Investigation of the Shear Thickening Fluid Dynamic Properties and its Influence on the Impact Resistance of Multilayered Fabric Composite Barrier

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Abstract

The results of experimental and computational study of properties of shear thickening fluid (STF) are observed. Two series of dynamic tests by the Split Hopkinson Pressure Bar method in rigid and soft casings are carried out to determine the dynamic bulk and shear properties of STF. A simplified mathematical model of the STF is formulated for the use in computer simulation of ballistic impact tests of multilayered fabric composite protective shells (Kevlar + STF). Numerical simulation is conducted with nonlinear LS-DYNA® code using ALE approach. The study confirmed the hypothesis about the possibility to describe STF behavior by a Newtonian fluid model in the characteristic range of strain rates. The parameters of shear viscosity and bulk compressibility of the model are defined. It is concluded that the contact interaction between STF and Kevlar basis is described by Coulomb friction law which is unnatural for fluid interactions. It is shown that the effectiveness of the STF impregnation is due to the facts of composite layers collapsing prevention and presence of internal friction.

Introduction

It was shown [1] that the ballistic properties of a multilayered Kevlar fabric barriers may be improved with insignificant mass increase when being impregnated with the Shear Thickening Fluid (STF). STF is a composite material containing solid nanoparticles embedded in a liquid polymer with a persistence of mobility, i.e. it is highly concentrated suspension in a polymer dispersion medium (concentrated colloidal suspension).

Although STF is commonly considered as a non-Newtonian fluid which viscosity increases with the strain, the question concerned the determination of any reliable dynamic viscosity diagrams is absent, and the formulation of an adequate STF mathematical model are currently open. The STF studies with standard rotational viscosimeters reveal complex (generally reversing) dependence of viscosity on strain rate [2]. In the strain rate range $500s^{-1}$– $2000s^{-1}$ that is characteristic for the impact interactions standard studies are usually unreliable. The development of light-weight Kevlar+STF barriers with high ballistic properties is impossible without introduction of an adequate mathematical model of impact interaction and understanding energy redistribution in the composite structure.

The results of experimental and computational studies of the STF and Kevlar+STF composites behaviors under dynamic loads that were carried out to develop the mathematical model of impact interaction are presented in this paper. To determine the STF dynamic properties, the experimental studies using the Split Hopkinson Pressure Bar (SHPB) method were carried out. Comparative analysis of energy-absorbing capabilities of different protective shells is performed on the base of mathematical model.

The Shear thickening fluid study

Dynamic wide-scale tests were carried out in the Institute of Mechanics of the Nizhny Novgorod State University. The SHPB tests included two series of experiments. In the first series the volume compressibility of STF was studied. The second series were directed to the determination of shear viscosity. The experimental conditions were chosen in such a way that practically interesting range of strain rate variation in STF (from 200 to 2000s^{-1}) could be realized.
Among known by now dynamic testing methods the technique, a variant of which was originally proposed by H.Kolsky [3] is most widely used due to its simplicity and proper theoretical grounds. The technique allows testing of a rather wide range of materials at strain rates within 102-104s^{-1}.

The technique uses two thin and long bars possessing high yield strength between which a sample of material to be tested is placed. The sample is much shorter than bars and possesses lower yield strength in comparison with bars properties. The split bar is loaded by elastic pulses usually recorded by strain gauge. Use of one-dimensional elastic wave theory and pulse records allow to obtaining the dynamic diagram of the sample.

When studying the dynamic properties of some materials such as concrete, soft soil, loose materials and others it is of great interest to determine not only uniaxial stress-strain curve but their bulk properties too. The modified Kolsky method was suggested for this purpose [4].

The experimental setup shown in figure 1 represents the modified Kolsky method used for determination of the basic mechanical characteristics under dynamic deformation.

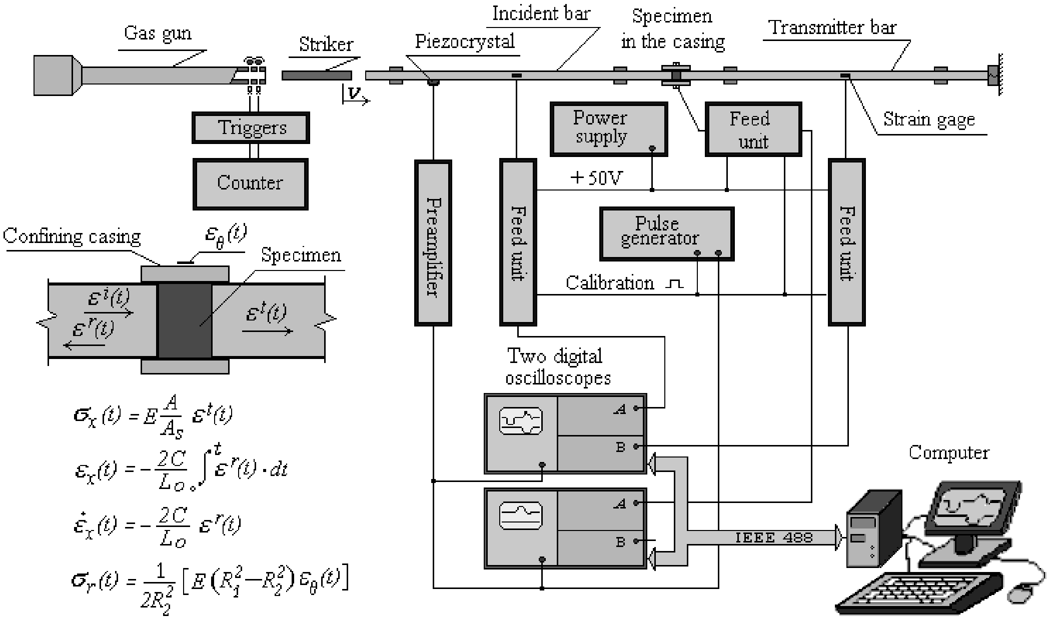


Fig. 1. Modified Kolsky method experimental setup.

The specimen is placed in a rigid elastic casing, which prevents radial deformation of the sample as shown on figure 2. Under these conditions, radial deformation of the sample can be neglected in comparison with longitudinal one. Thus, the strain state of the sample can be considered one-dimensional, while the stress state is considered bulk. In this case, the principal components of stress and strain tensors in the sample will be of the form:

$$\sigma_1 = \sigma_x;\ \sigma_2 = \sigma_3 = \sigma_r;\ \varepsilon_1 = \varepsilon_x;\ \varepsilon_2 = \varepsilon_3 = 0,$$

where σ_x and ε_x are the longitudinal stress and strain, σ_r is the radial stress in the sample.

To study the volume compressibility of the STF a test technique with a sealed container was developed in the laboratory of dynamic testing of Research Institute of Mechanics, University of Nizhny Novgorod.

The sample 5 (figure 3) was placed in a steel casing 3 with strain gauges 2 pasted on its surface. The casing's ends were closed by textolite gaskets with sealing film 6. The sample is deformed between incident 1 and transmission 4 bars.

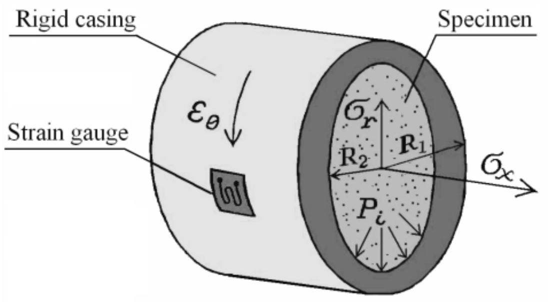


Fig. 2. Specimen in a rigid clip.

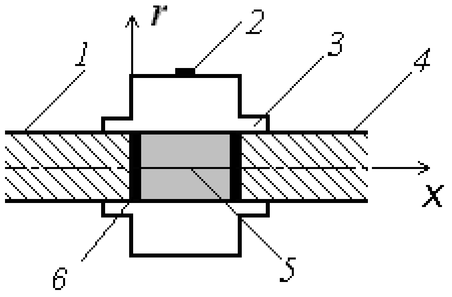


Fig. 3. Liquid armor test in a casing.

The SHPB setup used in the experiments consisted of 20mm steel bars with 1.5 and 3m lengths. Figure 4 compares the dependences of the axial and radial stresses on time, obtained from the steel casing test.

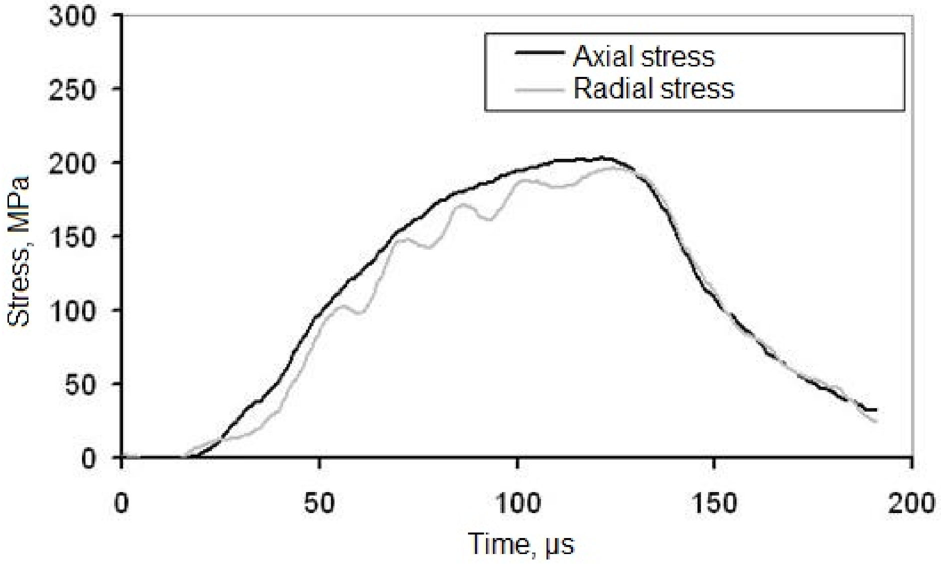


Fig. 4. Time dependences of axial and radial stresses obtained for the steel casing test.

It is seen that the values of radial and axial stresses are close enough, so it can be concluded that the stress state in the tested material is close to the uniform compression ($\sigma_1=\sigma_2=\sigma_3=p$). The figure 5 shows the test results for the one and the same sample, varying loading amplitude:

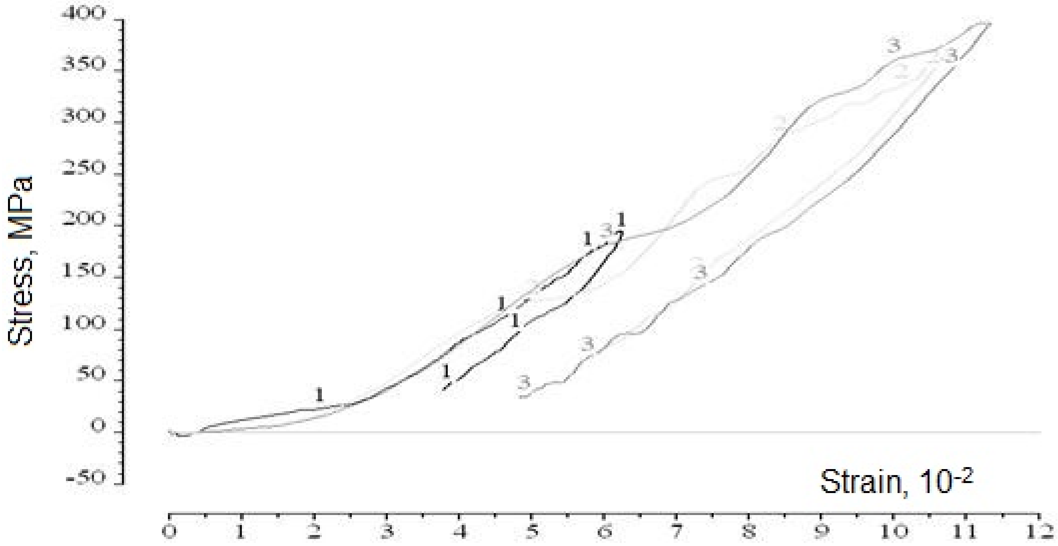


Fig. 5. Test results of tests for the same sample with different loading amplitudes.

It is evident that the nature of the diagrams does not change. The loading amplitude affects only the maximum stress realized in the specimen during testing. Figure 6 compares the graphs obtained under different strain rates from ~ 200 to 2500 s^{-1}. The corresponding strain rate diagrams are shown by dotted line.

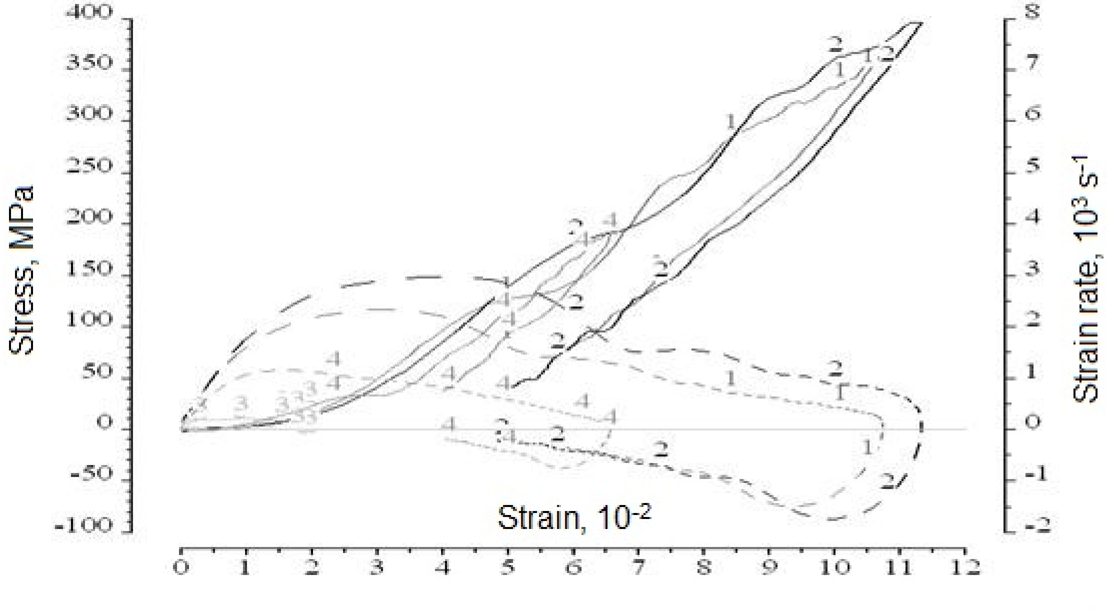


Fig. 6. Diagrams obtained at different strain rates.

The resulting bulk stress-strain relationship is nonlinear and it is well approximated by a quadratic equation:

$$p = K_1\theta = K_2\theta^2 \qquad (1)$$

Where K_1=767MPa, K_2=3000MPa.

The soft-casing tests by the Kolsky method were conducted in conditions close to one-dimensional stress. The fluid specimen was placed in a paper box and was sandwiched between the bars. The experimental setup is show on figure 7.

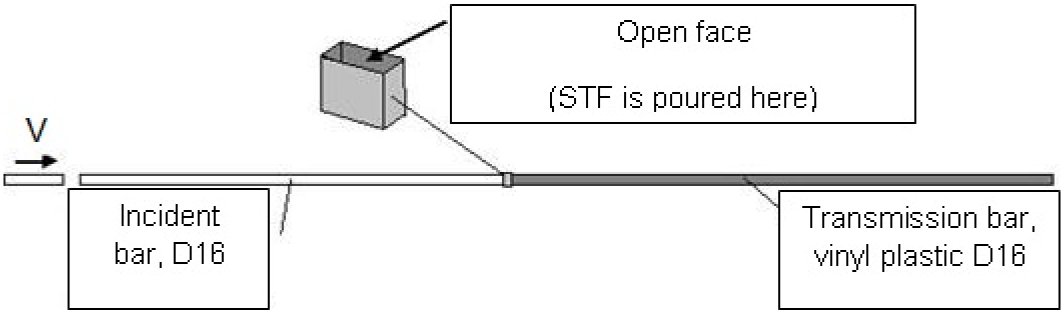


Fig. 7. The soft casing experimental setup.

Four series of tests at strain rates of 200, 500, 1000 and 2000s^{-1} were conducted. Derived stress-time and stress-strain curves for each test are shown in figures 8-11 (different curves denotes specimens within series).

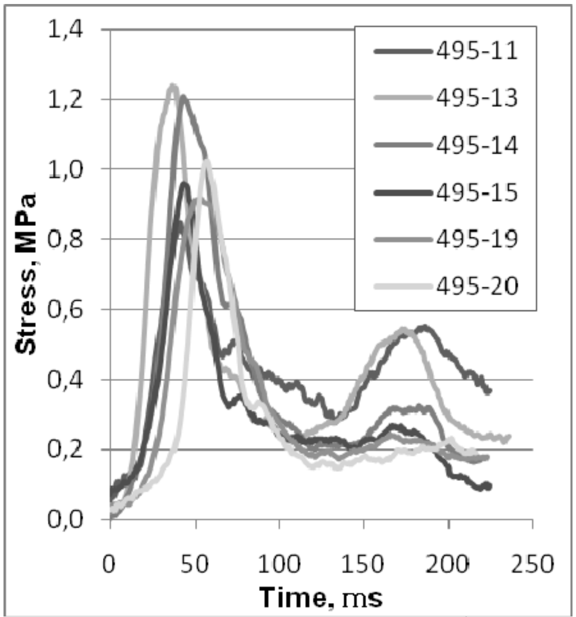


Fig. 8 – Strain rate ~ 200 s^{-1}.

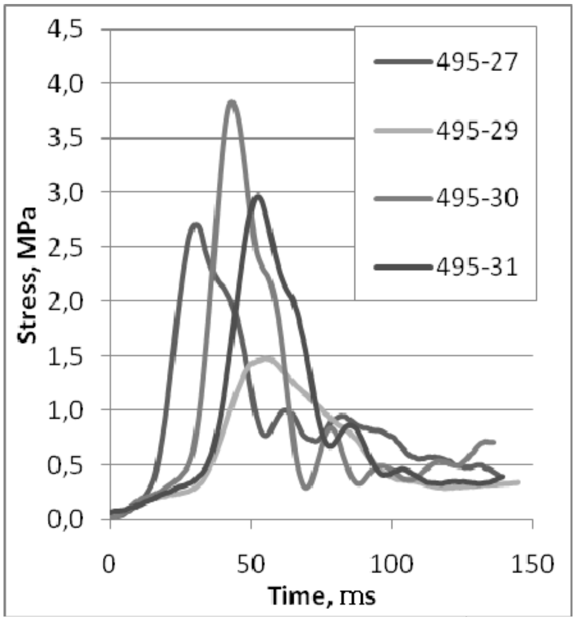


Fig. 9 – Strain rate ~ 500 s^{-1}.

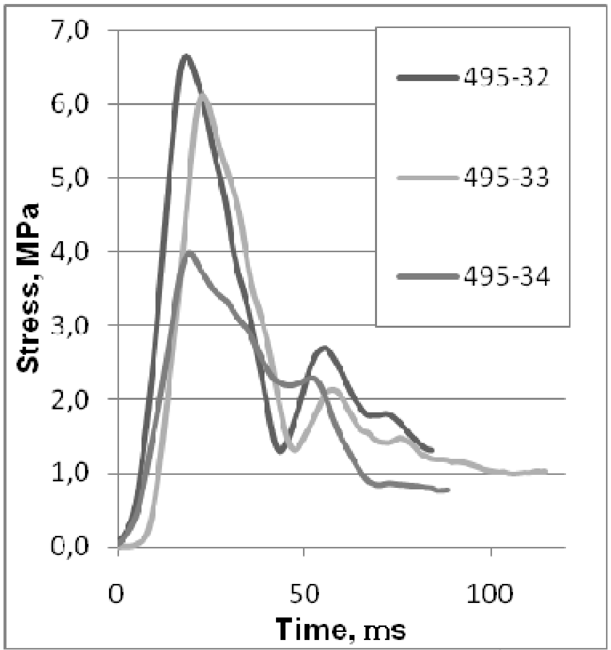


Fig. 10 – Strain rate ~ 1000 s^{-1}.

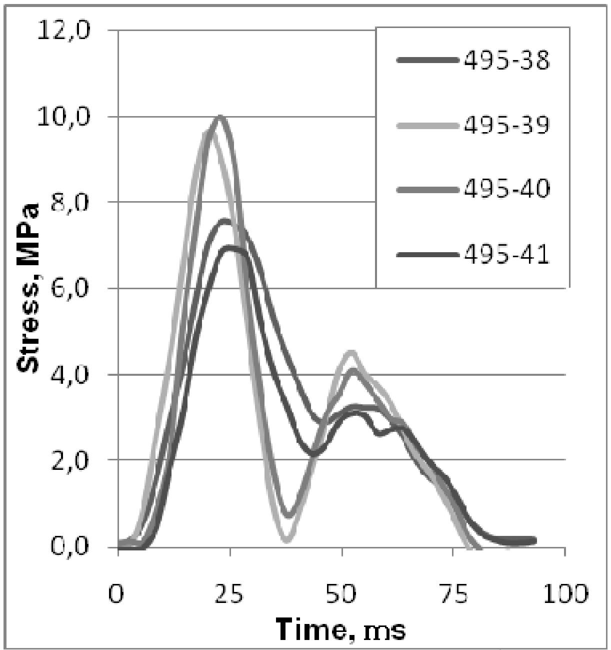


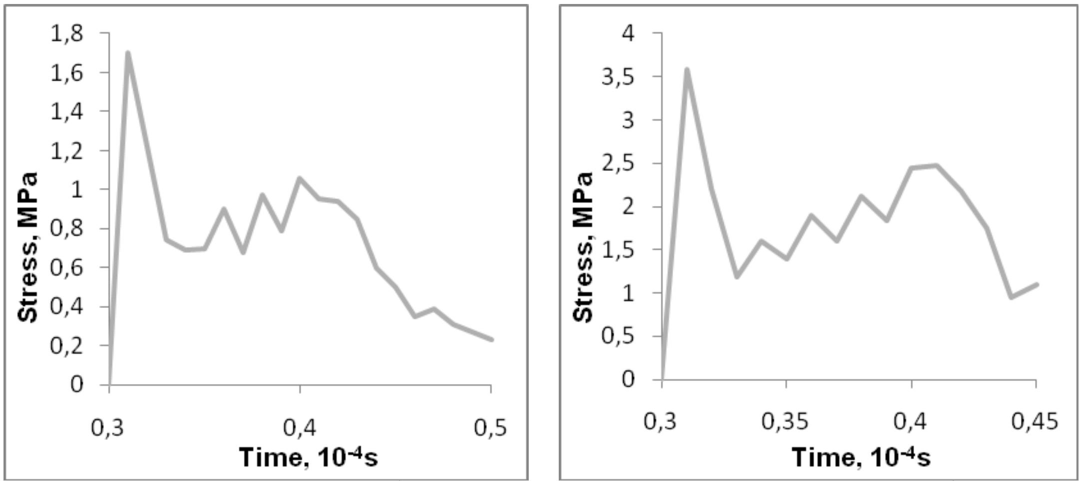
Fig. 11 – Strain rate ~ 2000 s^{-1}.

Characteristic peaks on the plots are supposed to be a consequence of high initial heterogeneity of stress state in the specimens. The computer model of the test system was developed and the virtual experiments on the base of corresponding program were performed to verify this hypothesis.

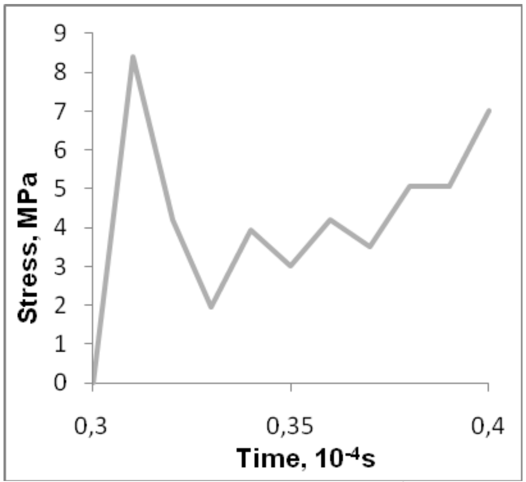
Virtual experiments were conducted using nonlinear LS-DYNA code. Newtonian fluid model was used to simulate the shear properties of STF. In the terms of stress and strain rate deviators it can be written in the following form: $s_{ij} = 2\mu\dot{e}_{ij}$, where s_{ij} is a deviatoric stress, $\dot{e}_{ij}$ is a deviatoric strain rate. Volume compressibility was set by using the quadratic approximation of the experimental charts of rigid clip tests (Eq. 1).

The initial value of shear viscosity was obtained by averaging the mean value of tangent muduli $\sigma/\dot{\varepsilon}$ of the soft casing experimental graphs after excluding the initial stress peak. The averaged value of shear viscosity equal to 400Pa·s was used in calculations because of the weak dependence of shear viscosity on strain rate. Virtual experiments consisted of series of calculations of STF sample under conditions simulating the soft casing wide-scale tests. For better correspondence of the virtual and wide-scale test results, the coefficient of friction between the sample and the bars was varied from 0 to 1.

The Lagrangian approach was used for the calculations of the sample's stress and strain states. The results of calculations for different strain rates with a coefficient of friction equal to 0.1 are shown in figure 12.



a – strain rate 200s^{-1} **b – strain rate 500s^{-1}**



c – strain rate 2000s^{-1}

Fig. 12. Stress-time experimental diagrams for different strain rates.

Calculated stress-time curves show sufficiently good qualitative correspondence with the experimental graphs. The presence of initial stress peak in virtual experiments confirms the hypothesis that it is caused by initial heterogeneity of stress state in the sample. Figure 13 shows heterogeneity of initial effective strain rate distribution in the sample. Figure 14 shows the steady-state distribution.

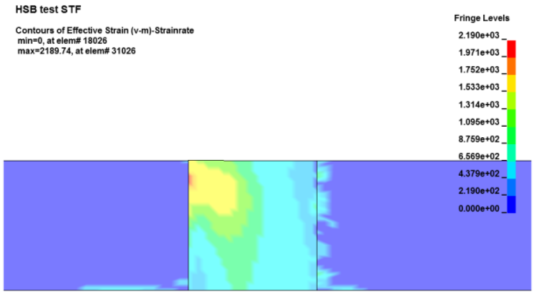


Fig. 13. Initial strain rate distribution.

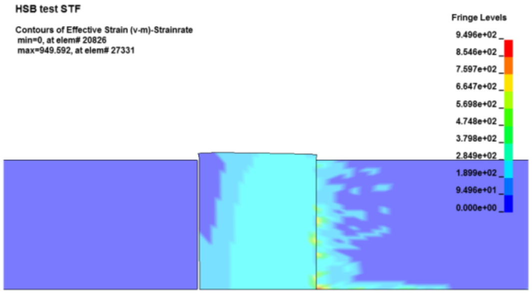


Fig. 14. Steady-state strain rate distribution

Ballistic impact tests

Ballistic impact tests were performed in the laboratory of dynamic testing of Research Institute of Mechanics, University of Nizhny Novgorod. Full-scale and virtual ballistic impact tests on the STF impregnated and dry woven Kevlar fabrics were performed to compare the energy absorbing characteristics of Kevlar and Kevlar + STF barriers, as well as to clarify the contact conditions between STF and Kevlar.

The ballistic tests were performed using a gas gun. The results of ballistic tests are presented in table 1.

#	Speed, m/s	Pressure, bar	Indentation diameter, mm	Indentation depth, mm	Notes
1	89.55	3	12.1	4	dry
2	93.75	3	13	3.4	impregnated
4	90.91	3	12.4	4.3	dry
5	85.71	3	12.55	3.2	impregnated
6	113.21	6	13.3	6.8	dry
7	107.14	6	13.6	4.2	impregnated
8	107.14	6	13.3	6.2	dry
9	111.11	6	14.6	4.5	impregnated
10	193.55	20	15.4	11.1	dry
11	187.5	20	16.8	8.5	impregnated
3	89.55	3	10	9.2	w/o barrier

Table 1. Ballistic test protocol.

Test results are shown in figure 15, where the clay witness photograph after the tests is presented. It can be concluded that the impregnated barrier absorbs up to 15% more energy in comparison to the dry one.

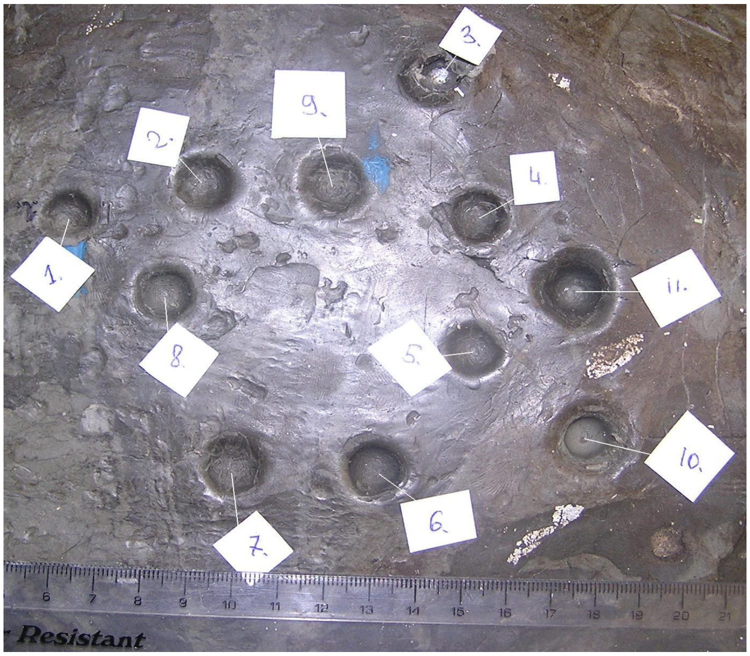


Fig. 15. Clay witness after the tests.

In order to verify the STF mathematical model as well as to compare different types of protective shells, a number of virtual experiments were carried out. Virtual experiments were conducted using the nonlinear LS-DYNA code. The process of interaction between STF, fibers, impactor and environment was simulated in a simplified arbitrary Lagrangian-Eulerian (ALE) formulation [5] using the Van Leer advection scheme.

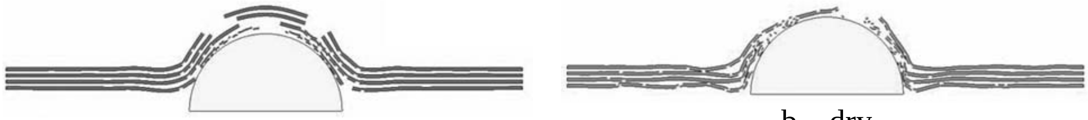
An ALE formulation consists of a Lagrangian time step followed by an advection step. The advection step performs an incremental rezone, where the positions of the nodes are moved only a small fraction of the characteristic lengths of the surrounding elements (for fluids this condition is simply stated as saying the Courant number, C, is less than one). Whereupon the main integral characteristics of elements (mass, momentum, internal energy) are updated using the following advection scheme:

$$\phi_e V_e = \phi_l V_l + \sum \phi_l^j f_j ,$$

where the sum is element faces total, φ is an advection variable, f – volume flow through the adjacent elements, indices l and e refer to the element type (Lagrange or Euler, respectively).

The virtual test scheme was build to simulate the impact test on STF impregnated and dry multilayered Kevlar fabric protection shell to evaluate the correctness of the STF mathematical model. Protection shell consists of 4 layers of 0.2 mm thick Kevlar fabric submerged in STF.

Virtual impact tests on impregnated protective shells were carried out to assess energy absorption capacity. The friction coefficient between the STF and the layers was varied from 0 to 1. Absorption capacity was measured by the reduction of the kinetic energy of the impactor. The best result was obtained for the 0.1 value of friction coefficient. The worst result was obtained for the dry shell. The difference in energy is more than 15%, which corresponds to of full-scale test results. The types of shell failure are shown on figure 16.



a – STF impregnated

b – dry

Fig. 16. Failure behavior of the containment.

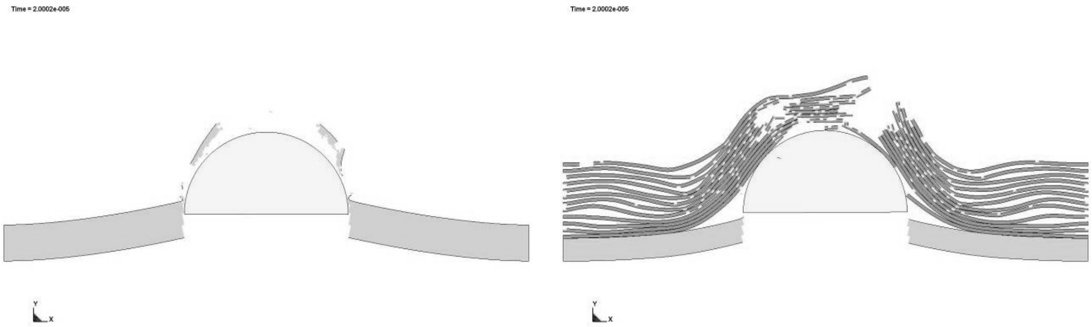
Containment tests on the three types of protective shells were carried out:

1. Impact test of 2.2 mm thick titanium shell for comparative analysis was performed. The shell thickness was chosen so that its mass was equal to the mass of the composite shell.
2. Impact test of a protection element consisting of a 1.4mm titanium layer and 12 layers of 0.2 mm Kevlar without impregnation was calculated.
3. Numerical simulation of impact test of the titanium layer and 12 layers of Kevlar with STF impregnation.

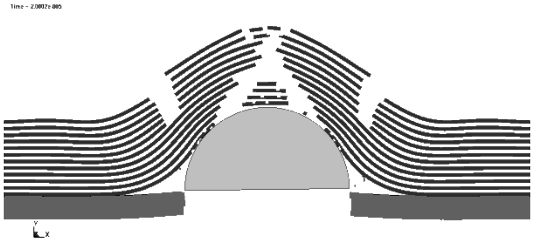
Performed numerical tests on the STF impregnated and dry protective shells showed a higher efficiency of the first one. The results of calculations are shown in Fig. 17.

It is known, that the shell layer collapsing promotes the deterioration of its protective characteristics. STF impregnation between the layers prevents the occurrence of this effect.

Impregnation also affects the value of deflection of the titanium framework. Thus, the deflection of unimpregnated protective shell base is 13mm versus just 3mm in impregnated one only.



a – Titanium casing. **b – Composite shell w/out impregnation.**



c – STF impregnated.
Fig. 17. Impact tests on the protection shells.

Fig. 18 shows the graphs of the kinetic energy of the impactor on time for all three types of protective shells.

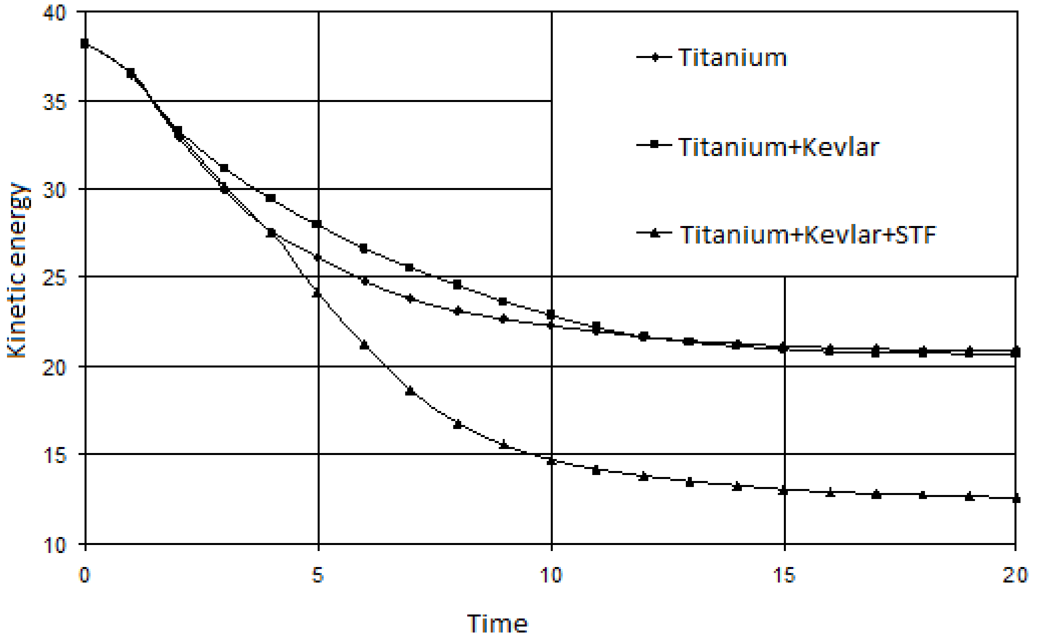


Fig. 18. Evaluation of energy absorption capacity.

The slight difference in the values of absorbed energy between pure titanium and unimpregnated shell was observed. One of the reasons of this result is due to the fact that in calculations the friction between the fibers within the layers was not taken into account. In the case of an impregnated protective shell the absorption capacity increases by about 20% in comparison with to the other tested types of protection.

Conclusions

Two series of dynamic tests by the SPHB method in rigid and soft casings were carried out to determine the dynamic bulk and shear properties of STF. A simplified mathematical model of the STF was formulated for the use in computer simulation of ballistic impact tests of multilayered composite protective shells (Kevlar +STF).

The study confirmed the hypothesis about the possibility to describe STF behavior by a Newtonian fluid model in the characteristic range of strain rate. The parameters of shear viscosity and bulk compressibility of the model were defined. It was concluded that the role of the contact conditions between STF and Kevlar basis in the process of increasing the energy absorption capacity of Kevlar-STF barrier is significant.

It should be noted that the mechanism of contact interaction between STF and Kevlar basis can be described by viscous friction law, i.e. the STF behaves almost as a rigid body during the interactions with the solids, while it normally behaves as a fluid. It was shown that the effectiveness of the STF impregnation for improving the protective properties of barriers is largely due to the internal friction.

It was established that the STF impregnation of protective shells with titanium framework not only increases the absorption capacity of Kevlar package, but also reduces the deflection of the metal base.

References

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