Journal of Engineering Physics and Thermophysics, Vol. 74, No. 6, 2001

USE OF SUPERHARD CARBON FIBERS FOR CREATION OF STRUCTURES WITH THERMAL ADAPTATION

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UDC 624.016

The use of modern composite materials based on carbon fibers in precision equipment makes it possible to retain its dimensional stability under the conditions of a varied temperature field. The main principle of development is the creation of a composite element of compensation for the thermal expansion of the structure.

At the present time, one of the incompletely resolved problems in creation of precision equipment is the problem of retention of its dimensional stability under the conditions of a varied temperature field. The action of a variable temperature field represents the greatest hazard to this equipment. This problem became especially pressing in developing structures for communications systems for operation under terrestrial conditions as well as in open outer space, where in large spaces even small deviations of the geometric parameters of the structure can lead to substantial errors.

The use of different protections in the form of coatings, shieldings, and so on cannot completely exclude the factor of disruption of the dimensional stability of a structure and only complicates and loads it.

These problems can be solved by two methods:

(1) the materials-science method — creation of a dimensionally stable structural material (SM);

(2) the designing method — creation of structures with the use of a functional composite material preventing changes in their geometry.

Each of these methods has advantages and disadvantages. Solution of the problem by the materials-science method is more universal, but it requires larger expenses and more time. What is more, it cannot be applied to structures in which other structural materials must be used. Therefore, solution of the problem by the designing method is preferred in the case of creation of more complex structures in which, because of their features, it is impossible or almost impossible to use one structural material. This is true first of all for systems of precision equipment, such as a telescope-type structure, which are used in outer space.

Different methods of mechanical compensation are insufficiently reliable, too complex, and have a time factor, as, for example, a structure with a cooled jacket, which operates by the following scheme: change in the body temperature — signal from the temperature-sensitive element — switching-on of the pump — arrival of the coolant — cooling of the body to the required temperature — signal from the temperature-sensitive element — shutting-off of the pump. Thermostabilization is even more problematic in the case of an alternating-sign temperature field.

These problems can be solved with the use of functional composite materials, which, along with the main properties inherent in structural materials, possess additional functions (synergism): for example, they react inadequately to changes in the temperature field.

The main principle of development of such structural materials can be the use of the anomalous reaction of individual fibers to a temperature change. The supermolecular structure of certain fiber anisotropic fillers possessing, as a rule, an increased hardness due to the high orientation of the structural elements along

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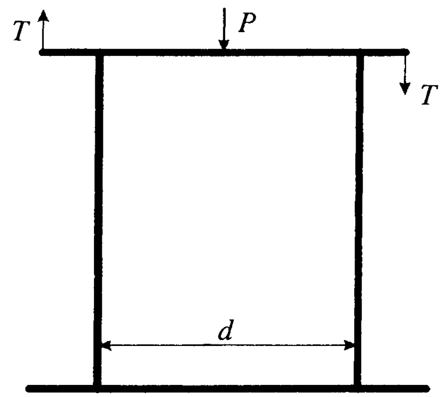


Fig. 1. Scheme of loading of a force shell (P = 58,860 Pa, M = 58,860 N·m).

the fiber is subjected to fixation (or thermofixation) in the process of production of the fillers for the required orientation to be retained. If such fibers are acted upon by a temperature field, they relax and shrink along their length, providing by doing so a negative coefficient of linear thermal expansion. Such changes are usually reversible in character, they are not always linear, and the value of the shrinkage frequently depends on the conditions of the technology of production of the fibers.

In this respect, of greatest interest are carbon fibers (CFs) having, along with high specific physicomechanical characteristics, unique thermal properties that are determined by their structure, the character of the surface, the temperature of heat treatment, etc. Among such properties is the coefficient of linear thermal expansion (CLTE) of carbon fibers, which can take on not only positive values but negative values as well. This is explained by the effect of reduction of linear and layered structures due to the formation of flexural waves along with ordinary thermal vibrations.

Unlike ordinary homogeneous bodies, in which thermal expansion is practically linear, in carbon fibers this process is complex, alternating-sign, and having extrema, and one can observe hysteresis at temperatures approaching the final temperature of heat treatment. The negative value of the CLTE depends on the heat-treatment temperature and increases with it. Therefore, the value of the shrinkage of the composite can be changed in a fairly large range in one direction or another if the reinforcing carbon-fiber filler, the matrix material, and the reinforcement scheme are chosen correctly.

But here the problem of determination of changes in the linear dimensions of carbon fibers in the temperature interval of the supposed operation of the product arises. The reference literature gives an approximate interval of values of the CLTE for carbon fibers in the case of a temperature increase of one degree at 293 K. Such data cannot be used as a criterion for calculation. Moreover, standard dilatometers designed for samples having a cross section of >1 mm cannot always be used in measurements of fiber materials.

The investigations of carbon fibers carried out using an optical comparator allowed us to obtain the principal curve of change in their linear dimensions with temperature. However, such investigations have a number of disadvantages, including the error introduced by optical devices, which is comparable to the value of the CLTE (10^{-6}). Therefore, for practical application we have developed the procedure of measuring the CLTE of hard fibers (the Young modulus is no less than 100 GPa), which makes it possible to use a push-type quartz dilatometer. The procedure is based on determination of the dilatometric curve of a bunch of parallel-connected hard fibers to a temperature of 423 K.

Taking into account the foregoing, we can develop a structural element that, being included in a precision device, will stabilize its geometric dimensions. The functional composite element must have a CLTE equal to that of the structure of the device but opposite in sign. The functional structural material will cancel all the variations in the linear dimensions of the device structure in the required temperature interval, reliably providing a high quality of its operation. The problem considered can be formulated as creation of such a structure from a functional structural material, which would "reasonably" change its geometry by the same value as the product in which it is included but opposite in sign and thus retain the dimensional stability of the system as a whole.

In the technology proposed, the material of the structure used as the object for stabilization of geometric parameters and acquisition of thermal-adaptation properties is of no importance.

The following main operations should be carried out in the process of development:

(1) analysis of the structure and changing its geometric parameters in the temperature range of operation;

(2) determination of the requirements of the absolute value of the shrinkage, the dimensions, and the physicomechanical and weight characteristics as well as the synchronism of interaction imposed on the composite compensative element;

(3) choice and analysis of the reinforcing and the matrix materials and calculation of the reinforcement scheme;

(4) choice of the technology and the machining attachments.

By way of example we consider a carbon-plastic compensative element with a round cross section for a telescope-type product with high physicomechanical characteristics. This is a structure in the form of a shell shaped as a cylinder with a length of 878 mm and an inside diameter of 548 mm, which is equipped with flanges at the ends of the cylinder for mechanical attachment. The total mass of the structure is no more than 22 kg.

The structure developed must comply with the following requirements:

(1) to stand up to a multiple load of up to P = 58,860 Pa and M = 58,860 N·m (the distribution of the limiting loads on the shell is shown in Fig. 1);

(2) to have a CLTE of $4.1 \cdot 10^{-6}$ K^{-1} in the longitudinal direction and of no more than $8.4 \cdot 10^{-6}$ K^{-1} in the circular (transverse) direction in the temperature range 281–301 K;

(3) to possess resistance to special actions without a coating:

• tolerable mass loss in vacuum	no more than 1%
• deposition of volatile substances	no more than 0.1%
• absorption of moisture after a test	no more than 0.2%
• protons	$2 \cdot 10^5$ rad
• electrons	$2.4 \cdot 10^4$ rad
• radiation	$1.33 \cdot 10^{-2}$ rad
• spectral range	$1.2 \cdot 10^{14}$–$1.5 \cdot 10^{15}$ Hz
• total energy	$4.94 \cdot 10^9$ J.

Under the above-indicated conditions, the mechanical and thermal characteristics of the structure without a coating must not change by more than 10% and the surface must be free of damage and flakings.

The technology of production of shells must provide recurrence of the properties of the product material and stability of the structural parameters.

In order that the requirements imposed on the structure be observed, we have made mathematical calculations modeling its behavior under the given conditions. As a result, we have obtained the physicomechanical characteristics of the product material: E_1 = 126.6 GPa, E_2 = 17.2 GPa, E_3 = 166.8 GPa, F_{12} = 34.4 MPa, F_3 = 686.7 MPa, and G_{12} = 36.3 MPa.

From the above-mentioned requirements imposed on the material and mass of the structure and anisotropy of its properties it has been inferred that the product can be manufactured from a composition reinforced with carbon fibers with an elastic modulus of no less than 200 GPa.

Since the CLTE of the structure is given with a high accuracy, we had to construct dilatometric curves of the reinforcing filler to determine accurately the value of the linearity of the coefficient in the given temperature range.

To choose the reinforcing material by the procedure developed, we constructed dilatometric curves of carbon fibers with an elastic modulus of no less than 200 GPa. As a result, we have chosen carbon fibers having a linear dependence of the CLTE on the temperature in the longitudinal direction and a different degree of heat treatment (final temperature of heat treatment) in the temperature range 275–325 K. We have chosen "Kulon-P" reinforcing fibers with a CLTE of $2.7 \cdot 10^{-6}$ K^{-1} for reinforcement of the shell and LU-P-0.1 with a CLTE of $1.1 \cdot 10^{-6}$ K^{-1} for the flanges and frames.

Based on the operation requirements, we used the thermoreactive binder of an ENFB epoxy compound (technical specifications 1-596-36-86) as the matrix material.

Thus, as a result of the analysis of the physicomechanical and thermophysical characteristics, we have chosen the following materials for the structure: a high-modulus (Young modulus of up to 500 GPa) graphitized "Kulon" strip in the longitudinal direction, a high-strength carbonized LU-P strip (Young modulus of up to 250 GPa) in the transverse direction, and an ENFB epoxy-novolac binder as the matrix material.

It is known from the theory [1] that stiffened shells work well in axial compression. Therefore, the calculation was made by the following algorithm.

Initial data:

(1) stiffness properties of a monolayer: E_1 = 270 GPa, E_2 = 5.5 GPa, ν_{12} = 0.3, and G_{12} = 2.9 GPa;

(2) ultimate strength in a single-axis stressed state, MPa: F_1^+ = 980, F_1^- = 690, F_2^+ = 150, F_2^- = 345, and F_{12} = 30;

(3) thermomechanical characteristics of a monolayer, K^{-1}: $\alpha_1 = 2.1 \cdot 10^{-6}$ and $\alpha_2 = 15 \cdot 10^{-6}$.

We used a classical approach to the calculation of stability, which implies that:

(a) the material of all the layers is linearly elastic;

(b) subcritical displacements and deformations are small as compared to bifurcational ones ("the body is stressed but not deformed");

(c) the Kirchhoff–Love hypotheses are true (i.e., the straight-normal hypothesis and the nonpressed-layer hypothesis);

(4) varied parameters for the shell: h_i and φ_i, and for the layers of ribs: n_x and n_y; the geometry of the cross section: h_i and B_i.

The properties were calculated based on the continuous model, in which the layer of ribs is arbitrarily considered as a homogeneous layer having reduced characteristics; account is taken of the discrete arrangement of the ribs (local stability, strength).

The stiffness characteristics are as follows:

$$B_{xx} = \sum_{i=1}^{n} g_{xx}^{(i)} h_i \, ;$$

$$D_{ss} = \frac{1}{3} \sum_{i=1}^{n} g_{ss}^{(i)} (z_i^3 - z_{i-1}^3) \, ;$$

$$g_{xx} = \sum_{i=1}^{n} \left[g_{11}^{(i)} \cos^4 \varphi_i + g_{22}^{(i)} \sin^4 \varphi_i + (2g_{12}^{i} + 4G_{12}^{i}) \sin^2 \varphi_i \cos^2 \varphi_i \right] \hat{h}_i \, ;$$

$$g_{11}^{(i)} = \frac{E_1^{(i)}}{1 - \nu_{12}^{(i)} \nu_{21}^{(i)}} \, ; \quad g_{22}^{(i)} = \frac{E_2^{(i)}}{1 - \nu_{12}^{(i)} \nu_{21}^{(i)}} \, ; \quad g_{12}^{(i)} = \nu_{12}^{(i)} g_{22}^{(i)} = \nu_{21}^{(i)} g_{11}^{(i)} \, .$$

For the axial ribs

$$\hat{g}_{xx}^{(i)} = \frac{n_x\,(\mathrm{EF})_x}{2\pi Rh}\,; \quad \hat{g}_{xy}^{(i)} = \hat{g}_{yy}^{(i)} = \hat{g}_{ss}^{(i)} = 0\,.$$

For the ring ribs

$$\hat{g}_{yy}^{(i)} = \frac{n_y\,(\mathrm{EF})_y}{Lh}\,; \quad \hat{g}_{xy}^{(i)} = \hat{g}_{xx}^{(i)} = \hat{g}_{ss}^{(i)} = 0\,.$$

The strength is

$$\begin{aligned}
&\varepsilon_x^{(0)} = \frac{\sigma_x^{(0)} - \nu_{xy}\sigma_y^{(0)}}{E_x}\,; && E_x = g_{xx} - g_{xy}^2 / g_{yy}\,;\\
& && E_y = g_{yy} - g_{xy}^2 / g_{xx}\,;\\
&\varepsilon_y^{(0)} = \frac{\sigma_y^{(0)} - \nu_{yx}\sigma_x^{(0)}}{E_y}\,; && \nu_{xy} = g_{xy} / g_{yy}\,;\\
& && \nu_{yx} = g_{xy} / g_{xx}\,;\\
&\gamma_{xy}^{(0)} = 0\,; && G_{xy} = g_{ss}\,;
\end{aligned}$$

$$\sigma_x^{(0)} = \frac{\xi_x^{(k)}}{2\pi Rh}\,; \quad \sigma_y^{(0)} = \frac{\xi_y^{(k)}}{Rh}\,; \quad \sigma_{xy}^{(0)} = 0\,; \quad \xi = \pm 1\,;$$

$$g_{yy} = \sum_{i=1}^{n} \left[g_{11}^{(i)} \sin^4 \varphi_i + g_{22}^{(i)} \cos^4 \varphi_i + (2g_{12}^{i} + 4G_{12}^{i}) \sin^2 \varphi_i \cos^2 \varphi_i \right] \hat{h}_i\,;$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = P \begin{Bmatrix} \sigma_x^{(0)} \\ \sigma_y^{(0)} \\ \sigma_{xy}^{(0)} \end{Bmatrix}.$$

The local stability is

$$\det \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} + B_{33}P_j \end{bmatrix} = 0\,;$$

$$a_{11} = (m_1\pi)^2\, B_{xx} + \left(\frac{m_2}{R}\right)^2 B_{ss}\,;$$

m_1 = 1, 2, ..., ∞ and m_2 = 0, 2, 3, ..., ∞ are the numbers of waves over the ring;

$$B_{ss} = \sum g_{ss}^{(i)}\,(z_i - z_{i-1})\,; \quad a_{12} = a_{21} = \left(\frac{m_1\pi}{2}\right)\left(\frac{m_2}{R}\right)(B_{xy} + B_{ss})\,;$$

$$B_{xy} = \sum_{i=1}^{n} g_{xy}^{(i)}\,(z_i - z_{i-1})\,;$$

$$g_{xy} = \sum_{i=1}^{n} \left[(g_{11}^{(i)} + g_{22}^{(i)} - 4G_{12}^{(i)}) \sin^2 \varphi_i \cos^2 \varphi_i + g_{12}^{(i)} (\sin^4 \varphi_i + \cos^4 \varphi_i) \right] \hat{h}_i ;$$

$$a_{13} = a_{31} = -\frac{m_1\pi}{L} \left[\left(\frac{m_1\pi}{2} \right)^2 C_{xx} + \left(\frac{m_2}{R} \right)^2 (C_{xy} + 2C_{ss}) + \frac{B_{xy}}{R} \right];$$

$$C_{xx} = \frac{1}{2} \sum_{i=1}^{n} g_{xx}^{(i)} (z_i^2 - z_{i-1}^2) ;$$

$$C_{xy} = \frac{1}{2} \sum_{i=1}^{n} g_{xy}^{(i)} (z_i^2 - z_{i-1}^2) ;$$

$$C_{ss} = \frac{1}{2} \sum_{i=1}^{n} g_{ss}^{(i)} (z_i^2 - z_{i-1}^2) ;$$

$$g_{ss} = \sum \left[(g_{11}^{i} + g_{22}^{i} - 2g_{12}^{i}) \sin^2 \varphi_i \cos^2 \varphi_i + G_{12}^{i} \cos^2 2\varphi_i \right] \hat{h}_i ;$$

$$a_{22} = \left(\frac{m_1\pi}{L} \right)^2 B_{ss} + \left(\frac{m_2}{R} \right)^2 B_{yy} ;$$

$$B_{yy} = \sum g_{yy}^{(i)} (z_i - z_{i-1}) ;$$

$$a_{23} = a_{32} = -\frac{m_2}{R} \left[\left(\frac{m_2}{R} \right)^2 C_{yy} + \left(\frac{m_1\pi}{L} \right)^2 (C_{xy} + 2C_{ss}) + \frac{B_{yy}}{R} \right];$$

$$C_{yy} = \frac{1}{2} \sum g_{yy}^{(i)} (z_i^2 - z_{i-1}^2) ;$$

$$a_{33} = \frac{B_{yy}}{R^2} + 2 \left(\frac{m_1\pi}{L} \right)^2 \frac{C_{xy}}{R} + 2 \left(\frac{m_2}{R} \right)^2 \frac{C_{yy}}{R} + \left(\frac{m_1}{L} \right)^4 D_{xx} + 2 \left(\frac{m_1\pi}{L} \right)^2 \left(\frac{m_2}{R} \right)^2 (D_{xy} + 2D_{ss}) + \left(\frac{m_2}{R} \right)^4 D_{yy} ;$$

$$D_{xx} = \frac{1}{3} \sum g_{xx}^{(i)} (z_i^3 - z_{i-1}^3) ;$$

$$D_{xy} = \frac{1}{3} \sum g_{xy}^{(i)} (z_i^3 - z_{i-1}^3) ;$$

$$D_{yy} = \frac{1}{3} \sum g_{yy}^{(i)} (z_i^3 - z_{i-1}^3) ; \quad B_{33} = \left(\frac{m_1\pi}{L} \right)^2 + \frac{\xi_x^j}{2\pi R} + \left(\frac{m_2}{R} \right)^2 \frac{\xi_y^j}{R} .$$

By setting the determinant equal to zero we obtain a linear equation, from which we find $P_j\ (m_1 m_2)$. The limiting load is

$$P_{\mathrm{cr}} = \min_{m_1 m_2} \left\{ P_j\ (m_1 m_2) \right\} .$$

For the axial ribs, we substitute $m_2\pi/\lambda_y$ for m_2/R into the formulas.

For the ring ribs, we substitute $m_2\pi/\lambda_x$ for $m_1\pi/L$.

Since there are axial ribs, ξ_x is decreased as many times as $\hat{N}$ is smaller than N (compressive force). The thermoelastic characteristics are as follows:

$$\beta_1^{(i)} = g_{11}^{(i)}\alpha_1^{(i)} + g_{12}^{(i)}\alpha_2^{(i)}, \quad \beta_2^{(i)} = g_{12}^{(i)}\alpha_1^{(i)} + g_{22}^{(i)}\alpha_2^{(i)};$$

$$\beta_x = \sum_{i=1}^{n} (\beta_1^{(i)} \cos^2 \varphi_i + \beta_2^{(i)} \sin^2 \varphi_i)\, \hat{h}_i, \quad \beta_y = \sum_{i=1}^{n} (\beta_1^{(i)} \sin^2 \varphi_i + \beta_2^{(i)} \cos^2 \varphi_i)\, \hat{h}_i;$$

$$\alpha_x = \frac{\beta_x - \nu_{yx}\beta_y}{E_x}, \quad \alpha_y = \frac{\beta_y - \nu_{yx}\beta_x}{E_y}.$$

As a result of the calculations, we have developed the following structure. The compensative element represents a shell of thickness 2 mm reinforced by sixteen longerons and two frames, positioned at a distance of 290 mm from the edges of the shell. At the edges of the shell there are flanges with holes for mechanical fastening to the main structure (Fig. 2). All the components of the structure are connected together rigidly.

We have chosen the following scheme of reinforcement:

Number of the layer	Grade of the material	Angle of reinforcement, deg
	Shell and longerons:	
1–8	"Kulon-P"	0
9–20	"Kulon-P"	+35
21–32	"Kulon-P"	–35
33–40	"Kulon-P"	0
	Flanges and frames:	
1–20±	LU-P	+45/–45
21–40∓	LU-P	

The prepreg technology (preliminary impregnation of the reinforcing material) has been chosen for production of all the primary elements of the shell. Slopregs (stacks of prepregs) were built up according to the required scheme of reinforcement with subsequent laying on the machining attachments (jigs).

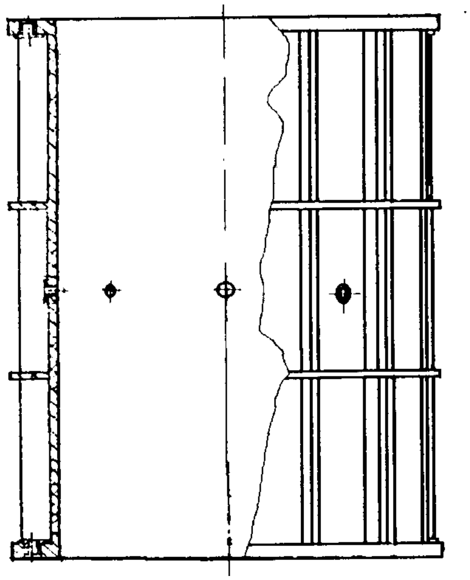
The shell was produced by laying a slopreg on a cylindrical mandrel with subsequent autoclave compaction. Since the design of the shell had a stringent limitation on the tolerance for the inside diameter, which excludes conicity, it was impossible to produce the shell on a solid mandrel with subsequent removal of the product from the mandrel using a capstan. We have developed a demountable mandrel of the unloading type (the pressure on the outer surface is equal to the pressure on the inner surface) to provide a high compaction pressure without changing the mandrel geometry.

The slopreg was alternately butt-laid on the jig mandrel using a winding machine with rolling by a pressing iron with a fluoroplastic roller and rotation of the mandrel by 30^{o} after each layer of the slopreg. The slab of the shell laid by this method was covered by a layer of T-10-80 glass cloth underwound by a perforated fluoroplastic film and a layer of RVMN glass braid with a tension of 590 N.

The slabs for production of longerons were laid on the coating sheets by the same scheme of reinforcement.

The shell and the slab of the longerons were moulded on a "Scholz" autoclave in the regime of hardening of the ENFB binder.

From the moulded shell we removed the layer of glass cloth, ground it by a diamond wheel with underwinding, and faced to size. The quality of the shell was examined by an ultrasonic flaw detector. The



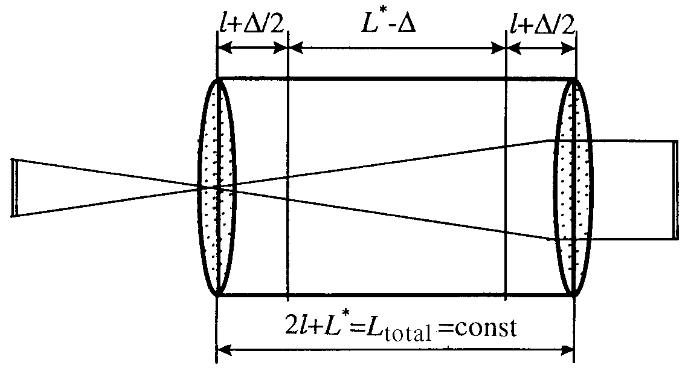


Fig. 2. Structure of a compensative shell.

Fig. 3. Schematic diagram of a compensative element.

longerons were cut from a slab to size on a miller. From the same slab we cut samples for conducting standard tests for verification of the required quality of the material.

The slabs of the flange and the elements of the frame were laid on the working surface of the matrix of a mould. The lower and upper layers of É2-62 glass cloth were laid; then, in accordance with the chosen scheme of reinforcement, two-layer LU-P slopregs were butt-laid with displacement of the butts of each subsequent layer by 50%. The stiffeners were formed by direct compaction of flat slabs with subsequent mechanical finishing.

The primary elements were attached to the shell by an epoxy binder with additional stiffering by UKN carbon filament. The structure as a unit had a weight of 20.6 kg.

The diagram and the principle of operation of a compensative force element is shown schematically in Fig. 3.

In the process of development of thermocompensative and dimensionally stable structures, we have created an "Adapter" system for adaptation of precision structures.

The spread in the characteristics of the fibers, deviation of the reinforcement trajectories from the calculated values, relaxation of the internal residual stresses, and macroinhomogeneities in the distribution of the binder inevitably cause additional displacements of the structure, which can reach critical values. The essence of the "Adapter" system is that a number of operations can be performed on the already produced and measured structure. These operations make it possible to obtain a structure with thermal displacements of any degree of smallness down to the resolving power of measuring devices.

The developments in question have secured a new direction in the last few years — they are related to the first generation of "intellectual" structural materials (reacting to changes in the construction by changing their characteristics in the required direction), which provide the basis for materials of the new century.

NOTATION

P, limiting load; P_j, limiting load in the *jth* number of the fracture mechanism; $M = T \cdot d$, bending moment of the cylinder body; d, diameter of the shell; E_1, elastic modulus along the fibers; E_2, elastic modulus across the fibers; E_3, flexural elastic modulus; ν_{12}, Poisson coefficient; G_{12}, shear modulus; F_1^+, ultimate tensile strength along the fibers; F_1^-, ultimate compression strength of a monolayer along the fibers; F_2^+, ultimate tensile strength across the fibers; F_2^-, ultimate compression strength across the fibers; F_{12}, shear strength; F_3, ultimate bending strength; α_1, CLTE along the fibers; α_2, CLTE across the fibers; h_i, thickness of the layer of the shell; φ_i, angle of reinforcement of the ith layer of the shell; n_x and n_y, number of layers of ribs along the x and y axes, respectively; h_i, height of a rib; B_i, width of a rib; B_{xx}, membrane stiffness; D_{ss}, flexural stiffness; g_{xx} and g_{ss}, coefficients of the stiffness matrix of the layer written in the coordinates of the structure; g_{11}, g_{22}, and g_{12}, coefficients of the stiffness matrix along the axes of the stack; $\hat{h}_i$, reduced thickness of the layer; Z_i, coordinate of the layer; $\hat{g}$, conditional stiffness; EF, stiffness of a rib in axial compression; R, radius; h, thickness of the shell; L, length of the shell; $\sigma^{(0)}$, initial strength; $\varepsilon^{(0)}$, initial deformation; $\gamma_{xy}^{(0)}$, initial shear deformation; ξ_x and ξ_y, load parameter; σ_{xy}, shear strength; m_1 and m_2, number of half-waves along the axis; C, membrane-flexural stiffnesses; β, thermal-stress coefficients; L_t, total length of the structure; L^*, length of the compensative element included in the structure; λ, length of a rib; l, length of the structural elements subjected to thermal elongation; Δ, thermal elongation of structural elements. Subscripts: x, coordinate along the axis of the shell and the rib; y, coordinate in the circle of the shell and a rib; (i) i, number of the layer; j, number of the fracture mechanism; ss, coefficient at the coefficient of flexural stiffness along the axes of the structure; xx and yy, coefficients at the coefficient of membrane stiffness along the axes of the structure; 11, along the axis of the stack; 22, across the axis of the stack; 12 and 21, shear in the plane of the stack; (k), number of the calculation of the loading scheme.

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