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TECHNOLOGY OF EXPERIMENTAL STUDIES OF THE INFLUENCE OF THE HOLE SIZE AND SHAPE ON THE STABILITY OF LONGITUDINALLY COMPRESSED CYLINDRICAL COMPOSITE SHELLS

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INTRODUCTION

Shell-type thin-walled structures made of composite materials are often used to create many constructions, machine parts and other objects. The presence of holes on the lateral surface reduces the bearing capacity of the shell, since it leads to the emergence of a local moment of stress state, whose intensity some cases determines its bearing capacity. One of the important tasks of the study is to determine the critical buckling force of a shell weakened by holes under the action of various external forces.

Efficiency of the use of structural elements made of composite materials in aviation and rocket - space technology was discussed in [1].

Applied problems of stability of multilayer composite materials were considered in [2–4]; for the case of a multilayer cylindrical shell, in [5–8]; for the inhomogeneous longitudinally reinforced cylindrical shells - in [9], in the paper [10] studies instability of a composite cylindrical shell under combined loading.

Possibilities of increasing the critical force of local buckling of composite structures were studied in [11]. In [12], the results of studies of experimental testing of composite panels for stability are offered to be used to determine rigidity parameters of composite materials of shell-type constructions, in [13] the solution of this problem was carried out by calculation.

The results of experimental studies of stability of cylindrical shells with circular, rectangular, and square cutouts in longitudinal compression were given in [14].

The experiments were carried out on models of shells made of Mylar film.

The results obtained in [14] are well matched with the data of the papers [15], where the results of a series of experiments on shells made of sheet steel are given. The shell had one or two through holes of a square or circular shape in the middle part. When tested, the shells lost stability in the elastic domain. The influence of the shape and sizes of the cutout on the character of subcritical deformation and the buckling forms was studied.

The results of experimental studies of the stability of orthotropic cylindrical shells, tortionally weakened in the aggregate of circular holes, were presented in [16], and study of the influence of circular cutouts on the stability of shells under transversal bending were given in [17] and under axial compression - in [18,19], where the shells made of steel, aliminium and epoxy material, were used for testing.

The papers [20, 21] were devoted to the problem of mathematical modeling of a supercritical significantly nonlinear deformation. Taking into account the peculiarities of manufacturing technology of shells made of composite materials, inhomogeneity of structure and physical - mechanical characteristics and also significant geometric nonlinearity of the process of shape change during buckling, the existing methods of theoretical and numerical analysis of the stress state can not adequately provide reliability of results satisfying practice requests.

Therefore, experimental studies of the influence of changing of the size and shape of holes of the lateral surface (technological or through damages arising in the operation process) on the value of critical force and buckling of models of longitudinally compressed fiberglass cylindrical shells are rather relevant. At the same time one should take into account that the published results of experimental studies of the process of buckling of shells with holes represent the data of test of shells made of various materials, of various size, for comparatively small amount of models, the area of change of hole parameters , their amount that have been tested by various technologies. Therefore, general comparative analysis of experimental data is rather problematic.

TEST MODELS

When conducting experimental studies of cylindrical shells, in order to reduce the scatter in the results of experimental studies and to increase their reliability, the problem of manufacturing nominally identical high-quality models is one of the most important ones. This time the basic difficulty is that the models should be such that the difference in critical loads for different nominal identical samples is less than the difference associated with a change in the parameter under study [22].

To this end, researchers used various methods for manufacturing models. To manufacture models of shells from plastic, they used hot forging method by explosion or hydrostatic pressure. The methods of electrotype, machining of thick-walled workpieces, chemical milling were used for metal samples. Spot welding or gluing were used to manufacture shells from sheet materials, though this time there raises a question of taking into account the influence of a local increase in stiffness due to the appearance of a connecting seam. Each of mentioned methods has its advantages and shortcomings. At the same time, in general there are no generally recognized “priority” method for manufacturing models that meets all the requirements of the experimenter when studying various problems of the stability of thin-walled shells [22, 23].

The most significant, almost uncontrollable factor especially in case of axial compression of cylindrical shells are initial geometric shape imperfections. Rather high sensibility of the value of the critical force of buckling of a smooth cylindrical shell to initial geometric shape imperfections, deficiences and damages, consilidation conditions, unevenness of the load, variation in thickness, inhomogeneity of mechanical properties and other factors that present during manufacture and as the results of studies show often initiates shell buckling, is known. The impact of these deviations of the real shell from the idealized model on its performance was studied in [23–27].

In great of majority of known experiments, the presence of these factors led to significant reduction (by 50–70%) in the critical load [23]. This time, the value of such imperfections for a model made of a sheet material in great extent is determined by its relative thickness δ / R, where δ , R is wall thickness and shell radius, respectively. Reducing parameter δ / R leads to an increase in influence of initial geometric imperfections and, as result to significant decrease of critical stresses and actual leveling of the impact of the change of the considered parameter on the process and quantitative parameters of buckling.

The desire of the experimenter to reduce or eliminate, if possible, the influence of such initial geometric imperfections leads to the need to conduct research on models with the largest possible value of the relative thickness δ / R. In this case, flexural stiffness of the shell increases and as a result, the influence of the relative initial flexure as imperfection of the geometrical shape, on subcritical behavior and the value of the critical load on the shell decreases. However, simultaneously with an increase in the thickness of the shell wall, critical stresses increase and as a result, another factor, appearance of plastic deformations begins and this excludes the possibility of conducting an experiment in the elastic domain.

The beginning of the manifestation of this factor for various materials is determined by the ratio of the yield point to the modulus of elasticity (σ_f / E), as some limit value of the relative thickness. The higher the value of this ratio, the greater the range of shell testing in the elastic domain.

Of these sheet metals, this parameter is of the greatest importance for the thin stainless hard-worked steel of grade X18H9n widely used in experimental studies and for which $\sigma_f\ / E \approx 4{,}0 \div 4{,}5\times10^{-3}$ that allows to conduct research of stability of cylindrical shells in an elastic domain when loading them by axial compressive forces to maximum values $\delta / R = 6{,}5 \div 7{,}0\times10^{-3}$

Mylar has a higher value of the parameter $\sigma_f\ / E$, but the significant instability of its mechanical properties significantly limits the use of this material for the manufacture of models. In this article, the shell models were manufactured from a composite material by laying on a cylindrical mandrel heated to 60°C (made of alloy liner AMG-6m) 2 layers of fabric preimpregnated with technological epoxy glue the ratio of the filler and connector of which ensured the process of polymerization and curing of at least 98 %.

The laying of the fabric was carried out at an angle of 0 degrees of the base of the fabric along the axis of the shell end to end, so that the second layer was laid diametrically opposite to the first layer. The shells had the following geometrical characteristics: shell radius R = 0,1 m, L_t = 0,29 m, L_w = 0,25 m is the total and working length of the shell, respectively; $\delta = 0{,}45 \div 0{,}47 \times 10^{-3}$ m is the thickness of the shell wall, whose system measurement (over the entire surface of the shell) was performed by the indicators with division value of 10^{-6} m.

Thus the manufactured models of fiberglass shells belonged to the class of thin-walled ones ($R/\delta \geq 200$) of medium length. It should be noted that the peculiarity of composite (multilayer) rotation shells manufactured by laying fabric, reinforcing fiber winding or other technology, is that the shell material is manufactured together with the research object itself. Obviously, this time for each model of shells, physical and mechanical characteristics of the model material may differ.

The main mechanical characteristics of the material that was used for manufacturing the studied models of shells were determined from the diagrams a «σ - δ» constructed according to the results of separate specially conducted experimental studies conducted both on plane samples (witnesses) manufactured from the material of shell models and directly on the studied shell models by means of electromechanical system that allowed to perform more exact measurements. After processing the results and appropriate averagings, the mechanical characteristics were as follows: modulus of elasticity E_x = 29 HPa, E_y = 16 HPa, shear modulus E_x = 29 HPa, E_y = 16 HPa, Shear modulus G_{xy} = 4 HPa , Poisson ratio μ_x = 0,11; μ_y = 0,09, $\sigma_f / E_x > 5 \times 10^{-3}$. Here the indices x, and y correspond to main directions of material orthotropy.

For avoiding possible failure of the end part of shells, due to their contact interaction with loading device, the manufactured models were additionally reinforced near the edges by a glass tape impregnated with technological epoxy mortal. The width of such an additional winding corresponded to the value of the end fixture and was about 0.02 *m*, the thickness of the shell on the ends was equal to $0,8 \div 1,2 \times 10^{-3}$ m .

Compression of the stacked layers of fiberglass in the form of a bunch of threads evenly spaced along the entire length of the shell with even tension from 50H to 70H was conducted by means of special annular fixtures.

Circular and square holes of diameter (of side) from 0.01 *m* to 0.1 *m* were made in the lateral surface in the midsection of the shell: circular ones by drilling using a flat bed base (lodgement), square ones by means of a lathe and cutters. In general, the manufacturing technology of the models met the requirements for the manufacture of fiberglass elements of real rocket designs.

The force on the tested model was transmitted through the end fixtures to which the shell trimmed on a special plate was glued using cold-curing epoxy glue. The end fixtures possessed great rigidity and this provided rigid built-in conditions during repeated tests.

The assembled shell with end fixtures was enstalled on ball bearings between the working traverses of the universal testing machine UME-10Tm. This time, four indicators were attached to the upper end of the shell with a division value 0.001, while on the lower ring, special rods that made possible to measure the displacements of the shell.

To check quality of models of thin-walled fiberglass shells manufactured in this way, and also to justify reliability of the obtained experimental results, additional tests were carried out for axial compression of 10 continuous shells. In this case, the average critical stresses turned out to be equal to with $\sigma_\varepsilon = 40$ MPa a data spread up to 5 %. The shells lost stability according to the classical scheme of buckling of cylindrical shells under axial compression in the elastic domain with a clamp with the formation of diamond-shaped dents without destruction and delamination of layers [15, 22, 23, 28].

Calculated values of critical stresses of a cylindrical orthotropic shell under axial compression were obtained in the form (1), using the solution given in [28]:

$$\sigma_x = \frac{\alpha}{\sqrt{3\left(1 - \mu_x \times \mu_y\right)}} \times \sqrt{E_x \times E_y}\left(\frac{\delta}{R}\right),$$

where coefficient α is calculated from (2) $\sigma_x = 60.3 MPa$

$$\alpha = \sqrt{\frac{\left[2E_y + 2\mu_y\sqrt{E_x \times E_y} + 4G_{xy}\left(1-\mu_x \times \mu_y\right)\sqrt{E_y/E_x}\right]G_{xy}}{2E_y \times G_{xy} + \left(E_x \times E_y - 2\mu_x \times G_{xy}\right)\sqrt{E_y/E_x}}}.$$

Design values of critical stresses turned to be equal to σ_x = 60.3 MPa for the chosen geometry of the studied shells and above-mentioned elastic characteristics of their materials. This time, the ratio of experimental values of critical stresses to design ones was about K_c = 66 % from theoretical ones, that testified high quality of the models of cylindrical shell used for tests[23].

In general, the manufactured models of the shells had the stability of the value of critical compression force, high elasticityof the material and did not have perturbations caused by the presence of a connecting seam, which made it possible to observe a wave formation almost identical wave formation picture without delamination and destruction of the shell material when retested in elastic domain one and the same models.

Reliability of the results of the repeated loading of the models was studied by the authors additionally. Multiple loading of glass reinforced plastic shells with a low level ($\approx 0,5 \div 0,75P_{cr}$) of effort and further to buckling showed that the spread of the value of the critical load with 25 multiple loadings, 5 of which were carried out by a local buckling, are only 2.5 %, which showed a fairly high reliability of the results of repeated tests.

It should be noted that the idea of multiple testing of one and the same model was mentioned in [18], where the experimental study of the influence of holes on shell stability under axial compression was carried out using the shells manufactured by the method of centrifugal casting from optically- active epoxy material. During the tests in each individual shell, a hole of increasing diameter was successively cut out on it.

In the present paper, this peculiarity was the basis of the test methodology for studying influence of change of the size and shape of hole on critical force of buckling of models of fiberglass shells by means of multiple reuse of one and the same model with gradual increase in the size of the holes of the lateral surface.

EXPERIMENTAL STUDIES

Stability of fiberglass shells weakened with one hole of circular or square shape located in the middle part of the shell, was studied. The loading of the shell was carried out up to buckling. The experiments were carried out for 3 shells with a weakened circular and 3 square holes of various sizes.

The hole size changed during the experiment. This time, the value of the critical load, displacement of the shell ends, general picture and wave formation parameters were fixed.

In the process of numerous control loading of a fiberglass shell with axial compressive force under repeated tests, it was established that it is expedient to carry out each subsequent loading in no than two days, necessary for “rest” of tested shells.

If after the repeated load the spread of values of the critical load did not exceed 1-2 %, the shell was used at later stages of the experiment, and if the deviation was more than 3 %, then additional research or model displacement was carried out.
After each test to buckling of one and the same shell that was under the identical boundary conditions of rigid built-in, the hole sizes increased from 0.01 m to 0.1 m, with the step 0.005 *m*, the test of the model was repeated and was carried out repeatedly according to the method described above.
The results of the research are given in figure 1 in the form of dependence of the relative critical load $P_{cr}^{*} = P_{cr} / P_{cr}^{0}$ on dimensionless parameter ω characterizing the value

$$\omega_1 = d / \left(2\sqrt{R\delta} \right)$$

for a circular, and

$$\omega_2 = a / \left(2\sqrt{R\delta} \right)$$

for a square hole, where *d* is a diameter, *a* is the side of the square hole respectively. The sign "●" indicates the test results for the case of a circular hole, the sign "□" - for the case of a square hole.

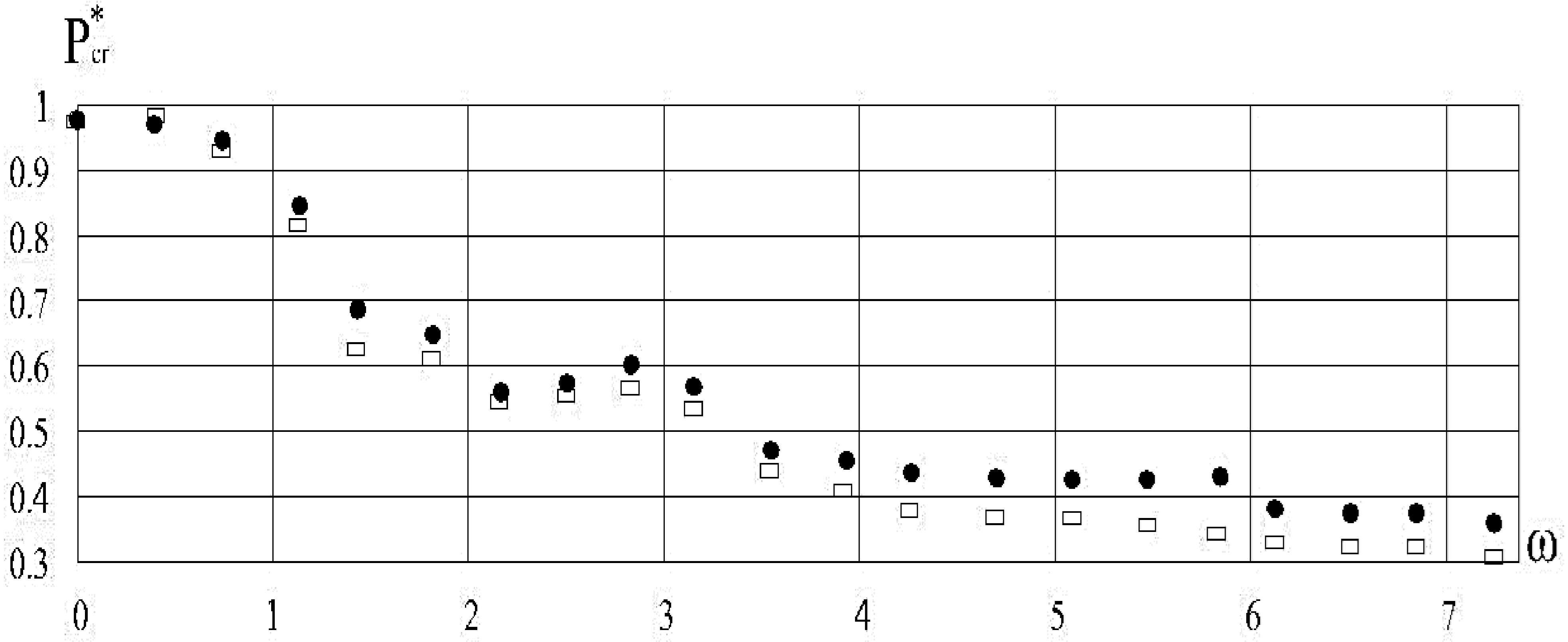

Figure 1 – Dependence of critical force on the size of a circular and square hole of lateral surface

Typical forms of buckling of fiberglass cylindrical shells under axial compression are given in figure 2.

a) **b)**

Figure 2 – The forms of buckling of a cylindrical shell with a circular (a) and square (в) hole.

It is noteworthy that the dependence of the given critical buckling force on the size of the hole of the lateral surface has a non-uniform character. The curves 1, 2 have two sections ($0,72 \leq \omega \leq 2$; $\omega \geq 3$) of a sharp drop in the critical load (in the first section to 0.6, in the second one to 0.35 ÷ 0,4 P_{cr}^{*} and further appropriate stabilization of its values.

It should be noted that in order to characterize the behavior of longitudinally compressed cylindrical shells made of isotropic material, in the paper [29], the classification of small, medium, and large ncutonts was adopted .

It follows from the results obtained in this paper that for the considered class of fiberglass shells the obtained experimental data qualitatively correlate well with the classification proposed in [29].

According to the results of the experiments, it was found out that for small (according to [29]) cutouts ($\omega \leq 1$), the stress concentration caused by the presence of a hole has little effect on the overall buckling of the shell; for medium cutouts ($1 \leq \omega \leq 2,5$), the buckling process takes place in two stages: Initially, at some value of the load, local dents are formed on the edges of the hole, and with a further increase in the load, a large buckling occurs with the appearance of dents far from the hole

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Existence of large cutouts ($\omega \ge 2,5$) significantly influence on the value of the critical load and buckling character. In this case, appearance of dents on the hole contour due to the uneven stress state around the hole and essential bends of the median surface led to their further development and total buckling.
It should be noted that in the range ($2 \le \omega \le 3$), the transition from medium size holes to large ones, the increase in the hole size does not lead to critical load drop. This is explained by the fact that in this range there are losses of deformation energy in the change (restructuring) of the forms of buckling.
The dependence of the critical force on the relative area of the hole

$$F^* = F_{cut} / F_{sh},$$

where F_{cut} , F_{sh} are cutout and shell surface area, respectively. As can be seen from the test results, the shape of the hole has little load, on the critical effect, while the size effects significantly.

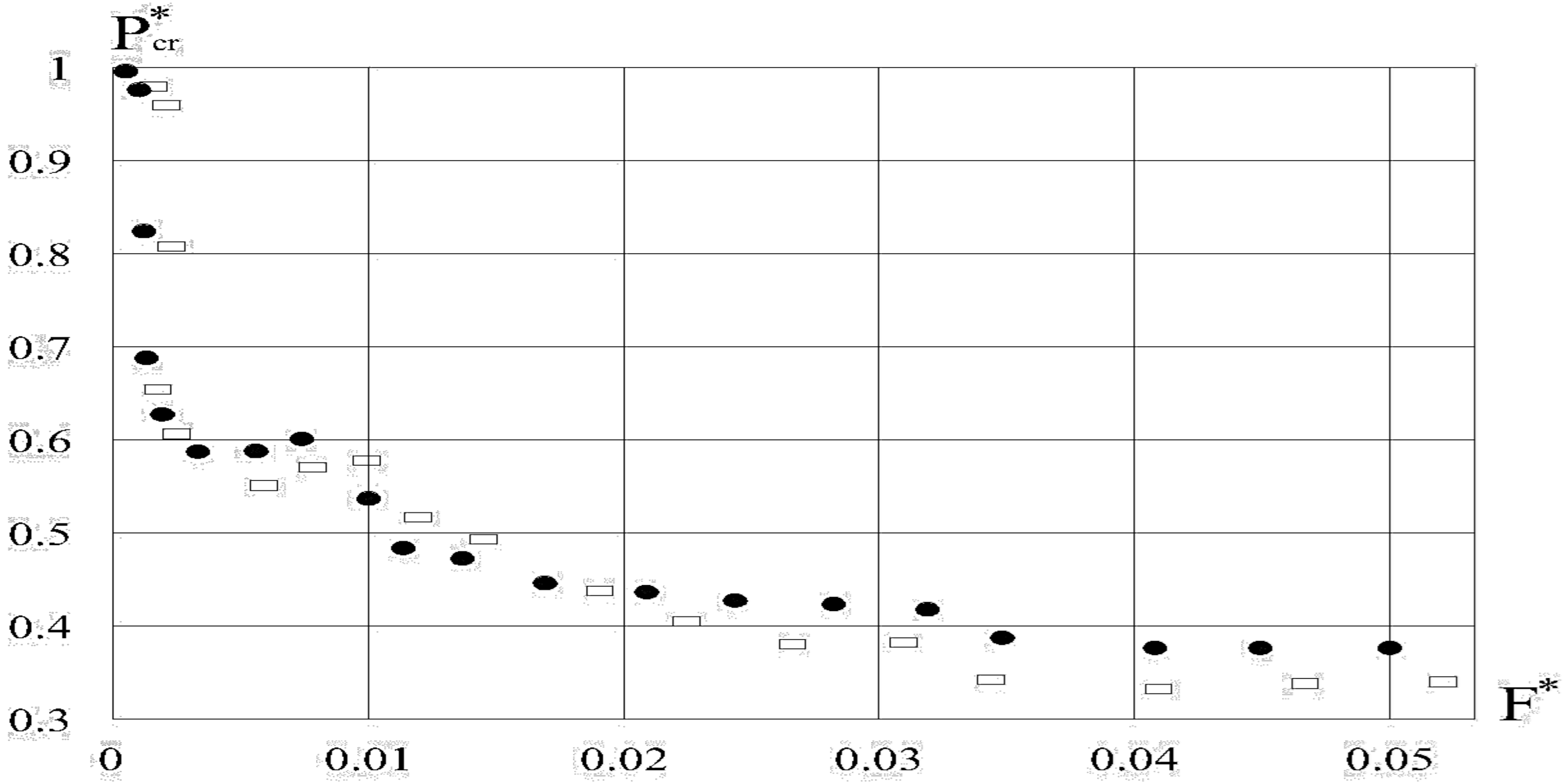

Figure 3 – Dependence of the critical force on relative area of the hole.

In general, wave formation shape at buckling, both for circular and square holes, is characterized by the appearance of local forms of buckling with a subsequent transition to the total buckling. In case of buckling of a fiberglass with a small hole (according to the classification of [29]), shapechange of the surface of deformation shell may be characterized both by a positive and negative curvature.

At the same time, already for a medium-sized hole, there is no such warping. With an increase of sizes of circular and square holes, total buckling is accompanied by a weak clap and happens when two local dents appear near the hole in circular direction.

When loading fiberglass shells with axial compressive force and weakened with large circular and square holes,the buckling is characterized by a smooth transition from local buckling to total one with no load increase. The amount of longitudinal deformation of the shell does not change significantly for small sizes of the hole. For large sizes of the hole the growth of the deformation of the shell increases significantly and when local buckling appears, it leads to a proportional decrease in the critical force.

CONCLUSIONS

The dependences of the critical buckling force of a composite cylindrical shell under axial compression on the size of one circular and square hole of the lateral surface of the shell are constructed.

It is shown that these dependencies are of irregular character. Initially, with a very small hole, its influence on the reduction of bearing capacity is negligible. Further increase in the hole size (as a quality accumulation of damage) leads to a sharply and rather rapidly reduce the critical force of buckling.

After that, a stabilization interval gradually sets in, in which the influence of an increase in the size of the hole on the value of the critical force decreases significantly and this is explained by the load energy loss to the reconstructing (change) of the form of buckling. This is followed again by an interval of a sharper decrease in the bearing capacity and a further gradual attenuation of such an influence.

For both circular and square holes, a local form of buckling occurs at the beginning , followed by the transition to a total buckling. The shape in the lateral surface has little effect on the value of the critical load, while the size has a significant effect. This time, the critical load of stability for the shells with a circular hole turns out to be greater than for shells with a square hole of equal area.

The obtained experimental data can be used to assess the reliability of new mathematical models and also to predict the value of the critical load of cylindrical composite shells weakened with hole.