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ANALYSIS OF THE BEARING CAPACITY OF AN ADHESIVE CONNECTION BETWEEN A CELLULAR FILLER AND SHEATHING AT THE ADDRESSED APPLICATION OF THE ADHESIVE ONTO THE ENDS OF HONEYCOMBS

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Reducing the surface mass of an adhesive is one of the most important means to improve the perfection of cellular structures. One of the promising technologies in this respect is the addressed application of the adhesive on the ends of the cells. This technology excludes the passive mass of the glue that fills the intercellular surface, which is not involved in ensuring the bearing capability of the adhesive connection. However, a decrease in the glue application leads to a decrease in the bearing capability of a product. Therefore, reliable estimation methods are required to determine the bearing capability of such structures under the conditions of detaching the sheathing prior to experimental test.

This work determines a mechanism of destruction of cellular structures under transversal loading depending on their parameters and factors of the technological process of addresses gluing. We have devised a method to analyze the bearing capability of the adhesive connection between a cellular filler and the carrying sheathing at the addressed glue application on the ends of the honeycombs. The method makes it possible to predict the character of their destruction depending on the relative depth of the penetration of the flange facets of a cellular filler into the melt adhesive. A modified mathematical model of the adhesive fillet has been synthesized, which takes into consideration the heterogeneity of glued materials and the existence of a gap between the ends of the facets of honeycombs and the bearing sheathing. A finite element method was used to obtain a rather complicated character of stress distribution in the zone of an adhesive fillet cross-section. We have drawn a practical conclusion that it is necessary to glue the sandwich structures of the examined type at a temperature and pressure that ensure the relative depth of the penetration of honeycombs' ends into the adhesive exceeding 50 %. Such technological parameters at the modern level of production of cellular products would help increase their weight perfection and achieve a certain economy of energy resources, used in the process of assembling-gluing the structures of the examined type

Keywords: sandwich structures, cellular filler, bearing capacity, adhesive connection, melt adhesive, addressed application, fillet

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1. Introduction

Sandwich structures with a cellular filler are widely used in the assemblies of different classes of equipment [1–3]. They possess a series of undeniable advantages among other structural and technological solutions, including high bending rigidity, weight perfection, thereby providing for a high level of thermal dimensional stability under a temperature effect [4–6].

The high performance properties of cellular structures are largely dependent on the technological methods that ensure the desired level and stability of the strength properties of the components of these structures – a cellular filler, the bearing sheathing, and their adhesive connections [7–9].

An analysis of the experience of gluing load-bearing sheathing with a cellular filler in the manufacture of sandwich structures has shown the wide application of film adhesives, the best samples among which have a surface mass of 120–140 g/m^2 [10, 11]. However, this amount of glue considerably exceeds that which is necessary to ensure durability when detaching the adhesive connection of bearing sheathing with a cellular filler [12, 13].

One of the ways to further reduce the surface mass of cellular structures is the implementation of the technology of the addressed dosed application of a melt adhesive on the ends of the honeycombs (Fig. 1) [14]. This has become the most widespread technology in the production of aircraft and rocket and space equipment structures [15]. For the assemblies of this class of equipment, a significant reduction of their surface mass due to the application of this technology is the determining factor [1, 2].

This technology excludes the passive mass of the adhesive that fills the intercellular surface, which is not involved in ensuring the bearing capability of the adhesive connection [14–16].

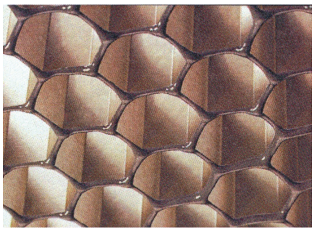

Fig. 1. Fragment of a cellular filler panel with the melt adhesive applied on its ends

To ensure the high-quality adhesive connection, it is necessary to determine and ensure the optimal parameters of the technological process, pressure, temperature [7, 8]. This, in turn, affects the forces of surface tension and, therefore, the process of the formation of adhesive fillets, determining the relative depth of the penetration of the honeycomb facets' edges into the glue and ensure the strength of the adhesive joint [14–16].

Given this, it appears relevant to study the dependence of the bearing capability of the addressed adhesive connection between the bearing sheathing and a cellular filler depending on the parameters of the honeycomb cell, the glue, and the technology of gluing them.

2. Literature review and problem statement

Many authors focus on experimental research when analyzing the effect of gluing technology factors on the bearing capacity of cellular structures [17]. Experimental determination of the bearing capability of adhesive connections of cellular structures in terms of transverse stretching is implied by a series of standards [18]. Paper [19] used various methods to conduct experimental studies of the adhesive connections of cellular structures, which made it possible to obtain the deformations of adhesive layers under different types of loading. Based on the reported results, the authors constructed a procedure for determining an adhesive layer thickness on the basis of experiment.

Work [15] varied the technological parameters of the gluing process to obtain the parameters for the application of a melt adhesive on the ends of honeycombs with different surface mass (Table 1). The strength of the connection between the bearing sheathing and a cellular filler is proposed in the cited work to control experimentally based on the results of testing samples for a uniform detachment.

However, the availability of procedures for the analytical determination of the bearing capability of adhesive connection between the load-bearing sheathing and a cellular filler makes it possible to significantly reduce the cost of development of the examined structural-technological solutions and increase their reliability [7, 8].

There are several approaches to building such procedures. Some authors devise the procedure of calculating the stressed-strained state of cellular structures by considering a package of layers with summarized characteristics. Thus, papers [20, 21] report analytical dependences for determining the stressed-strained state of a cellular structure taking into consideration the work of an adhesive layer based on the variational Lagrange principle. In another case, authors develop analytical models for determining the stressed-strained state of a cellular structure that is modeled by five layers – two load-bearing sheathings, two adhesive layers, and a filler [22]. Although the analysis of the component parts of a cellular structure employs more complex mathematical calculations, the accuracy of calculations is much higher than when applying the summarized characteristics of layers [23]. However, such approaches, while making it possible to analyze the distribution of stresses and deformations separately in the components of cellular structures, could be used only for film adhesives.

Table 1

Properties of the adhesive connection between the bearing sheathing and a cellular filler with the melt adhesive applied on its ends

Cellular filler mark	Cell side size, mm	The mass of glue application on one side, g/m^2	Tensile strength, MPa	Character of destruction
Aluminum foill honeycomb filler	2.5	93	4.145	on honeycombs
	5.0	60	1.91	on honeycombs
Glass cloth honeycomb filler	2.5	68	6.71	on glue
	5.0	52	2.53	on glue
Aramid paper honeycomb filler	2.5	70	2.24	on glue
	5.0	60	1.20	on honeycombs

Modeling the addressed dosed application of a melt adhesive on the discrete ends of honeycombs was tackled in a rather small number of publications. Thus, work [24] first attempted to analytically estimate the mass and carrying capacity of adhesive connection between the sheathing and a cellular filler when applying adhesive to the ends of the honeycombs in comparison with the film glue. However, work [24] considered the adhesive connection between the homogeneous materials of a cellular filler and the bearing sheathing. This allowed the authors to approximate the adhesive fillet only by an arc of the circle. In a general case, when a cellular filler and the load-bearing sheathing are made of dissimilar materials, the adhesive fillet should be approximated by an ellipse arc, shown in work [14].

Papers [14, 15] summarize work [24] and report a procedure to analyze the bearing capability of adhesive connections with the glue applied on the ends of a cellular filler. However, the analytical procedures proposed in [14, 15] are built on the implementation of the approximate mathematical models based on determining the maximum equivalent stresses by Mises σ_{vmax} while applying their averaged components that operate at a normal site of the adhesive fillet of single thickness. The results reported in the cited works do not make it possible to determine the influence exerted on the carrying capacity by the depth of the penetration of the facets of honeycombs' edges into the glue. As a result, the analytical dependences proposed in those works do not account for the main factors of the technological process of gluing.

Studies into the bearing capacity based on the analytical mathematical models in similar connections with a continuous adhesive layer (or film) are reported in papers [25, 26]. The analysis in the cited papers revealed that the use of mean stresses leads to substantial errors toward their under-statement compared to those calculated by a finite element method. In addition, the use of a finite element method allowed the authors to identify the influence of the depth of the penetration of the flange facets of a cellular filler into the adhesive layer on the bearing capacity of the connection. That allowed them to investigate the possibility of a certain economy of energy resources, used in the process of assembling-gluing structures of the examined type.

One can conclude that up to now the cellular structures have no sufficiently reliable estimation methods to determine their bearing capability at the addressed gluing of honeycombs and the bearing sheathing. The existence of such methods would make it possible to increase the weight perfection of the examined class of structures and obtain the rational parameters for the technological process of gluing.

3. The aim and objectives of the study

The aim of this study is to establish a mechanism of the destruction of cellular structures under transversal loading, depending on their parameters and factors of the technological process of the addressed gluing that determine the level of the penetration of the facets of honeycombs' edges into a melt adhesive.

To achieve the set aim, the following tasks have been solved:

– to develop a method of analysis of the bearing capability of the adhesive connection between a cellular filler and the bearing sheathing at the addressed adhesive application on the ends of the honeycombs, which would make it possible to forecast the character of their destruction;

– to compare the developed analytical method and a finite element method for the estimation of the bearing capability of cellular structures at the transversal detachment at the different relative depth of the penetration of the flange edges of a cellular filler into a melt adhesive.

4. The study materials and methods

Investigating the bearing capacity of the adhesive connection between a cellular filler and sheathing at the addressed application of an adhesive on the ends of the honeycombs employed the methods and mathematical models from the mechanics of a deformed rigid body in an elastic statement. At the same time, the mathematical models reported in [15, 16] were substantially improved. A finite element method was used to investigate flat deformation in an elastic statement for different sizes of the finite elements. The evidence of the justification of our conclusions is the comparison of results obtained on the basis of the developed analytical mathematical models and finite-element modeling, conducted for the entire range of relative depths of the penetration of the ends of honeycombs into a glue.

5. A procedure for the analysis of the bearing capacity of the adhesive connection between honeycombs and the bearing sheathing

Gluing the bearing sheathing and a cellular filler is accompanied by a local overflow of the glue when reaching a certain temperature. Local adhesive fillets (Fig. 2) [7, 8] are formed near the walls of a cell of the honeycomb. The formation of these fillets is due to the surface tension of the glue, after its transition to a liquid state, and to the displacement (lifting), which is based on the phenomenon of its wetting the bearing sheathing and a cellular filler [11, 15, 26].

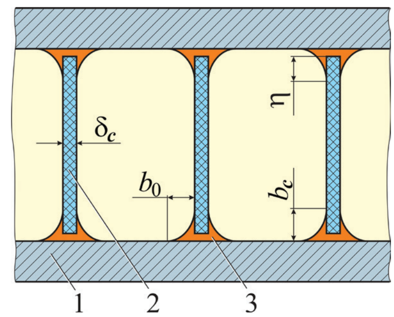

Fig. 2. Connecting a cellular filler to the sheathing of a sandwich structure using a glue applied on the ends of the honeycomb: 1 — sheathing, 2 — facets of honeycombs, 3 — melt adhesive

Underlying our calculation is a typical element of a honeycomb block. We have used an element of the honeycomb block in a general case with a hexagon cell of irregular shape (Fig. 3) [10].

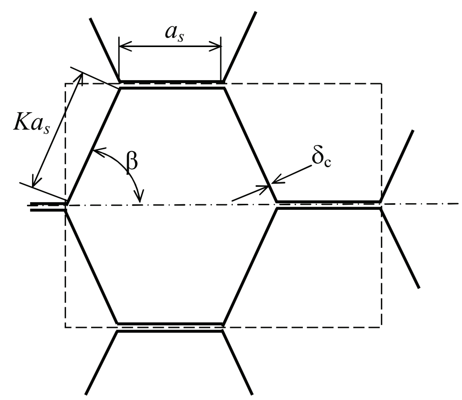

Fig. 3. The typical element of a honeycomb block with a cell of the irregular hexagonal shape

We shall assume that the internal excess pressure p_{int} is the root cause of the normal and tangent stresses in the region of the adhesive connection [14, 15]. This pressure acts at the site of a cell block (Fig. 3):

$$F_{cb} = 4a_s^2 K\left(K\cos\beta + 1\right)\sin\beta. \qquad (1)$$

At the ends of the honeycombs, there is the force of internal pressure P_{cb} (or suction):

$$P_{cb} = F_{cb} p_{int}. \qquad (2)$$

Under the action of force P_{cb}, there are stresses σ_c in the faces of a cellular filler

$$\sigma_c = \frac{P_{cb}}{\delta_c l_\eta} = \frac{F_{cb} p_{int}}{\delta_c l_\eta}, \qquad (3)$$

where l_η is the perimeter of a glue seam within the honeycomb block, which are equal to

$$l_\eta = 4a_s(K+1). \quad (4)$$

Taking into consideration (1), (2) and (4), the stresses in the material of a cellular filler

$$\sigma_c = \frac{p_{int} a_s K(K\cos\beta+1)\sin\beta}{(K+1)\delta_c}. \quad (5)$$

The threshold pressure value $p_{\underset{\lim}{int}}$ of a honeycomb block corresponds to the tensile strength of the cellular filler's material at stretching (σ_{bc}); it is expressed by the following dependence

$$p_{\underset{\lim}{int}} = \frac{\sigma_{bc}\delta_c(K+1)}{a_s K(K\cos\beta+1)\sin\beta}. \quad (6)$$

We have adopted the modified mathematical model of an adhesive fillet that takes into consideration the heterogeneity of glued materials. This forms different adhesive catheti on the bearing sheathing and honeycombs, which are equal to the half-axes of an elliptical surface formed during gluing [25, 26]. Then the volume of the adhesive on the unit width of the facet of a honeycomb edge at the time of gluing a filler and the sheathing, while remaining constant, would acquire, in a general case, the shape shown in Fig. 4.

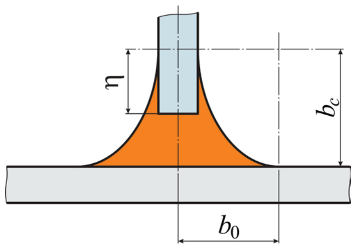

Fig. 4. An adhesive fillet in the connection between the honeycombs and sheathing made from different materials: b_c – an adhesive cathetus at the boundary of the honeycombs' edge; b_0 – an adhesive cathetus at the boundary of sheathing

In works [14, 15], the shape of the cross-section of the flow of a glue droplet from the end of the honeycombs on the surface of the sheathing at the time of gluing the connection made from different materials is adopted as a quarter of ellipse, and the ratio of catheti b_0 to b_c equals

$$\frac{b_c}{b_0} = \frac{\sigma_{\eta-s}(T_{st})\cdot\nu(T_{st})\cdot l_0(T_{st})}{\sigma_{\eta-h}(T_{gap})\cdot\nu(T_{gap})\cdot l_{hc}(T_{gap})} = \zeta_{\sigma,\mu}, \quad (7)$$

where $\sigma_{\eta\text{-}h}(T_{gap})$, $\sigma_{\eta\text{-}s}(T_{st})$ is the surface tension of an adhesive at the border "adhesive–honeycombs" at the temperature of the adhesive application on the ends of the honeycombs and at the border "adhesive–sheathing" at the temperature of gluing the connection; $\nu(T_{st})$, $\nu(T_{gap})$ is the adhesive's viscosity at the temperature of gluing the connection and at the temperature of the adhesive application on the ends of the honeycombs; $l_0(T_{st})$, $l_{hc}(T_{gap})$ are the perimeters of wetting a line that limits the surface of the interphases "adhesive–sheathing" at T_{st} and "adhesive–honeycombs" at T_{gap}.

It is rather difficult to define the parameters included in formula (7) experimentally [8, 11, 26]. In addition, other factors that are not reflected by formula (7) may affect the ratio of the adhesive catheti b_c/b_0. Thus, the dimensions of a fillet depend not only on the rheological properties of the glue but also on the technique of forming a cellular structure [11, 27]. For example, the use of an autoclave is, in terms of an increase in the gluing area, less effective than the vacuum forming method (Table 2) [27].

Table 2

Geometric dimensions of an adhesive fillet

Adhesive brand	Vacuum bag		Autoclave	
	b_c, mm	b_0, mm	b_c, mm	b_0, mm
VK-24	1.051	0.75	0.95	0.6
VK-31	0.79	0.68	0.59	0.7
VK-31T	0.64	0.79	0.6	0.69
VK-41	0.51	0.71	0.47	0.67

Therefore, it seems more reliable to experimentally measure, using a microscope, these catheti directly, for the specific glue and the materials of a sheathing and the honeycombs. At the same time, it is necessary to postulate, similarly to the justification of dependence (7) in [25], the constancy of the coefficient of proportionality between the sizes of the catheti and the corresponding parameters of the surface tension, the viscosity of the glue, and the perimeter of wetting $\zeta_{\sigma,\nu}$. This path seems more productive to establish the shape of the cross-section of the flow of a drop, adopted as a quarter of the ellipse.

Since the volume of the adhesive from the moment of its application to the ends of the honeycombs to the final shape formation of the connection remains constant, its value within a typical honeycomb block is

$$V_{\eta h} = 2F_{\eta f}\, l_\eta, \quad (8)$$

where $F_{\eta f}$ is the area of an adhesive fillet (Fig. 4).

The coefficient 2 in formula (8) reflects the fact of applying the adhesive onto two surfaces of the honeycombs' ends.

$$F_{\eta f} = 2\left[\left(b_0 + \frac{\delta_c}{2}\right)b_c - \frac{\pi b_c b_0}{4} - \frac{\delta_c}{2}(b_c - \eta)\right] = 2\left[0.43 b_0 b_c + \frac{\delta_c}{2}(b_c - \eta)\right]. \quad (9)$$

The weight of the glue within a honeycomb block equals

$$m_{\mu h} = V_{\eta h}\rho_\eta = 3.44 a_s \rho_\eta (K+1)\times \times\left[b_c b_0 + 1.16\delta_c(b_c - \eta)\right]\frac{1}{2}, \quad (10)$$

where ρ_η is the density of a glue.

The surface mass of the glue applied on both sides of a cellular filler is expressed by the following ratio

$$\bar{m}_\eta = \frac{m_{\eta h}}{F_{cb}} = \frac{0.86\rho_\eta(K+1)\left[b_c b_0 + 1.16\delta_c(b_c - \eta)\right]}{a_s K(1+K\cos\beta)\sin\beta}. \quad (11)$$

Substituting in (11) the ratio (7) and by solving it relative to the cathetus b_0, we obtain after the transformations:

$$b_0 = 0.58\delta_c \times \times\left\{\sqrt{1 + \frac{3.45}{\zeta_{\sigma,\nu}\delta_c^2}\left[\frac{\bar{m}_\eta a_s K(K\cos\beta+1)\sin\beta}{\rho_\eta(K+1)} + \eta\delta_c\right]} - 1\right\}. \quad (12)$$

Accordingly, b_c equals

$$b_c = 0.58\delta_c\zeta_{\sigma,v}\times$$
$$\times\left\{\sqrt{1+\frac{3.45}{\zeta_{\sigma,v}\delta_c^2}\left[\frac{\bar{m}_\eta a_s K\left(K\cos\beta+1\right)\sin\beta}{\rho_\eta\left(K+1\right)}+\eta\delta_c\right]}-1\right\}. \quad (13)$$

After determining the size of the catheti of the adhesive fillet, before proceeding to determining the stressed state in it and the bearing capacity of the adhesive, it is necessary to determine the width of the cross-sectional area to the right and to the left of the axis of symmetry of the connection *QN*. This occurs in the transition to *QM* when directing the facets of the edges of a cellular filler to the contact with the sheathing, that is, at $\eta\to 0$ (Fig. 5). In this plane, the maximum equivalent stresses act, determined according to the adopted strength theory [28].

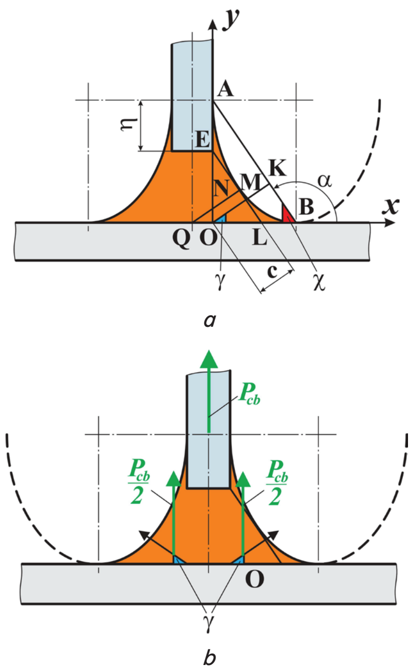

Fig. 5. The geometric parameters of an adhesive fillet: *a* – geometric parameters; *b* – the transfer of force P_{cb} to the fillet plane and its decomposition into components

By adopting the energy theory of strength for a glue, whereby the maximum equivalent stresses σ_v equal $\sqrt{\sigma_\eta^2+3\tau_\eta^2}$, we obtain

$$\sigma_{v\max}=\sqrt{\sigma_\eta^2+3\tau_\eta^2}\le\sigma_{b\eta}, \quad (14)$$

where $\sigma_{b\eta}$ is the tensile strength of the adhesive at stretching.

In other words, it is necessary to determine the inclination angle of the width of site *OM* to the $x\gamma$ axis. At the same time, the angles of mapping the force $P_{cb}/2$ from the full force P_{cb} will yield the components that cause the stresses (Fig. 5)

$$\sigma_\eta=\frac{P_{cb}\cos\gamma}{2c_{\max}l_\eta},\quad \tau_\eta=\frac{P_{cb}\sin\gamma}{2c_{\max}l_\eta}, \quad (15)$$

where $c_{\max}$ is the width of the site of the cross-section of an adhesive fillet where the maximum equivalent stresses act (14).

To this end, one first needs to determine the coordinates of the point *M* in the *xoy* system (Fig. 5).

The equation of an ellipse, whose part forms the fillets of a glue, takes the following form

$$\left(\frac{x-b_0}{b_0}\right)^2+\left(\frac{y-b_c}{b_c}\right)^2-1=0. \quad (16)$$

The equation of the straight line *OK*, which host the point *M* that closes the section *OM* of the width of site *c*, is written in the following form

$$y=x\text{tg}\gamma. \quad (17)$$

By solving jointly equations (16) and (17), we define the coordinates (x_M, y_M) for the point of their intersection *M*.

After a series of transformations, we derive the point *M* coordinates

$$x_M=\frac{b_0b_c}{b_c^2+b_0^2\text{tg}^2\gamma}\left(b_c+b_0\text{tg}\gamma-\sqrt{2b_0b_c\text{tg}\gamma}\right);$$

$$y_M=\frac{b_0b_c\text{tg}\gamma}{b_c^2+b_0^2\text{tg}^2\gamma}\left(b_c+b_0\text{tg}\gamma-\sqrt{2b_0b_c\text{tg}\gamma}\right). \quad (18)$$

The length of the section *OM* is then determined from

$$OM=c=\sqrt{x_M^2+y_M^2}=$$
$$=\frac{b_0b_c}{b_c^2+b_0^2tg^2\gamma}\sqrt{\left[\left(b_c+b_0\text{tg}\gamma\right)-\sqrt{2b_0b_c\text{tg}\gamma}\right]^2\left(1+\text{tg}^2\gamma\right)} \quad (19)$$

or, considering (7),

$$c=\frac{b_0\zeta_{\sigma,v}}{\zeta_{\sigma,v}^2+\text{tg}^2\gamma}\left[\left(\zeta_{\sigma,v}+\text{tg}\gamma\right)-\sqrt{2\zeta_{\sigma,v}\text{tg}\gamma}\right]\sqrt{\left(1+\text{tg}^2\gamma\right)}. \quad (20)$$

To find $c_{\max}$ in a general case, it is necessary to search for a derivative of (20) by γ (or tgγ) and, by equating it to zero, to determine the inclination angle of the width of the site corresponding to the maximum equivalent stress (14) based on components (15).

For the case when the material of the honeycombs and sheathing is the same and the conditions of applying the adhesive onto the ends of the honeycombs and of gluing the connection are identical to the temperature and pressure $b_0=b_c=b$, $\zeta_{\sigma,v}=1$, then

$$c=\frac{b_0}{1+tg^2\gamma}\left[\left(1+tg\gamma\right)-\sqrt{2tg\gamma}\right]\sqrt{\left(1+tg^2\gamma\right)}. \quad (21)$$

Thus, we obtained the dependences to determine the size of a glue fillet, taking into consideration the main factors of the technological process of gluing.

Fig. 6 shows the values of equivalent stresses σ_v with an accuracy to the constant

$$A=\frac{P_{cb}}{2l_\eta b},$$

derived from formula (14) considering (15) and (20).

When continuing to analyze the stressed state in an adhesive fillet using the developed analytical model, one must take into consideration one more feature. In the presence of incomplete immersion of the honeycombs' edges into the glue of the fillet (Fig. 5, *a*) at relative depth η/b_0, strictly speaking, it is necessary to calculate the stresses σ_v at a site not at $c=OM$ but along the segment QN parallel to it (Fig. 5, *a*). The length of this segment equals

$$QN = c + QR = c + \frac{\delta_c}{2}\cos\gamma = c + \frac{\delta_c}{2}\cos\operatorname{arctg}\frac{b_0}{b_c} = = c + \frac{\delta_c b_c \sqrt{b_0^2 + b_c^2}}{2\left(b_0^2 + b_c^2\right)} = c + \frac{\delta_c}{2}\frac{\zeta_{\sigma,\mu}}{\sqrt{\zeta_{\sigma,\mu}^2 + 1}}. \quad (22)$$

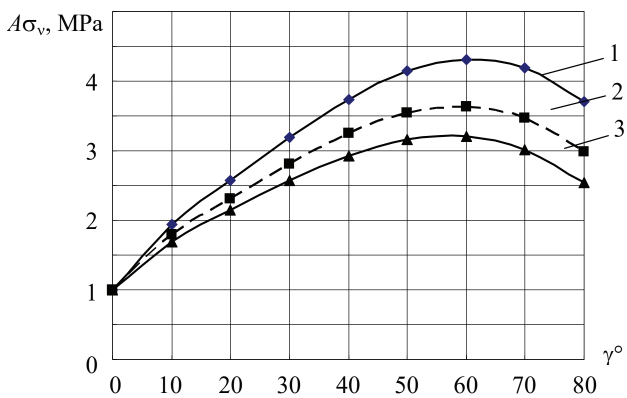

Fig. 6. The dependence of equivalent stress $A\sigma_v$ on the inclination angle of the site of the applied force γ of an adhesive fillet for different ratios of the properties of the materials of honeycombs and sheathing $\zeta_{\sigma,v}$: 1 – $\zeta_{\sigma,v}$=0.75; 2 – $\zeta_{\sigma,v}$=1; 3 – $\zeta_{\sigma,v}$=1.25

It is interesting to note that the increase QR in the length of segment c when changing in the range $0.8 \le \zeta_{\sigma,v} \le 1.25$, characteristic of the parameters that determine almost the entire interval of change $\zeta_{\sigma,v}$, lies within the limits $0.31\delta_c \le QR \le 0.39\delta_c$. Given that the thickness of the metal foil of honeycombs is usually δ_c=0.023...0.1 mm [29, 30] and, for honeycombs made of polymeric paper, δ_c=0.047...0.065 mm [31, 32], this indicates a small error in determining the width of the site of the cross-section of the adhesive fillet compared to *c*. In addition, failure to consider the increase in the width of the site of the cross-section of the fillet, compared to *c*, adds to the margin of an adhesive's strength. In this regard, the analytical calculation of the bearing capacity of an adhesive fillet could be performed based on the width of its site *c*.

6. The finite-element modeling of the adhesive connection between the honeycombs and the bearing sheathing

The main disadvantage of the performed analytical calculation is the approximate character of the mathematical models used in it. The obtained results do not make it possible to estimate the carrying capacity of an adhesive fillet at different relative levels of the penetration of a cellular filler's facets' edges into a melt adhesive η/b_0 (Fig. 4).

Given this, below is an analysis of the possibility of clarification of the bearing capacity of an adhesive fillet at a different relative level of the penetration into it of the facets' edges of a cellular filler using the finite-element mathematical models. These models will determine the maximum equivalent stresses $\sigma_{v\max}$ based on their non-averaged components using a dependence, similar to (14), but considering all the components of the stressed state, similarly to papers [25, 26].

At the same time, there is a well-known dependence of the results from calculating using a finite element method on the choice of the finite elements size, the degree of irregularity in a zone for determining stresses in a specific problem [33]. In this regard, we give as an example, in Table 2, the results of determining the relative maximum stress in an adhesive fillet for two glues (with the elasticity modules of, respectively, E_1=7 GPa and E_2=15.6 GPa), covering almost the entire range of adhesive compositions used in practice [8, 11, 27].

The calculation was performed for the case $\sigma_{v\max}$ for the normal and tangent components of the stresses σ_{yi} and τ_{xyi}, obtained at σ_{hc}=1 MPa. In this case, we investigated the case of the same material for a cellular filler and sheathing $\zeta_{\sigma,v}$=1, and a two-sided application of the glue on the ends of the honeycombs $\overline{m}_\eta = 1.2\cdot10^{-3}$ g/cm^2. We have examined the aluminum foil E_c=70 GPa; σ_{bc}= =50 MPa; δ_c=0.03 mm, of the proper hexagonal shape with a side of a_s= 5 mm [29, 30].

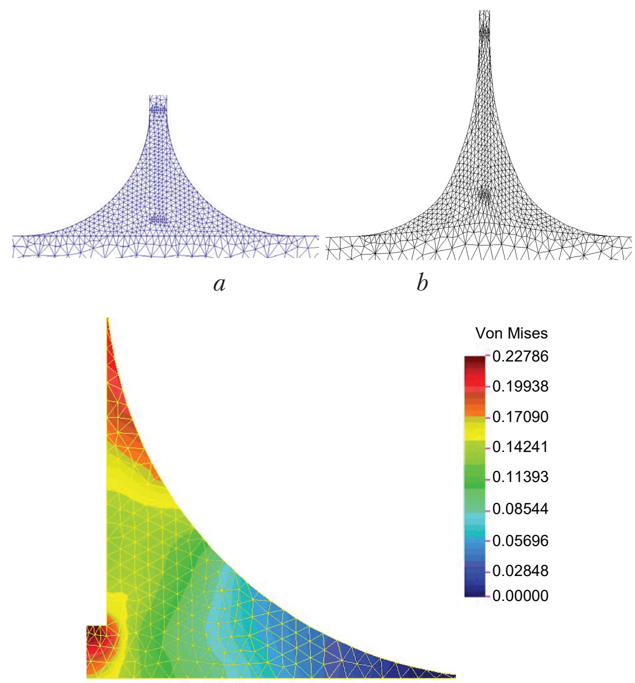

Fig. 7. A pattern of the distribution of deformations and equivalent stresses in an adhesive fillet: *a*, *b* – the distribution of deformations at the different relative depth of the immersion of the edges of the facets of honeycombs into an adhesive fillet; *c* – the pattern of distribution of equivalent stresses

The initial size of the adhesive fillet's cathetus, determined from formulae (11) to (13) at $\overline{\eta} = \eta/b = 1$, was equal to b=0.234 mm. The calculation was performed for three sizes of the tri-nodular finite elements r_{a1}=12 μm, r_{a2}=6 μm, and r_{a3}=3 μm, in order to trace the character and dynamics of change in the results of the calculation for these sizes.

In Table 3, the following designations are used: in rows $\sigma_{v\max} = f(\overline{\eta})$ for E_η=15.6 GPa, the column numerators are the values of stresses $\sigma_v(r_a)$; the column denominators are the number of finite elements when modeling an adhesive fillet in the corresponding mathematical model.

Table 3

The dependence $\sigma_{\text{vmax}} = f(\bar{\eta})$ for an adhesive fillet on the degree of the penetration of the edges of the facets of honeycombs into the glue

b_0	0.205	0.210	0.219	0.229	0.234	E_η, GPa
$\bar{\eta}$	0.131	0.285	0.589	0.869	1.0	
$\sigma_v(r_{a1})$	$\underline{0.654}$ 1322	$\underline{0.476}$ 1278	$\underline{0.281}$ 1212	$\underline{0.224}$ 1170	$\underline{0.202}$ 1446	15.6
$\sigma_v(r_{a2})$	$\underline{0.738}$ 5236	$\underline{0.519}$ 4864	$\underline{0.305}$ 4744	$\underline{0.228}$ 4630	$\underline{0.206}$ 580 6	
$\sigma_v(r_{a3})$	$\underline{0.765}$ 20472	$\underline{0.581}$ 19926	$\underline{0.335}$ 18820	$\underline{0.243}$ 18426	$\underline{0.240}$ 23088	
$\sigma_v(r_{a1})$	0.640	0.478	0.285	0.238	0.098	7.0
$\sigma_v(r_{a2})$	0.745	0.507	0.328	0.255	0.137	
$\sigma_v(r_{a3})$	0.783	0.604	0.368	0.284	0.210	

Fig. 8 demonstrates an example of the dependence, which is obtained by processing the columns of stresses σ_v from Table 3 for different sizes of the finite elements that correspond to $\bar{\eta}=0.131$ and $b_0=0.205$. It follows that at $r_a \to 0$, the stresses $\sigma_v=0.782$, which can be considered as an "absolutely accurate" value at the given size of the adhesive fillet

$$\sigma_v = -0.0006 r_a^2 - 0.004 r_a + 0.782. \qquad (23)$$

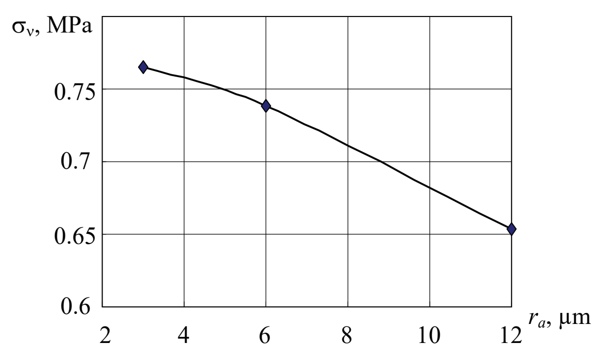

Fig. 8. The dependence $\sigma_v = f(\bar{\eta})$ for an adhesive fillet with parameters: E_η=15.6 GPa; $\bar{\eta}=0.131$; b_0=0.205 mm (example)

Given the diagram in Fig. 8, it is possible to make a qualitative conclusion that for the problems of the examined class at a predefined accuracy of the result, for example, 5 %, it is necessary to choose the size of a finite element based on the relative error

$$\frac{0.782-\sigma_v(r_a)}{0.782}\cdot 100\ \% = 5\ \%,$$

that is, $\sigma_v(r_a)$=0.746 and r_a=5 μm.

To compare the calculation results when using a finite element method with the developed analytical mathematical model based on the average components of stresses for the case $\zeta_{\sigma,\mu}$=1; δ_c=5 mm; K=1; β=60°, we determined the maximum equivalent stresses σ^a_{vmax} at a site at angle γ=60° at the stress in a foil of σ_{hc}=1 MPa. The site width, determined from formula (20), was $c_{60}=0.435 b_0$. The results of the calculations are given in Table 4 and shown by the diagram in Fig. 9.

Table 4

Comparison of the results of calculating the maximum equivalent stresses in an adhesive fillet by a finite element method and based on the analytical mathematical model

$\bar{\eta}$		0.131	0.285	0.589	0.869	1.0
b_0, mm		0.205	0.210	0.289	0.229	0.234
$\sigma^{FEM}_{\text{vmax}}$, MPa	E_h=7 GPa	0.811	0.756	0.420	0.327	0.319
	E_h=15.6 GPA	0.782	0.670	0.380	0.267	0.295
σ^{a}_{vmax}, MPa		0.530	0.520	0.495	0.470	0.460

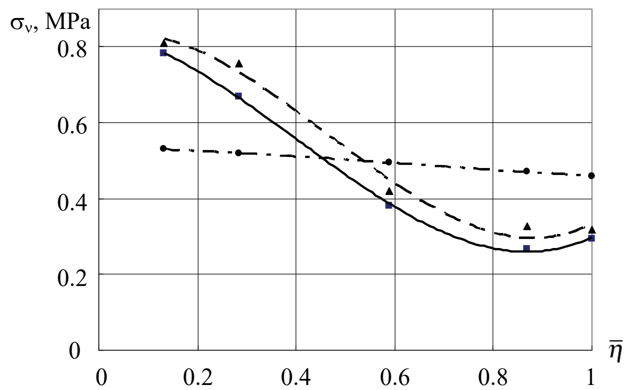

Fig. 9. The dependence $\sigma_v = f(\bar{\eta})$ for different adhesives at $r_a \to 0$: ———— – E_η=15.6 GPa; — — — – E_η=7 GPa (a finite-element model); — · — · – analytical model

Thus, a rather complex character of the stress distribution in the zone of the cross-section of an adhesive fillet (Fig. 7) demonstrates the high degree of closeness between determining the stresses σ_{vmax} based on their average components (14), which operate at a normal site $c_{\max}$.

7. Discussion of results of comparing the developed analytical method and a finite element method

We have established the mechanism of destruction of honeycomb structures under transversal loading depending on their parameters and factors of the technological process of gluing. To this end, a new method has been developed to analyze the bearing capacity of the adhesive connection between a cellular filler and the bearing sheathing. In contrast to papers [22, 23], which investigate the bearing capacity of the film adhesive connection, our study has examined the bearing capacity of the adhesive connection between a cellular filler and the bearing sheathing at the addressed glue application on the ends of the honeycombs.

When modeling, in contrast to papers [15, 24], we have used an element of the honeycomb block in a general case with a hexagon-faceted cell of irregular shape (Fig. 3), which corresponds to more correct operating conditions of a honeycomb block. In [15, 24], a typical honeycomb block element is selected in a slightly simplified manner. At the same time, unlike works [14, 15, 25, 26], we have adopted the modified mathematical model of an adhesive fillet that takes into consideration the heterogeneity of the glued materials and the existence of a gap between the ends of the facets of honeycombs and the bearing sheathing. This allowed us to form different adhesive catheti on the bearing sheathing and honeycombs and to derive the adjusted dependences to determine the size of a glue fillet, which, in contrast to [14, 15, 25, 26], take into consideration the main factors of the technological gluing process. In this case, the established dependences of the equivalent stresses σ_v on the angle of inclination of the site of the applied force γ of the adhesive fillet were synthesized for different ratios of the properties of the materials for honeycombs and sheathing $\zeta_{\sigma,v}$. Our study has shown that the relative deviation of the value for equivalent stresses σ_v at the inclination angle of the site of the applied force $\gamma=60°$ from this value at $\gamma=50$ is 1.6...2.2 %, and from $\gamma=70°$ – 3.5...6 %. This indicates that the choice of a site for applying a load in the angle range $45°\leq\gamma\leq70°$ will not lead, at $0.75\leq\zeta_{\sigma,v}\leq1.25$, to a noticeable error in determining the maximum equivalent stresses. As shown by Fig. 6, the maximum equivalent stresses σ_v correspond to the inclination angle of the site $\gamma=60°$, which disagrees with [14, 15], which *a priori* accepted $\gamma=45°$, although in the angle range $50°\leq\gamma\leq75°$ there is a gently sloping maximum relative to the angle $\gamma=60°$.

The effect of the depth of the penetration of the facets' edges of a cellular filler into the glue on the carrying capacity of the connection was studied by a finite element method, similar to papers [25, 26], which consider similar mathematical models as regards the connection with a continuous adhesive layer. We have obtained a rather complex character of the distribution of stresses in the zone of the cross-section of an adhesive fillet (Fig. 7) and established the degree of closeness in determining the stresses $\sigma_{v\max}$ based on their average components (14), which operate at a normal site $c_{\max}$. The results obtained partly confirm the preliminary conclusions from works [14, 15, 25, 26]. Thus, the comparison of the maximum equivalent stresses in the cross-section of an adhesive fillet, derived by the method of finite elements, and those based on the developed analytical mathematical model was performed over the entire interval of the depth of the penetration of the honeycombs' facets ends into the glue. The difference in the relative degree of divergence between the results

$$\Delta\sigma_{v\max}=\frac{\sigma_{v\max}^{FEM}-\sigma_{v\max}^{a}}{\sigma_{v\max}^{FEM}}\cdot100\ \%$$

is 35...32 %, at small penetration values, and, at a full depth of the penetration $\bar{\eta}=1$ is equal to 44...56 % (Fig. 9). Unlike analytical models, we have established a strong sensitivity of the finite element calculation results to the magnitudes of the adhesive elasticity modules.

In addition, the results obtained by a finite element method have shown a significant dependence of the level of the bearing capacity of an adhesive fillet on the depth of the penetration of the ends of a cellular filler into the glue. The relative difference in the bearing capacity at the beginning $(\bar{\eta}=0.131)$ and at the end $(\bar{\eta}=1)$ of this interval is, at various elasticity modules of an adhesive,

$$\Delta\sigma_{v\max}(\bar{\eta})=\frac{\sigma_{v\max}(0.131)-\sigma_{v\max}(1)}{\sigma_{v\max}(0.131)}\cdot100\ \%=60...62\,\%.$$

This result shows that gluing a sandwich structure at the addressed-dosed application of the glue on the ends of a cellular filler should be carried out at the technological parameters that ensure the depth of the penetration of honeycombs' ends in the glue of $\bar{\eta}\geq0.5$. This confirms the prediction by papers [15, 24, 27], obtained on the basis of experimental studies. The technological techniques to implement the obtained rational parameters of the penetration of the honeycombs' ends into the glue could be the permissible level of pressure at formation; the duration of structure formation at an acceptable level of pressure, a minimum viscosity of the adhesive, and a fixed value of the gap between the sheathing and the ends of the honeycombs; the time interval of the formation process over which the temperature reaches the value required for glue polymerization while its viscosity becomes minimal due to the short duration of the interval [7, 8, 15].

However, it should be noted that for more reasonable recommendations, further broad numerical experiments are needed, supported by testing the representative series of the actual samples of connections of the examined type.

8. Conclusions

1. We have proposed a method to analyze the bearing capacity of cellular structures under transversal loading, a special feature of which is the possibility of establishing the mechanism of destruction of the glue connection between a cellular filler and the load-bearing sheathing at the addressed application of glue on the ends of honeycombs. The method makes it possible to predict the character of their destruction depending on the parameters of the cell in a cellular filler, an adhesive layer for the predefined relative depths of the penetration of the ends of the facets of honeycombs into the glue.

2. The developed analytical method and a finite element method were compared in estimating the bearing capacity of cellular structures at transversal detachment for the case of applying the adhesive onto the ends of the facets of a cellular filler. The result has established that the difference in the relative degree of discrepancy in determining the maximum equivalent stresses based on the energy theory of strength does not exceed 35 % at small values of the penetration of honeycombs into the glue, and does not exceed 60 % at the full depth of penetration.

References

1. Nunes, J. P., Silva, J. F. (2016). Sandwiched composites in aerospace engineering. Advanced Composite Materials for Aerospace Engineering, 129–174. doi: https://doi.org/10.1016/b978-0-08-100037-3.00005-5
2. Slyvynskyi, V., Gajdachuk, V. E., Kyrychenko, V. V., Kondratjev, A. V. (2011). Basic parameters' optimization concept for composite nose fairings of launchers. 62nd International Astronautical Congress, IAC 2011. Vol. 9. Cape Town, 5701–5710.
3. Fomin, O., Lovska, A., Kulbovskyi, I., Holub, H., Kozarchuk, I., Kharuta, V. (2019). Determining the dynamic loading on a semi-wagon when fixing it with a viscous coupling to a ferry deck. Eastern-European Journal of Enterprise Technologies, 2 (7 (98)), 6–12. doi: https://doi.org/10.15587/1729-4061.2019.160456

4. Gaidachuk, V. E., Kondratiev, A. V., Chesnokov, A. V. (2017). Changes in the Thermal and Dimensional Stability of the Structure of a Polymer Composite After Carbonization. Mechanics of Composite Materials, 52 (6), 799–806. doi: https://doi.org/10.1007/s11029-017-9631-6
5. Slyvynskyi, V. I., Sanin, A. F., Kharchenko, M. E., Kondratyev, A. V. (2014). Thermally and dimensionally stable structures of carbon-carbon laminated composites for space applications. 65th International Astronautical Congress. Vol. 8. Toronto, Canada, 5739–5751.
6. Fomin, O., Logvinenko, O., Burlutsky, O., Rybin, A. (2018). Scientific Substantiation of Thermal Leveling for Deformations in the Car Structure. International Journal of Engineering & Technology, 7 (4.3), 125. doi: https://doi.org/10.14419/ijet.v7i4.3.19721
7. Astrom, B. T.; Virson, J. R. (Ed.) (1999). Sandwich Manufacturing: Past, Present and Future. Stockholm, 198.
8. Panin, V. F., Gladkov, Yu. A. (1991). Konstruktsii s zapolnitelem. Moscow: Mashinostroenie, 272.
9. Kondratiev, A., Gaidachuk, V. (2019). Weight-based optimization of sandwich shelled composite structures with a honeycomb filler. Eastern-European Journal of Enterprise Technologies, 1 (1 (97)), 24–33. doi: https://doi.org/10.15587/1729-4061.2019.154928
10. Ivanov, A. A., Kashin, S. M., Semenov, V. I. (2000). Novoe pokolenie sotovyh zapolniteley dlya aviatsionno-kosmicheskoy tehniki. Moscow: Energoatomizdat, 436.
11. Herrmann, A. S.; Virson, J. R. (Ed.) (1999). Design and Manufacture of Monolithic Sandwich Structures with Cellular Cares. Stockholm, 274.
12. Slyvyns'kyy, V., Slyvyns'kyy, M., Gajdachuk, A., Gajdachuk, V., Melnikov, S., Slyvynska, N., Kirichenko, V. (2007). Technological possibilities for increasing quality of honeycomb cores used in aerospace engineering. 58th International Astronautical Congress 2007 Hyderabad.
13. Kondratiev, A., Prontsevych, O. (2018). Stabilization of physical-mechanical characteristics of honeycomb filler based on the adjustment of technological techniques for its fabrication. Eastern-European Journal of Enterprise Technologies, 5 (1 (95)), 71–77. doi: https://doi.org/10.15587/1729-4061.2018.143674
14. Slyvyns'kyy, V. I., Gajdachuk, V. E., Gajdachuk, A. V., Slyvyns'ka, N. E. (2005). Weight optimization of honeycomb structures for space applications. 56th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law. doi: https://doi.org/10.2514/6.iac-05-c2.3.07
15. Slyvyns'kyy, V., Slyvyns'kyy, M., Polyakov, N., Gajdachuk, A., Gajdachuk, V., Kirichenko, V. (2008). Scientific fundamentals of efficient adhesive joint in honeycomb structures for aerospace applications. 59th International Astronautical Congress 2008.
16. Slivinsky, M., Slivinsky, V., Gajdachuk, V., Gajdachuk, A., Kirichenko, V. (2004). New Possibilities of Creating Efficient Honeycomb Structures for Rockets and Spacrafts. 55th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law. doi: https://doi.org/10.2514/6.iac-04-i.3.a.10
17. Huang, S.-J., Lin, H.-L., Liu, H.-W. (2007). Electronic speckle pattern interferometry applied to the displacement measurement of sandwich plates with two "fully potted" inserts. Composite Structures, 79 (2), 157–162. doi: https://doi.org/10.1016/j.compstruct.2005.07.008
18. Shah, V. (2006). Handbook of Plastics Testing and Failure Analysis. John Wiley & Sons. doi: https://doi.org/10.1002/0470100427
19. Rion, J., Leterrier, Y., Månson, J.-A. E. (2008). Prediction of the adhesive fillet size for skin to honeycomb core bonding in ultra-light sandwich structures. Composites Part A: Applied Science and Manufacturing, 39 (9), 1547–1555. doi: https://doi.org/10.1016/j.compositesa.2008.05.022
20. D'Ottavio, M., Dozio, L., Vescovini, R., Polit, O. (2016). Bending analysis of composite laminated and sandwich structures using sublaminate variable-kinematic Ritz models. Composite Structures, 155, 45–62. doi: https://doi.org/10.1016/j.compstruct.2016.07.036
21. An, H., Chen, S., Huang, H. (2016). Optimal design of composite sandwich structures by considering multiple structure cases. Composite Structures, 152, 676–686. doi: https://doi.org/10.1016/j.compstruct.2016.05.066
22. Huang, S. J., Chiu, L. W. (2008). Modeling of Structural Sandwich Plates with 'Through-the-Thickness' Inserts: Five-Layer Theory. Computer Modeling in Engineering and Sciences, 34 (1), 1–32. doi: https://doi.org/10.3970/cmes.2008.034.001
23. Huang, S.-J. (2002). Mathematical modeling of the stress-strain state of adhesive layers in sandwich structures. Mechanics of Composite Materials, 38 (2), 103–120. doi: https://doi.org/10.1023/A:1014925325217
24. Ogurek, O. N., Starikov, L. M., Bondar', V. G. (1977). O vybore parametrov kleya dlya sotovyh konstruktsiy. Voprosy optimizatsii tonkostennyh silovyh konstruktsiy, 3, 73–79.
25. Gajdachuk, V. E., Karpikova, O. A., Kyrychenko, V. V., Kondratyev, A. V. (2012). Dependence of carrying capacity of cellular structures at transversally break from gluing technology cladding with filler. Aviatsionno-kosmicheskaya tehnika i tehnologiya, 2 (89), 5–17.
26. Kondratiev, A., Gaidachuk, V., Nabokina, T., Tsaritsynskyi, A. (2020). New Possibilities of Creating the Efficient Dimensionally Stable Composite Honeycomb Structures for Space Applications. Advances in Intelligent Systems and Computing, 45–59. doi: https://doi.org/10.1007/978-3-030-37618-5_5
27. Aronovvich, D. A., Varlamov, V. P., Voytovich, V. A., Gladkih, S. N., Kalinchev, V. A., Malysheva, G. V. et. al.; Malysheva, G. V. (Ed.) (2005). Skleivanie v mashinostroenii. Moscow: Nauka i tehnologiya, 544.
28. Beer, F. P. (2009). Mechanics of materials. McGraw-Hill, 790.
29. Sypeck, D. J. (2005). Wrought aluminum truss core sandwich structures. Metallurgical and Materials Transactions B, 36 (1), 125–131. doi: https://doi.org/10.1007/s11663-005-0012-5
30. Aluminum Foil for Sandwich Construction. Aerospace Material Specification AMSA 81596A doi: https://doi.org/10.4271/amsa81596a
31. Roy, R., Park, S.-J., Kweon, J.-H., Choi, J.-H. (2014). Characterization of Nomex honeycomb core constituent material mechanical properties. Composite Structures, 117, 255–266. doi: https://doi.org/10.1016/j.compstruct.2014.06.033
32. Kondratiev, A., Slivinsky, M. (2018). Method for determining the thickness of a binder layer at its non-uniform mass transfer inside the channel of a honeycomb filler made from polymeric paper. Eastern-European Journal of Enterprise Technologies, 6 (5 (96)), 42–48. doi: https://doi.org/10.15587/1729-4061.2018.150387
33. Mackerle, J. (2002). Finite element analyses of sandwich structures: a bibliography (1980–2001). Engineering Computations, 19 (2), 206–245. doi: https://doi.org/10.1108/02644400210419067