STRENGTH AND RELIABILITY OF PIPING SYSTEMS*

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Analytical and numerical methods have been developed for the solution of stress-strain and limit state problems of piping systems (in the case of the presence of flaws in them as well). The fracture strength of pipe steels during long-term service has been studied. A methodology and a software have been developed for the assessment of stress-strain state to extend the life of active pipelines. The developments made are used to increase the reliability of Ukrainian piping systems.

Keywords: strength, reliability, piping systems, stress calculation, degradation of steels, computer programs, diagnostics.

Introduction. Piping systems are widely used in various industries (main pipeline transport, thermal and nuclear power stations, chemical industry, metallurgy, etc). Such objects had been mainly built in the times of the former USSR on the basis of the existing technological policy. At the present time, ensuring of the serviceability of piping systems has gained strategic importance to Ukraine, especially considering the fact that the requirements for environmental protection and reduction of service risks have become much more stringent. For instance, the territory of Ukraine is traversed by gas mains (>35,000 km), oil pipelines (>8000 km) and an ammonia pipeline (>1000 km), which have worked 25–40 years and in some cases 50 years and more. A similar situation exists in other industries that use piping systems. Therefore, the service safety, reliability and risk assessment of piping systems is topical both in terms of economy and in terms of ecology. The solution of the problems of improving methods for the strength analysis of new piping systems, extending the life of active piping systems and assessing the service risk of ageing piping systems is the main purpose of the work. In spite of many years of world research in this direction, many scientific questions remain unstudied. The constituents of this work are as follows.

Development of analytical and numerical methods for the solution of stress-strain and limiting state problems of piping systems (in the case of the presence of flaws in them as well).

Study of the fracture strength of pipe steels during long-term service.

Development of a methodology and a software for the assessment of stress-strain state to extend the life of active pipelines.

Use of the developments made to increase the reliability of Ukrainian piping systems.

This article reviews the main works published by the authors in the past five years, which consider questions associated with the above-mentioned directions of research. The results obtained allow a considerable contribution to be made both to the development of the scientific fundamentals of the strength of pipelines and to the solution of specific problems of their service.

In accordance with the above-mentioned four constituents of the work, below are set out the main results.

Analytical and Numerical Methods. Severe service conditions of pipelines, which cannot be taken into account in their design, on the one hand and the development of computer engineering and formalized mathematical and software computing facilities on the other hand gave rise to the development of analytical and numerical methods for the analysis of the stressed state and critical states of pipelines. A great attention is given to pipe bend as

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a key element of piping system, the determination accuracy and the way of representation of whose integral beam characteristics determine the design efficiency of piping system as a whole. On the basis of the theory of shells, a mixed mathematical statement of problem for toroidal shell has been formulated, where force components and circumferential displacements of shell points are considered as unknowns. For long shell, the flat cross-section hypothesis is used. This makes it possible to obtain numerical and analytical solutions for stress distribution and integral deformation characteristics of central-axis points in the case of loading pipe bend with an external moment, which acts in its plane and in the normal plane, with allowance for geometrically nonlinear effects, which arise for thin-walled shell additionally loaded with internal pressure [1–5].

Studies of the so-called “stiffening effect”, when not only initial ovalization (deviations from the perfectly circular shape of the pipe bend section), but also ovalization by loading with an external moment decrease with increasing internal pressure, have been carried out. When pipe bend is ganged to other piping system elements (flanges, straight pipe sections), edge effects arise since their deformation behavior is basically different [6–8]. An analytical approach to the description of these effects is proposed, the essence of which is the solution of quartic differential equations for unknown coefficients in expansion for tangential displacements. An approximate solution has been obtained, which has a herringbone structure and is written through Krylov functions. Two numerical approaches have been developed as alternative ones, which reduce to the solution of Cauchy problem for quartic and octic differential equations. As a result of comparing the solutions obtained with experimental data, sufficient accuracy of calculations has been confirmed.

The behavior of pipe bend as a shell under harmonic loading has been considered. The concept of dynamic integral compliance of pipe bend has been introduced for the first time, and analytic expressions for it have been derived as a function of loading frequency and geometric characteristics [9–11]. This makes it possible to represent bend as a beam element with variable compliance and to successfully solve some dynamical problems for short thin-walled pipelines with curved elements by the methods of the theory of beams but not shells, the accuracy of calculations being ensured. For the pipelines that are in an arbitrary medium with nonlinear interaction characteristics, an effective numerical iterative procedure has been developed for the analysis of stress-strain state with allowance for the possible presence of supports and branches [5, 12, 13]. The original equilibrium equations and geometric equations have been written in geometrically nonlinear formulation and supplemented with boundary conditions, which have been determined analytically for a semiinfinite pipe under transverse-longitudinal bending. Analytical procedures for the determination of critical force for a pipe in perfectly plastic soil in the case of horizontal and vertical forms of buckling have been developed. The effect of limited pipe length on critical compressive force has been studied.

The presence of shape and metal defects in pipelines leads to a local stress redistribution in their vicinity. An important characteristic of local stressed state around cracks as the most dangerous flaws is stress intensity factor (SIF). A number of efficient engineering approaches to the determination of SIF are proposed.

The approaches based on the method of weighting functions allow one to determine the SIF value by any other law of crack edge loading when there are solutions for some stress distribution [14]. These solutions are used for thick-walled pipes. The approaches based on the lumped compliance method allow known SIF values to be used for a strip with edge crack in the analysis of other configurations of cracked bodies [15–19]. For instance, analytical solutions have been obtained for pipes with axial cracks (including multiple ones) and circumferential cracks and for pipe bend with axial cracks; this made it possible to study analytically for the first time the effect of bend geometry on the SIF value and to show their difference from the solutions for a straight pipe. The geometrically nonlinear effect of the influence of internal pressure on SIF in thin-walled pipes, when pressure increase results not in proportional but somewhat slowed-down increase in SIF, has also been studied for the first time.

Another important characteristic of the state of pipe with flaw is limiting ductile failure pressure. On the basis of the ideal-plasticity theory, a number of statically permissible solutions for stress distribution in pipes with longitudinal flaws have been constructed. They take into account the geometrical dimensions and shape of flaw, the action of axial forces, the location of flaw (inside the wall, on the outer or inner surface), interaction between multiple flaws, etc [7, 14].