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Research of strength and deformation of metal-glass-plastic plates and shells taking into account inter-layer shears

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Abstract
In this article, the strength and deformability of two-layer plates and shells are studied, taking into account composite materials. In a specific example, analyze the results of accounting for interlayer shifts on the strength of combined plates.

Keywords: two-layer plate, combined structures, interlayer shifts

Introduction
The combined two-layer plates and shells in question are often found in some spatial structures in the chemical industry, construction, and other engineering industries. These structures consist of materials with significantly different physical and mechanical properties, which makes it possible to ensure reliable operation of systems in adverse conditions. The protection of such combined layers provides the necessary durability, high performance properties and corrosion resistance to aggressive media, liquid, gas, wet and dusty, which are often found in chemical and other enterprises. Numerous examples of applications indicate their high strength, reliability and efficiency, especially when operating under the influence of aggressive environments.

When using layered plates and shells, it is necessary to take into account the work of the bonding seam, since it allows you to create a reliable structure in adverse production conditions [1, 6, 7], protecting them from heating, external pressures and from the influence of aggressive media.

In machine-building structures, there are two-layer plates and shells, multi-layer cylinders, combined structures created on the basis of metal and composite materials.

We will continue to study the stress-strain state of combined plates and shells, taking into account the flexibility of the adhesive seam and various mechanical characteristics of individual layers. The stress-strain state of combined two-layer plates and shells, taking into account interlayer shifts, constructed on the basis of metal and fiberglass according to the refined theory [2], allows us to evaluate the strength and deformability with high enough accuracy in solving engineering problems.

Consider the connection of two-layer orthotropic combined plates (Fig. 1), considering that the first bearing (metal) layer is significantly different from the second (composite) reinforcing ($h>\delta$).

We believe that in relation to the plates considered in this case, the accepted hypotheses according to the refined theory [2] are valid: the thicknesses of the first and second layers are constant; the first layer is much more powerful than the second. Therefore, we assume approximation $e_{zz} = 0; w=w(x, y)$. Here e_{zz} is the relative elongation of the strain at the z coordinate; w is the deflection.

Shear deformations of the first layer

$$e_{xz} = 0{,}5\,(\frac{h^2}{4} - \gamma^2)F_1 + (0{,}5 - \frac{\gamma}{h})\frac{\tau_1}{G^{(1)}{}_{13}};$$

$$e_{xz} = 0{,}5(\frac{h^2}{4} - \gamma^2)F_2 + (0{,}5 - \frac{\gamma}{h})\frac{\tau_2}{G^{(2)}{}_{23}}. \quad (1)$$

Shear deformations of the second layer

$$e^{(2)}{}_{xz} = (0{,}5 + \frac{\gamma_1}{\delta})\frac{\tau_1}{G^{(2)}{}_{13}};$$

$$e^{(2)}{}_{yz} = (0{,}5 + \frac{\gamma_1}{\delta})\frac{\tau_2}{G^{(2)}{}_{23}}, \quad (2)$$

where *h*, *δ* is the thickness of the fiberglass metal layers;
$F_i = F_i(x, y)$ is an arbitrary unknown function of the coordinate shift *x*, *y*;
$\tau_i = \tau_i(x, y)$- the desired tangent stresses;
〖$G^{(1)}{}_{ik}$, $G^{(2)}{}_{ik}$-shift modes of the first and second layer (*i*=1,2; *k*=3).
The γ coordinates have the following boundaries of change;
for the first layer $-\frac{h}{2} \leq \gamma \leq \frac{h}{2}$;
for the second layer $-\frac{\delta}{2} \leq \gamma_1 \leq \frac{\delta}{2}$.

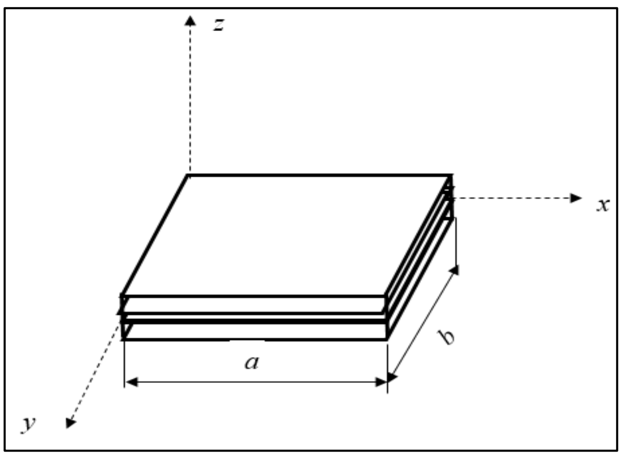


Fig 1: Connection of two-layer orthotropic combined plates.

The movements of the fiberglass layer are derived using the relations of the elasticity theory [2]:

$$u^{(1)} = u_0 - \gamma\frac{\partial w}{\partial x} + \left(\frac{\gamma h^2}{8} - \frac{\gamma^3}{6}\right)F_1 + \gamma(\frac{1}{2} - \frac{\gamma}{2h})\frac{\tau_1}{G^{(1)}{}_{13}};$$

$$v^{(1)} = v_0 - \gamma\frac{\partial w}{\partial y} + \left(\frac{\gamma h^2}{8} - \frac{\gamma^3}{6}\right)F_1 + \gamma(\frac{1}{2} - \frac{\gamma}{2h})\frac{\tau_1}{G^{(1)}{}_{13}}. \quad (3)$$

Similarly for a metal layer:

$$u^{(2)} = u_0 - \gamma_1\frac{\partial w}{\partial x} + \gamma_1(\frac{1}{2} - \frac{\gamma_1}{2\delta})\frac{\tau_1}{G^{(2)}{}_{13}};$$

$$v^{(2)} = v_0 - \gamma_1\frac{\partial w}{\partial y} + \gamma_1(\frac{1}{2} - \frac{\gamma_1}{2\delta})\frac{\tau_2}{G^{(2)}{}_{23}}. \quad (4)$$

where $u_0 = u_0(x, y)$, $v_0 = v_0(x, y) -$ the desired tangential displacements of the corresponding point on the middle surface of the first layer.

The tangential displacements $u^{(1)}$,$u^{(2)}$,$v^{(1)}$,$v^{(0)}$ $-$ in contrast to the classical theory, formulas (3) and (4) depend on *γ* non − linearly, in the second layer-on *γ₁*-linearly. This is due to the difference in the thickness of the layers and taking into account the transverse shift in the more powerful first.

Observing the conditions of continuous movement of the adhesive seam, we find a connection between the movements of the first and second layer.

$$u_{ш} = u^{в}{}_{ш} - \gamma \frac{\tau_1}{G^{(1)}{}_{ш13}};$$
$$v_{ш} = v^{в}{}_{ш} - \gamma \frac{\tau_2}{G^{(1)}{}_{ш23}}. \qquad (5)$$

We`ll write down the contact conditions for layers

$$u_{ш(\gamma=-\frac{h}{2})} - \tau_1 \varepsilon_{ш13} = u_{ш(\gamma_1=+\frac{\delta}{2})};$$
$$v_{ш(\gamma=-\frac{h}{2})} - \tau_2 \varepsilon_{ш23} = v_{ш(\gamma_1=+\frac{\delta}{2})}; \qquad (6)$$

where $u^{в}{}_{ш}$, $v^{в}{}_{ш}$ – movement of the seam at $\gamma = -\frac{h}{2}$; $\varepsilon_{шik} = h_{ш}/G_{шik}$;

$h_{ш}$, $G_{шik}$ – thickness and shear modulus of the seam.

Observing the conditions (6), after the necessary transformations of the second layer's displacement, we write

$$u^{(2)} = u_0(\xi_2 - \gamma_1)\frac{\partial w}{\partial x} - \frac{h^3}{24}\mathrm{F}_1 + \left[\left(\frac{\gamma_1}{2} + \frac{{\gamma_1}^2}{2\delta}\right)\frac{1}{{G_{13}}^{(2)}} - SH_{13}\right]\tau_1;$$
$$v^{(2)} = v_0(\xi_2 - \gamma_1)\frac{\partial w}{\partial y} - \frac{h^3}{24}\mathrm{F}_2 + \left[\left(\frac{\gamma_1}{2} + \frac{{\gamma_1}^2}{2\delta}\right)\frac{1}{{G_{23}}^{(2)}} - SH_{23}\right]\tau_2. \qquad (7)$$

Here:

$\xi_2 = 0{,}5\,(h + \delta)$;

$$\xi_{413} = \frac{3}{8}\left(\frac{h}{{G_{13}}^{(1)}} + \frac{\delta}{{G_{13}}^{(2)}}\right);$$
$$\xi_{423} = \frac{3}{8}\left(\frac{h}{{G_{23}}^{(1)}} + \frac{\delta}{{G_{23}}^{(2)}}\right);$$

$$SH_{13} = \xi_{413} + \varepsilon_{ш13};$$
$$SH_{23} = \xi_{423} + \varepsilon_{ш23}.$$

Deformation in the layers are determined by the well-known Cauchy relations

$$\varepsilon_x{}^{(i)} = \frac{\partial u^{(i)}}{\partial x};$$
$$\varepsilon_y{}^{(i)} = \frac{\partial v^{(i)}}{\partial y};$$
$$\varepsilon_{xy}{}^{(i)} = \frac{\partial v^{(i)}}{\partial x} + \frac{\partial u^{(i)}}{\partial y}, \qquad (8)$$

We have for stresses in layers

$$\sigma_x{}^{(i)} = \mathrm{B}^{(i)}{}_{11}\varepsilon_x{}^{(i)} + \mathrm{B}^{(i)}{}_{12}\varepsilon_y{}^{(i)};$$
$$\sigma_y{}^{(i)} = \mathrm{B}^{(i)}{}_{22}\varepsilon_y{}^{(i)} + \mathrm{B}^{(i)}{}_{12}\varepsilon_x{}^{(i)};$$
$$\tau_{xy}{}^{(i)} = G^{(i)}{}_{11}\varepsilon_{xy}{}^{(i)}; \qquad (9)$$

where

$$\mathrm{B}^{(i)}{}_{11} = \frac{\mathrm{E}^{(i)}{}_1}{1 - \mu_1\mu_2};$$

$$\mathrm{B}^{(i)}{}_{12} = \frac{\mu_1 \mathrm{E}^{(i)}{}_2}{1 - \mu_1\mu_2};$$

$$B^{(i)}_{22} = \frac{E^{(i)}_2}{1-\mu_1\mu_2};$$

$E^{(i)}_1, E^{(i)}_2 -$ is the modulus of elasticity of the layers;
μ_1 and $\mu_2 -$ Poisson's ratio for different layers;
i = *1, 2* – for the first and second layers.

The equation of plate deformation is obtained using the variational principle, taking the total energy of the plate as a functional. The functionality has the form

$$u = \frac{1}{2}\iiint_s \left(\sigma^{(i)}{}_x\varepsilon_x{}^{(i)} + \sigma^{(i)}{}_y\varepsilon_y{}^{(i)} + \tau^{(i)}{}_{xy}\varepsilon_{xy}{}^{(i)}\right)ds\cdot d\gamma +$$
$$+\frac{1}{2}\iint_s \left(\tau_1{}^2\varepsilon_{ш13} + \tau_2{}^2\varepsilon_{ш23} - 2qw\right)ds. \quad (10)$$

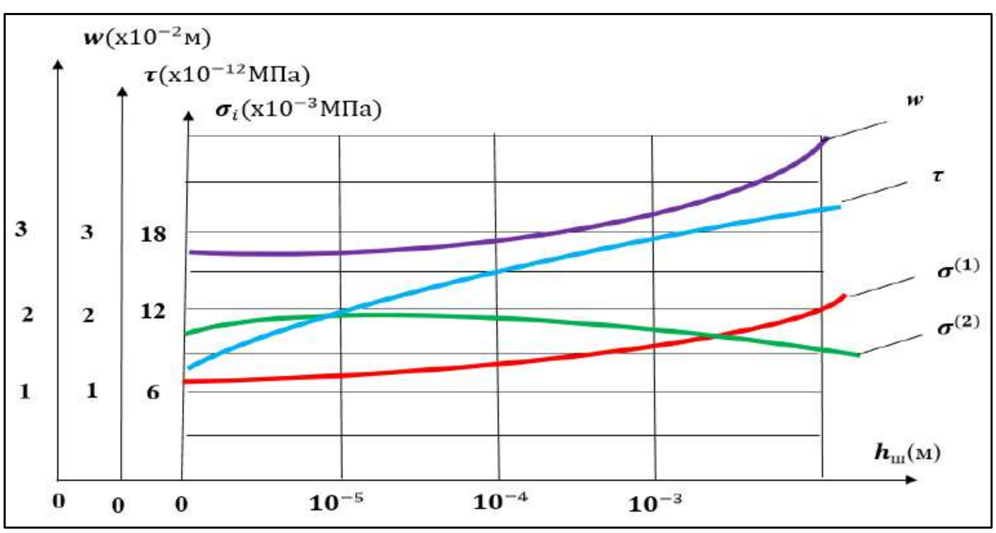
Using Euler's variational equation, we obtain a system of fourth-order partial differential equations with respect to unknown $w, u_0, v_0, F_1, F_2, \tau_1, \tau_2$. Due to the bulkiness of the system of differential equations, we do not give coefficients and boundary conditions. They are given in [5, 6].
To study the effect of interlayer shift, we take a plate that is freely supported along the contour. Using the Naiver method, we assume that the plate carries a uniformly distributed load q. The solution of the system of differential equations of equilibrium that satisfies the boundary conditions is a double trigonometric series.
Example. Consider a rectangular square two-layer plate of size *a*=*b* = 1.2 m. the Thickness of the first and second layers, respectively, *h* = 1.5×10^{-2}m, δ = 0.3×10^{-2}m. Elastic characteristics of combined plates are accepted according to the works [3, 4].
$E_1{}^{(1)} = 3.05$ Pa; $E_2{}^{(1)} = 1.88$ MPa; $\mu^{(1)} = 0.18$;

$E_1{}^{(2)} = E_2{}^{(2)} = 0.21 \times 10^2$ MPa; $\mu^{(2)} = 0.26$;

$G_{12}{}^{(1)} = 0.49$ MPa; $G_{13}{}^{(1)} = 0.31$ МПа;

$G_{23}{}^{(1)} = 0.35$ MPa; $G_{ik}{}^{(2)} = 81$ MPa;q = 1.

Numerical examples have shown that the shear modulus and seam thickness have a great influence on the strength and deformability of combined two-layer plates, if the shear modulus of the bonding layer is significantly less than the shear modulus of the layers. If the first powerful layer consists of a composite material, the effect of transverse shear on the stress-strain state of the combined plates will be greater.
It should be noted that the smaller the modulus, the greater the influence of the seam's pliability on the deformability of layered combined plates. Adopting for epoxy glue ($G_{шik} = 0.5 \times 10^{-2}$MPa)We will see that increasing the shear modulus of the seam by 10 times reduces the stress in the fiberglass layer, which is 4.45 % ($\sigma^{(1)}$), and in the metal layer increases it by 10%. Changing the thickness of the bonding layer twice from (с $h_ш = 10^{-4}$ до 0.5×10^{-4}m) changes the stress in the fiberglass towards *x* by 4.1 % (see Fig. 2, 3), constructed for the point *x* = 0.5 *a*, *y* = 0.5 *b*.



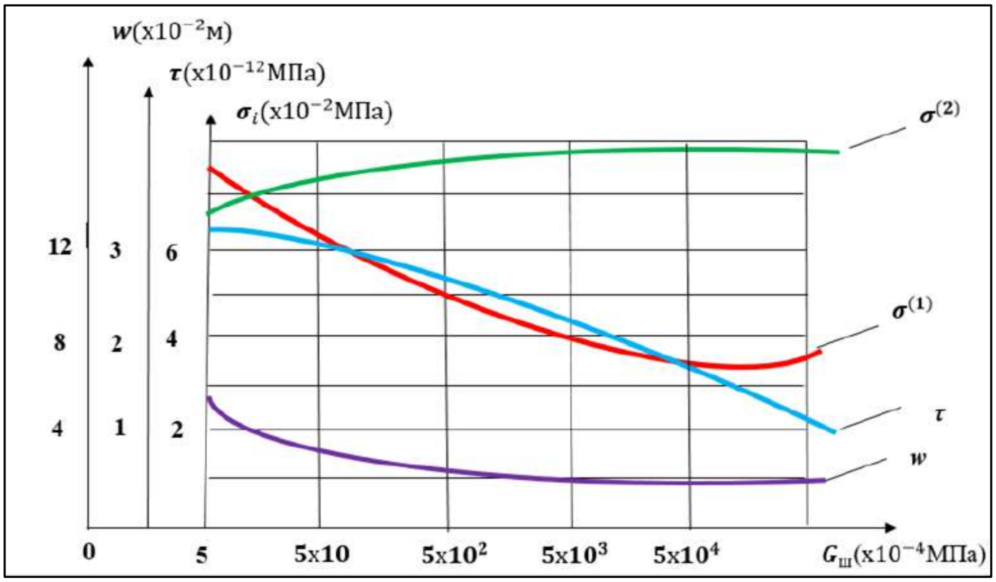


Fig 3

Thus, the larger the shear modulus of the seam, the less its effect on the stress-strain state.

The analysis showed that an increase in the thickness of the bonding layer made of K-147 epoxy ($G_{шik} = 0.5 \times 10^{-2}$MPa), 10 times (from 10^{-4} to 10^{-3} m) increases the plate deflection by 22 % . With a large value of $G_{шik}$of the order of 0.81×10^{2}MPa, the thickness of the seam affects the deflections slightly (less than 1 %). The regularity is established that the greater the thickness of the load-bearing fiberglass layer, the less the influence of the seam shear modulus on the stress and deformability of two-layer combined plates. Deflection of fiberglass plates with external metal reinforcement according to the considered theory [2], which takes into account the interlayer shift at h = 1.5$\times 10^{-2}$m, δ =0.3$\times 10^{-2}$m, $h_{ш} = 0.5 \times 10^{-3} m$ and $G_{шik} = 0.5 \times 10^{-2}$MPa, less by 54.6 % compared to the deflection of the plate without an external reinforcing layer.

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