

## **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).

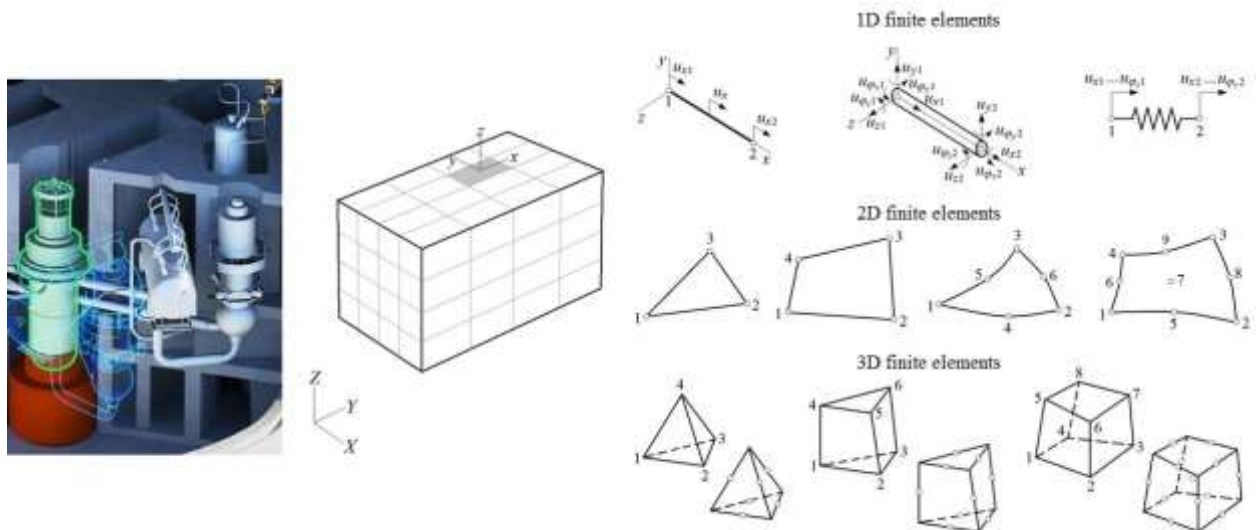
**The fundamental effectiveness of FEM** in relation to equipment and pipelines of nuclear installations is determined by the following:

- 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:

### 1 Application area

### 2 Terms, definitions and abbreviations

### 3 General provisions

- 3.1 Purpose, features and framework of strength analysis
- 3.2 Grounds for the application of finite element method
- 3.3 Procedure of strength analysis using the finite element method

### 4 Fundamentals of finite element method

- 4.1 Types of finite elements, internal and nodal variables, shape functions
- 4.2 Finite element matrices
- 4.3 Assembling the matrices of finite element model in global coordinates
- 4.4 Equilibrium equations in physical coordinates: linear statement

- 4.5 Transformation of dynamic equilibrium equations to normal coordinates
- 4.6 Calculation of dynamic response in the frequency domain
- 4.7 Nonlinear equilibrium equations
- 4.8 Coupled mechanical behavior of a structure and fluid

## **5 Pre-calculation analysis of the problem**

- 5.1 Purpose of pre-calculation analysis
- 5.2 Determination of the necessary constituent parts of the calculation
- 5.3 Determination of the model boundaries
- 5.4 Selection of the calculation technique
- 5.5 Adjustment of the framework of strength analysis and the loading cases to be considered

## **6 Building the finite element model**

- 6.1 Generalized building procedure
- 6.2 Finite element meshing
- 6.3 Assigning properties to finite elements
- 6.4 Setting boundary conditions

## **7 Verification of the built finite element model**

- 7.1 Verification methods
- 7.2 Verification based on experimental data
- 7.3 Verification based on sensitivity analysis

## **8 Determination of loads**

- 8.1 Methods for determining loads
- 8.2 Specifying known loads
- 8.3 Calculation of loads in specified loading conditions

## **9 Strength analysis calculations**

- 9.1 Principles of the checking calculation
- 9.2 Static analysis calculations and checking the strength criteria
- 9.3 Recommendations for dynamic analysis

## **Appendix A (non-mandatory) – Shape functions for some types of finite elements**

- A.1 Finite elements with simple geometry
- A.2 Isoparametric finite elements

## **Appendix B (non-mandatory) – Calculation of finite element matrices**

## **Appendix C (non-mandatory) – Methods for solving linear static equilibrium equations**

- C.1 Categories of methods and errors
- C.2 Direct methods
- C.3 Iterative methods

## **Appendix D (non-mandatory) – Dynamic step-by-step analysis in time**

- D.1 Categories of numerical integration methods and basic step-by-step algorithm
- D.2 Algorithms using explicit numerical integration methods
- D.3 Algorithms using implicit numerical integration methods

## **Appendix E (non-mandatory) – Dynamic analysis in the frequency domain**

- E.1 Basic algorithm and loading cases under consideration
- E.2 Analysis in case of stationary deterministic loading
- E.3 Analysis in case of stationary random loading

## **Appendix F (non-mandatory) – Methods, equations and algorithms used in solving the nonlinear equilibrium equations**

F.1 Categories of nonlinear problems

F.2 Iterative solving the nonlinear static equilibrium equations obtained by the method of variable parameters

F.3 Matrices describing large bending displacements and stability of components

F.4 Algorithms of the incremental method

**Appendix G (non-mandatory) – Linearization of stress distributions obtained by finite element calculation for checking the strength criteria**

G.1 Principles of linearization

G.2 Selection of the stress classification line

G.3 Integration of stress distributions along the component thickness

G.4 Determination of stresses by nodal forces

G.5 Integration of stress distributions over a limited set of elements

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