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Ilmārs Blumbergs

Modeling of composite material strength

Doctoral Thesis Summary

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Modeling of composite material strength

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I hereby declare that the work presented in this thesis is my own and has been carried out through the (name the structural unit) at Riga Technical University, during my candidature as a PhD student. This thesis contains no material previously published or written by another person, or substantial proportions of material, which have been accepted for the award of any other degree or diploma at RTU or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at RTU or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the produce of my own work except to the extent that assistance from others in the projects design and conception or in style, presentation and linguistic expression is acknowledged.

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The Doctoral thesis written in Latvian, consists of introduction, 6 chapters, the final part, conclusion, list of literature, appendix, 92 drawings and illustrations, total number of pages 116 and appendix. The list of literature contains 34 headlines.

1. Topicality

This paper is devoted to important issues of strength determination, prediction of destructive processes and processing acoustic emission signals of composites; these issues enable determining the limits of safe use of a product and to recognize when limits are reached.

2. Objective

The objective of the paper is studying the characteristics of composite components, simultaneously using material diagnostics with the acoustic emission method and developing a destruction model of the collapse process, to be able to view the collapse processes from a joint position.

In order to achieve the objective, the following tasks should be realized:

- Analyze composite strength measuring and influencing factors;
- Manufacture and carry out experiments on micro samples of carbon fiber;
- Carry out static strength and elasticity module distribution research on composite thread microsamples;
- Manufacture samples and do experiments with acoustic emission signal recording and variance monitoring;
- Develop a method for evaluating experiment results;
- Develop a model, where the ultimate strain dispersion and critical stress dispersion of threads are taken into account. On the basis of the developed model gain a description curve of stress increase for composites for tensile load.

3. Scientific novelty

In the process of developing the model, the experimental results, destruction model and acoustic emission signals were interconnected.

The developed model enables to describe not only the predictable strength of unidirectional composites, but also the character of the destruction, taking into account the fiber stress and/or ultimate strain distribution.

The developed experimental data quality evaluation methodology enables to compare and assess different experimental data and its conformity with the predictable nature.

Acoustic emission signal analysis was done in context of composite collapse dynamics, allowing to distinguish different collapse processes in composite.

4. Practical significance

The developed fiber composite collapse model can be used to predict composite strength, according to the characteristics of its components. The model, as well as experimental data quality evaluation methodology can be used for scientific and practical purposes, and in education. The model can be used in product design; it enables choosing the optimal material characteristics, which would ensure temporal recognition of collapse initiation and simultaneously ensuring maximum strength. The main results are published in 7 international publications in the form of articles and thesis. They have been presented in 14 international conferences and seminars.

1. Introduction

Composites are increasingly being used in aviation sector. They are widely used in aircraft industry – for constructing the fuselage of fighter jets, sport and special use aircraft, as well as for building the fuselage of the large and heavy passenger jets, such as ‘Boeing-777’ and ‘A380-800’, and especially ‘Boeing-787’, for whom the use of modern composites is vital for reducing weight and costs. To ensure durability and safety of these aircraft, it is necessary to know precisely the relation of statistical strength and safe life characteristics, to predict how changes these values, if composite component characteristics are being changed.

Using composites rationally in aircraft constructions, it is possible not only to reduce weight, but also lower the prime costs and costs, and shorten the time of maintenance. It is possible to manufacture constructions of constant size and shape from composites. Different composites may have one or many advantages and it is not always possible to achieve these advantages at the same time.

In order to achieve the objective and obtain the results, the paper was divided into eight parts. The core of the paper is six chapters, the first of which views general information about composites and the benefits of using them. The second chapter analyzes various aspects of fiber composites. This analysis includes the necessary information for conducting practical studies in accord with the objective and developing material collapse model. The third chapter is devoted to practical research. These studies include static tensile load experiments on microsamples, static tensile load experiments for complex reinforced samples with acoustic emission signal recording and dynamic tensile load experiments on complex reinforced samples with acoustic emission signal recording. The fourth chapter contains analysis of the experimental data, and the fifth chapter is dedicated to development of the destruction model. The sixth chapter contains the conclusion with general findings. The other two chapters include references and appendixes. In general, on the ground of experimental results, a model for rendering material destruction dynamics and evaluating strength is developed in this paper, in addition destructive processes was associated the with acoustic emission signal readings, as indicators of internal material collapse processes.

2. Analysis of composite strength

This chapter briefly views the most significant information, which the paper is based on. For example, the classification of composites is described, so that it would be possible to understand the material denotations from a unified position. The paper acknowledges and analyses the basic methods of measuring composite strength and the influencing factors of composite strength are described shortly, such as fiber composite deformation depending on the type of loading, the relation of fiber and matrix volume or density. The how's and why's of fiber tension dependency on its diameter are viewed.

The paper is based on previous research of various scientists. The main principles used in studying destructive process characteristics were from the research of M. Kleinhoff, Yu. Paramonov, R. Chatys as well as A. Griffith and J. Giliman, who define both elasticity and strength characteristics, taking into account the principle of energy used for the formation of cracks and new planes. The strength and wear durability of mechanical constructions and especially composites, have been studied by many famous scientists, each providing own material collapse model. The first brittle collapse statistical theory studies were carried out by V. Weibull, J.I. Frenkel and T.A. Kontorova. B.V. Gņedenko was the first to view these issues from a mathematical point of view. V. Weibull's distribution is one variation of the sustained minimum distribution: the strength distribution of a link of homogeneous samples corresponds to the strength distribution type of a single sample. Only the distribution parameters change. This effect is the basis of explaining the so-called brittle collapse scale factor: strength decreases as size of the sample increases.

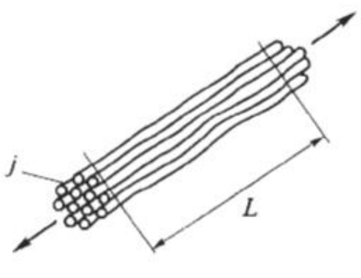
Composite strength model has been studied in detail by M. Kleinhoff, J. Andersosn, Yu. Paramonov, F. Paskual and V. Mikers. The weakest-link model denotes that a material has various weak spots, near which the wear accumulation processes are relatively homogeneous and independent. The total strength of a specimen conforms to strength of the weakest link, therefore meeting the Weibull distribution. The opposing theory is grounded in the assumption that between the weakest spots there is a process of tension redistribution and damage accumulation is changed. The collapse occurs when the accumulated damage reaches a certain level.

There are many publications devoted to composites and their components' strength and durability statistical data analysis. Valuable reviews of such publications are in the works edited by J. Ņemecs, SV. Serenesen, V.S. Streļajev as well as V.P. Tamuzh and V.D. Protasov. Fiber strength statistical account is unfolded in the work of T.A. Kontorova, G.M. Barteņeva, L.G. Sedrakjana and others. For processing experimental data, the following distributions are used: Weibull, lognormal and normal distribution. V.P. Tamuzh, J.A. Gutāns, VV.J. Padget, A.S. Watson, R.L. Smith, W.A. Curtin offer an improved Weibull distribution, which allows better taking into account the length of a sample. J. Andersons, R. Joffe, M. Hojo, S. Ochiai used this distribution in their experimental fiberglass strength distribution research. There is also a proposition to use distribution into orthogonal polynomials, which is known as A type Gram-Charlier series. L.G. Sedrakjan recommends using distribution with four parameters, which is actually a generalization of Weibull distribution (the upper and lower durability threshold is established).

V.V. Bolotin's work on composite collapse mechanics shows a generalized approach to the issue of composite collapse and it is based on using kinetic models. However a large volume of initial information is necessary to calculate wear durability using this theory.

In order to consider the possibility of using wear effects for achieving the objective, as well as to better understand processes in the material, a brief review of durability and wear was done.

Fiber and thread research is very important in achieving the objective, therefore in this chapter, additional analysis of critical value behavior of single fibers and threads is done. The difference between a fiber and thread is shown in Figure 1. In fiber and thread analysis the parameter dispersion is an essential characteristic.



1.fig. A schematic depiction of loading a thread, which consists of many fibers – j.

Sample length is a significant parameter; it has been studied by Miķelsons, Gutāns. Tensile loading for fiber bundles or thread samples have been researched by Vasiļjev and Tarnopolski. The transition from composites' components characteristic distribution to composites' characteristics was first described by F. Peirss and H. Daniels. H. Daniels achieved a fundamental result: he proved that, independently from the type of single fiber strength distribution, the destructive load distribution for a bundle consisting of N fibers inclines towards a normal distribution, if the count of fibers is large enough.

D. Gjuser and J. Gurland suggested viewing composites as chains, which consist of fiber bundles of a particular length.

After collapsing, the fibers do not decay, but decompose to a critical length. On the basis of this assumption, B. Rozen conducted fiber composites destruction analysis, assuming that it is a chain composed of sequentially linked bundles, which is included in taking the load in the ineffective length. C. Zvēbens introduced tension concentrations in calculations, took the collapse sequence in the defective spot into account, which takes place after collapse of nearby fibers; he also proved that for the collapse of the whole laminated package no more than a few (2-3) adjacent collapses are needed.

As the decision was taken to conduct the experiments and manufacture the samples on our own, production factor effect on composites' strength was also considered and analyzed, as well as various types of material diagnostics. After analysis, acoustic emission method was chosen. In the end of the chapter, a brief review of the effect of exploitation factors on composites is offered. Such review was necessary to evaluate analyzable material's state changes affected by these external effects.

3. Practical experimental research

Carbon fiber microsample experiments

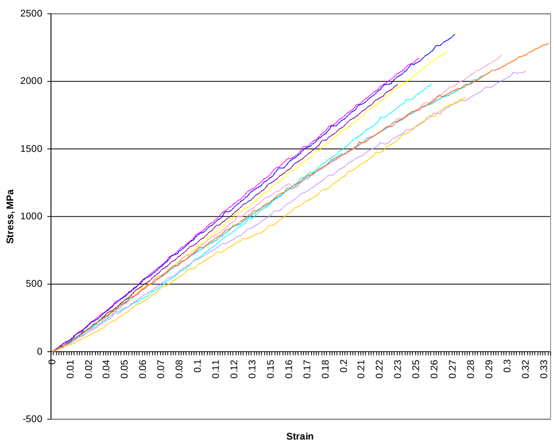
The main idea of experiments in this chapter is to understand the processes of single thread breakage; these processes are very significant in predicting material strength and collapse process, and are best reflected by acoustic emission signal changes. To achieve the objective of the paper, different experiments were carried out, and emphasis was not put on determining maximally precise fiber or matrix strength and elasticity model (measuring exact values is resource-intensive and in this case it is favourable, but not necessary), but indeed on finding correlation and assessing influences to the total strength.

Experimentally studied microsamples were carbon fiber threads with the diameter of 150 μm (irregularity 20 μm), impregnated with epoxy resin ED-20, hardener Politelen-poliamin and plastificator Dibutilftolat. The tests and calculations were done according to the so-called zero-order model. The zero-order model is a monotropic model, were the matrix strength and elasticity module is ignored, assuming that the layer is effective only in the direction of fibers. It means that the elasticity module in the perpendicular direction of the direction of tensile force E_2=0, shear module G_{12}=0 and Poisson relation ν_{12}=0. These processes can be described with the following formulas: $\sigma = E_1\varepsilon_1$ $\sigma_2 = 0$; $\tau_{12} = 0$, where $E_1 = E_f v_f$; σ_1- microsamples' strength in direction parallel to the fibers; σ_2- microsamples' strength in direction perpendicular to the fibers; ε_1- extension in direction parallel to the fibers; τ_{12}- shear tension; E_f- fiber elasticity module; v_f- fiber volume part.

This model is correct for cases, where the fiber strength does not exceed rhe strength of the matrix.

Experiments were done by static loading, adding tensile force in normal atmosphere conditions of humidity and temperature. The loading extension rate was 1 mm/min. The tested samples were 15, 40 and 60 mm in length. The tensile force was measured from zero till the collapse of the samples. Experiments were carried out on a device specially suited for measuring little loads (up to 2,5 kN). All the measurements were done automatically in a digital form, using the included original data processing program. The loading force and clamp movement distance were measured.

Figure 2 shows loading curves for microsamples 15 mm long. It can be seen from the curves that the elasticity module which is reflected as the linearity of the line, can be assumed to be constant for every single microsample, but varies in comparing different samples, which is seen as the varying slope of the lines, in relation to the coordinate axes.



2.fig. Static loading for 15 mm long carbon fiber microsamples

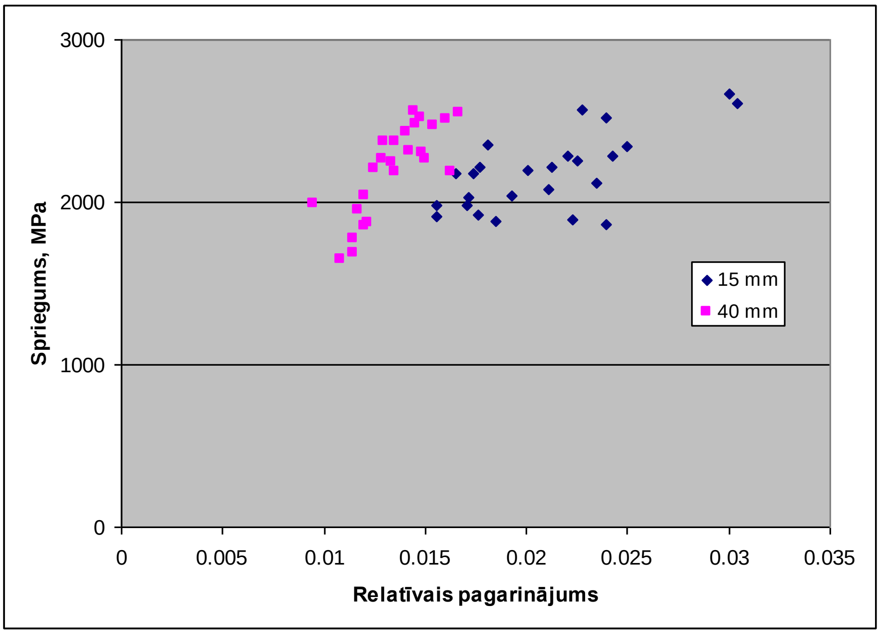
Table 1

Variation of experimental data

	Valid samples	Mean	Minimum	Maximum	Standard deviation
ultimate strain 15mm	25	0.021	0.016	0.030	0.0040
elastic modulus 15mm	25	106493.1	77863.7	131630.9	15291.70
ultimate stress 15mm	25	2181.7	1864.4	2663.7	233.89
ultimate strain 40mm	25	0.013	0.009	0.017	0.0018
elastic modulus 40mm	25	164576.7	134458.9	209910.1	14851.59
ultimate stress 40mm	25	2202.4	1643.9	2554.6	278.81
ultimate stress 60mm	45	1980.904	1299.454	2520.874	260.1377

In Figure 3 critical value dispersion of two different microsamples' lengths is shown. It can be seen that for the shorter samples, comparing with longer ones, there is greater extension dispersion, and the longer samples have slightly higher critical tension dispersion. After analyzing the measurement processes, the possible reasons for dispersion were drawn. The data is used in further research.

During the study, quantitative information was gained about the characteristics of three different length microsamples from the same carbon fiber thread. Tension – deformation curves for composite samples of different length were obtained, therefore enabling to derive strength, elasticity module and critical extension distribution.



3.fig. Experimental value dispersion of relative extension and tension for two microsamples of different length

Acoustic emission data experiments for static loading

The aim of the study was to gather acoustic emission signals to understand the collapse process of complex reinforced fiber composites. For this purpose, testing samples were manufactured in accord with the standard PN-EN 10002–1+AC1,1997. The samples were made from multilayer carbon fiber fabric, with thread diameter of 3 nm with irregularity 0,2 nm. Epoxid-fenolo-anilino-formaldehid was used as a binder. The composite sample has 11 layers with threads oriented in different directions ($0^0{}_4$ /-+$45^0{}_8/90^0{}_3$). During loading, 16 acoustic emission signal parameters, characterizing sample condition, were recorded.

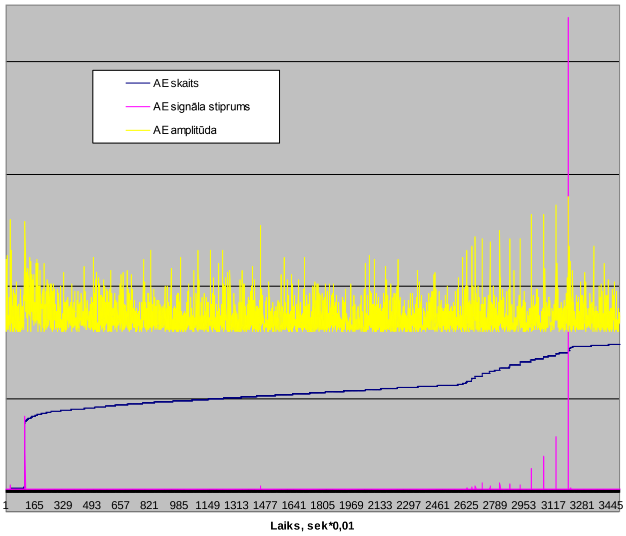
After carrying out the experiments, material characteristic values at static loading were gained. The experiments were done with the aim to determine acoustic signals caused by the collapse process and, on their basis, to identify mechanical processes in the material. Loading was done from zero value until sample collapse. The samples were tested with tensile loading and the tensile force increase was linear, with the rate of 2 mm/min, which is considered static. Experiments were done in normal conditions of temperature, humidity and pressure. Sample collapse occurred in the predicted spot (approximately in the middle part), as seen in Figure 4, and it characterizes the correct loading conditions in the sample. The cross-section parameters of the sample are 2.5*11.0 mm, layer combination $0^0{}_4$ /-+$45^0{}_8/90^0{}_3$, the average strength for 6 samples is 275 MPa.

Table 2

Strength of tested carbon fiber samples

Nr. of sample	Ultimate load, $F_{max.}$, N	Ultimate stress, σ_{max}, MPa
1	7790,50	286,64
2	7643,85	277,95
3	7338,20	266,84
4	6832,34	248,44
5	7963,73	288,86
6	8712,61	316,82
Mean	***7713,55***	***275,925***

Figure 5 shows three acoustic signal parameters recorded in testing one sample; the scale has been changed to better illustrate the correlations of the signals in one timeline. It is clearly visible that the AE signal amplitude in the time of loading changes minimally, with exceptions in the beginning and end. At the first phase of loading, there is a little increase due to many little events, which are associated with the effect of first loading. Another systematic signal increase is at the end of loading and it is associated with the collapse of the stronger fibers.

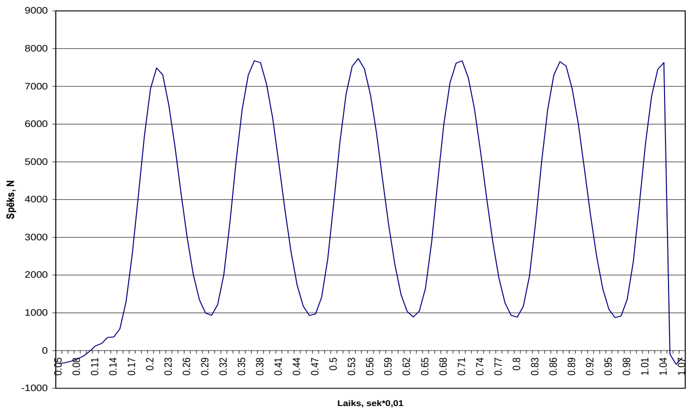


5.fig. Acoustic emission signals during static loading

Acoustic emission data experiments for dynamic loading

Loading was done with the frequency of 6 hz, cycle amplitude of 1000 N up to 95% from maximum tensile strength, the temperature of surroundings was 19 C and the experiment was done until sample collapse. One example of dynamic loading is shown in Figure 6. During loading, 16 acoustic emission signal parameters, characterizing sample condition, were recorded.

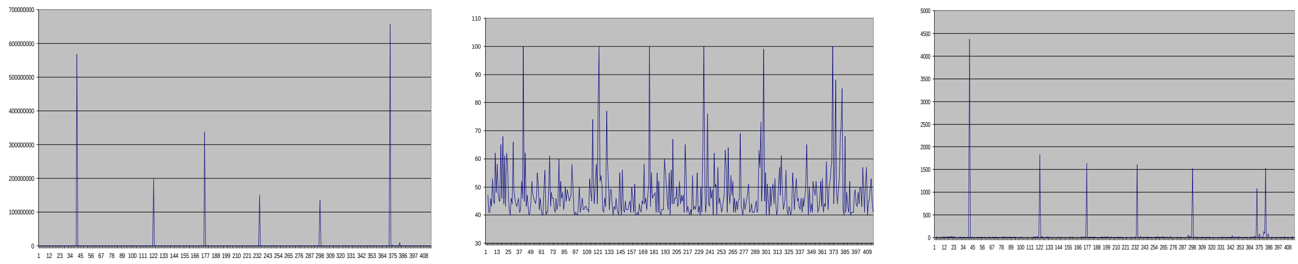
4.fig. Complex reinforced carbon fiber sample after testing



6.fig. Loading force depending on the time

To lessen the effect of clamps on sample mount spots, they were specially prepared. Medium size grain sandpaper was glued with the grain inside to the sample mounts. Such sample processing allowed increasing adhesion between the clamps and the sample, while leaving the mounting force intact, which could have influenced sample strength and after long lasting cyclic loading the sample mounts could have worn out and the sample could have slipped out of the clamps.

The Figures 7 a, b and c illustrate acoustic signal for a sample, which endured 7 cycles of loading. Each cycle has high acoustic emission energy (7 a), as well as high count of events (7 c), and every cycle can be distinguished by AE signal amplitude (7 b). In the beginning of loading at the first cycle the same sight as in static loading can be observed; that is the first loading effect. Figure 7 c shows a large count of minor events.



a) b) c)

7.fig AE signal energy depending on the time (a); EA signal amplitude depending on the time (b); AE event count depending on the time 9c) for cyclic tensile loading

In this case the initially released AE energy is relatively higher than for static loading, but it must be taken into account that here loading is significantly faster and up to 95% of the average sample maximum tensile strength. Therefore here not only matrix cracking occurs, but some weaker fibers collapse and ply delamination happens. Such experiment with extensive loading enables to easily distinguish different phases of the collapse mechanism.

4. Analyzing the gathered experimental data

This study was done with the aim to determine the differences in microsamples' distribution and to draw conclusions about the reasons of both varying maximum tension and elasticity characteristics, and differences in their distributions. The study used previously gathered experimental data about material characteristics. Overall, three samples of different length will be viewed, all of them manufactured in one series, therefore it can be assumed that their characteristics differ only slightly. It must be taken into account that the samples were made by hand, without automation, introducing greater parameter dispersion as it would be in real laminates.

Testing the samples for tensile strength the main material collapse reasons at the beginning of loading are thread and matrix delamination as well as delamination between layers of the material. At the beginning of loading, threads are not torn, but 'extracted' from the matrix. It means that sample strength is less determined by material of the matrix, and more by adhesion between the material and fibers.

However, at the end phase collapse occurs by failure of material fibers. The collapse process for fiber composites can be distinguished in three phases:

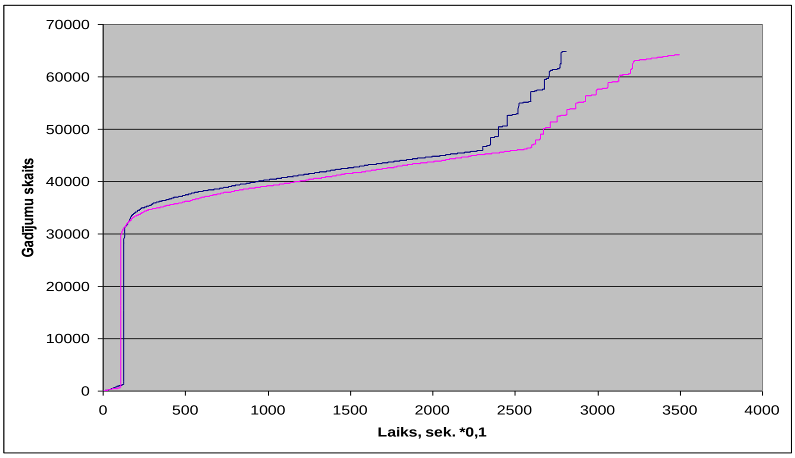
Phase 1 – when signal with minimal energy appears (e= $3.31e^{1} \div 3{,}52e^{3}$ eV). It conforms to formation of cracks at the sides of the sample;

Phase 2 – characterized by release of large energy (e= $8.98e^{6} \div 2{,}3e^{7}$ eV). Its magnitude points to crack formation in the volume of the sample;

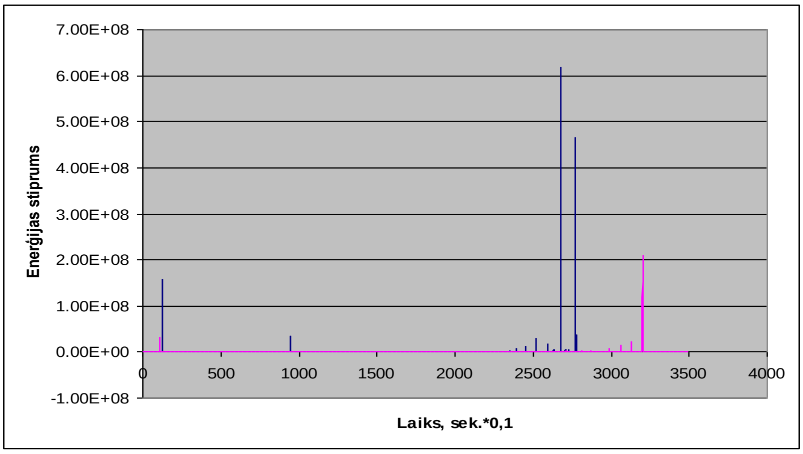
Phase 3 – after reaching the collapse level, fiber and matrix collapse process occurs, which is reflected by the amount of acoustic signal energy ([e]= of 2,09[e]8 of [e]V).

The character of signal proves the assumption that collapse processes in composites are indeed gradual and end with rapid fiber collapse. From the character of signal it is possible to determine, which types of collapse are happening in the sample at the particular time. Thus the large increase in count of events reflects tiny, but many insignificant processes, but the relatively little increase in events with large signal strength characterizes the more powerful process of fibers collapse.

Figures 8 and 9 show comparison of acoustic signals of two samples at the time of loading. The sample, whose acoustic emission signal sum is shown with a blue line, collapsed faster, showing a critical loading force of 6685 N, but the other sample (purple line) gave a critical loading force of 6549 N. Figure 8 shows that the count of signals is approximately equal, as was predicted, because both samples are identical in size and material. During long lasting sample monitoring, there are problems with diagnosing material state from the signal sum, because there are noises to be filtered out; the noise can be significantly larger than the signal count caused by the actual collapse process. Figure 9 illustrates the graphical effect of a larger elasticity module and higher sample strength. Thus, from figure 8 it can be seen that the sample depicted in blue, which is less elastic, but stronger, creates significantly higher acoustic emission signal strength.



8.fig. Acoustic signal sum for two samples



9.fig. Acoustic signal strength for two samples

There is an assumption associated with AE signal behaviour linked with individual thread studies that elasticity module dispersion affects the collapse process, increasing signal amplitude in the area of loading, which is near critical, because, as the study indicates, many stronger fibers will be torn before reaching critical load, and some of the weakest fibers with higher elasticity will endure until reaching the critical level of loading and then collapse, facilitating rapid collapse. The assumption is proved by the large AE signal strength increase in the end phase of loading at relatively tiny increase of signal amplitude.

We will view the dynamic testing data, on the basis of the sample, which endured 6 loading cycles. In the first cycle, AE showed collapse of the layers, which are oriented in 90^o angle relative to loading, therefore being the easiest to break. Then fiber delamination from the matrix occurs with intensive cracking of the matrix itself. Collapse in the next 4 cycles mainly happens in the layers, which are oriented in 45^o angle relative to loading. The 6^{th} cycle shows fiber collapse process from the layers which are oriented in 0^o angle relative to loading. This cycle is characterized by a higher signal energy, but lower event count. At the end phase the matrix is virtually destroyed.

It must be noted that fibers are destroyed in every cycle, but, in comparison with the first 5 cycles, the count of events is much greater in the last cycle.

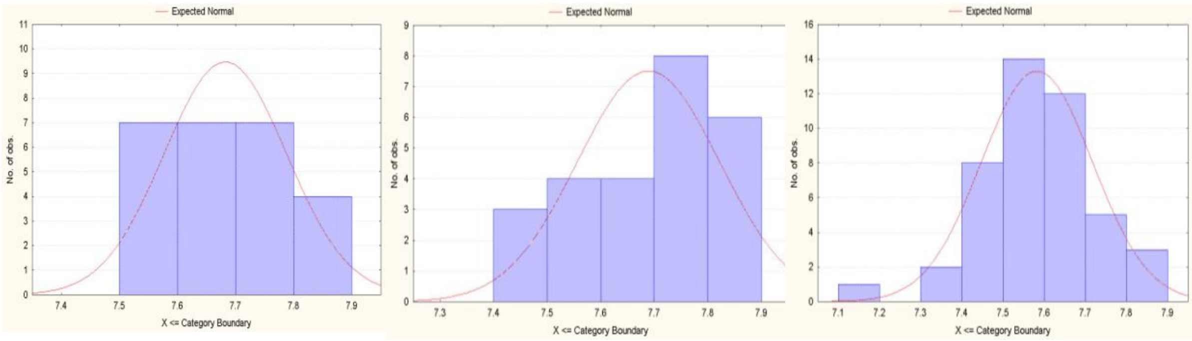
After doing such experiments, material behaviour at static and dynamic loading can be observed easily. Experiments with carbon fiber laminate samples helped to understand that the acoustic emission method allows distinguishing collapse processes in the material and is suitable for determining material characteristics, but, in order to carry out a quantitative remaining longevity assessment, a more in-depth research with testing different composite samples must be done. The collapse process in a complex reinforced sample initially occurs in the composite matrix and ends with rapid material destruction, which is partially facilitated by promiscuity of elasticity modules and strength characteristics.

Reviewing the gathered data from a statistical point of view, doing calculations, it can be obtained that the experimental values' offset from predicted values for 15 mm sample tensions is k=0,12, 40 mm samples – 0,077, but for elasticity models – 15 mm samples have k=0,08 and 40 mm samples – 0,10.

Looking numerically at the dispersion proportion, composed by dispersion against the average tension value, an opposite relationship is obtained – 15 mm long samples have dispersion of 10%, 40 mm – 12%, but 60 mm – 13%. It means that, viewing only tension distribution, their maximum and minimum values differ more for longer samples, than shorter ones. Therefore, a wider analysis is necessary to determine external factors' effect on sample characteristics. For this purpose elasticity module dispersion for these measurements was viewed. Comparing the elasticity modules, it can be seen that they are more concentrated for the longer samples, but, comparing the offsets, it can be concluded that, unlike the tensions, elasticity modules for longer samples have less dispersion, 14% for samples 15 mm long and 9% for 40 mm.

As was predicted, a larger count of experiments allows further compliance with the normal distribution function, and elasticity module dispersion decreases with higher sample length.

The compliance with normal distribution of the logarithmic values of the experimental data was determined. Tension logarithm distribution compliance with normal distribution for 15 mm, 40 mm and 60 mm long microsamples is shown in Figures 10 a, b and c. In the first case d_2 = 0,088 and $c_{n,\alpha}$=0,20, the second d_2 = 0,188 and $c_{n,\alpha}$=0,20, and the third d_2 = 0,076 and $c_{n,\alpha}$=0,20. It means that in all the cases, a hypothesis can be assumed that the experimental data complies with normal distribution; therefore the data can be recognized as valid.



a) b) c)

10.fig. Tension distribution a – 15 mm, b – 40 mm, c – 50 mm long microsamples

As was predicted, a larger count of experiments allows further compliance with the normal distribution function, and elasticity module dispersion decreases with higher sample length. It proves the assumption that there was a minor inaccuracy in mounting the smaller samples, which lead to approximately 13% decrease in strength.

Having conducted data analysis, the author offers a simple method, how to qualitatively determine the quality of individual experimental data series in five steps. To determine the quality of a series of experimental data one must:

- visually inspect the distribution graph of the data in the coordinates of interest. If the values are centered and/or distributed in a type of curve, then the first step gets 0 points; if the data is completely chaotic, it gets 0,1, and a neutral rating is 0,005;
- determine the data offset from the predicted function;
- determine data dispersion numerically in the percentage part;
- assess the data compliance with the distribution function in accord with Kolomogorov-Smirnov criterion. To get the indicator of interest, divide $d_2/c_{n,\alpha}$;

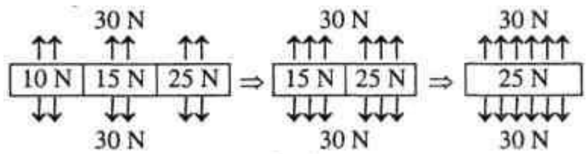
- sum the acquired values. Thus a value is gained, for which inclination towards zero indicates that quality of the experimental data is high, and the data complies with the specified conditions, whereas, if the value exceeds 2, the experimental data is not valid and the corresponding parameters are specified incorrectly.

As a result of the study, factors that influence microsample strength, its distribution, elasticity module and its distribution were recognized, the influence of various factors on experimental results was numerically evaluated and a simple model for assessing data quality was offered. For example, tension values for 15 mm long samples were assessed with 0,71, but 40 mm samples – 1,88, which indicate acceptable quality of gathered data. Such simplified value assessment model allows getting an overview of the experimental data and comparing them. The data gathered by author can be assessed as medium- medium good, thus they are valid for use in research.

5. Predicting sample collapse, taking into account the individual thread characteristics

The main idea behind this study is to develop a material collapse model, which takes thread breakage processes into account, assuming that these are the most significant processes, reflected in changes of acoustic emission signal. The strength of laminates is usually predicted using the maximum tensions or their distributions of its fibers or threads. This study viewed predicted strength value changes and collapse nature differences of a laminate, if they are determined on the basis of fiber thread maximum extension distribution and/or, if strength distribution is taken into account. Thus it will be possible to numerically evaluate, what role in material strength does one or another influencing factor play. The developed model was based on the works of M. Kleinhoff and Yu. Paramonov on fiber composite strength studies.

The model was based on a collapse pattern depicted in Figure 11.



11.fig. A schematic illustration of collapse process

In more complex structures strength decreases and along with dispersion. H. Daniels proved that fiber strength distribution is a normal distribution with standard deviation, which is inversely proportional to $\sqrt{n}$. However, in practice, the normal distribution is substituted with logarithmical normal or Weibull distribution. The standard deviation predicted decrease is also not accomplished inversely proportional to $\sqrt{n}$. The deviations from H. Daniels' model can obviously be explained by the fact that the assumption about homogeneous distribution between elements is not true. In a composite, unlike an independent bundle of threads, the development of collapse does not occur homogeneously in all its cross section, but only in proximity of damage. This collapse mechanism can be viewed as a process, which starts with the collapse of a particular critical set of elements (located on the top of the sample). Then the collapse proceeds in the cross section of the sample, consequentially destroying it. Even 'approximate homogeneity' can only be observed in a limited volume of the sample, which gradually changes its position.

Cross section collapse mathematical model can be described with formulas, which determine strength for i-th cross section and for the whole sample:

$$X_i^* = \max_t (x_t : n_C - K_{Ci}(t) > 0) \quad (5)$$

$$X = \min_{1 \le i \le n_L} \qquad X_i^* = \min \min_{1 \le i \le n_L} \max_t (x_t : n_C - K_{Ci}(t) \ge 0) \quad (6)$$

where in the first case in K_L cross section stages $0<K_L<n_L$ damage appears K_{Ci} (t), $0<K_{Ci}(t)<n_C$, $i=1,...,K_L$, n_L – count of stages or elements in the whole length of sample, n_C – count of the parallel elements, K_L –value of the case, K_{Ci} (t) – case time function, but in the second case evolution of the collapse happens in one or more cross sections. The loading process is described as an increasing sequence $\{x_1, x_2, ...x_t, ...\}$.

To predict the tensile strength of a material in accord with the characteristics of microsamples (threads), three variants will be viewed – the first variant consists of a strength calculation depending on the critical tensions of threads and the second provides determining material strength depending on the criterion of reaching thread critical extension. The third variant is a combination of the first two, with the condition that each thread of the laminate can be torn only one time after reaching one of the criterions $\varepsilon_{i\ max}<\varepsilon$ or $\sigma_{i\ max}<E\varepsilon$, where $\varepsilon_{i\ max}$ is the maximum relative extension of the i-th thread and ε is the relative extension of the laminate, and $\sigma_{i\ max}$ is the maximum tension of the i-th thread. All the variants consider a simplified model with the assumption that a layer consists of threads of i fibers. These threads are mutually connected with the material of the matrix and fiber volume relation to matrix volume is the same as in the tested microsamples. All the threads and their fibers are perfectly

linked and deform equally. Each fiber or thread together with the matrix takes up a particular area and they have equal relation of fiber and matrix volume. As a result, an ortotropic laminate with 4 elasticity constants is obtained. The laminate model is viewed as parallel, geometrically identical cells (fibers impregnated in the matrix). It is assumed that a thread, which is in the laminate, can be torn only once. Thread collapse is assumed to be approximately symmetrical and thus, when a thread breaks in tension, no torques form and only the tensile force is active in the laminate in direction 1 (there are no shifts towards y). This study does not examine processes, which occur at compression, torsion or hack; similarly, tension in the direction 2 (perpendicular to the direction of tensile force) and shear processes at tension are not considered.

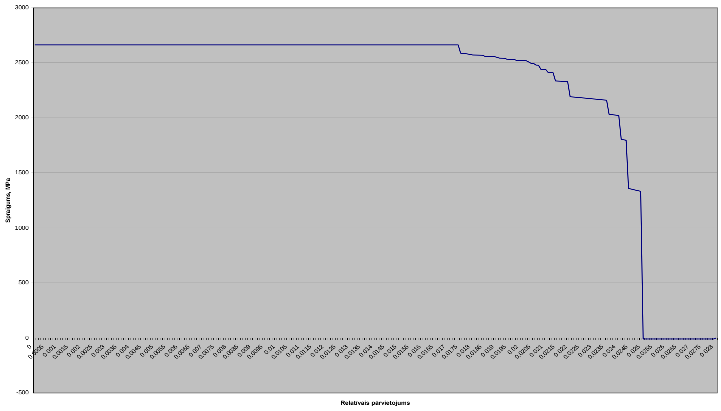
The main idea of carbon fiber laminate collapse simulation, which depends on uniform displacement of tension criterion, is that every fiber or thread breaks, when the critical tension $\sigma_{i\ max}$ is reached. The tensions formed by tensile force are distributed on all the fibers and threads equally $\sigma_n = \sigma / i$, where i is the count of intact fibers or threads. Therefore, when an external force is added, the laminate faces tension, which will be equally distributed to all fibers and some of them will break, if the tension will be equal to or will exceed the critical tension of the fiber. When the critical level of a fiber or thread is reached, it breaks and the cross section area of the bundle loses one unit, therefore its strength potential is decreased by 1/i-th part.

Mathematically the model is described this way:

$$\sigma(\varepsilon) = \varepsilon \sum_{i=1}^{n_C} 1(\overline{\sigma}_i < X_i) E_i \varepsilon_i f_i \qquad (7)$$

where X_i – critical tension of i-th cross section, f_1, ...f_n – cross section areas n, E_1, E_2, ... E_n, – elasticity modules

To simulate the collapse process, software was designed in the Matlab environment. The critical relative extensions of threads were not taken into account in the calculations. The calculated sample strength potential change curve is depicted in Figure 12. Here the blue line shows the decrease of the strength potential of a sample at an evenly increasing disposition. The collapse character at the set conditions can be observed, as well as influence of each thread on the total strength potential, or, in other words, how much tension will the sample be able to withhold after the breakage of each weak thread.



12.fig. Strength potential decrease depending on the criterion of reaching critical tension for 15 mm long samples.

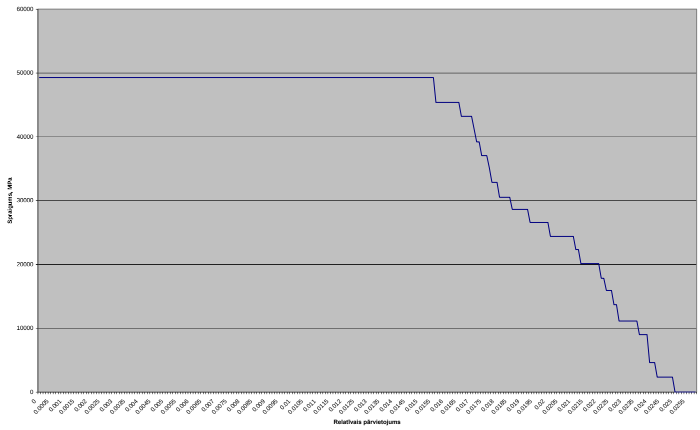
The main idea of carbon fiber laminate collapse simulation, which depends on extension criterion for uniform displacement, is that every fiber or thread breaks, when the critical extension εi max is reached. The tension created by tensile forces is not taken into account. It is assumed that extensions of all the fibers are equal and they are equal to extension of the laminate. Therefore, when external force is added, the laminate will be extended equally in all the fibers, and some of them will break, when the extension will be equal to or will exceed its critical value. When the critical level of a fiber or thread is reached, it breaks and the cross section area of the bundle loses one unit, therefore its strength potential is decreased by 1/i-th part. Mathematically it is described this way:

$$\sigma(\varepsilon) = \varepsilon \sum_{i=1}^{n_C} 1(\varepsilon \bar{\varepsilon}_i E_i < X_i) E_i \bar{\varepsilon}_i f_i \qquad (8)$$

where $\bar{\varepsilon}_i = \varepsilon_i / \varepsilon$ is the relative deformation for the i-th element at the average cross section deformation ε, the distribution of the case value $\bar{\varepsilon}_i$ is independent from ε

To simulate the collapse process, software was designed in the Matlab environment. In the calculated variant, data of 25 microsamples from known experimental data were used. Therefore it can be assumed that a virtual sample of 25 threads was created. To simulate collapse, a series of predictable displacements were generated. These values were compared to the critical extension values of all the samples after each step of the calculation. If the n-th calculated extension value is equal to or greater than the critical value of the i-th sample, the strength potential is decreased by 1/i-th part, where i is the count of intact threads. The critical tension value is not considered in the following calculation steps. Thus all the fibers are broken in virtual reality and the fiber breakage spots are determined. A curve of the calculated strength potential of the sample is depicted in Figure 13. Here the blue line shows as strength potential decreases at evenly increasing displacement.

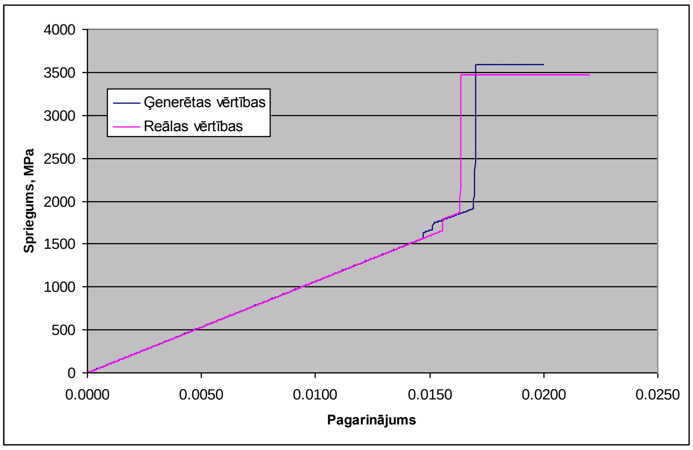
The previous two cases show the different nature of material collapse under different circumstances. Carbon fiber laminate simulation in accord with both extension, and tension criterions adds such simulation conditions to the upper mentioned assumptions and conditions: a virtual sample, consisting of i fibers, is tested in virtual reality; the mechanical properties of these fibers are known; the sample is loaded with tensile force with a steady pace; the tensions are applied to the intact fibers; each fiber can only be torn once, after one of the levels is exceeded; after each breakage, the tensions, which are applied to the intact fibers, increase by the part of the broken fiber; tensions are distributed evenly to all threads.



13.fig. Strength potential decrease depending on the criterion of reaching critical extension for 15 mm long samples

Figure 14 depicts a case with the generated and real values of reaching critical extension and tension conditions. To simulate processes occurring in the material, it is necessary to know the predictable strength, critical extension and their standard offsets of thread microsamples, and, as noted before, the function of experimental data distribution is a normal distribution function. Figure 14 illustrates tension increase in a material with simulated data with normal distribution function and 15 mm long samples offset and scale coefficients. As it can be observed, the comparison between curves of the simulated data and experimental data prediction shows coincidence of both character, and critical values.

If we compare the critical values of the material with the average values, then, for example, for 15 mm long samples, the critical deformation is 0,021 and critical tension 2181,7 MPa, but the calculated values are respectively 0,01633 and 1870 MPa. The critical deformation for 40 mm long samples is 0,012 and critical tension is 2202,4 MPa, but the calculated values are respectively 0,010 and 2190 MPa.



14.fig. Collapse simulation of carbon fiber samples

So, if we need to assess the strength of a composite laminate or to find the properties, which would ensure the necessary conditions, it is vital to know the critical extension values and their dispersion, as well as the critical tension values and their dispersion, of thread microsamples. Value distribution for a large number of threads inclines towards normal distribution. The main advantage of assessing the critical parameters of a material this way, is the possibility of evaluating the nature of collapse. Testing manufactured composite laminate samples allows determining the critical tensions and extensions relatively simply, but it is hard to measure the brittleness or elasticity of a sample. Only using non-destructive methods of diagnostics we can get an overall view of the collapse; use of the developed model allows numerically determining the phase of collapse at particular loading.

Sample collapse analysis enables not only better predicting the maximum total strength and collapse rate of a material, but also understanding the nature of acoustic emission signals.

6. Conclusion

Conclusions of the paper:

- Association of sample collapse results with acoustic emission signal behavior at the time of material breakage allows simultaneously ascertaining the correct understanding of acoustic signals and compliance of the collapse model with collapse processes in the samples;

- The gained results can be used practically, as well as supplemented and used for further improvement.

The following information and results were gained while composing the paper:

- Composites' strength measurement and influencing factor analysis was done;
- Carbon fiber thread microsamples were manufactured and 200 experiments were carried out;
- Analysis was done on composite thread microsample statistical strength and elasticity modules;
- 50 complex reinforced samples were manufactured and experiments were done with recording and studying acoustic emission;
- A method for evaluating experimental results was developed;
- A model was developed, allowing modeling the collapse dynamics of samples in the cases, where the critical extension dispersion and critical tension dispersion of threads are taken into account. On the basis of the developed model a description of the curve of tension increase for composites at tensile force was gained.

Practical use

- The developed model enables evaluating and choosing optimal material characteristics in the design phase;
- The association of acoustic emission signal with the developed models, allows warning about reaching the maximum strength of a construction, using acoustic emission sensors;
- The developed experimental data evaluation methodology can be used for comparing and assessing different experimental data and their compliance with the predictable nature.

List of authors publications

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2. I.Blumbergs, R. Chatis, M. Kleinhofs, „Experimental Research of Carbon Fibber Composite Material Characteristics"(IVth International Conference On Scientific Aspects of Unmanned Aerial Vehicle, Suchedniów/k.Kielc, Poland, 5 – 7.may 2010.; 46-51 lpp. ISBN 978-83-88592-70-6
3. I.Blumbergs ,R. Chatis, M. Kleinhofs, „Experimental Research of Carbon Fibber Composite Material Zero order Model Characteristics" Chapter Edited by prof. Zdigniew Koruba "Monografy - SCIENTIFIC ASPECTS OF UNMANNED AERIAL VEHICLE" Polish SOCIETY OF Theoretical and Applied Mechanics (in print)
4. J. Paramonovs, J. Andersons, M. Kleinhofs, I.Blumbergs „MINIMAXDM Distribution Family for Analysis of the Tensile Strength of a Unidirectional Composite", Mechanics of Composite Materials, Springer New York, USA, vol 46,No. 3 2010, 275-287 lpp., 11029 ISSN 0191-5665
5. I.Blumbergs, M. Kleinhofs. Experimental research of composite material characteristics using acoustic emision//RRDPAE 2008 conference CD, oct. 16-17, 2008. (ISSN: 1425-2104)/ Brno,Čehija
6. I.Blumbergs, M. Kleinhofs. Experimental research of composite material acoustic emision characteristics.// 3rd International Conference „Supply on the wings" Conference manual, nov.11-13, 2008, Frankfurt, Germany
7. I.Blumbergs, M. Kleinhofs, Rafal Chatys. Experimental research of composite material characteristics.//Mašīnzinātne un transports (sērija 6, sējums27),2008, Rīga , Latvija