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EXPERIMENTAL STUDY OF THE STABILITY OF REINFORCED CYLINDRICAL SHELLS UNDER AXIAL COMPRESSION

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Abstract

*Purpose: Show the real effect of initial imperfections on the upper critical load of cylindrical shells. **Method:** Analysis of experimental data. **Results:** This article presents the results of experimental studies of the stability of cylindrical shells reinforced with stringers with initial imperfections in shape under axial compression. A detailed analysis of the experimental data has been performed. A conclusion is made regarding the stability of cylindrical shells. Recommendations on the directions of further research are given. **Discussion:** The large difference between the experimental and theoretical axial critical loads of cylindrical shells made researchers look for the reasons for this difference. It was considered that one of the main reasons is the presence of initial imperfections in the shells. Then doubts arose as to the veracity of this statement. There were conflicting opinions. It became necessary to find out the real influence of the initial imperfections on the stability of cylindrical shells.*

Keywords: critical load, initial imperfections, displacement, stability, experiment

1. Indroduction

In connection with the use of thin shells in aircraft construction, experiments were carried out with very thin cylindrical shells under axial compression. It turned out that the critical loads of real shells, as a rule, differ significantly from the calculated ones. Many scientists believed that the discrepancy between theory and experiment was mainly due to the initial imperfections of the tested samples.

Then doubts arose as to the veracity of this statement. There have been conflicting opinions, especially regarding reinforced shells.

It became necessary to find out the real influence of the initial imperfections in the shape of the reinforced cylindrical shells on the value of the upper critical loads.

Such research has been performed and presented in this article.

2. Analysis of research and publications

A large number of review papers have been published, in which the state of the stability problem is covered in sufficient detail and there is no need to repeat it. The most extensive material, apparently, is contained in the review [1], where it is noted that the experimental values of stresses are 10–90% of the upper critical stress.

Consider works that are related in their content to the topic of the article.

S.P. Timoshenko [2] obtained a formula for calculating the critical stresses of a freely supported cylindrical circular shell

$$\sigma_*^{e} = \frac{Eh}{\sqrt{3(1-v^2)}R},$$

where
E – Young's modulus; v – Poisson's ratio; R and h – radius and thickness of the shell.

These voltages are called upper or classical.

One of the first, tests for the stability of cylindrical shells and comparison of theoretical and experimental values of axial critical loads, made L. H. Donnell [3]. The experimental values of the critical stresses obtained in these experiments were less than 60% of the theoretical ones. He found that the greater the ratio of the radius to the thickness of the shell, the greater the difference between theory and experiment. To explain this difference, Donnell put forward a theory that takes into account the initial deviations from an ideal cylindrical surface.

Apparently, S.N. Kan and D.E. Lipovskii were the first to study the stability of imperfect ribbed shells [4, 5]. They obtained expressions for the critical stresses of a structurally orthotropic cylindrical shell with an axisymmetric regular deflection.

I. Ya. Amiro, V.A. Zarutskiy, P.S. Polyakov conducted an experimental study [6] of the bearing

capacity of ribbed cylindrical shells under axial compression and the combined action of axial compression and internal pressure. A significant (up to 50%) decrease in the critical load in comparison with the calculated one for perfectly shaped shells was established experimentally. It is noted that with an increase in the number of ribs, the difference between theory and experiment decreases.

The works [4 - 6] do not take into account the eccentricity of the reinforcing ribs.

D. V. Khachinson and D. K. Amazigo presented a study [7] of the sensitivity of loosely supported eccentrically reinforced cylindrical shells of medium length to shape imperfections. The main conclusions made by the authors are that shells with external reinforcement are more sensitive to imperfections in shape than those with internal reinforcement. It is noted that there is a certain critical region of sensitivity to shell imperfections, characterized by a parameter $Z = (L^2/Rh)\sqrt{1 - v^2}$ (where L is the shell length), with external reinforcement under axial compression. The large difference between theoretical and experimental axial loads is due to the influence of axisymmetric deflections.

In the survey report [8], Budyanskiy and Khachinson basically repeat the conclusions of [7]. However, the indicated ranges of sensitivity areas for "weak", "medium" and "strong" reinforcement are very different and therefore cannot be considered reliable.

In the overview report [9] O.I .Terebushko notes that under the action of an axial compressive load, shells with external reinforcement are much more sensitive to initial irregularities than shells reinforced from the inside.

Experimental critical loads close to the upper critical ones were obtained by: R. C. Tennyson, D. B. Muggeridge, R. D. Caswell, V. I. Weingarten, E. J. Morgan, P. Seide, A. V. Pogorelov and others.

The author, together with V.M. Kots and D.E. Lipovskii, carried out an experimental study [10] of the stability of cylindrical shells reinforced with stringers with initial imperfections under axial compression. The complete version of this study is presented in [11]. The research presented in this article is based on the results of this experiment. This study was selected because it describes:
- the initial state of the surface of the shells;
- fixing the edges of the shell in the support rings;
- characteristics of the materials from which the shells are made;
- stress – strain state of the shells in compression;

- the behavior of the shell – compressing device during buckling of the shell. In other words: everything is known that is necessary for a comprehensive analysis of experimental data.

3. The purpose of the work

The purpose of the work is to show the real effect of initial imperfections on the upper critical load of cylindrical shells.

4. Solution method

Solution method is analysis of experimental data.

5. Solution of the problem

In an experimental study, the effect on the stability of shells reinforced with stringers was studied:
- initial imperfections in the shape of the median surface;
- uneven loading of shells;
- the eccentricity of the reinforcing elements in relation to the skin.

The process of buckling of shells was also studied.

The study was carried out on six series of shells. The first series consisted of 12, the second – 8, the third, fourth, fifth and sixth – of 6 shells each.

The casings of the first, second and third series were made of L62TM sheet brass (E = 1 * 105MPa). These shells had longitudinal ribs of rectangular cross-section located on their outer surface. In this case, the height of the ribs and their number varied. The connection of the ribs with the skin was carried out with BF-6 glue.

The shells of the fourth, fifth and sixth series were made of AMTsaM aluminum alloy (E = 0.71 * 105MPa) at the Kharkov Aviation Plant. The shells were reinforced with 16 corner-section stringers that were spot-welded to the shell at 5mm pitch.

All shells were subjected to thorough mechanical treatment associated with leveling their ends under the plane.

In order to exclude destruction due to the edge effect when the shells are loaded with axial forces, as well as to give their ends a circular shape, special support rings were provided. The surface of these rings, adjacent to the casing, was milled according to the second class of accuracy. This was necessary, since in the future, the areas of the shells near their ends were taken as basic when measuring the initial deflections in their middle surface.

When testing casings with internal stringers, profiled cutouts for stringers were provided in the support rings.

To test shells with external stringers, segment inserts were included in the support device, with the help of which the shell was pressed against the support ring by tightening bands.

With the help of a special setup along 32 generatrices of each shell, the initial deflections in their middle surface were measured.

In addition, measurements of the skin and stringers (thickness, height and width of the shelf, etc.) were made and their average values were determined. The measurement accuracy corresponded to 0.002 mm.

Deformations in the shell during its loading were measured using a tensometric device UTS-VT-12 and recorded on photographic paper using loop oscilloscopes of the N-700 type. The deviation from linearity of the measuring channels in the device UTS-VT-12 does not exceed 2%

The shells were loaded using an IPS-200 press (series 1,2,3) and a GSM-50 universal testing machine (series 4,5,6).

For continuous recording of loads in the hydraulic systems of the press and testing machine, special sensors were connected, the readings of which were also recorded using oscilloscopes. To create uniform loading of the shells along their perimeter, a stepwise stress equalization was applied:
- at 4910 N, 6880N and 9820N (for shells of the first and second series) by adjusting the load plate of the IPS-200 press;
- at 4910 N, 9820N and 14730N (for shells of the fourth, fifth and sixth series). In the GSM-50 machine, a special load ring was used, which was strictly centered in relation to the load cushion.
The uniformity of loading was controlled using strain gauges installed near the ends of the shell. In most cases, the uneven loading did not exceed (1.5-2.0)% of the load.

The shells of the third series (table 3) were tested with significant initial disturbances:
- with great value $f_0/h_{sr} > 1,4$;
- with great uneven loading $\Delta\sigma_{max} > 40\%$;
- shell 6 was loaded only along ½ of the perimeter.

For casings of the sixth series (table 6), by their compression with the help of special devices, artificial axisymmetric dents.
The processing of the obtained oscillograms allowed:

- to clarify the value of the critical load (which was recorded using the measuring pressure gauges of the press and the testing machine);
- to establish more reliably the zones of buckling of the shell;
- find geometric deviations of the shell surface from an ideal cylinder;
- to specify the value of deviations from ideal loading;
- describe the behavior of the shell - loading device system during testing.

Exploring the surface of real shells in the subcritical state, we see that the initial geometric imperfections (different in the samples under study and located in different places of the shells) behave differently during loading. Some develop quickly, others slowly; some develop constantly, others stop in their development. One and the same death can constantly develop; may pause in development and then develop again. There is a redistribution of stresses in the shell, and, therefore, the mentally selected shell rods "bear" a different external load.

When a critical state is reached, the following occurs instantly:
- the cotton shell loses its stability and passes into a new equilibrium state;
- at the same time, the readings of the manometer (power meter) fall sharply (due to inertia, the arrow falls below zero), and then rapidly increases to a value less than the maximum;
- the supply of fluid to the loading system is stopped (the hydraulic press is turned off):
- the distance between the load plates does not change, since the inertia of the load system is large, the loading occurs very slowly, the hydraulic press turns off quickly, the liquid is practically incompressible, and the loss of stability occurs instantly.
A sharp change in the pressure gauge readings at the time of loss of stability suggests that:
- the pressure in the load system drops instantly, and, therefore, the axial compressive load instantly drops;
- load plates of the hydraulic press do not track the movements of the ends of the shell.
Visual observations are confirmed by recordings of shell deformations and changes in external load using measuring equipment.
In most cases, the pattern of wave formation was typical, corresponding to the general loss of stability.

For shell 6 of the third series, in which loading was carried out only along ½ of the perimeter, the wave formation had a specific character with the

formation of dents elongated along the shell axis and located at a certain angle to its generatrix. Here the wave formation pattern resembled the loss of stability of cylindrical shells during torsion.

The test results are shown in tables 1-6. The tables indicate:

L – the length of the shell (the total length of the shell minus the sections adjacent to the support rings);

R – the shell radius;

h_{sr} – average skin thickness, defined as the arithmetic mean of all thicknesses;

n_1 – number of stringers;

h_1 – reduced sheathing thickness, including stringers;

P_e – the critical experimental force;

$P_*^{в} = 2\pi R h_1 \sigma_*^{в}$ – upper critical force. When determining it, it was assumed that the shells are structurally orthotropic and the ratio R/h_1;

f_0 – amplitude of axisymmetric drop;

$f_н$ – amplitude of non-axisymmetric drop;

$P_e max$ – maximum value of the experimental strength of the same type of shells;

$$\Delta_e = \frac{P_{e\max} - P_e}{P_{e\max}} 100 \qquad \Delta_* = \frac{P_{e\max} - P_e}{P_*^{в}} 100$$
and

show the real influence of the initial imperfections on the experimental and upper critical forces, respectively.

Table 1

Brass shells with 8 stringers

№	$\dfrac{L}{R}$	R, mm	$\dfrac{R}{h_{sr}}$	n_1, pc	$\dfrac{R}{h_1}$	$\dfrac{f_0}{h_{sr}}$	P_e, kN	$P_*^{в}$, kN	$\dfrac{P_e}{P_*^{в}}$	Δ_e, %	Δ_*, %
					low stringers						
1			278		214	0,184	17,46	45,48	0,382	0,0	0,0
2			277		227	0,219	15,49	40,64	0,381	11,3	4,8
3	3,18	75	274	8	226	0,263	15,20	40,82	0,372	12,9	5,5
4			272		225	0,278	15,00	41,01	0,366	14	6,0
5			277		217	0,281	17,06	45,09	0,378	2,2	0,9
6			283		220	0,406	16,08	43,21	0,372	7,9	3,2
					tall stringers						
7			283		200	0,143	16,87	51,72	0,326	4,4	1,5
8			276		191	0,183	17,65	57,09	0,309	0.0	0.0
9	3,18	75	276	8	191	0,216	16,97	57,09	0,297	3,9	1,2
10			266		191	0,273	17,26	57,09	0,302	2,2	0,7
11			266		196	0,463	16,48	54,20	0,303	6,7	2,2
12			266		196	0,512	16,38	54,20	0,302	7,2	2,4

Table 2

Brass shells with 16 stringers

№	$\dfrac{L}{R}$	R, mm	$\dfrac{R}{h_{sr}}$	n_1, pc	$\dfrac{R}{h_1}$	$\dfrac{f_0}{h_{sr}}$	P_e, kN	$P_*^{в}$, kN	$\dfrac{P_e}{P_*^{в}}$	Δ_e, %	Δ_*, %
					low stringers						
1			275		188	0,121	22,06	59,43	0,371	0,0	0,0
2	3,18	75	268	16	188	0,283	21,67	59,43	0,364	1,8	0,7
3			268		192	0,536	20,59	56,79	0,362	6,7	2,6
					tall stringers						
4			286		148	0,196	25,30	96,34	0,262	4,4	1,2
5			270		148	0,203	26,48	96,34	0,275	0,0	0,0
6	3,18	75	266	16	148	0,242	24,52	96,34	0,254	7,4	2,0
7			266		149	0,340	24,52	93,81	0,261	7,4	2,1
8			266		154	0,478	24,03	88,97	0,270	9,3	2,8

Table 3

Brass shells with significant initial perturbations

№	$\dfrac{L}{R}$	R, mm	$\dfrac{R}{h_{sr}}$	n_1, pc	$\dfrac{R}{h_1}$	$\dfrac{f_0}{h_{sr}}$	$\Delta\sigma_{max}$ %	P_e, kN	$P_*^{\text{в}}$, kN	$\dfrac{P_e}{P_*^{\text{в}}}$	$\Delta_{\text{э}}$, %	Δ_*, %
							low stringers					
1			276		196	1,47	15,3	12,91	54,55	0,237	21,7	6,5
2			281		197	1,43	18,7	14,77	54,03	0,273	10,4	3,2
3	3,18	75	266	8	220	0,193	40,2	12,85	43,29	0,297	20,1	7,3
4			268		192	0,184	39,4	13,34	56,85	0,235	19,0	7,6
5			266	16	187	0,261	46,0	17,65	59,92	0,295	20,0	7,4
6			266	8	211	0,225	-	10,98	47,10	0,231	37,1	13,8

Table 4

Shells made of aluminum alloy

№	$\dfrac{L}{R}$	R, mm	$\dfrac{R}{h_{sr}}$	$\dfrac{R}{h_1}$	$\dfrac{f_0}{h_{sr}}$	$\dfrac{f_{\text{н}}}{h_{sr}}$	P_e, kN	$P_*^{\text{в}}$, kN	$\dfrac{P_e}{P_*^{\text{в}}}$	Δ_{e}, %	Δ_*, %
					16 stringers inside						
1	2,6	200	312	229	0,083	0,93	50,01	202,18	0,247	0,0	0,0
2			258	174	0,038	1,06	50,01	200,39	0,250	0,00	0,0
3	2,64	160	254	176	0,071	1,37	48,05	197,13	0,244	3,92	1,0
4			258	174	0,110	1,13	47,07	200,39	0,235	5,88	1,5
5			250	176	0,132	1,05	48,25	196,91	0,245	1,21	0,3
6	2,66	120	188	118	0,048	0,88	47,07	247,88	0,190	0,00	0,0

Table 5

Shells made of aluminum alloy

№	$\dfrac{L}{R}$	R, mm	$\dfrac{R}{h_{sr}}$	$\dfrac{R}{h_1}$	$\dfrac{f_0}{h_{sr}}$	$\dfrac{f_{\text{н}}}{h_{sr}}$	P_e, kN	$P_*^{\text{в}}$, kN	$\dfrac{P_e}{P_*^{\text{в}}}$	Δ_{e}, %	Δ_*, %
					16 stringers outside						
1	2,6	200	317	229	0,149	1,78	47,27	202,18	0,234	00	00
2			258	173	0,063	1,05	49,23	202,58	0,243	1,56	0,4
3	2,64	160	258	174	0,120	1,59	46,09	200,39	0,230	5,62	1,4
4			254	173	0,257	1,77	48,84	202,58	0,241	0,00	0,0
5	2,66	120	189	119	0,083	0,95	47,07	240,65	0,196	0,00	0,0
6			190	120	0,104	1,19	43,54	238,27	0,183	7,50	1,48

Table 6

Aluminum alloy shells with artificial axisymmetric dents

№	$\dfrac{L}{R}$	R, mm	$\dfrac{R}{h_{sr}}$	$\dfrac{R}{h_1}$	$\dfrac{f_0}{h_{sr}}$	$\dfrac{f_{\text{н}}}{h_{sr}}$	P_e, kN	$P_*^{\text{в}}$, kN	$\dfrac{P_e}{P_*^{\text{в}}}$	Δ_{e}, %	Δ_*, %
					16 stringers inside						
1	2,6	200	308	230	0,095	1,83	44,72	199,87	0,224	10,6	2,66
2	2,64	160	254	173	0,071	1,25	45,89	202,58	0,227	8,23	2,03
					16 stringers outside						
3	2,6	200	320	233	0,181	2,14	44,13	195,30	0,226	6,6	2,91
4	2,64	160	263	178	0,175	1,31	43,35	193,04	0,225	11,24	2,90
5			258	174	0,201	1,25	43,15	200,39	0,215	11,66	3,00
6	2,66	120	190	120	1,035	1,02	42,36	238,27	0,178	10,00	1,96

6. Results

Analyzing the results obtained, we see the following:

- from tables 1, 2, 4, 5 it can be seen (see columns Δe) that bends in general and axisymmetric, in particular, do not have a noticeable effect on the magnitude of experimental critical forces;

- a significant decrease in the experimental critical forces for shells of series 3 and 6 indicates the sensitivity of ribbed shells to axisymmetric components of the initial deflection and non-uniformity of loading. However, these are specially created imperfections of large sizes;

- the significant decrease in critical forces obtained in the experiment in comparison with ideal shells cannot be explained by the presence of small defects in the shape of the middle surface (see columns Δ *, except for shells 3 and 6 of series). The decline is less than 6%, not 62 - 82% (see columns $\frac{P_e}{P_*^e}$);

- the influence of the eccentricity of the reinforcing elements in relation to the skin on the value of the critical forces was not found. This, apparently, is explained by the fact that in most cases the quality of manufacture of shells with outer ribs was lower than - shells with inner ribs;

 - the experiment confirmed the correctness of the interpretation of the process of buckling of the shell with the loss of stability stated in [12].

When calculating the critical forces of ideal shells, it is necessary to pay attention to the choice of the parameters E and ν. If selected incorrectly, results can vary significantly. So, for example,

for steel:

*E = (2.0-2.2) * 105 MPa;*

ν = (0.24 - 0.3);

Δ = 11.2%;

for brass: *E = (0.91 - 1.0)) * 105 MPa;*

ν = (0.32 - 0.42);

Δ = 11.47%; this is much more than the influence of the initial imperfections.

7. Conclusions

1. Initial defects in the shape of the middle surface of a cylindrical shell compressed by axial forces are not the cause of large discrepancies between theoretical and experimental critical loads.

2. When solving the problem of the stability of a cylindrical shell under axial compression, it is imperative to take into account the change in the external load at the moment of loss of stability.

3. The problem of stability has not been finally solved. We must look for other factors. Such factors can be:

- accurate accounting of boundary conditions;

- pay special attention to the correct choice of additional displacements corresponding to the boundary conditions and the physical meaning of the problem. The final result depends on this [12];

- problem solving in a dynamic setting; - taking into account the moment of the subcritical state of the shell.

Note* In addition to the author, the following took part in the development and conduct of the experiment: Bessonov N.B., Ivashkevich V.V., Kots V.M., Lipovskiy D.E., Nazarov V.A., Novichenok M.E., Petrichenko V.A.

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В. О. Тодчук

Експериментальне дослідження стійкості підкріплених циліндричних оболонок при осьовому стисканні

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Мета: показати реальний вплив початкових недосконалостей на верхнює критичне навантаження циліндричних оболонок. **Метод:** Аналіз експериментальних даних. **Результати:** У статті представлені результати експериментальних досліджень стійкості циліндричних оболонок, підкріплених стрінгерами з початковими несовешенствамі форми, при осьовому стисненні. Проведено детальний аналіз експериментальних даних. Зроблено висновок про стійкість циліндричних оболонок. Дано рекомендації щодо напрямків подальших досліджень. **Обговорення:** велика різниця між експериментальними і теоретичними осьовими критичними навантаженнями циліндричних оболонок змусила дослідників шукати причини цієї відмінності. Вважалося, що однією з основних причин є наявність первинних дефектів в оболонках. Потім виникли сумніви в правдивості цього твердження. Були суперечливі думки. Виникла необхідність з'ясувати реальний вплив початкових дефектів на стійкість циліндричних оболонок.

Ключові слова: критичне навантаження, початкові дефекти, переміщення, стійкість, експеримент.

В. А. Тодчук

Экспериментальное исследование устойчивости подкрепленных цилиндрических оболочек при осевом сжатии

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Цель: показать реальное влияние начальных несовершенств на верхнюю критическую нагрузку цилиндрических оболочек. **Метод:** Анализ экспериментальных данных. **Результаты:** В статье представлены результаты экспериментальных исследований устойчивости цилиндрических оболочек, подкрепленных стрингерами с начальными несовешенствами формы, при осевом сжатии. Проведен подробный анализ экспериментальных данных. Сделан вывод об устойчивости цилиндрических оболочек. Даны рекомендации по направлениям дальнейших исследований. **Обсуждение:** большая разница между экспериментальными и теоретическими осевыми критическими нагрузками цилиндрических оболочек заставила исследователей искать причины этого различия. Считалось, что одной из основных причин является наличие первоначальных дефектов в оболочках. Затем возникли сомнения в правдивости этого утверждения. Были противоречивые мнения. Возникла необходимость выяснить реальное влияние начальных дефектов на устойчивость цилиндрических оболочек.

Ключевые слова: критическая нагрузка, начальные дефекты, перемещение, устойчивость, эксперимент.

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