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Research of the Stress-Strain State for Steel Support Structures of Nuclear Power Plant Components under Seismic Loads

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Seismic resistance of equipment and piping of nuclear power plant units is determined, particularly, by seismic resistance of their steel support structures. A significant number of these structures are located in the reactor building of nuclear power plants and belong to seismic resistance categories I and II. Therefore, such support structures of nuclear power plant equipment and piping, in general, shall perform their functions under seismic hazards that correspond to the safe shutdown earthquake and design-basis earthquakes, respectively.

Steel support structures of serial equipment (piping valves, electric and pneumatic drives of piping and pump valves, expansion tanks, etc.) are often designed "on site" in the limited conditions of their actual location. Therefore, it is necessary to design steel support structures of a number of equipment taking into account the fact that it can be connected, in particular, to existing piping with their actual routing. In connection with the above, the research of operation for such support structures under seismic loads is relevant.

The article presents the research results for the spectrum of natural oscillation frequencies of the equipment support structure, and the stress-strain state of the considered structure under seismic loads is determined. At the same time, the parameters during normal operation and maximum design basis accident at the nuclear power plant power unit are considered. The calculated combination of loads, which simultaneously includes two episodic impacts (maximum design basis accident and an earthquake) is considered.

Keywords: natural frequencies, seismic loads, steel support structures, stress-strain state.

Introduction

Seismic resistance of equipment and piping of nuclear power plant (NPP) units is determined, among other things, by seismic resistance of their steel support structures. The examples of these structures can be found in [1], [2]. A significant number of support structures of NPP unit equipment and piping are located in the reactor compartment and belong to seismic resistance categories I and II according to [3]. Therefore, such support structures of NPP equipment and piping in general shall perform their functions during the safe shutdown earthquake (SSE) and design basis earthquake respectively. The analysis and summary of a number of designs, for example [4], [5], of support structures of Ukrainian NPP equipment and piping, allows conditionally distinguishing their following main standard structural forms: 1) rack, 2) console, 3) ceiling frame and 4) floor frame. Standard structural forms 1), 2) and 3) are used mainly for piping, 4) is used for equipment.

For now, let us pay some more attention to the consideration of steel support structures of type 4) for serial equipment (piping valves, electric and pneumatic drives of piping and pump valves, expansion tanks, etc.) The peculiarity of these support structures is that they are often designed "on site" in the limited conditions of the actual location in the reactor compartment of the NPP power unit. Therefore, it is necessary to design steel support structures of a number of equipment considering the possibility of its connection, in particular to the existing piping with their actual routing (for example, it is necessary to accept the presented height of the support stands, which will ensure the possibility of connecting the equipment to the existing piping, which is located at the respective height from the floor).

Articles [6]-[9] consider certain types of steel structures, including under significantly increased temperatures. However, for steel support structures of NPP equipment, a special interest is represented by consideration of their specific operation conditions, in particular, the simultaneous action of two episodic impacts such as an earthquake and the maximum design basis accident (DBA) "Two-side rupture of the main coolant piping Dn 850", during which the temperature in the reactor compartment rises up to 150 °C.

The Article objective is to:

research the spectra of natural frequencies of support structure oscillations of the "floor frame" standard structural form;

determine the stress-strain state of the considered support structure under seismic loads.

Methodology of the numerical modal analysis and research of the stress-strain state, initial data

For the numerical modal analysis and research of the stress-strain state (SSS), the ANSYS calculation package is used, in which global stiffness matrices [K], damping [C] and mass matrix [M] are generally formed to solve the main system of equations during finite element calculations, as well as the external nodal load vector {F}. A system of algebraic equations is solved [10]:

$$[K]\cdot\{u\}=\{F\} \tag{1}$$

or

$$[K]\cdot\{u\}=\{F^a\}+\{F^r\}, \tag{2}$$

where $[K]=\sum_{m=1}^{N}[K_e]$;

$\{u\}$ is the vector of nodal displacements;

N is the number of components;

$[K_e]$ is the component stiffness matrix;

$\{F^r\}$ is the reaction vector from loads;

$\{F^a\}$ is the global external load vector.

In its turn

$$\{F^a\}=\{F^{nd}\}+\{F^{ac}\}+\sum_{m=1}^{N}(\{F_e^{th}\}+\{F_e^{pr}\}), \tag{3}$$

where $\{F^{nd}\}$ is the vector of applied nodal load;

$\{F^{ac}\}$ is the vector of inertial forces.

$$\{F^{aA}\}=-M\cdot\{a_c\}, \tag{4}$$

where $[M]=\sum_{m=1}^{N}[M_e]$, $[M_e]$ is the element matrix of masses;

$\{a_c\}$ is the global vector of accelerations;

$\{F_e^{th}\}$ is the temperature load vector within one component;

$\{F_e^{pr}\}$ is a pressure vector within one component.

The equation of motion for the tasks of determining natural frequencies and modes of oscillations is [10]:

$$[M]\cdot\{\ddot{u}\}+[K]\cdot\{u\}=\{0\}. \tag{5}$$

where $\{\ddot{u}\}$ is the node acceleration vector.

For harmonic oscillations, the equation will be (5)

$$\left(-\omega_i^2\cdot[M]+[K]\right)\cdot\{\phi\}_i=\{0\}. \tag{6}$$

where $\{\phi\}_i$ is the own vector that corresponds to its own frequency i-th;

ω_i – i-th own circular frequency (radian per unit of time).

One of the solutions (6) is

$$\left|[K]-\omega^2\cdot[M]\right|=\{0\}. \tag{7}$$

It is possible to find the frequencies of natural oscillations *{f}* through the obtained values of the circular frequency of natural oscillations *{ω }*

$$f_i=\frac{\omega_i}{2\pi}. \tag{8}$$

Modal contributions (γ_i) for the corresponding excitation direction are defined as [10]:

$$\gamma_i=\{\phi\}_i^T[M]\{D\}, \tag{9}$$

where $\{\phi\}_i^T$ is the displacement vector for i-th mode of oscillations;

$\{D\}$ is the vector describing the excitation direction (X, Y, Z).

Table 1 – Physical and mechanical characteristics of St3sp5 steel depending on the temperature

Characteristic	Calculated temperature, °C	
	under 100	150
Characteristic resistance beyond the yield stress, R_{yn} (MPa)	255	
Proportionality limit, R_{pt} (MPa)	255	231
Density, r	7850	
Elasticity modulus, E_a (MPa)	2.060×10^5	1.957×10^5
Poisson ratio, n	0.3	

The determination of the total response of the system (R_a) from seismic loads is carried out according to the "square root of the sum of squares" rule

$$R_a = \sqrt{\sum_{i=1}^{N}(R_i)^2}, \quad (10)$$

where R_i is the system response for i-th mode of oscillations.

The state construction codes for calculation of metal structures are aimed at the use of the fourth theory of strength (criterion of the specific potential energy of deformation) [11]. Taking into account the above, in general, the stress intensity σ_{int} in numerical studies is determined by the following ratio

$$\sigma_{int} = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]}, \quad (11)$$

where $\sigma_1, \sigma_2, \sigma_3$ are main stresses.

The numerical SSS research of a steel support structure was performed in the following sequence [2]: development of a finite element model in the ANSYS calculation package; calculation of static strength during normal operation; calculation of natural frequencies and modes of oscillations; performance of linear-spectral analysis. Under the calculations, the simultaneous load of three spatial mutually perpendicular components of the seismic hazards (two horizontal and a vertical) was taken into account.

The material of the steel support structure is St3sp5 steel. The physical and mechanical characteristics of steel depending on the temperature are accepted according to [12]-[14] and presented in Table 1.

In the SSS research of the support structure [15]:

material is assumed to be continuous, homogeneous and isotropic;

hypotheses of flat sections and small deformations are used.

Since according to [16] the design basis accident and seismic hazards are episodic ones, the emergency combination of loads is considered during the SSS research. At the same time, to fulfill the requirements of [3], and in contrast to the approaches stated in [16], these two episodic impacts are included in the emergency combination together.

Environment parameters in the premises of the VVER-1000 NPP unit containment during normal operation (NO) and DBA "Two-sided rupture of the main coolant piping Du 850" are accepted according to the analysis performed in [14].

During an earthquake, buildings and structures are directly subjected to seismic shaking. Seismic loads from an earthquake are transmitted to the structures inside these buildings, for which we will use floor response spectra. The analysis of sources [17]-[21] allowed determining that for the Zaporizhzhya NPP (ZNPP) units and Pivdennoukrainska NPP (PNPP), the floor response spectra of the reactor compartment were calculated taking into account the soil-structure interaction. According to the results of the recent additional seismological research of the ZNPP and PNPP industrial sites, the peak ground acceleration values of the horizontal component of soil displacement during SSE [17]-[21] were determined, which are 0,17 g and 0,12 g, respectively. Therefore, we will research SSS of the support structure specifically for these NPP sites.

Support structures of the NPP equipment are mainly located in the range of height elevations from 0.0 m (lower elevations) to 36-38 m (upper elevations) of the reactor compartment. Within the SSS research of the support structure under seismic loads, we applied the scientific cognition method – generalization [22]. Considering the above, based on the data [20], [21], [23]-[26], we will use the enveloping floor response spectra in three mutually perpendicular directions of seismic hazards during the SSE at the lower and upper elevations of the reactor compartments of the ZNPP and PNPP for 2 % damping. The direct calculation of the enveloping floor response spectra was performed using the following ratios:

$$a_{x,y,z}^{\text{ZNPP}}(\text{f})=\left\{\max\left\{\begin{matrix}a_{1(x,y,z)}^{\text{ZNPP}-1}\\a_{1(x,y,z)}^{\text{ZNPP}-2}\\a_{1(x,y,z)}^{\text{ZNPP}-3}\\a_{1(x,y,z)}^{\text{ZNPP}-4}\\a_{1(x,y,z)}^{\text{ZNPP}-5}\\a_{1(x,y,z)}^{\text{ZNPP}-6}\end{matrix}\right\};\max\left\{\begin{matrix}a_{2(x,y,z)}^{\text{ZNPP}-1}\\a_{2(x,y,z)}^{\text{ZNPP}-2}\\a_{2(x,y,z)}^{\text{ZNPP}-3}\\a_{2(x,y,z)}^{\text{ZNPP}-4}\\a_{2(x,y,z)}^{\text{ZNPP}-5}\\a_{2(x,y,z)}^{\text{ZNPP}-6}\end{matrix}\right\};\ldots;\max\left\{\begin{matrix}a_{\text{k}(x,y,z)}^{\text{ZNPP}-1}\\a_{\text{k}(x,y,z)}^{\text{ZNPP}-2}\\a_{\text{k}(x,y,z)}^{\text{ZNPP}-3}\\a_{\text{k}(x,y,z)}^{\text{ZNPP}-4}\\a_{\text{k}(x,y,z)}^{\text{ZNPP}-5}\\a_{\text{k}(x,y,z)}^{\text{ZNPP}-6}\end{matrix}\right\}\right\}, \quad (12)$$

$$a_{x,y,z}^{\text{PNPP}}(\text{f})=\left\{\max\left\{\begin{matrix}a_{1(x,y,z)}^{\text{PNPP}-1}\\a_{1(x,y,z)}^{\text{PNPP}-2}\\a_{1(x,y,z)}^{\text{PNPP}-3}\end{matrix}\right\};\max\left\{\begin{matrix}a_{2(x,y,z)}^{\text{PNPP}-1}\\a_{2(x,y,z)}^{\text{PNPP}-2}\\a_{2(x,y,z)}^{\text{PNPP}-3}\end{matrix}\right\};\ldots;\max\left\{\begin{matrix}a_{\text{k}(x,y,z)}^{\text{PNPP}-1}\\a_{\text{k}(x,y,z)}^{\text{PNPP}-2}\\a_{\text{k}(x,y,z)}^{\text{PNPP}-3}\end{matrix}\right\}\right\}, \quad (13)$$

where $a_{\text{x,y,z}}^{\text{ZNPP}}(\text{f})$, $a_{\text{x,y,z}}^{\text{PNPP}}(\text{f})$ are the enveloping acceleration values a(m/s^2) of floor response spectra in three mutually perpendicular directions of seismic hazards (X, Y, Z) from the 1st to the k-th values of the frequency values f (Hz) of the floor response spectra for the ZNPP and PNPP units, respectively.

The examples of the developed enveloping floor response spectra of reactor compartments for the ZNPP and PNPP units are shown in Figures 1 and 2.

Based on the developed enveloping floor response spectra at the lower and upper elevations, the ranges of acceleration values in three mutually perpendicular directions of seismic hazards are determined, which will be transmitted to the support structure (for cases when it is located at different height elevations) of the reactor compartment during SSE at the ZNPP and PNPP sites. Figures 3 and 4 present examples of the defined enveloping ranges (highlighted in gray) of the mentioned acceleration values.

Based on the requirements [16], the list of loads considered in the SSS research of the support structure was compiled and presented in Table 2.

According to the approaches [16], based on the determined list of loads, the calculated combination of loads (CCL) was compiled. Taking into account the research objective (in particular, determining the SSS under seismic loads), we will assume that the load from the equipment environment during the maximum DBA is not changed compared to the NO mode (the possibility of using this precondition is substantiated in [14]). So, for the SSS research of the support structure under seismic loads under temperatures in the reactor compartment of 60°C and 150° C, we adopted the CCL as follows: 1,0×LR1W+0,95×LVL1W+1,0×LE1SM+1,0× LE3SM.

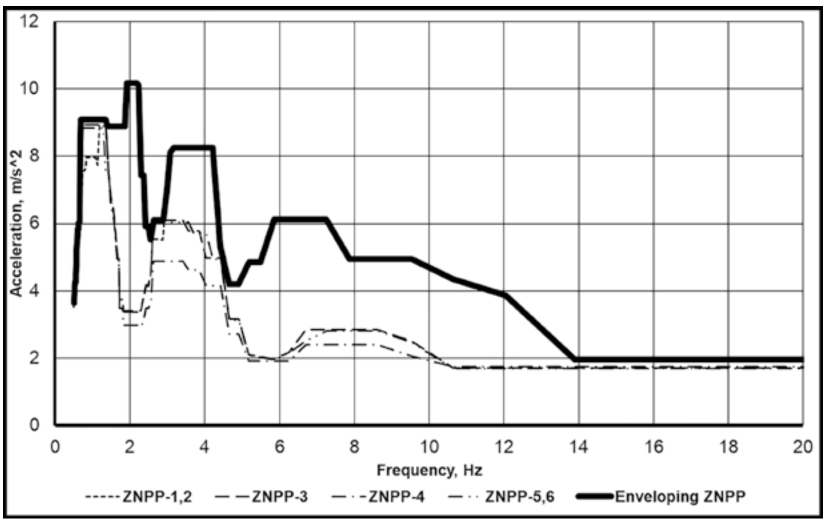


Figure 1 – Enveloping floor response spectrum at the lower elevations of the reactor compartments for ZNPP units for the horizontal direction Ax and 2 % damping

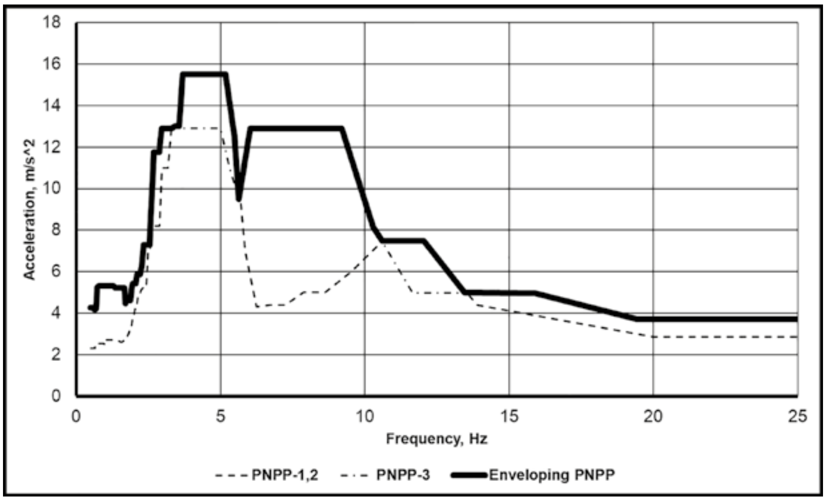


Figure 2 – Enveloping floor response spectrum at the upper elevations of the reactor compartments for PNPP units for the horizontal direction Ax and 2 % damping

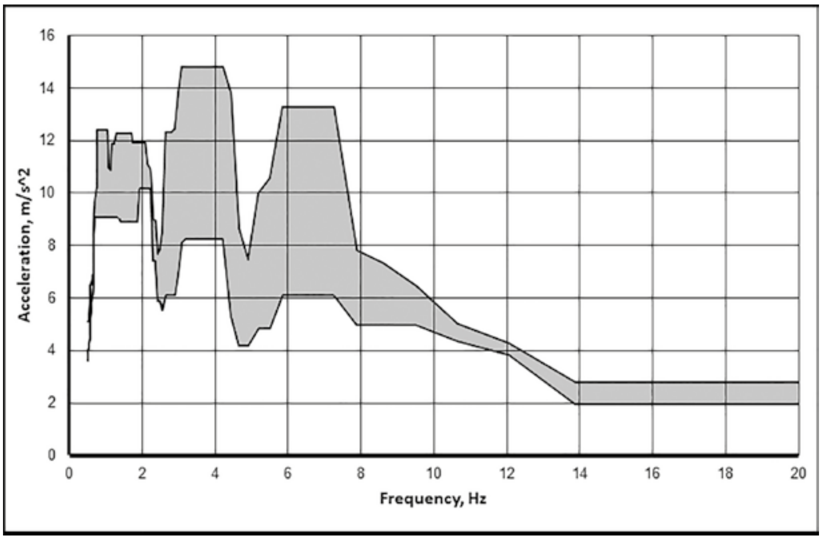


Figure 3 – Enveloping ranges of acceleration values of the reactor compartments for ZNPP units for the horizontal direction Ax and 2% damping

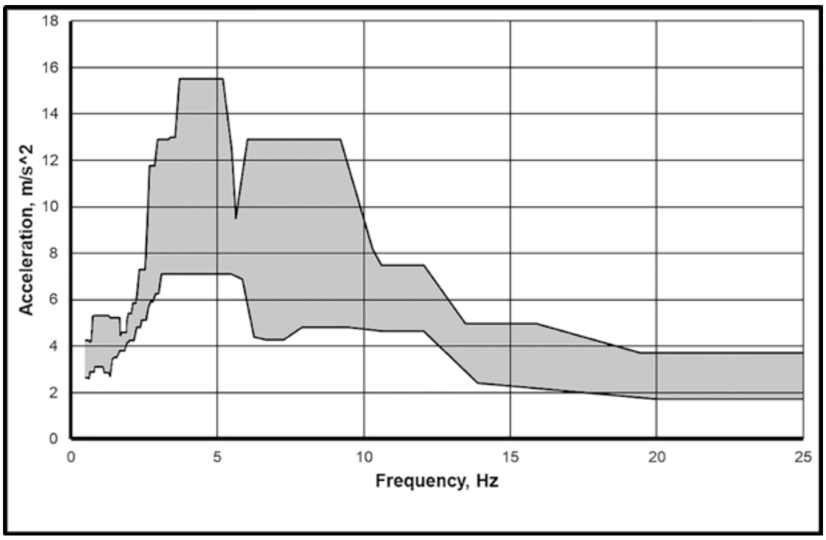


Figure 4 – Enveloping ranges of acceleration values of reactor compartments of the PNPP units for the horizontal direction Ax and 2% damping

Table 2 – The list of loads considered in the SSS research of the support structure St3sp5 steel depending on the temperature

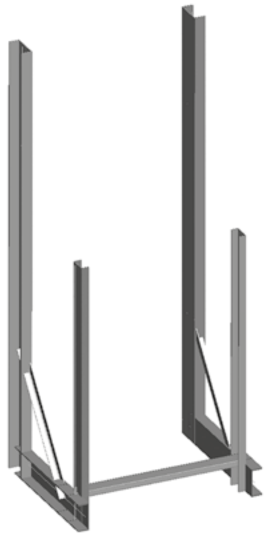
No.	Load description	Reference designation
Basic loads		
Permanent:		
1.	Own weight of the support structure	LR1W
Long-term variables:		
2.	Equipment weight	LVL1W
3.	Load from the equipment environment during NO	LVL3IW
Episodic loads		
4.	Seismic loads transmitted from civil structures during SSE	LE1SM
5.	Seismic loads transmitted from equipment during SSE	LE3SM
6.	Load from the equipment environment during maximum DBA	LE5IAW

Development of a finite element model of the support structure

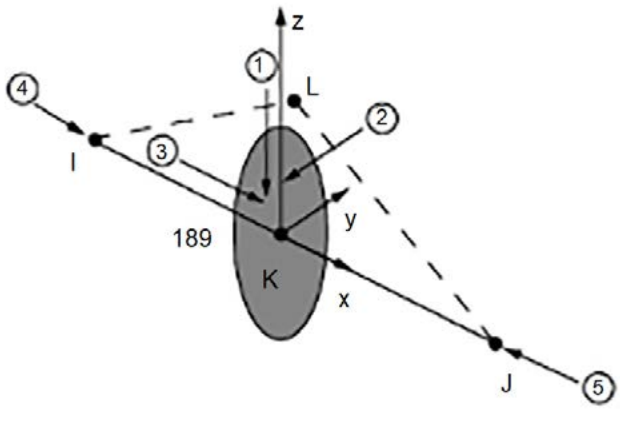
The finite element model of the support structure consists of a 3-D 3-node BEAM 189 component. According to the data of the finite element library of the ANSYS calculation package [27], the BEAM 189 component: has six degrees of flexibility in each node (three displacements and three rotations), can have a cross-section composed of more than one material, is recommended to be analyzed as a composite structure (that is, consisting of two or more components connected together). Figure 5 presents the developed three-dimensional model of the support structure, as well as the geometry, location of nodes, and the coordinate system of the BEAM 189 element [27].

As kinematic boundary conditions in the place of fastening of the support structure to the floor, rigid fixation is adopted, that is, movements and moments in three directions are prohibited.

The definition of a rational finite element mesh is an important part of the numerical simulation, because its quality affects the convergence and accuracy of the results. Therefore, in order to determine the optimum size of the finite element in the SSS research of the support structure, the calculation results on three different finite element meshes with BEAM 189 elements were analyzed. Since the research is devoted to the behavior of the support structure under seismic loads, the finite element size was chosen under loading of the support structure by seismic loads in the form of floor response spectra. Figure 6 presents finite element meshes of three different sizes.



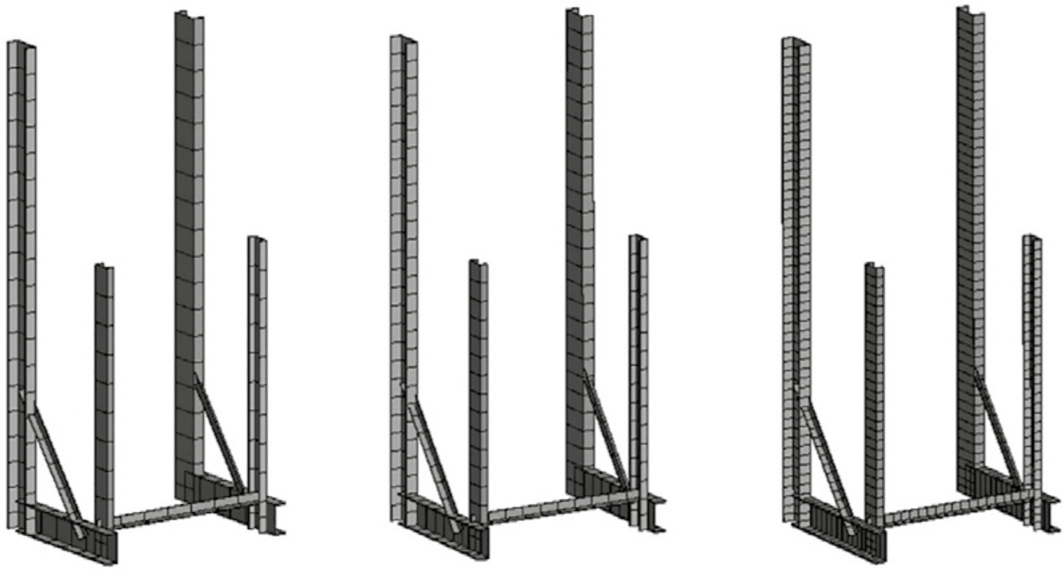
a) Support structure model



b) Finite element BEAM 189

Figure 5 – 3D support structure model and description of BEAM 189 finite element

SSTC NRS ДЕРЖАВНЕ ПІДПРИЄМСТВО ДЕРЖАВНИЙ НАУКОВО-ТЕХНІЧНИЙ ЦЕНТР З ЯДЕРНОЇ ТА РАДІАЦІЙНОЇ БЕЗПЕКИ



a) Mesh 1 b) Mesh 2 c) Mesh 3

Figure 6 – Different sizes of finite element mesh

The selection of the finite element mesh was based on the results of the stress intensity calculation according to the fourth theory of strength for different meshes. It was identified that mesh 2 provides acceptable convergence of the results.

Numerical research of the natural frequency spectrum for the support structure

Table 3 presents the results of the numerical determination of support structure natural frequencies for the following cases:

1) Without load, that is, the support structure is considered without the equipment installed on it;

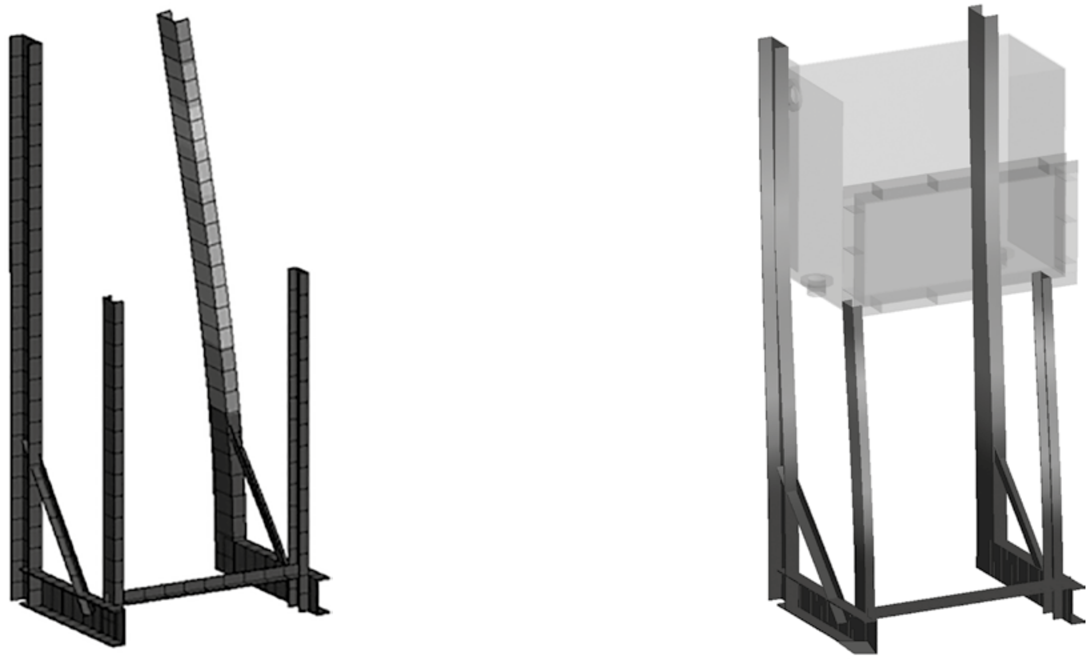
2) With load, that is, the support structure is considered with the equipment (own weight, internal pressure, load from connected piping, etc.) in the NO mode.

Figure 7 represents the first mode of support structure natural frequencies for the without load and with load cases.

Column “Range of seismic accelerations, m/s^2” in Table 3 shows the range of acceleration values that will be transmitted to the support structure at the corresponding natural frequency during its location between the lower (0.0 m.) and upper (36-38 m) elevations of the reactor compartment. Taking into account the fact that we consider the simultaneous

Table 3 – Results of determining the natural frequencies of the support structure for temperatures up to 100 °C

Natural frequency mode No.	Without load		With load	
	Natural frequency, Hz	Range of seismic accelerations, m/s^2	Natural frequency, Hz	Range of seismic accelerations, m/s^2
1	9.87455	8.4 – 15.7 (ZNPP) 6.7 – 16.1 (PNPP)	6.9466	8.8 – 19.6 (ZNPP) 6.2 – 22.7 (PNPP)
2	9.87455	8.4 – 15.7 (ZNPP) 6.7 – 16.1 (PNPP)	20.9732	3.2 – 4.8 (ZNPP) 2.3 – 6.2 (PNPP)
3	19.5371	3.2 – 4.8 (ZNPP) 2.4 – 6.4 (PNPP)	21.9799	3.2 – 4.8 (ZNPP) 2.2 – 6.2 (PNPP)
4	19.9259	3.2 – 4.8 (ZNPP) 2.3 – 6.3 (PNPP)	36.4633	3.2 – 4.8 (ZNPP) 2.2 – 6.1 (PNPP)
5	21.9947	3.2 – 4.8 (ZNPP) 2.2 – 6.2 (PNPP)	52.1668	3.2 – 4.8 (ZNPP) 2.2 – 6.1 (PNPP)
6	21.9947	3.2 – 4.8 (ZNPP) 2.2 – 6.2 (PNPP)	52.3933	3.2 – 4.8 (ZNPP) 2.2 – 6.1 (PNPP)
7	37.7591	3.2 – 4.8 (ZNPP) 2.2 – 6.1 (PNPP)	59.0476	3.2 – 4.8 (ZNPP) 2.2 – 6.1 (PNPP)



a) without load b) with load

Figure 7 – The first mode of support structure natural frequencies for the without load and with load cases

impact of seismic loads in three directions (two horizontal and vertical), the acceleration values presented in Table 3 are defined by the following ratio:

$$a_i^{rez} = \sqrt{a_x^2(f_i) + a_y^2(f_i) + a_z^2(f_i)}, \quad (14)$$

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

Table 4 shows the research results of the changes in the spectrum of the support structure natural frequencies with load during temperature increase up to 150 °C (which corresponds to maximum BDA mode "Two-sided rupture of the main coolant piping Du 850" in the unit reactor compartment).

Table 4 – Research of the changes in the natural frequency spectrum of the support structure during temperature increase from 100 ° C to 150 °C

Natural frequency mode No.	Natural frequency value in the range up to 100 °C , Hz	Natural frequency value under 150 °C , Hz	Difference in natural frequency values under 100 °C and 150 °C, %
1	6.9466	6.8227	1.8160
2	20.9732	20.6174	1.7257
3	21.9799	21.6031	1.7442
4	36.4633	36.4330	0.0832
5	52.1668	51.7644	0.7774
6	52.3933	52.0218	0.7141
7	59.0476	58.9791	0.1161

Numerical research of the stress-strain state of the support structure under seismic loads

The numerical research results of support structure SSS located between the lower (0.0 m) and upper (36 – 38 m) elevations of the ZNNP and PNPP are presented in Tables 5 and 6, respectively.

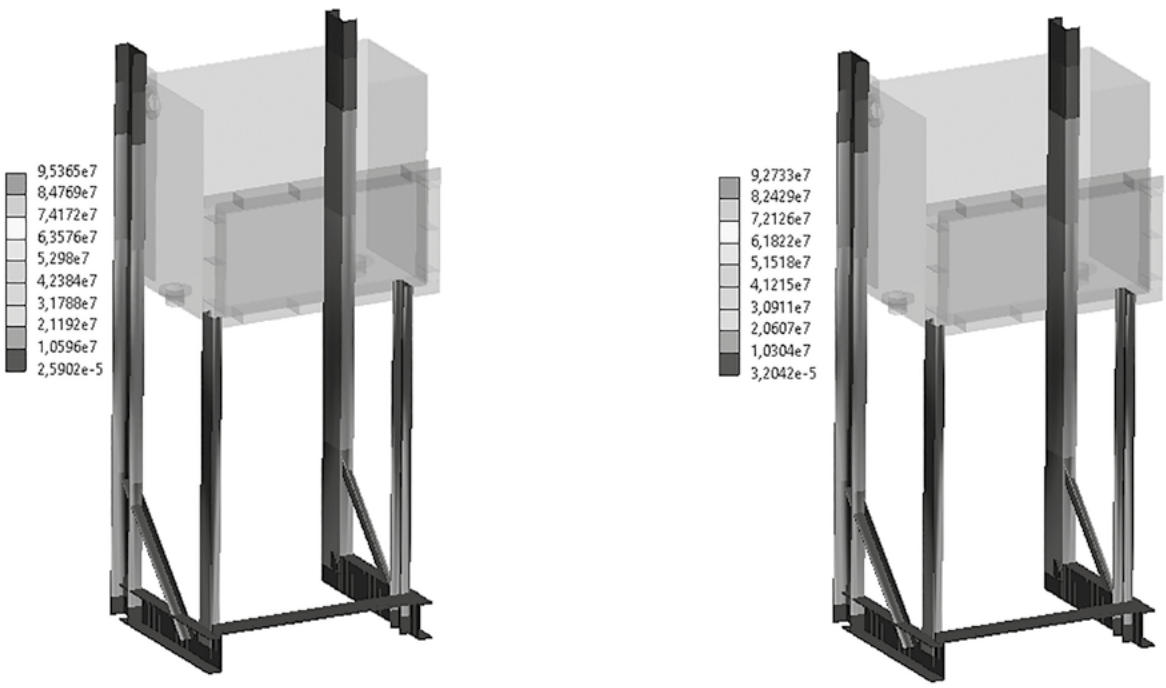
As an example, Figure 8 presents isofields of the stress intensity σ_{int} under seismic loads of the support structure (under temperature of 150 °C in the reactor compartment) if it is located at the upper elevations of the ZNPP and PNPP reactor compartments.

Table 5 – Numerical research results of support structure SSS located in the reactor compartments of the ZNPP units

Loads	Maximum stresses, MPa	
	$SSE^{60°C}$	$SSE^{150°C}$
The enveloping response spectrum at the lower elevations of the ZNPP + seismic loads from the equipment	44.347	43.982
The enveloping response spectrum at the upper elevations of the ZNPP + seismic loads from the equipment	96.157	95.365

Table 6 – Numerical research results of support structure SSS located in the reactor compartments of the PNPP units

Loads	Maximum stresses, MPa	
	$SSE^{60°C}$	$SSE^{150°C}$
The enveloping response spectrum at the lower elevations of the PNPP + seismic loads from the equipment	31.048	30.792
The enveloping response spectrum at the upper elevations of the PNPP + seismic loads from the equipment	93.503	92.733



a) ZNPP b) PNPP

Figure 8 – Examples of isofields of the stress intensity σ_{int} (Pa) if the support structure is located at the upper elevations of the ZNPP and PNPP reactor compartments

Discussion of results

The conducted research of the natural frequency spectrum of the support structure demonstrated that equipment consideration in the computer model of the support structure, changes both the modes of its natural frequencies and the values of the natural frequencies themselves. This situation is due to the fact that taking into account the equipment, changes among other things, the kinematic boundary conditions of the support structure, as it imposes additional loads on its structural components. In our opinion, the obtained result is important and indicates that, in general, taking into account the equipment in the computer model only in the form of additional weight, can lead to a situation when such a computer model will not reflect actual operating conditions of the support structure, as well as features of the geometry that are important for the assessment of seismic strength, distribution of masses and stiffness. In addition, it was established that consideration of the equipment leads to a change in the level of seismic loads (both to a greater and to a lesser extent) on the support structure due to a change in the values of its natural frequencies (see Table 3). At the same time, numerical research have shown that the temperature increase in the NPP unit reactor compartment up to 150 °C under SSE does not significantly (within 2 %) affect the change in the values of natural frequencies of the support structure. At the same time, the change in seismic loads practically does not occur and is at the level of $\pm 0{,}1\,m/s^2$. This situation is stipulated by a minor difference in the value of the modulus of elasticity under temperatures up to 100 °C and under 150 °C.

The numerical SSS studies have shown that the calculated stresses from seismic loads can increase by 2-3 times depending on the elevation of the support structure location in the NPP unit reactor compartment. It was determined that the temperature increase in the NPP unit reactor compartment up to 150 °C under the maximum DBA does not significantly affect support structure SSS. The identified insignificant changes in support structure SSS are within the limits of nonrelevant changes in the values of natural frequencies of the support structure, seismic loads and physical characteristics of St3sp5 steel.

The results of the performed research allow us formulating the following principle of rational design for steel support structures of equipment subjected to seismic loads: under designing, it is necessary to use such connections of structural components that ensure the absence of changes in the kinematic boundary conditions of the support structure in case of direct consideration of the equipment in the computer model. Following this principle will simplify calculations of the support structure by considering the equipment only as concentrated or distributed weight.

Conclusions

1. The range of natural oscillation frequencies of equipment support structure under the parameters of NO and maximum DBA in the ZNPP and PNPP reactor compartments was studied. It was established that equipment consideration in the computer model of the support structure changes the modes and values of its natural frequencies, as well as seismic loads (both to a greater and to a lesser extent). At the same time, the temperature increase in the NPP reactor compartment up to 150 °C under the maximum DBA does not significantly affect the change in the natural frequencies of the support structure.

2. As seismic loads, enveloping floor response spectra were used in three mutually perpendicular directions of seismic impact under SSE at the lower and upper reactor compartment elevations of the ZNPP and PNPP power units for 2 % damping. It has been determined that in this case, the calculated stresses from seismic loads can increase by 2-3 times depending on the elevation of support structure location in the NPP unit reactor compartment. The performed numerical studies demonstrated that the temperature increase in the reactor compartment up to 150 °C under the maximum DBA does not significantly affect support structure SSS.

3. Based on the research results, the following principle of rational design for steel support structures of equipment subjected to seismic load was developed and formulated: under design, it is necessary to use such connections of structural components that ensure the absence of changes in the kinematic boundary conditions of the support structure in the case of direct consideration of the equipment in the computer model. Following this principle will simplify calculations of the support structure by equipment consideration only as concentrated or distributed weight.

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Дослідження напружено-деформованого стану сталевих опорних конструкцій елементів енергоблоків атомних станцій за сейсмічних навантажень

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Сейсмостійкість обладнання та трубопроводів енергоблоків атомних електростанцій визначається, зокрема, сейсмостійкістю їх сталевих опорних конструкцій. Значна кількість цих конструкцій знаходиться в будівлі реакторного відділення енергоблока атомної електростанції та належить до I і II категорій сейсмостійкості. Отже, такі опорні конструкції обладнання та трубопроводів енергоблоків атомних електростанцій загалом повинні виконувати свої функції під час сейсмічних впливів, які відповідають максимальному розрахунковому та проєктному землетрусам відповідно.

Проєктування сталевих опорних конструкцій серійного обладнання (трубопровідна арматура, електро- та пневмоприводи трубопровідної арматури і насосів, розширювальні баки тощо) часто відбувається «за місцем» у стиснених умовах фактичного розташування, тому проєктувати сталеві опорні конструкції низки обладнання доводиться так, щоб воно могло бути під'єднаним, зокрема до існуючих трубопроводів з їх фактичним трасуванням. З огляду на зазначене актуальним постає питання дослідження роботи таких опорних конструкцій під час сейсмічних навантажень.

У статті наведено результати дослідження спектра власних частот коливань опорної конструкції обладнання, а також визначено напружено-деформований стан конструкції, що розглядається, під час сейсмічних навантажень. До того, враховуються параметри під час нормальної експлуатації та максимальної проєктної аварії на енергоблоці атомної електростанції. Розглядається розрахункове сполучення навантажень, яке одночасно охоплює два епізодичні впливи (максимальна проєктна аварія та землетрус).

Ключові слова: власні частоти, напружено-деформований стан, сейсмічні навантаження, сталеві опорні конструкції.

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