Calculation and experimental substantiation of optimal sizes of large-size tanks filled with bulk material

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Abstract. The numerical calculation of elastic-plastic deformation and limiting states of shell structures of large-size tanks filled with bulk material is carried out. The solution of a three-dimensional geometrically and physically nonlinear problem is based on the finite element method and an explicit cross-type time integration scheme. The critical load at which the tank loses stability is determined. The influence of the length of the tank on its stability is investigated.

1. Introduction
The problem of deformation and loss of stability of large-sized containers for automobile transportation of bulk materials is considered. The investigated design is a thin-walled shell. When unloading, it is preloaded with an internal pressure of 0.1 MPa and tilted at an angle of 40.29°. To do this, one end of the tank is hinged to the frame, and the other is lifted by a telescopic device. Under the influence of the weight load, the container body bends when lifting. This process can be accompanied by the formation of plastic deformations in the central region and loss of stability. Therefore, to justify the compliance of the designed structure with the requirements of regulatory documents, it is necessary to solve the three-dimensional geometrically and physically nonlinear problem of stability of a closed shell filled with a bulk material, taking into account the moment of stress-strain state, shells. The most likely area of loss of stability, where the greatest stresses occur, is the middle part of the cylindrical.

At present, the problem under consideration is not sufficiently studied. Imperfections of the shell shape, loading conditions and other factors have a great influence on the critical load [1-5] in the problems of loss of stability of thin-walled cylindrical shells during bending without taking into account the influence of backfill on stability and the magnitude of the critical load were investigated.

2. Experimental investigation of the stability of thin-walled shells.
The experiments were performed on thin-walled steel pipes (Fig.1), outer diameter R=8 cm, wall thickness h=0.075 cm (h/R=0.0094), length L=250 cm. The pipe with sand was installed at the ends on two supports, the distance between which is 240 cm. As shown by preliminary studies under the influence of its own weight and the weight of sand, the shell under study does not lose stability. Therefore, it was loaded with additional transverse forces created by the Jack through the dynamometer DOSM-3-3 and transmitted through the loading device. The distance between the supports of the loading device is 60 cm. The middle part of the pipe (the zone of loss of stability) remained free from the load. The deflection of the pipe at the end of the length was measured by an indicator of the clock type ICH-10. Experimental studies were carried out according to the following method. The sample after installation on the supports was loaded with transverse forces, the value of which increased in increments of 0.5 kN. As it approached the critical value, the loading step decreased to 0.1 kN. At each loading step, the deflection of the shell in the center of the lower surface
of the shell was fixed. Five samples were tested. After statistical processing of the measurement results, a critical value of the load created by the Jack was obtained, equal to 4.9 kN. The deflection of the shell, at which the critical load was reached, was 0.99 cm. according to experimental data, when the critical load is reached, the shell loses stability and local transverse dents are formed in the middle part of its surface from the side of the loading device, located in a staggered order.

The experimentally obtained critical load value and the form of stability loss for samples without filler are in good agreement with the experimental data of other authors.

3. Analysis of stability of freely supported cylindrical shells with filler during bending under the action of its own weight and shear forces.

The problem of stability of freely supported cylindrical shells filled with bulk material under bending under the action of its own weight and transverse shear forces is considered. The weight load was given in calculations by the analytical function depending on spatial variables and on time. The distribution of the weight load along the axis of rotation of the shell was assumed to be uniform. The backfill weight was assumed to be \( P_0 = 60 \text{ kg} \). the Loading device was modeled by an elastic body that moves in the vertical direction at a constant speed of 1 m / s. in Fig. 2, the zones of loss of stability of the shell in the residual position obtained in the calculation and experiment are compared.

As the analysis of the results of calculations and experiments shows, when the loading device is shifted by 10 mm, a local transverse dent of the rhombic type is formed in the middle part of the cylindrical shell. With further loading, the length of the dent increases in the circumferential direction until it reaches approximately half the diameter of the shell, after which its development stops. The subsequent displacement of the loading device leads to the expansion of the zone of loss of stability of the shell in the circumferential direction due to the formation of new dents staggered relative to the first. Comparative analysis of the results of numerical and experimental studies showed that the developed computational model qualitatively correctly and with acceptable accuracy for engineering practice describes the elastic-plastic deformation, loss of stability and supercritical behavior of a thin-walled cylindrical shell filled with bulk material during bending.
4. Method for determining the critical weight load leading to the loss of stability of the cylindrical shell of the tank

In the calculations, the capacity was modeled by a closed cylindrical shell (h=0.5 cm, R/h = 255, L/R =12.5), which at the ends rested on fixed, non-deformable plates. The shell is made of AMg5. To simulate the quasi-static loading mode, the change in internal pressure in time when solving the problem in a dynamic formulation is given by the formula:

\[
P(t) = \begin{cases} \frac{p_0}{t_0}, & t \leq t_0 \\ p_0, & t > t_0 \end{cases}
\]

where \( p_0 = 1 \)At. To reduce the influence of the dynamic component, the pressure rise time \( t_0 \) is taken at least two to three periods of oscillation of the tank in the lowest form.

It is assumed that the container is completely filled with bulk material. The distribution of the weight load along the axis of rotation of the shell is assumed to be uniform, and in the cross section the pressure change \( P_\varphi \) by rotation is given by the formula:

\[
P_\varphi = P_1 \times \sin(\varphi/2), \quad 0 \leq \varphi \leq 2\pi
\]

The value \( P_1 \) is determined from the condition:

\[
\int_0^{2\pi} P_\varphi d\varphi dx = P_{\text{lo}}
\]

where = 400 kN-permissible weight of bulk cargo. The change in weight load over time was given by the formula:

\[
P = \begin{cases} 0, & t \leq t_0 \\ k \times \frac{P_\varphi(t-t_0)}{(t_1-t_0)}, & t_0 \leq t \leq t_1 \\ k \times P_\varphi, & t > t_1 \end{cases}
\]

where \( k \) is the stock ratio. The values \( t_0, t_1 \) in formulas (1) – (4) were determined based on frequency analysis and subsequently corrected in accordance with the results of numerical experiments.

Let us consider the results of numerical studies performed on the basis of the computer system of finite element analysis "Dynamics-3" [9, 10] in a three-dimensional formulation. Preliminary verification of the system "Dynamics-3" was carried out on a number of test problems of stability of model samples (shells of rotation) under similar loading conditions, which showed good compliance with experimental data [11].

The results of solving the problem are shown in Fig. 3. For rice.3 shows the shape of the thin-walled structure at different stages of loading, determined by the ratio F/P of the weight load to the permissible weight of the load.
Figure 3. The form of buckling of the shell

The analysis of the calculation results shows that when the weight load reaches a value equal to 4.2 of the permissible maximum weight of the load, two transverse folds are formed in the middle part of the cylindrical shell. Subsequently, an increase in the weight load leads to the expansion of this zone and an increase in the number of folds. Longitudinal stresses in the corrugation zone at the moment of loss of stability change sign (compressive stresses pass into tensile). At the same time, their value exceeds the yield strength, which indicates the occurrence of plastic deformations in this zone.

Thus, in the considered design the factor of a stock k for critical loading makes 4.2 to admissible weight of the transported cargo. It is possible to draw a conclusion-the tank presented in the project does not lose stability during lifting for unloading at observance of the recommended technology: admissible weight does not exceed 400 kN.

5. Analysis of the influence of the length of the tank for the transport of bulk materials on the critical bending load

For comparison, numerical studies of deformation and loss of stability of a closed cylindrical shell L/R= 9.28, R/h = 255, h=0.5 cm (the length of the shell is reduced by 1.35 times) were carried out. The permissible weight of the transported cargo in this case is 296 kN. Two variants of shell loading were considered: a) weight load and b) internal pressure plus weight load. It was assumed that the weight load P is applied on the lower half of the shell and evenly distributed along the axis of rotation. The results of solving the problem are shown in Fig. 4, shows the forms of the thin-walled structure at different times obtained in the first and second versions of the loading.
Figure 4. Forms of buckling of the shell under loading a) by weight load and b) by internal pressure plus weight load

In the first variant of the problem at the initial stage of loading there is a change in the shape of the cross-section of the shell in the Central part, the cross-section of the shell acquires a teardrop shape over time. At a load value of \( P \approx 3P_0 \), vertical folds are formed in the middle part of the cylindrical shell. Subsequent loading leads to an increase in the number of folds and their sizes. At \( P/P_0 \approx 5 \), a transverse horizontal dent is formed in the upper part of the shell. Over time, it increases and leads to a General loss of stability of the shell.

In the lower part of the shell, the tensile longitudinal stresses in the Central cross-section exceed the yield strength, which leads to the appearance of plastic deformations. Longitudinal stresses in the corrugation zone after loss of stability change sign (compressive stresses pass into tensile). At the same time, their value also reaches the yield point.

Thus, in the first variant of the problem (only the weight load is valid), the stock factor \( k = P_c / P_0 \) (the ratio of the critical load to the permissible weight of the transported cargo) of the tank is 5.

When combined loading by weight load and internal pressure (the second variant of the problem), the critical load value increases by 1.76 times and the safety factor \( k \) becomes equal to 8.8. The folding zone narrows and the size of the folds decreases. The lower stretched part of the shell is deformed elastically, the amplitude of oscillations of longitudinal stresses in the zone of folding before the loss of stability is significantly reduced. Reducing the length of the shell by 1.35 times increases the critical load value by more than 2 times.

6. Conclusions

1. The computational model qualitatively correctly and with acceptable accuracy describes the elastic-plastic deformation and loss of stability of a thin-walled cylindrical shell with a loose filler during bending. The moment scheme of FEM at small deformations of transverse shear allows to solve problems of stability of thin-walled elastic-plastic shells on a grid with one layer of finite elements in thickness.

2. The tank under consideration, filled with 100% bulk material, in the absence of internal pressure, withstands a distributed transverse load exceeding 4 times the permissible weight of the project, and the tank, loaded half, loses stability when the permissible weight of the cargo is twice exceeded.
3. Taking into account the results of verification calculations, it can be said that the tank presented in the project does not lose stability in the process of lifting for unloading, subject to the recommended technology: the transported weight does not exceed 400 kN.

4. Reducing the length of the cylindrical shell of the housing by 1.35 times increases the value of the critical load by more than 2 times.

References

[1] N.A. Abrosimov, V.G. Bazhenov Nonlinear problems of dynamics of composite structures. Monograph. N. Novgorod: publishing house of NNSU, 2002. 400 PP. (In Russian).

[2] A.S. Volmir, Stability of deformable systems (Science, Moscow, 1967) (In Russian).

[3] I. I. Vorovich, Mathematical problems of the nonlinear theory of shallow shells. (Science, Moscow, 1989) (In Russian).

[4] E. I. Grigolyuk, V.V. Kabanov Stability of shells. (Science, Moscow, 1978) (In Russian).

[5] V.S. Gudramovich, Stability of elastic-plastic shells (Naukova Dumka, Kiev, 1987). (In Russian) (In Russian).

[6] L.P. Zheleznov, V.V. Kabanov Stability of a circular cylindrical shell when bending by force through a pad // Applied mechanics. 25 (1989) 8. (In Russian).

[7] D.V. Boyko, L.P. Zheleznov, V.V. Kabanov Investigation of nonlinear deformation and stability of discretely reinforced elliptical cylindrical shells under transverse bending // Applied mechanics and technical physics 2 (2012) 111. (In Russian).

[8] D.V. Boyko, L.P. Zheleznov, V.V. Kabanov Investigation of nonlinear deformation and stability of non-circular cylindrical shells under transverse bending // Journal of Russian Academy of Sciences. Mechanics of Solids 2 (2012) 59. (In Russian).

[9] Computer complex «Dynamics -3». Scientific and technical center for nuclear and radiation safety. Certification passport of the software. Registration passport of certification of PS No. 325 of 18.04.2013.

[10] Software product "Package of applied programs for solving three-dimensional problems of unsteady deformation of structures including massive bodies and shells," Dynamics-3 "(PPP "Dynamics-3"): Certificate of conformity of the state standard of Russia no. ROSS RU. ME20.H00338.

[11] Bazhenov V. G., Kibets A. I., Petrov M. V., Fedorova T. G., and others. Experimental and theoretical study of nonlinear deformation and loss of stability of shells of rotation during bending // Problems of strength and plasticity. Vol. 72. Nizhny Novgorod: NSU Publishing house, 2010. Pp. 80-85. (In Russian).