FE Analysis of Contact Interaction Between Rigid Ball and Woven Structure in Impact Process

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Abstract

The current paper presents the results of finite element solution of the problems simulating contact interaction between woven structures and striker in the form of rigid ball. The woven structure is represented by a great number of the fibers braided in such way that each of them can come into contact interaction with others. In this paper the analysis results for ball impact direction effect on the woven structure dumping properties was demonstrated. For simulation of the impact process and subsequent multiple contact interaction between woven structure fibers FE mesh containing about 1 million degrees of freedom was used. The efficiency of contact algorithm realization in finite element software LS-DYNA is visually presented. The zone with largest contact pressure and redistribution of contact interaction zone in impact process was analyzed

Introduction

Multiple results of researches and analyses in the field of dynamic behavior of constructions and materials arouse an ever-increasing interest to this problem. In the process of analyzing system dynamics, impact loadings present those of the great interest.

The notion “impact” defines a phenomenon taking place in a mechanical system as a result of the dynamic contact between a construction (structure) and a striker. Impact is characterized by abrupt alteration of velocities of mechanical system points during an extraordinarily minute period of time and short-time action of extremely significant forces.

Depending upon the amount of energy absorbed in the impact process, impacts may be classified as abrupt, of intermediate abruptness or nonabrupt (soft).

In the first case the supplied energy portion absorbed by a structure significantly exceeds that absorbed by a striker; thus, for abrupt impacts a striker may be considered as undeformed.
In the second case energy portions absorbed by a striker and by a structure are comparable. And at last, the energy portion absorbed by a striker in nonabrupt impacts significantly exceeds the energy share absorbed by a structure. It is evident that for the first two cases it is necessary to take into account the interaction between a striker and a structure; for the last case – a structure may be assumed as undeformed in the impact process. More information from theory of impact is presented in [6, 11, 12].

One of the most interesting but insufficiently studied problems still remains the problem of dynamic behavior of composite materials, including textile and woven materials under external nonstationary action, in particular – in impact loading. Development model of woven structures for finite element impact simulation is present, for example, in [9]. The important peculiarity of woven structures is the presence of contact interaction between separate fibers in them. Incidentally, fibers, being in contact interaction, may slide with regard to one another as well as adhere to each other. These peculiarities of material may substantially influence the dynamic behavior of a woven structure as a whole, e.g. in the process of collision with a flying object. It is clear that in order to detect these effects, fibers of a woven structure shall be modeled as three-dimensional elements [3, 4] with all their geometrical features, taking into account their possibility of coming into contact interaction with each other.

The present paper considers the analysis of the dynamics of collision of a woven structure and an rigid ball. For example, the investigates of the collision of a plate and a rigid ball are presented in [1, 8]. The paper presents the results of the research of damping properties of a woven structure, estimation of which has been implemented on the base of solutions of a series of problems of the contact interaction between this structure and a striker. Damping properties of a woven structure will be understood here as absorption of the supplied energy in consequence of multiple contact interaction with friction between woven structure fibers as well as energy redistribution inside the woven structure itself.

Construction of the Mathematical and Finite Element Models of a Woven Structure

A woven structure formed with the system of two filaments interwoven in orthogonal directions (Fig.1) has been chosen as a material for the analysis. Aiming at obtaining most exact solution and fundamental understanding of the dynamic behavior of both a woven structure and a ball, a three-dimensional interweaving model with all geometrical and main physico-mechanical features, including fiber distortion and contact interaction between fibers, has been designed.

The woven structure geometry presents the square shape with the side length equal to L = 0.5m. The distance between fibers comes to $\lambda = 2.5$cm, distortion amplitude being A = 1cm and fiber diameter equal to d = 5mm. The unit cell of the woven structure considered is shown in Fig.2. Fiber material has been assumed as isotopic linearly elastic material with the Young's modulus E = 2MPa, Poisson's ratio $\upsilon = 0.35$ and density $\rho = 1800\text{kg/m}^3$.

All fibers are assumed to be in contact interaction with one another, coefficient of friction being equal to $\mu = 0.25$.

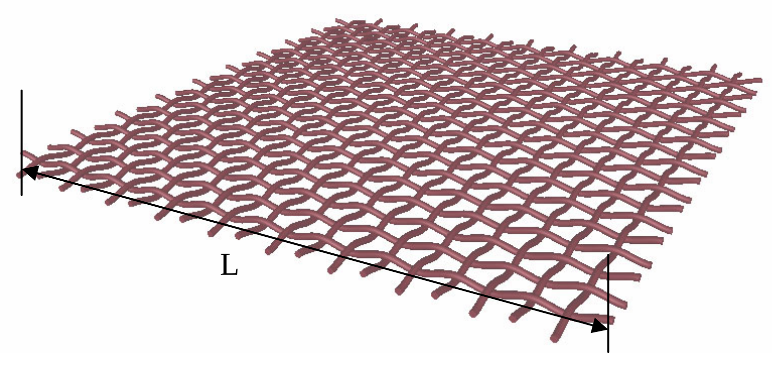


Fig.1.

All in all, one hundred periodicity unit cells have been used for modeling the analyzed woven structure, the number of interwoven fibers and, consequently, contact pairs coming to 361.

For numerical simulation of contact interaction between all components of the model considered (woven structure fibers ; the striker), the mostly suitable and efficient algorithm determined by the AUTOMATIC-SINGLE-SURFACE-card [5,7] has been applied. The finite element contact algorithm is presented, for example, in [10, 11].

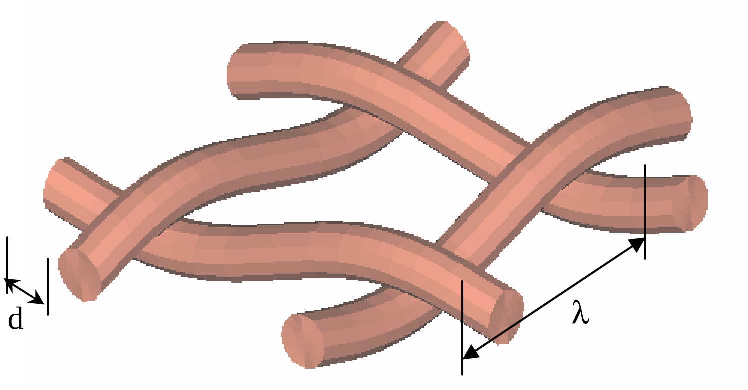


Fig.2.

For the development of the three-dimensional finite element model of the woven structure chosen, there have been used isoparametric finite elements with the second formulation [5, 7]. The total number of elements comes to about 240 000, number of degrees of freedom (NDF) making about 920 000. Such great quantity of finite elements and, consequently, degrees of freedom is explained by the necessity of creating a regular mesh adequately describing both geometrical features of the woven structure and its deformation properties, as well as of providing more stable operation of the contact algorithm.

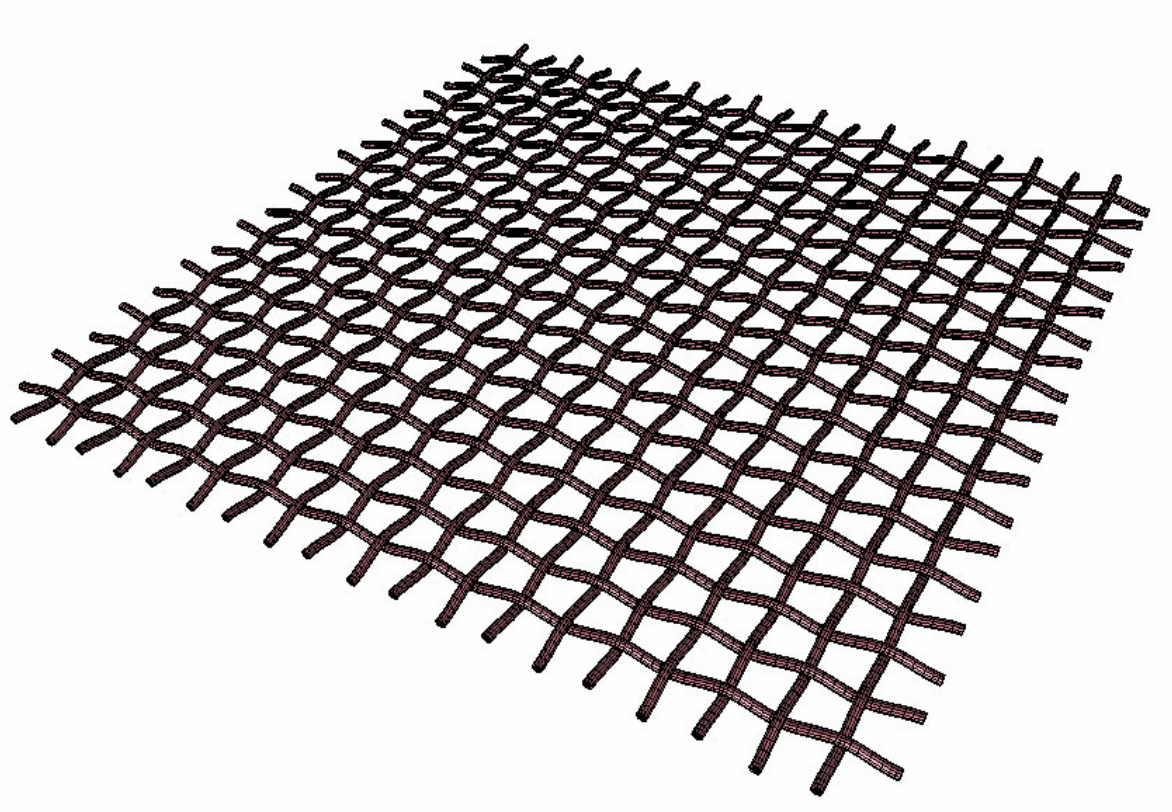


Fig.3.

The finite element model of the woven structure is shown in Fig.3. Magnified fragments of the finite element model of the woven structure are presented in Fig.4.

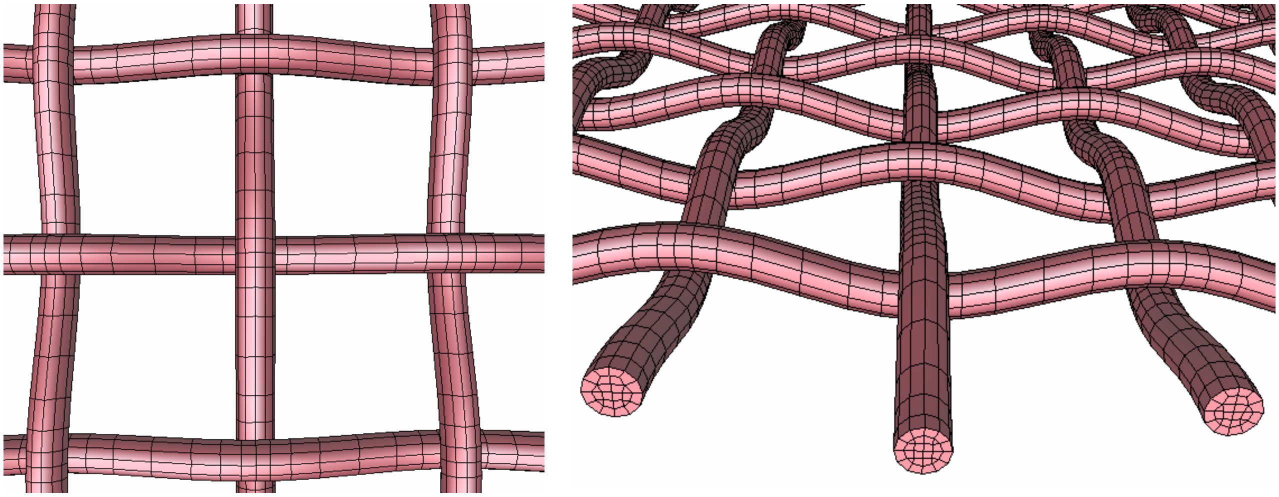


Fig.4.

Problem Statement

The problem considers direct simulation of the impact contact interaction of the woven structure with the absolutely rigid ball falling at various angles of incidence, without initial spinning. The modulus of the ball is taken equal to |V| = 50m/sec. The ball is modeled as absolutely rigid body with mass value m = 160 gram, radius of the ball being taken equal to R = 5cm.

The woven structure plane is arranged on the plane XZ. The velocity vector of the ball lies on the plane XY. The direction of initial velocity (angle of incidence α) of the ball is varied from 0° to 60° with regard to the normal of the interweaving plane (Fig.5).

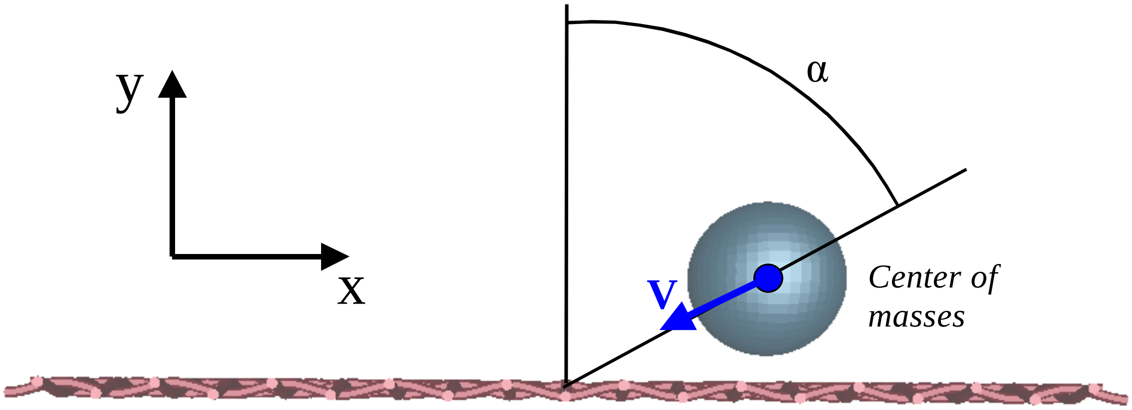


Fig.5.

Fibers arranged along the external boundary are assumed to be rigidly fixed. Inasmuch as three-dimensional elements have only forward degrees of freedom, rigid fixing will be implied as the absence of displacements throughout the whole cross section of a fiber. The statement of boundary conditions for fibers is illustrated by Fig.6.

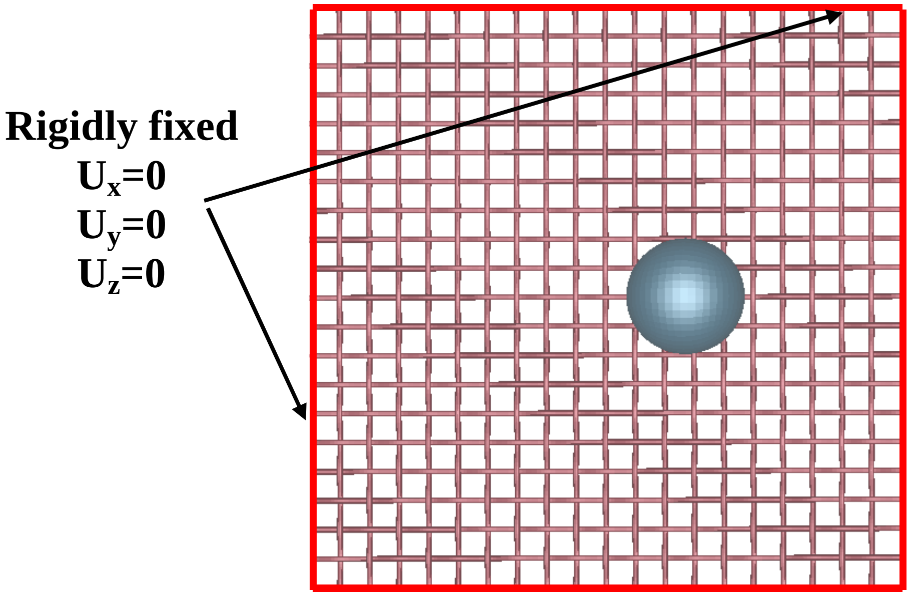


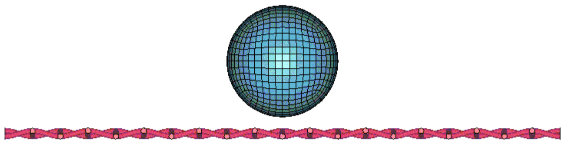
Fig.6.

Dynamic Behavior of the Woven Structure in Collision with the Flying Ball on Condition of the Presence of the Symmetry Plane in the Model

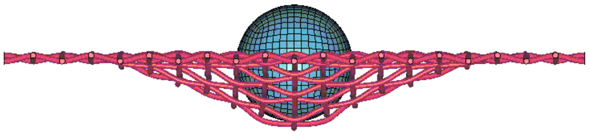
The analysis of the dynamic behavior of the woven structure and the ball during their collision has been carried out on the base of their deformation behavior and the dynamics of redistribution of kinetic and potential energies within the system.

Selection of energy as a parameter defining movement is most convenient because it presents the integral characteristic for each component of the system taken separately as well as for the whole system totally.

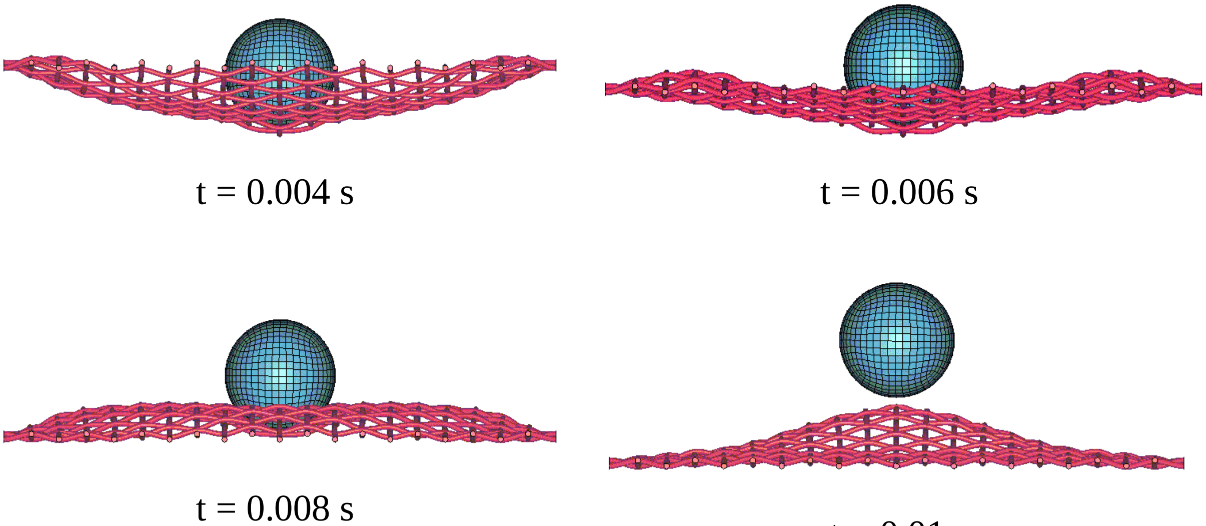
Dynamic behavior of the woven structure and the position of the ball at various instants of time and various angles of incidence are illustrated below (Figures 7-9).



t = 0 s



t = 0.002 s



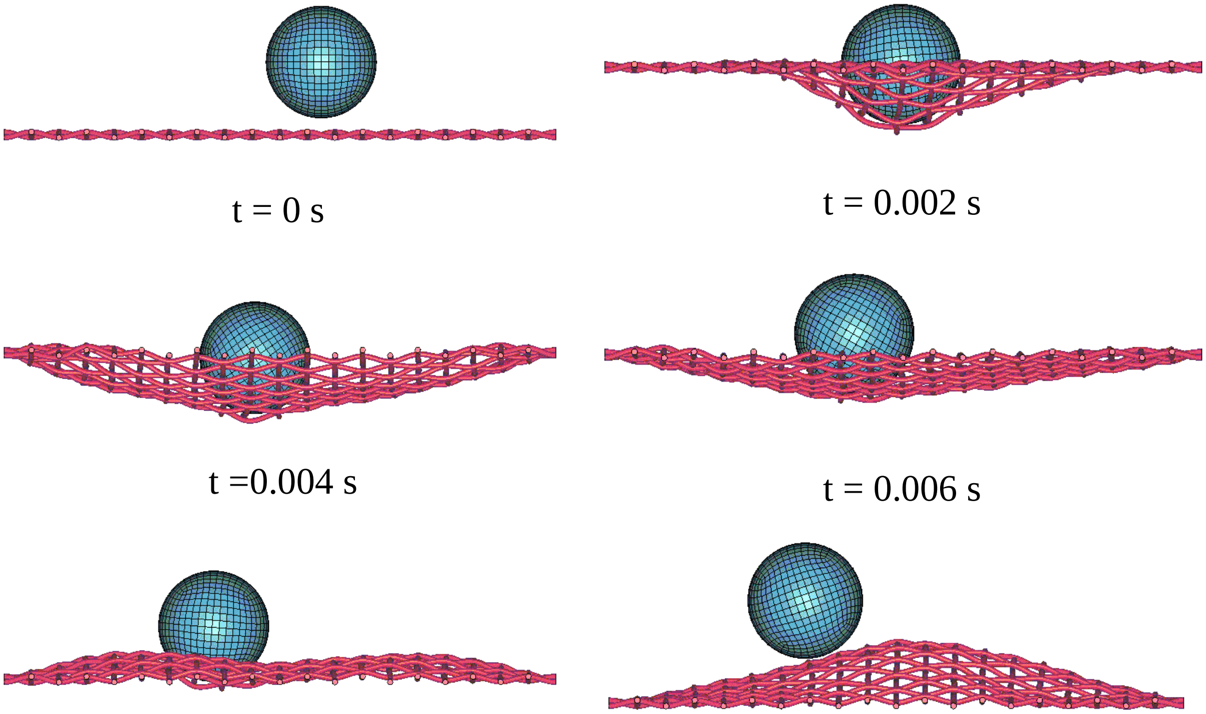
t = 0.004 s

t = 0.006 s

t = 0.008 s

t = 0.01 s

Fig.7. (α = 0°).



t = 0 s

t = 0.002 s

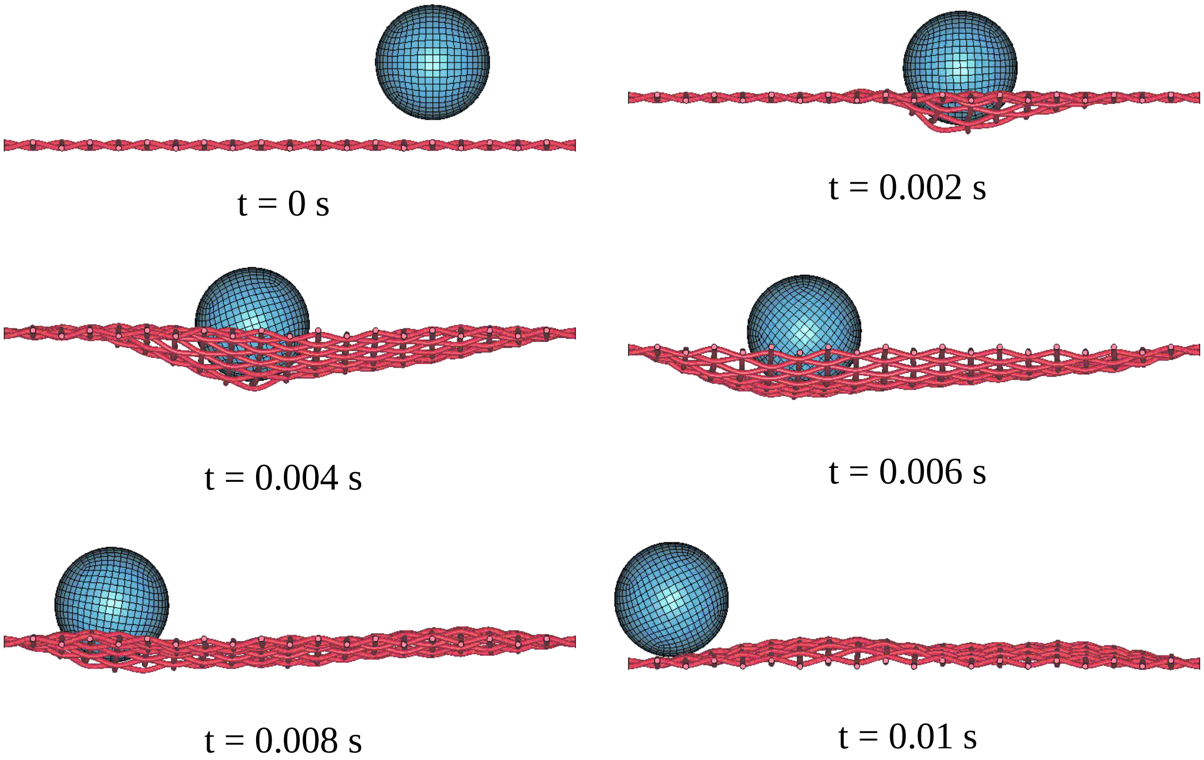
t =0.004 s

t = 0.006 s

t = 0.008 s

t = 0.01 s

Fig.8. (α = 30°).



t = 0 s

t = 0.002 s

t = 0.004 s

t = 0.006 s

t = 0.008 s

t = 0.01 s

Fig.9. (α = 60°).

As it may be seen from Figures 8 and 9, in every case, except that when the angle of incidence is equal to zero, the ball acquires spinning after collision. This effect is caused by that circumstance that in the process of collision of the ball with the woven structure, the ball is subjected to the action of friction forces applied to woven structure cross-fibers it contacts with and directed to the side opposite to the forward movement direction of the ball; this leads, in its turn, to initiation of a spinning moment around its center of gravity.

Let us estimate the dynamic behavior of the ball and the woven structure on the basis of energy redistribution during the process of collision.

Inasmuch as the ball is simulated as absolutely rigid body, its potential energy is equal to zero on condition of the absence of gravity forces. The woven structure is modeled as deformed three-dimensional body possessing both kinetic and potential energies. For convenience of the analysis of energy redistribution in the woven structure, the alteration of total energy (kinetic plus potential) during the impact contact is considered for this case. It should be noted that the system in its turn is not conservative – total mechanical energy diminishes with time in consequence of the action of friction forces both between the ball and the woven structure and between the fibers of woven structure itself. Therefore, the plotting of the graphs of energy dissipation caused by the action of friction forces is of a certain interest.

Fig.10 shows the graphs of energy alteration and energy dissipation during the process of collision of the ball with the woven structure. From the graphs presented, we may trace the following development of the impact contact process.

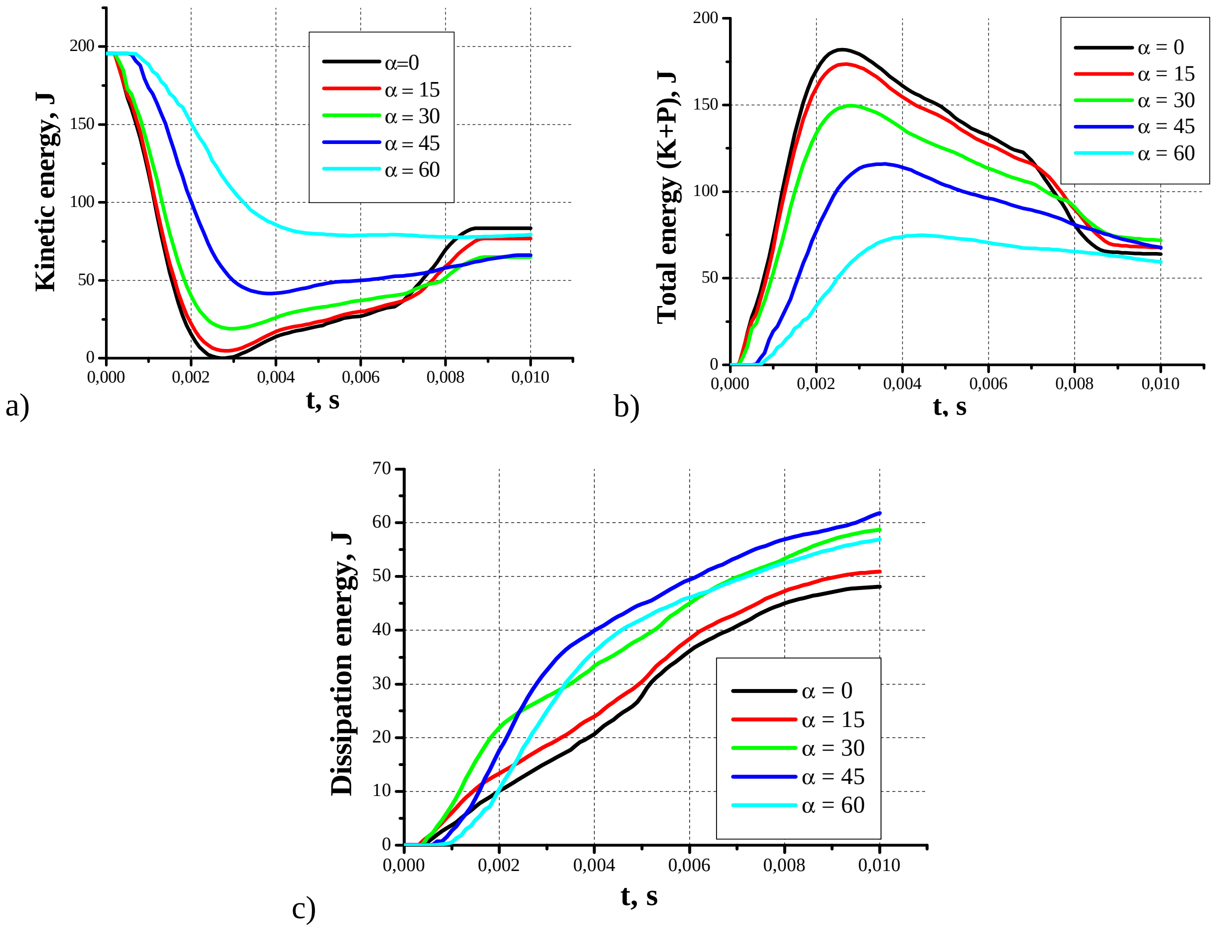


Fig.10.

From the instant of the ball's coming into contact with the woven structure, kinetic energy of the ball gradually transforms into kinetic and potential energy of the woven structure. This process is uninterrupted and monotonous, and it continues up to a certain instant of time (t_{min}, Fig.10), after which accumulated potential energy of the woven structure starts to transform back into kinetic energy of the ball, causing the growth of velocity of the ball and its subsequent bounce. It is important to note that at low angles of incidence in the system takes place the duplicate (second) pushing of the ball by the woven structure during the ball's bouncing.

This second pushing is characterized by the sharp change of alteration rate of both kinetic energy of the ball and total energy of the woven structure. Starting from the angle of incidence equal to $\alpha = 45°$, the duplicate pushing disappears, and the bounce curve becomes even.

The other interesting peculiarity of the ball movement is connected with that fact that at the angle of incidence equal to $\alpha = 60°$ the curve of kinetic energy alteration has only a downward arm, descending to some constant value.

Thus, one may conclude that the greater angle of incidence of the ball, the less energy returned to the ball by the woven structure after their collision. Incidentally, there is such an angle of incidence at which the woven structure only absorbs energy, returning nothing to the ball.

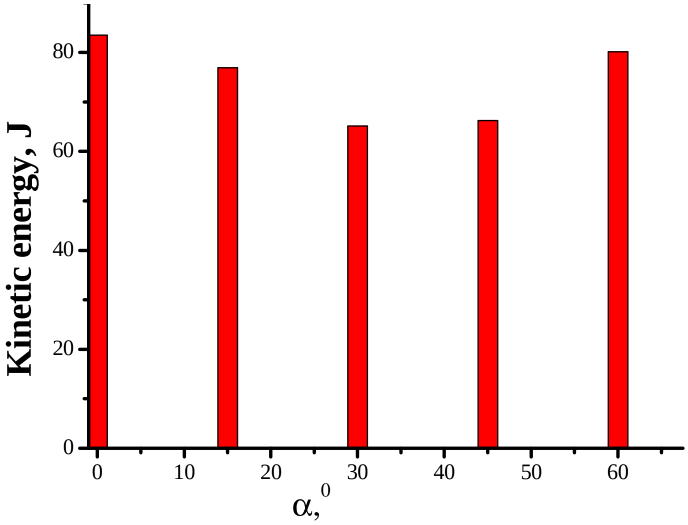


Fig.11

Let us analyze the dependence of kinetic energy of the ball (after its lifting-off) upon angle of incidence. As it is seen from the columnar diagram, Fig.11, there is a certain maximum in transferring energy between the ball and the woven structure. Incidentally, there is some value of the angle of incidence corresponding to maximum amount of energy lost by the ball. Among the angles analyzed, such value is 30°.

Dynamic Behavior of the Woven Structure and the Ball in Collision for the Case of Asymmetrical Impact Contact

The statement of the problem for collision of the ball and the woven structure in the case of asymmetrical impact contact is illustrated by Fig.12.

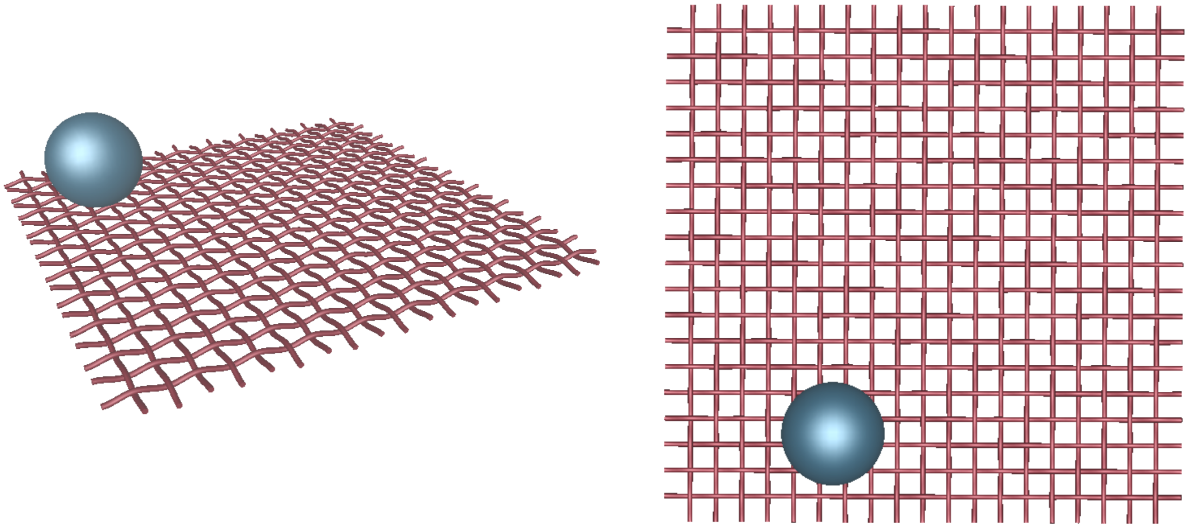
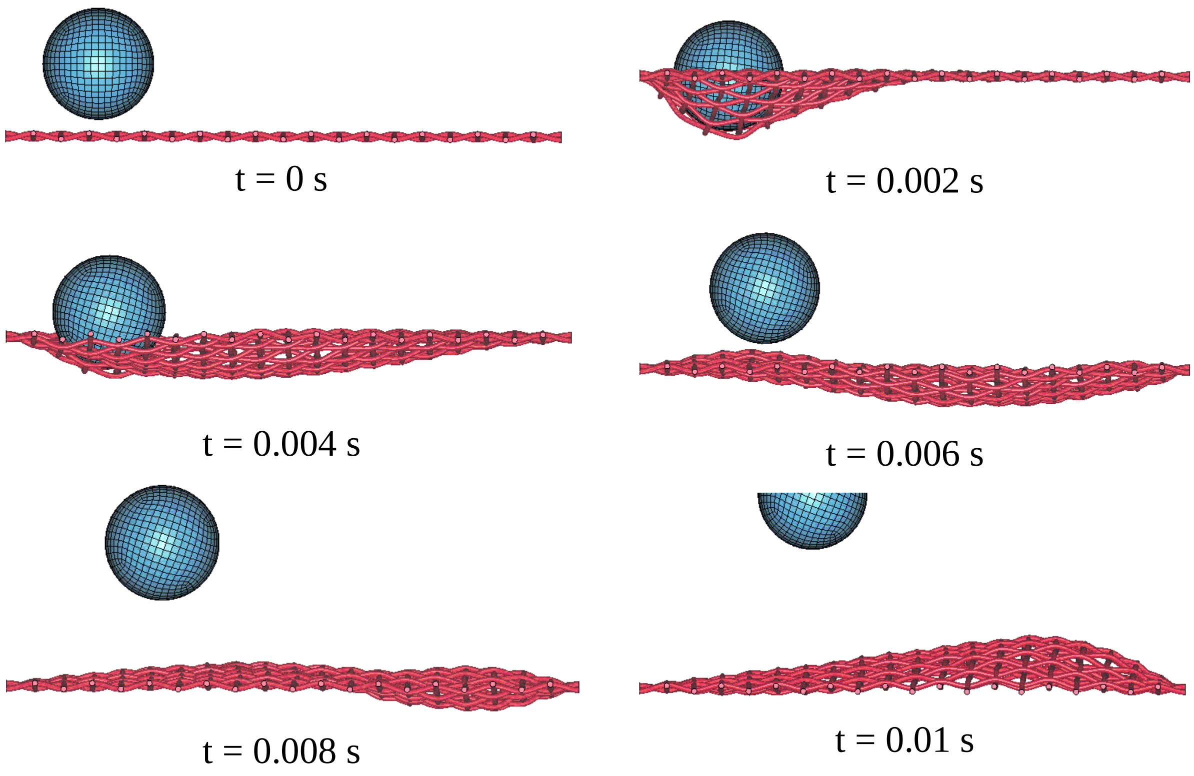


Fig.12

Just as in the model with the symmetry plane present, the initial velocity of the ball is taken equal to V_0 = 50m/sec, and the edges of the woven structure are assumed to be rigidly fixed.

The behavior of the ball and the woven structure is demonstrated in Fig.13.



t = 0 s

t = 0.002 s

t = 0.004 s

t = 0.006 s

t = 0.008 s

t = 0.01 s

Fig.13

The case of asymmetrical impact contact is the most interesting because its practically impossible to predict beforehand the behavior of the ball as well as that of the woven structure after their collision. One of the specific features of such collision is rather unusual behavior of the ball after its bouncing; the ball, still being in contact with the woven structure, turns around by some angle and, not acquiring spinning, continues its movement after its lifting-off.

Now, let us estimate the energy redistribution between the ball and the woven structure in the process of their collision. Alteration of kinetic energy of the ball and total energy (kinetic plus potential) of the woven structure is shown in Figures 14 and 15.

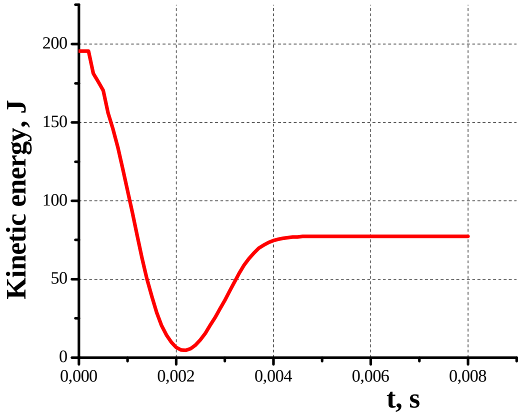


Fig.14

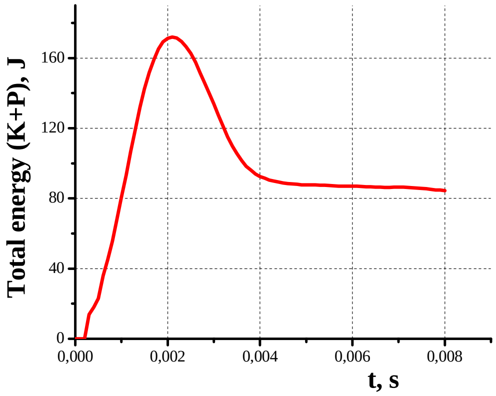


Fig.15

One may distinctly see the minimum of kinetic energy of the ball and corresponding maximum of total energy of the woven structure. It should be noted that the ball does not completely lose its energy. Attentively following the movement of the ball (Fig.13), one may observe that at the instant of its losing the forward movement velocity the ball acquires spinning for some short period of time and turns around its center of gravity. This is the selfsame small amount of energy that the ball retains after collision. Afterwards, the ball loses its spinning velocity, acquiring that of advancing movement, and, obtaining energy from the woven structure, the ball bounces off it at some angle.

Analysis of Contact Pressure Distribution in the Woven Structure During the Process of Collision

Let us consider distribution and redistribution of contact pressure in fibers of the woven structure for the following three cases: symmetrical direct impact, impact collision at the angle of incidence equal to 45° and asymmetrical impact.

For the cases of symmetrical direct impact and asymmetrical impact, we will define contact pressure and follow its alteration at the points arranged in the areas of contact between the ball and woven structure fibers during their touch as well as at the points between fibers of the woven structure at the space of collision. For the case of collision at the angle of incidence equal to 45°, values of contact pressure are defined at the points located in the fiber areas directly contacting with the ball in the process of collision. The arrangements of points for which the values of contact pressure are defined and analyzed are shown in Figures 16 and 17.

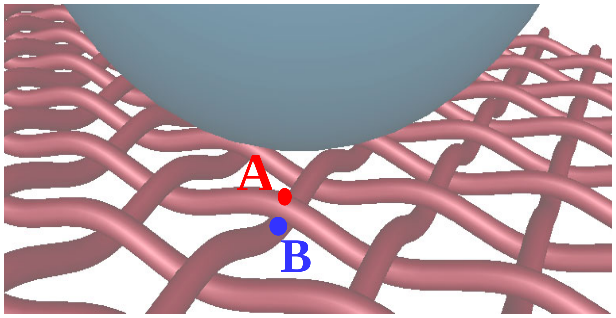


Fig.16

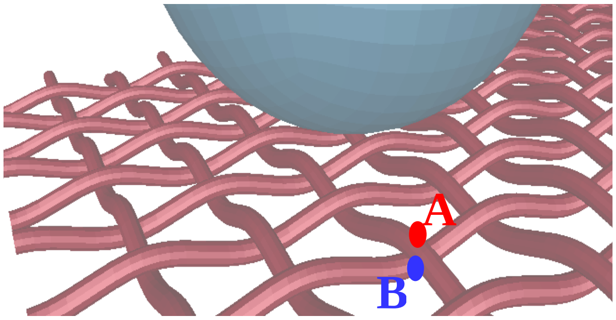
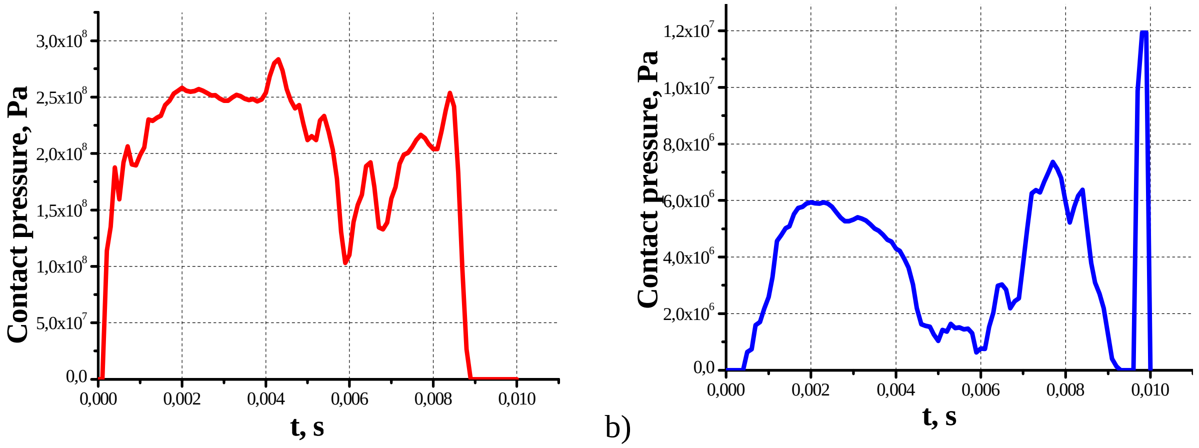


Fig.17

The evolution of the values of contact pressure at the points A and B for the case of symmetrical direct contact is shown in Fig.18.

The values of contact pressure originating at the point A of contact between the ball and woven structure fibers and the point B of the touch of two fibers are different. Contact pressure at the point A exposes impulse character, while situation at the point B is quite different: fibers at one moment come into contact interaction, at another – come out of it.

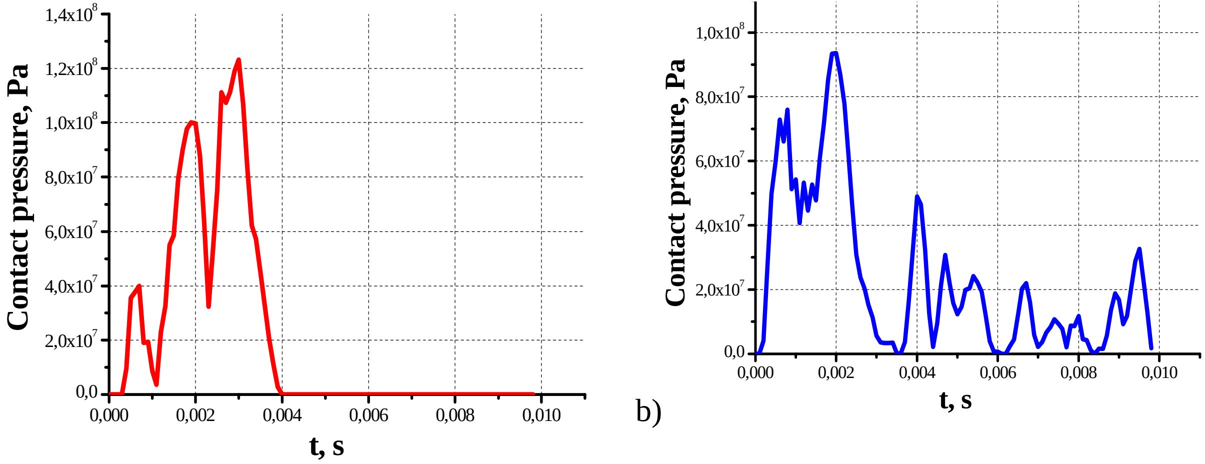
The contact pressure evolution at points A and B for the case of asymmetrical impact is shown in Fig.19. It should be noted that for point B (Fig. 19b) values of contact pressure first sharply rise then fall even down to zero, repeatedly, giving evidence of throbbing originating between fibers.



a) b)

Fig.18

a)



b)

Fig.19

Let us consider the contact pressure distribution along the fiber, as it is shown in Fig.20. The evolution of the contact pressure values is illustrated by the graphs in Fig.21, from where one may trace the following: during the time period corresponding to contact interaction between the ball and the woven structure, asynchronism of contact pressure distribution between the considered points takes place. After the ball’s lifting-off, the evolution of contact pressure values at all points acquire a similar character – coincidence of time instants at which pressure jumps are watched, or, in other words, it may be stated that fiber throbbings acquire some kind of synchronism.

And at last, let us analyze the evolution of contact pressure distribution for the case of impact collision of the ball with the woven structure at the angle of incidence equal to 45°. It is evident that during the impact process the ball will roll on the woven structure inducing contact pressure at various points of the structure (Fig. 22).

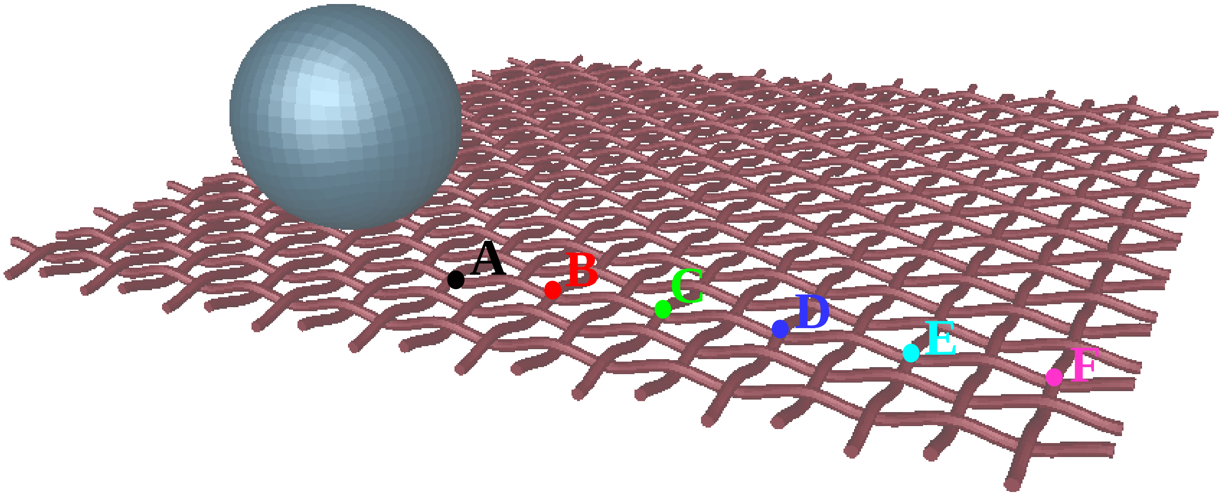


Fig.20.

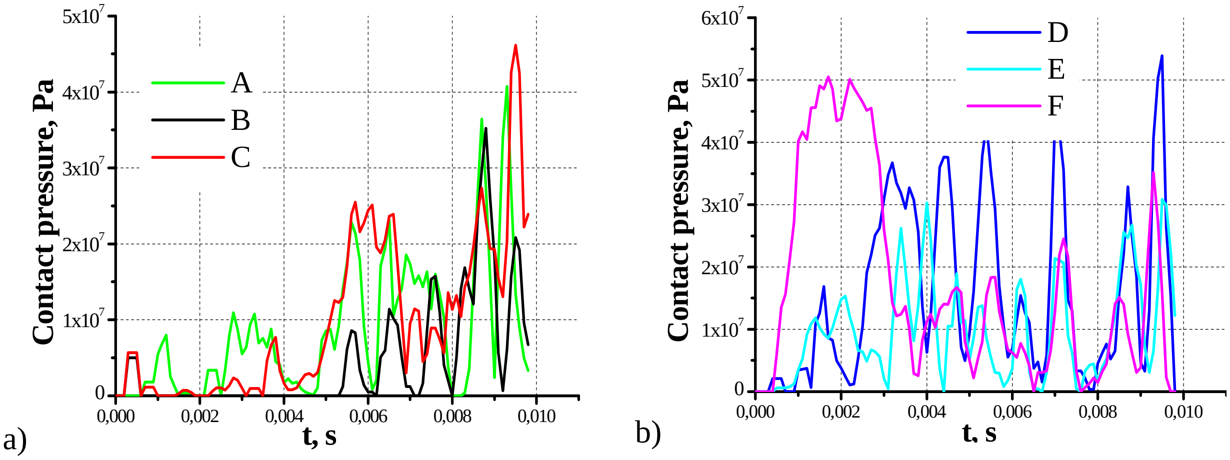


Fig.21.

Let us mark some points on the external surface of cross-fibers and trace contact pressure alteration at these points. The distribution of contact pressure values throughout the line between points A and H is shown in Fig.23. From the graph presented, the process of ball's rolling may be interpreted the following way: the ball colliding with the woven structure at point A transfers some amount of energy to the structure. This induces abrupt movement of fibers in the direct vicinity of the collision place, what, in its turn, causes collision of neighboring fibers with the moving ball. This effect corresponds to superimposition of contact pressure graphs for points A, B and C. Then, the ball, rolling over, strikes next fibers giving rise to pressure jumps in them, and so on.

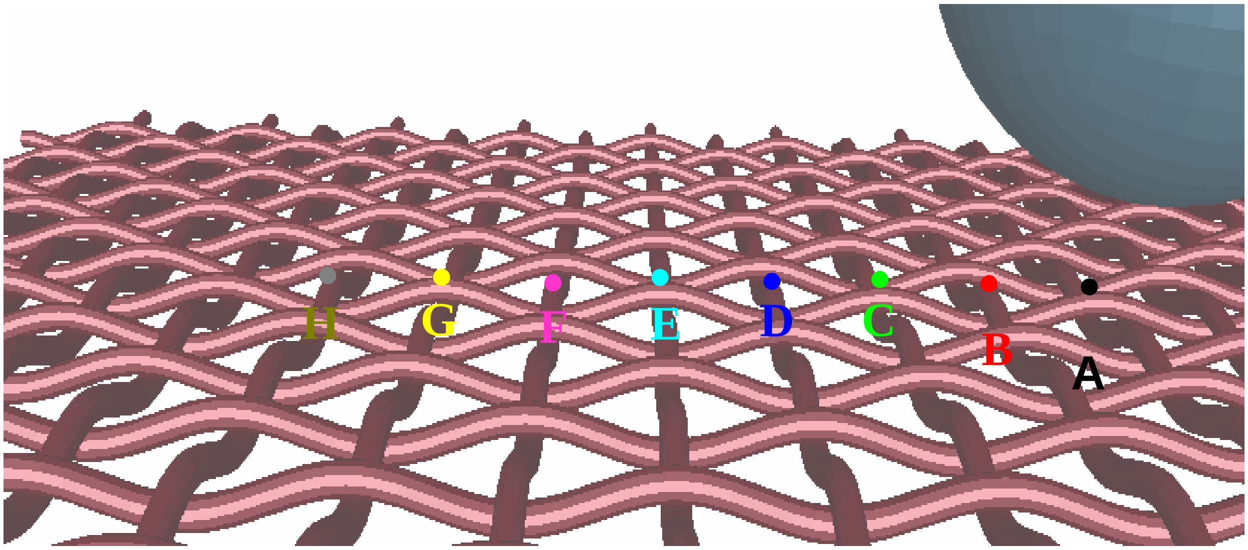


Fig.22.

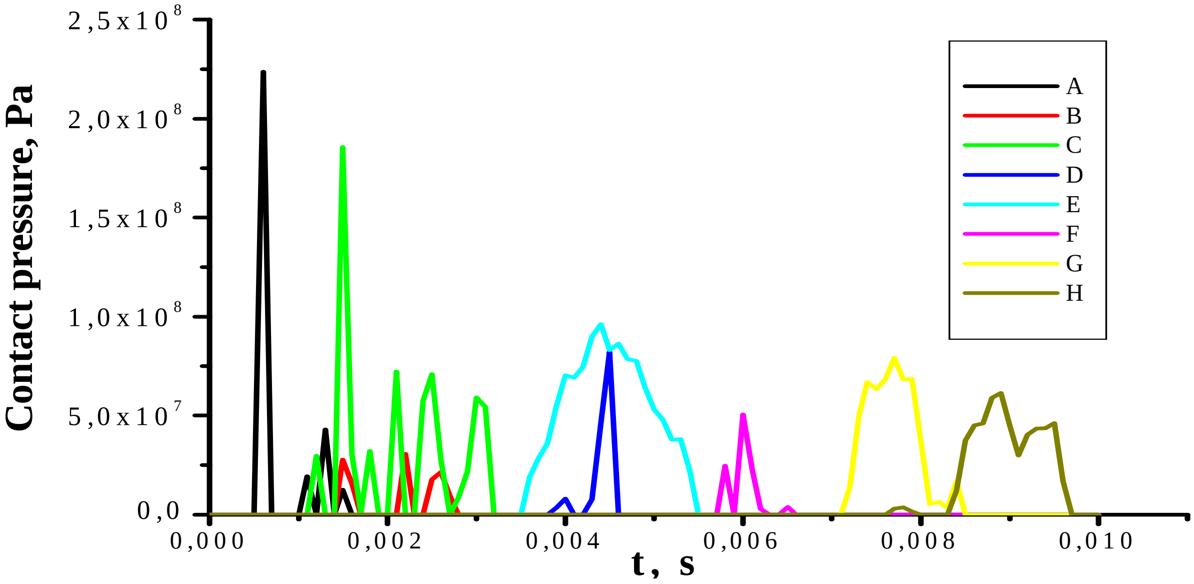


Fig.23.

Conclusion

The paper demonstrates the possibility of applying finite element simulation software LS-DYNA for analysis of three-dimensional contact interaction of a woven structure and a striker. With the use of LS-DYNA tools has been designed a principally new mathematical and finite-element model of a woven structure with subsequent direct simulation of dynamic behavior of each fiber separately and in their contact interaction.

There have been plotted graphs of energy distribution and evolution during the impact contact both individually for a striker (the ball) and the system comprising the ball and the woven structure. Dissipation energy in the system, caused by friction forces, has been estimated. Some interesting, unusual effects have been found out. Evolution of contact pressure originating both between the surfaces of the ball and the woven structure fibers and between fibers themselves has been analyzed.

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