SN-EVM unit for experimental studies of stability in circular cylindrical shells under combined loading

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Abstract. The article summarizes results of experimental studies of stability in circular cylindrical shells under combined loading by compressive force, internal pressure and torsion at the SN-EVM unit, developed by the Department for Strength of Materials, Theory of Elasticity and Plasticity at Tver State Technical University. It gives description of the test facility and methodology of experiments for studying the elastoplastic properties of materials under combined loading. It cites the processed experimental results for comparison with the formulated theory of bifurcation for the thin-walled circular cylindrical shell.

1. Introduction

Cylindrical shells are widely used in various structures of machines and mechanisms. Thin-walled shells without stiffeners and most cost-efficient under certain conditions. Along with cost efficiency, they require very precise computational rationale most closely approximate to results of full-scale studies in order to enable selection of parameters and structural materials. A slightest imperfection, a structural defect in a shell nearly guarantees the loss of stability for a structure even in case of simple loading.

To date, we observe multiple formulated theories to calculate the circular cylindrical shells. The papers by [1-11] deal with tweaking the theory of elastoplastic stability for thin-walled circular cylindrical shells. These review the behavioral patterns of the shells under combined loading (compressive force, internal pressure and torsion) in view of the loading history at varying loading speeds.

Experimental studies for the stability loss process in thin-walled cylindrical shells under simple subcritical loading beyond the elastic limit have already been taken by various authors. However, they were mainly done for a restricted class of flat trajectories, i.e. in case of torsional compression or compression with an internal pressure on the shell.

The need for experimental testing of applicability limits for the suggested theory under combined loading required designing and constructing of a device that is able to solve the problems.
2. Description of SN-EVM test facility and its operating principle

State-of-the-art experimental systems to study the patterns of elastoplastic properties of materials under combined loading must meet a bunch of criteria: implementability of multiparameter loading while ensuring the reversal of loading; highly precise traceability of implemented processes in a widely varying range of loading speeds and specimen strain; process controllability, both in the stress, and in the strain space; clarity of visualizing the implemented processes; automated processing of test results. These criteria are fully met with the SN-EVM automated calculation and experimental facility, developed at the mechanical testing laboratory at the Department for Strength of Materials, Theory of Elasticity and Plasticity at Tver State Technical University.

The facility is comprised by a loading unit that implements a three-parameter effect on the specimen. The loads that act on the specimen are measured using a two-component axial load and torsion force gauge. An extensometer is applied to measure axial, circumferential and shear displacements of the shell. For online and high-quality monitoring of the experiment progress, the process data is graphically displayed on a screen. For general view of the experimental unit see Figure 1.

![Figure 1. General view of the SN-EVM experimental unit.](image)

Thin-walled circular cylindrical shells (Figure 2) serve as the specimens for testing with a facility. Steel specimen are fabricated by turning from a bar under the following technology: roughing of the external surface with the side allowance of 2 mm, drilling and boring of the internal surface with the side allowance of 0.1 mm, finishing of the internal surface by reaming, workpiece installation onto a mandrel and subsequent finishing of the specimen external surface by finish turning. The external and internal surfaces of specimens are machined to match precision class VII. The thin-walled tubular specimens have wall thickness \( h = 1 \text{ mm} \) and \( h = 0.5 \text{ mm} \), middle surface radius \( R = 15.5 \text{ mm} \) and \( R = 15 \text{ mm} \), respectively.
Figure 2. Stability testing specimen.

The axial straining of a specimen causes axial relative displacement of the upper and lower parts, which is recorded by elastic elements with strain gauges glued onto them. The specimen torsion results in the relative angular displacement of the upper part versus the lower one, which is also recorded by an elastic element with the glued strain gauges. Installing the Archimedean spiral on the top part of the extensometer improves the accuracy in measuring the angular strains by eliminating the nonlinearity in the output signal characteristic from the rotation angle.

Using the extensometer (Figure 3) the axial displacement of the specimen is measured with the error not more than ±6·10⁻³ mm, rotation angle ±7·10⁻³ rad. The displacement range is 2 mm axially, 0.25 rad angularly, and ± 0.8 mm radially. The measurement errors result in the linear approximation of the strain gauge’s inherent characteristics.

Figure 3. Specimen assembly with extensometer.

Prior to mounting onto the specimen, the strain gauge is graded on a special device made from T-30 theodolite. The device enables to independently simulate the process of extension (compression) and strain gauge torsion with the accuracy of 1·10⁻³ mm for axial strain and 1·10⁻⁴ rad for rotation angle.

Clamps for the specimen used in the testing are comprised by two rings and a block-type fork, horizontally coupled in the reverse perpendicular direction and forming a cross-shaped Hooke’s joint.
The block-type fork of the upper clamp is attached to the upper crosshead, and of the lower clamp – directly to the dual-component force gauge. The integrated unit of the lower clamp-force gauge is mounted to the lower moving crosshead. The clamps are easy to disassemble, which facilitates assembly and disassembly of the test module. The inner ring of clamps has two parallel through holes, fitted with rolls that have eccentric surfaces. The specimen heads have half-sectoral flats that are similar in shape. When the specimen is being mounted, the rolls fit into the relevant grooves of the flats after being rotated, thus achieving reliable transfer of axial forces and the torsional moment to the specimen. Due to availability of cross pieces, the clamps can be self-aligning under the action of the applied forces, which rules out any impact from misalignment of the axial force applied.

When the specimen is loaded with internal pressure, its ends are generally sealed with caps. This generates an additional tensile force, which complicates the experiment control and reduces the accuracy. To exclude this phenomenon, the SN-EVM unit uses a device resembling a solid cylindrical core with sealing elements on its ends. In the working part of the specimen length its diameter is by 2 to 5 mm below the specimen’s inner diameter. The pressure force is locked to the hard core and does not influence the axial force control channel.

Executing of operations in the control computer starts from defining the input data, such as the experiment type attribute (control by strain or by loads), number of trajectory sections, loading speed. The following are defined locally for each section: trajectory type (a straight interval or a radial arc), proposed length of interval, interval slope angle, initial phase and arc curvature radius, number of turns, initial radius, spiral development direction. The input data are entered from the keyboard, and then scaled into the machine equivalents. Programmed conditions for transfer from one section to another could be definable interval lengths, achievement of a certain value by the measured parameter, fulfilment of a certain calculable condition, or mere button pressing on a control unit.

The experiments are done at constant straining or loading speed. To rule out the impact of relaxation effects on the test results, the straining speed is accepted equal to $\dot{\varepsilon} = 10^{-6}$ s$^{-1}$ in the area of elastoplastic strains and $\dot{\varepsilon} = 5 \cdot 10^{-6}$ s$^{-1}$ within the elasticity limits.

3. **Results of experiments done at the SN-EVM unit**
To verify the theory proposed in [12-17], we performed experiments at specimens from Steel 40X and Steel 45.

To verify the initial isotropy of the material, we compared the strain diagrams in simple loading processes. For the superimposed diagram see Figure 4 (numbers indicate the loads: 1 – torsion, 2 – compression, 3 – proportional compression with torsion at $\alpha_1 = 45^\circ$, $\alpha_2 = 0^\circ$). It enabled a conclusion that the material of the specimens is isotropic, since in the advanced plastic strains the spread in values of the stress vector modulus does not exceed 3%.

![Figure 4. Superimposed diagram for strain of shells from steel 40X with wall thickness $h \approx 1 \cdot 10^3$ m.](image-url)
The results obtained for complex loading processes are represented as a superimposed diagram in Figure 5 (numbers indicate the loads: 1 – torsion, 2 – compression, 3 – proportional compression with torsion and internal pressure at \( \alpha_1 = 60^\circ, \alpha_2 = 75^\circ \)). Comparison of strain diagrams enabled a conclusion that the material of specimens is conventionally isotropic, since in the advanced plastic strains the spread in values of the stress vector modulus does not exceed 14%.

![Figure 5. Superimposed diagram for strain of shells from steel 40X with wall thickness \( h \approx 0.57 \times 10^3 \) m.](image)

4. Summary
Processing results from experiments on torsion of shells from steel 40X with various material wall thickness also enabled a conclusion that in advanced plastic strains the lateral strain ratios for the material under review are close to the value of \( \mu = 0.5 \).
The constructed SN-EVM unit and the designed method of testing using the same enabled to obtain all the required experimental data to verify the proposed theory for stability of circular cylindrical shells and evaluate the degree of its compliance with the full-scale experiments.

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