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Monitoring of damage of the composite leaf spring using methods of acoustic emission

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Abstract. The paper presents the application of acoustic emission (AE) for the operational testing of the composite leaf springs. The method applied is characterized by a high sensitivity of detection and can be used as a way of monitoring the condition of structures in real time. The characteristics of the acoustic emission enable the evaluation of damage accumulation and intensity of their formation and propagation. The state of a composite structure of the leaf springs can be, perfect monitored using the acoustic emission. Any change in the stiffness of the leaf spring was accompanied by a change in density of the acoustic emission. There is a noticeable regularity between the degree of degradation of the structure of the leaf spring and the level of emissions. The increase in the rate of degradation was accompanied always by the increase in the level of acoustic emission. Immediately prior to the decrease of stiffness occurred the marked increase in the level of the AE. Knowing the characteristics of the AE for the leaf spring, the status of its structure can be assessed.

Introduction

Use of polymer composite materials for the construction of vehicle suspension elements is not only a simple replacement of steel with a different material. Composite materials allow any formation of transverse sections of elements being produced, at the same time affecting the stiffness of such elements. Thus, it is possible to construct suspensions with the prescribed characteristics as well as integrated elements of suspensions which work as springy and leading elements. Due to the above it has been possible to simplify the construction of vehicle suspension and to lower considerably its weight and costs of production. Moreover, a greater capacity of composite materials to accumulate springy energy may allow the use of smaller and simpler dampers. Numerous researchers [1,2,3] prove that springy elements constructed from composites materials in comparison with steel springs are characterized by higher fatigue durability, they are resistant to corrosion and they are many times lighter. A great advantage of composite materials is the way they get damaged under fatigue loading. Elements made of these materials, as opposed to steel elements, do not break or get damaged rapidly. This in turn increases considerably the safety of vehicle operation. The above mentioned properties of composite materials will decide about their wider application in the construction of vehicles, including also the construction of springy elements of suspensions. Increasing competition and innovation in automobile sector tends to modify the existing products by usage of the new and advanced materials – polymer composites.

During the operation the composite leaf springs are subject to heavy loads and the environment with high humidity, chemical and physical aggressiveness. Under these conditions, the composite structure may change due to a nucleation and growth and accumulation of damages [5]. The formation and accumulation of defects in the material during operation lead to changes in the technical state of construction. However, the "local" individual damages do not result in the destruction of the entire leaf spring. This justifies the need to monitor its state for safe operation. For this purpose you can use the method of non-destructive examination (non-destructive examination—NDE), which allows the examination of the material state periodically or continuously in real time [4,6].

Damage of the composite leaf springs, due to operation, may arise as a result of rupture of the boundary layer fiber-matrix (called debonding), matrix cracking, fiber breakage and delamination. The local damage (the order of several microns) do not cause significant deterioration of its performance characteristics. Damages occurring in the individual layers of the composite have greater impact on the condition of the leaf spring These can be individual layers transverse cracks, splits of roving bands, longitudinal and intra-layer cracks (local delamination) and breaking or shearing of roving bands [5]. These damages usually lead to destruction of the leaf spring. In order to study the composite leaf springs, it is possible to use the method of measuring the acoustic emission. It is characterized by high sensitivity of detection and can be used as a method of monitoring the condition of structures in real time. The characteristics of the acoustic emission enable the evaluation of damage accumulation, the intensity of their formation and propagation. In next part of article, the study of fatigue strength and AE will become proven.

AE is a result of disturbance over test. During knowledge resources [11], a sound source is being if under the influence of vibrations of sufficient energy to make the human reaction. For AE test this value is changed: in frequency domain to max. 10 MHz (in this cas to 1MHz) and in magnitude value (confine in discriminator). This disorder was first described by Isaac Newton, as rapid changes in pressure and vibration of air. This means that identical air density at each point in space is the same time is a silence. Changes in air density, causing changes in sound pressure, that is atmospheric pressure disturbances are called acoustic density [12]. In addition to atmospheric disturbances, the acoustic wave is accompanied by disorder temperature of the medium. A full description of the acoustic wave should contain all the parameters characterizing it (density acoustic, acoustic pressure, temperature, acoustic, acoustic deflection of particles, particle velocity of acoustic, acoustic particle acceleration). AE test uses accelerometers sensors, with high sensitivity and flat response (which is important for valuable tests) in the bandwidth of operation.

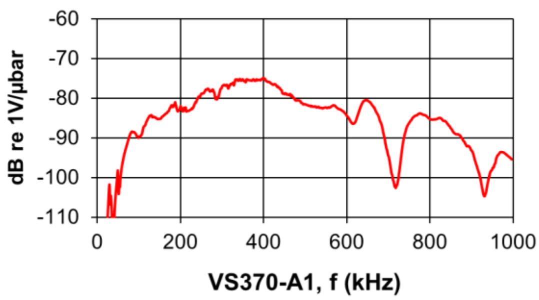


Fig. 1. The characteristic of AE sensor VS370-A1 [13]

Because it is complicated (Figure 1 presents example characteristic of single AE sensor) to obtain sensor with all mentioned necessary parameters, often in one measurement head are a few sensors, for different frequency range.

Piezoelectric sensors built from semiconductor have a large internal resistance. Therefore, it is necessary signal conditioning as possible to the sensor in order to avoid additional inductance and capacitance and thus increase the impedance of the entire measurement path. Conditioning is to join an operational amplifier integrator circuit with a capacitor in the feedback block [14].

In the case of piezoelectric materials working conditions (e.g. temperature) are very important. In this case pyroelectric effect is also very important (induction of surface load during temperature) [14].

The test program, test equipment

The term acoustic emission [AE] applies to both physical phenomena and methods of measurement. In the first case, the term AE is understood as generation of elastic waves in a given environment as a result of the local and dynamic release of elastic energy. EA method relies on the detection, analysis and measuring the emitted wave parameters, which can be sourced by motion of dislocation, phase transitions associated with changes in the microstructure of the material, formation and propagation of macro-and micro-cracks, breakage of fibers and matrix in composites. The metering of AE creates, therefore, the possibility of a direct linkage of the information contained in the AE signals with the cause of their excitation.

The correlation between the acoustic emission and degradation of the composite leaf spring structure undergoing fatigue testing on the testing stand was observed. The force bending leaf spring was measured and the acoustic emission was registered. Long-term fatigue tests on testing stand were carried out according to the author's method, which involved conducting tests for the four levels of load of the leaf spring. The loads were determined using the equation

$$P_K = k_z \cdot Q_i \tag{1}$$

where:

i = 1 or 2, K=1, 2, 3, 4,
Q_1 - static load of the leaf spring with vehicle mass and car cargo,
Q_2 - static load of the leaf spring with vehicle mass without cargo,
K_z - dynamic load coefficient.

Full characterization of the leaf spring fatigue loads are shown in Table 1.

Table 1. Characteristics of the leaf spring fatigue loads

	Level I $P_1=1.6Q_1$ [N]	Level II $P_2=1.3Q_1$ [N]	Level III $P_3=Q_1$ [N]	Level IV $P_4=Q_2$ [N]
$P_{max.}$	13000	10562.5	8125	6400
$P_{min.}$	6200	3762.5	1425	0
$P_{śr.}$	9600	7162.5	4775	3200
P_a	3400	3400	3350	3200

Each leaf spring was loaded with a single value of the force until its failure. The deflection of leaf spring was set before test, and maintained constant until destruction of the spring. With increase of the number of load cycles, decrease in the stiffness of leaf spring was observed; at constant deflection the decrease manifested itself by a decline of extorting force. Extortions were carried out in the sinusoidal cycle unilaterally positive. The amplitude of extortions was 0.085m, which represented 70% of the maximum of deflection. The study was conducted in the cycle of fixed-kinematic extortions whose frequency was 1.0 Hz. If the leaf spring has not been destroyed and reached 6 million cycles of fatigue, the test was stopped.

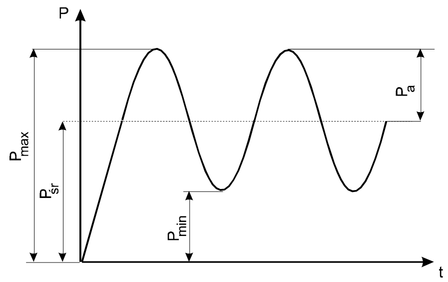


Fig. 2. The time course of fatigue loads of leaf spring

Schematic of the composite leaf springs testing stand is shown in Figure 3. The leaf spring tested - 1 was deformed cyclically by a hydraulic servomotor - 3. The servomotor stroke was established at the beginning of the testing. The leaf spring loading force was measured indirectly by the strain gauge system - 2 and the strain gauge bridge -7. The acoustic emission was measured using a head - 4. The measured values were stored in the recorder - 9, and hence transmitted to PC and collected in the data sets. The acoustic emission was measured at every 100 thousands of fatigue cycles. The average density of the emission for fifty consecutive cycles close to the assumed number of fatigue cycles was determined.

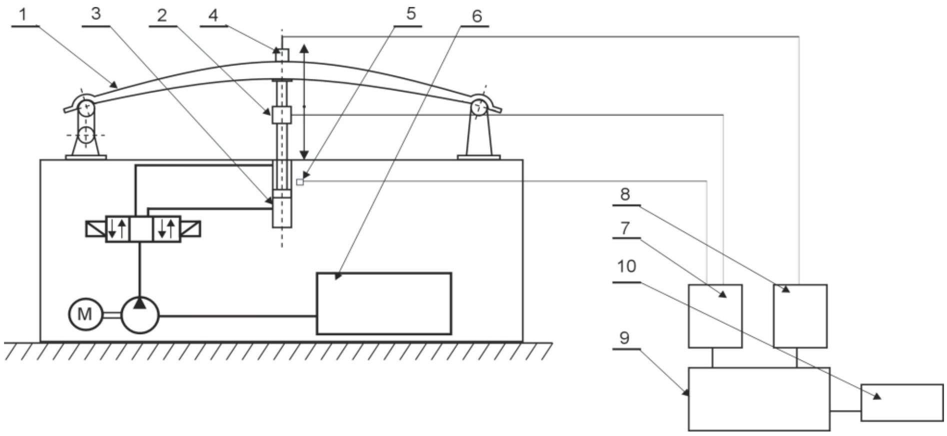


Fig.3. Scheme of the leaf spring fatigue test stand using AE:1-tested spring, 2- dynamometer, 3- hydraulic servomotor, 4-piezoelectric head for receiving signals AE, 5- position sensors, 6- hydraulic system, 7- tensometric bridge, 8- analyzer AE-3, 9- recorder, 10- computer PC

An electromechanical transducer (piezoelectric) was the receiver of the induced stress waves, which was fixed to the surface of the material being tested. The acoustic signals received by the transducer were converted into electrical impulses (discrete in time domain), which were then amplified and recorded by the AE analyzer (Fig. 4). AE is saved by system in digital form, thus – under digital signal processing (DSP).

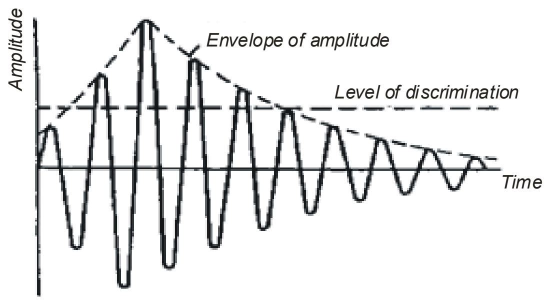


Fig. 4.The AE counts (elastic wave amplitudes above the level of discrimination) and the AE event (the wave envelope) received by the transducer [7]

Form of the recorded AE signal depends not only on its source of origin, but also on the type of converter that changes the elastic wave energy into an electric signal from the environment in which the signal propagates and the location and method of mounting the sensor. Taking as a criterion the method of attachment and signal transduction in the leaf spring testing, an acoustic emission sensor SEA (Schall-Emissions-Aufnehmer) was used that is characterized by low noise and which transmits frequencies within the band from 0 Hz to 1 MHz. The measuring apparatus, whose diagram is shown in Figure 5, can record many descriptors characterizing the source signal, allows their registration in real time and analyze the impulse shapes, their distribution and the frequency characteristics. Signal, after process of discrimination (which is made in comparator) is filtered by low – pass filter (0 – 1MHz) in next step signal is sampling and quantizing. In this case, according to Shannon – Kotielnikov – Whitaker – Niquist law [8 - 10], minimum sampling frequency is 2MHz.

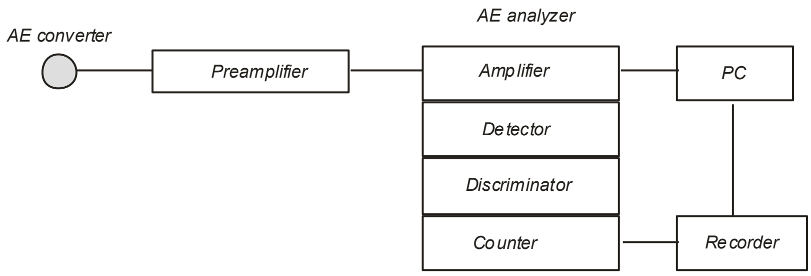


Fig. 5. Block diagram of the AE metering system

Analysis of changes in the structure of the test material on the basis of descriptors EA is difficult and requires a lot of preliminary tests in order to correctly choose the parameters of the measurement channel and properly interpret the results. In this study, it was decided, after the pilot tests, to apply the easiest measurable signals:

- count rate – the number of counts in a given time, and
- the sum of AE counts – the sum of amplitudes of the stress waves exceeding the established threshold of discrimination.

The rate of AE counts and energy of the emitted signals have proven to be the most sensitive indicators of the leaf spring structure destructive changes. These descriptors are associated with the amplitude and energy of the original signal, and thus indirectly determine the energy characteristics of the AE sources. This fact makes these parameters reflect well the changes in the structure of the material being tested.

During DSP operation is possible to pre-diagnosis (failures predict), not only for whole leaf spring, but also particular parts of system. Moreover it is possible to detect of failure, under one frequency test. In this case necessary is provide signal processing methodology.

The aim of all the signal digital processing operations performed during the investigations was to change the shape of the signal spectrum in a replicable way using standard methods. The first operation is signal windowing. In this case, windowing in the time domain since it is limited to the multiplication of the discrete vibration signal and the discrete window spectrum. Naturally, one could use a window in the frequency domain, but this would require the convolution of the two discrete signals.

A rectangular spectrum would have an ideal windowing sequence for damping uncharacteristic (from the investigation point of view) parts of the spectrum and simultaneously amplifying its characteristic parts. The ideal window would not distort the signal and prevent spectral leakage (an effect in which a part of the signal component, not situated by the frequencies for which the analysis is made, appears in all the output discrete signal values after transformation to the frequency domain [8, 9]). This case od processing is a base for comparison analysis – thus it must be done on proper working leaf and this value is the reference value.

Conclusions from the study of composite springs

The process of fatigue destruction of the leaf spring resulted due to the formation, near the neutral axis, of micro-cracks which connected with each other and gradually led to the formation of local macro-cracks. The continuation of destruction process proceeded similarly. Macro-cracks united and weaken the entire structure. As a result, the composite leaf spring underwent dissection near its neutral axis (Fig. 6). Then the weakening of the structure occurred which was expressed by the significant decrease in stiffness. The gustily running damage threatening the security have never been observed.

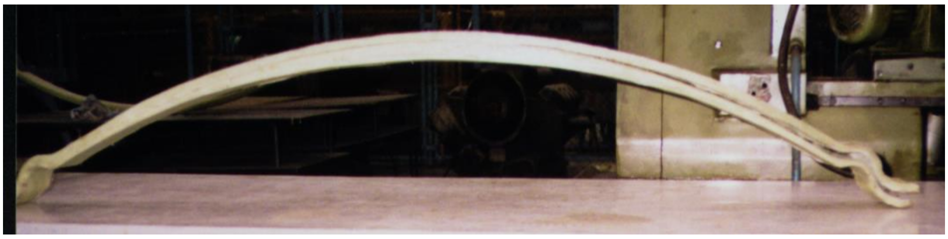


Fig.6. Example of damaged composite spring

In fatigue tests, the 18% decrease of bending force compared to its initial value was assumed as the criterion of leaf spring failure. Then the first micro- cracks of spring occurred. Thus, the leaf spring for which the bending force decreased by 18% compared to its initial value was regarded as damaged. It should be emphasized that the leaf spring was still able to carry the load reduced.

The leaf springs loaded with the bending force of about 60% greater than the allowable static load (13kN) became destroyed very quickly. In accordance with the accepted criterion, the failure occurred after 700 thousand fatigue cycles. Typical course of changes of the extorting force at the above load is shown in Figure 6. The fall of extorting force and thus the reduction of composite leaf spring stiffness were accompanied by an increase in the density of the acoustic emission. In the leaf spring, a rapid process of its structure degradation in the form of splitting of bands of roving, longitudinal and intra-layer cracks, occurred. This process was accompanied by a gradual increase of the acoustic emission.

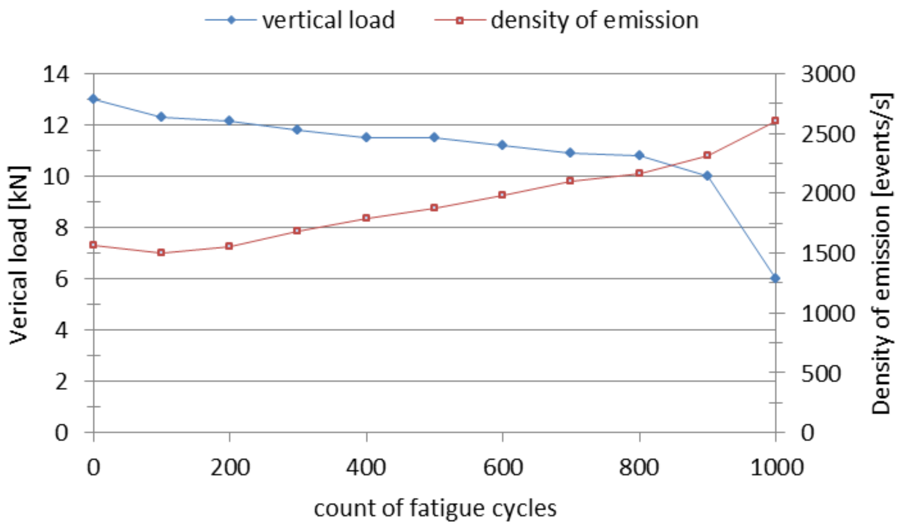


Fig.7. Changes in the leaf spring bending force, initial load 13 kN

Figure 8 shows the typical course of the force extorting the bending of springs and the EA density as the function of the number of fatigue cycles. In this case, the initial load was 130% of the static load resulting from the weight of the vehicle and the permissible cargo mass. The leaf spring kept operational efficiency up to 1.6 million fatigue cycles. The total lifetime of the leaf spring can be clearly divided into three periods. The first lasted about 200 thousand of the fatigue cycles characterized by a rapid decrease in stiffness accompanied by the acoustic emission. The second period included the stabilization of both rigidity and acoustic emission. It lasted up to 2.8 million cycles. The stiffness of the leaf spring and the acoustic emission level stabilized. The third period was the period of stiffness decline accompanied by the EA increase. The period lasting about 500 thousand cycles between 2.2 million and about 2.7 million cycles can also be distinguished. In this range, a small increase in the EA compared to the immediately preceding period is noticeable.

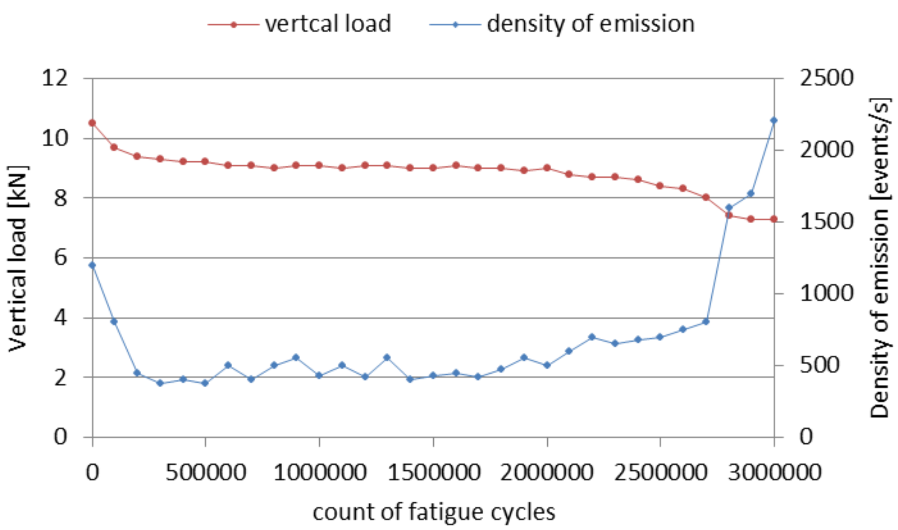


Fig.9. Changes in the leaf spring bending force, initial load 10.6 kN

Figure 9 shows the course of the leaf spring bending force and corresponding EA as the function of the amount of fatigue cycles for the initial load of 100% of the permissible static load (8.12 kN). Figure 10 presents the bending force course resulting from the burden of their leaf spring with the vehicle mass without cargo (6.4 kN). Loading of the leaf spring with the force corresponding to the maximum static load led to the destruction of the leaf spring after reaching approximately 5.7 million cycles. In contrast, the loading with the forces corresponding to the static load of vehicle without cargo did not lead to the destruction of the leaf springs. For the 8.12kN load the course of stiffness and EA are similar to the load of 10.6 kN force. In turn, in case of the lower load with the force of 6.4 kN, the leaf spring destruction process and the accompanying EA were not observed. The leaf spring reached 6 million cycles and the test was stopped.

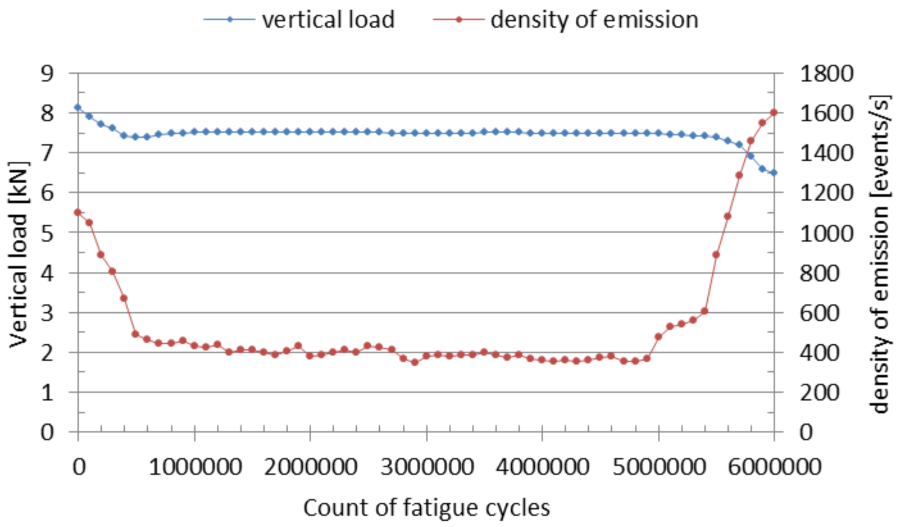
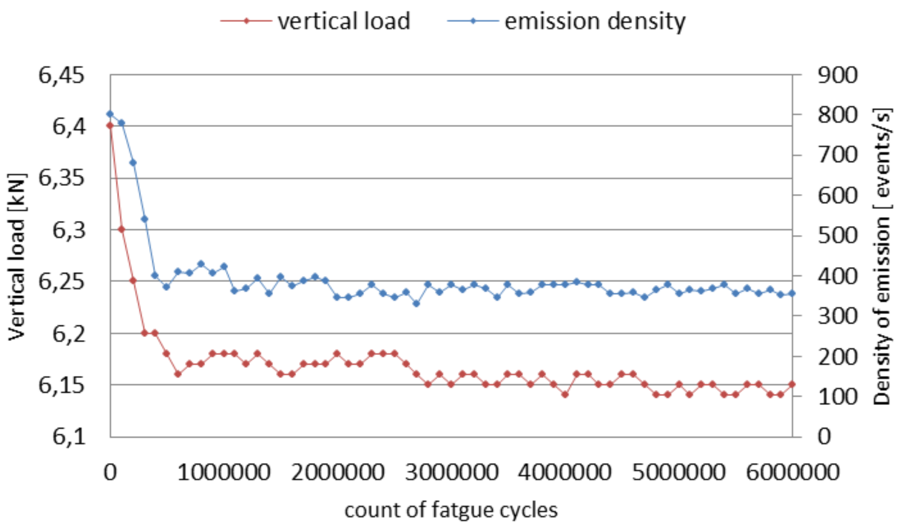


Fig.10. Changes in the leaf spring bending force, initial load 8.12 kN



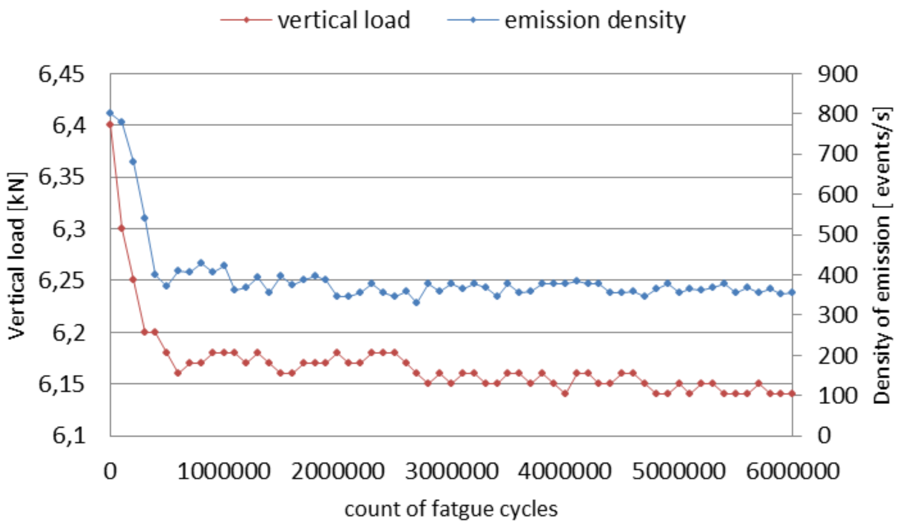


Fig.11. Changes in the leaf spring bending force, initial load 6.40 kN

Regardless of the load, during the initial period a decline of the spring stiffness and decrease of the acoustic emission density occurred. During this period the phenomena of accumulation and disclosure of the composite technology failures occurred. With the increase in the number of cycles, the stiffness of the leaf spring and the acoustic emission stabilized and remained at a relatively constant level until the leaf spring destruction.

Conclusions

The leaf spring destruction process was due to the spring stratification in the neutral axis. Nonetheless the leaf spring is still able to carry the loads smaller by about 20%. The overall durability of the leaf spring can be divided into three distinct periods: the initial decrease in stiffness of the leaf spring, the period of stiffness stabilization, and the final interval where an accelerated decline in the stiffness occurred. The decrease in stiffness of the leaf spring, characteristic for the last period of durability, can be taken as the criterion for destruction of the leaf spring. The lengths of subsequent periods are dependent on the value of the leaf spring bending loads. In the case of the maximum load used in tests, the lack of period of rigidity stabilization was evident. The construction was subject to the explosive growth of micro-cracks within the first load cycles. This resulted in the destruction the leaf spring in a short time.

When the springs were loaded with smaller forces, the decrease of stiffness ended after 300 thousand cycles followed by a stabilization period of stiffness. This phenomenon was caused by the accumulation of existing micro-cracks and discontinuities, introduced into the structure of the leaf spring as the result of technological errors. Simultaneously, the level of internal stresses did not generated the new damages.

The state of structure of the composite from which the leaf springs were made can be monitored using the acoustic emission. Any change in the stiffness of the leaf spring was accompanied by the change in density of the acoustic emission. There is a noticeable regularity between the degree of degradation of the leaf spring structure and the level of emissions. The increase of the degradation level was accompanied always by the increase in acoustic emission. The increase in the level of AE directly before the stiffness decrease is also interesting. Thus, knowing the AE characteristics for the leaf spring, it could be used to diagnose the state of the leaf spring structure.

The use of DSP in the research, based on AE, gives the opportunity to pre – diagnostic research and of leaf springs. Using the signal conditioning is possible not only to test a variety of materials (e.g. polymer), but also the individual parts of the system.

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