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AMPLITUDE-ENERGY PARAMETERS OF ACOUSTIC RADIATION WITH COMPOSITE PROPERTIES CHANGING AND MISES DESTRUCTION

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Abstract:
The main problem with using acoustic emission to control and diagnostics of composite materials and products from composite materials is the interpretation and identification of recorded information during development processes occurring in the material's structure. This is due to the high sensitivity of the acoustic emission method to various influencing factorsand the practical absence of acoustic radiation models. To solve this problem, it is necessary to determine the influence of various factors on acoustic radiation parameters. In this study, based on the acoustic radiation developed model we simulate the influence of one parameter characterizing composite properties on acoustic emission energy parameters during composite material destruction by shear forces according to the von Mises criterion. Simulation of acoustic radiation under given conditions makes it possible to determine the patterns of acoustic emission signals energy parameters changes and their sensitivity to changes of influencing factor, as well as to obtain mathematical expressions for describing obtained patterns. The results of this case study can be useful for developing methods of control, monitoring and diagnostics of composite materials and products made from composite materials.

Keywords: *composite, destruction, acoustic emission, signal amplitude, signal energy, von Mises criterion*

1. Introduction

Methods of the control, monitoring, and diagnostics of composite materials (CM) are aimed at ensuring quality at all stages of the product life cycle[1, 2]. One of the widely used methods is the method of acoustic emission (AE)[3]. The AE method is highly sensitive to sub-micro, micro, and macro processes occurring in the structure of various materials during their deformation, including CM.

One research areaisthe study of CM destruction processes under shear force[4, 5]. In studies of the destruction of CM by transverse force, the concept of the destruction of CM represented as a bundle of fibers (FBM model) has become widespread [6, 7]. In studies of CM destruction by transverse force, the analysis of models and modeling of the CM destruction process is carried out. At the same time, the complex dynamics of developing processes, and significant amounts of AE information recorded at various levels, lead to ambiguity in the patterns of AE parameter changes and their use for constructing methods for the control, monitoring, and diagnostics of CM.

In some articles, we obtained analytical dependencies that describe acoustic radiation during CM destruction by shear force using the OR criterion and von Mises criterion. It was shown that the generated parameters of AE signals are influenced by various factors: the rate of composite deformation, the composite physical and mechanical characteristics, the dispersity properties of composite, and the area of composite destruction. Theoretical studies make it possible to obtain patterns of AE parameters change under the action of various factors. Such regularities provide the interpretation of AE information and can be the basis for the development methods of control, monitoring, and diagnostics of CM.

At the same time, to increase the reliability of the methods of control, monitoring, and diagnostics of CM, it is important to determine the sensitivity of AE amplitude-energy parameters to the action of various factors.

2. Review of Publications

Conducted studies using the FBM concept [8, 9, 10, 11] are based on some assumptions. CM is represented as a bundle of discrete fibers or elements. If an external linearly increasing load is applied to a material, then its destruction is considered as a process of successive destruction fibers.

The fibers have a linear elastic behavior before failure. Each fiber fractures brittle when its strength value is reached. The value of fiber fracture strength is a random variable with a certain probability density and distribution function. To study the process of CM fibers destruction, the rule for redistributing load on the remaining fibers is determined. These rules are the uniform distribution of load, that is, when the fiber is destroyed, the applied load is evenly redistributed to all remaining fibers; local distribution of load, that is, when the fiber is destroyed, the applied load is redistributed only to the nearest fibers.

The main provisions of the FBM concept are used for the analysis of CM fracture processes both under tension [12, 13, 14] and under the action of shear force [15, 16, 17]. However, in most of the articles, the process of CM destruction under tension conditions is considered. At the same time, using the general provisions of the FBM concept for the analysis of CM destruction processes, additional conditions are introduced: the introduction of two subsets of fibers, one of which is characterized by a probabilistic distribution tensile strength [18]; each fiber having thermal fluctuations of its energy characteristics in the form of white Gaussian noise, which add to the fiber fracture stresses [19]; varying dimension of the system from location fibers at an equal distance from each other along the line to location the fibers at the nodes a square lattice with side L [20]; restoration (sintering) of broken fibers and relaxation of load inhomogeneities (sintering compensates for damage by creating additional undamaged load-bearing fibers, which leads to increase the strength of bundle) [14]; the randomness of fiber configuration, that is, random distribution of fibers along the length [21]; strength distribution of elements according to Weibull [22]; the use of different distributions of threshold levels of destruction [23]; modeling of two materials with different mechanical properties that interact with each other [24]; and others. When modifying models, as a rule, studies are carried out on stresses change, the number of destroyed or remaining elements, time of composite full destruction change, distributions of destruction avalanches change (the number of fiber failures that occur due to the destruction of one fiber) and other characteristics.

At AE analysis in studies[25, 26, 27], AE is considered during the destruction of a CM according to the FBM model. The studies were based on the fact that an AE event is formed when a fiber is destroyed. It was believed that the radiation energy in the event is proportional to the fracture stress, and the rate of destruction obeys a power law with an exponent of 2-5 (determined experimentally). When analyzing the destruction process of a CM, we consider not the process of generating an AE signal, but the process of releasing and accumulating the energy of acoustic radiation. The research results made it possible to obtain an expression for the AE energy release rate. In this case, at the moment of destruction, the functions have a discontinuity.

In other articles [15, 16], the process of CM destruction under the action of shear force was studied for the following cases: independent CM fibers destruction by bending or tension or "or rule" (OR); destruction of fibers according to von Mises criterion; and failure only by tension. Analytical expressions for change of the equivalent stresses and the number of remaining elements during the development destruction process are obtained. Analysis was completed of the patterns of change in equivalent stresses and patterns of change in the number of destroyed CM fibers for different destruction modes, as well as destruction avalanches distributions for different fracture criteria.

Analytical expressions for the number of remaining fibers and AE generated signal in time during CM destruction by shear force using OR criterion and von Mises criterion are considered in articles by Filonenko et al.[28, 29]. These studies were based on the main provisions of the FBM works [15, 16]. It was believed that when a single CM element fails, a single perturbation pulse is formed, the amplitude of which is proportional to the fracture stress. In this case, the kinetics of the destruction process were taken into account, the rate of which, according to the kinetic theory, changes according to an exponential law. The conducted studies' results have shown that with the development of the CM destruction process, dependencies of the number of remaining elements (fibers) change over time and have a continuous falling character. In this case, continuous pulsed AE signals are formed. It was also shown that expressions for the number of remaining fibers and AE-generated signal over time include parameters that affect the CM destruction and AE-generated signals. These parameters are composite deformation rate, composite physical and mechanical characteristics, composite dispersion properties, and composite destruction area.

In one article by Filonenko et al. [30], the influence of composite properties on amplitude-time parameterAE during its destruction by shear force using the von Mises criterion was studied. It was shown that increasing the value of parameter characterizing the CM properties leads to increasing steepness of the fall of the change curves of the remaining elements number over time, decreasing of AE signals' maximum amplitude and duration. The patterns of AE signal maximum amplitude and duration change are determined and described. It is also shown that decreasing AE generated signal maximum amplitude is ahead decreasing of AE signal duration with increasing parameters characterizing the CM properties. The obtained patterns can be used in the development of the methods of control, monitoring, and diagnostics of CM. However, to improve the reliability of methods it is important to determine the sensitivity of AE amplitude-energy parameters to changes in CM properties.

3. Research Results

3.1. Simulation Conditions

The study influence of CM properties on acoustic radiation amplitude parameters in the previously mentionedarticle by Filonenko et al. [30] was carried out when modeling AE signals by expression of the form

$$U(t)=U_0 v_0[\sigma_m(t)-\sigma(t_0)]\cdot e^{r[\sigma_m(t)-\sigma_0(t_0)]}\cdot \\ \cdot e^{-v_0\int_{t_0}^{t} e^{r[\sigma_m(t)]-\sigma_0(t_0)]}dt}, \tag{1}$$

where $\sigma_m(t)$, $\sigma_0(t_0)$ is,respectively, the equivalent stress change on CM elements in time and threshold stress corresponding to a time t_0 of CM beginning destruction; U_0 is the maximum possible displacement during the instantaneous CM destruction, consisting of N_0 elements; v_0, r are constants depending on CM physical and mechanical characteristics.

Modeling of AE signals, according to expression 1, was carried out under the following conditions. The CM deformation rate α was taken equal to $\tilde{\alpha} = 10$. The time $\tilde{t}_0$ of CM beginning destruction was taken equal to $t_0 = 0.004$. This time t_0 corresponds to the threshold stress $\tilde{\sigma}(\tilde{t}_0)$ of CM beginning destruction equal to $\tilde{\sigma}_0 = 0.03037385029676163$. The value of the parameter $\tilde{r}$ was taken equal to $\tilde{r} = 10000$. The value of the parameter $\tilde{v}_0$, which characterizes the CM properties, changed in the range of values from $\tilde{v}_0 = 100000$ to $\tilde{v}_0 = 500000$ with an incremental step $\Delta\tilde{v}_0 = 100000$.

According to the calculation dependence of AE signals amplitudes change at $\tilde{v}_0$ change, we will study the patterns of AE signal energy and AE signal total energy changes. We will calculate the energy of AE signals and total energy of AE signals using expressions of the form

$$\mathrm{E(t)} = \Delta \mathrm{t}_{\mathrm{k}} i U_i^2 \tag{2}$$

$$\mathrm{E}_{\mathrm{sum}} = \Delta \mathrm{t}_{\mathrm{k}} i \sum_i U_i^2 . \tag{3}$$

where $i = 0, \ldots .,$ k is the number of AE signal amplitude calculated value at its duration t; $\Delta \mathrm{t}_{\mathrm{k}}$ is the time interval between the AE signal amplitudes calculated values ($\Delta \mathrm{t}_{\mathrm{k}}$ =constant).

Modeling dependencies of generated AE signal energy change in time, according to expression 2, taking into account (1) at $\tilde{v}_0$ change will be carried out in relative units under the conditions considered above. The time interval $\Delta \mathrm{t}_{\mathrm{k}}$ between AE signal amplitudes calculated values is the $\Delta\tilde{\mathrm{t}}_{\mathrm{k}} = 1 \cdot 10^{-7}$.

3.2. Simulation Results

The results of the calculations of the dependencies of the change in the energy of the AE signals over time in relative units, according to expression 2, are shown in Fig. 1. The results of the calculations of the dependencies of the change in the total energy of AE signals over time in relative units, according to expression 3, are shown in Fig. 2. When plotting Fig. 1 and Fig. 2, the time is given to the time $\tilde{\mathrm{t}}_0 = 0.004$ of CM elements beginning destruction.

The obtained data processing in the form of AE signals maximum and total energy dependencies change in relative units at increase the value of a parameter $\tilde{v}_0$ is shown in Fig. 3.

Analysis dependencies (Fig. 3) showed that they are well described by a power function of the form

$$E_{EA} \quad av \tag{4}$$

where $\tilde{E}_{EA}$ is the AE signals maximum or total energy; a and b are the coefficients of the approximating expression.

The values of approximating expression coefficients (4) are: for the AE signals maximum energy (Fig. 3, *a*) - $a = 0.00001$, $b = -0.24322$; for the AE signals total energy (Fig. 3, *b*) - a = 6.79966, $b = -0.97332$. In describing the dependence in Fig. 3, the determination coefficient R^2 was $R^2 = 0.97435$, and the dependence in Fig. 3, b - $R^2 = 0.99997$. Thus, residual dispersion SD^2 made: for the maximum energy of AE signals - $SD^2 = 3.9944 \cdot 10^{-16}$; for the total energy of AE signals - $SD^2 = 3.1908 \cdot 10^{-16}$.

For describing the dependencies of AE signals maximum and total energy change with the increasing $\tilde{v}_0$, shown in Fig. 3, a criterion for choosing expression 4 was the minimum value of residual dispersion.

To compare the sensitivity of AE signals amplitude and energy parameters change to parameter $\tilde{v}_0$, processing of AE signals maximum amplitude, maximum

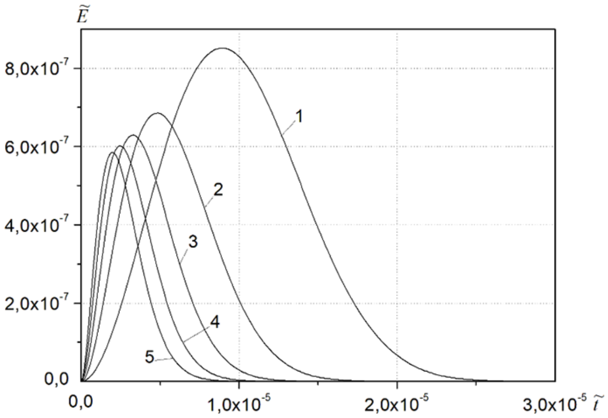


Fig. 1. Graphs of AE signal energy changes in time in relative units during CM destruction by shear force with a change of a parameter $\tilde{v}_0$. The value of parameter $\tilde{v}_0$: 1 - 100000; 2 - 200000; 3 - 300000; 4 - 400000; 5 - 500000. Simulation parameters: $\tilde{\alpha} = 10$, $\tilde{r} = 10000$, $\tilde{\sigma}_0 = 0.008897277688462064$

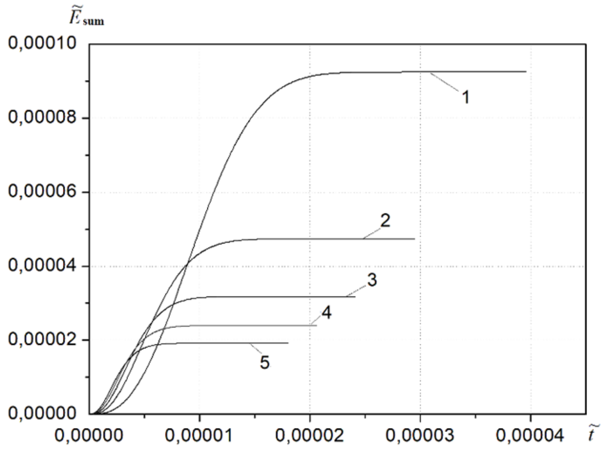
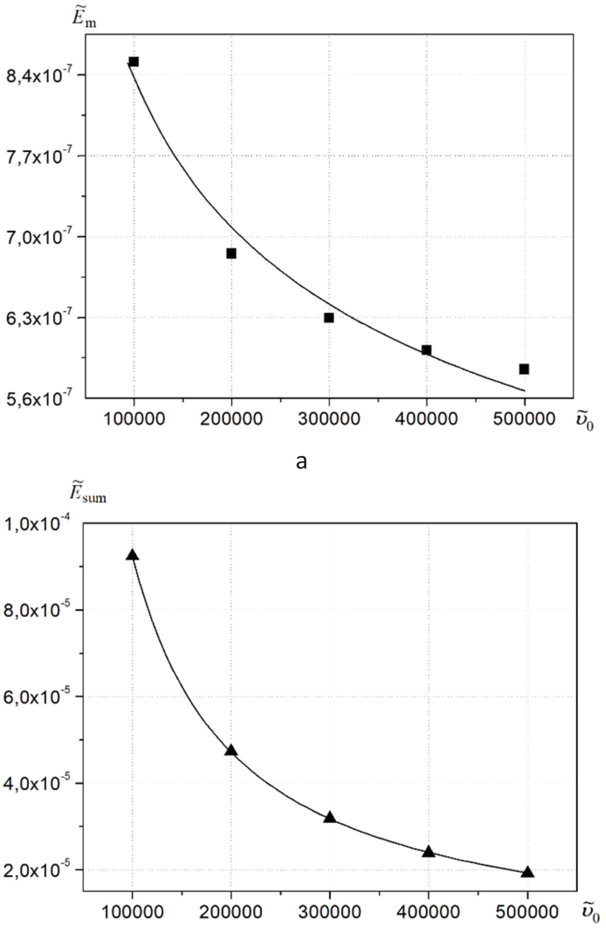


Fig. 2. Graphs of changes in the total energy of AE signals in time in relative units during the destruction of the CM by a transverse force with a change in the parameter $\tilde{v}_0$. The value of the parameter $\tilde{v}_0$: 1 - 100000; 2 - 200000; 3 - 300000; 4 - 400000; 5 - 500000. Simulation parameters: $\tilde{\alpha} = 10$, $\tilde{r} = 10000$, $\tilde{\sigma}_0 = 0.008897277688462064$

energy and total energy decrease concerning their initial values at $\tilde{v}_0$ equal to $\tilde{v}_0 = 100000$ as a percentage was carried out. The results of performed processing are shown in Fig. 4.



a

b

Fig. 3. Dependencies of AE signals maximum energy change (a) and AE signals total energy change on a parameter $\tilde{v}_0$ value in relative units during CM destruction by shear force. Simulation parameters: $\tilde{\alpha} = 10$, $\tilde{r}$=10000, $\tilde{\sigma}_0 = 0.008897277688462064$

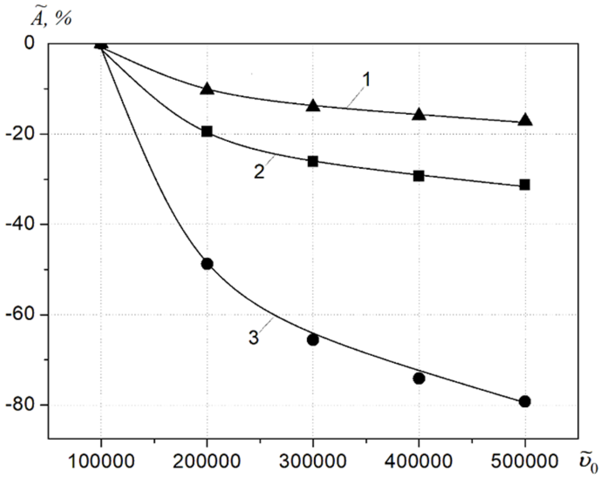


Fig. 4. Dependencies of AE signals maximum amplitude (1), maximum energy (2) and total energy change as a percentage with the increasing parameter $\tilde{v}_0$ value

In Fig. 4, the following notation is adopted: $\tilde{A}$, % isthe analyzed parameter of AE signals – maximum amplitude, maximum energy or total energy of AE signal.

4. Discussion of Research Results

The study of the influence of various factors on AE is important from the point of view of control, monitoring and diagnostics of the state of CM and CM products. In previous studies [30], the influence of the parameter characterizing the properties of the QM on the amplitude-time parameters of the AE was determined. It was shown that an increase in the value of the analyzed parameter leads to a decrease in the amplitude and duration of the generated AE signals. At the same time, the regularity of the decrease in the maximum amplitude of the generated AE signals is ahead of the regularity of the decrease in the duration of the AE signals, which can be used in the development of methods for controlling, monitoring and diagnosing the state of CM and CM products. However, to improve the reliability of the methods, it is important to determine the sensitivity of the amplitude-energy parameters of the AE to changes in the properties of the CM. In this work, we studied the influence of the parameter characterizing the properties of the CM on the energy parameters of the AE, and also determined the sensitivity of the amplitude-energy parameters to its change.

The results of the conducted research show that at CM destruction by shear force according to von Mises criterion, with increasing parameter $\tilde{v}_0$, which characterizes CM properties, both the maximumenergy (Fig. 1) and total energy (Fig. 2) of AE signals decrease. Thus, the dependencies of AE signals' maximum energy and total energy change with the increasing $\tilde{v}_0$ have a non-linear nature of decrease (Fig. 3). Both the maximum amplitude of the AE signals and their duration have similar nonlinear dependencies on the decrease.

Analysis of simulation results shows that the patterns of AE signal maximum and total energy change are well described by power functions, as in the case of the maximum amplitude and duration of AE signals. Such a change in the parameters of AE signals requires determining their sensitivity to a change in the parameter characterizing the properties of the KM.

To compare the sensitivity of the amplitude-energy parameters of the AE signals to a change in the parameter $\tilde{v}_0$, the processing of the decrease in the maximum amplitude, maximum energy, and total energy of the AE signals concerning their initial values at $\tilde{v}_0$ equal to $\tilde{v}_0$ =100000 as a percentage was carried out.The calculation results showed (Fig. 4) that with increasing parameter $\tilde{v}_0$ value decrease of AE signals maximum energy ahead decreasesAE signals maximum amplitude. At the same time, a decrease AE signals total energy ahead decreases AE signals maximum energy. Thus, at increasing $\tilde{v}_0$ 2 times (from $\tilde{v}_0 = 100000$ to $\tilde{v}_0 = 200000$) AE signals' maximum amplitude decreases by 10.29%, and AE signal maximum and total energy, respectively, decrease by 19.53% and by 48, 78%. At increasing $\tilde{v}_0$ 4 times (from = 100000 to $\tilde{v}_0$ = 400000) AE signals maximum amplitude decreases by 15.95%, and AE signal maximum and total energy, respectively, decrease by 29.35% and by 74.15 %. At increasing $\tilde{v}_0$ in 5 times (from $\tilde{v}_0$= 100000 to $\tilde{v}_0$ = 500000), AE signals maximum amplitude decreases by 17.11%, and AE signal maximum and total energy, respectively, decrease by 31.3% and by 79.29%.

It can be seen from the obtained results that the most sensitive parameter of acoustic radiation to a parameter change, which characterizes CM properties, is registered AE signal total energy (accumulated energy) – its decrease is much ahead of the decrease of AE signal maximum amplitude and maximum energy. The obtained pattern of changes in the total energy of AE signals with a change in the parameter up to $\tilde{v}_0$ can be used in the development of methods for control, monitoring and diagnostics of CM, as well as predicting the destruction of products from CM when registering AE signals under given conditions. At the same time, the developed methods should be based on monitoring the rate of change in the total energy of AE signals, the pattern of change of which is well described by a power function.

At the same time, according to expression 1, the AE parameters are affected by several other factors, which are the dispersity of the properties of the CM, the area of the destroyed CM, and the rate of loading of the CM. Undoubtedly, the analysis of their AE influence will make it possible to determine the most significant factors, patterns of change in the amplitude-energy parameters of the AE and their sensitivity. The choice of the analyzed parameters will increase the reliability of the developed methods for control, monitoring and diagnostics of CM and CM products.

5. Conclusion

The paper presents the results of modeling AE signal energy during CM consisting of N_0 elements destruction by shear force using the von Mises criterion depending on a parameter $\tilde{v}_0$, which characterizes CM properties. It is determined that increase of parameter $\tilde{v}_0$, there is a decrease in acoustic radiation maximum energy and total energy. It is shown that the patterns of AE signals maximum and total energy change have a non-linear nature decrease. It is determined that the dependencies of AE signal maximum and total energy change are well described by power functions. The influence of parameter $\tilde{v}_0$ on the acoustic radiation amplitude and energy characteristics is compared. It is shown that with an increasing value of the parameter $\tilde{v}_0$, the decrease in the maximum energy is ahead of the decrease in the AE signals maximum amplitude, and a decrease of AE signals total energy ahead decreases AE signals maximum energy. Thus, at increasing $\tilde{v}_0$ 2 times AE signals maximum amplitude decreases by 10.29%, and AE signal maximum and total energy, respectively, decrease by 19.53% and by 48.78%. At increasing $\tilde{v}_0$ in 5 times, AE signals' maximum amplitude decreases by 17.11%, and AE signal maximum and total energy, respectively, decrease by 31.3% and by 79.29%. Obtained results showed that the most sensitive AE parameter to change of parameter $\tilde{v}_0$ is the registered AE signal total energy.

Research data can be used in the development methods of control, monitoring, and prediction of product destruction from CM at the stages of their production and operation. In the future, it may beinteresting to study the influence of CM properties' dispersity on AE signals' amplitude-energy parameters.

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References

[1] S. Clay et al., „Comparison of Diagnostic Techniques to Measure Damage Growth in a Stiffened Composite Panel," *Composites Part A: Applied Science and Manufacturing*, vol. 137, 2020, 106030.

[2] B. Wang et al., „Non-Destructive Testing and Evaluation of Composite Materials/Structures: A State-of-the-Art Review," *Advances in mechanical engineering,* vol. 12, no. 4, 2020, 1687814020913761.

[3] R. Gupta et al., „A Review of Sensing Technologies for Non-Destructive Evaluation of Structural Composite Materials," *Journal of Composites Science,* vol. 5, no. 12, 2021, p. 319.

[4] Z. Fan, M.H. Santare, and S.G. Advani, „Interlaminar Shear Strength of Glass Fiber Reinforced Epoxy Composites Enhanced With Multi-Walled Carbon Nanotubes," *Composites Part A: Applied Science and Manufacturing,* vol. 39, no. 3, 2008, pp. 540–554.

[5] Y. Liuet al., „Experimental Research on Shear Failure Monitoring of Composite Rocks Using Piezoelectric Active Sensing Approach," *Sensors,* vol. 20, no. 5, 2020, 1376.

[6] B.D. Coleman, „Time Dependence of Mechanical Breakdown Phenomena." *Journal of Applied Physics,* vol. 27, no. 8, 1956, pp. 862–866.

[7] A. Hansen, P.C. Hemmer, and S.Pradhan. *The Fiber Bundle Model: Modeling Failure in Materials*, John Wiley & Sons, 2015.

[8] F. Kun, S. Zapperi, and H.J. Herrmann, „Damage in Fiber Bundle Models," *The European Physical Journal B-Condensed Matter and Complex Systems,* vol. 17, no. 2,2000, pp. 269–279.

[9] Y. Moreno, J.B. Gómez, and A.F. Pacheco, „Self-Organized Criticality in a Fibre-Bundle-Type Model," *Physica A: Statistical Mechanics and its Applications,* vol. 274, no. 3–4, 1999, pp. 400–409.

[10] Hemmer, P. C., and Hansen, A. (December 1, 1992). "The Distribution of Simultaneous Fiber Failures in Fiber Bundles." ASME. *J. Appl. Mech*. December 1992; 59(4): 909–914.

[11] W.I.Newman and S.L. Phoenix, „Time-Dependent Fiber Bundles with Local Load Sharing," *Physical Review E,* vol. 63, no. 2, 2001, 021507.

[12] S. Pradhan, A. Hansen, and B.K. Chakrabarti, „Failure Processes in Elastic Fiber Bundles," *Reviews of Modern Physics,* vol. 82, no. 1, 2010, p. 499.

[13] A. Hader, et al., „Failure Kinetic and Scaling Behavior of the Composite Materials: Fiber Bundle Model with the Local Load-Sharing Rule (LLS)," *Optical Materials,* vol. 36, no.1, 2013, 3–7.

[14] A. Capelli et al., „Fiber-Bundle Model with Time-Dependent Healing Mechanisms to Simulate Progressive Failure of Snow," *Physical Review E,* vol. 98, no. 2, 2018, 023002.

[15] F. Raischel, F. Kun, and H.J. Herrmann, „Simple Beam Model for the Shear Failure of Interfaces," *Physical Review E*, vol. 72, no. 4, 2005, 046126.

[16] F. Raischel, F. Kun, and H.J. Herrmann, „Local Load Sharing Giber Bundles with a Lower Cutoff of Strength Disorder," *Physical Review E,* vol. 74, no. 3, 2006, 035104.

[17] G. Michlmayr, D. Or, and D.Cohen, „Fiber Bundle Models for Stress Release and Energy Bursts During Granular Shearing," *Physical Review E,* vol. 86, no.6, 2012, 061307.

[18] K. Kovácset al., „Brittle-to-Ductile Transition in a Fiber Bundle with Strong Heterogeneity," *Physical Review E,* vol. 87, no. 4, 2013, 042816.

[19] S.G. Abaimov, „Non-Equilibrium Annealed Damage Phenomena: A Path Integral Approach," *Frontiers in Physics,* 2017, p. 6.

[20] Z. Danku, G. Ódor, and F.Kun, „Avalanche Dynamics in Higher-Dimensional Fiber Bundle Models," *Physical Review E,* vol. 98, no. 4, 2018, 042126.

[21] Y. Yamadaand Y.Yamazaki, „Avalanche Distribution of Fiber Bundle Model with Random Displacement," *Journal of the Physical Society of Japan,* vol. 88, no.2, 2019, 023002.

[22] A.R. Oskoueiand M.Ahmadi, „Fracture Strength Distribution in E-Glass Fiber Using Acoustic Emission," *Journal of Composite Materials,* vol. 44, no.6, 2010, 693–705.

[23] S. Pradhan, J.T. Kjellstadli, and A.Hansen, „Variation of Elastic Energy ShowsReliable Signal of Upcoming Catastrophic Failure," *Frontiers in Physics,* vol. 7, 2019, p. 106.

[24] M. Monterrubio-Velascoet al., „A Stochastic Rupture Earthquake Code Based on the Fiber Bundle Model (TREMOL v0. 1): Application to Mexican Subduction Earthquakes." *Geoscientific Model Development,* vol. 12, no. 5, 2019, pp. 1809–1831.

[25] Shcherbakov, R. "On modeling of geophysical problems: a dissertation for degree of doctor of philosophy/Robert Shcherbakov.-Cornell university, 2002.-209 p." (2002).

[26] D.L. Turcotte, W.I. Newman, and R.Shcherbakov, „Micro and Macroscopic Models of Rock Fracture," *Geophysical Journal International,* vol. 152, no. 3, 2003, pp. 718–728.

[27] F. Bosiaet al., „Mesoscopic Modeling of Acoustic Emission Through an Energetic Approach," *International Journal of Solids and Structures,* vol. 45, no. 22–23,2008, pp. 5856–5866.

[28] S. Filonenko, V. Kalita, and A. Kosmach, „Destruction of Composite Material by Shear Load and Formation of Acoustic Radiation," *Aviation,* vol. 16, no. 1, 2012, pp. 1–9.

[29] S. Filonenkoand V.Stadychenko, „Influence of Loading Speed on Acoustic Emission During Destruction of a Composite by Von Mises Criterion," *American Journal of Mechanical and Materials Engineering,* vol. 4, no.3, 2020, pp. 54–59.

[30] S. Filonenkoand A.Stakhova, „Acoustic Emission at Properties Change of Composite Destructed by von Mises Criterion," *Electronics and Control Systems,* vol. 1, no.67, 2021, pp. 54-60.