Dynamic Resistance of Multi-Layered Protective Elements Under Impact Loads

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Abstract. To ensure the dynamic strength of modern constructions, protective elements are used. Studies have shown that even with the use of double-layer elements from similar materials, multilayer elements have enhanced protective properties with a smaller overall thickness compared to single-layer elements. Even greater effect is achieved when using layers of different materials. These features are widely used in the creation of linings to strengthen the bodies of gas turbine engines when exposed to fragments of blades and foreign objects. Numerical studies of the stress-strain state of three-layer element from two thin layers of a titanium alloy and an average ceramic layer under the influence of projectile with different velocities are carried out. The top layer of the titanium alloy perceives the main local load and plastic deformations occur up to the formation of the crater. In the average ceramic layer, the extensive deformations develop, during which the basic energy of impact is absorbed. The third layer limits the velocity of deformation and increases the protective properties of the element. Thus, it is shown that the multilayer elements can have improved protective properties with a general reduction of the weight of structure.

1 Introduction and statement of the problem

Modern constructions often work under the impact of local shock loads. Protective elements are also used as individual means of safety for people. Experience with the use of protective elements shows that the most effective are the multilayer elements. Under the influence of local shock loads, there is a high-rate elastic-plastic deformation of the material of the elements. Analysis of this process requires taking into account the dynamic properties of materials and finite deformations and displacements. It is shown that taking into account the dynamic properties of materials significantly affects the maximum dynamic stresses under impact loads [1-5]. Moreover, for equal loads and thicknesses of elements, the stresses and displacements differ substantially for different materials. Therefore, it is advisable to use multi-layer elements, different layers which consist of different materials. Analysis of the increase in the dynamic strength of protective elements is closely related to the dynamic properties of the material. An important feature of high-rate deformation of most structural materials is their hardening with increasing of strain rate. These properties can be reflected by means of the dependences of stress components on deformations and strain rates [6, 7]. For example, in a cylindrical coordinate system, these dependences have the form of

\[
\begin{align*}
\sigma_r - \sigma &= \frac{1}{\nu} \left( \varepsilon_r - \frac{1}{2} \varepsilon \right) \\
\tau_r\theta &= \frac{1}{\nu} \varepsilon \theta \\
\tau_r z &= \frac{1}{\nu} \varepsilon_z \\
\sigma_{\theta} - \sigma &= \frac{1}{\nu} \left( \varepsilon_{\theta} - \frac{1}{2} \varepsilon \right) \\
\tau_{\theta} z &= \frac{1}{\nu} \varepsilon_z \\
\tau_{\theta}\theta &= \frac{1}{\nu} \varepsilon_{\theta}
\end{align*}
\]

(1)

where \( \sigma_r, \sigma_{\theta}, \sigma_z \) - components of normal stresses, \( \tau_r\theta, \tau_r z, \tau_{\theta} z \) - components of tangential stresses, \( \varepsilon_r, \varepsilon_{\theta}, \varepsilon_z \) - components of normal deformations, \( \gamma_{r\theta}, \gamma_{r z}, \gamma_{\theta z} \) - components of tangential deformations.

In the case of elastic deformations \( \varepsilon = \frac{\sigma}{E} \) and dependences (2) are transferred to Hooke’s law. In the case of plastic high-rate deformations \( \varepsilon = \frac{\sigma}{E} \). Dynamic hardening of materials reflects dependencies of intensities stresses \( \sigma_i \) from strain intensity \( \varepsilon_i \) and intensity of strain rate \( \varepsilon \):

\[ \sigma_i = \sigma_i(\varepsilon_i, \dot{\varepsilon}). \]

The dynamic characteristics of the material can be taken into account using known dependencies in the form of Perzyna [8].
Using the dependencies of Perzyna and Pierce gives close results. An attempt to solve the problem in an elastic formulation leads to significant errors. Equivalent stresses, when using the dependence of Perzyna, are somewhat higher than when using Pierce's dependence.

Using the dependence of Perzyna in the future leads to a margin of strength. The nature of the high-rate deformation of the material depends essentially on the mechanical properties and the parameters of hardening. Therefore Fig. 3 shows the variation of equivalent stresses in time in plates from different materials when the speed of impactor is 200 m/s.

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When a similar fragment was applied to a single-layer element with greater thickness \((h = 8 \text{ mm})\), the maximum stresses were 133 MPa. Thus, the two-layer element showed a much greater efficiency. Therefore, it is more appropriate to use multi-layered protective elements from different materials. Taking into account that titanium alloys tend to be more hardened than even steel ones, their capabilities should be used to perceive the main load in combination with materials capable of absorbing impact energy [11]. For example, we are going to consider a three-layer protective element of light armoured vehicles in Fig. 5.

![Scheme of a three-layer protective element of light armoured vehicles.](image)

The three-layer element of length \(a = 100 \text{ mm}\) and width \(b = 100 \text{ mm}\) is being considered here. The top and lower layers made of titanium alloy Ti6Al4V, have the same thickness \(h_1 = h_3 = 2 \text{ mm}\). The thickness of the inner ceramic layer \(h_2 = 3.2 \text{ mm}\). The main mechanical properties of materials are following:
- for titanium alloy density \(\rho = 4420 \text{ kg/m}^3\), elastic modulus \(E = 1.19 \times 10^{11} \text{ Pa}\), Poisson’s ratio \(\nu = 0.342\), elastic limit \(\sigma_T = 9.1 \times 10^8 \text{ Pa}\),
- for ceramic: density \(\rho = 4900 \text{ kg/m}^3\); elastic modulus \(E = 6.32 \times 10^{11} \text{ Pa}\); Poisson’s ratio \(\nu = 0.204\),
- steel projectile of mass \(m = 0.1 \text{ kg}\): \(\rho = 7800 \text{ kg/m}^3\), elastic modulus \(E = 2.06 \times 10^{11} \text{ Pa}\); Poisson’s ratio \(\nu = 0.3\), elastic limit \(\sigma_T = 2.99 \times 10^8 \text{ Pa}\), hardening module \(E_1 = 7.39 \times 10^8 \text{ Pa}\).

The impact of the projectile on a three-layer element at a speed of 600 m/s is investigated. Fig. 6 shows the displacements and deformations, which occur in \(3 \times 10^{-4} \text{ s}\). In the top layer, the deformations have a clearly pronounced local character. In this case, a crater appears in the top layer, and an extensive region of deformations arises in the average ceramic layer. But the middle layer prevents the further spread of large displacements into the interior of the element. However, the deformation region in the middle layer is extensive, which leads to absorption of the impact energy [12]. The lower layer limits the deformations of the middle layer.

![Displacements (unit: m) (a) and deformations \(\varepsilon^{pl}\) (unit: nondimensional quantity m/m) (b) in the three-layered protective element under the action of projectile.](image)

Fig. 7 shows the isolines of equivalent stresses at the moment \(t = 0.3 \times 10^{-4} \text{ s}\). The localization of high stresses in the crater area and the propagation of dynamic stresses in the middle layer are visible. In the third layer, much lower stresses are observed.

After the impact, the element has obvious damage in the form of a crater in the top layer, but since the new impact of the projectile on the protective element is most likely to occur outside the zone of the original local damage, the element practically retains its protective properties.

![Distribution of equivalent stresses (unit: Pa) in a three-layer element at the speed impact of projectile of 600 m/s.](image)

### 3 Conclusions

The results of numerical analysis show that the use of several layers makes the protective elements more effective than single-layer ones. Even with the use of two-layer elements from the same materials (like steel), which is typical of some elements of gas turbine corps (where there are elevated temperatures), these elements have higher protective properties than single-layer ones.

When layers of materials with high dynamic hardening characteristics are used in combination with a thicker ceramic layer, the efficiency of the protective structures is further improved. The top layer perceives the main shock load, when the projectile actions with high speeds. Due to hardening, plastic deformations occur in it and a crater is formed. In the middle layer, with a lower hardening, a considerable area of deformation arises.

Due to its size, the energy of its deformation is distributed throughout the volume and damped. The third layer limits the displacement of the middle layer. When the impactor is exposed on the top layer the local damage occurs, but it is limited by deformations of the middle layer. The whole element retains its protective properties when the projectile again hits the area unaffected by the first impact. In general, it can be noted...
that multi layered protection elements have increased strength properties and provide a reduction in the weight of the structure.

References
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