Application of FEM for strength analysis of equipment and pipelines of nuclear installations

FEM (finite element method) is one of the numerical methods used in solving problems of mathematical physics that describe behavior of a continuous medium under various loading factors (mechanical, temperature, hydrodynamic, gas-dynamic and other impacts) using partial differential equations. It demonstrates itself as the most effective modelling tool in analyzing the strength of machine structures (as specific continuous media).

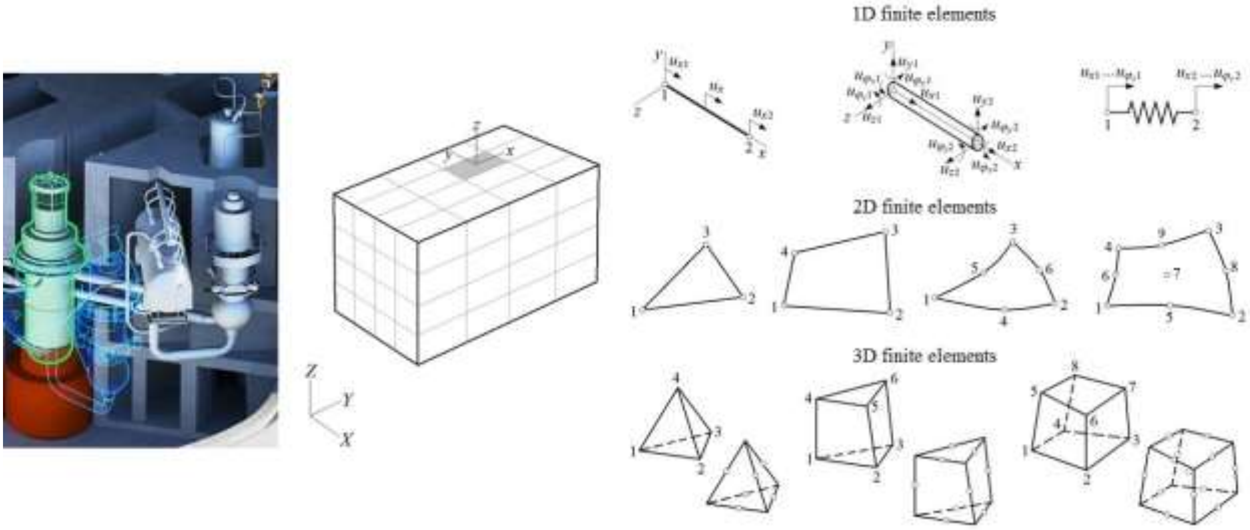
The fundamental effectiveness of FEM in relation to equipment and pipelines of nuclear installations is determined by the following:

- finite element mesh can approximate structure of any geometry with heterogeneous distribution of mechanical properties, and the built finite element model allows engineers to calculate kinematic and force parameters of structural response to static or dynamic loads;
- interaction of the analyzed component (equipment, pipeline or their part) with coupled mechanical objects (other components, building structures, fluid, gaseous or other media) can be described in a convenient way – by distributed or concentrated forces, boundary conditions of various types or by including these objects in a united mechanical system (with the extension of finite element modelling to them);
- change in the properties of the analyzed component depending on its response (physical or geometric nonlinearity, variable boundary conditions, etc.) can be taken into account in algebraic equations obtained from differential equilibrium equations by the finite element approximation, or when solving these equations by known algebraic methods;
- control of the accuracy of the calculation of response parameters is possible by selecting the types of finite elements and the mesh density;
- advanced computer software implementing FEM and certified for use in nuclear industry is available.

All these aspects have led to the widespread use of FEM in the design of nuclear installations (e.g. nuclear power plants), as well as in the engineering support of their operation. But this use was not properly regulated in terms of controlling the complexity of finite element models, optimizing modelling and calculation procedures, etc. Due to the lack of rules established in standards based on the best, proven practices, **there is a risk of errors** by analysis engineers**, excessive computational costs, insufficient compatibility of calculation outputs with the strength criteria and, as a result, ineffectiveness of strength substantiation by finite element analysis** in real cases. This risk is discussed, for example, in the book:

Spirochkin YK (2020) Chelovecheskii faktor i proektirovanie (Human factors and design). Right Print, Saint Petersburg.

In the 2020s, **an attempt was made** in Russian nuclear power industry **to create a standard for application of FEM for strength analysis** of equipment and pipelines, taking into account the specifics of nuclear installations and relevant regulatory requirements. This work was commissioned (by the State Corporation Rosatom) to NIKIET, and I took part in it during the last year before I left the service.



Equipment components and pipelines of a nuclear installation with WWER and finite elements

When preparing the draft standard, I proceeded from the concept that analysis engineer should have, along with a general theoretical description of FEM, detailed practical rules for using this method for all known loading cases that determine strength of nuclear equipment components and pipelines. And all these rules should be presented in one document, regardless of the categorization of loading cases on external or internal, static or dynamic, as well as of dividing the problems on linear and nonlinear. The foundation of the analysis methodology should be unified. In the draft standard, strength analysis includes, in addition to the conventional checking calculation (calculation of stresses, strains and displacements under specified loads and subsequent consideration of the established strength criteria), also **calculation of loads in coupled problems** and **simulation of mechanical behavior in beyond design basis accidents**. Calculation of loads can be needed in the analysis of dynamic loading events, when, as a rule, reliable input data on loads are not available, especially in cases of coupled behavior of the structure and fluid (when load and response to it are interdependent and should be determined synchronously). The analysis of beyond design basis accidents is required for the more complete safety substantiation (when stresses, strains and displacements in the structure can exceed the established design limits, and the safety principle based on structural strength does not work). It complies, in particular, the modern approaches of the IAEA and the U.S. Nuclear Regulatory Commission.

The working materials underlying the draft standard have the following content:

Yuri Spirochkin November 11, 2022