International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2022	Issue 53	Volume 14	Number 4	Pages 175-181

NUMERICAL AND EXPERIMENTAL SIMULATION OF DESTRUCTION OF STRETCHED CYLINDRICAL SHELL DAMAGED BY RANDOM CUTS-CRACKS

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Abstract- The results of a numerical and experimental researches of the destruction of circular cylindrical shells weakened by randomly located and oriented rectilinear through cuts-cracks under loading by an axial tensile force are presented. The features of the construction of finite element modeling of the stress state are considered shells with a rectilinear through cuts-cracks of the side surface located at different angles to the generatrix of the shell. The results of experimental studies of 288 models of shells with different numbers from 0 to 50 such damages are presented. The angle of inclination of the cuts-cracks to the generatrix and the coordinates of their location on the side surface of the shell were chosen according to the law of uniform distribution of random variables. Dependences of the values of breaking loads on the number of damages are constructed. The results are presented in the form of graphs and pictures of shell destruction.

Keywords: Finite Element Method, Cylindrical Shells, Random Transverse Cuts-Cracks, Experimental Researches, Longitudinal Stretching, Destruction.

1. INTRODUCTION

Researching the bearing capacity of power elements of shell structures and, in particular, cylindrical shells widely used in many branches of mechanical engineering, is one of the important tasks of mechanics. These tasks become especially difficult in the case of predicting the strength and stability of such objects in the presence of damage of various nature, in particular, holes, cutouts, surface and through cracks of the side surface, the appearance of which in the shell can be caused by a fairly wide range of external influences. The presence and accumulation of such stress concentrators of various origins leads to significant disturbances in the stress-strain state and is often the cause of the destruction of structures and buildings [1-6].

Theoretical research of the bearing capacity of such structural elements with stress concentrators is connected with the need to solve rather complex mathematical problems.

Thus, the method of researching the stress-strain state in orthotropic shells of arbitrary Gaussian curvature with cuts, holes, and other stress concentrators, which was developed in works [7-9], is based on the use of the theory of generalized functions of the two-dimensional Fourier transform, the integral representation of displacements and internal force factors and fundamental solutions of the statics equations of shallow shells. Works [4, 5, 10] are devoted to the research of significantly nonlinear mathematical models of behavior, loss of stability, and destruction of thin-walled shells with holes and cracks. Asymptotic research methods in the nonlinear mechanics of the destruction of bodies with cracks are used in [11].

The research of the stress-strain state in shells near holes, cracks, or cuts, as well as the behavior of the crack itself, its influence on the stress state, loss of stability of thin-walled structural elements, and subsequent destruction in the crack zone are presented in articles [2, 3, 12, 13]. The processes of damage accumulation in structural elements were studied in [14, 15], and the maximum permissible defects were studied in [16, 17].

Works [10, 18] are devoted to the experimental study of the behavior and load-bearing capacity of shell structures with damage in the form of through holes of various shapes under longitudinal tension, internal pressure, bending, and combined loading, and [19] to the torsional stability of cylindrical shells with a system of circular holes. Engineering methods for calculating structural elements with cracks within the framework of linear fracture mechanics are summarized in [6].

The complexity of the task of researching the load-bearing capacity of thin-walled shell elements increases significantly when the size and location of damage, in particular, in the form of circular holes or through cracks, is random, and the amount of damage accumulates during operation. One of these problems is the problem of predicting the strength of shells with randomly located cracks under axial expand tensile force loading.

The presented article is devoted to conducting an experimental study of the process of destruction of circular cylindrical shells loaded with an axial tensile force, weakened by a different number of rectilinear cross-sections, the coordinates of the location and the angle of inclination of which to the generatrix shell are random values, with the aim of obtaining results that could provide reliable real information about the behavior and the value of the bearing capacity of the shell structure under the conditions of damage accumulation and would serve as a reliable scientific and methodological basis for the development of adequate calculation schemes and corresponding theoretical calculation methods.

2. PREPARING MODELS AND EXPERIMENT TECHNOLOGY

When conducting experimental studies, the problem of manufacturing high-tech, nominally identical, high-quality models of shells is one of the most important for reducing the dispersion of experimental results. Models should be such that the difference in critical loads for different nominally identical samples is smaller than the difference associated with a change in the studied parameter [20]. Moreover, taking into account the random nature of the location of the damage, the statistical number of tested models should be quite significant. It is obvious that this requires a reduction in labor costs and the cost of manufacturing technology of nominally identical models.

In the presented article, special paper was used for the mass production of models of cylindrical shells. For the first time, the possibility of effectively using paper to study the behavior of thin-walled shells was shown in [21], and later in [22]. The rationale and results of an extensive approbation of the effective use of paper as a material for manufacturing shell models intended for experimental research are given in [19].

The main mechanical characteristics of the selected orthotropic material of the models were determined according to the results of the "σ-ε" diagrams of separate specially conducted experiments of tensile tests of samples and are: modulus of elasticity $E_x = 6.9\times10^3$ MPa, $E_y = 3.45\times10^3$ MPa, Poisson's ratios $\nu_x = 0.3$; $\nu_y = 0.15$ (here the indices x, y correspond to the main directions of orthotropy of the paper sheet). Sheet thickness $h = 0.23\times10^{-3}$ m.

As shown by experimental studies of mechanical properties, for the specified material, the ratio of the conditional yield strength σ_T to the modulus of elasticity E_x in the longitudinal direction is $\sigma_T/E_x \approx 3.6\times10^{-3}$. Of the sheet metals, this parameter is of the greatest importance for the thin tempered stainless steel of the X18H9н brand, which is widely used in experimental studies, for which $\sigma_T/E \approx 4.0\text{-}4.5\times10^{-3}$.

Thus, it turns out that, despite the low absolute values of the elastic characteristics of the selected material compared to metals, the ratio of its yield strength to the modulus of elasticity is higher than that of most other materials, including metals, and almost reaches these indicators for high-strength (high-alloy stainless) steel. This makes it possible to have fairly wide limits for conducting an experiment at the elastic stage of deformation.

The most important property of this material is its high ability to process, which leads to fairly simple manufacturing technologies of high-quality, practically identical samples and their preparation for testing without significant material costs. The specified properties of the selected material for the manufacture of shell models allow conducting large-scale systematic experimental studies of the influence of the accumulation of randomly damage on the value of the critical force of the loss of bearing capacity.

To make shells, rectangular sweeps were cut from a standard sheet of paper so that their sides were parallel to the main directions of orthotropy. The direction of E_x always coincided with the direction of the forming shell, and E_y with its direction guiding. Strips with a width of 0.02 m remained along the long sides of the model blank, which were later used for gluing to the cylindrical ends in the circumferential direction. A strip with a width of 0.005 m was also left in the longitudinal direction for gluing the model.

On the scan of the shell, damage was created in the form of through straight cuts. To obtain their random location on the side surface of the shell (coordinate (x_i, y_i) of the middle of the section in the circumferential and longitudinal direction and the angle φ_i, i of its inclination to the generating line $i = \overline{1,n}$) a special computer program was developed, which made it possible to obtain random values (based on a uniform distribution) to determine the specified parameters and create a general picture of the scan of the shell with randomly damage for each number of n cuts. This picture in the appropriate scale was printed on a separate sheet of paper and superimposed on the scan of the shell (Figure 1), which made it possible to make cuts on each of the blanks with fairly high accuracy. Next, the ends of the sections were pricked on the sweep with the help of a drawing gauge to ensure the identity of their shape. Through cuts were made with the help of a sharp tool under the ruler.

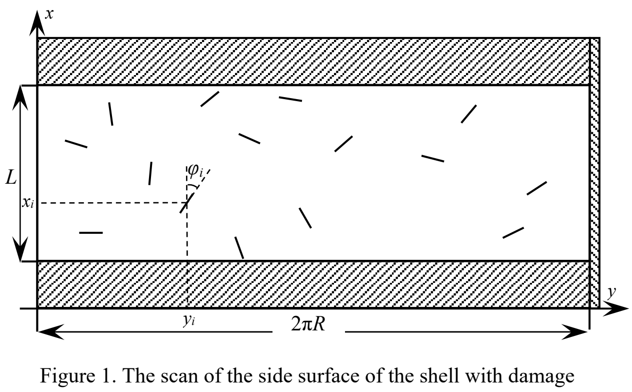

Figure 1. The scan of the side surface of the shell with damage

To give a cylindrical shape, each workpiece was superimposed on a steel cylinder, the diameter of which was $R = 0.0375$ m, and then was glued. The width of the adhesive joint was 5×10^{-3} m, and the working length of the shell was $L = 0.075$ m. The workpiece was held on the cylinder with the help of an elastic rubber band until the glue was completely polymerized. After that, the shell was removed from the cylinder and glued to the end devices, which ensured a rigid clamping of the ends and uniform transmission of longitudinal forces to the curvilinear edges of the shell.

The tests were carried out on the MP-0.5-1 kinematic press, the scheme of which is shown in figure 2. The lower end of the shell (1) was rigidly attached to the movable massive part of the press (3) with a screw (4) using an end device (2). The upper end (5) was connected to the MP-0.5-2 dynamometer (10) by means of a screw (6) and a suspension (7), which was rigidly connected to the upper part of the installation. A horizontal rod (8) was also attached to the upper end for the purpose of measuring the amount of tension with clock-type indicators (9), which were placed on the moving part of the press.

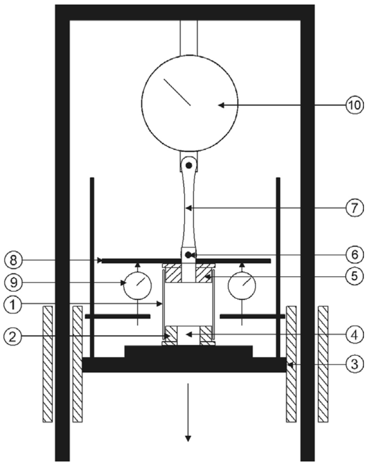

Figure 2. Loading scheme

The external tensile force always coincided with the axis of the shell. For shells with slits, this pattern of loads to a certain extent corresponded to off-center tension, since the slits were placed irregularly on the surface of the shell. The readings of the dynamometer and the indicator of longitudinal movement were recorded through equal intervals of the load values, which changed monotonically. On average, 15 load levels and measurements were obtained for each test. When the load reached a certain value, the shell ruptured. This load was considered the maximum that the shell can withstand.

3. NUMERICAL SIMULATION

As is known [23, 24], in the tasks of calculating the stress-strain state using the finite element method, the method of division into finite elements, the correct selection of the grid step, and the type and size of the finite element are of particular importance. It is especially important to correctly solve these issues in the presence of a stress concentrator, since theoretical solutions [7, 8, 12] imply the hypothetical possibility of "infinite" stress values at these "special" points. It is obvious that in this case it is advisable to reduce the mesh size of the elements near the cuts-cracks of the lateral surface, although it is obvious that this technique cannot fully reproduce the real state of the object. In addition, the difference in the sizes of the elements obtained in this way can also lead to a decrease in the accuracy of the calculation. Therefore, these issues require additional attention when applying the finite element approach to solving these problems, and if possible, experimental verification.

In the presented article, within the selected test scheme, the dependence of the maximum critical tensile load on the angle of random inclination of the cuts-cracks line φ_i to the generatrix of shell (Figure 1) was experimentally investigated and relevant comparisons were made. At the same time, the shell models had one section with a length of $l = 0.01$ m, located in the average cross-section of the shell at an angle $\varphi_i = 0°$, 15°, 30°, 45°, 60°, 75°, 90° to the generatrix of shell.

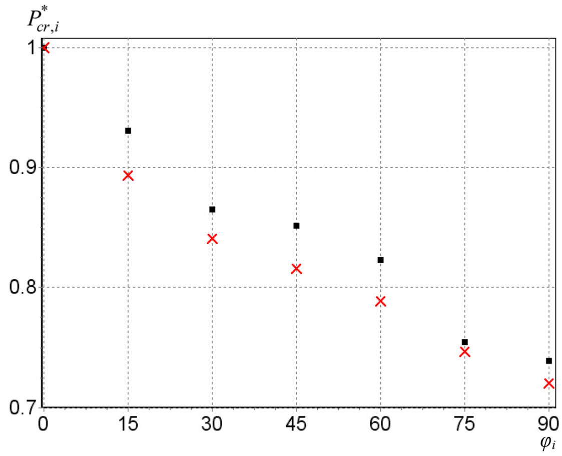

Figure 3. Dependence of critical loads on the angle of inclination of the cuts-cracks

Results of an experimental researches in the form of the dependence of the destructive load (marked - ■) from the angle of inclination slits are presented in Figure 3. From which it can be seen that the longitudinal section ($\varphi_i = 0°$) does not actually reduce the critical load, at the value of the angle $\varphi_i = 45°$ a certain transitional process is observed, and in general the largest decrease in the strength of the shell with a horizontal ($\varphi_i = 90°$) location of the section is almost 25%, as the result of reducing its "full" section by the length of the section. To increase the reliability of the finite-element calculation, a numerical experiment was conducted to select such parameters of the problem as the type of finite element, grid step, as well as the shape and width of the slit concentrator.

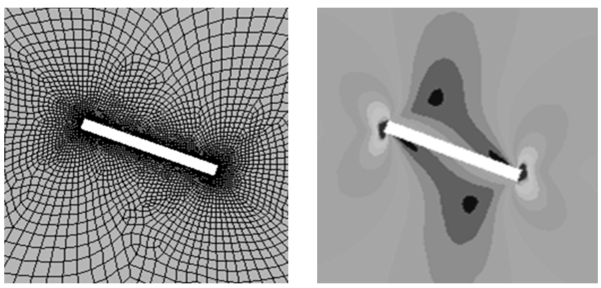
(a) (b)

Figure 4. Results of numerical calculations.

A series of calculations was carried out for models with rectangular damage of different widths and a variable grid step (Figure 4a). This made it possible to establish that when the grid step increases, the spread of $\sigma_{\max}$ values increases, at the same time, when the step decreases below a certain value (10^{-3}), the spread of stress values $\sigma_{\max}$ also increases, which is associated with the accumulation of calculation error, because in places of concentration the stress rather large values took Based on the results of numerical modeling using the obtained diagrams in the form of "slits width-average deviation" dependences, the optimal grid step and the width of the slit-concentrator were found, for which the spread of $\sigma_{\max}$ values was the smallest.

The pattern of stress distribution around the damage for a shell with one cut is shown in Figure 4b. The results of calculations for different φ_i in Figure 3 are marked with ×.

The calculated values were lower than the experimental values (with a deviation of up to 5%). This is explained by the fact that at the end of the crack there was a sharp increase in stresses, while the criterion of destruction failure in the calculations take into account the achievement of a certain calculated critical value σ_{cr} by the maximum stress, which corresponded to a certain experimentally determined destructive force for the shell without damage during axial stretching.

It should be noted that the correct determination of σ_{kr} for the calculation in the case of a complex stress-strain state in the presence of slits, which would correspond to the real destructive load, is possible only with the joint use of experimental and calculated data.

Due to the random nature of the location, the slits in the experiment could intersect, branch out, accumulate in separate zones, etc. Therefore, the finite-element calculation of all experimentally tested shell models leads to more significant differences between the calculation results and the test data. This is due to the need to take into account the mutual influence of stress concentrators and is a separate problem for research [9].

4. RESULTS OF EXPERIMENTAL RESEARCHES

In the course of the experiment, the value of the critical load, longitudinal displacements and images of destruction of the shells were recorded. A total of 288 models of 11 series of shells were tested, each of which had its own location of a different number of n randomly located and oriented rectilinear damages. The length of slits on all shells was the same and was 0.01 m. The number of slits varied from $n = 0$ (solid shell) to $n = 50$.

Data from experimental studies are presented in Table 1, where n is the number of damages; k is the number of tested models of each series; P_{cr} is experimental values of averaged destructive loads.

Table 1. Data of numerical calculations and experimental tests

n, шт	0	1	3	5	10	15	20	25	30	40	50
k, шт	6	8	8	42	32	32	32	32	32	32	32
P_{cr}, H	2316	1726	1619	1494	1349	1172	1172	1116	1036	909	811

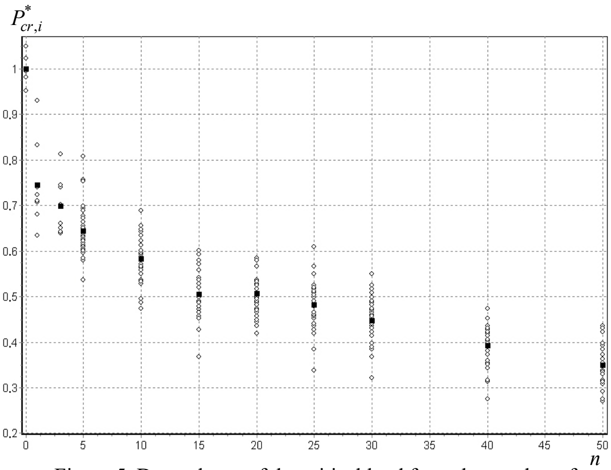

Figure 5. Dependence of the critical load from the number of damages

The dependence of the relative critical load P^*_{cr} on the number of cuts is shown in Figure 5, where, P^*_{cr} is the ratio of destructive (rupturing) loads for the shell with damage and without damage; the symbol "○" shows the values $P^*_{cr,i}$ for each of the k tests of all 288 models depending on the number n of damage to the side surface, and their averaged values are indicated by the symbol "■".

Statistical analysis of the obtained experimental data was carried out to assess the influence of the random nature of the location of the coordinates of the middle of the through rectilinear slits and the angles of their inclination to the generatrix on the side surface of each of the shells on the scatter of the experimental data based on the results of the tests.

To construct the histogram, the test results of all 288 shells models of the specified 11 series were taken with the fixed number of damages (n = 0, 1; 3; 5; 10; 15; 20; 25; 30; 40; 50 pieces), for each of which was tested for k shell models, and for each of the 288 models had a different arrangement of slits. The values of the relative critical force $P_{cr,i}$ of the loss of stability were reductioned to the corresponding samplings which were normalized according to the Equation (1) [25]

$$z_i = \left(P_{cr,i} - P^*_{cr}\right) / S \tag{1}$$

where, $S^2 = \frac{1}{k-1}\sum_{i=1}^{k}\left(P_{cr,i} - P^*_{cr}\right)^2$, $P_{cr,i}$ and P^*_{cr} are the relative critical forces of the ith test and their average value, respectively; and k is the total number of trials.

Next, a normal distribution was restored for each of the samples [25]. Density histograms and theoretical density functions $g(z)$ for the reconstructed distribution of the random value of the relative critical force of the loss of stability for the results of test specified data sets are shown in Figure 6. Despite the random nature of the placement of slits, the deviation of the values $P_{cr,i}$ from the average P^*_{cr} does not exceed 20%.

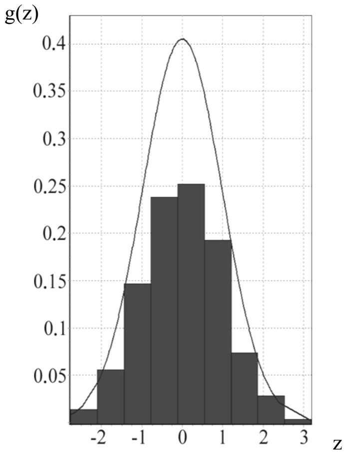

Figure 6. Histogram and density function of the restored distribution of the critical force

Among the features of the behavior of the shell models during the tests, it should be noted a significant drop in the bursting load of the shell (by almost 25%) at the very beginning of the graph (Figure 5), which means that even one damage already significantly reduces the strength of the shells. Further, the rate of reduction of the bearing capacity decreases, and the entire dependence has an uneven character. In particular, an increase in the number of damages in the interval n = 15-25, practically does not affect the decrease in P_{cr}^{*}.

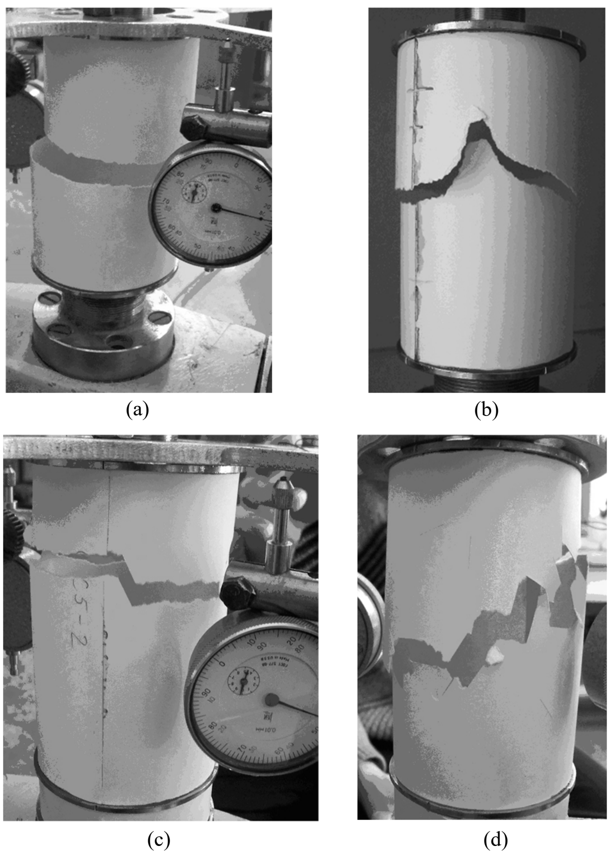

Figure 7. Pictures of shell destructions with randomly n slits (a) n = 0; (b) n = 3; (c) n = 5; (d) n = 30, in longitudinal tension

Photographs of the tested shells with n = 0, 3, 5, 30 damages are shown in Figure 7. The shell without damage destruction along a circular contour, almost along the cross section (Figure 7a). For a small amount (n=1, 3 damages), a "tab" appears on the side opposite to the accumulation of damages during the rupture. And this is natural, since the shell distracted first, along some weakened generatrix line, and then, after skewing, the break line takes the form of a "tongue".

For $n \geq 5$ (Figure 7. b), this phenomenon is not observed, because the damages are already sufficient not to provoke such destruction. At the same time, it becomes more difficult to describe the process and predict the path of shell rupture. From the observations, it can only be noted that this "live cross-section" path is the shortest by which the cross-section of the shell could be covered. The shorter this path, the lower the bearing capacity of the shell.

It should be noted that, for example, with n = 20, the total length of the slits actually reaches the length of the perimeter of the shell. At the same time, its bearing capacity remains at the level of 50% of the undamaged shell (Figure 5). In general, the most dangerous are transverse damages and the accumulation of a collection of damages, in which a certain part of the shell is actually "removed" from the process of ensuring the load-bearing capacity of the shell.

5. CONCLUSIONS

The features of finite-element modeling were investigated and numerical results were obtained for calculating the stress-strain state of a stretched cylindrical shell with a rectilinear cuts-cracks located at different angles to its generator. Sufficiently effective technology of production of identical models and a method of testing cylindrical shells with randomly located damage in the form of rectilinear cuts-cracks of the side surface at axial tension are proposed.

The obtained results of experimental tests of 288 models are presented in the form of pictures of destruction of shells and dependences of destructive loads on the number of the damages.

It is shown that, despite the random location of the lateral cuts-cracks, the deviation of the critical loads from their averaged values does not exceed 20%.

The convergence of numerical and experimental data for the case of one cuts-cracks does not exceed 5%. The specified difference is explained by errors in the measurement of forces and displacements, the determination of the mechanical characteristics of the material, as well as the peculiarities of the compilation of the finite-element calculation scheme in the tasks of calculating tensile shells in the presence of stress concentrators.

The results of the conducted numerical and experimental studies can be a reliable basis for ensuring truth in the construction of appropriate mathematical models and useful for predicting the strength of cylindrical shells when damage to their surface accumulates.

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