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EXPERIMENTAL AND PROBABILISTIC NUMERICAL MODELING OF IMPACT OF FIBER-REINFORCED COMPOSITES AT HIGH AND LOW VELOCITIES

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Summary. *Peculiarities of energy absorption dynamics and the damage of plates of multicomponent composite material are analysed depending on the impact speed at impact velocities ranging from 20 to 1500 m/s in view of causing them physical damage processes based on experimental data and numerical calculation using a developed probabilistic model. The results are compared with experimental data obtained by other authors.*
Key words: *fiber-reinforced composites, damage evolution, probabilistic modeling, high-velocity impact, strain rate, electromagnetic emission, acoustic emission.*

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Peculiarities of material models of fiber-reinforced composites. The complex internal structure of a composite material specifies the material strength as an ability to withstand external loads due to the presence of bonds between internal structural elements of each homogeneous constituent component of the composite and also bonds between these structural components [1]. In this case examples of the components of the composite material are reinforcing fibers and matrix. Examples of their structural elements can be atoms, molecules, grains or other structural formations depending on the type of components used [2, 3]. It is important that exactly this combination of bonds between elements at different levels, namely, the nano-, micro- and macrolevels, is responsible for the total strength, and failure of bonds at any of them determines an appropriate type of damage [4].

Starting position for this study are the following conventional approaches. First, the mechanical behavior of a material can be described within the framework of solving a boundary value problem with the account of balance equations of mass, momentum, energy, taking into account symmetry properties of the material, kinematic constraints and material model equations of one of the four basic types, namely models of elastic, plastic, viscoelastic or viscoplastic behavior. This concept is discussed in detail and used in the studies presented in [5-8]. It is important that these models are idealized, and real materials exhibit both presence of hysteresis and change of the character of the stress-strain dependence in case of changing the relative velocity of the mutual motion of interacting bodies (further for brevity – the velocity of interaction), which can, however, be ignored in some cases.

Second, the actual behavior of the material, taking into account the energy dissipation due to damage, can be described using the same equations of the chosen material model as described above, but with the reduction of the actual undamaged working area δA of the material to the new corrected value $\delta \widetilde{A}$, where δA and $\delta \widetilde{A}$ are cross-sectional areas which

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provide resistance to the applied loads before and after the damage was formed. Change of the area corresponds to reduction of the material specimen stiffness C_{ij} (undamaged stiffness tensor) to the value of $\widetilde{C}_{ij}$ (damaged stiffness tensor), while the relation of the stress tensor components σ_i and the strain tensor components ε_j can be represented as a functional dependence:

$$\sigma_i = f[\widetilde{C}_{ij}(D_{ij}), \varepsilon_j], \ i, j = 1,2,3, \quad (1)$$

where D_{ij} – is some damage parameter, i, j – indexes that indicate the tensor components. This approach is proposed in [9, 10] and successfully developed in numerous works, including researches devoted to analysis of composite materials [11-15].

Thirdly, as it was shown in the international study World Wide Failure Exercise WWFE [1, 16-18], successful modeling of composite material behavior is possible only taking into account the presence of combination of different types of damage that occur in the material, and the types of damage are determined by the physical nature of processes of destruction of bonds between the structural elements occurring in the material. The need to consider reforming of the material microstructure during the loading application, including the restoration of the polymer molecular network, is indicated in [8, 19].

A key role of molecular interaction, which manifests itself in the presence of bonds between structural units of the polymer matrix and in the quality of these bonds, during deformation in a wide temperature range is shown in [20, 21]. An important role of the associated with recovery and destruction of bonds between material structural units, statistically caused dynamic balance between accumulation and mutual compensation of dislocations at impact and creep conditions at different ambient temperatures is emphasized in [22-24].

As shown in [11, 12, 25-27], composite materials based on polypropylene matrix and glass fibers, which are considered in this paper, and similar to them materials are characterized with a generally elastic behavior until damage initiation, which is the cause of further non-linearity of the stress-strain curve, also at impact.

In accordance with the objectives of this research and based on presented in other works theoretical and experimental data, modeling of the material behavior is proposed to be realized within the traditional scheme of simulating the stress-strain dependence including damage, but the different types of damage will be analyzed in relevance to the physical phenomena of their appearance due to destruction and recovery of bonds in the material, that was previously described in [28, 29], so that to minimize the amount of the specially defined in experiments under dynamic and complex stress state fracture phenomenological model parameters, replacing them whenever possible with basic mechanical of physical characteristics of the material, which define its composition, internal structure and state.

The objective of this study, therefore, is an experimental determination of the behavior of flat plates made of hybrid garn composite materials under direct central impact and verification of using possibility and modeling adequacy of such impact by means of the proposed and developed probabilistic model.

Results of experimental studies. The range of materials studied covered two typical representatives of fiber-reinforced composites based on glass fiber fabric of plain weave (type A) and stitched with auxiliary transverse fibers unidirectionally reinforced mutually perpendicular layers (type B) utilizing infinite filaments and thermoplastic matrix. Fiber material is E-glass, matrix material is polypropylene. Fiber volume content ς_V was 35 – 40% and 50% correspondingly, the ratio of warp and weft fibers 1:1 in both cases, fiber thickness 1200 tex, the laminate composition – symmetrical lay-up $[0/90]_s$ (eight layers at angle 90° relative to each other). Manufacturing technology is hot pressing of hybrid garn prepreg. Basic mechanical properties of materials in statics and their general physical characteristics were determined experimentally as part of the present study and supplemented with data given in [11, 12, 27, 30].

The problem of a direct central impact of a spherical body with a composite barrier, which is a test specimen, is considered. Impactors are made of steel ШХ15СГ and they had no residual deformation or damage in all the experiments. For the studied range of testing conditions they were considered to be absolutely rigid bodies. The impactor diameter $d =$ $8{,}75 \cdot 10^{-3}$ m, mass $m = 2{,}7 \cdot 10^{-3}$ kg.

In order to minimize the influence of rigid fixation of the tested material plate along its edge on the processes in the viscinity of the impact spot, the diameter of the specimens was 200 mm, the diameter of the working area of the specimen after clamping along the edge was 150 mm. The impactor linear velocities ranged from 20 to 1500 m/s, that is explained not only with relevance of the study of dangerous high-speed impact of transport and building structures and prospects of high-speed unmanned and passenger aircrafts, including further development of hypersonic aviation, but also with relevance of elaboration of material model of composites under impact in a wide range of speeds.

Previously developed and described in [31-33] experimental system for studying the processes of impact interaction was used as the research installation. It allows registration of energy redistribution between the impactor and material specimen, registration of acoustic and electromagnetic emission, which accompany phenomena of high-velocity impact of complex composite materials of the investigated type, as it was found in [31, 34].

The focus during the experiments and analyzing experimental data was given to the following parameters [28, 29, 31, 32]:

- the total energy E_a absorbed by the specimen, which characterizes its protective properties, i.e. a protective barrier function (Fig. 1);
- damaged area of the specimen, by the magnitude of which the value of irreversibly scattered for the damage formation energy and residual impact-resistant material properties can be estimated (Fig. 2);
- energy and interrelationship of acoustic (AE) and electromagnetic (EME) emissions, which characterize the formation of damages in the specimen material (Fig. 3).

The corresponding to experimental data points in Fig. 1 reflect the fact that at low speeds (prior to through-out material punching) the absorbed by the material energy E_a increases parabolically, proportionally to the square of the impactor velocity. This is due to the fact that the material for every higher value of impactor velocity that does not exceed the ballistic limit, which is 200 (type A) and 270 (type B) m/s for the tested specimens, is subject to gradually more significant damages (see. Fig. 2), but the total strength all its layers still is enough for stopping the impactor. With further growth of the impactor velocity after reaching the through-out material punching, a tendency of stabilization and further reduction of the damage size almost to the size of the impactor itself is observed (Fig. 2).

At the same time after the start of the through-out punching the character of the increase of the energy absorbed by the specimen dramatically changes. As the impact velocity increases, this value is now growing very slowly, so that neglecting some transition zone in the viscinity of the ballistic limit velocity, all the experimental data can be appropriately approximated with only one common equation and corresponding curve for the studied velocity range (Fig. 1).

Differences between the two studied types of materials in the nature of growth of the absorbed energy should be noted. Due to the presence of the third stitch system of supporting fibers, which are perpendicular to the laminate plane, in the material of type B, it is considered to be three-dimensionally reinforced. However, a more gradual decrease of energy absorption properties after reaching ballistic limit compared to the material of type A is due not only to the three-dimensional reinforcement (percentage of supporting system fibers is rather small). It is essential that the stitching connects together mutually perpendicular fiber bundles that form adjacent layers of the laminate. This fact prevents their mutual sliding. Thus the loading is distributed in the composite material not only by the binder matrix but also by the fibers directly due to their interweaving. For the material of type A, though a plain weave of mutually perpendicular fiber bundles is incorporated in it, but this type of binding poorly prevents slipping of fiber bundles relative to the initial position of their mutual contact, so much smaller role in the redistribution of the loading is realized by the very fiber weaving structure of composite layers.

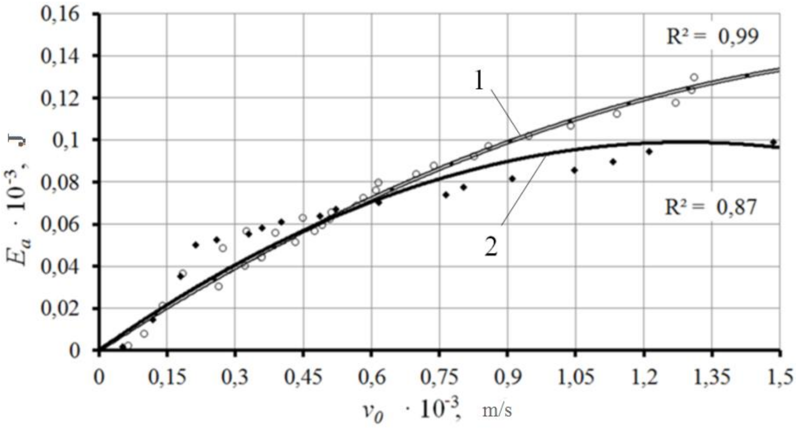

Figure 1. Dependency of the total energy absorbed by the specimen E_a on linear velocity of the impactor: 1 – material of type A; 2 – material of type B

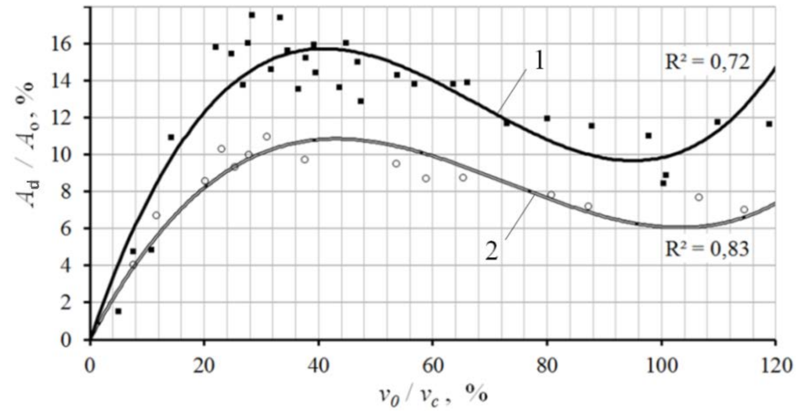

Figure 2. Dependency of damaged area A_d to the initial specimen area A_0 ratio on specific impact velocity: 1 – material of type A; 2 – material of type B

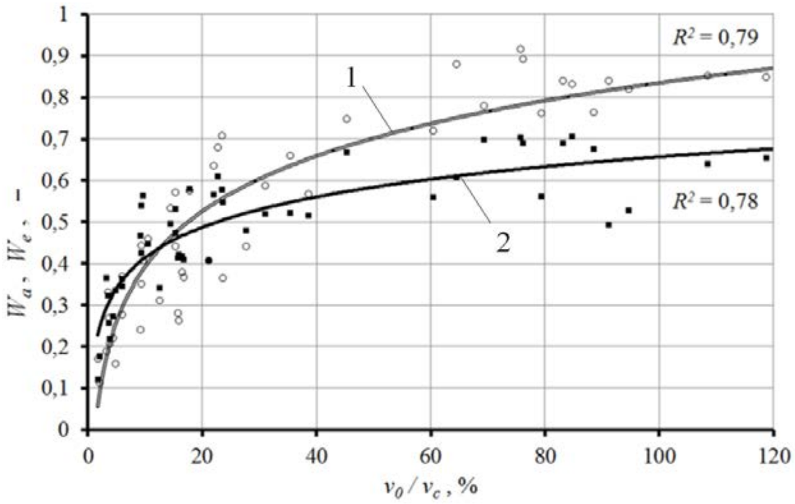

Figure 3. Dependency of energy of acoustic W_a (1) and electromagnetic W_e (2) emissions on specific impact velocity

Thus, based on the experimental data, we can conclude that a more optimal energy absorption of a fiber-reinforced laminted material can be achieved if a permanent connection is provided between reinforcing fiber bundles which are situated at an angle to each other (usually mutually perpendicular). So we have proposed a new type of fiber-reinforced laminated composite material which is net-reinforced material, which incorporates fiber connections by means of binding them into knots and thus forming a structure similar to fishing nets. This composite net-reinforced material was manufactured by us, also using a three-dimensional fiber reinforcement, and may in the future be used for heavy loaded by impact protective structures [35-37].

Unlike results of further ultrasound scanning of damaged by impact specimens, data on energy of acoustic and electromagnetic emissions (Fig. 3) were received in situ during the very experimental process of impacting, with a non-destructive method of monitoring the impact interaction (via remote sensors of AE and EME). As seen from the curves, a precursor of beginning of potentially dangerous process of through punching of a specimen was overrun of the AE energy characterizing the processes of destruction, over the EME energy, which as it has been shown in [31] is related to restoration of damaged material bonds between particles at micro level.

Obtained experimental data were analysed using the developed and for the first time presented in [31] deep analysis of parameters of acoustic and electromagnetic emissions on specially determined so called multiple frequencies which characterize processes of recovery of bonds between structural elements in the material. This made it possible to investigate the experimental curve of the energy of emission processes W_m at different impact velocities v_0. It was found that approximation of this relationship can be with a sufficient accuracy (coefficient of determination $R^2 \geq 0{,}8$) realized with a normalized second Hermitian function on the parameter, which it is proposed to represent as a scaled value of the impact velocity and to denote it as v_n:

$$v_n(v_0) = \frac{(\kappa \cdot v_0 - \mu)}{\sqrt{2} \cdot \vartheta}, \tag{2}$$

where v_0 – impact velocity, κ – scale factor, μ – offset of the approximation function maximum relative to the zero point of the impact velocity axis, ϑ – factor that plays role analogous to a standard deviation, if we consider the allocation of quantities of the energy W_m of the emission processes along the impact velocity axis as an indicator of the probability of occurring of the processes at these impact velocities. This is because the total energy of the registered by the measuring equipment emissions signal W_m is directly related to the number of such bonds between the structural particles of material, destruction or restoration of which originates the appearance of the emission signal.

Said normalized second Hermitian function was thus applied as an approximation according to [38]. If to consider scaling according to (2), it can be represented as follows:

$$W_m(v_0) = \frac{2 \cdot \lambda}{\sqrt{3} \cdot \pi^{1/4}} \cdot \left(1 - \frac{(\kappa \cdot v_0 - \mu)^2}{2 \cdot \vartheta^2}\right) \cdot e^{-\frac{(\kappa \cdot v_0 - \mu)^2}{4 \cdot \vartheta^2}} + \beta_0, \tag{3}$$

where λ, and also β_0 – the normalization coefficients, that take into account measurement equipment parameters (including the gain of the signal), such that for $\lambda = 1$ the area under the curve of the emissions energy, i.e. the total energy at all impact velocities, is equal to one (negative impact velocities are not considered); other parameters are denoted as described above. The resulting energy of the emissions signal is a generalizing characteristic of the impact process and depends not only on the speed of impact and the specimen material, but also on its geometrical dimensions, applied impactor etc.

However, in [28] it was shown that factors κ, μ, ϑ in practise can be calculated from the value of the material ballistic limit velocity v_b, which is obtained precisely for the same impact conditions (including the size and shape of the specimen and impactor), and the speed v_c of propagation of transverse sound waves in the material matrix (in this case coefficient κ considers the overall influence of the higher velocities of longitudinal sound waves in matrix and also transverse and longitudinal sound waves in fibers, which significantly exceed the studied range of impact velocities). There are several ways to determine the material ballistic limit. This value is considered to be the minimal velocity v_b, at which at least one of the tested specimens was punched through. It can also be the minimal velocity, at which all specimens tested at this given impactor velocity, were punched, i.e. at 100% probability of through-out punch. In other cases the 50% probability level of punching is considered. As this research is devoted mainly to studying the protective properties of the material, so the first of the three above methods for determining the ballistic limit was adopted.

According to the assumption made by the authors, the complex nature of the relationship (3) may be due to mutual overlapping of the set of probabilistic processes of destruction and restoration of bonds in the material, which are bonds of various types (i.e. between matrix molecules, between fiber atoms, adhesive bonds in boundary layers etc.). Actually, from a mathematical point of view, the dependence (3) can be represented, if to correspondingly recalculate appropriate coefficients, as a sum of mutually superimposed Gaussian curves of general form [38]:

$$A_i(a_j) = B_i \cdot e^{-\left(\sum_{j=1}^{k} \frac{1}{2} \left(\frac{a_j - d\mu_j}{dS_j}\right)^2\right)}, \quad j = 1,2,\ldots,k, \tag{4}$$

where A_i – a component of the signal W_m, caused by a certain i-th group of k influence factors a_j, or probability of occurrence of such the component; B_i – normalization factor; $d\mu_i$ – value of the parameter a_j, that corresponds to the maximum A_i; dS_i – parameter that controls the significance of the influence of deviation of the value a_j from the value $d\mu_i$ by the ammount A_i.

Thus, the analysis of experimental data, on the one hand, demonstrated a critical role of accompanied by acoustic and electromagnetic emissions processes of destruction and restoration of bonds in the material in the realization of the energy absorption. This implies the possibility of their use to describe and further to model the damage of the material under loading, and thus its resulting protective properties. On the other hand, the possibility of using the Gaussian curves of the general form (4) for modeling the dependence of AE and EME energies on the impact velocity allows it to make suggestions about a determinative influence of random factors in the development of the material damage under application of a load. However, the use of the mathematical tools for probabilistic modeling of the damage processes can afford it, as it is shown below, to take into account the influence of such random factors in a generalized way, so that to achieve a resulting acceptable accuracy and predictive capabilities of the simulation by means of incorporation of the description of probabilistic processes that actually occur in the material into the material model used to simulate it.

Comparison of results of experiment and simulation. To simulate the obtained experimental data a proposed in [39] probabilistic model was used. Isofields of values of absorbed energy and material damage were analyzed in [40] for several impact velocities under the studied conditions of impact interaction. Below the character of changing of these quantities depending on the initial impactor velocity compared to the experimental data (Fig. 1 – 3) is analyzed.

In the devoted to probabilistic modeling work [39] the important role of critical values of impact velocity v_c, temperature T_c and strain ε_c for the simulation of an impact of a composite was shown. In the carried out tests and respectively in the numerical experiment the temperature T of the specimen before impact was equal to the ambient temperature T_0, which remained unchanged in all trials. Strain ε in each experiment increased from zero in general case to a critical strain ε_c in that part of the material specimen, which was subjected to destruction, or to a smaller value in that part, where a damage was observed. In order to deduce he influence of the critical impact velocity onto the process of damage and destruction, dependences of the energy of destruction and the parameters of the damage on the relative velocity of impact (and impactor) v_0/v_c were analyzed, where v_0 – initial collision velocity, v_c – critical velocity corresponding to the speed of propagation of transverse sound waves in the composite, namely 1300 m/s.

The dependence of the total energy E_a absorbed by the specimen on the relative impact velocity v_0/v_c is shown in Fig. 4, where materials of types A and B correspond to the materials described above.

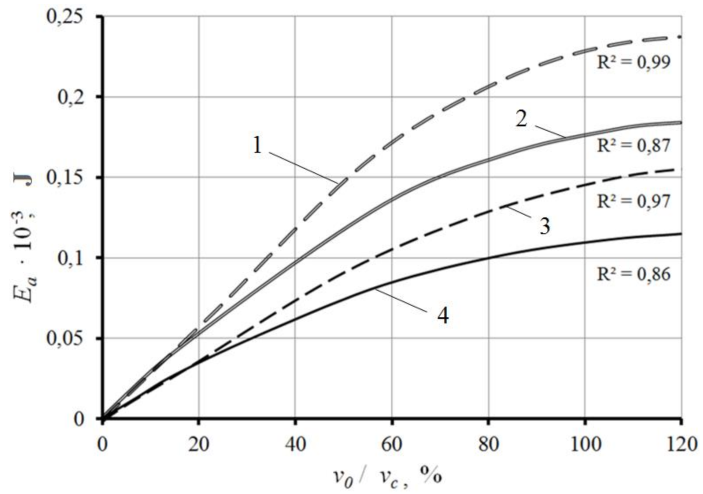

Figure 4. Dependency of the total absorbed by the specimen energy E_a on specific impact velocity v_0/v_c: 1 – simulation according to standard model of type A material specimens; 2 – simulation according to probabilistic model of type A material specimens; 3 – simulation according to standard model of type B material specimens; 4 – simulation according to probabilistic model of type B material specimens

As it can be seen from the graph in Fig. 4, the simulation of material specimens of both studied types using the standard model results in excessively increased values of absorbed energy at high impact velocities. The influence of the following interrelated factors should be taken here into account. On the one hand, at higher strain rates a strengthening of material is observed. Increase of elasticity modulus E or G and strength R actually could lead to a significant increase in absorbed energy E_a at the same strains ε. But taking into account of the interaction time Δt, which is relevant to the strain rate $\dot{\varepsilon}$ and strain ε, is also necessary. It was realized in the framework of the proposed model and is reflected in the curves in Fig. 4 which correspond to the simulation of materials of both types using the probabilistic model.

This simulation was carried out according to an algorithm described in [40]. A specific value of the probabilistic variable (hereinafter, for brevity, probability) d of destruction of bonds in the material is calculated on the basis of current values of both strain ε and strain rate $\dot{\varepsilon}$. It appears that indeed as the strain rate $\dot{\varepsilon}$ increases, the probability of destruction of bonds per unit time increment $\dot{d}$ also increases, however the time duration Δt of this process, during which a certain amount of strain increase ε is achieved, is also small enough. Accordingly, not so many bonds have enough time to be destructed, that is d does not have enough time to reach high values (maximum value of probability of damage, which corresponds to destruction, is unity).

This means that also decrease of the stiffness due to the damage of material by means of destruction of these bonds appears to be smaller than in the case of the low-speed deformation when the states of the material at same strain values ε are compared. However, at high strain rates $\dot{\varepsilon}$ an increase of the probability of bond destruction per unit time $\dot{d}$, which depends on $\dot{\varepsilon}$ non-linearly, is so significant that despite the small value of Δt, still some maximum of the material ability to dissipate energy on damage formation is achieved and its further decline and stabilization in the studied range of velocities is observed. Later below the process is analyzed in details on the example of Fig. 6 and 7.

Described features explain the lower values of absorbed energy E_a, which were obtained in case of simulation using the proposed probabilistic model compared with the standard one, and also their proximity to the obtained experimental research data, as shown in Fig. 5. The figure illustrates the dependency of the ratio of the difference between calculated and experimental energy values ΔE_a to the experimental value E_a, which was obtained using the curve of experimental data approximation, on the specific impact velocity v_0/v_c. That is, in fact, it describes the discrepancy between the results of simulation and experiment.

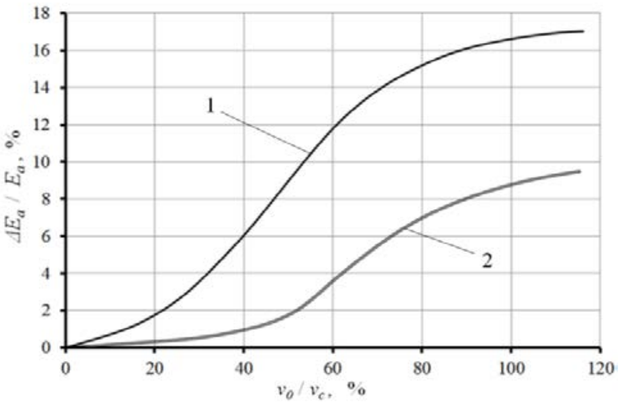

Figure 5. Dependency of specific absorbed by the specimen energy $\Delta E_a/E_a$ on specific impact velocity v_0/v_c for material of type A: 1 – simulation according to standard model; 2 – simulation according to probabilistic model

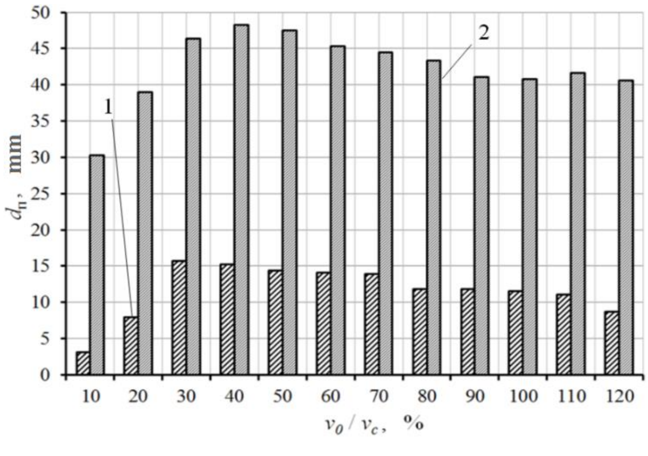

Figure 6. Histogram of specimen damaged area simulated diameters d_n on specific impact velocity v_0/v_c : 1 – material of type A; 2 – material of type B

Thus, it would be logical to assume that at the impact speed $v_0 = v_c$ equal to the speed of sound in the composite, i.e. $v_0/v_c = 100\,\%$, the threshold value of the absorbed energy is reached. However we consider the composite material and the speed of sound in the fibers is four times higher than the speed of sound in the matrix and approximately equal to 5400 m/s. It explains the further increase in the value of the absorbed impact energy at $v_0/v_c > 1$ in the investigated range of impactor speeds both in experiment and in the simulation results for the proposed model (Fig. 4, curves 2, 4). Below we will concentrate specifically on the results of its usage.

The second by importancy in terms of protective properties of the material after the absorbed by the specimen energy E_a is the specimen damage area. Fig. 6 shows a histogram of diameters d_n of the specimens damaged area according to simulation results depending on the specific impact velocity v_0/v_c. The corresponding area values are consistent with a coefficient of correlation of 0.84 with the experimental data shown in Fig. 2.

The phenomenon of stabilization of the ability to dissipate energy for damage formation after some decrease of it was mentioned above. It manifests itself in the reduction of the diameter of the damaged spot after some maximum and is consistent with the experiment. At higher impact velocities again a repeated increase of the damaged area spot is expected due to the perception of the loading by the fibers of the composite. This expection correlates with the trend visible in the graph of the experimental curve (Fig. 2) at its extrapolation in the range of high impact velocities.

The stabilization is due to the fact that during the contact with the supersonic impactor the bonds of contacting with it molecules or atoms with the surrounding molecules or atoms are broken before the disturbance has time to spread across the material, which could otherwise result in involvement of other acting between structural particles of material bonds into the process of the loading perception and redistribution.

Understanding the peculiarities of processes occurring in the velocity range of maximal diameters d_n and areas of damage can be obtained from consideration of experimental data in Fig. 7 and 8. Character of change of signals of acoustic and electromagnetic emissions is of particular interest. Direct comparison of these signals taking into account the peculiarities of sensors of the recording system described in [31] does not have a physical sense. But we can consider the ratio of the signal intensity in each experiment to the maximal one and then calculate the difference of these values corresponding to the acoustic W_{AE} and electromagnetic W_{EME} emissions $\Delta_E = W_{AE} - W_{EME}$. The dependence of this parameter on the specific impact velocity is shown in Fig. 7.

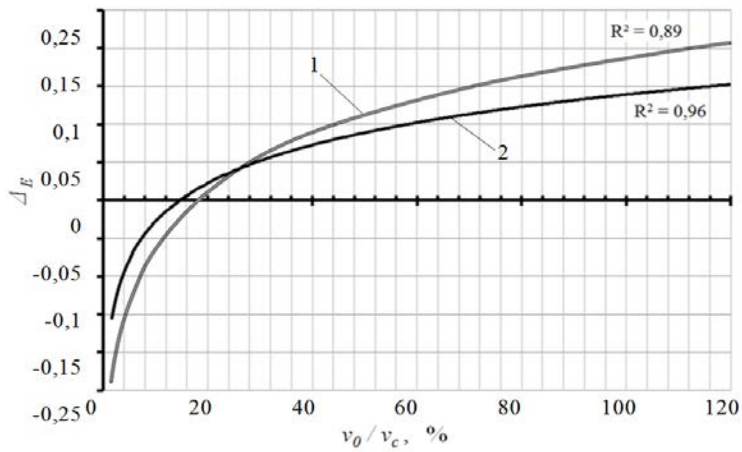

Figure 7. Dependency of intensity of AE and EME signals Δ_E on specific impact velocity v_0/v_c :
1 – material of type A; 2 – material of type B

If the obtained value of intensity of AE and EME signals Δ_E is higher than zero, this means that the processes of destruction occur more intensively than the processes of recovery of bonds in the material at the micro- and nanoscale, that is described in detail in [29, 31].

The opposite case, i.e. if the signal intensity Δ_E is less than zero, corresponds to the predominance of processes that prevent destruction. Thus, the critical point $\Delta_E = 0$ should take place at about the velocity at which a maximal number of bonds is completely destroyed (i.e. their damage is unity). This is observed during an intense ruprure and pull-out of fibers at that minimum velocity, at which already all layers of the composite are damaged, but which is still not high enough to prevent the damage spread to a larger area. And this value is actually exactly the ballistic limit of the material, the minimum velocity of through-out destruction of the plate material. It is also confirmed with the following. As the experimental data both for EME and AE, and also for impact punching are subject to a statistical analysis, so the point of intersection of the horizontal axis by the curves in Fig. 7 is close to exactly the speed of impact, which corresponds to a through-out penetration of 50% specimens, i.e. at 50% probability, and exactly this parameter is usually determined in ballistic laboratories as ballistic limit.

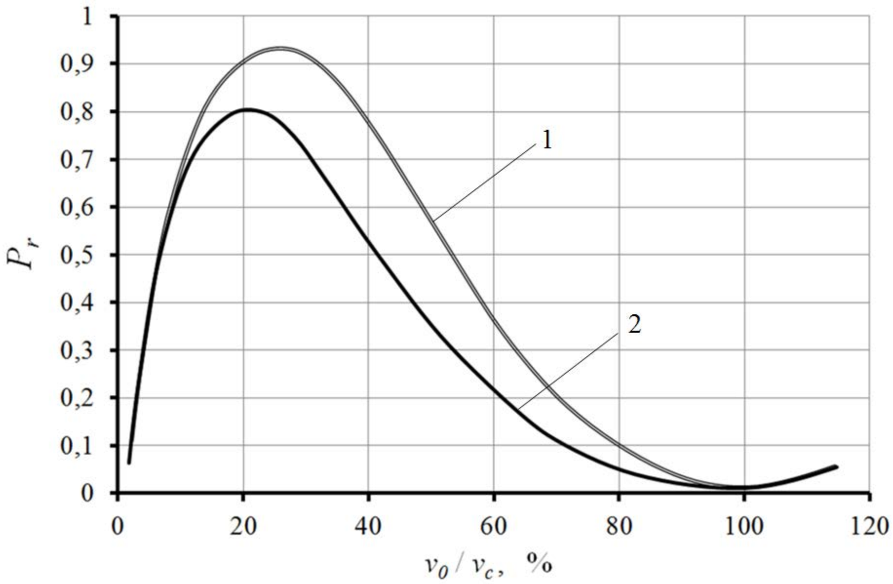

Figure 8. Dependency of EME-signal intensity at multiple frequencies on specific impact velocity v_0/v_c : 1 – material of type A; 2 – material of type B

Maximum of diameter of the damage spot (Fig. 6) is close to the velocity of material ballistic limit, but slightly higher than it. Presumably, this is due to the peculiarities of different types of damage of the composite structure and can be explained as follows. Fig. 8 shows dependences of the simulated probability P_r of recovery of bonds in the material, which is averaged across the contact spot with the impactor, on the specific impact velocity.

With the impact velocity increasing higher than the ballistic limit, the matrix damage, which is caused directly by the interaction with impactor, continues to become more localized, as the probability of irreversible local destruction of bonds between its molecules and atoms of macromolecules is increased, that is due to a relatively low speed of sound in the matrix if compared to one in the fibers.

Mainly the matrix damage becomes to be observed, which is initiated at the fiber-matrix interfaces along the length of the fibers by the oscillations, which have been initiated in it and spread through its length at a high velocity. So in more remote from the point of contact with impactor regions of material, more favorable conditions for a less significant damage of bonds at the fiber-matrix interface and further of the very matrix are created, than it would be in the contact spot.

Less significant damage means that at some given probability of destruction of bonds this destruction is more fully compensated by their restoration, that corresponds in the Fig. 8 to areas of maximum values of simulated probability of bonds recovery. It is important that the character of change of this parameter at increasing impact velocity is similar to shown e.g. in Fig. 9 in [28] relationships of the intensity of the EME signal at multiple frequencies, which more accurately characterize the processes directly connected with recovery of bonds at the fiber-matrix interfaces [41], which are particularly important for provision of the composite material strength [42 43].

Thus at velocities higher than the ballistic limit, as it is seen, there is an increase in the size of the damage spot. But at the same time the gradient of the damage magnitude along the spot diameter is substantially non-linear. The destruction region is thus localized near the spot of contact with the impactor. And a large area is occupied by minor damages, but it still dissipates the impact energy. This is evident in the presented in work [40] simulated isofields of the absorbed damage energy (Fig. 1, *d*) and of the damage magnitude itself (Fig. 2, *d*).

Thus, the damage area is increasing just like the absorbed energy (Fig. 4), but these values are not interrelated directly, as the described above character of distribution of the damage magnitude in this area is essential. It should also be noted that the size of the registered with the ultrasound scanning damage area is affected by the equipment sensitivity. Therefore, special monitoring methods such as AE and EME registration are particularly important in research studies, as they allow deep analysis of the process of damage origination directly during the time of its formation.

With further increase in impact velocity, reducing of the area, which is occupied by the maximum energy absorption due to the most significant damages, can also be seen in Fig. 1, *f* in [40]. However, despite the high energy absorption, the heavily damaged area is undesirable in terms of the design of protective materials. Of great importance is the maximum increase of the subjected to damages area but providing at the same time minimal values of damage at any its part. Experimentally, these materials will be characterized with higher values of EME at perhaps lower intensity of AE. Another case is more high-frequency AE of low amplitudes. Such materials will also be characterized with presumably high sound velocities and modules of elasticity.

It is important to analyze the differences of shown in Fig. 6 extreme values of the damaged area of material specimens of both types. Shift of the extremes of the damaged area along the horizontal axis relatively to the critical velocity of the matrix material for the studied two types of composites can be explained by the different mass and volume percentage of matrices in them. Since the speed of sound in the matrix is substantially lower than the speed of sound in the fibers, so it is this velocity which provides a decisive influence on the behavior of the material in the investigated range of velocities.

These differences are seen also in the probability P_d, which is calculated in accordance with (12) in [40] and averaged over the impactor contact area. This is the probability of irreversible damage of bonds in the material at a given temperature T and impact velocity v_0. Appropriate dependence on the specific velocity of the impactor it is shown in Fig. 9.

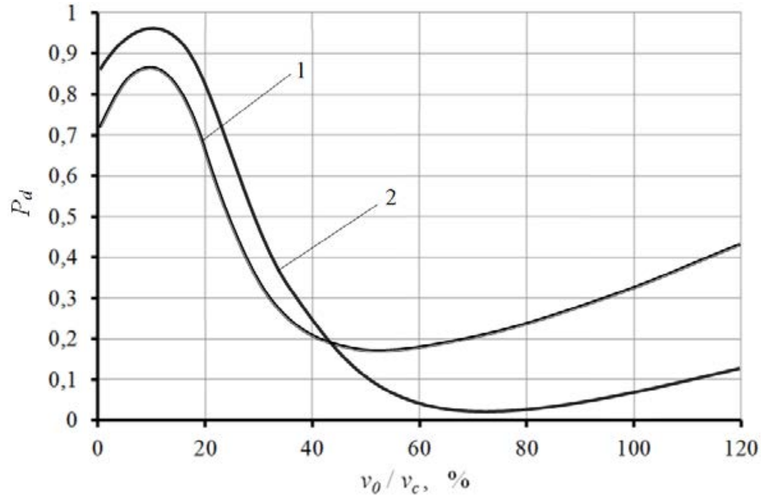

Figure 9. Dependency of averaged over the impactor contact spot estimated probability of recovery of bonds in material P_d on specific impact velocity v_0/v_c : 1 – material of type A; 2 – material of type B

The character of change of this value is determined with the analyzed above nature of the interrelationship between the probabilistic processes of destruction and restoration of bonds at the micro- and nanoscale in accordance with changes in the strain rate. The value of strain rate is directly affected by the initial velocity of the impactor and the damage evolution process itself, which causes a corresponding decrease of stiffness.

The proposed model was also tested for low impact velocities v_0 in the range of from 1 to 5 m/s, that does not exceed 4 thousandths of the critical velocity v_c, i.e. $v_0/v_c \leq 4‰$. For this aim the impact tests of composite plates based on carbon fibers and epoxy resin were modeled based on the elastic characteristics of the material, strength parameters and experimental conditions presented in [26]. Fig. 10 and 11 show comparative graphs, which illustrate results of simulation using the proposed model and results of obtained in [26] independent experiments, i.e. data on the resistance force of jammed along their edges circular plates of material against penetration by a falling weight and on its energy absorption at impact.

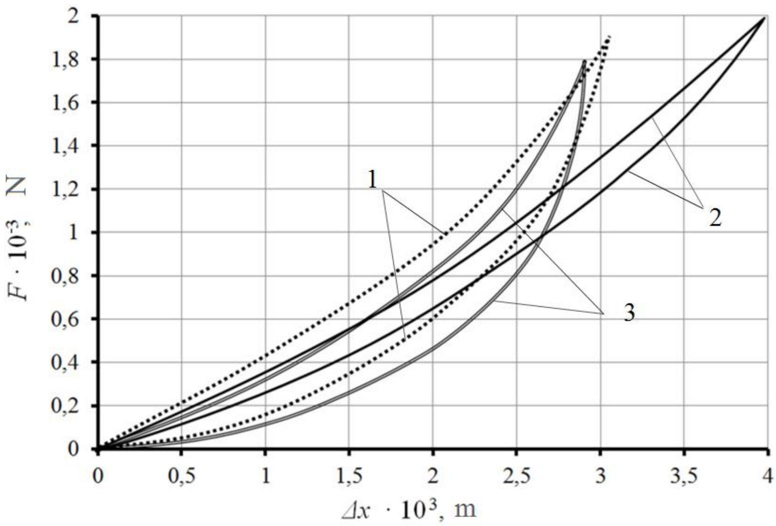

Figure 10. Dependency of impact force F on the depth of impactor penetration Δx into the material for carbon epoxy plastic: 1 – according to experimental data [26]; 2 – results of simulation according to standard and 3 – results of simulation according to probabilistic model

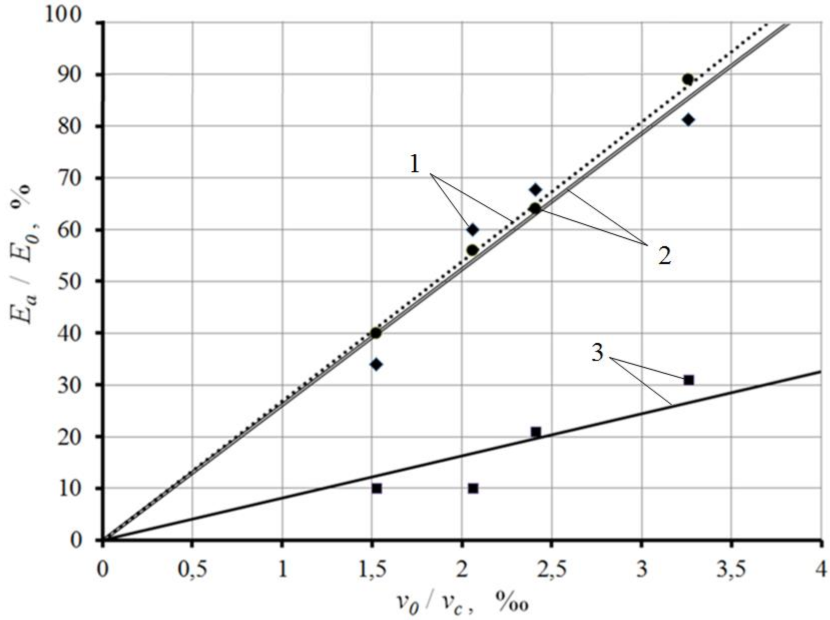

Figure 11. Dependency of specific energy absorbed by the specimen E_a / E_0 on specific impact velocity v_0 / v_c for carbon epoxy plastic: 1 – according to experimental data [26]; 2 – results of simulation according to probabilistic and 3 – according to standard model, as well as the corresponding approximating lines

As shown in Fig. 10, the impact force is increased during the impactor penetration into the composite material. Then during unloading of the composite until there is no stress, a hysteresis loop takes place because of dissipation of part of the energy due to deformation and damage. Improvement of the probabilistic model for simulation of low impact velocities is possible by means of a more detailed distiguishing of damage processes of the fibers and the matrix. That will allow a more precise calculation of the initiated in the material forces taking into account the different contribution of fiber and matrix at the same constant value of strain ε, which corresponds to a certain depth of penetration Δx of the impactor into the material.

The initial impact energy E_0 corresponds to the initial impactor velocity v_0. The ratio of deviations of the simulated energy values from the experimental data $\Delta E_a / E_a$, that can be obtained from the data in Fig. 11 for low velocities, similar to the data in Fig. 5 for the range of high velocities, both illustrate the benefits of the proposed probabilistic model in terms of increasing the accuracy of simulation of impact interaction.

A small deviation of the line 2, which approximates the simulated data, from the experimental data 1 is closely related to differences of the simulated 3 and experimental 1 hysteresis loops in Fig. 10. Therefore, although a special interest is possessed by the possibility to link the behavior of the material with such a parameters as the average estimated speed of sound in the composite, but consideration of critical processes in the fiber and matrix separately permits thus a more detailed accounting of the peculiarities of deformation and fracture. As it becomes evident from analysis of the carried out research, the influence of the speed of sound in the fibers is substantially affecting the process of high-velocity interaction of composite and impactor in case of investigation of an impact in a range of velocities close to this speed of sound and higher.

Conclusions. Characteristics of energy absorption and damage formation of flat plates of fiber-reinforced material under impact in the range of high velocities (20 – 1500 m/s) are experimentally determined and analysis of adequacy of their modeling using a previously developed [39, 40] probabilistic model is realized.

Maximal areas of specimen damages are observed in the impact velocity range of about ballistic limit of the material. Damage area of the studied three-dimensionally reinforced hybrid-garn laminate is less than that of the two-dimensionally reinforced one at the same velocities. The energy absorption is on the contrary greater, i.e. damage formation consumes a relatively larger part of the kinetic energy of the impactor.

This means that at the ballistic limit velocity the most intensive rupture of bonds in the material takes place together with a still high level of their recovery, while the recovery is much less likely at higher velocities. For these processes the impact energy is consumed. However, in the three-dimensionally reinforced material these processes are realized somewhat more efficiently due to the greater percentage of fiber content, which is manifested in a higher calculated speed of sound and is taken into account by the probabilistic model, but also due to additional binding of longitudinal and transverse fibers with the fiber, which are perpendicular to the laminate plane. Therefore, the development of the proposed probabilistic model in the future is seen in the inclusion of additional terms that take into account not only the average for all types of bonds in the material parameters, but also distinguish them by type of the bond to be destroyed or, in some cases, restored.

Based on these experimental data a new type of characterized with an improved energy absorption composite materials is suggested which are net-reinforced composites. Increased energy absorption is achieved due to redistribution of stresses in the material volume realized not only by means of the matrix, but also by means of the permanent connection of longitudinal and transverse fibers in the places where they intersect.

Increased energy absorption and hardening of the materials in the velocity ranges of 200 – 300 m/s, and 1100 – 1400 m/s is successfully modeled. The first range corresponds to the ballistic limit of the hybrid-garn materials, which presence is explained by the fact that at this impact velocity the probability of fracture of such a number of bonds, which is critical for the given thickness and number of layers of the material, taking into account the bonds in the fiber-matrix interface, begins to exceed the probability of their recovery, which is determined by current conditions of the experiments.

The second range corresponds to similar processes of irreversible damage of bonds in the matrix material. Accordingly, we can expect a slightly expressed (due to the complete destruction of bonds in the matrix and in the fiber-matrix interface) display of similar energy absorption properties, in the form of a third maximum range, at higher velocities, which are close to the speed of sound in the fibers and are accompanied by similar processes of irreversible damage to the fibers.

Thus, on the basis of these original experimental studies and experimental data of other authors, the applicability of the proposed and developed probabilistic model of multi-component materials is shown for simulation of material behavior under loading at high strain rates of low- and high-velocity impact.

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ЕКСПЕРИМЕНТАЛЬНЕ І ЙМОВІРНІСНЕ ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ УДАРУ ВОЛОКОННОЗМІЦНЕНИХ КОМПОЗИТІВ ПРИ ВИСОКИХ І НИЗЬКИХ ШВИДКОСТЯХ

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Резюме. *Проаналізовано особливості динаміки енергопоглинання й пошкодження пластин із багатокомпонентного композиційного матеріалу залежно від швидкості удару в діапазоні швидкостей зіткнення від 20 до 1500 м/с з урахуванням визначаючих їх фізичних процесів пошкодження на основі даних експерименту й чисельного розрахунку за допомогою розробленої ймовірнісної моделі. Проведено порівняння результатів з дослідними даними, отриманими іншими авторами.*

Ключові слова: *волоконнозміцнені композити, еволюція пошкодження, ймовірнісне моделювання, високошвидкісний удар, швидкість деформації, електромагнітна емісія, акустична емісія.*

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