Experimental and numerical determination of the bearing capacity of the honeycomb panel with potted inserts when loading the panel in its plane

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Abstract. A typical three-layer honeycomb panel of a spacecraft (SC) is considered. For connection to the power frame of the spacecraft, as well as for rigging works, embedded elements (inserts) are installed in the panel. The results of experimental and numerical determination of the bearing capacity of the panel in the places of installation of potted inserts under the action of the load in its plane are presented in the article.

Keywords: three-layer panel, honeycomb core, embedded elements, strength, bearing capacity, static tests, finite element modeling

Introduction
At present, composite materials are widely used in the space industry, due to their high specific strength characteristics.

The work is devoted to the determination of the bearing capacity of a honeycomb panel with potted inserts when loading the panel in its plane experimentally and by numerical simulation using the MSC software package. MSC.Patran/Nastran followed by a comparison of the results [8-10].

The obtained experimental data have practical significance, which consists in the possibility of their use in the design and calculations of similar types of structures with the considered type of loading [12,14].

1. Description of construction
A honeycomb panel (Figure 1) is considered, which is a three-layer structure consisting of two bearing layers – skins with a thickness of 0.8 mm, made of aluminum alloy V95pch AT1 [1,11] and honeycomb core 2,75-5056-23P of perforated aluminum foil with a thickness of 0.023 [2, 4]. The panel thickness is 30 mm. The honeycomb core has a hexagonal shape of cells and is connected to the skins with a thin adhesive film VK-51 on an epoxy basis. The structural dimensions of the cells are shown in Figure 2.
Along the edges of the panel in the seats are installed smooth aluminum potted inserts (Figure 3) made of material D16 [3,6,7], which are intended for fastening the honeycomb panel to the frame of the spacecraft. The connection of the inserts with the bearing layers is carried out by means of a sealing compound of the MA 562 brand. Due to the lack of information about the mechanical characteristics of the compound, the data for its closest analogue LOCTITE EF 562 AERO were used. The mechanical properties of the honeycomb panel materials are shown in Table 1.
Table 1 – The mechanical characteristics of the materials of the honeycomb panel

| Material          | Specific elongation after a gap, % | Yield strength, MPa | Shear strength, MPa | Ultimate tensile strength, MPa |
|-------------------|-----------------------------------|---------------------|---------------------|-------------------------------|
| V95pch AT1        | 7,0                               | 400                 | 290                 | 480                           |
| VK 51             | 7,0                               |                     | 32,4                | 3,9                           |
| AMg 2H (honeycomb foil) | 8,0                       | 145                 | 156                 | 260                           |
| D16T              | 10,0                              | 275                 | 234                 | 390                           |
| LOCTITE EF 562 AERO | 7,5                       |                     |                     | 51,7                          |

2. Static tests
To determine the experimental values of the bearing capacity, a test scheme was developed (Figure 4). Fastening of the panel to a steel plate (equipment) was carried out by means of steel bolts M6x80 through regular inserts №№ 1, 3, 6, 8, 10, 12, 14, 16, 18, 20, 22, 25 (positions in Figures 1, 3) and through special steel inserts (Figure 4). Plate (equipment) is fixed to the power floor. A sharp drop in load during testing is taken for the destruction of the work.

Tests of the honeycomb panel were carried out by alternately applying the load to the inserts №№ 21, 5, 2, 24, 26.
The loading of the honeycomb panel through the considered insert was realized by means of a steel special bolt (Figure 5) with a nut. The test load was applied to the bolt head by means of a cable. The test scheme is shown in Figure 6.
Figure 5. Special bolt

(a) Load test pattern; (b) assembled the test configuration of the honeycomb panel

1 – bearing layers; 2 – potted inserts; 3 – inserts (equipment); 4 – plate (equipment); 5 – special load bolt; 6 – special bolts of fastening of the panel (equipment); 7 – washer; 8 – nuts; P – applied load

Notes: figure (a) does not show the honeycomb core

Figure 6. (a) Load test pattern; (b) assembled the test configuration of the honeycomb panel

The load was applied in two main directions according to the orientation of the honeycomb core cells (figure 2). In direction 1, the honeycomb core is stiffer and stronger than in direction 2. In this regard, the results obtained during the tests were compared in each direction separately.

The test results of the honeycomb panel are shown in Table 2 and in Figure 7.

The test results of the honeycomb panel through the insert № 26 significantly (about 10 %) differ from the test results of the inserts № 2 and № 24 due to the presence of a free (loose) edge in the direction of application of the load.

The nature of the destruction of a three-layer structure in the test zones of the inserts is similar. In the process of loading the installation, there are no visible deformations of the honeycomb panel; characteristic deformation sounds are practically absent. When the maximum load is reached, there is sharp and sudden destruction of the adhesive layer between the potted insert and the bearing layers of the honeycomb panel, accompanied by a loud clap, residual deformations of the sheeting in the compression zone and a drop in load.
Table 2 – The results of testing the honeycomb panel

| Loaded insert number | Load direction | The value of breaking load obtained from test results, kN |
|----------------------|----------------|--------------------------------------------------------|
| 21                   | 1              | 7,6                                                   |
| 5                    | 1              | 7,5                                                   |
| 2                    | 2              | 6,9                                                   |
| 24                   | 2              | 7,2                                                   |
| 26                   | 2              | 6,5                                                   |

Figure 7. (a) test results through the insert № 2 (top view of the honeycomb panel); (b) test results through the insert № 2 (bottom view of the honeycomb panel)

3. Calculation of the bearing capacity of the honeycomb panel by the finite element method

A finite-element study of the bearing capacity of the honeycomb panel was carried out in the MSC.Patran/Nastran package. The modeling of the bearing layers and the adhesive film of the honeycomb panel was carried out with isotropic behavior material. To implement the joint work with the adhesive layer, a model of layered composite Laminate [5,13] was used with a combination of materials: V95pch AT1 0.8 mm thick and adhesive film VK 51 0.13 mm thick. To simulate the compound, embedded elements and honeycomb cores are used isotropic materials with mechanical characteristics given in Table 3.

Table 3 – Mechanical characteristics of materials

| Material               | Poisson's coefficient | Modulus of elasticity, MPa |
|------------------------|------------------------|----------------------------|
| V95pch AT1             | 0,3                    | 66708                      |
| VK 51                  | 0,5                    | 139                       |
| AMg 2H                 | 0,32                   | 69650                      |
| LOCTITE EF 562 AERO    | 0,34                   | 2,377                      |
| D16T                   | 0,3                    | 70632                      |

To reduce the dimension of the model in a computational experiment, several separate sections of the honeycomb panel were simulated for loading: with inserts №№ 20, 21, 22; №№ 22, 23, 24, 25; №№ 1, 2, 3 (Figure 1). The principle of FE modeling of the previously mentioned sections of the honeycomb panel is considered by the example of a section with inserts № 1, 2, 3 (Figure 8).
Setting the boundary conditions is carried out on the regular fixing inserts № 1 and № 3 on the nodes belonging to the area of fit of the bolt cap to the collar of the insert during static tests, as well as in the area of the washer to the skin on the back of the honeycomb panel in all degrees of freedom (Figure 9b). Loading of the FE model of the panel is carried out using the application to the FE model of the special bolt used in the test (Figures 9a, 9b), the concentrated force acting in the plane of the panel and equal to 6.9 kN. The special bolt was modeled with beam elements of the CBEAM type with variable cross-section. The load transfer from the FE model of the special bolt is carried out through absolutely rigid RBE2 elements, which distribute the load between the nodes of the FE model of the insert in places corresponding to the area of contact of the special bolt with the insert when testing.

For the purpose of finding the bearing capacity, the calculation was performed in a nonlinear static formulation. According to the results of full-scale tests, it was found that the main cause of failure is the stresses that occur in the adhesive joint of the insert.

According to the calculation results, the maximum stresses in the adhesive joint when loading the insert № 2 are equal to 7.61 MPa. The result differs from the value of the tensile strength of the glue VK-51 more than 2 times, which indicates the need to clarify the FE model. The results of the nonlinear static calculation are given in Table 4 and shown in Figures 10, 11.
Figure 10. Stress-strain state of the honeycomb panel under loading through the insert № 2

Figure 11. Stress state in the upper and lower adhesive layers near the insert № 2

Table 4 – Calculation results of the section of the honeycomb panel when loading the insert №2

| The feature of the honeycomb panel | Maximum stress, MPa |
|-----------------------------------|---------------------|
| Skin                              | 293,0 (von Mises)   |
| Adhesive film                     | 7,61 (shift)        |
| Honeycomb core                    | 86,3 (shift)        |
| Insert                            | 304,0 (von Mises)   |
4. Analysis of the results
Analyzing the results obtained during the tests, and the data of the finite-element modeling, one can see that the best fit (error no more than 1%) is achieved for those strain gauges that measure the deformation in the direction of load application (Table 5).

Table 5 – Comparison of results

| Number of strain gauge | Stress obtained from experimental data, MPa | Stress of FE model, MPa | Convergence, % |
|------------------------|---------------------------------------------|------------------------|---------------|
| TP 7                   | 4,7                                         | 5,0                    | 6,38          |
| TP 8                   | -15,6                                       | -8,3                   | 46,8          |
| TP 9                   | -222,7                                      | -225,0                 | 1,03          |
| TP 10                  | 139,0                                       | 105,0                  | 24,5          |

Comparing the pictures of the stress state in the adhesive joint, obtained by simulating three different sections of the honeycomb panel, with the tensile strength of VK-51 adhesive, we find that the adhesive joint under the action of the test load has a safety factor (least) equal to:

$$\eta = \frac{\sigma_\theta}{\sigma^p} = \frac{32,4}{15,2} = 2,1,$$

where $\sigma_\theta$ is tensile strength of adhesive VK-51,

$\sigma^p$ is calculated stress in the adhesive layer obtained from the FE model.

The obtained results show that there is no destruction in the computational experiment in this formulation of the problem, when the maximum load is applied to the finite-element model, under the action of which the adhesive joint was destroyed when testing. It can be concluded that the developed finite element model does not allow obtaining realistic results for the considered problem of local loading of the honeycomb panel through the embedded elements. This demonstrates the need to develop a more detailed and accurate model.

5. Conclusions
The method of conducting static tests of the honeycomb panel of a spacecraft under the action of a load in the plane of the panel is described in the paper; a design scheme of loading the honeycomb panel through the embedded elements is formed. The description of the test scheme and the used equipment is given. The local bearing capacity of the panel in the vicinity of the installation sites of embedded elements is investigated by full-scale tests. Finite element models of three typical sections of the honeycomb panel corresponding to the tested ones are constructed. The bearing capacity of the three-layer panel in the places of installation of embedded elements is determined by calculation.

Based on the comparison of as-built dimensions with the results of numerical modeling, it can be concluded that the results largely depend on a number of factors, such as the location of the embedded element relative to the edge of the three-layer panel, the distance between adjacent embedded elements, the distance to the panel fastening and the direction of application of the load. In addition, the value of the maximum load is influenced by the geometry of the area filled with compound, the quality of gluing of embedded elements to the skin.

6. References
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