Impact response of textile-reinforced composite materials

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Abstract

Experimental and numerical studies of impact strength of a textile-reinforced composite material at collision velocities of up to 1,5 km / sec. Probabilistic model of material damage is proposed taking into account the probabilistic nature of restoring of bonds in it at different impact velocities. A method for determining the criterion of probabilistic restoring of bonds in the material is proposed based on the analysis of oscillatory processes in the material under impact. The numerical results showed a better agreement between calculated and experimental curves in comparison with standard numerical models.

1. Introduction

Used in aircraft and other areas modern textile-reinforced composite materials are complex multi-component systems, which demonstrate complexity of processes occurring in them under application of loads due to peculiarities of their structure. Predicting the conditions under which structural failure occurs for the structure made of such material and having a certain shape and size is an important task for practical application of such structures with a high degree of reliability and safety. Such analysis has an especially important role in the case of considering structures intended for exploitation at anticipated significant impact loads. In such cases on reliability of the structure people's lives often depend or its damage leads to substantial inventory losses. The problem of damage of aircrafts as well as of other high-velocity vehicles during their operation due to impact interaction with other objects explains the relevance of studies of the used for design purposes materials under action of impact loads.

Development of numerical models of composite materials demands understanding of the fundamental mechanisms of damage of their meso-structure [1]. Complexity of the analysis of material destruction at the fiber-matrix interface as of a separate type of fracture, which in many cases plays a key role in the loss of composite strength, since the bonding at fiber-matrix interface directly affects the quality of stress redistribution in the material volume, causes the importance of additional experimental researches in this direction. Hence the task of developing physically based models of behavior of textile-reinforced composites in a wide range of intensity of applied loads and also of finding ways to increase the strength and resilience of these materials to destroying impact loads. Attempts of development of such models of material behavior, both in static and under dynamic loads, rely on the works [2-10]. Key provisions in this case is are usage of damage mechanics approaches in combination with physically reasonable failure criteria, as well as the use of energy approach in the analysis of processes occurring in the material. The special role is given to a comprehensive experimental study of the material under the load action [8, 11].

In this paper an attempt is made to develop a probabilistic approach to modeling the behavior of textile-reinforced composite materials under impact on basis of analysis of experimentally obtained data. A new approach is realized at conducting research, which includes a joint analysis of electromagnetic (EMO), acoustic (AO) oscillations and energy distribution analysis in design. This approach allowed insight into the processes of material damage and destruction and to simulate them within the bounds of methods of numerical analysis of composite structures.

2. Materials and Methods

A representative textile-reinforced multiphase composite material was chosen as the object of investigation, which is a hybrid-garn composite GF/PP HG on the basis of the E-type glass fibers and polypropylene matrix. Fiber content is equal to 60% by weight of the material, which corresponds to 35% by volume. Material is manufactured using the twill weave type. Panels of which the test samples were subsequently cut were prepared using the technology of hot pressing. Material was placed in a vacuum chamber and subjected to heating to a temperature of 200°C under a pressure of 6 atm. Layers of the material are arranged with the angle of mutual rotation of 90°. The thickness of a single layer is 0,5 mm. Characteristics of the material in accordance with the data presented in [12] are listed in Table. 1.

Table 1: Characteristics of the studied material

Material properties	tension	compression
Density	372,5 kg/m^3	
Strength properties in fiber direction 0°		
Young's modulus in tension	13,8 GPa	15,4 GPa
Ultimate strength	283 MPa	125 MPa
Strength properties in fiber direction 90°		
Young's modulus in tension	11,5 GPa	15,5 GPa
Ultimate strength	279 MPa	103 MPa
Shear modulus	1,05 GPa	
Shear strength	44 MPa	
Poisson's ratio	0,09	0,1

In the context of this problem the prospects of using this material as a protective layer or multilayered or sandwich - structures against impact damage with high-velocity objects are considered. In the case of work under conditions of impact loading this multiphase material is characterized with a complex stress-strain state, so its behavior under high-velocity loads needs a thorough investigation. It conditions reasonability of investigations of the impact strength of the chosen material.

Circular samples with a diameter of 200 mm were used at the study. Rigid clamping of the samples was implemented along the edges with massive pressing plates with a central circular hole of diameter 150 mm, which defined the work area of the sample. The choice of samples of thicknesses of 2, 4 and 8 mm is conditioned with technological capabilities of typical manufacturing processes, that determines the maximum prevalence of structural elements of the panels of these characteristic thicknesses. The resulting number of individual consolidated layers in each case was equal to 4, 8 and 12 layers respectively. Fig. 1. shows a general view of the surface and drawing of the material sample.

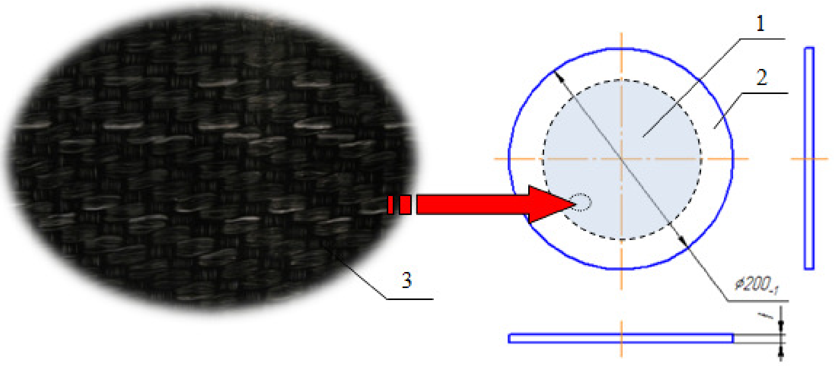


Figure 1: Investigated material: 1 - working area of the sample, 2 - clamped region of the sample, 3 - surface structure of a material sample; t - sample thickness

To exclude the influence of edge effects of the sample's jamming the sample fixing pressure load of the plates was controlled with a torque wrench in accordance with GOST 25605-83. This approach provided a uniform fixation of the sample along its perimeter, excluded disbalance and additional oscillations of the system due to uneven clamping of edges. It also provided further comparability of the results of individual experiments and uniqueness of the computational mathematical model elaboration.

Tests were conducted using specially developed patented laboratory research complex «aSTanin» («Acceleration System for Testing of Anti-damage Innovations») for investigation of impact strength [13, 14]. The principle of the tests execution consists in that a collision of an impactor of a certain shape and size with the tested sample is realized.

Special features of the complex are the ability to accelerate the impactor to velocities of more than 1500 m / s, usage of ballistic pendulums for recording parameters of energy redistribution in the system of impactor and fixed material test sample [15-17]. Test facility is equipped with instrumentation for recording the acoustic and electromagnetic oscillatory processes occurring during impact interaction [18].

Before selection of velocities of collision between the impactor and samples the following was taken into account. The results of preliminary tests have shown that samples have typical ballistic limit velocities of throughout penetration for selected test conditions equal to 200, 310 and 430 m / s for samples of 2, 4 and 8 mm thickness respectively. This defined the experiment planning including the choice of the investigated velocity ranges, the number of tests in each sub-range taking into account the necessity of obtaining additional data in the critical velocity range of beginning of the throughout penetration. The influence of a large number of random factors on the processes at impact interaction of composite materials condition dispersion of values of the studied output parameters that determines the need to widely use methods of probability theory, mathematical statistics and experimental planning for their estimation [19, 20]. Table. 2 shows the planned velocity ranges of the impactor acceleration, the number of tests in each range for each value of the samples' thicknesses.

Table 2: Velocity range of the impactor acceleration for various sample thicknesses

Velocity range	Sample thickness t, mm					
	t = 2 mm		t = 4 mm		t = 8 mm	
№	V, m/s	N	V, m/s	N	V, m/s	N
1	0..100	6	0..100	2	0..200	5
2	100..180	6	100..400	5	200..400	4
3	180..215	6	400..600	4	400..600	3
4	215..900	12	600..800	4	600..1100	5
5	900..1750	10	800..1400	5	1100..1400	3

Analysis of energy redistribution in the studied system is achieved with help of using a ballistic pendulum, on which the sample should be fixed, as well as of an additional ballistic pendulum with an impactor trap, which catches the impactor after penetration of the sample. Energy conversion is estimated according to the following general equation:

$$E_0 + E_1 + E_2 + E_s = 0\,, \tag{1}$$

where $E_0 = (m \cdot V_0^{\ 2})/2$ is initial energy of the accelerated impactor of a mass m, if its registered immediately before the collision velocity is equal to V_0; $E_1 = M \cdot g \cdot L \cdot (1 - \cos\alpha)$ - mechanical energy recorded as an energy of the first ballistic pendulum suspension deviation and thereby transferred to the supporting structure, here also M is the weight of the supposed to mechanical motion structure elements, g - acceleration of gravity, L - the distance from the centre of mass of the movable structure to the axis of rotation, α - the suspension rotation angle;

$E_2 = (m \cdot V_i^2)/2$ - the impactor residual energy, which recorded with the second ballistic pendulum or calculated from the value of the residual impactor's velocity V_i recorded after the material penetration; E_s - absorbed by the material sample during interaction with the impactor energy. This energy value includes both the reversible component E_r as energy of elastic waves, presented in the form of kinetic energy of the elements of the sample or the potential energy of deformation, as well as irreversible component E_{ir}. The latter is due to the formation of local plastic deformation, damage of structural elements of the material, rupture of bonds between them, as well as heating of the material, change of its structure and possible phase transitions.

3. Development of the probabilistic approach to modeling the processes of impact interaction

To estimate the significance of the internal material structure influence on the basic parameters of the impact strength its structural model with developed functional connections is analyzed (Fig. 2). Revealed with the analysis complexity of investigation of the impact strength of textile reinforced composite materials identified the need to study its behavior as of a stochastic system, i.e. a system in which the functioning of individual elements and its parameters depend on the influence of many random factors.

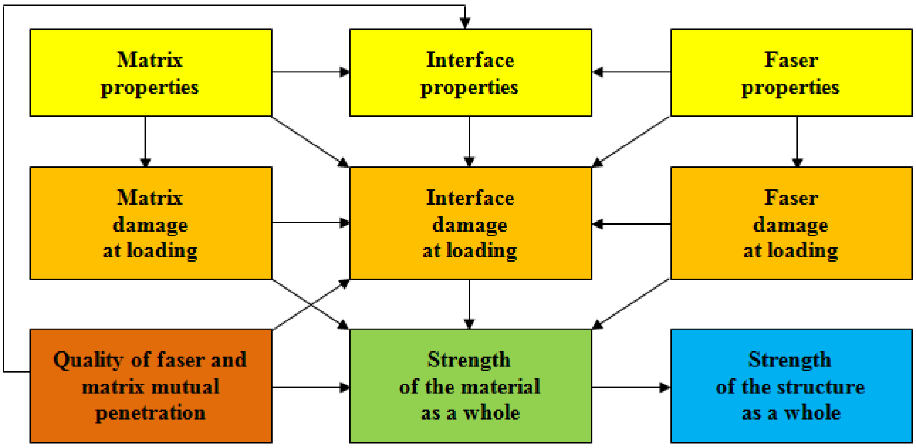


Figure 2: Structural model of material strength

For a textile-reinforced laminated composite material such factors are: deviation from the straight-line arrangement of threads in the composite fibers, deviations of the thickness of component layers of the composite as well as the total thickness of the laminate from the average value, relative position of the regions with longitudinal and transverse fibers in the contiguous surfaces of adjacent layers, the quality of the matrix penetration between the strands of fiber in local areas which are often commensurate with the characteristic size of the impactor etc. The complex nature of the destruction can be illustrated with obtained using a microscope photos shown in Fig. 3. Damage is not homogeneous, the matrix particles are present at fluffed fibers of the composite. The complexity of the destruction nature is also confirmed by other experimental studies of similar materials [21].

As it may be seen in the photos, the final destruction of the material occurs at fracture of reinforcing fibers. It finishes the intense formation of cracks in the matrix material as well as in the fiber-matrix interface. Established at the initial stage of the process micro-cracks may develop further or in the case of a timely removal of the load the material may recover its properties. If the probability of formation of new bonds between molecules or atoms of the walls of the microscopic cracks is relative high at low velocities, at high interaction velocities the rate of crack growth and of the relative motion of its walls is so high that restoring of bonds is rarely observed in most cases.

Thus, in the case of study of textile-reinforced materials, the interaction process should be viewed not from the deterministic but from probabilistic point of view. It is necessary to develop an integral probability characteristic describing the overall flow of the process, taking into account the probabilistic nature of the restoration of bonds at the molecular and atomic levels, and directly affecting the result of the interaction, providing specified experimentally confirmed nature of its outcome, regardless of the local probable oscillations.

In this regard, for the reasons of determination of a criterion for assessing the integral probability characteristic experimentally determined energy dependences, as well as data on registered AO and EMO accompanying impact process were analyzed.

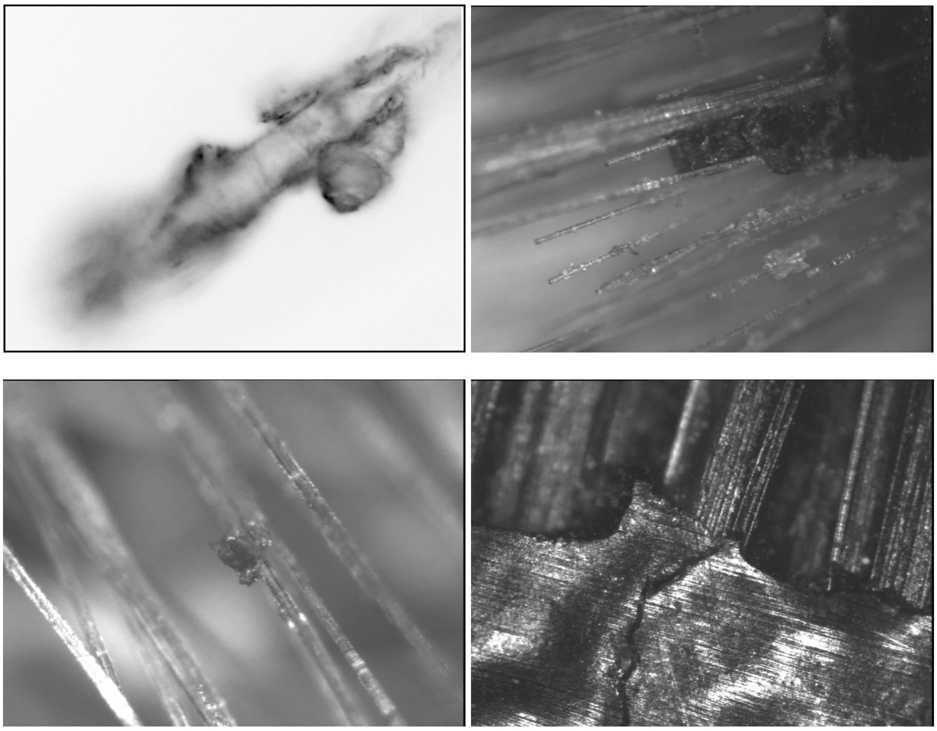


Figure 3: Photos of areas of the material damage: matrix particles on the fluffed fibers (left) and the failures along the fiber-matrix interface (right)

Regions of the recorded signals of 10 ms length, covering the main surge of oscillatory processes initiated in the material with the impact interaction, were separated. To analyze the relationship of acoustic and electromagnetic oscillatory processes the mathematical apparatus of the continuous wavelet transform was applied defined as [23, 24]:

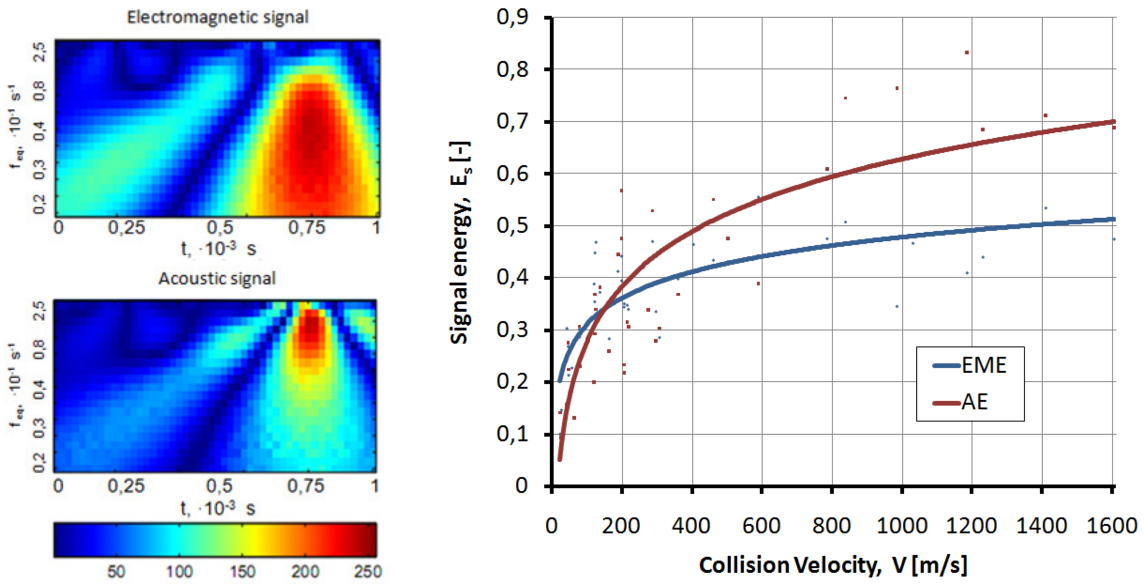
$$\gamma(\tau, s) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{s}} \psi^* \left(\frac{t-\tau}{s} \right) dt , \qquad \textbf{(2)}$$

where τ is translation the mother wavelet function, s is its scale, t – is the time at the amplitude-time representation of the function $x(t)$, and $\psi^*(t)$ is the mother wavelet function itself. Results of the analysis of these sections of specified signals recorded during collisions of the sample material with the impactor with an initial velocity of V = 214,27 m / s are shown in Fig. 4, a. Analysis of similar plots obtained for other velocities shows that the intensity of the AO and EMO varies with increasing initial energy of the interaction differently. To quantify this the graphs of the total intensity of signals of AO and EMO for the executed experiments were built (Fig. 4, b).

It was found out that the total energy of the EMO signal at velocities above the ballistic limit is substantially lower than the overall AO signal energy. Recorded AO parameters characterize the mechanical deformation of the specimen. EMO describes the physical processes of destruction and re-establish of bonds in the material. At low velocities higher absorption of mechanical energy by the sample is accompanied with more intensive mechanical vibrations, including acoustic ones, and also is accompanied with a higher degree of energy absorption due to destruction of bonds in the material.

The described effect at high velocities can be explained with the fact that at higher velocities the probability of restoring of the bonds in the material decreases. Accordingly less energy is spent on creation of similar material damage. Thus, this effect must be taken into account at modelling the interaction at high velocities using a model that shows good agreement with experiment at low velocities.

Consideration of the processes during the high-velocity impact damage from this point of view allows us to offer a criterion of the probabilistic restoring of bonds in the material in the form:



a b

Figure 4: Diagrams of the wavelet coefficients (a) and plots the total intensity (b) of the signals of AO and EMO

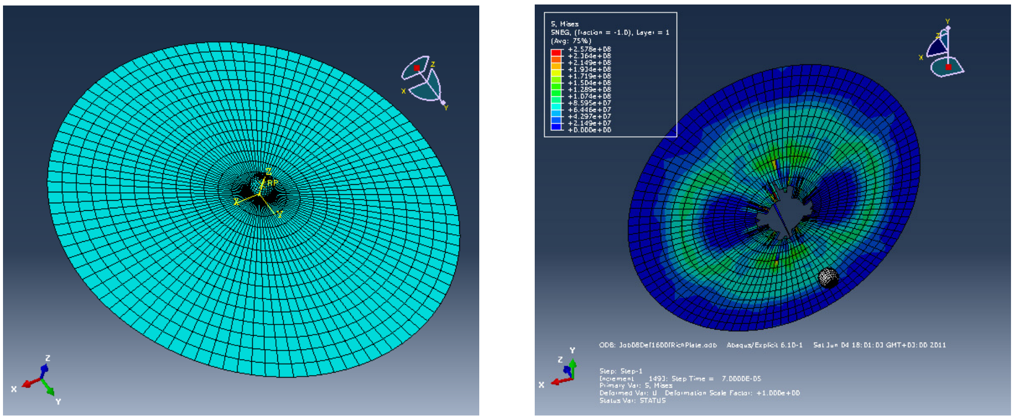
$$P_{BKP}(E_i) = 1 - K_p \left\{ \frac{P\left[A_{\Sigma}^{AO}(E_i)\right] - P\left[A_{\Sigma}^{EMO}(E_i)\right]}{P\left[A_{\Sigma}^{AO}(E_i)\right]} \right\} = \begin{cases} 0 \\ 1 \end{cases}, \qquad \textbf{(3)}$$

where $A_{\Sigma}^{AO}(E_i)$ - amplitude-frequency response of AO at the interaction with a total energy of the system equal to E_i, $A_{\Sigma}^{EMO}(E_i)$ - by analogy for EMO, $P\left(A_{\Sigma}^{AO}(E_i)\right)$ and $P\left(A_{\Sigma}^{EMO}(E_i)\right)$ - accordingly the total intensity of AO and EMO signals, calculated from the existing amplitude-frequency responses, K_p - discrete random value, taking values of 0 or 1 with a probability appearing in the parentheses. Thus, the quantity in brackets in (3) characterizes the probability of irreversible destruction of bonds in material, and K_p - its concrete implementation for a particular calculation point of the sample.

4. Testing of the probabilistic model of material damage

The proposed probabilistic model of damage of the material was tested using a special developed in a form of a user subroutine program implementing the proposed criterion of restoring of bonds. The subroutine is intended for usage within the numerical calculation of in software Abaqus^{TM}. The general view of the finite element model of the tested specimen is shown in Fig. 5. The model is fully consistent with the geometrical size and the realized fixation method of the experimentally tested specimens. Rigid clamping of the sample along its edge was modelled by imposing restrictions on deflections and rotation angles for the locus along the edge of the plate. Thus, the workspace of round specimens with a diameter of 150 mm and thickness of 2, 4 and 8 mm respectively was simulated. For comparison with standard methods of calculation the same model was tested using the standard damage model for fibre-reinforced materials by Hashin.

Modeling of the probabilistic restoring of bonds was realized by introducing of solution dependent state variables being processed by the developed user procedures written in Fortran. Removing of the elements was consistent with the current parameters of the material and the level of perceived by the sample energy. Calculation introduced a dependency of the level of critical fracture energy, which controls the evolution of the textile-reinforced composite material damage, upon the energy parameters of the studied area, which values were calculated with the user subroutine for each calculated point at each iteration of the solution in accordance with the accepted probabilistic model. Upon reaching the level of critical fracture energy in the integrated point of the element, it was assumed that the degree of its damage is equal to unity, i.e. complete destruction took place. Upon reaching this level in all the integration points across the thickness of the shell element, it was assumed that the element is destroyed and no longer supports the load. The destruction of the element in the used software system was irreversible.



a b

Figure 5: Finite-element model of the tested material sample before (a) and after (b) penetration by the impactor

The performed calculations allow construction of a comparative graph (Fig. 6) of the calculated and experimental values of overall energy perceived with material samples at collisions with impactors accelerated to various velocities, which affected the initial energy level of the system. As is evident from the graphs, using the developed probabilistic model of behavior of composite materials under high-speed impact processes gave an opportunity to obtain the calculated energy values, which better correlate with experimental data.

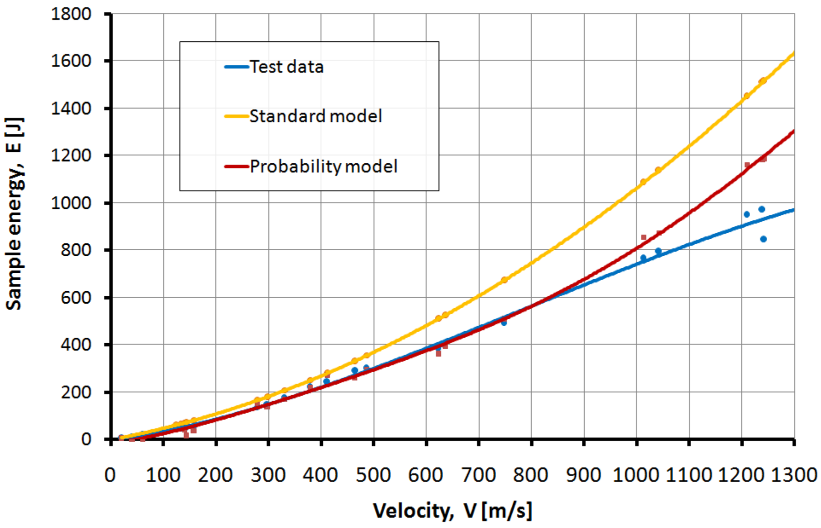


Figure 6: Calculated values of perceived with material energy at application of standard (1) and probability (2) models

5. Conclusions

Using the developed patented laboratory research complex «aSTanin» for impact strength investigations, tests of flat samples of textile-reinforced hybrid-garn material of thickness equal to 2, 4 and 8 mm at impact velocities of up to 1,5 km / sec are carried out.

Probabilistic model of the material damage taking into account the probabilistic nature of restoring of bonds in it at different impact velocities is proposed. A method for determining the criterion of probabilistic restoring of bonds in the material based on the analysis of oscillatory processes in the material upon impact is elaborated.

The proposed probabilistic model of the material damage is tested in the AbaqusTM software for numerical calculations being realized in the form of a user subroutine. The numerical results showed a better agreement between calculated and experimental curves in comparison with standard numerical models.

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