Wavelet Analysis of Acoustic Emissions during Tensile Test of Carbon Fibre Reinforced Polymer Composites

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Abstract. The increase of the interest in polymer composites in technology and in people's everyday lives has been noticed in the recent years. Producing new materials with polymer matrix of particular properties that cannot be achieved by traditional construction materials contributed to high interest in fibre composite materials. However, a wider use of these materials is limited because of the lack of detailed knowledge about their properties and behaviour in various conditions of exposure under load. 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: deboning, matrix and fibers cracks and delamination. The article presents the example of the application of acoustic emission method based on the analysis of the waves through the use of wavelet analysis for the evaluation of the progress of the destructive processes and the level of the degradation of composite tapes that were subject to tensile testing.

1. Introduction
The notion of "composite" means the material produced in an artificial way, consisting of two or more phases, creating a material heterogeneous structure. The composite can consist of any materials (metals, ceramic, glass, etc.). Thanks to the appropriate combinations of composite components, a composite material is obtained, and it has the required properties and parameters that individually - in the case of a single material - could not be obtained (or obtaining them would not give measurable benefits). It can be indicated that such a strong emphasis put on the development of composites depends on two main factors - the first one of them is mainly the low weight of the structure. Excellent mechanical and strength properties of the produced structure are the second factor: high tensile strength values, shock resistance, energy dissipation, fire resistance or rigidity of the structure [1-3]. The properties of composites are determined by their structure, which is defined by the proportion, shape, measurements and spatial distribution of particular components. As in the majority of materials in technical meaning, except from the above mentioned factors, the properties of composites are influenced by the quantity, measurements and the distribution of technological defects, as well as by the defects that occurred during exploitation. At the stage of obtaining the composites, the defects that mainly appear are blisters, gaps formation, delamination, as well as the damages of the fibers. These defects can occur, among others, as the result of different thermal expansion of the components and their different contraction during the process of producing the composites [4,5]. During the exploitation, the composites are affected by heavy stress and specific environment of particular humidity, chemical (acid rain) and physical (ultraviolet light) aggressivity. In these...
conditions, the structure of the composites may change because of nucleation, the development of and accumulation of the damages that are forming, and the intensity of these processes is generally high in polymer composites [6-8].

Occurring and accumulation of defects in material during the exploitation of the construction lead to the changes of its technical condition. At the same time, attention should be paid to the fact that the "local" individual damage does not always result in the destruction of the whole element. 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, the methods of non-destructive testing (NDT) can be used, and they allow to determine the state of the material in a periodic or continuous manner in real time [9,10]. NDT methods have been used for many years with respect to constructions made of metallic materials. The significance of non-destructive tests is currently increasing because of wider use of these materials in constructions connected with structural engineering (bridges and flyovers), as they must meet the highest safety standards.

The method of acoustic emission is useful in the case of composite testing. It is characterized by a high level of detection and it can be used as a method controlling the state of the material's structure in real time. This method allows to detect and to follow the development of damages of both reinforcement and composite's matrix, including the condition of the boundary layer between its components. The characteristics of acoustic emission allow to evaluate the accumulation of damages and the intensity of their appearance [11-13].

2. Materials and methods

2.1. Materials

Tests were carried out on carbon composite tapes in rectangular shape measuring 200x10mm. Tensile testing 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 coefficient 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).

Figure 1. The sample of carbon fibre tape for testing

AE signals were recorded during the test with the use of two broadband sensors (Figure 2). The sensors were mounted with a clamp on the central part of the sample. A layer of resin was applied on the surface of the contact. AE measurement was carried out with the use of Vallen AMSY-5 measuring apparatus. 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. The amplitude of those signals was about 98 dB.

![Figure 2. Mounting the sample in a machine together with AE sensors.](image)

2.2. Methods
Programs analysing measurement data used by Vallen company are based mainly on waves analysis, using fast Fourier transform and wavelet analysis.

In diagnostic applications, the most common method of analysis of signals is time-frequency analysis based on Fourier transform. However, it does not provide the possibility to localize short-time changes in a signal, i.e. to localize the signals coming from transient processes. Implementing to Fourier transform a localization window defined as $w(t - b)$, where $b$ determines the replacement (localization) of the window in time, short-time Fourier transform was defined:

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

which is a generalized form of the Gabor Transform. Implementing a localization window largely increased the quality of the results obtained in localization of the transient signals in reference to the traditional Fourier transform. However, the main restriction of short-time Fourier transform is a permanent width of the window, it hinders the analysis of signals consisting of constituents that considerably differ in frequency. The next stage of signal analysis method development was extending the attribute of localization window to scale parameter $a$, an analysis function was defined as: $\Psi\left(\frac{t-b}{a}\right)$. Function $\Psi(t)$ can be basically any function described in the range in which it takes on the values different from zero. It allows to select the analysis function in such a way that it will reproduce the sought-after transient process in the best manner. Based on the above mentioned function called parent, basis or main function (wavelet), a two-dimensional function was defined, known as continuous wavelet transform [14,15]:

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**Figure 2.** Mounting the sample in a machine together with AE sensors.
\[ WT(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \cdot \Psi \left( \frac{t-b}{a} \right) dt, \ a, b \in R, a \neq 0 \quad (2) \]

where:
- \( x(t) \) – analysed signal
- \( a \) – parameter determining frequency (scale)
- \( b \) – parameter determining time (translational value)

By changing the \( a \) parameter, the change of duration of the wavelet is achieved, i.e. its frequency changes, and by changing the \( b \) parameter, its location within the time domain can be changed. By using the variability of these parameters, they can be optimised in terms of the desired definition in the domain of time and frequency. In the recent years, together with the increase of interest in microprocessors technology, mainly in their computing power, there has been the increase in this method of signal analysis. It is justified by works published by people working in different fields of science, from medical science, through astrophysics, to clearly engineering applications [16,17].

3. Results and discussions

It results from the data shown in table 1 that the tensile strengths of CFRP tapes and the values of their coefficients of elasticity correspond to the nominal data. During the tensile testing, carbon fibre tapes did not exhibit the phase of plastic activity. During the increase of the load, particular carbon fibers started to rupture and split off - until the moment of violent break of the whole tape, which was accompanied by characteristic splitting of carbon fibers bundle (Figure 3,4).

| Table 1. The results of the tensile testing of carbon fiber tapes. |
|---------------------------------------------------------------|
| Average coefficient of elasticity of tapes [GPa] | Average tensile strength [MPa] | Average elongation at rupture [%] |
| **The result of the test** | 200 | 2550 | >1,5 |
| **Nominal values** | 170 | 2600 | >1,5 |

Figure 3. The view of destroyed sample
The evaluation of AE signals of the tested tapes was carried out in time-frequency domain, by determining three-dimensional spectrograms of spectral density. In these figures, 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 absolute energy of the signal is at the level of $2.76 \times 10^5$ eu (energy units), and the "b" symbol at the moment of time of 990 s, where the absolute energy of the signal is at the level of $3.15 \times 10^{10}$ eu (Figure 5).

Figure 6 shows spectrograms of spectral density of AE signals generated by the carbon tape. On these spectrograms of spectral density, time-frequency structures differing in dominant frequency bands can be seen. On figure 6a, the dominant frequency band is included in the range of 50 - 150 kHz, and on figure 6b, in the range of 50-350 kHz. The highest amplitude is in the case of the structures that occur at the beginning of the analyzed run in the case of 6a, and at the beginning of and at the center of the time span in the case of 6b. Frequency components between 75 kHz and 125 kHz for the moment of time of 100 s have the highest values of amplitudes. For the moment of time of 990 s, three main ranges of frequency components of high amplitudes can be distinguished. All of them are between 75 kHz and 100 kHz. 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 990 s have
time-frequency structures of the highest amplitudes (Figure 6b). On the basis of spectrograms
analysis, determined for AE signals generated by the tape at the moment of time of 990 s (Figure 6b),
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 analyzed AE signal, as well as different
distribution of particular frequency structures in time.

4. Conclusions
It results from the conducted research that the deformations of CFRP tapes are linear and elastic, until
their brittle breaking in a violent manner. In contrast to the steel, composite materials are characterized
by the lack of plastic range of their reaction to loads - the condition before the break is not signalled,
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.
Therefore, it is such a significant problem to find an NDT method which would allow to detect,
localize and follow the destructive processes that occur in composite constructions that are used. Such
a method is the acoustic emission method. On the basis of the results presented in the article, it can be
stated that with the application of modern methods of digital signal processing in the domain of time
and in the time-frequency domain, there is a possibility to use AE method to evaluate the condition
of carbon fibre composite tapes. An appropriate interpretation of the signals of acoustic emission
allows to identify the current state of the material in real time.

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