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Plane Problem of Impact on Composite Two-Layer Material Reinforced by Crystalline Fibers

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Abstract
A generalized approach was developed for solving contact problems in a dynamic elastic-plastic formulation. For the design of composite and reinforced materials, a technique for solving dynamic contact problems in more adequate an elastic-plastic mathematical formulation is used. To consider the physical nonlinearity of the deformation process, the method of successive approximations is used, which makes it possible to reduce the nonlinear problem to a solution of the sequences of linear problems. The problem of a plane strain state of a beam made from the composite reinforced two-layer material is being solved. The reinforced or armed composite material consists of three materials: metal of top thin layer, the main material of glass and the reinforcing crystalline seven fibers of basalt. Glass is a non-crystalline, often transparent amorphous solid, that has widespread practical and technological use in the modern industry. Glass has high strength and is not affected by the processes of aging of the material, corrosion, and creep. In addition, this material is cheap and widely available. The reinforced composite beam is rigidly linked to an absolutely solid base and on which an absolutely solid impactor acts from above in the centre on a different size of the area of initial contact.

Keywords: Plane, strain, stress, state, impact, composite, armed, reinforced, material, elastic-plastic, deformation.

Introduction

The use of a generalized approach to solving dynamic contact problems in an elastic-plastic formulation makes it possible to use it to solve contact problems for a body of arbitrary shape, which is subjected to an arbitrary distributed over the contact zone or shock loading.

Since glass is a cheap, ubiquitous material that is not susceptible to corrosion and aging and creep processes, like metals and alloys, the study of composite materials containing glass is relevant and actual. Glass is also convenient in that it can be poured into the frame of the reinforcement and thus can be further strengthened. As reinforcing elements, metal wire, polysilicate, polymer, polycarbon, crystalline compounds, which can have a fairly small thickness, can be used.

In (Bogdanov, 2023; Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023), a new approach to solving the problems of impact and nonstationary interaction in the elastoplastic mathematical formulation was developed. In these papers like in non-stationary problems (Bogdanov, 2023; Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023), the action of the striker is replaced by a distributed load in the contact area, which changes according to a linear law. The contact area remains constant.

The solution of problems for composite cylindrical shells (Lokteva et al., 2020), elastic half-space (Igumnov et al., 2013), elastic layer (Kuznetsova et al., 2013), elastic rod (Fedotenkov et al., 2019; Vahterova & Fedotenkov, 2020) were developed using method of the influence functions (Gorshkov & Tarlakovsky, 1985).

In (Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023) dynamic interaction process of plane hard body and two layers reinforced composite material was investigated and the fields of summary plastic deformations and normal stresses arising in the base are calculated using plane strain (Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023) and plane stress (Bogdanov, 2022; Bogdanov, 2023) states models. In (Bogdanov, 2022) results depend on the size of the area of an initial contact between the impactor and the upper surface of the base and depend on the thickness of the top metal layer of the composite base. In (Bogdanov, 2022) results were calculated depending on the material of top layer of the composite base. Composite bases reinforced by steel, titanium and aluminium top layers were investigated. In (Bogdanov, 2023) the problem of plane strain state of four-layer composite reinforced base was solved.

In contrast from the work (Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023; Bogdanov, 2018), in these papers, we investigate the impact process of hard body with different size of plane area of its surface on the top of the composite beam which consists main glass layer reinforced by seven crystalline basalt fibers and thin metal layer which reinforcing main material from the top.

Problem Formulation

Deformations and their increments (Bogdanov, 2023), Odquist parameter $\kappa = \int d\varepsilon_i^p$ (ε_i^p is plastic deformations intensity), stresses are obtained from the numerical solution of the dynamic elastic-plastic interaction problem of infinite composite beam $\{-L/2 \le x \le L/2; 0 \le y \le B; -\infty \le z \le \infty\}$, in the plane of its cross section in the form of rectangle. It is assumed that the stress-strain state in each cross section of the beam is the same, close to the plane deformation, and therefore it is necessary to solve the equation for only one section in the form of a rectangle $\Sigma = L \times B$ with three materials: thin top metal layer, main glass layer $\{-L/2 \le x \le L/2; -\infty \le z \le \infty; B-h \le y \le B\}$, $\{-L/2 \le x \le L/2; -\infty \le z \le \infty;\ 0 \le y \le B-h\}$ and seven reinforcing crystalline basalt fibres $\{|x| \le b_1;$, $\{b_i \le |x| \le b_{i+1}; -\infty \le z \le \infty;\ B_1 - h_1 \le y \le B_1\}$ $(i = 2; 4; 6)$. The contact between top metal layer and glass, glass and basalt fibres is ideally rigid. The main glass layer contacts absolute hard half-space $\{y \le 0\}$. We assume that the contact between the lower surface of the reinforced glass base and the absolute hard half-space is ideally rigid.

From above on a body the absolutely rigid drummer contacting along a segment $\{|x| \le A; y = B\}$. Its action is replaced by an even distributed stress -*P* in the contact region, which changes over time as a linear function $P = p_{01} + p_{02}t$. Given the symmetry of the deformation process relative to the line $x = 0$, only the right part of the cross section is considered below (Fig. 1). The calculations use known methods for studying the quasi-static elastic-plastic (Bogdanov, 2023; Mahnenko, 1976; Mahnenko, 2003; Mahnenko et al., 2009) model, considering the non-stationarity of the load and using numerical integration implemented in the calculation of the dynamic elastic model (Bogdanov, 2023; Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023).

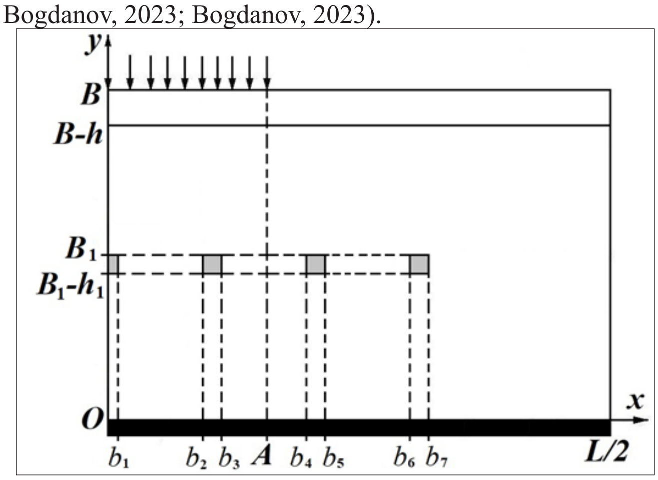

Fig. 1: Geometric scheme of the problem

The equations of the plane dynamic theory are considered, for which the components of the displacement vector **u** = (u_x, u_y) are related to the components of the strain tensor by Cauchy relations:

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x},\quad \varepsilon_{yy} = \frac{\partial u_y}{\partial y},\quad \varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right).$$

The equations of motion of the medium have the form:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} = \rho \frac{\partial^2 u_x}{\partial t^2},\qquad \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = \rho \frac{\partial^2 u_y}{\partial t^2}, \tag{1}$$

where ρ − material density.

The boundary and initial conditions of the problem have the form:

$$\begin{aligned} &x = 0,\ 0 < y < B:\ u_x = 0,\ \sigma_{xy} = 0,\\ &x = L/2,\ 0 < y < B:\ \sigma_{xx} = 0,\ \sigma_{xy} = 0,\\ &y = 0,\ 0 < x < L/2:\ u_y = 0,\ \sigma_{xy} = 0,\\ &y = B,\ 0 < x < A:\ \sigma_{yy} = -P,\ \sigma_{xy} = 0,\\ &y = B,\ A < x < L/2:\ \sigma_{yy} = 0,\ \sigma_{xy} = 0. \end{aligned} \tag{2}$$

$$u_x\big|_{t=0} = 0,\ u_y\big|_{t=0} = 0,\ u_z\big|_{t=0} = 0,\ \dot{u}_x\big|_{t=0} = 0,\ \dot{u}_y\big|_{t=0} = 0,\ \dot{u}_z\big|_{t=0} = 0. \tag{3}$$

The determinant relations of the mechanical model are based on the theory of non-isothermal plastic flow of the medium with hardening under the condition of Huber-Mises fluidity. The effects of creep and thermal expansion are neglected. Then, considering the components of the strain tensor by the sum of its elastic and plastic components (Bogdanov, 2023; Mahnenko, 1976), we obtain expression for them:

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p,\ d\varepsilon_{ij}^p = s_{ij} d\lambda,\qquad \varepsilon_{ij}^e = \frac{1}{2G} s_{ij} + K\sigma + \varphi. \tag{4}$$

here $S_{ij} = \sigma_{ij} - \delta_{ij}\sigma$ – stress tensor deviator; δ_{ij} – Kronecker symbol; *E*– modulus of elasticity (Young's modulus); *G* – shear modulus; $K_1 = (1-2v)/(3E)$, $K = 3K_1$ – volumetric compression modulus, which binds in the ratio $\varepsilon = K\sigma + \phi$ volumetric expansion 3ε (thermal expansion $\phi \equiv 0$); $\sigma = (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$ – mean stress; *d*λ – some scalar function (Mahnenko, 1976), which is determined by the shape of the load surface and we assume that this scalar function is quadratic function of the stress deviator S_{ij} (Bogdanov, 2023; Mahnenko, 1976), which has form as in (Bogdanov, 2023; Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023).

It should be noted that the developed algorithm makes it possible to use the function which describes area of plastic fluidity not only in the form of a quadratic function (in this case, we obtain the plastic fluidity condition in the Huber-Mises form), however also in the form of a function containing terms of third and higher power. This statement requires further research.

The material is strengthened with a hardening factor η^* as in (Bogdanov, 2023; Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023; Mahnenko, 1976; Mahnenko, 2003; Mahnenko et al., 2009).

Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023; Mahnenko, 1976; Mahnenko, 2003; Mahnenko et al., 2009).

The solution algorithm is similar as in (Bogdanov, 2023; Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023).

Numerical Solution

For both problems the explicit scheme of the finite difference method was used with a variable partitioning step along the axes *Ox* (M elements) and *Oy* (N elements). The step between the split points was the smallest in the area of the layers contact and at the boundaries of the computational domain. Since the interaction process is fleeting, this did not affect the accuracy in the first thin layer, areas near the boundaries, and the adequacy of the contact interaction modelling.

The use of finite differences (Zukina, 2004) with variable partition step for wave equations is justified in [20], and the accuracy of calculations with an error of no more than $O\left((\Delta x)^2+(\Delta y)^2+(\Delta t)^2\right)$ where Δx, Δy and Δt – increments of variables: spatial x and y and time t. A low rate of change in the size of the steps of the partition mesh was ensured. The time step was constant.

The resolving system of linear algebraic equations with a banded symmetric matrix was solved by the Gauss method according to the Cholesky scheme.

In Weisbrod and Rittel, (2000), during experiments, compact samples were destroyed in 21 –23*ms*. The process of destruction of compact specimens from a material of size and with contact loading as in (Weisbrod & Rittel, 2000) was modelled in a dynamic elastoplastic formulation as plane strain state, considering the unloading of the material and the growth of a crack according to the local criterion of brittle fracture. The samples were destroyed in 23*ms*. This confirms the correctness and adequacy of the developed formulation and model.

Figs. 2 – 19 show the results of calculations of one layer specimens with a hardening factor of the material $\eta^*=0{,}05$. The main material has made from quartz glass. The reinforcing fibres have made from basalt. Contact between glass and basalt is an ideal. Calculations were made at the following parameter values: temperature $T = 50$ °C; $L = 20$ *mm*; $B = 5$ *mm*; $h = 0.5$ *mm*; $h_1 = 0.1$ *mm*; $\Delta t = 3.21.10^{-8}$ *s*; $p_{01} = 8$ *MPa*; $p_{02} = 10$ *MPa*; $M = 94$, $N = 103$. The smallest splitting step was 0,02 *mm*, and the largest 0,82 *mm* ($\Delta x_{min} = 0{,}\ 02$ *mm*, $\Delta y_{min} = 0{,}\ 02$ *mm* (only the first layer); $\Delta x_{max} = 0{,}\ 82$ *mm* ; $\Delta y_{max} = 0{,}\ 05$ *mm*); $b_1 = h_1/2$; $b_2 = 1{,}\ 05$ *mm* ; $b_4 = 2{,}\ 15$ *mm* ; $b_6 = 3{,}\ 25$ *mm* ; $b_i = b_{i-1} + h_1$, ($i = 3,5,7$); contact zone was equal $a = 2A = a_1 = 3mm$.

Let us define the problems of plane strain state for one-layer and two-layer composite materials reinforced with basalt fibers as case 1 and case 2 respectively.

Figs. 2 – 10 and 11 – 19 show results for cases 1 and 2 respectively. Figs. 2 – 4, 11 – 13; 5 – 7, 14 – 16; 8 – 10, 17 – 19 show the fields of the Odquist parameter κ, normal stresses σ_{xx} and σ_{yy} at times $t_1 = 3.24.10^{-6}\,s$, $t_2 = 3.85.10^{-6}\,s$ and $t_3 = 4.49.10^{-6}\,s$, respectively.

As can be seen from Fig. 2–19, the greatest plastic deformations and stresses occur directly under the striker and in the area near the reinforcing fibers, which work as concentrators, leading to the redistribution of the resulting contact disturbances. If a layer of glass is reinforced with a top layer of steel, then these stresses and deformations have a structure more similar to waves in the top layer. The compressive stress is greater when the top layer of steel is missing.

The Odquist parameter at the moments of time t_1, t_2, t_3 in case 1 is greater than the corresponding values in case 2 by 98%, 88% and 78%, respectively. The maximal absolute values of the compressive stresses σ_{xx} at times t_1, t_2 in case 1, are greater than the corresponding values in case 2 by 30% and 16%, respectively. These values differ by 1% at a time t_3.

The maximal absolute value compressive stresses σ_{yy} in case 1 are greater at the moments of time t_1, t_2 and less at the moment of time t_3 than the corresponding values in case 2 by 33%, 15% and 14%, respectively.

In case 1, tensile stresses do not occur at the moments of time t_1, t_2 and at the moment of time t_3 normal tensile stresses σ_{xx} and σ_{yy} are 3.37 and 3.1 times less, respectively, than in case 2. This indicates that the two-layer composite material resists to the contact load better.

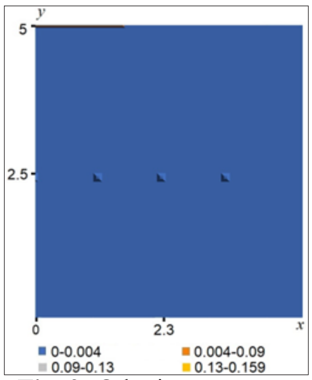

Fig. 2: Odquist parameter K when $a = a_1$ and $t = t_1$

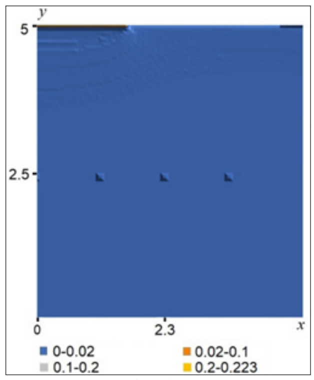

Fig. 3: Odquist parameter K when $a = a_1$ and $t = t_2$

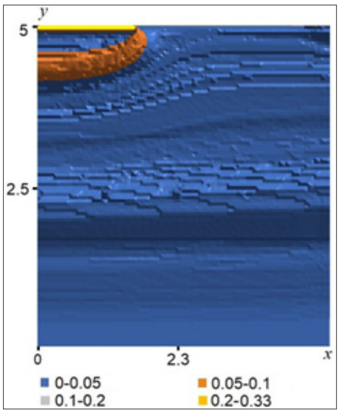

Fig. 4: Odquist parameter K when $a = a_1$ and $t = t_3$

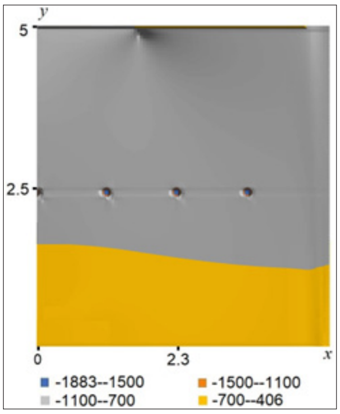

Fig. 5: Stress σ_{xx} when $a = a_1$ and $t = t_1$

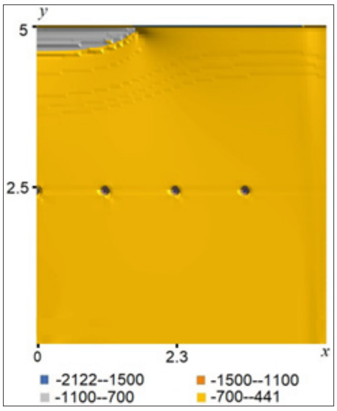

Fig. 6: Stress σ_{xx} when $a = a_1$ and $t = t_2$

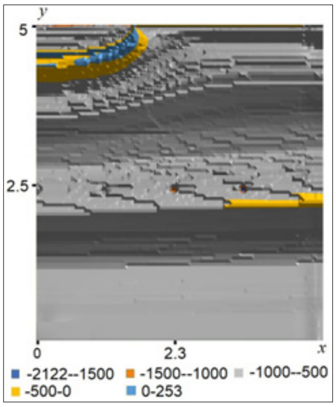

Fig. 7: Stress σ_{xx} when $a = a_1$ and $t = t_3$

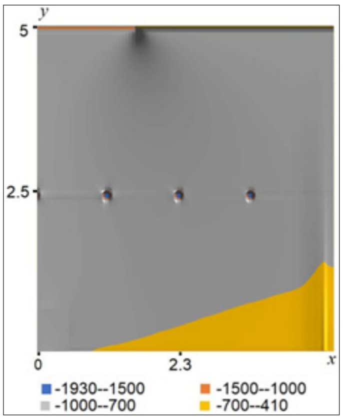

Fig. 8: Stress σ_{yy} when $a = a_1$ and $t = t_1$

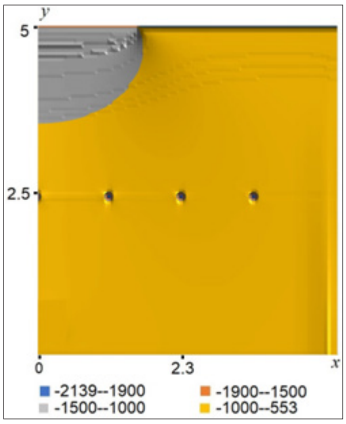

Fig. 9: Stress σ_{yy} when $a = a_1$ and $t = t_2$

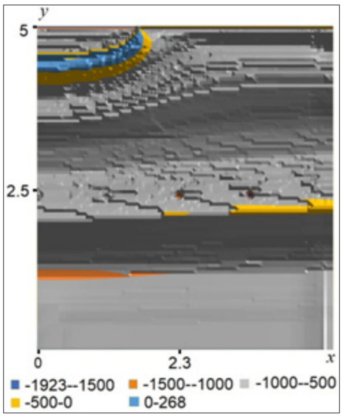

Fig. 10: Stress σ_{yy} when $a = a_1$ and $t = t_3$

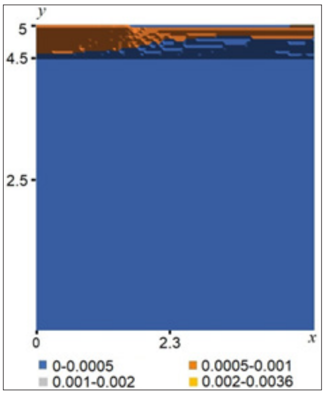

Fig. 11: Odquist parameter K when $a = a_1$ and $t = t_1$

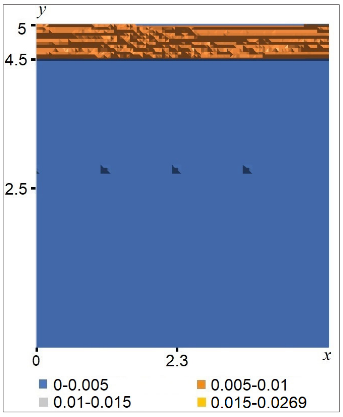

Fig. 12: Odquist parameter K when $a = a_1$ and $t = t_2$

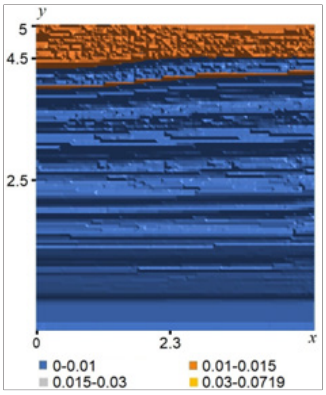

Fig. 13: Odquist parameter K when $a = a_1$ and $t = t_3$

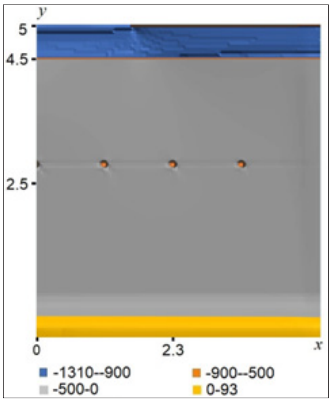

Fig. 14: Stress σ_{xx} when $a = a_1$ and $t = t_1$

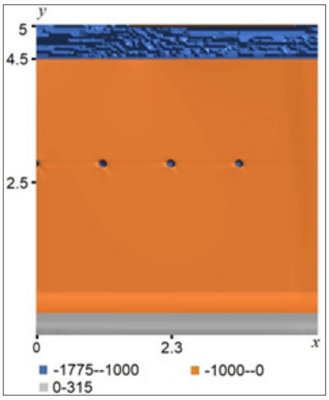

Fig. 15: Stress σ_{xx} when $a = a_1$ and $t = t_2$

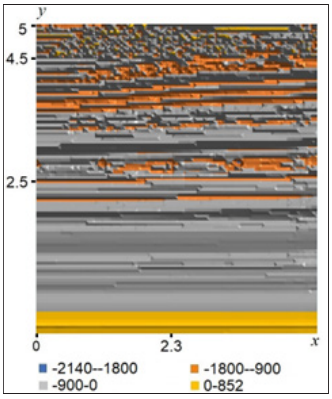

Fig. 16: Stress σ_{xx} when $a = a_1$ and $t = t_3$

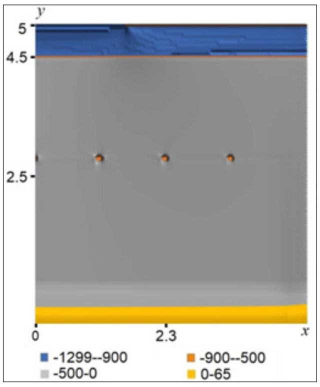

Fig. 17: Stress σ_{yy} when $a = a_1$ and $t = t_1$

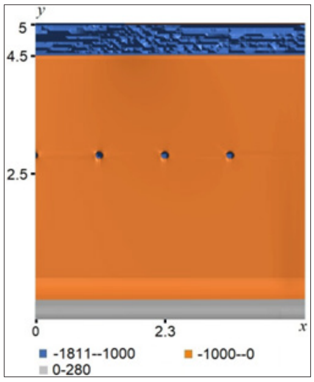

Fig. 18: Stress σ_{yy} when $a = a_1$ and $t = t_2$

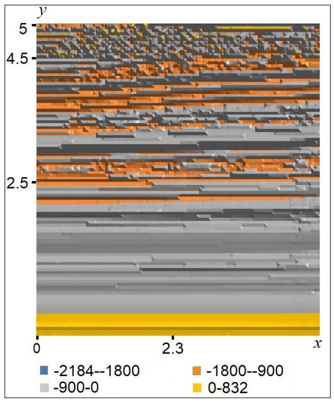

Fig. 19: Stress σ_{yy} when $a = a_1$ and $t = t_3$

Figs. 2 – 19 show that the highest stresses occur in the area close to the upper surface of the specimen and near basalt fibres and the process of accumulation of plastic deformations is more intense there. These Figs. show areas where the normal stresses in layers are tensile. This is due to the fact that the contacts between the layer and fibres and the lower boundary of the specimen with an absolutely rigid base are ideally rigid.

At Figs. 2 – 4, 11 – 13 it can be seen that the greatest plastic deformations occur in a thin layer under the contact zone. Figs. 5 – 10 and 14 – 19 show how stresses are concentrated in the vicinity of crystalline basalt fibres which work as concentrators of these stresses.

Conclusions

The developed methodology of solving dynamic contact problems in an elastic-plastic dynamic mathematical formulation makes it possible to model the processes of impact, shock and non-stationary contact interaction with the elastic composite base adequately. In this work, the process of impact on a two-layer glass base reinforced by row of seven crystalline basalt fibres and thin steel layer is adequately modelled and investigated relative to the small enough contact area size. The fields of parameter Odquist and normal stresses arising in the base are calculated. The numerical results confirm the need to strengthen the glass layer with a thin layer of steel/metal on the upper surface of the base (Bogdanov, 2022; Bogdanov, 2022; Bogdanov, 2023; Bogdanov, 2023). The row of seven basalt fibres inside the glass layer redistribute the stresses and plastic deformations that occur in such composite base. Normal stresses are concentrated in the areas of crystalline basalt fibres and top steel layer. The results obtained make it possible to design the narrow strips of new composite reinforced armed materials.

References

1. Bogdanov, V. (2023). Problems of impact and non-stationary interaction in elastic-plastic formulations. *Cambridge Scholars Publishing*. 282. Retrieved from https://www.cambridgescholars.com/product/978-1-5275-9339-8
2. Bogdanov, V. R. (2022). Problem of plane strain state of two-layer body in dynamic elastic-plastic formulation (Part I). *Underwater Technologies*, 12, 3-14. DOI: https://doi.org/10.32347/uwt.2022.12.1101
3. Bogdanov, V. R. (2022). Problem of plane strain state of two-layer body in dynamic elastic-plastic formulation (Part III). *International scientific journal "Transfer of Innovative Technologies", 5*(1), 62-70. DOI: https://doi.org/10.32347/tit.2022.51.0302
4. Bogdanov, V. (2023). Plane strain and stress states of two-layer composite reinforced body in dynamic elastic-plastic formulation. *Journal of Materials and Polymer Science, 3*(2), p. 1-7. DOI: doi.org/10.47485/2832-9384.1029
5. Bogdanov V. (2023). Plane strain state of four-layers composite reinforced body in dynamic elastic-plastic formulation. *Journal of Materials and Polymer Science, 3*(2), p. 1-7. DOI: doi.org/10.47485/2832-9384.1032
6. Lokteva, N. A., Serduk, D. O., Skopintsev, P. D. & Fedotenkov, G. J. (2020). Non-stationary stress-deformed state of a composite cylindrical shell. *Mechanics of Composite Materials and Structures, 26*(4), 544-559, DOI: 10.33113/mkmk, ras.2020.26.04.544_559.08 (in Russian). Retrieved from https://bulletin.incas.ro/files/fedotenkov_makarevskii__all__vol_13_special_issue.pdf
7. Igumnov, L. A., Okonechnikov, A. S., Tarlakovskii, D. V. & Fedotenkov, G. J. (2013). Plane nonsteady-state problem of motion of the surface load on an elastic half-space. *Mathematical Methods and Physicomechanical Fields, Lviv,* 56, 2, 157-163. (in Russian). Retrieved from http://tit.knuba.edu.ua/article/view/275917
8. Kuznetsova, E. L., Tarlakovsky, D. V., Fedotenkov, G. J. & Medvedsky, A. L. (2013). Influence of non-stationary distributed load on the surface of the elastic layer, *Works MAI.* 71, 1-21 (in Russian). Retrieved from http://tit.knuba.edu.ua/article/view/275917
9. Fedotenkov, G. J., Tarlakovsky, D. V. & Vahterova, Y. A. (2019). Identification of Non-stationary Load Upon Timoshenko Beam, Lobachevskii. *Journal of Mathematics, 40*(4), 439-447. Retrieved from http://tit.knuba.edu.ua/article/view/275917
10. Vahterova, Y. A. & Fedotenkov, G. J. (2020). The inverse problem of recovering an unsteady linear load for an elastic rod of finite length. *Journal of Applied Engineering Science, 18*(4), 687-692,

DOI: 10.5937/jaes0-28073. Retrieved from http://tit.knuba.edu.ua/article/view/275917
11. Gorshkov, A. G. & Tarlakovsky, D.V. (1985). Dynamic contact problems with moving boundaries. *Nauka, Fizmatlit, 352* (in Russian). Retrieved from http://tit.knuba.edu.ua/article/view/275917
12. Bogdanov, V. R. (2018). Impact a circular cylinder with a flat on an elastic layer. *Transfer of In-novative Technologies*, 1(2), 68-74, DOI: 10.31493/tit1812.0302. Retrieved from http://tit.knuba.edu.ua/article/view/275917
13. Mahnenko, V. I. (1976). Computational methods for studying the kinetics of welding stresses and deformations. *Naukova Dumk*a, Kiev, 320 (in Russian). Retrieved from http://tit.knuba.edu.ua/article/view/275917
14. Mahnenko, V. I. (2003). Improving methods for estimating the residual life of welded joints in long-life structures. *Automatic welding*, Kiev, 10–11, 112–121 (in Russian). Retrieved from http://tit.knuba.edu.ua/article/view/275917
15. Mahnenko, V. I., Pozniakov, V. D., Velikoivanenko, E. A., Rozynka, G. F. & Pivtorak, N. I. (2009). Risk of cold cracking when welding structural high-strength steels, Collection of scientific works "Pro-cessing of materials in mechanical engineering", *National Shipbuilding University*, 3, 5–12 (in Rus-sian). Retrieved from http://tit.knuba.edu.ua/article/view/275917
16. Zukina, E. L. (2004). Conservative difference schemes on non-uniform grids for a two-dimensional wave equation. Work of N.I. Lobachevski Math. *Centre, Kazan*, .26, 151–160 (in Rus-sian). Retrieved from http://tit.knuba.edu.ua/article/view/275916
17. Weisbrod, G. & Rittel, D. (2000). A method for dynamic fracture toughness determination using short beams. *International Journal of Fracture*, 104, 89–103. Retrieved from http://tit.knuba.edu.ua/article/view/275916