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ADAPTIVE SELECTIVELY-DEFORMABLE STRUCTURES; NEW CONCEPT IN ENGINEERING

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A new class of machine and engineering construction components - Adaptive Selectively - Deformable Structures (ASDS) -has been developed, with their main specific feature to be easily deformed in one "useful" direction while keeping rigidity in others thus providing assigned structure shape under external operational loads. The ASDS has been originated from the concept of active structural flexibility utilization and can be widely implemented in aerospace industry, in "smart" structures in particular, in terrestrial transport and water-carriage, in building constructions, medical and home appliances, damping devices of various functions. The main formula relations for designing techniques for an elementary cell as a major part of ASDSs are presented. The need to correct analysis, including FEM, is proven on the base of experimental measuruements. Presented as an example, with description of research techniques used, are stiffness, load carrying and fartigue properties of an Elastomeric Armoured Panel EAP as a part of an adaptive wing structure to close the gap between wing and an aileron.
For more complex ASDS as a rule it is necessary to use multydisciplinary methods of investigations.

Adaptive Selectively-Deformable Structures represent an ultimately new class of components for machinery and building constructions, with the ability of ASDSs to be easily deformed in one "useful" direction while keeping rigidity in others thus providing control and sustaining of variable assigned structure shape under external loads applied.

The main component of an ASDS is a load-carrying cell of variable geometry, the cell comprising thin-wall reinforced (as a rule) rigid central and peripheral elements as well as elastic deformable supporting ones. Special arrangement of the elements within the cell result in cell's negligible compression/tension stiffness whereas bending, torsion and shear stiffness remain at assigned finite levels. Combined into chains, the cells can form internal adaptive framework of any structure. Depending on a certain application, the framework can be filled (or not) with an elastomeric material. The filling may be necessary to get smooth and continuous impenetrable load-carrying surface, e.g. for aerodynamic applications.

The areas of ASDSs' usage are as follows:
- aerospace industry;
- ships;
- railway, automobile and pipeline transportation;
- building and road engineering;
- furniture;
- home and medical appliances.

ASDSs can be used for smooth continuous attachment between adjacent rigid structural segments, e.g. sections of an aircraft adaptive wing, railway carriages, sections of bridges and floating platforms. When used in sections of gas and oil pipelines to provide freedom of thermal deformations, they allow any U-type expansion bends to be avoided. All the above implementations result in reduction of aerodynamic drag and pressure drops thus increasing performance and efficiency.

Through ASDSs's usage, various capabilities in multiple areas can emerge, e.g. in smart materials and structures developing, in creation of aerospace vehicles and other structures for which shape control may be well required, i.e. antennas, conveyer belts, adjustable wind tunnel and jet nozzles, transformable formwork for concreting, single-degree-of-freedom springs, various sport/health recovering training simulators and medical facilities, as well as shock/vibration absorbers.

The start of the work has been motivated with the evolution of a new (proposed by the author at early 60-th) concept of aircraft design based on airframe flexibility utilization, as opposite to the traditional approach. The last meant that some problems of aeroelasticity, aileron reversal in particular, were usually solved only by total structural stiffness augmentation, naturally accompanied

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with total mass increase. A range of new aircraft controls was proposed by the author to realise the new concept and take advantages of structural flexibility, the controls efficiency being increased with wing stiffness reduction.

Structural flexibility was also utilized in the direct predecessor of an ASDS - an adaptive wing(1), which was the first design to feature a so-called Elastomeric Armoured Panel (EAP), expandable in mid-surface but capable of carrying normal-to-panel loads.

A more simple and reliable structure with much more capabilities of attaining minimum in-plane compression/tension stiffness (even with elastomeric filling) alongside with required bending/shear stiffness of a panel was proposed in (2), (3). A version of a cell with possibility of forced mutual displacements of cell central elements was also developed to open new prospects of "smart" structures(3).

To consider an example of employing ASDS, here is an element of an adaptive wing. Its main specific feature is that airfoil shape is formed with Elastomeric Armoured Panel. And this is an elementary cell which is in the heart of all ASDS- and EAP-based structures. The ability to compute true strength and stiffness properties of a cell is the necessary condition of literate design of any structures assembled of multiple cells.

To prove analysis methods developed, analytical results were compared with stiffness measurements - both for separate cell (fig.1) and a chain of cells forming a panel.

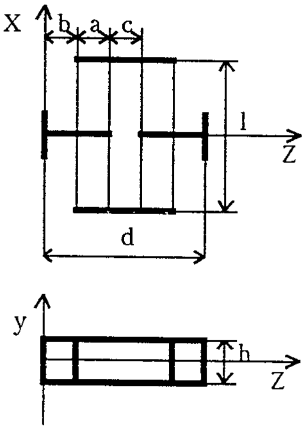

Fig.1. Load-carrying cell of variable geometry - the main component of an Adaptive Selectively-Deformable Structures (ASDS).

The cells were made of composite orthotropic material with Young's modulus E=11 kN/mm^2; the cell dimensions with respect to its length d=25 mm are as follows:
$a/d = 0.2$, $b/d = 0.2$, $c/d = 0.2$, $l/d = 2$, $h/d = 0.4$, $\delta/d = 0.014$, $\delta_l/d = 0.04$, fig. 1. One of the cell's or panel's end was rigidly clamped whilst forces or moments were applied to another free one. Equivalent beam or set of beams were associated with the cell (panel), the equivalence being in the same linear and angular free end deflections both for the cell and the beam under the same loads and the same beam/cell length d (D).

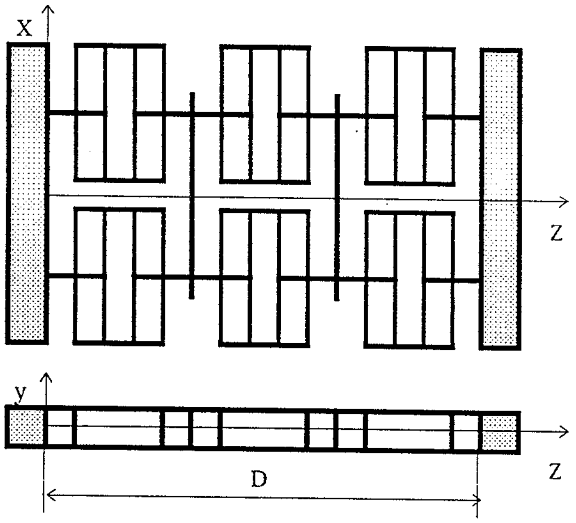

Fig.2. A chain of cells forming Elastomeric Armoured Panel (EAP) as a variant of Adaptive Selectively-Deformable Structures (ASDS).

Equivalent tension/compression ES, bending EIx, EIy, and torsional GIp stiffness of a cell (panel) were determined through known beam-applicable relationships between:

- linear displacement **u** along **Z**-axis under force **Fz** applied in the same direction
- linear displacement **v** along **X** axis under force **Fx**
- linear displacement **w** along **y** axis under force **Fy**
- angular deflections θ**x**, θ**y**, θ**z** about **X**-, **Y**-, **Z**-axes under moments **Mx**, **My**, **Mz** respectively.

Two different linear methods were used in analysis. The first is a simplified one based on known formulas of the theory of elasticity (4), the formulas defining stain/stress state within a cell under various forces and moments.

The second method is based on Finite Element Method - FEM analysis(5), with modelling of a cell as a set of intersecting beams and plates.

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It so appeared that this was only tension/compression stiffness that could exhibit rather good agreement between experimental and analytical values. This is explained by the fact that other types stiffness depends to a great extent on a cell thin supporting elements buckling which is not taken into account in linear methods. According to experiments, buckling onset takes place just under small loads, but with keeping linear relationship between elastic deformations and loads under further loads increase after buckling onset (fig.3).

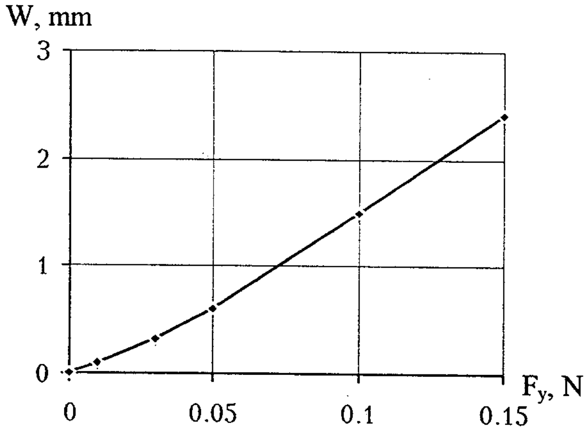


Fig.3. Linear displacement of the free end of a cell rigidly clampered at the other end under force applied to the free end.

The estimations of critical buckling compression stresses in supporting elements under in-plane panel bending $\sigma_{cr}^{bc} = 4\pi^2 E\delta^2 / 3l^2$, as well as of lateral buckling critical stresses

$$\sigma_{cr}^{bl} = 2.623(\delta^2 / hl)E\sqrt{1 - 0.630(\delta / h)}$$

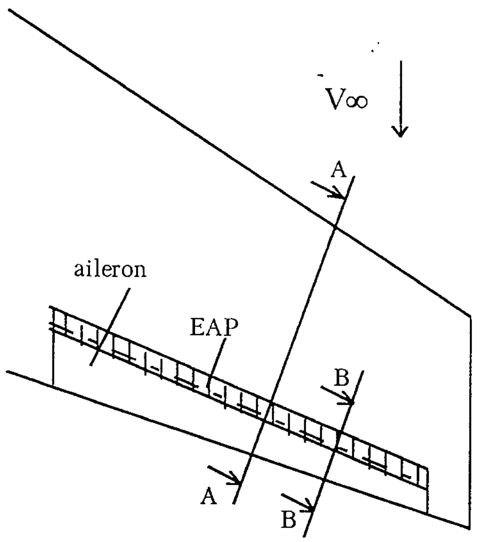
showed that critical stresses were below the maximum values attained in these cell loading cases. So it could be expected, and this was confirmed in experiment that to get better agreement between measured and calculated stiffness values would need some precautions against supporting elements buckling in experiment. One of possible precautions is to fill the structure with elastomeric material. According to experiment, this results in essential reduction of panel elastic deformations thus making experiment/analysis agreement much more satisfactory.

The other, NASTRAN-based FEM analysis of the cell with accounting of geometric nonlinearity produced the cell bending stiffness EIx (under moderate bending moment) three times less than that determined through formulas, and this FEM result is in good agreement with measurements. Such an FEM / formula-based results discrepancy is attributed to supporting elements buckling under the cell bending. When at pure bending under moderate loads, the formula-based model gives overestimated values of the cell stiffness, while normal stresses are close to each other for both models. As for pure tension, both models give close results for both stiffness and normal stresses. To return back to bending, cells those under tension exhibit greater stiffness than compressed ones, but bending stresses are higher for compressed cells.

The ultimate FEM-determined load-bearing capacity of the cell framework is essentially less than that given by linear method. Besides, it decreases by step due to buckling onset in any supporting element. In practice however, essential increase of deformations (and stresses) in a cell framework will be restricted by means of elastomeric material increasing cell's load-bearing capacity - the fact also proved by experiment.

As an example of applying these methods to cells and ASDSs, let us consider the sequence of design procedures and proving calculations for an element of an adaptive wing, i.e. EAP connecting a wing box with an aileron leading edge at lower side. Assume that uniform pressure $p = 2.34$ kN/m^2 is applied to the lower panel in up direction.

The pattern of panel deformation depends on deflections of the panel tip cross-section which in turn depends on location of aileron hinge axis with respect to the tip cross-section (distance f at fig. 4).



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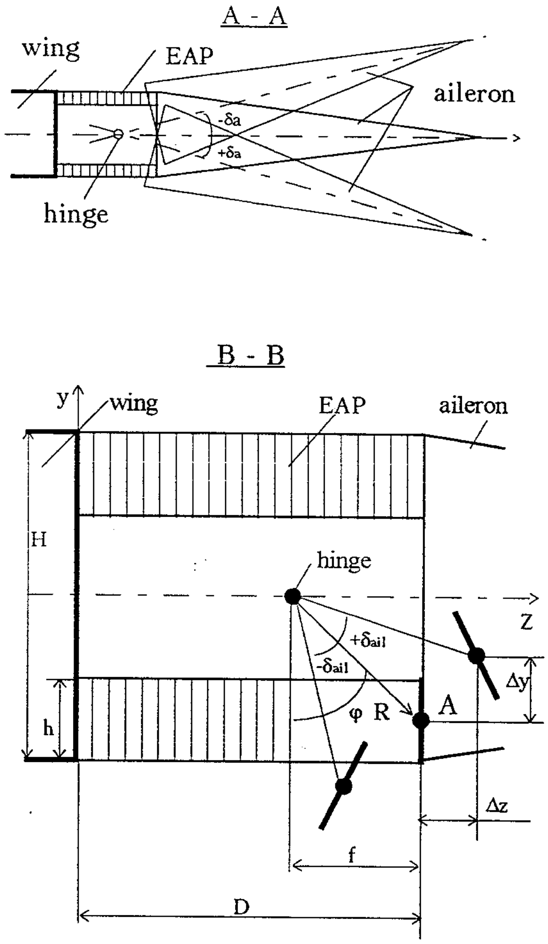

Fig.4. Element of an adaptive wing - Elastomeric Armoured Panel (EAP) as variant of ASDS - connecting a wing box with an aileron leading edge at lower and upper sides.

Δy due to aileron deflection by an angle δa are determined from relations:

$$R=\sqrt{\left(\frac{H-h}{2}\right)^2+f^2},\quad \varphi=\arcsin(f/R),$$
$$\Delta z=R\sin(\delta_a+\varphi)-f, \qquad (1)$$
$$\Delta y=(H-h)/2-R\cos(\delta_a+\varphi)$$

According to the formula-based model [(4)], a cell is characterized by compression/tension ES, as well as bending stiffness in two planes EIx, EIy depending on the cell parameters:

$$ES=\frac{16Edh\delta^3}{l^3},$$
$$EIx=\frac{Edh^3}{(12d/\delta_1)+(l^3/4a^2\delta)}, \qquad (2)$$
$$EIy=\frac{Edh}{(12d/\delta_1^3)+(l/a^2\delta)}$$

Each cell exhibits the same strain $\varepsilon = \Delta z/D$ as the whole panel do, and a force acting on a cell supporting element is directed along Z axis. Maximum stresses occur in surface layer of a supporting element where it is attached to central and peripheral elements:

$$\sigma_y=\frac{12Ed\delta(\Delta z/D)}{l^2} \qquad (3)$$

Since the panels are bent under Mx moment alongside with tension, bending stresses occur in cell supporting elements due to Y-directed concentrated force. These stresses are maximum at the points of attachment of a supporting element to central and peripheral ones:

$$\sigma_b=\frac{3Eldh}{4Ra\delta}\,\frac{1}{(12d/\delta_1+l^3/4a^2\delta)} \qquad (4)$$

The external load Pb is uniformly distributed over all cells thus producing stresses in supporting elements due to bending caused by Pb loading.

$$\sigma_p=\frac{3P_bDl^2}{32h^2\delta La} \qquad (5)$$

The maximum arc deflection of the chain of cells in its centre with aileron non-deflected (δa) is determined as:

$$W_{max}=\frac{P_bD^3l}{192L\dfrac{Edh^3}{(12d/\delta_1)+(l^3/4a^2\delta)}} \qquad (6)$$

To estimate framework durability let us consider the stress/number of cycles up to failure relation in a form of a power law:

$$N=N_0(\sigma_0/\sigma_{-1})^k \qquad (7)$$

where N_0 is a base number of cycles,

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σ_0 is a fatigue limit for a base number of cycles,
σ_{-1} is a symmetric cyclic stress value to cause failure after N cycles.
For non-symmetric cycles equivalent stress value is taken via Oding's formula:

$$\sigma_{-1eq} = \sqrt{\sigma_a\left(\sigma_m + \sigma_a\right)}\ , \qquad (8)$$

where $\sigma_a = (\sigma_y + \sigma_b + \sigma_p)/2$ is an amplitude cycle value, σ_m is a mean value; in this particular case $\sigma_m = \sigma_a$.

On assigning cell parameters (dimensions in mm):
a = 5, b = 5, c = 10, d = 30, δ_1 = 1.0, δ = 0.2
E=210 kN/mm^2, fatigue limit σ_W = 380 N/sm^2,
one can get cell dimensions l and h from (3) and (6) providing $\sigma_y = \sigma_W$ and Wmax = 1.0 mm.

For such a cell the minimum summed up stress $\sigma_\Sigma = \sigma_y + \sigma_b + \sigma_p$ is realized at l=120 mm. In this case the cell height h=25 mm meets required condition for Wmax under applied loading, but summed up stress σ_Σ= 3706N/mm^2 is high, so:
- for number of cells in a chain n= 5, number of chains in a panel m=45, number of cycles up to fatigue failure, according to (8), (9) will be N=9.73$*10^5$.

On attenuating the limitation for W max, the summed up stress versus further increase of a cell parameter, l, can be determined (fig.5) :

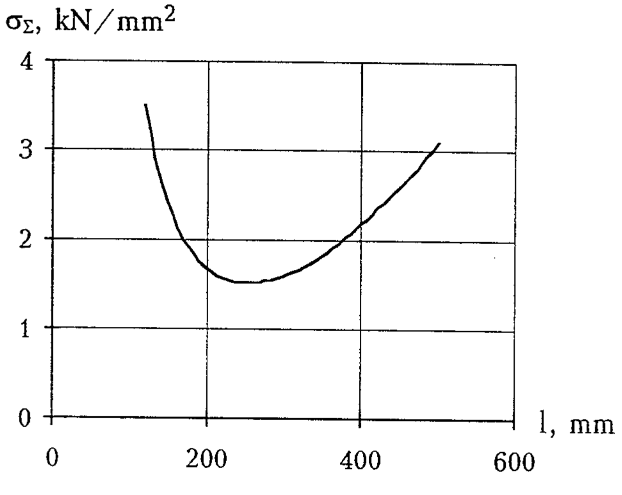

Fig.5. Summed up stress in surface layer of cell supporting elements versus length of supporting elements or versus cell width.

Minimum stress value is achieved at l=250 mm. Taking this as a cell parameter, one can get dependences σ_Σ=f(h) and W_{max}=f(h) , fig. 6, 7 for different thickness of a supporting element:

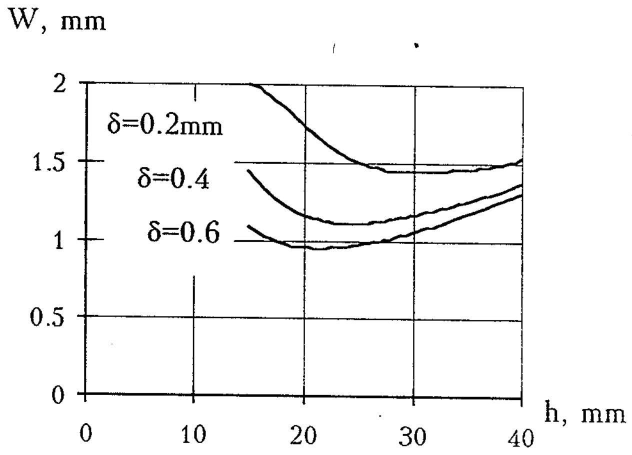

Fig 6. Summed up stress versus cell hight for different thickness of supporting elements.

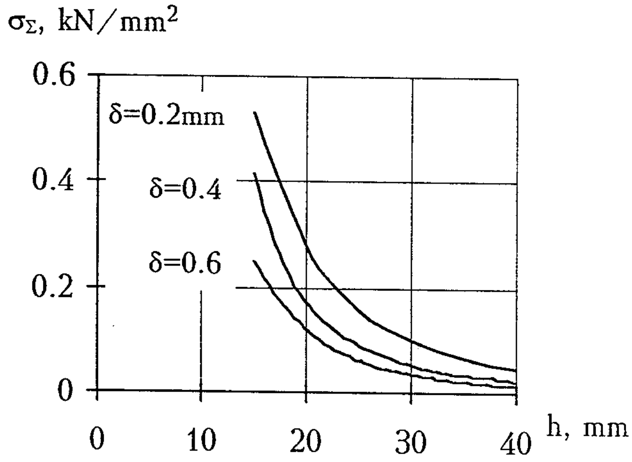

Fig 7. Deflection of the chain of cells in the chain center in case of non-deflected aileron versus cell hight for different thickness of supporting elements.

Now let us assume the following cell parameters: l=250 mm, h=25 mm, δ=0.6 mm. For them, σ_Σ=1097 N/mm^2. Number of cells in a chain is n=5, number of chains in a panel m=22. Number of cycles up to fatigue failure, according to (8), (9) N=2.78$*10^8$. A cell weight is Gc=1.29 N, a chain weight is Gch=6.44 N, a panel weight is Gp= 142 N.

For more precise analysis of stress/strain state of the designed chain of cells of the panel framework, the FEM was used. To get strain/stress state, a chain was clamped at

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the left end, at the first central element of the first cell, while necessary deflections Δz, Δy, and θx=δa were assigned at the right end (central element of the 5th cell, point A (fig.4). Concentrated forces Fy were applied to node points through sharing uniformly distributed load among cells and cell node points:

$$F_y = \frac{P_b}{nmk} = 0.923N,$$

where k=140 is a number of load carrying points in computational scheme of a chain.

Linear deflection of EAP lower surface W and here angular deformation along aileron chord for positive and negative angles of aileron deflections are shown on fig. 8 and 9.

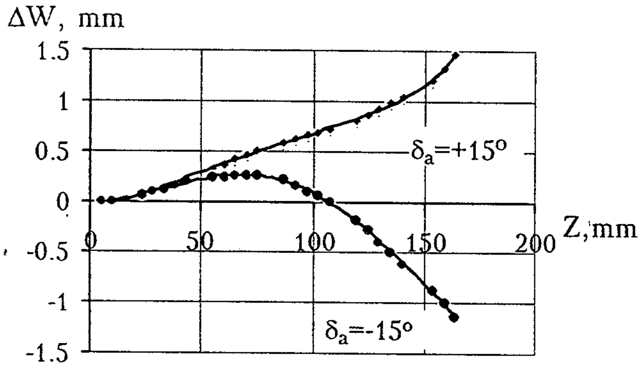

Fig.8. Linear deflection of EAP lower surface along aileron chord for positive and negative angles of aileron deflectionю.

Linear deflection of EAP lower surface ΔW and here angular deformation $\Delta\theta_x$ along aileron chord for positive and negative angles of aileron deflectionю are shown on fig. 8 and 9.

Analysis showed that for the loading case considered and aileron deflection δa=± 15°, the maximum calculated stresses σ_c obtained with the aid of the theory of maximum potential energy of shape variation (energetic strength theory) are equal to σ_c=260N/mm^2 and does not exceed allowable ultimate stresses.

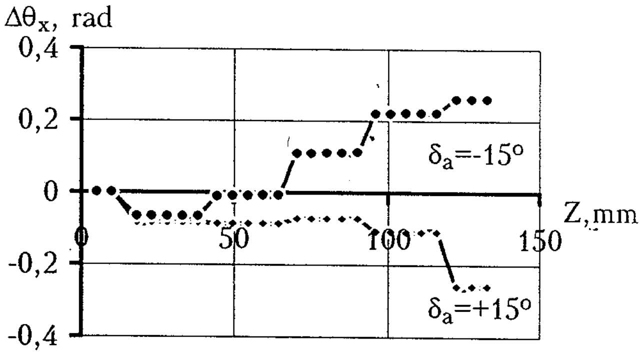

Fig. 9. Angular deformation of EAP lower surface along aileron chord for positive and negative angles of aileron deflections.

Discussed simple examples give opportunity to understand the main essentialities of separate elementary cells and a chain of cells that forms Elastomeric Armoured Panel - EAP as variant of Adaptive Selectively Deformable Structures - ASDS. These examples also indicate some methods of their design and research. For more complex cases as a rule it is necessary to use multydisciplinary methods of investigations - for achieving necessary characteristics of stiffness, damping, load carrying and fatigue of Adaptive Selectively Deformable Structures.

REFERENCES

1. G. Amiryants. Adaptive Wing. Patent of Russia N 1762488, 1990.

2. G. Amiryants. Elastomeric Armoured Panel. Patent of Russia, 1993.

3. G. Amiryants, S. Vatchyants. Elastomeric Adaptive Panel and Its Cell. PCT RU 96/00246, 1996.

4. G. Amiryants, S. Vatchyants, S. Efimenko, O.S.Mamedov, V. Tokar. Elastomeric Armoured Panel and its Cells. Scientific/technical Proceedings of the Ministry of Military Industry, 1997. (Russian Edition).

5. S. Efimenko. FEM application to computing of wing elastic properties (Russian Edition). (TsAGI Proceedings - Trudy TsAGI, issue 1753, 1976.)