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THE IMPACT OF CHANGES IN THE CONDITIONS OF FASTENING OF STEEL SUPPORTING STRUCTURES OF NUCLEAR POWER PLANTS EQUIPMENT AND PIPING ON THEIR SEISMIC RESISTANCE

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The seismic resistance of nuclear power plants equipment and piping is determined, inter alia, by the seismic resistance of their steel supporting structures. The linear-spectral method, which involves using the results of the modal analysis of the structure under consideration, is widely used to assess the seismic resistance of these supporting structures. During the modal analysis, the structure's dynamic characteristics are researched (in particular, the modes and values of natural oscillation frequencies). The dynamic characteristics of steel supporting structures affect the number of seismic loads that will be transmitted to them during an earthquake. The value of dynamic characteristics, among other issues, is influenced by the conditions of the steel supporting structures fastening. Therefore, it is relevant to research the impact of changes in the conditions of fastening of steel supporting structures of nuclear power plant equipment and piping on their seismic resistance. The paper gives the results of the research of dynamic characteristics, as well as the stress-strain state of steel supporting structures of nuclear power plant equipment and piping during changes in the conditions of their fastening.

***Keywords**: steel structures, finite element model, seismic load, dynamic characteristics, form of oscillations, frequency of natural oscillations, strength.*

Introduction

Seismic resistance of nuclear power plants (NPP) power units equipment and piping is determined, inter alia, by the seismic resistance of their steel supporting structures. Examples of these structures can be found in [1–3]. A significant amount of steel supporting structures of NPP power unit equipment and piping is located in the reactor compartment (RC) building. In general, these steel supporting structures must perform their functions during and after the safe shutdown earthquake (SSE) and/or the design basis earthquake. As noted in the paper [4], the previously performed analysis and generalization of a number of projects of steel supporting structures of equipment and piping of power units of NPPs of Ukraine allowed to conditionally distinguish such their main typical structural forms: 1) "rack", 2) "console", 3) "ceiling frame"; 4) "floor frame". At the same time, typical structural forms 1, 2 and 3 are used mainly for piping, and 4 is used for equipment.

In the theory of seismic resistance, three main methods of determining the dynamic response of a structure during an earthquake are distinguished [1, 5–10] depending on the dynamic characteristics (in particular, the mode and frequency of natural oscillations) of the object under consideration, namely: the equivalent static load method, linear-spectral method (LSM) and dynamic analysis method.

The equivalent static load method consists in static loading of the structure under study with an inertial load distributed or concentrated in the nodes of the calculation model. This method is usually used for structures with the first frequency of natural oscillations higher than 20 Hz. In turn, the inertial load is defined as the product of the weight load of the structure and the seismic acceleration of the earthquake.

The dynamic analysis method applies the integration of the equations of motion over time, as a rule, in order to take into account nonlinear effects. At the same time, accelerograms are used as the initial seismic influence.

To assess the seismic resistance of steel supporting structures of the NPP power units equipment and piping, LSM, which involves conducting a modal analysis of the structure under consideration, is widely used. At this stage, the modes and frequencies of the natural oscillations of the structure are determined. Next, the system is loaded with an inertial load for each of the calculated modes of oscillations and for each spatial direction of seismic hazards. When using LSM, the floor response spectra calculated on the basis of the dynamic analysis of the structure are accepted as the initial seismic hazards.

The LSM is based on the reduction method, which allows to reduce a linear system with N degrees of freedom to N equivalent systems with one degree of freedom, the superposition of the oscillations of which gives in total the oscillations of the original system [1, 5–9]. The seismic load S_{ij} (that is, the force that arises in the structure due to seismic hazards), acting in the direction of the i-th generalized coordinate and corresponding to the j-th mode of the structure's natural oscillations, is determined by the formula:

$$S_{ij} = m_{ij}\ddot{\varphi}_j \Phi_j x_{ij}\,, \qquad (1)$$

where m_{ij} are coefficient of inertia of the i-th partial system; $\ddot{\varphi}_j$ is the seismic acceleration according to the response spectrum for the corresponding value of the frequency of natural oscillations of the structure; x_{ij} is the translation in the direction of the i-th generalized coordinate of the j-th mode of natural oscillations; Φ_j is the constant of the j-th mode of oscillations, which is determined by the formula

$$\Phi_j = \frac{\sum_{i=1}^{N} m_{ii} x_{ij} \cos\alpha_i}{\sum_{i=1}^{N} m_{ii} x_{ij}^2}\,, \qquad (2)$$

where α_i is the angle between the directions of seismic hazards and the i-th generalized coordinate.

As can be seen from relation (1), the value of the seismic load S_{ij} is directly affected by the value of the frequency of natural oscillations of the structure, since the value of S_{ij} includes the parameter $\ddot{\varphi}_j$. Therefore, the change in the natural frequency of oscillations of the structure affects the change in the seismic load S_{ij}. As noted above, LSM provides for the use of the results of the modal analysis of the structure under consideration. During its implementation, the dynamic characteristics of the structure are studied, which, inter alia, are affected by the conditions of steel supporting structures fastening. Thus, it is relevant to study the impact of changes in the conditions of fastening of steel supporting structures of equipment and piping of NPP power units on their seismic resistance. Therefore, the purpose of the paper is to research the dynamic characteristics and establish the regularities of the stress-strain state (SSS) of steel supporting structures of typical structural forms during changes in the conditions of their fastening.

Methodology of conducting a numerical research of dynamic characteristics and stress-strain state, initial data

For numerical research of the dynamic characteristics and SSS of steel supporting structures, the ANSYS calculation complex is used. In this complex, global stiffness matrices, damping and mass matrix, as well as the external nodal load vector are formed to solve the main system of equations in finite element calculations as a whole [11].

In turn, the state building codes for the calculation of steel structures are focused on the use of the fourth theory of strength (criterion of the specific potential energy of deformation) [12]. Therefore, the stress intensity σ_{int} during numerical research was determined precisely according to the fourth theory of strength.

The material of steel supporting structures of typical structural forms is St3sp5 steel, for which the following physical and mechanical characteristics are set [13]: characteristic resistance beyond the yield stress – 255 MPa, modulus of elasticity – 2.06×10^5 MPa, density – 7850 kg/m^3, Poisson's ratio – 0.3.

The parameters of the environment in the premises of the hermetic enclosure system of the NPP power unit with the VVER-1000 reactor unit during normal operation are set according to the analysis performed in [14].

During an earthquake, buildings and structures are directly exposed to seismic shaking. Seismic accelerations from the earthquake, which will use the floor response spectra, are transmitted to the structures that are inside these buildings. According to [15–19], for the RC of power units of Zaporizhzhya NPP (ZNPP) and Pivdennoukrainska NPP (PNPP), the floor response spectra are determined taking into account the "soil-structure" interaction. According to the results of modern additional seismological research of the industrial sites of the ZNPP and PNPP, the peak ground acceleration of the horizontal component during the SSE [4] were established, which are 0.17 g and 0.12 g, respectively. Therefore, the research of SSS of steel supporting structures of typical structural forms was carried out specifically for these NPP sites.

As seismic accelerations from the earthquake, the enveloping floor response spectra in three mutually perpendicular directions of seismic hazards were used during the SSE at the lower and upper RC marks of the ZNPP and PNPP power units for 2% damping, constructed on the basis of data from [18–23]. The method of constructing enveloping floor response spectra is given in the paper [4]. On the basis of the developed enveloping floor response spectra, the ranges of acceleration values in three mutually perpendicular directions of seismic hazards, which will be transmitted to the steel supporting structure (for cases where it is located at different elevations of the RC) during SSE at the sites of ZNPP and PNPP, are determined. Below, in Fig. 1 and 2, examples of the calculated enveloping ranges (highlighted by shading) of the mentioned acceleration values are given [4].

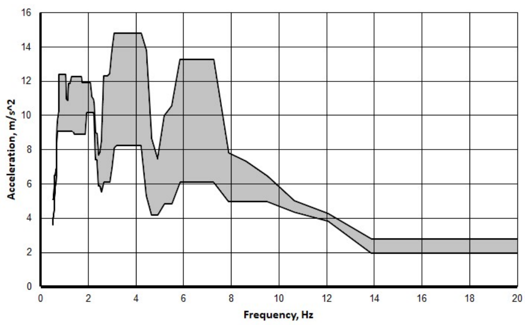


Fig. 1. Enveloping ranges of acceleration values of reactor compartments of the ZNPP units for the horizontal direction X and 2% damping

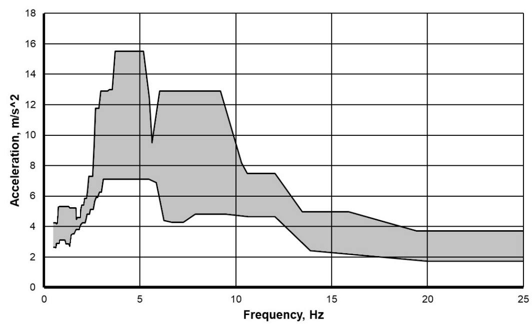


Fig. 2. Enveloping ranges of acceleration values of reactor compartments of the PNPP units for the horizontal direction X and 2% damping

During the research, LSM was used and simultaneous loading was taken into account for three mutually perpendicular spatial components of the seismic hazards (two horizontal and vertical one).

The nomenclature of loads taken into account in the research of the SSS of steel supporting structures of typical structural forms, as well as the calculated combinations of loads are set similar to those given in the paper [4], based on the approaches developed in the paper [24].

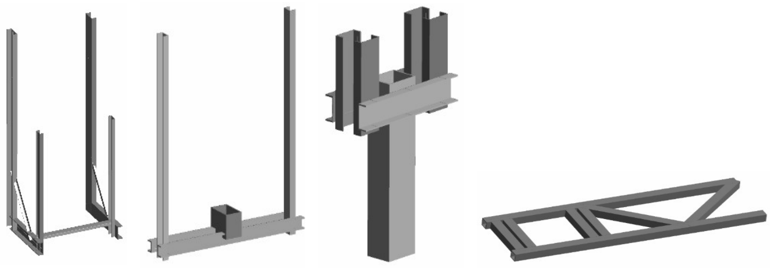
Development of finite-element models of steel supporting structures

Finite element models of steel supporting structures consist of BEAM 189 3-D 3-node element, which has six degrees of freedom at each node (three translations and three rotations), and is recommended for the analysis of composite structures, that is, those made of two or more elements connected together [5]. Fig. 3 shows developed three-dimensional models of steel supporting structures of typical structural forms.

The following are accepted as boundary conditions in the places of attachment of steel supporting structures to the structural base (floor, wall or ceiling):

– translations (*U*) and moments (*M*) are prohibited in all three directions, i.e. $U_X=U_Y=U_Z=0$, $M_X=M_Y=M_Z=0$ (hereinafter referred to as BC 1);

– translations in all three directions are prohibited, and moments are allowed, i.e. $U_X=U_Y=U_Z=0$, $M_X\neq0$, $M_Y\neq0$, $M_Z\neq0$ (hereinafter referred to as BC 2).



a b c d

Fig. 3. Three-dimensional models of steel supporting structures of typical structural forms:
a – "floor frame"; b – "ceiling frame"; c – "rack"; d – "console"

In order to determine the optimal size of the finite element during the SSS research for each steel supporting structure, the results of calculations on three different finite element meshes were analyzed. The determination of the finite element size was carried out during the loading of each steel supporting structure by seismic hazards in the form of floor response spectra. The final selection of the finite element mesh was carried out on the basis of the results of the stress intensity calculation according to the fourth theory of strength for different mesh. The finite element mesh that ensures acceptable convergence of the results is chosen (see, for example, [4]).

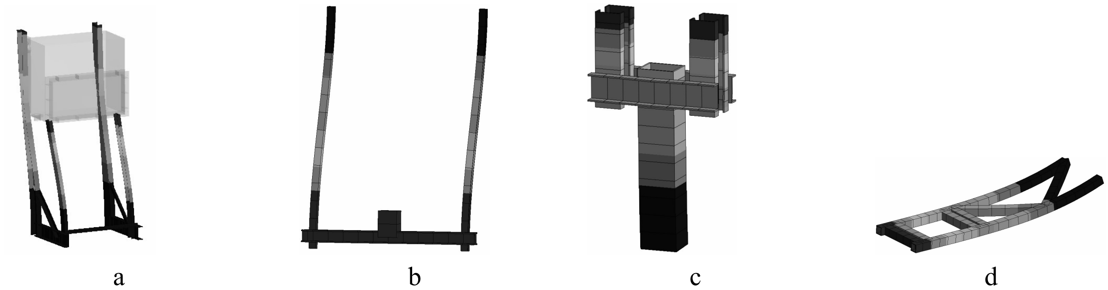
Results of research of dynamic characteristics and stress-strain state of steel supporting structures for the BC 1case

Table 1 show values of frequencies of natural oscillations of steel supporting structures of typical structural forms. At the same time, the number of natural oscillation modes is limited by the value of the acceleration of the zero period of the corresponding floor response spectra of the ZNPP and PNPP RCs. By zero-period acceleration we understand [5] the frequency range for which, with any damping, the seismic accelerations on the floor response spectrum become unchanged (see, for example, the constant values of seismic accelerations in the frequency range from 20 Hz to 25 Hz in Fig. 2).

Fig. 4 shows the first modes of natural oscillations of steel supporting structures of typical structural forms.

Table 1. The value of the frequencies of natural oscillations of steel supporting structures of typical structural forms for the BC 1 case

The natural oscillation mode number	The value of the frequencies of natural oscillations of the structure, Hz			
	"floor frame"	"ceiling frame"	"console"	"rack"
1	6.9466	18.0073	17.2897	71.7016
2	20.9732	21.8154	80.1230	–
3	21.9799	30.3552	–	–
4	36.4633	–	–	–



a b c d

Fig. 4. The first modes of natural oscillations of steel supporting structures of typical structural forms for the BC 1 case:
a – "floor frame"; b – "ceiling frame"; c – "rack"; d – "console"

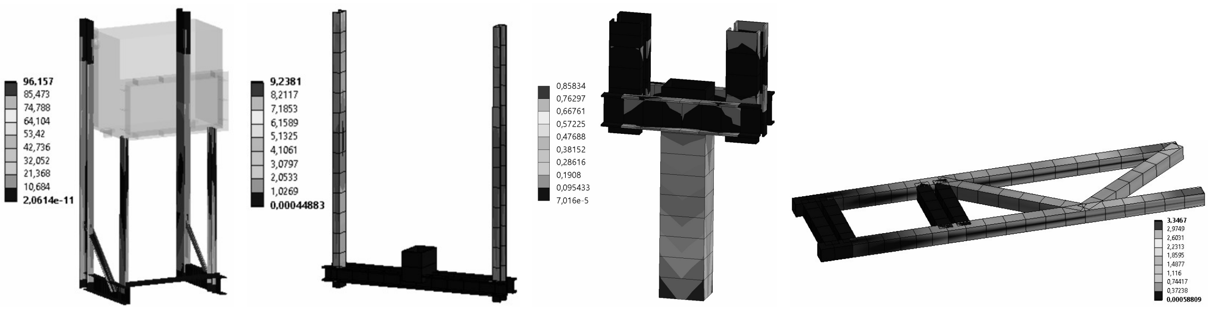
Table 2 show the results of the SSS research of steel supporting structures of typical structural forms. At the same time, the following notations are adopted in these tables: "ZNPP (bottom)", "ZNPP (top)" – correspond to the combination of loads "Enveloping response spectra at the lower/upper marks of the ZNPP RC +

seismic loads from equipment/piping". In relation to the PNPP, the designations are adopted in a similar way, taking into account the fact that the PNPP power units RC with their own seismic loads (floor response spectra) are considered.

As examples, Fig. 5 shows isofields of stress intensity σ_{int} under seismic loads of steel supporting structures of typical structural forms in the case of their location on the upper marks of the ZNPP and PNPP RCs.

Table 2. The results of SSS research of steel supporting structures of typical structural forms for the BC 1 case

Load	Maximum stresses, MPa			
	"floor frame"	"ceiling frame"	"console"	"rack"
ZNPP (bottom)	44.35	3.73	0.53	1.50
ZNPP (top)	96.16	5.48	0.86	2.56
PNPP (bottom)	31.05	3.53	0.39	1.11
PNPP (top)	93.50	9.24	1.09	3.35



a b c d

Fig. 5. Examples of isofields of stress intensity σ_{int} (MPa) in the case of the location of steel supporting structures of typical structural forms on the upper marks of the ZNPP and PNPP RCs for the BC 1case:
a – "floor frame" for the ZNPP (top) case; b – "ceiling frame" for the PNPP (top) case;
c – "rack" for the ZNPP (top) case; d – "console" for the PNPP (top) case

Results of research of dynamic characteristics and stress-strain state of steel supporting structures for the BC 2 case

On the basis of the obtained results of numerical research of dynamic characteristics and SSS under seismic loads of steel supporting structures of typical structural forms in BC 1, for further research in the BC 2 case, the designs of typical structural forms "floor frame" and "ceiling frame" were selected according to the following criteria:

– the lowest values of natural oscillation frequencies;

– the largest number of first frequencies of natural oscillations in the range up to the acceleration value of the zero period;

– the largest values of seismic loads;

– the largest stress values in the structure from seismic loads.

Table 3 shows values of frequencies of natural oscillations of steel supporting structures of typical structural forms "floor frame" and "ceiling frame". At the same time, the natural oscillation modes number, as in the BC 1 case, is limited by the value of the acceleration of the zero period of the corresponding floor response spectra of the ZNPP and PNPP RCs.

Fig. 6 shows the first modes of natural oscillations of steel supporting structures of typical structural forms "floor frame" and "ceiling frame".

Table 4 shows the results of SSS research of steel supporting structures of typical structural forms "floor frame" and "ceiling frame". At the same time, the conventional designations in this table are adopted similar to the BC 1 case.

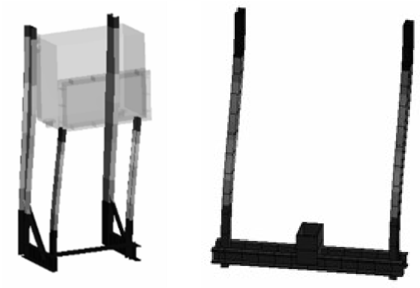
As examples, Fig. 7 shows the isofields of the stress intensity σ_{int} under seismic loads of steel supporting structures of the typical structural forms "floor frame" and "ceiling frame" in the case of their location on the upper marks of the ZNPP and PNPP RCs.

Table 3. The value of the frequencies of natural oscillations of steel supporting structures of typical structural forms "floor frame" and "ceiling frame" for the BC 1 case

The natural oscillation mode number	The value of the frequencies of natural oscillations of the structure, Hz	
	"floor frame"	"ceiling frame"
1	6.5075	17.3399
2	20.1812	21.8154
3	20.9379	30.3551
4	36.4077	–

Table 4. The results of SSS research of steel supporting structures of typical structural forms "floor frame" and "ceiling frame" for the BC 2 case

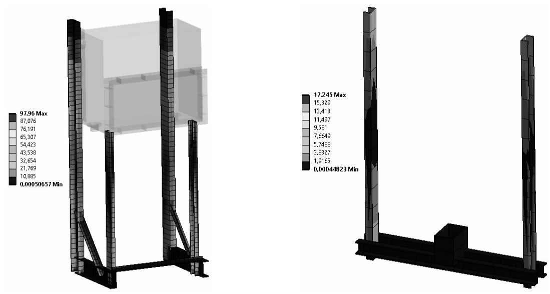
Load	Maximum stresses, MPa	
	"floor frame"	"ceiling frame"
ZNPP (bottom)	45.17	6.80
ZNPP (top)	97.96	9.63
PNPP (bottom)	31.96	6.97
PNPP (top)	95.25	17.25



a b

Fig. 6. First modes of natural oscillations of steel supporting structures of typical structural forms "floor frame" and "ceiling frame" for the BC 2 case

a – "floor frame"; b – "ceiling frame"



a b

Fig. 7. Examples of isofields of the stress intensity σ_{int} ***(MPa) in the case of the location of steel supporting structures of the typical structural forms "floor frame" and "ceiling frame" on the upper marks of the ZNPP and PNPP RCs for the BC 2 case:***

a – "floor frame" for the ZNPP (top) case;
b – "ceiling frame" for the PNPP (top) case

Results discussion

According to the results of the research of the effect of changes in the conditions of steel supporting structures fastening on their seismic resistance, it was established that changing BC 1 to BC 2 reduces the value of frequencies of natural oscillations of supporting structures of typical structural forms, namely: by 6.75% for the "floor frame" and by 3.84% for the "ceiling frame". At the same time, modes of natural oscillations of steel supporting structures also undergo changes.

In absolute terms, the decrease in frequencies of natural oscillations values of steel supporting structures (for various modes of natural oscillations in the frequency range up to the zero-period acceleration value) when replacing BC 1 with BC 2 is in the range from 0.4391 Hz to 1.042 Hz. The peculiarity of the floor response spectra of the ZNPP and PNPP RCs is that, on the one hand, they have jump-like areas of increased seismic accelerations for certain frequency values (see Fig. 1 and 2). To assess the influence of this effect on the structural safety of steel supporting structures of typical structural forms, we will use the resulting values of seismic accelerations (a_i^{res}), calculated according to the rule "Square root of the sum of the squares" (SRSS)

$$a_i^{\mathrm{res}} = \sqrt{a_x^2(f_i) + a_y^2(f_i) + a_z^2(f_i)} \qquad (3)$$

where $a_x(f_i)$, $a_y(f_i)$, $a_z(f_i)$ are values of the seismic accelerations of the upper or lower enveloping of the floor response spectrum of the ZNPP, PNPP for the corresponding frequency, which coincides with the value of the frequency of the natural oscillations of the structure.

So, we get, for example, that for RC:

– at the ZNPP, the decrease in the value of the natural frequency of the steel structure from 4.90 Hz to 4.22 Hz leads to a sudden increase in the value of the seismic acceleration, calculated according to the SRSS rule, from 12.4 m/s^2 to 20.97 m/s^2;

– at PNPP, the decrease in the value of the natural frequency of the steel structure from 5.64 Hz to 5.18 Hz leads to a sudden increase in the value of the seismic acceleration, calculated according to the SRSS rule, from 20.09 m/s^2 to 25,59 m/s^2.

On the other hand, on the floor response spectra of ZNPP and PNPP, there are also areas of a jump-like decrease in seismic accelerations when the values of the frequencies of natural oscillations of the structures decrease. Therefore, the change from BC 1 to BC 2 can have both positive and extremely negative effects on the structural safety of steel supporting structures.

Research results also indicate that the change from BC 1 to BC 2, inter alia, leads to a certain increase in seismic stresses due to a decrease in the overall stiffness of the structure.

The obtained results give the reason, when designing steel supporting structures of NPP power units equipment and piping, to recommend the performance of an analysis of their dynamic characteristics for the cases of BC 1 (U_X=U_Y=U_Z=0, M_X=M_Y=M_Z=0) and BC 2 (U_X=U_Y=U_Z=0, $M_X \neq 0$, $M_Y \neq 0$, $M_Z \neq 0$). Finally, it is recommended to adopt those fastening conditions that ensure the transmission of the smallest seismic accelerations to the steel supporting structures.

When considering existing steel supporting structures, replacing BC 1 with BC 2 or, conversely, BC 2 with BC 1 can be considered as an effective tool for shifting the values of frequencies of natural oscillations from the peak values of seismic accelerations on the floor response spectrum, which will positively affect the seismic resistance of steel supporting structures.

Conclusions

1. The dynamic characteristics were researched, and the regularities of the SSS of the steel supporting structures of the equipment and piping of the power units of the NPP of Ukraine during the change in the conditions of their fastening on the structural basis were established.

It was established that the change in the fastening conditions from BC 1 to BC 2:

– reduces the value of frequencies of natural oscillations of steel supporting structures. At the same time, the modes of natural oscillations of structures also undergo changes;

– leads to a certain increase in seismic stresses due to a decrease in the overall stiffness of the structure.

2. The peculiarity of the floor response spectra of the ZNPP and PNPP RCs is that they have jump-like sections of changes in seismic accelerations for certain frequency values. Therefore, a change in the dynamic characteristics of steel supporting structures, due to a change in the conditions of their fastening, can have both positive and extremely negative effect on the structural safety of steel supporting structures of the NPP power units equipment and piping during seismic loads.

3. The obtained research results made it possible to develop recommendations regarding approaches to assessing the strength of steel supporting structures of the NPP power units equipment and piping, compliance with which will increase their structural safety during seismic loads.

4. The results will be used in the future during the development of the methodology for assessing the seismic resistance of the steel supporting structures of the NPP power units equipment and piping, which takes into account the specific conditions of their operation and the degree of responsibility for ensuring the safety of the NPP during and after seismic hazards.

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Вплив зміни умов закріплення сталевих опорних конструкцій обладнання і трубопроводів енергоблоків атомних станцій на їх сейсмічну міцність

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Сейсмостійкість обладнання і трубопроводів енергоблоків атомних електростанцій визначається, серед іншого, сейсмостійкістю їх сталевих опорних конструкцій. Для її оцінки широко застосовується лінійно-спектральний метод, який передбачає використання результатів модального аналізу конструкції, що розглядається. Під час його виконання досліджуються динамічні характеристики конструкції (зокрема, моди і значення частот власних коливань). Динамічні характеристики сталевих опорних конструкцій впливають на величину сейсмічних навантажень, які передаватимуться на них під час землетрусу. На значення динамічних характеристик, крім іншого, впливають умови закріплення сталевих опорних конструкцій. У зв'язку із викладеним актуальним є вивчення впливу зміни умов закріплення сталевих опорних конструкцій обладнання і трубопроводів енергоблоків атомних електростанцій на їх сейсмічну міцність. У статті представлені результати дослідження динамічних характеристик, а також напружено-деформованого стану сталевих опорних конструкцій обладнання і трубопроводів енергоблоків атомних електростанцій під час зміни умов їх закріплення.

***Ключові слова**: сталеві конструкції, скінчено-елемента модель, сейсмічні навантаження, динамічні характеристики, форма коливань, частота власних коливань, міцність.*

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