphite that was being broken, its diameter was 0.5 mm and it was made by Pentel company. It was stated that each sensor recorded AE signals with the amplitude of about 98 dB.

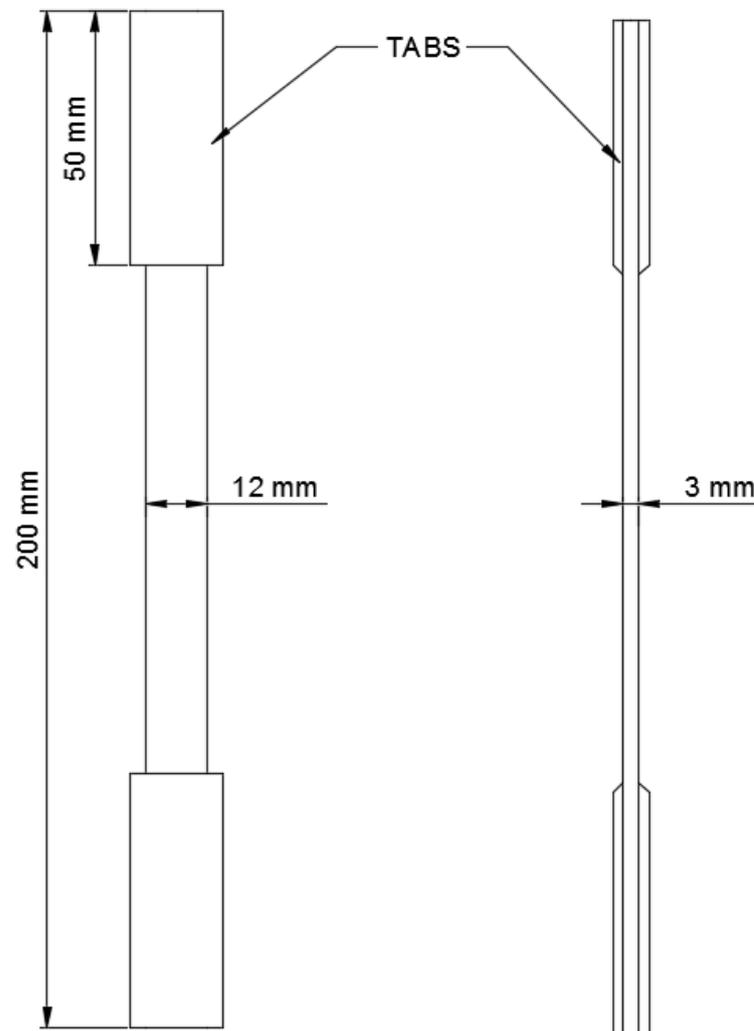


Figure 1. The sample of glass fibre tape for testing.

2.2. Time-frequency methods of vibration signals analysis

Programs analysing measurement data used by Vallen company are based mainly on waves analysis, using fast Fourier transform and wavelet (time-frequency) analysis. The basic technique of frequency analysis is Fourier transform. However, the disadvantage of this method is the lack of the possibility to determine the time of occurrence of effects caused by local non-stationarities of the signal. This inconvenience has been partially removed in Gabor transform, which is the modification of Fourier transform. On the other hand, the generalisation of Gabor transform is Short Time Fourier Transform (STFT), which is the following [23]:

$$S(b, f) = \int_{-\infty}^{+\infty} x(t) \cdot e^{-j2\pi ft} \cdot w(t - b) dt \quad (1)$$

In this transform, a localisation window $w(t-b)$, was implemented, in which b parameter replaces the window in time domain. The function of the window can be any function which meets specific conditions. This window, because of its permanent width, turned out to be not much effective in the analysis of signals that simultaneously consist of components of low and high frequencies. After implementing an additional scale parameter a to localisation window in Gabor transform, a continuous wavelet transform has been developed. An analysis function, $\Psi\left(\frac{t-b}{a}\right)$, called a main wavelet, has a scale factor a , which causes the change of duration of a wavelet and the moving factor b , which changes the position of the wavelet on time axis. The equation therefore represents a band-pass filtration of the signal with the use of filters of different passbands. Wavelet transform is the following dual function:

$$WT(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \cdot \Psi\left(\frac{t-b}{a}\right) dt, \quad a, b \in R, a \neq 0 \quad (2)$$

The basic advantage of wavelet transform is an optimal compromise in selecting resolution in the domain of frequency and time. The modulus of wavelet transform of the signal presents the changes of vibration energy in the time and frequency function.

Wavelet theory has been in the focus of attention of both mathematicians and engineers for several years, apart from time-frequency analysis, it has a wide application in the fields of, among others, speech analysis, images recognition and it improves the quality of recordings, etc [24], [25], [26], [27].

3. Results and discussions

Table 1 and Figure 2 present the results of the tensile testing of glass fibre reinforced composite tapes.

During the test, three stages of the deformation process were noticed:

- rupture of matrix
- delamination and dividing the fibres from the matrix
- rupture of fibres, causing the tape destruction

Table 1. The results of the tensile testing of tapes with glass fibre.

	Average coefficient of elasticity of tapes [GPa]	Average tensile strength [MPa]	Average elongation at rupture [%]
The result of the test	59	600	<1,5

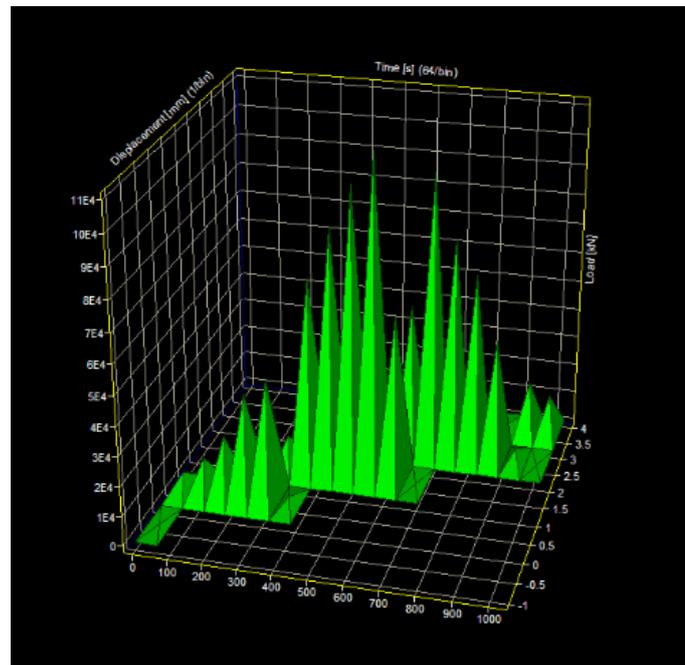


Figure 2. Dependency graph of force and displacement in time for the representative sample.

The evaluation of AE signals of the tested tapes was carried out in time-frequency domain, by determining two-dimensional spectrograms of spectral density. For the purpose of comparing the results, the spectrograms for one of the samples for two significantly different levels of count and absolute energy of the signals are presented. In this figure, the "a" symbol shows the results of the analysis of AE signals generated by the tape at the moment of time of 100 s, where the count is about 100 and the absolute energy of the signal is at the level of 2×10^5 eu. The "b" symbol shows the results of the analysis of AE signals generated by the tape at the moment of time of 910 s, where the count is 10703 and the absolute energy of the signal is at the level of $5,1 \times 10^9$ eu (Figure 3,4).

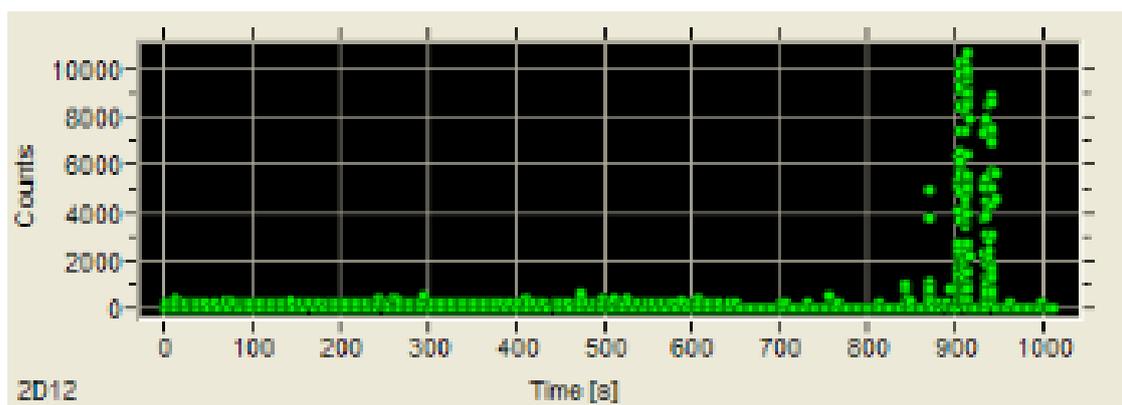


Figure 3. Dependency graph of count in time for representative sample.

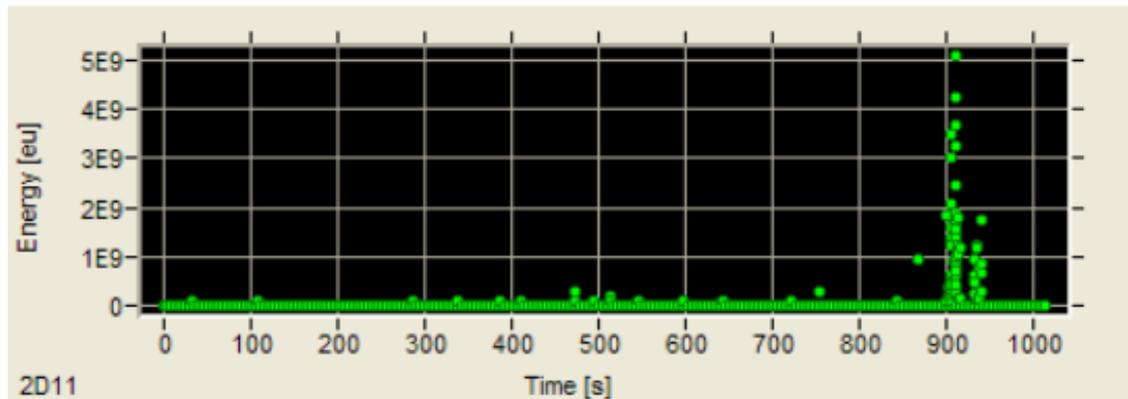


Figure 4. Dependency graph of absolute energy of the signals in time for representative sample.

On the two-dimensional spectrograms of spectral density, time-frequency structures occurring in the range of frequency: (5 - 250) kHz for both cases that were considered are visible. The range of frequency of the structure at the moment of time of 100 s decreases along with coming to the end of the considered time window, and the structures at the moment of time of 910 s reach the frequencies on the level of 150 kHz in the whole analysed run (Figure 5a, 5b).

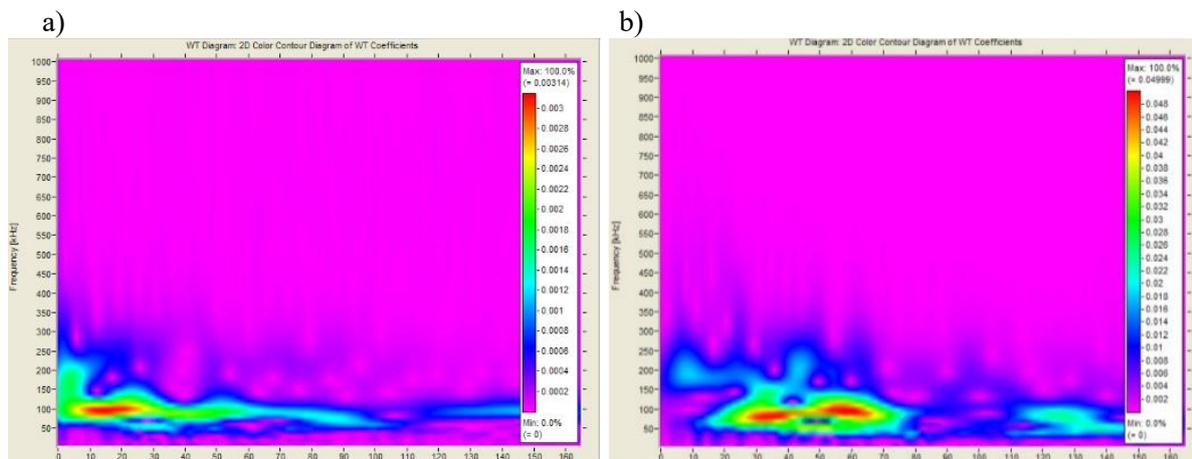


Figure 5. Two-dimensional spectrograms of spectral density of AE signals generated during the tensile test of a representative tape with glass fibre a) at the moment of time of 100 s b) at the moment of time of 910 s.

Frequency components between 75 kHz and 110 kHz for the moment of time of 100 s and 60 kHz to 125 kHz for the moment of time of 910 s have the highest values of amplitudes, whereby in the second case, two areas of occurrence of maximum values of the amplitudes can be distinguished. The analysis of the measurement results also proved that the signals corresponding to the activity of the elongated tape at the moment of time of 910 s have time-frequency structures of the highest amplitudes (Figure 5b). On the basis of the analysis of spectrograms determined for AE signals generated by the glass fibre tape at the moment of time of 910 s (Figure 5b), it was stated that explicit differences in their time-frequency structure occur. It was noticed that there was a substantial delamination of the acoustic structure of the analysed AE signal, as well as different distribution of particular frequency structures in time. Based on the analysis of the presented results, the signals generated by the tape at the moment of time of 100 s are attributed to the rupture of matrix, while the signals generated at the moment of time of 910 s are attributed to the rupture of the fibers. Analyzing the time-frequency structures, the power of AE

density spectra was significantly higher at the moment of time of 910 s. In further investigations, a precise analysis of the frequency of damage of a given type and attributed them to specific damages is planned.

4. Conclusions

During the conducted tests, the lack of plastic reaction of glass fibre reinforced composite tapes on the loads and sudden destruction of the material after passing boundary deformations were observed. Composite materials are characterized by the lack of plastic range of their reaction to loads – the condition before the break is not signaled, the break occurs unexpectedly, after the violation of boundary deformations. The process of destruction itself can only be seen in laboratory tests under scanning microscope, and this hinders or even makes it impossible to diagnose reinforced constructions that are active in real conditions. It is substantiated by the necessity to control the state of the composite material on account of determining the conditions of safe exploitation of the construction. For this purpose, non-destructive testing (NDT) methods can be used, and they allow to determine the condition of the material periodically or in a continuous manner in real time. On the basis of the results presented in the article it can be stated that with the application of modern methods of digital image processing in the domain of time and in the time-frequency domain, there is a possibility to use the acoustic emission method to evaluate the condition of glass fibre composite tapes.

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