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THE SPECIFICS OF THE COMPILATION OF THE CALCULATED LOAD COMBINATIONS IN THE ASSESSMENT OF SEISMIC RESISTANCE OF STEEL SUPPORTING STRUCTURES OF NUCLEAR POWER PLANT EQUIPMENT AND PIPING

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The seismic resistance of nuclear power plant equipment and piping is determined, inter alia, by the seismic resistance of their steel supporting structures. During the operation of the nuclear power plant power unit, mechanical loads from the elements installed on them are transferred to the steel supporting structures of the equipment and piping. During an earthquake, seismic loads are added to these loads. By state building codes, when considering steel structures in special operating conditions (in particular, exposed to seismic hazards), it is necessary to comply with additional requirements that reflect the features of these structures. Given this, the issue of developing approaches to the compilation of load combinations in assessing the seismic resistance of steel supporting structures of nuclear power plants equipment and piping is acute, taking into account the specific conditions of their operation. The paper is also relevant as it is one of the priority areas of science and technology under the legislation of Ukraine. The development of approaches to the compilation of the calculated load combinations will contribute to the improvement and development of methods for assessing the safety of nuclear power facilities. The paper presents the results of the review of the provisions of state building codes on the calculated combinations of loads when assessing the strength of steel structures. Approaches to the compilation of the calculated load combinations in assessing seismic resistance of steel supporting structures power units of nuclear power plants equipment and piping taking into account the specific conditions of their operation have been developed.

Keywords*: steel structures, seismic resistance, calculated load combinations.*

Introduction

Seismic resistance of equipment and piping of power units of nuclear power plants (NPP) is determined, inter alia, by the seismic resistance of their steel supporting structures. For the manufacture of these structures, I-beams, C-channels, corners, bent closed welded square and rectangular profiles are generally used for building structures (examples of supporting structures of the NPP power unit elements can be found in [1, 2]). Analysis of the operation of steel supporting structures of NPP power units equipment and piping under seismic loads is aimed at clarifying and improving approaches to assessing their seismic resistance. In general, the result of this activity is the improvement and development of methods for assessing the safety of nuclear power facilities. The relevance of this study is also due to the fact that it, in accordance with:

– The Law of Ukraine [3], refers to the priority direction of the development of science and technology (namely: "Energy and energy efficiency");

– Resolutions of the Cabinet of Ministers of Ukraine [4], is included in the list of priority thematic areas of scientific research and scientific and technical development (namely: "Nuclear energy technologies and methods of assessing its safety").

During the operation of the NPP power unit in any design mode, mechanical loads from the elements installed on them are transferred to the steel supporting structures of the equipment and piping. In the event of an earthquake at the NPP site, seismic loads are also added to these loads. In paper [2], it is determined that the assessment of the seismic resistance of the steel supporting structures of NPP power units equipment and piping must be performed on the basis of specific requirements regulated by norms, rules and standards on nuclear and radiation safety (in particular, NP 306.2.208-2016 [5]), and also taking into account the provisions DBN V.2.6-198:2014 [6], DBN V.1.1-12:2014 [7], DBN V.1.2-2:2006 [8], DBN V.1.2-14:2018 [9]. In accordance with DBN V.2.6-198:2014 [6], when considering steel structures that are in special operating conditions (in particular, exposed to seismic hazards), it is necessary to comply with additional requirements that reflect the peculiarities of the operation of these structures.

For now, let's stop at a detailed consideration of the issue of calculated load combinations (CLC) compilation when assessing the seismic resistance of the steel supporting structures under consideration. When it comes to the supporting structures of the NPP power units equipment and piping, document NP 306.2.208-2016 [5] generally regulates only the requirements for combinations of technological operating conditions and seismic hazards. At the same time, the issue of establishing detailed requirements for the CLC compilation when assessing the seismic resistance of steel supporting structures is not considered. The current situation occurred due to the modern concept of the development of the regulatory legal framework of Ukraine for ensuring the safety of nuclear power plants, which provides for the development and implementation of regulatory legal acts containing general regulatory requirements.

Steel supporting structures of NPPs equipment and piping are designed to withstand the simultaneous action of such specific loads as [5]:

– high temperatures occurring in the reactor compartment during the maximum design basis accident at the NPP power unit;

– impacts from equipment and piping with corresponding internal environments (steam, water, steam-water mixture) in various technological conditions of the NPP power unit operation;

– seismic hazards.

The specified factors are the initial data for determining the calculated loads on the supporting structures. However, there are quite a few cases when the CLC used in the calculation of these structures to assess their seismic resistance are not sufficiently complete, for example [10, 11]: the CLC includes seismic loads transmitted to the supporting structures from the buildings to which they are attached, but the additional seismic loads that act on supporting structures during seismic disturbance of equipment and piping are ignored. Such situation arises as a result of the lack of clear rules for compiling the CLC, which take into account the specific conditions of operation of the steel supporting structures of the NPP power units equipment and piping.

As the analysis of sources [12–19] showed, the issue of the CLC compiling for steel supporting structures of NPP equipment and piping, taking into account the specific conditions of their operation, is also not considered in literary and scientific works. At the same time, papers [1, 2, 20–22] consider the general aspects of determining the above-mentioned specific loads on the NPP power units elements (including the supporting structures of equipment and piping), in particular, the preparatory stage for the CLC compilation.

Taking into account the results of the already completed papers [1, 2, 20–22], the need to develop detailed approaches to the CLC compilation when assessing the seismic resistance of steel supporting structures of the NPP power units equipment and piping, taking into account the specific conditions of their operation, became actualized. So, the aim of the paper is:

– review of the provisions of the state building codes regarding CLC when assessing the strength of steel structures;

– development of detailed approaches to the CLC compilation when assessing the seismic resistance of steel supporting structures of NPP power units equipment and piping, taking into account the specific conditions of their operation.

Overview of the provisions of the state building codes regarding calculated load combinations when assessing the steel structures strength

Load values, schemes of their application and consideration conditions are regulated [8, 9]. Spatial distribution of loads in general has a rather complex nature. As a result, in engineering practice, it is customary to simplify the description of such loads by introducing loads that are simpler in structure (for example: uniformly distributed over the surface or concentrated). At the same time, this simplification should ensure the same influence of the load on the structure as the load with a complex spatial structure [23].

According to [8, 9], when calculating the strength of steel structures, mechanical loads are considered as a set of forces (force factors and influences) applied to the structure, including forced movements and additional deformations of structural elements. Loads of non-mechanical origin (for example, the influence of an aggressive environment), as a rule, are taken into account in the calculation indirectly, for example, using the appropriate reliability factors.

Depending on the causes of load and influences, it is customary to divide them into main and episodic ones. At the same time, the main loads are generally caused by technological processes, and the episodic loads are caused by an undesirable result of human activity, an unfavorable coincidence of circumstances, and extreme natural phenomena.

Loads and influences are divided into permanent and variable ones depending on the variability over time. The latter ones, depending on the duration of continuous action, are divided into long-term, short-term and episodic ones. Long-term loads and impacts include those for which the duration is comparable to the structure service life, short-term loads are those for which the duration is much shorter compared to the service life. The set period of operation of the structure is accepted in accordance with the design and operational documentation for the structure.

Permanent loads include: the weight of parts of constructions, including the weight of load-bearing and enclosing structures; weight and pressure of soils (embankments, fills), bearing rock pressure.

Variable long-term loads include: the weight of stationary equipment, piping with valves, supporting parts and insulation, as well as the weight of liquid and solid substances filling the equipment; pressure of gases, liquids and bulk bodies in tanks and piping, excess pressure; temperature technological influences from stationary equipment; the weight of the water layer on water-filled flat surfaces; the weight of industrial dust deposits, if its accumulation is not excluded by appropriate measures.

Variable short-term loads include: loads from equipment that occur in start-stop, transition and test modes, as well as during its rearrangement or replacement; useful and technological loads; loads from mobile lifting and transport equipment and bridge and overhead cranes, as well as loads that occur during the manufacture, storage, transportation and installation of structures.

Episodic loads include: seismic hazards; explosive effects; loads caused by sudden disruptions of the technological process, temporary malfunction or destruction of equipment; impacts caused by deformations of the base, which are accompanied by a radical change in the soil structure (when subsided soils are soaked) or its subsidence in areas of mining and karst areas.

CLC are formed as a set of their calculated values or their corresponding forces and/or movements, which is used to check the structure in a certain limit state and in a certain calculated situation. CLC include loads that can physically act simultaneously and most adversely affect the structure from the point of view of the considered limit state. Two types of combinations are used in structural calculations: basic and emergency ones. At the same time, in addition to constant and variable loads, only one episodic impact can be included in the emergency combination.

The low probability of simultaneous implementation of the calculated values of several loads is taken into account by multiplying the calculated values of the loads included in the CLC by the combination factor $\psi \leq 1$. The values of the combination factors for the loads are given in Table 1 [8, 23, 24].

In the main combinations of loads, taking into account three or more short-term loads, their calculated values are allowed to be multiplied by the loads combination factor, which is accepted for the first (by degree of influence) short-term load as 1.0, for the second one as 0.8, for the rest as 0.6.

In the calculations, the load reliability factor γ_f, which is set taking into account the type of load and depends on the structure service life, is also used. The calculated load values are determined by multiplying the characteristic values by the load reliability factor.

Table 1. The values of the combination factors for loads

Combinations and loads included in them	Combination factor ψ for loads			
	Permanent	Long-term (ψ_1)	Short-term (ψ_2)	Episodic
1) Basic:				
1.1) permanent + 1 long-term	1.0	1.0	–	–
1.2) permanent + 1 short-term	1.0	–	1.0	–
1.3) permanent + long-term + short-term	1.0	0.95	0.9	–
2) Emergency				
2.1) permanent + long-term + short-term + episodic	1.0	0.95	0.8	1.0

Development of detailed approaches to compiling calculated loads combinations when assessing the seismic resistance of steel supporting structures of NPP power units equipment and piping, taking into account the specific conditions of their operation

The design operation modes of the NPP power unit are established by the standard technological regulations for the safe operation of the power unit [25]. This document also defines the permissible number of relevant operation modes of the NPP power unit. In general, the operation of the NPP power unit can be carried out in the following groups of design modes: normal operation (NO), violation of normal operation (VNO), design basis accident (DBA). In relation to the NPP, the specified terms are used in the following meanings [26]:

– normal operation – NPP operation within the operational limits and conditions defined by the project (for example: planned heating of the reactor plant from a "cold" state at a speed value of no more than 20°C/hour; false activation of the reactor's emergency protection; inclusion of the main coolant pump on the main circulation circuit loop, which did not work before; testing of the passive unit of the emergency cooling system of the reactor active zone; scheduled cooling to a "cold" state with a cooling rate of no more than 30°C/hour, etc. [25]);

– violation of normal operation – a violation of NPP operation, during which there was a deviation from the established operational limits and conditions, which did not lead to an emergency situation (for example: de-energization of the main coolant pump in the state of the reactor plant "Working at capacity"; cessation of feed water supply to the steam generator; steam generator leaks mode: rupture of the heat exchange tube; sudden transition to primary circuit feeding with feed water temperature in the range of values from 60 °C to 70 °C; complete shutdown of the NPP; sudden transition to primary circuit feeding with feed water temperature in the range of values from 60 °C up to 70 °C, etc. [25]);

– design basis accident – an accident for which initial events and final states are defined by the project and safety systems are provided, which ensure, taking into account the principle of a single failure of the safety system (system channel) or one additional error of the personnel, the limitation of its consequences by established limits (for example: rupture of piping of the first circuit with a nominal pipe diameter less than 100 mm; high flow mode: rupture of the piping of the first circuit with a nominal pipe diameter more than 100 mm, including 850 mm; rupture of the steam piping of the steam generator; rupture of the piping of the feed water of the steam generator; rupture of the collector of steam piping of "sharp" steam, etc. [25]).

Table 2 shows the requirements [5] for the combination of technological operating conditions and seismic hazards for thermomechanical equipment, piping and their supporting structures of the NPP power unit.

At the same time, in the combination of technological operating conditions and seismic hazards NO + DBA + SSE and NO + DBA + DBE, loads NO refer to constant loads (for example, from own weight).

Table 2. Combination of technological operating conditions and seismic hazards for thermomechanical equipment, piping and their supporting structures of the NPP power unit

Seismic resistance category of the NPP element	The combination of technological operating conditions and seismic hazards according to NP 306.2.208-2016 [5]
I	NO + SSE
	VNO + SSE
	NO + DBA + SSE
	NO + DBA + DBE
	NO + DBE
	VNO + DBE
II	NO + DBE
	VNO + DBE

Notations accepted in the table:
DBE – design basis earthquake;
SSE – safe shutdown earthquake

As noted above, during the operation of the NPP power unit in any design mode, mechanical loads from the elements installed on them are transmitted to the steel supporting structures of the equipment and piping. The study of sources [25, 27] made it possible to research and form a nomenclature of calculated loads to which the steel supporting structures of the NPP power units equipment and piping in groups of NO, VNO and DBA modes are subjected. Herewith, for the first time, a comprehensive system of load symbols was developed, which takes into account the specific operating conditions of the steel supporting structures of the NPP power units equipment and piping. This system of symbols uniquely characterizes the type of load to ensure the correct CLC compilation. Therefore, the following symbols components are accepted: L (**L**oad); R (**R**egular); W (**W**eight); VL (**V**ariables **L**ong); THI (**TH**ermal **I**solation); I (**I**nternal) – internal environment; VSH (**V**ariables **SH**ort); T (**T**ransient) – load in transient mode; E (**E**pisodic) – episodic load; SM (**S**eismic **M**aximum) – load from SSE; SD (**S**eismic **D**esign) – load from DBE; A (**A**ccident) – load from DBA.

Table 3. Nomenclature of calculated loads to which steel supporting structures of the NPP power units equipment and piping are subjected in groups of modes NO, VNO and DBA

No.	Load description	Load symbol
	Basic loads	
	Regular:	
1	Own weight of the supporting structure	LR1W
	Variable long-term:	
2	Weight of equipment/piping	LVL1W
3	Weight of thermal insulation of equipment/piping	LVL2THIW
4	Load from the environment of the equipment/piping at NO	LVL3IW
	Variable short-term:	
5	Load from equipment/piping in start-stop and test modes	LVSH1TW
6	Load from the environment of the equipment/piping in transient mode (VNO)	LVSH2TW
	Episodic loads	
7	Seismic loads transmitted from building structures at SSE	LE1SM
8	Seismic loads transmitted from building structures at DBE	LE2SD
9	Seismic loads transmitted from equipment/piping at SSE	LE3SM
10	Seismic loads transmitted from equipment/piping at DBE	LE4SD
11	Load from the environment of the equipment/piping at DBA	LE5IAW

The effect of seismic hazard on three components (two horizontal and vertical one) is considered as one episodic load. The developed nomenclature of calculated loads, as well as their symbols, are shown in Table 3.

According to [8], when determining the load from the weight of the structure, the factor γ_f for metal structures is taken to be equal to 1.05, if the forces from its own weight are less than 50%, and 1.10, if they are equal to or exceed 50%. At the same time, for other loads from Table 3, the factor should be taken equal to one, since in [8] it is not regulated for these specific types of loads of steel supporting structures of the NPP power units equipment and piping.

The establishment of numerical values of changes in the parameters of the internal environment (in particular, pressure), as well as its state of aggregation (steam, water, steam-water mixture) of specific equipment and piping at VNO and DBA is also carried out on the basis of consideration of project design, technological and operational documentation (analyses of design basis accidents, protection and blocking installation maps, operating instructions, element passports, etc.) [21].

The following prerequisites and approaches are adopted when compiling the CLC:

– it is assumed that all loads in the selected CLC simultaneously affect the supporting structures of equipment and piping;

– CLC includes loads that most adversely affect the supporting structures of equipment and piping;

– influences that mutually exclude each other are not included in one CLC;

– the low probability of simultaneous implementation of the calculated values of several loads is taken into account by the combination factor $\psi \leq 1$, which is determined according to [8].

According to [8], seismic hazards and DBA are episodic influences, therefore emergency combination is considered for the supporting structures of the NPP equipment and piping. At the same time, in accordance with the requirements [5] and in contrast to the approaches [8], these two episodic effects are simultaneously included in the emergency combination.

According to [5], combinations of technological operating conditions and seismic hazards do not include start-stop and test modes. Therefore, the LVSH1TW load is not included in the CLC. Table 4 shows the nomenclature of the developed CLC for steel supporting structures of the NPP power units equipment and piping, taking into account the specific conditions of their operation.

During the development of approaches to the CLC compiling, it was established that the VNO modes at the NPP according to the approaches [8, 9] can be attributed to variable short-term loads in relation to the supporting structures of the equipment and piping. In this case, when compiling load combinations taking into account seismic hazards, the combination factor should be taken as the minimum of all possible values for the basic and emergency combinations (see Table 1), which reduces the conservatism of the results of the supporting structures strength assessment. This decrease is a cause for some concern given the fact that in certain VNO modes the safety systems of the NPP power unit are activated, i.e. systems to which increased safety requirements must be imposed. Therefore, in further research, it is advisable to develop recommendations for adjusting this factor for steel supporting structures of equipment and piping of safety systems, the operation of which occurs in VNO modes at NPPs.

Table 4. Nomenclature of the developed CLC for steel supporting structures of the NPP power units equipment and piping, taking into account the specific conditions of their operation

Combination of technological operating conditions and seismic hazards	CLC for supporting structures of equipment and piping
Supporting structures of the I earthquake resistance category	
NO + SSE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THI+0.95×LVL3IW+ +1.0×LE1SM+1.0×LE3SM
VNO + SSE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+ +0.8×LVSH2TW+1.0×LE1SM+1.0×LE3SM
NO + DBA + SSE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+1.0×LE5IAW+ +1.0×LE1SM+1.0×LE3SM
NO + DBA + DBE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+1.0×LE5IAW+ +1.0×LE2SD+1.0×LE4SD
NO + DBE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+0.95×LVL3IW+ +1.0×LE2SD+1.0×LE4SD
VNO + DBE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+ +0.8×LVSH2TW+1.0×LE2SD+1.0×LE4SD
Supporting structures of the II earthquake resistance category	
NO + DBE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+0.95×LVL3IW+ +1.0×LE2SD+1.0×LE4SD
VNO + DBE	1.0×LR1W+0.95×LVL1W+0.95×LVL2THIW+ +0.8×LVSH2TW+1.0×LE2SD+1.0×LE4SD

Conclusions

1. During the operation of the NPP power unit, mechanical loads from the elements installed on them are transmitted to the steel supporting structures of the equipment and piping. During an earthquake, seismic loads are also added to these loads. Taking into account the above, a review of the provisions of the state building codes regarding CLC in assessing the strength of steel structures was carried out.

2. The nomenclature of calculated loads to which steel supporting structures of the NPP power units equipment and piping are subjected in groups of NO, VNO and DBA regimes is defined. For the first time, a comprehensive system of calculated loads symbols has been developed, which takes into account the specific operating conditions of the steel supporting structures of the NPP power units equipment and piping.

3. According to [8], seismic hazards and DBA are classified as episodic influences, therefore emergency combination is considered for the supporting structures of NPP equipment and piping. At the same time, in accordance with the requirements [5] and in contrast to the approaches [8], these two episodic effects are simultaneously included in the emergency combination. Therefore, based on the results of the work performed, approaches to the CLC compilation have been developed when assessing the seismic resistance of steel supporting structures of the NPP power units equipment and piping. On the basis of these approaches, a specific nomenclature of CLC for steel supporting structures has already been developed, taking into account the specific conditions of their operation.

The developed approaches to the CLC compilation and the specific nomenclature of the CLC will be used by us in the future during:

– numerical studies (using the ANSYS calculation complex) of the stress-strain state of steel supporting structures of NPP equipment and piping under seismic loads;

– development of a methodology for assessing the seismic resistance of steel supporting structures, which takes into account the specific conditions of their operation and the degree of responsibility for ensuring the safety of nuclear power plants during and after seismic hazards.

4. During the development of approaches to the CLC compilation, it was established that the VNO modes at the NPP according to the approaches [8, 9] can be attributed to variable short-term loads in relation to the supporting structures of equipment and piping. In this case, during the compilation of load combinations taking into account seismic hazards, the combination factor should be taken as the minimum of all possible values for the basic and emergency combinations, which reduces the conservatism of the results of the supporting structures strength assessment. This decrease is a cause for some concern given the fact that in certain VNO modes the safety systems of the NPP power unit are activated, i.e. systems to which increased safety requirements must be imposed. Therefore, in further studies, it is advisable to develop recommendations for adjusting this factor for steel supporting structures of equipment and piping of safety systems, which are triggered in the VNO modes at the NPP.

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Особливості складання розрахункових сполучень навантажень при оцінці сейсмічної міцності сталевих опорних конструкцій обладнання і трубопроводів атомних станцій

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Сейсмостійкість обладнання і трубопроводів енергоблоків атомних станцій визначається в тому числі й сейсмостійкістю їх сталевих опорних конструкцій. При експлуатації енергоблока атомної станції на сталеві опорні конструкції обладнання і трубопроводів передаються механічні навантаження від елементів, які на них встановлені. При землетрусі до цих навантажень додаються також сейсмічні. Відповідно до державних будівельних норм під час розгляду сталевих конструкцій, що знаходяться в особливих умовах експлуатації (зокрема, піддані сейсмічним впливам), необхідно дотримуватися додаткових вимог, які відображають особливості їх роботи. З огляду на це актуальним є питання розробки підходів до складання розрахункових сполучень навантажень при оцінці сейсмічної міцності сталевих опорних конструкцій обладнання і трубопроводів енергоблоків атомних станцій з урахуванням специфічних умов їх експлуатації. Крім того, актуальність роботи зумовлена також тим, що згідно з чинним законодавством України вона належить до пріоритетних напрямів розвитку науки і техніки. Розробка підходів до складання розрахункових сполучень навантажень сприятиме покращенню та розвитку методів оцінки безпеки об'єктів атомної енергетики. У статті наведено результати огляду положень державних будівельних норм щодо розрахункових сполучень навантажень при оцінці міцності сталевих конструкцій. Розроблено підходи до складання розрахункових сполучень навантажень при оцінці сейсмічної міцності сталевих опорних конструкцій обладнання і трубопроводів енергоблоків атомних станцій, спираючись на специфічні умови їх експлуатації.

***Ключові слова**: сталеві конструкції, сейсмічна міцність, розрахункові сполучення навантажень.*

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