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Nonlinear Deformation of Structure Elements from Different Materials under Impulse and Shock Loads

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Abstract
Elements are exposed to impact and impulse loads during exploitation in many modern constructions. In the simulation of high-rate deformation processes, three-dimensional models are used The following determined relationships are taken into account: elastic-plastic deformation (according to the theory of dynamic plastic deformation); the dynamic properties of the materials, which change during deformation; the finite displacements and deformations.
The problem is solved by the finite elements method. The paper analyzes the impact of pulse and shock loads performed on the elements of various constructions made of different materials. Comparison of the research results shows that the elements from the improved composite material possess both the required strength and lowest weight. Furthermore, the experimental and numerical results are compared as an example of the influence of the impulse load on the composite material plate with a cut.
The paper shows the features of the distribution and localization of the stress intensity and displacements at the impulse and impact loading in the multi-layered structural elements. The deformation processes occur in different stages up to the elastic-plastic finite deformations depending on the speed of the projectile.
The results of these studies were used in the analysis of the dynamic strength of real structural elements.

Keywords
High-rate deformation, shock loads, finite elements method

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Introduction

Structural elements of many modern constructions are exposed to shock loads and pulse loads during the operation. These include elements of the corps, the input and output devices of gas turbine engines, the equipment enclosures for the series of productions, the linings of vehicles, the protective elements, etc.

This research belongs to the simulation of high-rate deformation processes using three-dimensional models. The following defining dependences are taken into account: elastoplastic deformations (according to the theory of dynamic plastic deformation); dynamic properties of materials, which change during deformation; finite displacement and finite deformation.

The problem is solved by the version of the finite element method, which takes into account the specifics of the process. An important requirement to the choice of the finite element type is the account of all the factors. The boundary conditions at the nodes of the elements must satisfy the equality as displacements as well as derivatives. Functions' forms in this case allow us to describe a continuous and smooth change in the stress.

The numerical studies were carried out for the high-rate deformation of elements of real structures under impact loads. The paper analyzes the effect of pulse and impact loads on the elements of various constructions which are made from different materials. Numerical analysis of dynamic stress-strain state of structural elements made of steel, aluminum and composite materials are considered. Comparison of the results of the research shows that the elements from the improved composite material possess the required strength and lowest weight. It is known that the titanium alloys have a higher impact resistance, which increases together with increasing strain rate. Therefore, the impact of a steel projectile with mass m = 0.1 kg on the bilayer plate from titanium alloy

(Ti6Al4V) is examined here. It is used in the protective elements and is also considering a three-layer protective element from titanium - ceramic - titanium. In addition, the paper considers a comparison of the experimental results and numerical example of impulse load effect on the composite material plate with a cut. Research shows the features of dynamic strain state plates which lie near the tops of cuts, along the edges of the cuts and on the borders of rigid support. The results confirm the possibility of reliable results in a numerical analysis based on the finite element method of thin-walled structures with cuts under the influence of short-term loads.

1. Problem statement

In numerical studies different dependences are used to describe the dynamic properties of the material. Their form is determined by means of experimental data used by various authors [1 – 6]. The account of dynamic properties material by Perzyna type dependence [4] is of the form:

$$\sigma_i = \left[1 + \left(\frac{\dot{\varepsilon}_i^{pl}}{\gamma}\right)^m\right] E\varepsilon_i \tag{1}$$

where: E – elastic modulus;

m and r – coefficients of sensitivity to strain rate;

$\dot{\varepsilon}_i^{pl}$ - rate of deformation in the plastic phase.

The dynamic properties of the material can be accounted in a somewhat different form by Peirce dependence [5].

$$\sigma_i = \left[1 + \left(\frac{\dot{\varepsilon}_i^{pl}}{\gamma}\right)\right]^m E\varepsilon_i \tag{2}$$

Also quite often the model of Johnson-Cook [6] is used.

$$\sigma = \left[A + B\varepsilon^n\right] \cdot \left[1 + C\, ln\dot{\varepsilon}^*\right] \cdot \left[1 - T^{*m}\right] \tag{3}$$

where: A – static yield stress;

ε – equivalent plastic strain;

$\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$ – dimensionless rate of plastic deformation;

B, n, C, m – factors determining the properties of the material;

$T^* = \dfrac{T - T_p}{T_t - T_p}$ – dimensionless temperature;

T – actual temperature;

T_p – ambient temperature;

T_t – melting temperature.

In paper [7] the influence of different dependences to describe the dynamic properties of the material on stress-strain state of structure elements is analyzed. These results are used in further research depending on the input data [8, 9].

In all cases, the nonlinear problem can be solved by successive approximations. Stiffness matrix is adjusted for each step, depending on the value and rate of deformation $K(\varepsilon_i, \dot{\varepsilon}_i)$.

Accounting for finite displacements and deformations is based on the Eq. 4 and uses the method of successive approximations.

$$\varepsilon_x = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2\right)$$

$$\varepsilon_y = \frac{\partial v}{\partial y} + \frac{1}{2}\left(\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right)$$

$$\varepsilon_z = \frac{\partial w}{\partial z} + \frac{1}{2}\left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right) \tag{4}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{1}{2}\left(\frac{\partial u}{\partial y}\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\frac{\partial v}{\partial x} + \frac{\partial w}{\partial y}\frac{\partial w}{\partial x}\right)$$

$$\gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} + \frac{1}{2}\left(\frac{\partial u}{\partial z}\frac{\partial u}{\partial y} + \frac{\partial v}{\partial z}\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\frac{\partial w}{\partial y}\right)$$

$$\gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} + \frac{1}{2}\left(\frac{\partial u}{\partial z}\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z}\frac{\partial v}{\partial x} + \frac{\partial w}{\partial z}\frac{\partial w}{\partial x}\right)$$

where: $\sigma_x, \sigma_y, \sigma_z$ - components of normal stresses,

$\tau_{xy}, \tau_{xz}, \tau_{yz}$ - components of tangential stresses;

$\varepsilon_x, \varepsilon_y, \varepsilon_z$ - components of normal strain;

$\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ - components of tangential deformation.

For solving the problem by FEM, isoperimetric, hexagonal element in the curvilinear coordinate system with the functions of serendipity type, which forms are not lower than the second order are used. At the beginning of numerical process, the size of an element is 0,0005 m. For a projectile, tetrahedral elements with the size of 0,001 m are used.

2. Numerical results

2.1 Numerical analysis of the local impact on the plates from the different materials

Studies of the stress-strain state of the protective elements, which are used for the lining of vehicles and other objects are significant not only for modern science but also for the industry. The elements must possess the necessary dynamic strength for a given thickness and weight. For comparison, the elements are examined from various materials: steel, aluminum alloy composite. The boundary conditions for these plates are rigid clamping on the contour. In this research, the Perzyna type dependence is used. Thus, Fig. 1 shows the maximum equivalent stress in the plane steel element under the action of a projectile weighing 200 g and a speed of 200 m/s.

The steel element has a density $\rho = 7800$ kg/m^3, elastic modulus $E = 2.06 \cdot 10^{11}$ Pa, Poisson's ratio $\nu = 0.25$, yield stress $\sigma_T = 2.99 \cdot 10^8$ Pa and a hardening modulus $E_1 = 7.39 \cdot 10^8$ a.

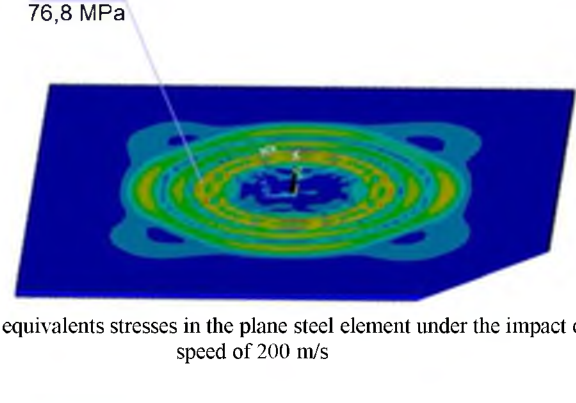


Figure 1: Maximum equivalents stresses in the plane steel element under the impact of a projectile with a speed of 200 m/s

Fig. 2 shows distribution of maximum equivalent stress in the plane element of aluminum alloy under the action of a projectile with a mass of 200 g and the speed of 200 m/s.

The element from aluminum alloy has a density ρ = 2700 kg/m^3, elastic modulus $E = 7.1 \cdot 10^{10}$ Pa, Poisson's ratio ν = 0.33, yield stress $\sigma_T = 9.6 \cdot 10^7$ Pa and the hardening modulus $E_1 = 7.24 \cdot 10^7$ Pa.

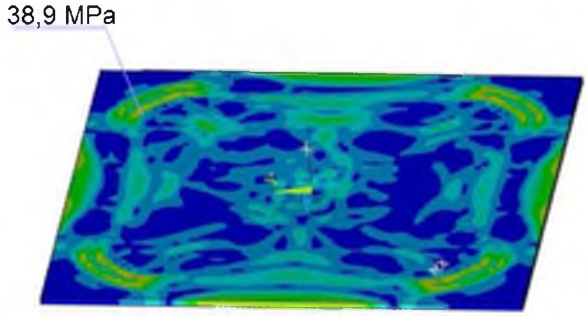


Figure 2: Maximum equivalents stresses in the plane element of aluminum alloy under the impact of a projectile with a speed of 200 m/s

Fig. 3 shows the maximum equivalent stresses in the composite element. The properties of the materials material: density ρ = 2400 kg/m^3, elastic modulus $E = 5.4 \cdot 10^{10}$ Pa, Poisson's ratio ν = 0.4, yield stress $\sigma_T = 6.8 \cdot 10^7$ Pa and the hardening modulus $E_1 = 7.99 \cdot 10^8$ Pa.

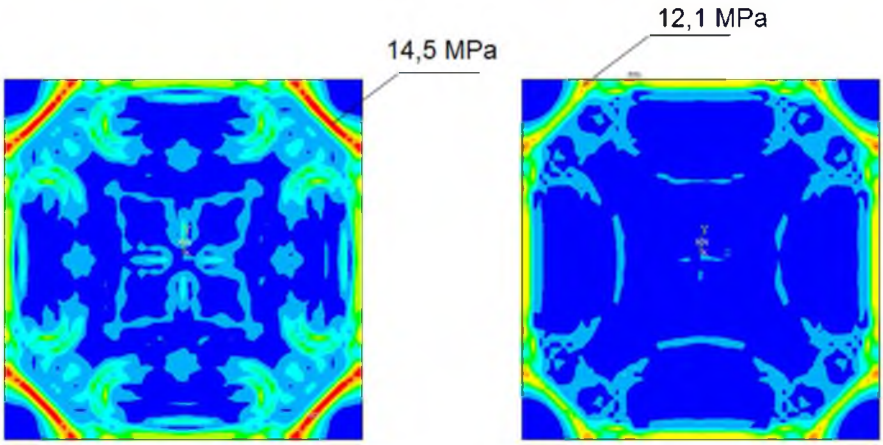


Figure 3: Maximum equivalents stresses in the plane composite element under the impact of a projectile with a speed of 200 m/s

The elements which consist of aluminum alloys or composite materials obtain larger dynamic displacements compare to steel but they have smaller maximum stresses in the area of loading. The comparison of the results shows that the elements from the improved composite material show both required strength and lowest weight.

2.2 Numerical analysis of the local impact on the multi-layer plates

Previous studies have shown that the bilayer structure is more resistant to impact loads than the single-layer one with a greater thickness of the same material [7-9]. Also, titanium alloys are more resistant to impact loads than steel, and the resistance increases with increasing impact speed.

Fig. 4 shows a comparison of resistance to impact loads for different materials [10].

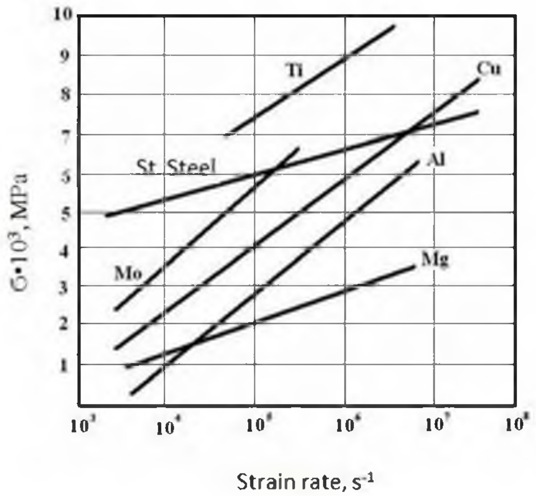


Figure 4: Comparison of resistance to impact loads for different materials. depending on strain rate, σ - dynamic tensile strength.

In this case, the impact of the steel projectile weighing m = 0.1 kg on a bilayer plate of titanium alloy (Ti6Al4V) which is used in the protective elements is being considered. Thickness of each identical layer is equal to 3 mm. The speed of the projectile varied from 800 m/s to 1500 m/s, which brought consideration of elastic-plastic deformation of the plate up to its penetration. Fig. 5 shows the elastoplastic deformation of the material after contact with a projectile travelling with a speed of 800 m/s for $3\cdot10^{-5}$ s. At the same time, the maximum stress reaches the value of 1300 MPa.

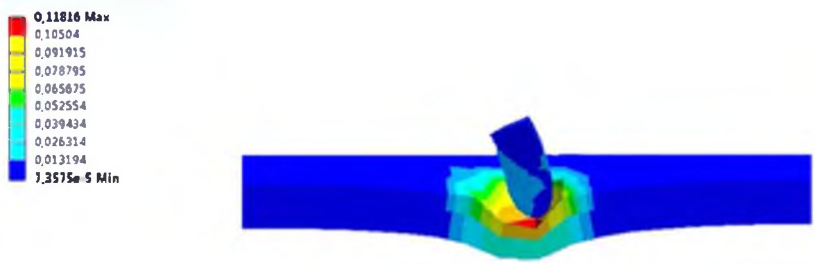


Figure 5: Elastoplastic deformation when the material is subjected to a projectile with a speed of 800 m/s for $3\cdot10^{-5}$ s after contact with the material.

After $3\cdot10^{-4}$ s a projectile rebounds and stress reduction occurs, however permanent deformation remains (Fig. 6). Impact occurs along the normal to the plate surface.

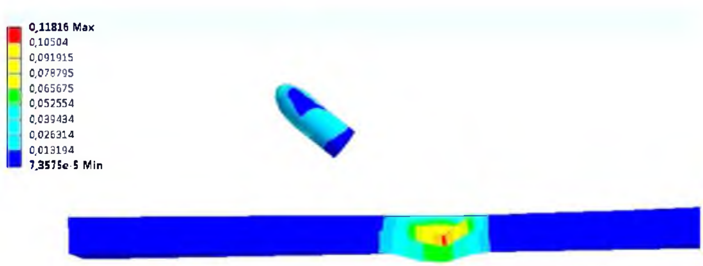


Figure 6: Elastoplastic deformation when the material is subjected to a projectile at speed of 800 m/s for $3\cdot10^{-4}$ s after contact with the material.

Thus, when the projectile speed of 800 m/s acts on the protective element, penetration does not occur, however, the element undergoes remarkable elastic-plastic deformation.

By increasing the speed of the striker up to 1500 m/s, unacceptable deformation of the two-layer plate with the deflected rebound occurs. A further increase in speed causes penetration of the protective element.

The further development of the multi-layer protective elements may be a three-layer structure (titanium-ceramic-titanium). The protective element has thin layers of titanium alloy, between which a ceramic alloy is placed. The result of the projectile impact at a speed of 800 m/s is present on the Figure 7, which shows the equivalent stress contours

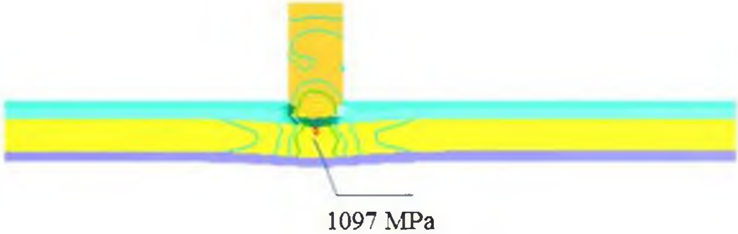


Figure 7: Equivalent stress contours of the three-layer protective element for the normal projectile impact of 800 m/s.

It can be noticed that in the first layer, high stresses develop and the layer is destroyed. However, the protective element in general is resistant to the impact and the stresses in the impact zone quickly decrease. Such studies allow selecting the most efficient combination of a layer in the security element.

2.3 Comparison with experimental data

In [11], the results of experimental studies of dynamic deformation in the plates with cuts under the action of the shock wave are presented. A numerical study is conducted for a plate with a cut depth y/a = 0.14, when the localization of stress is expressed the most clearly. A rectangular plate in the coordinate system x y with the following dimensions: thickness h = 2.5 mm, width a = 140 mm and length b = 210 mm, the plate material of glass fiber density $\rho = 1.7$ g/cm^3, modulus of elasticity $E = 2.6 \cdot 10^{10}$ Pa is considered. The plate is clamped on both sides and there is a cut of 0.5 mm wide in the middle of the plate (Fig. 8).

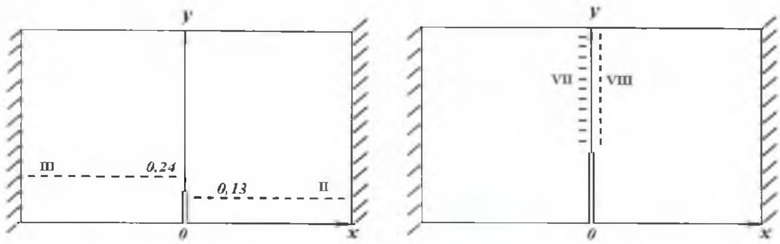
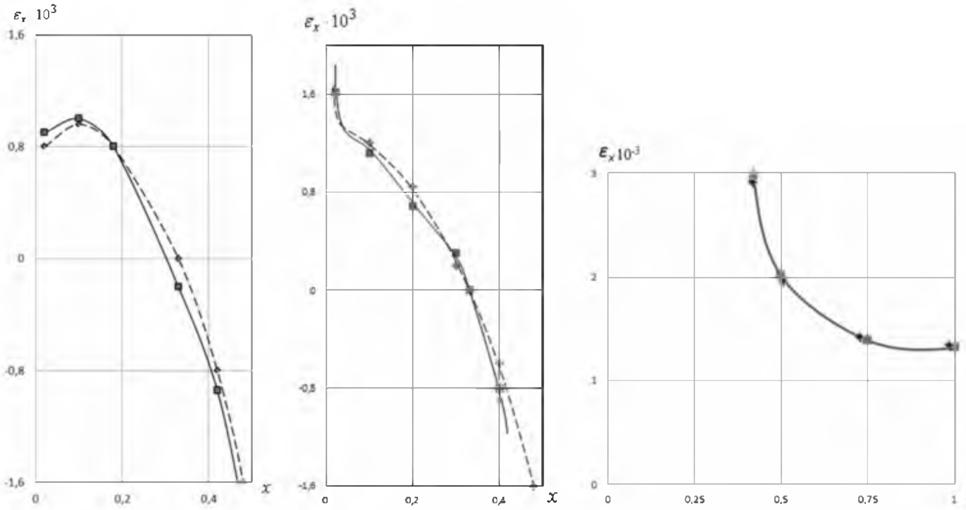


Figure 8: The general scheme of the plate

The plate is subjected to the action of the shock wave which duration is $t = 8 \cdot 10^{-3}$ s, peak pressure which influences the surface of the plate is $0.1 \cdot 10^5 \pm 5\%$ Pa and is equal to the pressure in the reflected wave. Strain gauges at a distances y/a = 0.13 (line II) and y/a = 0.24 (line III) have been located closest to the top of the section.

Fig. 9 shows the comparison of the calculated (solid line with squares) and experimental (dotted line with diamonds) strains ε_x along line II, when y/a = 0.13 (a), strain ε_x along line III, when y/a = 0.24 (b) and the strain ε_x along line VII, when a cut depth y/a = 0.37.



a) b)............................ ......c)

Figure 9: Comparison of the calculated (solid line) and experimental (dotted line) strains ε_x when y/a = 0.13 (a), y/a = 0.24 (б), y/a = 0.37 (c)

So-called localization of ε_x deformations appears at the area approaching directly over the incision. In both cases, a significant increase in ε_x strain values near the side of the plate has been noted. The greatest discrepancy between the numerical and experimental results in the values of deformations ε_x close to zero has been observed. In the change of the strain ε_x along line VII the localization of deformation can be seen near the cut tops. Thus, the calculated and experimental results are almost merged on plots.

Conclusions

It is shown that intensity of the stresses in local shock loads decreases rapidly in both space and time. This makes it possible to use a denser grid in the area, where specified calculations are advisable to be carried out. In this case the grid density varies tenfold [8, 9].

The protective elements of the composites possess the necessary dynamic strength and lower weight than steel, although experience great dynamic displacement.

The composite plate with the a cut is able to maintain the protective properties at a pressure of the front wave at 10^4 Pa. In addition, the results of these researches suggest the possibility of a reliable analysis of the dynamic stress-strain state of thin-walled elements of constructions with cuts subjected to short-term loads.

Double layer protective elements made of titanium alloys can resist the effects of steel projectiles weighing 0.1 kg up to speeds of 800 m/s. At high speeds of projectiles, even if complete penetration does not occur, the deformation of the protective elements is inadmissible.

The greatest impact resistance from among considered protective elements has a three-layer element, comprising of thin layers of titanium alloy, between which a ceramic alloy is placed.

The results of the research allow providing practical advice to reduce dynamic stresses and to increase the dynamic strength of the elements of responsible structures.

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