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V.R. Ibnoyaminov. **Bearing Capacity of the Underwater Pressure Hulls with Initial Shape Imperfections.** Pp. 4–57.

The paper presents the theoretical basis of a method for calculating the bearing capacity of stiffened underwater hull shells with shape imperfections. The V. V. Novozhilov theory of thin shells is used, which is complemented by the method taking into account the complex bending and geometrically non-linear deformation. Material behaviour beyond the elastic limit is examined using the theory of small elastic-plastic deformations. The conditions of joining the shell and transverse stiffener (frame) are formulated taking into account the discreteness of its location and eccentricity with respect to the shell median surface. The paper presents the basic principles of the numerical boundary problem solution method (matrix run procedure in a factorization method version), integration methods of the differential equations for matrix factors, and the critical load estimation algorithm implemented in computer software.

Based on numerous calculations of the main shell types (cylindrical, conical, and spherical) the concept of approximate bearing capacity calculation is formulated. This concept is common for all types of the shells. The method takes into account inelastic properties of the material and initial shape imperfections. The graphs of correction factors to the theoretical critical loadings of the elastic shells have been plotted. These graphs make it possible to find the critical loading of the shell with bending in the elastic-plastic state. In addition to common geometrical parameters these functions include bending value and material yield point.

The bearing capacity calculations for spherical shell with bending are compared with the test results obtained in the David Taylor Model Tank with good agreement.

Results of numerical studies of the bearing capacity for some cylindrical shells with local lateral bulging between frames are provided. Different combinations of wave (in circumferential direction) and axisymmetric bendings are examined.

The results and software packages can be used for investigating the bearing capacity of a wide range of underwater hull shells with initial manufacturing deviations from the regular shape.

A.I. Shitov. **The Use of Plastic Theory Finite Relationships for Estiming the Collapse Load of Shells Intended for Underwater Engineering Applications.** Pp. 58–75.

The collapse load of shells is characterized by limiting values of external forces for which equilibrium equations, strain compatibility conditions and boundary conditions are satisfied while the material is in plastic state.

Based on general relationships of the deformation plasticity a finite force-strain relationship for ideal incompressible elastic-plastic material is obtained.

The constant relations between strain components under elastic and plastic material behavior allow us to use the obtained finite relationships for formulating the problem of elastic structure deformation.

The static definability of one of the internal forces, which is a characteristic feature of closed underwater shells, gives an additional equation for calculating the actual collapse load using the formulas derived from the finite relationships.

For using the finite relationships in the problems where statically definable internal forces are not available recommendations are given on the application of analytical or numerical solutions for elastic shell strains.

The proposed method of the load bearing capacity analysis provides sufficiently reliable estimates of the critical load based on the limiting equilibrium theory principles.

The examples where the proposed method has been used for calculating critical collapse loads of underwater shells show that the results are in good agreement with the numerical computations on computer.

A.V. Alexandrov. **Investigation of Shell Buckling Behavior Under an External Follower Uniform Hydrostatic Load Using the Method of Reduced Elements.** Pp. 76–79.

An extension of the reduced elements method theory is offered to take into account the follower-type character of external pressure in the calculation of elastic shell buckling behavior. The critical load is sought using the reduction procedure and the concept of coextensive elements aimed at reducing the resolving system dimension combined with the matrix run procedure in application to the root separation method for seeking any eigenvalue and eigenvector in a general eigenvalue problem, which offers considerable saving of computation time without compromising the accuracy. A procedure has been elaborated for calculating the factors of tangential matrix for the following load. Based on the suggested algorithms the software has been developed for solving the buckling problems.

V.M. Ryabov. **Buckling of Conical Shells Under Different Boundary Conditions and Joining of Two Conical Shells.** Pp. 80–87.

The paper develops further the results of previous studies aimed at finding approximate solution of equations for buckling of variable stiffness conical shells under different boundary conditions and considers a case of two joint shells. The solution is reduced to simple (though approximate) analytic relationships. Rather cumbersome intermediate computations are omitted.

The resolvent equation for buckling of an axisymmetric conical shell of variable thickness (h/r=const, h – thickness, r – radius of circular cross-section normal to cone axis) is the equation with constant coefficients. Taking into consideration the bending stiffness of frames with flange lh in the plane normal to shell axis $EJ_{ц}$ (ignoring the bending stiffness of the flange itself $Eh^3l\big/12(1-\nu^2)$, l – distance between frames, E, ν – elastic modulus and Poisson ratio) for $J_{ц}\big/r^3\,l = \text{const}$ it is possible to obtain expression for critical pressure of ultimate buckling for conical shell without inflection of the generating line under uniform compression.

Apart from prior specified parameters of the shell and number of buckling waves, this equation includes a parameter dependent on both shell geometry and boundary conditions.

An algorithm for approximate estimation of this parameter is developed and formulae for its estimation at different combinations of free- and fixed-ended cone are given.

Two joint conical shells are also considered.

Two important conclusions have been made based on its investigation.

External inflection always increases buckling strength as compared to straight shell (i. e. a shell without inflection of the same length and base). Internal inflection may either increase or drastically reduce the buckling strength.

When joining the free-ended shells with internal inflection and equal relative stiffness throughout the length at

$$\frac{r_{и}}{r_{с}} = \frac{n^2-1}{n^2}$$

where $r_{и}$ – is the radius of shell section in the area of inflection; $r_{с}$ – radius of straight shell in the same section; n – number of buckling waves along circumference, the shells are subject to buckling without tension/compression and median surface shear. The frames are subject to buckling like isolated rings. In this case the critical pressure may be drastically reduced as compared to the straight shell.

G.I. Yefremova, Y.A. Libov, V.M. Ryabov. **Analytical and Experimental Studies on Buckling Behaviour of Combined Conical Shells.** Pp. 88–101.

The paper presents the results of numerical computations for three similar models (cylinder, cylinder – cone, joint cones) tested in 1969 to examine the risk of drastic reduction in buckling strength of joint conical shells with generating line inflection as compared to similar cylindrical and conical shells without inflections. The influence of boundary conditions including specific structural features of model plugs is investigated, and it is shown that there is a potential risk even in the case of minor geometry changes in the shells with inflected generating line.

In 1965–69 the approximate solution of the buckling problem was obtained for structurally orthotropic conical shell with generating line inflection, i.e. the shell composed of two cones with joined bases. The main practical result was the conclusion that the shell buckling strength with internal inflection is subject to significant buckling strength reduction as compared to a single-span «straight» shell.

It was the purpose of the tests to prove this conclusion. It has been qualitatively proven but due to approximations of the computations performed at that time, in particular, regarding the boundary conditions of model shells, it was not possible to ensure full treatment of the experiment data and agreement with the calculations. The paper presents a new treatment of these test data using numerical methods including possible effects of small changes in the shell geometry on buckling behaviour.

The results of refined computations practically coincide with experimental values for two models and the model with welded plug. For the latter model with a thick plug and rubber gaskets the agreement is somewhat less.

The possibility of strong influence of even smallest changes in the taper angle has been shown by modification of the model made up of two cones. For simplicity all frame sections, plating thickness and model length are kept the same, and only the taper angle γ is varied from 0 to 10° at the initial γ=6.425°.

As computations show, even minor variation of the taper angle (as small as 2°) may change the critical pressure by about 2 times.

In general, analytical and experimental investigation of the joint conical shells buckling has proved that for some shapes there is a risk of sharp reduction in buckling strength at small variations of the taper angle. It has also been proved that buckling may drastically change depending on the boundary conditions. Satisfactory agreement of the refined computation and the experiment has been obtained.

B.V. Druzhilovskiy, N.V. Bournasheva. **Influence of Elastic Coatings on Stress and Strain State of Metallic Components of Underwater External Hulls.** Pp. 102–114.

In some cases, basing on general design requirements the external hulls of modern underwater vehicles are coated with elastic materials including rubber.

Due to considerable thickness of these coatings their flexural rigidity becomes comparable to that of steel plating. In this case as it follows from the practical experience (for example, data obtained from inspection of the «Kursk» submarine during salvage operation) the adhesive strength between the coating and metal plating is sufficiently high. Therefore, it is important to examine the effect of such coatings on the loaded external hull components. In particular, investigation of reinforcing effect of these coatings in case of possible loss of steel component strength due to corrosion.

The authors used results of experimental study and analysis of the interaction between full-scale plates of the external hull plating and coating under pressure using simplified model.

The paper contains results of calculation and analytic investigation of characteristic components of such an important external hull structure as main ballast tank under effect of internal pressure. The finite element method and software package ANSYS was used for numerical studies. Considering significant differences in thickness and elasticity modules between rubber coating and steel components, the finite element method computations used universal 3-D models.

Analytical estimations are based on application of shell theory and theory of arcs with extendable axes. Correspondence between numerical and accurate analytical estimations (where it was possible) was good. It confirms that the calculation model was correct.

The results demonstrate that modern elastic coatings in characteristic case under study reduce stresses in plating approximately by 20 %. In this case the stresses in frames remain practically unchanged. As a whole, effect of interaction between external hull and coating should be considered as positive. The paper provides a formula for approximate analytical estimation of reduction in load on external hull plating due to coating.

A.V. Lavrov. **Service Life Prediction for Polymer Composites Subject to Cyclic Loading Taking into Account Interruption in the Test Process.** Pp. 115–132.

The paper considers a phenomenological approach to the problem of accelerated service life evaluation of the polymer composites (based on short-term static tests) under long-term cyclic loading taking into account possible interruptions in the loading process. Previously derived basic equations are given for calculation of the material damage, number of cycles to failure under continuous loading and the total number of cycles to failure under interrupted loading. In case when there is no experimental data for the temperature effect on the material strength, recommendations are given for approximate estimate of possible temperature difference for the short-term and long-term cyclic tests.

Results of predictions and experimental service life investigations are given for three types of glass-fibre materials (with different deformation curves) demonstrating that interruptions in the loading process have significant influence on the service life of the materials under study. Based on acceptable agreement of the test results and theoretical calculations, which take into account the features of the material deformation curves, the suggested version of the accelerated evaluation technique can be recommended for verification of other types of structural materials whose failure process is primarily (time-wise) determined by accumulation of critical minute fractures scattered in the material volume.

A.P. Fyedorov, V.M. Ryabov, K.M. Parnov, I.A. Sarayeva. **Investigation of Acrylic Plastic Properties under Three-dimensional Compression.** Pp. 133–149.

The properties of acrylic plastic, the main material to manufacture view ports of deep-water submersibles, have been experimentally investigated under 3D compression; two cases have been examined: a cylindrical model under nearly uniform compression and a rectangular parallelepiped with a free edge.

In the uniform compression case the acryl plastic properties have been tested under static, long-term and cycle loading. Static loading tests have been conducted on English and Russian acryl plastic samples for comparing their properties. Analytical relationships are used for analysis of static loading test results and experimental data are compared with finite element numerical computations. Under 3D compression tests a significant increase in strength is observed like in case of metals, but also non-elastic recoverable strains occur under long-term loading. Stresses of up to $7000\ \text{kgf/cm}^2$ have been reached without failure or residual strain. Russian and English acryl plastics have practically similar mechanical properties. Low-cycle loadings of up to 10 000 loading cycles and stresses of $1000\ \text{kgf/cm}^2$ have not revealed any noticeable changes in acryl plastic properties.

Under static loading of free edge models contrary to the von Mises criterion-based predictions according to which no or little hardening could be expected as compared to co-axial loading, there is about a two-fold increase of yield stress and a significant hardening effect in the range of non-elastic recoverable strains. During the tests stresses of up to $2200\ \text{kgf/cm}^2$ have been achieved without specimen failure.

The tests provide an explanation for high bearing capacity of acryl plastics in the view port structure of deep-water submersibles (this material can be used without degradation of optical properties at pressures up to $1300-1400\ \text{kgf/cm}^2$ at the initiation of non-elastic strain under uniaxial compression $\sim 500\ \text{kgf/cm}^2$ and yield point $\sim 1100-1200\ \text{kgf/cm}^2$).