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ACOUSTIC EMISSION DURING COMPOSITES FRACTURE ACCORDING VON MISES CRITERION AND CHANGING OF ITS PROPERTIES DISPERSTION

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Abstract**—***The results of modeling composite elements process destruction by shear force according to von Mises criterion and acoustic emission signals generated with decrease of composite properties dispersion are considered. It has been determined that decrease of composite properties dispersion leads to increase the rate of fall the curves change in the remaining elements in time and decrease the time of fracture process. It was found that with decrease of composite properties dispersion there is increase of generated acoustic emission signal amplitude and decrease in its duration. It has been determined that the regularities of generated acoustic emission signals maximum amplitude increase and acoustic emission signals duration decrease are well described by power-law functions. Comparison of the obtained data with the data at composite destruction according to the OR criterion is carried out. It has been determined that the patterns of acoustic emission signals maximum amplitudes and durations change are similar. However, when using the OR criterion, the values of acoustic emission signals amplitudes and durations are higher than when using the Mises criterion.*

Index Terms—Acoustic emission; amplitude of acoustic emission; signal duration; destruction criterion; composite material.

I. INTRODUCTION

Investigation of composite materials (CM) processes destruction is carried out using various methods. This is due to the need ensure the quality products made of composite materials, which are prone to brittle destruction. One of the research methods is the method of acoustic emission (AE). Its application is due to the peculiarities of AE method. AE method is a dynamic method. The recorded AE signals are reflection of dynamic processes occurring in the structure material during its deformation and destruction. Radiation of AE signals occurs during the development of plastic deformation processes, the formation and cracks growth at submicro, micro and macrolevels. AE method is the integral method - registration of acoustic radiation sources is carried out from the entire volume of deformable material (product).

Such advantages of the AE method make it possible to obtain significant amounts information about the mechanisms and processes that develop in the structure of the material when it is loaded. The processing and analysis of this information is aimed at finding the patterns of AE parameters changes. These patterns are used to develop methods for control, monitoring and assessment of products state or processes that determine the bearing capacity of material (product).

However, the significant advantages of AE method lead to the problem of interpreting the AE recorded information and the problem of identifying the processes developing in the structure of the material when it is loaded. The problem is also complicated by the influence of various factors on AE. These problems lead to the complexity of creating methods for control, monitoring and assessment of products condition. In solving the above problems, first of all, the interpretation and identification of processes in the material structure, theoretical studies of AE signals formation and radiation are importance. Models and modeling of AE signals for the accepted models of materials destruction, including CM, makes it possible to study the influence of various factors on radiation processes and generated signals parameters, as well as to determine the patterns of their change. The results of such studies are basis for the methods of control, monitoring and assessment of material (product) bearing capacity, taking into account the processes that developing in material structure.

II. PROBLEM STATEMENT

The aim of this work is analyzing the effect of CM properties dispersion on generated AE signals parameters upon composite fracture by shear force according to von Mises criterion.

For achievement the purpose of article the following problems were put:

- to simulate the process of CM destruction by shear force according to von Mises criterion in time and AE signals when changing the composite properties dispersion;
- to process the data to determine the patterns of generated AE signals maximum amplitude and duration change when changing the CM properties dispersion, which is destroyed by shear force according to von Mises criterion.

III. REVIEW OF PUBLICATIONS

When studying the CM destruction processes, various models are used, one of which is the fiber bundle-model (FBM). The model was first considered in [1]. The model was developed and used to study a wide range of heterogeneous materials, including CM [2] – [8].

In the FBM model, the behavior of system is considered as a result of given number single elements (fibers) interaction.

Elements of the system have certain properties (strength) that have a given distribution law. When loading elements, the elastic deformation condition is met.

To analyze the destruction process, two main approaches to distribute the load on the remaining elements are used: global distribution, i.e. even load distribution on all remaining elements; local distribution, i.e. load distribution on the nearest (adjacent) elements. Thus the analysis of remaining elements rate change in time depending on elements stress change is carried out, as well as the analysis of expected time distraction at a given load, i.e. formation of a forecast.

In the majority works using the FBM model, the conditions of inhomogeneous material uniaxial tension are considered [2] – [8]. At the same time, the FBM model is used when considering of material destruction process under the action of shear force [9] – [11], including granular materials [12], [13]. Thus, the original positions of the FBM model remain unchanged. In articles [9] – [11], it was assumed that under the action of shear force, CM elements fracture can occur upon reaching critical stresses in bending, tension, or jointly bending and tension. Expressions that describe of material elements equivalent stress change for various fracture criteria are obtained. Thus the analysis of remaining CM elements number regularities changes during development of destruction process was carried out. In articles [12], [13] use the basic provisions of FBM model under the action of shear force. However, during the elements (granules) destruction they are considered as a new group of elements with a new values of threshold fracture stresses.

When analyzing the fracture process using the FBM model, the AE is also considered [4], [5], [9], [14], [15]. However, is considered not the process of AE signal formation, but AE energy release rate or AE energy accumulated, which is aimed at predicting of material destruction.

In articles [16], [17], using the FBM model and self-development destruction process when loading CM with a shear force, expressions for the number of remaining elements in time and generated AE signal were obtained. The studies were carried out, respectively, using destruction according to the "OR" ("or rule") rule and von Mises criterion. In both cases, it was shown that with the development of CM elements destruction process, the dependences of remaining elements change in time have a continuous character of falling. Thus continuous impulse AE signals are formed. However, it was shown that for simulating conditions of the same type, when using the von Mises criterion, the amplitude of generated AE signal is less, and its duration is longer than when using the OR criterion. In article [18], studies the influence of CM elements fracture process according to von Mises criterion and the generated AE signals with increase of deformation rate were carried out. It is shown that with increase of CM deformation rate the regularity of generated AE signals maximum amplitude change has a linear character of increase, and their duration is non-linear character of decrease. Thus, a gradual transformation of AE signal form into a triangular signal is observed.

In articles [17], [18], it is shown that when CM distraction at the expressions of remaining elements number in time and generated AE signal include parameters that effect on rate destruction process and generated AE signal parameters. One of these parameters is the CM properties dispersion. Of course, it is of interest to study the effect of CM properties dispersion on AE upon its destruction according to von Mises criterion.

IV. RESULTS OF RESEARCHES

Modeling the composite destruction process by shear force according to von Mises criterion (the number of remaining elements in time $N(t)$) and generated AE signal $U(t)$ will be carried out according to the expressions considered in article [17], in the form

$$N(t) = N_0 e^{-\upsilon \int_{t_0}^{t} e^{r[\sigma_m(t) - \sigma(t_0)]} dt}, \qquad (1)$$

$$U\left(t\right)=U_0\upsilon_0\left[\sigma_m(t)-\sigma(t_0)\right]\cdot e^{r[\sigma_m(t)-\sigma(t_0)]}\cdot e^{-\upsilon_0\int\limits_{t_0}^{t}e^{[\sigma_m(t)-\sigma(t_0)]}dt}, \qquad (2)$$

where $\sigma_m(t)$, $\sigma_0(t_0)$ is the respectively, equivalent tension change on CM elements in time with linear strain input $\varepsilon=\alpha t$ (α is the strain rate) and threshold tension corresponding to a time point t_0 of CM beginning destruction;

$$\sigma_m\left(t\right)=\alpha t\cdot 0.5\left[\left(2-2\sqrt{\alpha t}+\alpha t^{\frac{3}{2}}\log\left(\frac{1+\alpha t}{1-\alpha t}\right)\right)\right.$$
$$\left.-\alpha t^{\frac{3}{2}}\left(2\sqrt{\frac{1-\sqrt{\alpha t}}{\alpha t}}+\log\left(\frac{1+\sqrt{1-\sqrt{\alpha t}}}{1-\sqrt{1-\sqrt{\alpha t}}}\right)\right)\right], \qquad (3)$$

$$\sigma_0\left(t_0\right)=\alpha t_0\cdot 0.5\left[\left(2-2\sqrt{\alpha t_0}+\alpha t_0^{\frac{3}{2}}\log\left(\frac{1+\alpha t_0}{1-\alpha t_0}\right)\right)\right.$$
$$\left.-\alpha t_0^{\frac{3}{2}}\left(2\sqrt{\frac{1-\sqrt{\alpha t_0}}{\alpha t_0}}+\log\left(\frac{1+\sqrt{1-\sqrt{\alpha t_0}}}{1-\sqrt{1-\sqrt{\alpha t_0}}}\right)\right)\right], \qquad (4)$$

$U_0=N_0\beta\delta_s$ maximum possible displacement during instantaneous destruction of a CM sample consisting of N_0 elements; β proportionality coefficient between the fracture stress and amplitude single disturbance impulse at single CM element destruction; δ_s parameter, the numerical value of which is determined by shape of single impulse disturbance during of CM single element destruction; υ_0, r constants depending from CM physical-mechanical characteristics.

Parameter that characterizes of CM properties dispersion is the parameter *r*. Increase of parameter *r* corresponds to decrease of CM properties dispersion.

Modeling the number of remaining elements at CM destruction in time and the generated AE signals will be carried out in relative units. In this case, the value of the parameter *r* will be changed in the range of values from $\tilde{r}$ = 10000 to $\tilde{r}$ = 26000 with an increment step of $\Delta\tilde{r}$ = 40000.

When modeling value of sizes υ_0 and α in expressions (1), (2), (3) and (4) we will accept the equal: $\tilde{\upsilon}_0$ = 100000, $\tilde{\alpha}$ = 10. Let's consider that at deformation speed $\tilde{\alpha}$ = 10 destruction of CM elements begins in a time point t_0. We will accept the time t_0 of CM beginning destruction equal $\tilde{t}_0=0.001$.

According to the carried-out calculations of equivalent stresses dependence change in time according to (3) at $\tilde{\alpha}=10$ (Fig. 1), to a time point $\tilde{t}_0=0.001$ there corresponds the threshold stress of CM beginning destruction equal $\tilde{\sigma}_0=0.008897277688462064$.

The results calculations in the form of quantity remained elements dependences change in relative units $\left(\tilde{N}(t)=N(t)/N_0\right)$, agrees (1), at CM destruction for modeling accepted conditions are shown in Fig. 2.

Let's carry out calculations of AE signals amplitude dependence change in time at reduction of CM properties dispersion. Results of carried-out calculations in the form of AE signal amplitude dependences change in relative units $\left(\tilde{U}(t)=U(t)/U_0\right)$, for the accepted modeling conditions, agrees (2), are shown in Fig. 3.

The received results (Fig. 3) show that reduction of CM properties dispersion does not lead to a change of acoustic radiation character, the formed of AE signals are continuous pulse signals.

In Figure 4 dependences of formed AE signal maximum amplitude and duration change with reduction of cm properties dispersion are shown.

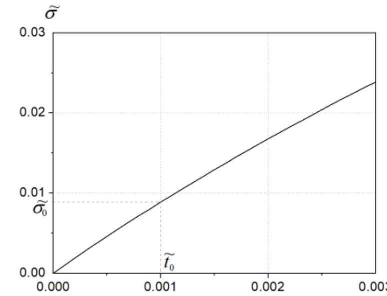


Fig. 1. Dependence of equivalent stress change in time, agrees (3), at linear deformation speed change $\tilde{\alpha}=10$

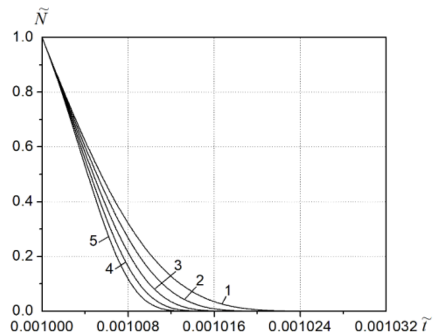


Fig. 2. Graphs of quantity remained elements change, agrees (1), in relative units at CM destruction by shear force. Value of parameter *r*: $1-\tilde{r}=10000$; $1-\tilde{r}=14000$; $1-\tilde{r}=18000$; $1-\tilde{r}=22000$; $1-\tilde{r}=26000$. $\tilde{\upsilon}_0=100000$, $\tilde{\alpha}=10$. $\tilde{\upsilon}_0=0.008897277688462064$. Time of beginning destruction $\tilde{t}_0=0.001$

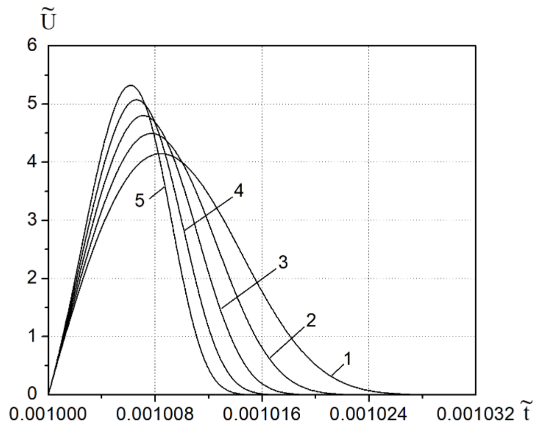
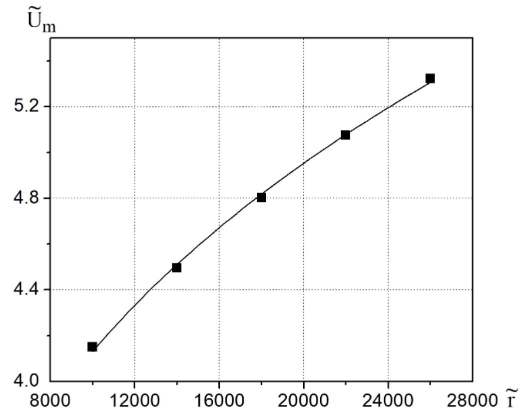
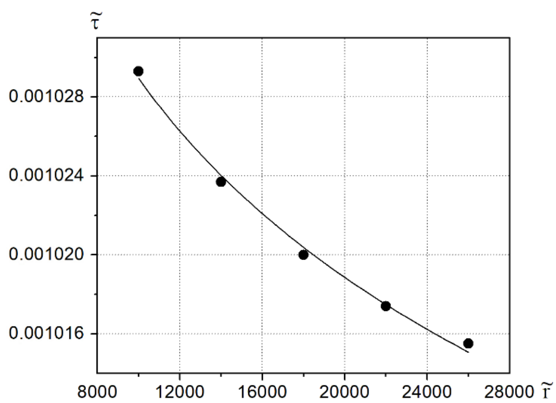


Fig. 3. Graphs of AE signals amplitude change AE in time, agrees (2), in relative units at CM elements destruction by shear force. Value of parameter *r*: $1-\tilde{r}=10000$; $1-\tilde{r}=14000$; $1-\tilde{r}=18000$; $1-\tilde{r}=22000$; $1-\tilde{r}=26000$. $\tilde{\upsilon}_0=100000$, $\tilde{\alpha}=10$. $\tilde{\sigma}_0=0.008897277688462064$. $\tilde{\upsilon}_0=100000$, $\tilde{\alpha}=10$. $\tilde{\sigma}_0=0.008897277688462064$. Time of beginning destruction $\tilde{t}_0=0.001$



a)



b)

Fig. 4. Dependences of AE signals maximum amplitude (a) and duration (b) change in relative units at CM elements destruction by shear force with reduction of composite properties dispersion (increase of parameter *r*)

The obtained results show that with reduction of CM properties dispersion dependence of formed AE signals maximum amplitude change has nonlinear nature of increase (Fig. 4a).

Approximation of the obtained dependence shows that it is well described by a power function of a look

$$\tilde{U}=a\tilde{r}^{b}, \tag{5}$$

where *a* and *b* approximating expression coefficients which values make: *a* = 0.3691, *b* = 0.26221.

At description dependence that shown in Fig. 4a, expression (5) determination coefficient R^2 made R^2 = 0.99862. Thus residual dispersion SD^2 made SD^2 = 0.0004. For description dependence on Fig. 4a criterion for choice approximating expression (5) was minimum of residual dispersion.

At the same time, with reduction of CM properties dispersion dependence of AE signal duration change has not linear nature of reduction (Fig. 4b).

Approximation of the obtained dependence shows that it is well described by a power function of a look

$$\tilde{\tau}=c\tilde{r}^{d}, \tag{6}$$

where *c* and *d* approximating expression coefficients which values make: *c* = 0.00117, *d* = – 0.01418.

At description dependence that shown in Fig. 4b, expression (6) determination coefficient R^2 made R^2 = 0.99516. Thus residual dispersion SD^2 made $SD^2 = 1.9177 \cdot 10^{-13}$. For description dependence on Fig. 4b criterion for choice approximating expression (6) was minimum of residual dispersion.

For comparison the obtained regularities of AE signals maximum amplitude and duration change at reduction of CM properties dispersion at composite destruction by von Mises criterion calculations of similar regularities at composite destruction by OR criterion was carried out. Calculations were moved, according to expression of AE signal amplitude change in time considered in work [17] for conditions approach model of CM destruction by OR criterion to model of composite destruction by von Mises criterion. The carried-out calculations results are shown in Fig. 5.

From Figure 5 it is visible that at CM destruction by OR criterion and von Mises criterion with reduction of CM properties dispersion dependence of AE signals amplitude and duration change are similar.

V. DISCUSSION OF RESEARCHES RESULTS

Modeling of stress change by von Mises criterion at linear deformation input shows that it has nonlinear nature of change (see Fig. 1). At reduction of CM properties dispersion (increase value of parameter r) the remained CM elements curve changes in time have the continuous and accelerated nature of falling. Thus the bigger value has parameter r, the more steepness falling of remained CM elements dependence change in time, i.e. is higher the speed of CM elements destruction. Such increase in speed of destruction at constant quantity CM elements N_0 leads to reduction of course CM destruction process time (see Fig. 2).

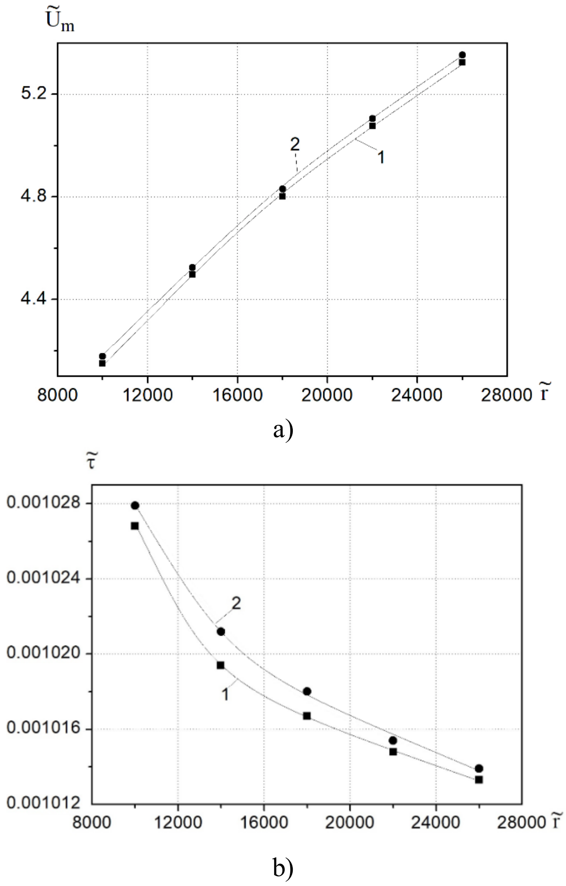


Fig. 5. Dependences of AE signals maximum amplitude (a) and duration (b) change in relative units at CM elements destruction a shear force with reduction of composite properties dispersion (increase parameter r): *1* is the composite destruction by von Mises criterion; *2* is the composite destruction by OR criterion

The carried-out calculations also show (see Fig. 3) that reduction of CM properties dispersion does not lead to deviation in nature of formed AE signals change. Signals of AE are continuous pulse signals. However, reduction of CM properties dispersion leads to increase of AE signal amplitude and reduction of its duration (compression of AE signal in time) (see Fig. 3). Such change of AE signal parameters is caused by increase in speed of CM destruction process (see Fig. 2) and reduction of its course time. Thus AE signals amplitude and duration have nonlinear nature of change. Processing the results modeling showed that dependences of AE signals amplitude and duration change are well described by power functions.

The researches results show that dependences of AE signals amplitude and duration change at CM destruction by von Mises criterion and OR criterion at reduction of composite properties dispersion are similar. Regularities of a.e. signals maximum amplitude change have a nonlinear nature increase, and regularities of AE signals duration change have a nonlinear nature reduction.

At the same time, both for amplitude, and for duration of AE signals at CM destruction by von Mises criterion smaller values of calculated parameters are observed, than at composite destruction by OR criterion. As show calculations, the deviation in values of AE signals maximum amplitudes at CM destruction by OR criterion OR and von Mises criterion is not exceeded by 2%, and deviations in duration of AE signals do not exceed 1%. Such deviation of AE signals parameters as it is noted in article [17], is caused by distinction in the equivalent stress speed change with approach to the moment of the destruction beginning time $\tilde{t}_0 = 0.001$ – equivalent stress speed increase by OR criterion is higher, than by von Mises criterion. At the same time, at smaller values of beginning destruction threshold stress the smaller values of AE signals parameters deviations are observed. So, it agrees [17], at CM beginning destruction time $\tilde{t}_0 = 0.01$ (the beginning destruction threshold stress made $\tilde{\sigma}_0 = 0.05862777965495844$) amplitude deviation made 7.86%, and duration deviation made 3%. Such reduction of AE signals parameters deviations at reduction of beginning destruction threshold stress is connected with reduction of distinctions in equivalent stress speeds change by von Mises criterion and OR criterion with approach to the moment of time CM elements beginning destruction.

VI. Conclusion

Results of modeling CM elements destruction process by shear force by von Mises criterion and formed AE signals at reduction of composite properties dispersion are considered. It is shown that to reduction of composite properties dispersion there is increase in the steepness of falling curves CM remained number elements in time. Thus there is reduction of CM elements destruction process time. Such change regularities of CM remained number elements in time and reduction of composite destruction process time course is caused by increase of CM destruction process speed course.

It is shown that reduction of CM properties dispersion does not lead to change of formed acoustic radiation character. AE signals are pulse continuous signals. Regularities of AE signals maximum amplitude and duration change at reduction of CM properties dispersion are received. Description regularities of AE signals maximum amplitude increase and duration decrease at reduction of CM properties dispersion is carried out. It is defined that the received regularities well are described by power functions. Comparison of the received regularities with similar regularities at CM destruction by shear force with using OR criterion is carried out. It is shown that dependences of formed AE signals amplitude and duration change with reduction of composite properties dispersion at its destruction by von Mises criterion and OR criterion are similar. At the same time, it is observed deviations in values parameters of formed AE signals. It is shown that when using OR criterion value of AE signals amplitudes and duration is higher, than when using von Mises criterion. Such distinctions in AE signals parameters are caused by distinctions in equivalent stress speeds change with approach to the moment of CM elements beginning destruction time. Thus with reduction of beginning destruction threshold stress level percentage deviation of formed AE signals parameters at composite destruction by von Mises criterion and OR criterion is decreases.

In further researches influence of CM square (quantity elements) at destruction processes and formed AE signals parameters is of interest.

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С. Ф. Філоненко, А. П. Стахова. Акустична емісія при руйнуванні композита за критерієм Мізеса і зміні дисперсності його властивостей

Розглянуто результати моделювання процесу руйнування елементів композита поперечною силою за критерієм Мізеса і формованих сигналів акустичної емісії при зменшенні дисперсності властивостей композита. Визначено, що зменшення дисперсності властивостей композита приводить до зростання швидкості падіння кривих зміни елементів, що залишаються, в часі і зменшенні часу протікання процесу руйнування. Отримано, що із зменшенням дисперсності властивостей композита відбувається зростання амплітуди формованого сигналу акустичної емісії і зменшення його тривалості. Визначено, що закономірності зростання максимальної амплітуди формованих сигналів акустичної емісії і зменшення тривалості сигналів акустичної емісії добре описуються степеневими функціями. Проведено порівняння отриманих даних з даними при руйнуванні композита по критерію OR. Визначено, що закономірності зміни максимальної амплітуди і тривалості сигналів акустичної емісії подібні. Однак при використанні критерію OR значення амплітуд і тривалості сигналів акустичної емісії більше, ніж при використанні критерію Мізеса.

Ключові слова: акустична емісія; амплітуда акустичної емісії; тривалість сигналу; критерій руйнування; композиційний матеріал.

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С. Ф. Филоненко, А. П. Стахова. Акустическая эмиссия при разрушении композита по критерию Мизеса и изменении дисперсности его свойств

Рассмотрены результаты моделирования процесса разрушения элементов композита поперечной силой по критерию Мизеса и формируемых сигналов акустической эмиссии при уменьшении дисперсности свойств композита. Определено, что уменьшение дисперсности свойств композита приводит к возрастанию скорости падения кривых изменения оставшихся элементов во времени и уменьшение времени протекания процесса разрушения. Получено, что с уменьшением дисперсности свойств композита происходит возрастание амплитуды

формируемого сигнала акустической эмиссии и уменьшение его длительности. Определено, что закономерности возрастания максимальной амплитуды формируемых сигналов акустической эмиссии и уменьшения длительности сигналов акустической эмиссии хорошо описываются степенными функциями. Проведено сравнение полученных данных с данными при разрушении композита по критерию OR. Определено, что закономерности изменения максимальных амплитуд и длительностей сигналов акустической эмиссии подобны. Однако при использовании критерия OR значения амплитуд и длительностей сигналов акустической эмиссии выше, чем при использовании критерия Мизеса.
Ключевые слова: акустическая эмиссия; амплитуда акустической эмиссии; длительность сигнала; критерий разрушения; композиционный материал.

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