# Acoustic Emission Monitoring of the Destruction Process of Carbon Fiber Reinforced Plastic Samples in Different Temperature Ranges

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**Abstract.** The paper provides the results of a study of the destruction process of carbon fiber reinforced plastic samples under simultaneous impact of static loads and positive or negative temperatures using acoustic emission (AE). Samples of *T*800 CFRP with dimensions 100 × 600 × 0.9 mm and a lamination pattern of nine monolayers at [±45/90/$0_3$/90/±45] were statically loaded. Heating or cooling was applied in the central region, where a stress concentrator as an opening with a diameter of 12 mm was provided. The destruction process was monitored with a certified digital acoustic emission diagnostic system DADS-16.10 with variable selection thresholds. The real time location of the sources of AE signal allowed monitoring sample destruction in the conditions of limited visual access. The main information bearing parameters of the AE signals (amplitude, dominant frequency and structural coefficient) were analyzed from their load dependences. The registered AE signals were evaluated using wavelet transformations, which also provided the structural coefficient. It was found that, at temperatures −20 °C and +20 °C, an increase in loading resulted in the most pronounced variations in AE signal parameters. A pre-destruction state of the material was revealed by characteristic points on the load dependences of the information bearing parameters. The developed monitoring technique may be used for AE diagnostics of composite structures operated at positive and negative temperatures.

**Keywords:** Carbon fiber reinforced plastic samples · Static loads · Positive or negative temperatures

## 1 Introduction

The current production quality of composite materials (CM) based on carbon fiber reinforced plastic (CFRP) makes them an attractive option for application in the transport sector [1–8]. Current composite materials are not inferior in terms of their strength properties to their metal counterparts, while having high rigidity, low density, corrosion resistance, durability, and high fatigue strength. This makes them suitable for manufacturing critical elements, including structural ones [1]. However, operation of


Z. Popovic et al. (Eds.): TransSiberia 2019, AISC 1115, pp. 877–884, 2020.
https://doi.org/10.1007/978-3-030-37916-2_86

transport units leads to a gradual deterioration of their mechanical properties due to external factors (shock loads, overloads, humidity, temperature).

Thermal and mechanical stresses experienced by a composite structure result in accumulation of deformations and are associated with an increased risk of fatigue cracks [7]. With time, the fatigue damage builds up in CFRP, compromising their strength properties, service life and rigidity [8, 9]. Such damage may result in a destruction of the composite structure caused by matrix cracking, broken reinforcing fibers, and delamination. Therefore, the problem of an early detection of CM item destruction requires solution and calls for modern methods and means of diagnostics [1].

A major step in developing a technology for manufacturing various CM elements is designing the methods for non-destructive examination (NDE) of their quality. Every CM destruction is accompanied by acoustic signals emission. Therefore, acoustic emission (AE) is widely used for continuous monitoring of CFRP structures in the process of loading. It is capable of localizing defects in real time, does not require scanning the surface of the monitored object, is highly sensitive and efficient for monitoring early stages of defect development in CM.

A drawback of this method is that it picks up noise during loading. The noise affects the accuracy of results and contributes to the scattering of the points of AE signal location. A frequency filtration performed at the level of electronic circuitry cannot remove the noise and interference [9, 10]. This problem has to be solved to improve reliability of information obtained from the AE measurements.

The purpose of this paper is to adopt AE for monitoring the destruction process of CFRP samples under simultaneous impact of static loads and positive or negative temperatures.

## 2 Research Methods

Static tests of samples made of T800 CFRP were performed at temperatures T1 = −60 °C, T2 = −20 °C, T3 = +20 °C, T4 = +100 °C; the samples had dimensions 100 × 600 × 0.9 mm and a lamination pattern of nine monolayers at [±45/90/03/90/±45]. The positive or negative temperatures affected the central region of the samples, where a stress concentrator as an opening with a diameter of 12 mm was provided. To maintain a positive temperature during loading, a heater was used, while a chamber supplied with liquid nitrogen was employed for cooling the samples. Sample temperatures were measured with a chromel-alumel thermocouple fastened to the sample surface and connected to a TRM-10 controller, which maintained the temperature within (1–1.5) °C of the preset value.

The static tensile load was applied to the samples using an MTS-100 loading machine equipped with hydrogrips. At each temperature, two samples were loaded to destruction. The AE signals were registered with a rectangular piezoprobe located outside the zone of thermal impact and consisting of four acoustic emission transducers (AET) type PK 01-07 with a bandwidth of (100–700) kHz. The AE data were processed with a certified digital acoustic emission diagnostic system DADS-16.10 with floating selection thresholds (Certificate RU.C.27.007.A No. 40707, State Register of Measuring Equipment registration number 45154-10).

Analysis of transient signals emitted upon deformation and destruction of solids requires a method of decomposing the AE signals with respect to both frequency and time. A frequency decomposition reveals the low frequency component, while decomposition with respect to time provides the high frequency components. This problem was solved using wavelet transformations.

Structural coefficients reflecting changes in the ratio of energies in the spectrum of AE signals were calculated. This corresponded to the process of position shifting of the time-frequency energy maximum, which was a sign of changes in the type of sample failure [8].

The structural coefficient of the AE signal was calculated as:

$$P_{Dij}(f) = \frac{\max D_i}{\max D_j}, \tag{1}$$

where $D_i$, $D_j$ are sets of coefficients of wavelet decomposition of the $i$-th and $j$-th level of refinement, obtained for incoming signal sampling rate $f$ = 2 MHz.

## 3 Research Results

The AE data were registered in the course of static loading of CFRP samples with simultaneous application of positive or negative temperatures. The AE signals were located in real time, which allowed observation of the process of failure propagation upon increasing static load (Fig. 1).

For samples cooled down to −60 °C, active sources of the AE signals were observed near the opening, as well as in the lower part (Fig. 1, a), where the destruction occurred. For samples tested at −20 °C, the highest activity of the AE signals was observed near the opening (Fig. 1, b). A load increase up to P = 60 kN and beyond resulted in the destruction propagation into the upper part of the sample.

During sample loading at positive temperatures, it was found that the main source of the AE signal emission was the opening with a diameter of 12 mm at the center of the sample, where the onset of destruction occurred (Fig. 1, c–d). Raising temperature to +100 °C and increasing load resulted in delamination of the sample monolayers. This was caused by matrix transition into rubber-like state [8].

Location helped select for analysis of the main information bearing parameters (amplitude, dominant frequency and structural coefficient) only those AE signals, which were characteristic of the destruction process of the sample material. Load dependences of each of the parameters were considered in the range of 20 kN to 70 kN (Figs. 2, 3 and 4). This range corresponded to sample destruction from its onset to pre-destruction state or destruction.

It was demonstrated that at different temperatures the changes in the load dependences of the main information bearing parameters of the AE signals had their specific features. At the maximum and minimum temperatures, the AE signal amplitude did not exceed 700 mV. A load increase resulted in its change by $\Delta U$ = 350 mV (Fig. 2, a).

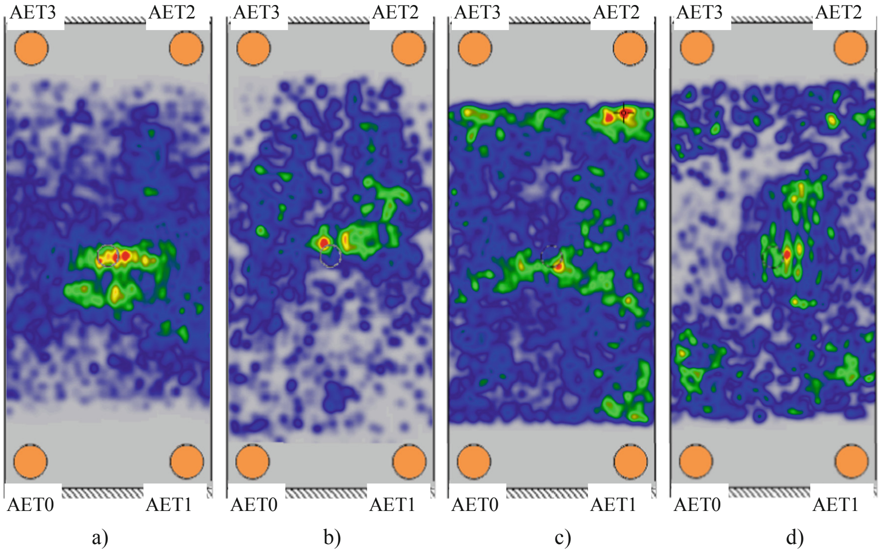


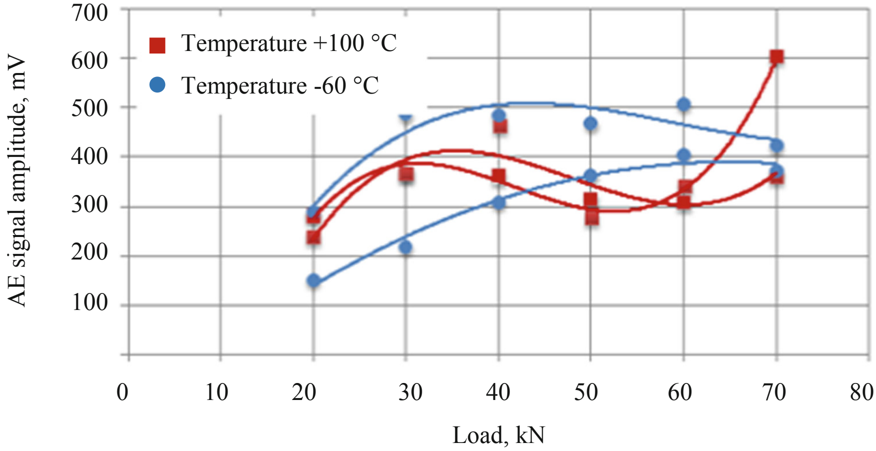

**Fig. 1.** Location of the AE signals upon sample loading at temperatures $T_1$ = −60 °C (a); $T_2$ = −20 °C (b); $T_3$ = +20 °C (c); $T_4$ = +100 °C (d).

At temperatures $T_2$ = −20 °C and $T_3$ = +20 °C, a more significant amplitude increase by 3,500 mV was observed (Fig. 2, b), while at loads of (50–60) kN, the maximum values preceding sample destruction were observed.

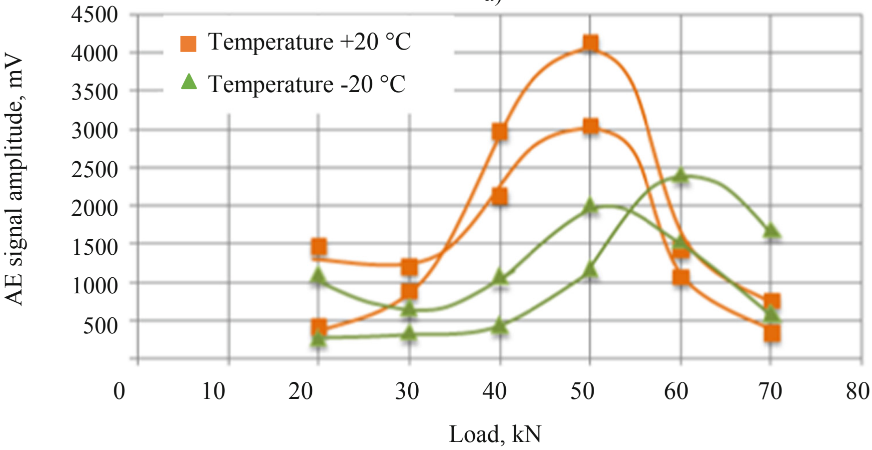
The analysis demonstrated a minor change in the dominant frequency by $\Delta f$ = (20–25) kHz from load at maximum and minimum temperatures. The frequency changed in the range of (215–240) kHz (Fig. 3, a). The load dependence of the dominant frequency for samples tested at temperature $T_3$ = +20 °C also remained virtually constant. However, one sample at a load of $P$ = 50 kN demonstrated a frequency drop down to $f$ = 185 kHz. The greatest frequency change of $\Delta f$ = 120 kHz was observed in the process of sample loading at temperature $T_2$ = −20 °C (Fig. 3, b). A load increase from 30 kN to 50 kN resulted in a frequency decrease from 210 kHz down to (140–160) kHz. Upon further loading, the dominant frequency changed by $\Delta f$ = (10–20) kHz.

The highest sensitivity to changes in the shape of the AE signals was exhibited by the structural coefficient determined from Eq. (1). When processing the AE data, the coefficients of wavelet decomposition of the second and third levels of refinement were chosen for evaluation. The coefficient D2 corresponded to the frequency band of the AE signal of (250–500) kHz, and the coefficient D3 corresponded to (125–250) kHz. The selected frequency bands were within the bandwidth of AET. Thus, the equation to calculate the structural coefficient was as follows:

$$P_{D32} = \frac{\max D_3}{\max D_2}. \qquad (2)$$




a)




b)

**Fig. 2.** Load dependence of the AE signal amplitudes at temperatures $T_1$ = −60 °C and $T_4$ = +100 °C (a); $T_2$ = −20 °C and $T_3$ = +20 °C (b)

As the structural coefficient increased, the AE signal energy shifted to the frequency band of (125–250) kHz, and upon its decrease, it moved to the frequency band of (250–500) kHz. Such changes were characteristic of the destruction process of samples of matrix or fiber [8].

For samples tested at temperature $T_1$ = −60 °C, a decrease in the structural coefficient upon increasing load was observed (Fig. 4, a). In contrast, at temperature $T_4$ = +100 °C, the coefficient increased, which corresponded to a shift of the AE signal energy to the region of lower frequencies. A similar variation of the structural coefficient at temperature +100 °C was observed for samples from *T*700 CFRP [8]. At this temperature, the matrix was in elastic state, and thus the main destruction mechanism was fiber breakage, which corresponded to an increase in the structural coefficient.

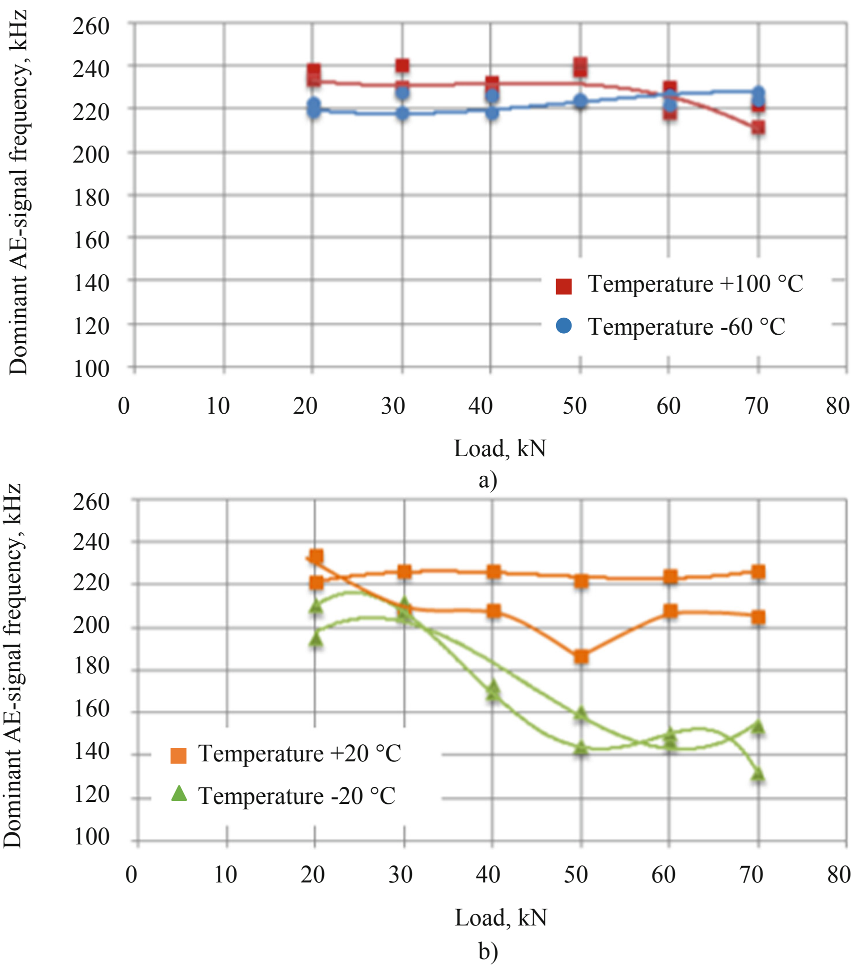
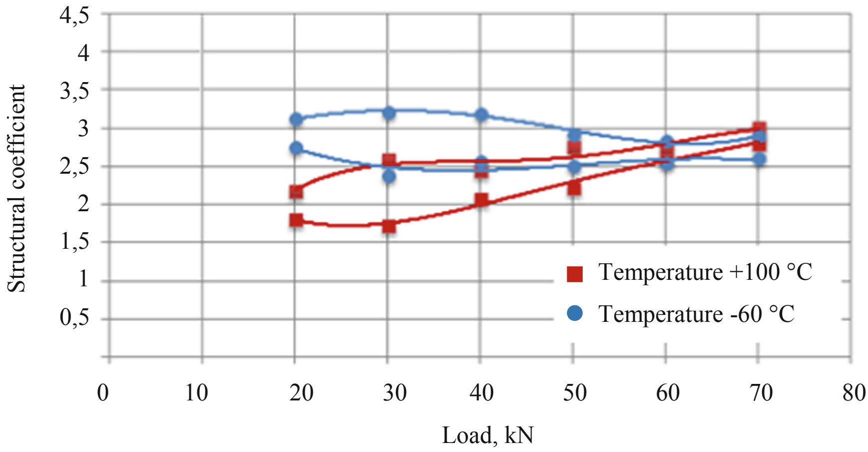
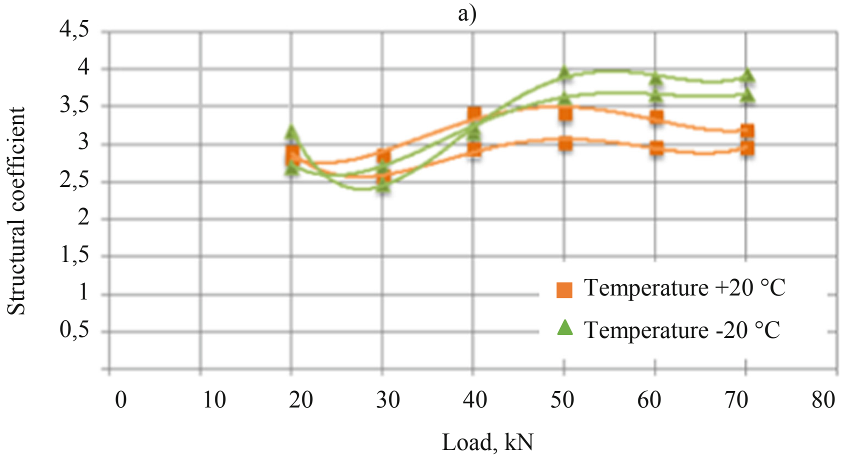



**Fig. 3.** Load dependence of the dominant frequency at temperatures $T_1 = -60$ °C and $T_4 = +100$ °C (a); $T_2 = -20$ °C and $T_3 = +20$ °C (b)

Sample loading at temperatures $T_2 = -20$ °C and $T_3 = +20$ °C was accompanied by an increase in the structural coefficient up to loads $P$ = (40–50) kN (Fig. 4, b). Afterwards, this parameter virtually did not change until the end of testing. These load values corresponded to the onset of active sample failure. A local minimum was observed at load $P$ = 30 kN.




a)




b)

**Fig. 4.** Load dependence of the structural coefficient at temperatures $T_1 = -60$ °C and $T_4 = +100$ °C (a); $T_2 = -20$ °C and $T_3 = +20$ °C (b).

## 4 Discussion

To approach the problem of an early detection of failures in the CFRP structures, samples were tested under simultaneous static loading and an impact of positive or negative temperatures. Load dependences of the main information bearing parameters of the AE signals (amplitude, dominant frequency, and structural coefficient) were obtained.

The paper provides the results demonstrating that the considered parameters are the most informative for the tests performed in the temperature range of −20 °C to +20 °C. Analysis of the load dependences of the main information bearing parameters of the AE signals demonstrated that the onset of active sample destruction is accompanied by an increase in amplitude and structural coefficient and a decrease in frequency. The obtained data may be used to develop algorithms for processing AE data registered during tests of composite structural elements both at positive and negative temperatures.

## References


1. Barsuk, V.E., Stepanova, L.N., Kabanov, S.I.: Acoustic emission monitoring of defects during static testing of a composite airplane structure. Control Diagn (4), 14–19 (2018). (In Russian)
2. Prosser, W.H., et al.: Structural Health Management for Future Aerospace Vehicles. NASA Technical Reports Server (2004)
3. Kanji, O., Antolino, G.: Research and applications of AE on advanced composites. Int. J. Psychophysiol. **30**, 180–229 (2012)
4. Aljets, D.: Acoustic emission source location in composite aircraft structures using modal analysis. Ph.D. thesis, University of Glamorgan, 163 p. (2011)
5. Cardoni, M., Giglio, M.: A low frequency lamb-waves based structural health monitoring of an aeronautical carbon fiber reinforced polymer composite. J. Acoust. Emiss. **32**, 1–20 (2014)
6. Sause Markus, G.R.: Acoustic emission signal propagation in damaged composite structures. J. Acoust. Emiss. **31**, 1–18 (2013)
7. Gorman, M.: Modal AE analysis of fracture and failure in composite materials, and quality and life of high composite pressure vessels. J. Acoust. Emiss. **29**, 1–28 (2011)
8. Stepanova, L.N., Chernova, V.V., Petrova, E.S., et al.: Acoustic-emission testing of failure in samples of CFRP exposed to static and heat loads. Russ. J. Nondestruct. Test. **54**(11), 748–756 (2018)
9. Stepanova, L.N., Ramazanov, I.S., Chernova, V.V.: A procedure for locating acoustic-emission signals during static testing of carbon composite samples. Russ. J. Nondestruct. Test. **51**(4), 227–235 (2015)
10. Oskouei, A.R., Ahmadi, M., Hajikhani, M.: Wavelet-based acoustic emission characterization of damage mechanism in composite materials under mode I delamination at different interfaces. Express Polym. Lett. **3**(12), 804–813 (2009)