Testing of thin-walled cylindrical shells made of steel 45 in solving the problem of stability

S V Cheremnykh

Tver state technical university, Naberezhnaya Afanasiya Nikitina 22, Tver, Russia

E-mail: cheremnykh_s.v@mail.ru

Abstract: The theory of shell stability beyond the elastic limit is considered when studying the issue of testing, diagnostics and quality control of materials made of steel shells of round cylindrical cross-section. Since, depending on the history of the loading process of an elastic-plastic system, its final deformation corresponding to the same external load is different, by studying the inelastic stability problems should proceed from the analysis of simple combined loading processes that lead to different critical deformations. Not only the question of the loading history, which leads to the minimum value of critical loads, but also the question of choosing and implementing such a loading history of a given system, which gives it the maximum value of the stability limit and the load-bearing capacity of the material, is solved. Innovative methods are proposed for solving the problem of shell stability in tests of complex loading of steel cylindrical shells by internal pressure, compression and torsion in the direction of structural mechanics and mechanics of deformable solids, implemented on an experimental complex. The obtained results allow us to determine the loss of stability of the material beyond the elastic limit with a sufficient degree of accuracy for a given cross-section and the loading trajectory of a cylindrical thin-walled shell made of steel 45, while the correctness of the obtained results is justified experimentally.

1. Introduction
The thoughts of a modern engineer about the rational use of materials by reducing the coefficients of the margin of safety and stability can be achieved by improving the calculation methods using software systems, and by using the resource of materials when taking into account the elastic-plastic stage of deformation.

One of the most optimal cross-sections in construction is circular. Depending on the industry, circular sections are used in the oil and gas and chemical industries, laboratories, aircraft construction, mechanical engineering, industrial and civil areas. Along with the variety of cross-sections, tubular samples also have different properties and composition of the material from which they are made [1-7].

For educational and scientific purposes, samples made in the form of thin-walled cylindrical shells made of various, at the same time common steels belonging to carbon steels of ordinary quality are currently used to study circular cross-sections. In turn, it is worth noting that the use of thin-walled shells allows us to reveal the full potential of a circular closed section, study its behavior under various loads and impacts, systematize the solutions obtained and draw decisive conclusions about the use of these materials for the development of modern construction mechanics and mechanics of deformable solids in general [8, 9].
In addition to the test samples, a mechanical researcher needs a modern complex that can fully reveal all the properties of the test sample. These conditions are met by the automated calculation and experimental complex CH-computer, developed in the laboratory of mechanical Tests of the Department of Material Resistance, Theory of Elasticity and Plasticity of Tver State Technical University.

Experiments to determine the point of loss of stability of shells under simple loading beyond the elastic limit were the first step in the experimental verification of the reliability of various versions of the stability theory. However, these studies were carried out mainly for a limited class of plane trajectories, for example, in torsion compression or in compression with internal pressure transmitted to the shell. A large number of problems for stability beyond the elastic limit under combined loading on a test machine CH-computer were solved by mechanical scientists of the Tver school on the basis of the theory of V. G. Zubchaninov [9-11].

Nowadays, the effect of complex subcritical loading on the critical value of the stress modulus has been studied quite well experimentally. The accumulation of new theoretical and experimental data in the study of the stability of thin-walled elastic-plastic shell systems under complex stress conditions is of particular importance for the development of effective methods for engineering calculation of structures. Many researchers indicate the insignificance of this effect, but there are no clear and quantitatively comparable estimates on this issue for different types of materials and loading paths. The question of changes in the values of critical deformations depending on the type of loading trajectories is practically not touched upon in the estimates. There is no comparison of experimental data with the results of theoretical calculations for some classes of curved paths [12-15].

It’s worth to note that the issues of shell stability in the implementation of simple subcritical processes are not fully investigated and there is a need for experimental studies.

2. Methods
The performed experimental studies in the field of stability of cylindrical shells are difficult to compare in terms of results and cannot unambiguously answer the question of the degree of influence of complex combined loading on the critical parameters of stresses and strains. At the same time evaluation of critical parameters of deformation in many of the works were not carried out. However, for example, for shells of low flexibility, which lose stability under developed plastic deformations, a slight difference in stresses can lead to a significant change in the values of critical deformations. Therefore, in studying the influence of the history of complex loading on the processes of structural stability loss, attention should be paid to the study of processes implemented in the deformation space, that is, the given path should be tracked not by loads, but by deformations, with parallel measurement of the parameters of the stress state.

In considering the problems of elastic-plastic stability of shells under various combinations of loads, taking into account the effects of complex loading, researchers used many variants of the theory of plasticity. Thus, the question of the physical reliability of the determining relations based on different versions of the theory of plasticity and used to describe the deformation process becomes particularly important, since they often lead to different results in practice. The answer to this question cannot be given without performing experimental studies, because many effects of complex loading were obtained first in an experiment, and then described theoretically.

Experiments and studies with loading thin-walled cylindrical shells with axial compressive force, torsion and internal pressure to the point of loss of stability were the first step in experimental verification of the validity of various versions of the theory of plasticity used in solving problems of shell stability beyond the elastic limit.

The most detailed experimental loss of stability under complex loading is studied in the works of V. G. Zubchaninov and his co-authors on an experimental complex of CH-computers [8, 9]. However, there is no determination of the criterion of stability loss under combined loading based on experimental dependences in the solved problems.

To determine the loss of stability in experiments when loading shells with a combined force, we consider the process of three-stage loading of the shell in accordance with figure 1, where at the first
stage the material is stretched to the level of radius R, after -1.25 turns of the trajectory of constant curvature on the second link and compression to loss of stability. Figure 2 shows the response to the realized deformation trajectory – the stress trajectory in the stress space. The triangle here and in the following figures will mark the experimental point of loss of stability of the sample.

![Figure 1. Trajectory of deformation of the steel shell 45.](image1)

![Figure 2. Stress trajectory of the steel shell 45.](image2)

3. Results
According to the results of the experiment, figure 3 shows the diagram of material deformation for the process corresponding to figure 1. The accepted values of the shear modulus fully correspond to the linear-elastic section of the experimental deformation diagram.

![Figure 3. Deformation diagram of the material steel 45.](image3)

As you can see, graphs 3 are oscillatory in nature, different from universal dependencies. It is also worth noting that after the break of the paths, there is a «dive» of the stress vector module.

Thin-walled tubes made of 45 steel were used as test samples. Thin-walled tubular samples had a wall thickness h=1 mm, a radius of the middle surface 15 mm, and a length of the working part 90 mm. The temperature of the material did not differ much from the average ambient temperature, which was 20°C. The shear modulus of the material was assumed to be 78 GPa, and the elastic modulus of steel 2.1*10^5 MPa.
Visually, the loss of stability during the experiment is estimated by a sudden change in the shape of the sample with the formation of bulges and dents on the surface of the shell, which causes a sharp change in the angle of twisting and/or convergence of its ends (figure 4).

![Figure 4. Samples of steel 45 shells before testing (left) and after testing (right)](image)

Further, the graphical and numerical analysis of experimental results the time of buckling is determined by the deviation of the deformation path from a given program of the experiment that a population is characterized by rapid change in the value derived from the component of the vector of deformations $\mathcal{E}_1$, $\mathcal{E}_3$, at monotonically increasing loading parameter – the arc length of the deformation path. Figures 5 and 6 show locals train diagrams.

![Figure 5. Local charts of deformation $\mathcal{E}_1 = S$.](image)

![Figure 6. Local charts of deformation $\mathcal{E}_3 = S$.](image)

4. Conclusions

Processing of experimental data on the processes of complex loading and deformation of materials involves obtaining dependences for functions that determine the vector and scalar properties of materials based on the used determining relations of the theory of plasticity, and constructing experimental graphs based on these dependences. It is impossible to obtain universal equations for processing experimental data that would be applicable to arbitrary paths of complex loading and deformation. This is because, for example, the vector properties of materials when conducting experiments in stress and strain spaces characterize different functions. The number of plasticity functions used in various defining relationships and their physical nature also differ. In addition, the equations for processing experimental data are usually semi-analytical in nature, which makes them dependent on the class of a particular implemented trajectory and the accuracy of its assignment.
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