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Consideration of the structures working conditions in the method of limit states

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In the method of limit states, the coefficient of working conditions must take into account all the features of the work and operation of structures. In the code editions, the scale of these coefficients was regularly reviewed and supplemented. Probabilistic aspects of substantiating the coefficients of the working conditions were developed by researchers of the building structure's reliability. The interpretation of the constructive correction as an experimental analog of the coefficient of working conditions was achieved by full-scale tests of industrial buildings structures. The analysis of the reliability of compressed-bent elements and statically uncertain systems determined the additional coefficients of the working conditions. The article contains a systematic analytical review of normative documents and scientific publications with an analysis of the evolution of steel structure design codes in terms of changes in the coefficient of working conditions and the involvement of research, experimental and statistical data.

Keywords: design codes, reliability, limit states, coefficient of working conditions, constructive correction

Врахування умов роботи конструкцій в методиці граничних станів

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У загальній методиці розрахунку конструкцій за граничними станами коефіцієнт умов роботи повинен враховувати всі особливості роботи й експлуатації конструкцій, що не враховані в явному вигляді іншими коефіцієнтами методики. Можна вважати, що цей коефіцієнт покриває всі неточності розрахункової моделі, що виникають внаслідок її спрощення і ідеалізації, для того, щоб розрахунок можна виконати з необхідною точністю та з розумними працевтратами. Відомо, що у будь-якому розрахунку вводять спрощуючі положення, зокрема, основні гіпотези опору матеріалів та будівельної механіки. Унаслідок цього в будь-якому розрахунку виникають неминучі відхилення, обумовлені неточністю розрахункової моделі, котрі мають або систематичний, або випадковий характер. Для того щоб врахувати (або компенсувати) ці похибки і забезпечити необхідну надійність конструкції, що проєктується, вводять коефіцієнт умов роботи. Очевидно, що він має статистичну природу, в окремих випадках він детально вивчений і обґрунтований. Однак у деяких випадках його значення встановлені експертним методом на основі досвіду проектування та експлуатації і потребують подальшого вивчення й уточнення. Дані стосовно розрахункових коефіцієнтів методики граничних станів, зокрема коефіцієнта умов роботи, вміщено в численних випусках нормативних документів, затверджених у різні роки. Таким чином створено значний масив інформації, котрий не проаналізовано у достатній мірі. Не систематизовано результати натурних випробувань будівель і конструкцій як основи нормування коефіцієнта умов роботи. Маловідомими залишаються наробки дослідників надійності будівельних конструкцій, які можна залучити до обґрунтування нових коефіцієнтів умов роботи різних конструкцій. Тому метою і задачами статті є систематизований аналітичний огляд нормативних документів і наукових публікацій, починаючи з 1950-х років, з аналізом еволюції норм проектування сталевих конструкцій у частині змін коефіцієнта умов роботи та залученням до цього дослідних експериментальних і статистичних даних.

Ключові слова: норми проєктування, надійність, граничні стани, коефіцієнт умов роботи, конструктивна поправка

Introduction

In the general method of calculating structures according to limit states, the coefficient of working conditions γ_c (preliminary designation m) must take into account all the features of the work and operation of structures, which are not explicitly taken into account by other coefficients of the method. Therefore, this coefficient is the most loaded by purpose and the least determined by content and value. The value $\gamma_c < 1$ takes into account the unfavorable operating conditions of the structure, the value $\gamma_c < 1$ – favorable operating conditions.

It can be assumed that this coefficient covers all the inaccuracies of the calculation model, which arise as a result of its simplification and idealization, so that the calculation can be performed with the necessary accuracy and with reasonable labor costs. It is known that in any calculation, simplifying provisions are introduced, in particular, the main hypotheses of resistance of materials and construction mechanics. Let us name here as examples assumptions about the operation of the material (for example, the Prandtl diagram), elements (hypothesis of flat sections), structures (hinged nodes of steel trusses), constructive systems (simplified schemes of the industrial buildings frames). As a result, in any calculation there are inevitable deviations caused by the inaccuracy of the calculation model, which are either systematic or random in nature.

In order to take into account (or compensate) these errors and ensure the necessary reliability of the designed structure, the coefficient of working conditions γ_c is entered. It can be considered that it has a statistical nature, in some cases it is studied in detail and substantiated. However, in some cases, its values are established by an expert method based on design and operation experience and require further study and clarification.

Review of research sources and publications

Some aspects of the substantiation of the future coefficient of working conditions were developed even within the framework of the methodology for calculating building structures according to allowable stresses, which prevailed in design until the middle of the 20th century [1, 2]. The initial values of the working conditions coefficients were included in the first limit state design codes introduced in the 1950s. In subsequent editions of the codes, the scale of these coefficients was regularly reviewed and supplemented. With additional changes, the coefficients of working conditions were transferred to the codes of Ukraine, in particular, in DBN B.2.6-198:2014 "Steel structures. Design codes" [3]. Probabilistic aspects of substantiating the coefficients of the working conditions of structures of various purposes were developed by researchers of the building structures reliability [4, 5] and representatives of the scientific school "Reliability of Building Structures" of the National University "Yury Kondratyuk Poltava Polytechnic" [6, 7]. A significant contribution to the interpretation of the structural correction as an experimental analog of the coefficient of working conditions was achieved by full-scale tests of steel structures of industrial buildings [8]. The analysis of the reliability of compressed-bent elements determined the additional coefficient of the working conditions of stepped steel columns of shops equipped with overhead cranes [9, 10]. The result of the successful application of the probabilistic method of limit equilibrium to the reliability assessment of statically uncertain systems was the development of a scale of their working conditions coefficients [11-13]. The substantiation of the calculated coefficients of the limit state method, in particular the coefficient of working conditions, was in the field of view of leading foreign researchers of reliability [14-18]. The national codes of recent years outline the prospects for the development of the general methodology for calculating building structures and the scale of calculation coefficients [19-20].

Definition of unsolved aspects of the problem

Data regarding the calculation coefficients of the limit state methodology, in particular the coefficient of working conditions, are included in numerous issues of normative documents approved in different years. In this way, a significant mass of information was created, which has not been analyzed to a sufficient extent. The results of field tests of buildings and structures have not been systematized as a basis for normalizing the coefficient of working conditions. Little is known about the achievements of researchers of the building structures reliability, which can be involved in justifying new coefficients of the working conditions of various structures.

Problem statement

Carrying out a systematic analytical review of normative documents and scientific publications, starting from the 1950s, with an analysis of the evolution of steel structure design codes in terms of changes in the coefficient of working conditions and the involvement of research, experimental and statistical data.

Basic material and results

Evolution of the coefficient of working conditions in codes.

The initial values of the working conditions coefficient were included in the first design codes for limit states. In particular, in NITU 121-55 "Codes and technical conditions for the design of steel structures" a rather extensive scale of the values of this coefficient was included, we will give an explanation for some of them.

• For tank hulls and bottoms, a reduced coefficient of working conditions of $m = 0.8$ was introduced, which takes into account the increased risk of tank collapse and the complex stress state of the sheet structure of the tank, in particular, the connection of the hull with the bottom, where the edge effect is created.

• The coefficient of working conditions, less than the unit $m = 0.9$, is regulated for columns, trusses and beams of public buildings, that is, in relation to structures under the action of a mainly constant load (with a small reliability coefficient for the load). This is justified by the fact that these responsible structures can collapse from any minor accidental overload. It should also be noted that the listed structures work on a low-variable load, and their limit state can occur when the value of the resistance of the material of the structure is the smallest. For comparison, if the structure works on a load with significant variability, the limit state occurs when the smallest values of material resistance are combined with the largest values of loads, which happens much less often and is less dangerous.

• The coefficient $m = 0.9$ is attributed to compressed elements of roof trusses, the possible destruction of which occurs suddenly and is particularly dangerous.
• It is taken into account that rods made of single corners transmit forces with an eccentricity, which reduces their load-bearing capacity, in the places where they join one of the shelves, which is taken into account by the coefficient of working conditions $m = 0.75$.
• The reduced operating conditions coefficients of riveted and bolted connections $m = 0.6 – 0.8$ take into account their specifics of operation and are associated with transition coefficients for the allowable resistances of the same connections [1].
• Significantly reduced coefficient of working conditions of anchor bolts $m = 0.65$ takes into account their increased responsibility, since they ensure the stability of the building as a whole, being at the same time in a hidden concreted state; in addition, they have a thread and can be loaded unevenly. This approach became the method of limit states from calculations based on allowable stresses [1].
In the following codes of SNiP II-V.3-72 "Steel structures. Design codes" from the table of coefficients of working conditions, the items regarding structures of tanks, roof trusses and purlins loaded with snow load, and connections of structures were removed from the table, and the following additional coefficients of working conditions were introduced.
• Reduced coefficient $m = 0.8$ in relation to the compressed elements of the truss lattice. This was due to the fact that the compressed rods, which were usually located in the middle parts of the trusses, were picked up with little effort, had small sections and were too flexible; they were easily damaged during transportation, installation and operation, could prematurely lose stability and lead to truss accidents (such cases really happened in the 1960s-1970s of the last century). The introduction of this coefficient removed the specified problem.
• The coefficients $m = 0.75...0.9$ regulated the specific features of the rods work of the of spatial lattice structures from single corners.
• The reduced coefficient of working conditions $m = 0.9$ was intended to increase the reliability of steel crane beams, which suffered frequent damage in difficult operating conditions.
In the codes of SNiP II-23-81 "Steel structures. Design codes"), the table of coefficients of working conditions, from which the reduced coefficient for crane beams was removed, was significantly supplemented with new items.
• Reducing coefficient $\gamma_c = 0.95$ for checks of the overall stability of solid beams, which takes into account the nature of this type of destruction, which occurs suddenly and dangerously.
• Reduced coefficient $\gamma_c = 0.9$, which takes into account the presence of threads in stretched elements in the calculation of the main section.
• Coefficients for the rod structures elements: reduced $\gamma_c = 0.95$ for compressed elements during stability testing and stretched elements in welded structures; at the same time, for the same structures with bolted connections, an increased factor $\gamma_c = 1.05$ is regulated in strength calculations.
• Increased coefficients $\gamma_c = 1.05 – 1.1$ for structures connected by bolts, which takes into account the more favorable nature of work and possible destruction of such structures compared to welded structures.
In addition to the given coefficients γ_c, which can be considered "basic", the codes of SNiP II-23-81 contained the scales of the working conditions coefficients of connections $\gamma_b = 0.75 – 1.0$; elements of power transmission line supports $\gamma_c = 0.75 – 0.95$; structures of communication antenna structures $\gamma_c = 0.55 – 1.10$ and separately – determination of coefficients of working conditions for a stretched single corner, which is fastened to one shelf with bolts.
With additional changes, the scale of coefficients of working conditions was transferred to the codes of Ukraine DBN V.2.6-198:2014 "Steel structures. Design codes" [3]. From the previous version of the codes, a reduced coefficient for calculating solid beams for overall stability and an increased coefficient for checking the strength of solid beams and columns with bolted connections under static load were removed.
At the same time, new items of the table of coefficients of working conditions were entered into the DBN.
• Coefficient $\gamma_c = 1.05$ for the columns of industrial structures with bridge cranes, which partially takes into account the increased level of reliability of the columns compared to other structures due to the combined action of several random loads on them (information on this issue is given below and in more detail in the monograph [4]).
• A group of increased coefficients of working conditions $\gamma_c = 1.10 – 1.20$ in relation to support plates of different thicknesses under the action of static load, taking into account, obviously, the relatively favorable working conditions under the load of these structural elements.
As in the previous version of the code for the design of steel structures, DBN B.2.6-198:2014, in addition to the general coefficients of working conditions, regulates the corresponding coefficients for specific types of steel structures:
• for bolted connections – in the form of an expanded table;
• for structures of supports of overhead power lines, structures of open devices and contact lines of electrical transport networks - $\gamma_c = 0.75 – 0.95$;
• for structures of communication antenna structures up to 500 m high –$\gamma_c = 0.55 – 1.10$;
• for structures of river hydrotechnical structures - $\gamma_c = 0.55 – 1.10$ in the main combinations of loads; $\gamma_c = 0.70 – 1.50$ in special combinations of loads.

Constructive correction as an experimental assessment of the coefficient of working conditions.

The constructive correction k is the ratio of the actual stress or deflection from the selected load to the conditional calculated stress (or deflection) from the same load:

$$k_\sigma = \frac{\sigma_{експер}}{\sigma_{теор}}; \quad k_f = \frac{f_{експер}}{f_{теор}}. \tag{1}$$

The size of the constructive correction is a characteristic of the approximation of the accepted calculation assumptions to the actual operating conditions of the structure, it shows how close the conditional calculation scheme is to its actual scheme. This interpretation of the constructive correction practically coincides with the above definition of the content of the coefficient of working conditions, so it can be considered that the constructive correction is an experimental assessment of the coefficient of working conditions. Considering the limit inequality of the limit states of the first group, the operating conditions coefficient is the inverse of the constructive correction, i.e.

$$\gamma_c = 1/k_\sigma; \quad k_\sigma = 1/\gamma_c. \tag{2}$$

Therefore, constructive corrections, smaller units, correspond to the values of the operating conditions coefficient, larger units, which indicates favorable features of work and possible reserves of the structure's bearing capacity. On the contrary, constructive corrections, larger units, indicate an underestimation by the selected calculation models of real stresses, which requires the introduction of coefficients of working conditions, smaller units and corresponding strengthening of the structure.

The experience of field tests of real structures, in particular steel structures, convincingly shows that the constructive corrections in most cases are not equal to unity. DSc. G.A. Shapiro, who conducted large-scale studies of the actual operation of steel structures in industrial workshops in 1936...1951 [8], developed the approximate structure of constructive correction of steel structures as follows:

$$k = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5\alpha_6\alpha_7\alpha_8, \tag{3}$$

where α_1 is a general correction to the calculation scheme;

α_2 – correction to the geometric scheme;

α_3 – correction to structural elements;

α_4 – correction for cross-sections of working elements;

α_5 – correction for spatial work;

α_6 – correction for draft and rotation of supports;

α_7 – load correction: its magnitude, relative position and change;

α_8 – correction for stiffness of nodes.

As we can see, this still incomplete list of components clearly shows the rather complex structure and content of the constructive correction and, accordingly, the coefficient of working conditions.

In the years preceding the Second World War, TsNIPS and Gynstalmost performed tests of 300 light roof trusses [8], which made it possible to construct an experimental distribution curve of the constructive correction by stresses with numerical characteristics: average value $\bar{k} = 0,90$, standard $\hat{k} = 0,11$. The experimental curve was approximated by normal distribution.

In order to understand the nature of the constructive correction of steel roof trusses, let us remind you that for determining the forces, the trusses are represented by an idealized system with rectilinear rods converging at one point (the center of the nodes) and connected by hinges. It is usually believed that the rods are made of perfectly elastic material, and the circuit itself does not deform. Therefore, the constructive corrections for the deflections are less than one unit (Table 1) due to the influence of the nodes stiffness and the indistinctness of the belts. These features have less effect on the values of axial forces in the rods: the design correction for stresses is equal to $k = 0.96$ for light-type welded trusses (Table 1). This tendency appears to a lesser extent for heavy trusses with H-shaped bar sections, as well as for riveted trusses.

Table 1 – Constructive corrections of steel trusses of various types

Truss tape	Constructive corrections	
	by deflections	by stresses in the middle of the truss belts
Welded light type	0,89	0,96
Welded heavier type	0,79	0,79
Riveted light type	0,76	0,68
Riveted heavier type	0,59	0,55

It is obvious that the calculation model of the trusses must correspond to their general static scheme (split, non-split, freely supported, clamped). This provision is clearly illustrated by the data in the Table 2.

Table 2 – Constructive corrections of steel multi-span uncut truss (with different calculation methods)

Calculation scheme	Constructive corrections	
	by stresses in the middle of the truss in the lower and upper belts	by deflections in the middle of truss
Inseparable system	0,96	0,89
Split system	0,71	0,75
Truss freely supported on two supports	0,88	0,86

During the above-mentioned studies, G.A. Shapiro [8] investigated the actual operation of some steel crane beams, the resulting constructive corrections are listed in the Table 3. Rather unusual values of corrections exceeding unity are the result of rather complex work of crane beams. This was explained by the presence of a biaxial stress state in the wall of the beams, the early appearance of plasticity, and the influence of the curvature of the beam wall. In fact, there are many other factors affecting the operation of crane beams, which at the time of the tests (1936...1951) were insufficiently investigated. So, this is an example of how the values of the constructive correction reflected the level of structural research.

Table 3 – Constructive corrections of crane beams by stresses

	Crane beams			
	1	2	3	4
Constructive corrections	1,29	1,26…1,33	0,955…1,070	1,18…1,47

During the period of transition from the method of allowable stresses to the method of limit states (50s...60s of the 20th century), full-scale experimental studies of structures were intensified to clarify their actual operation and identify constructive corrections. Tests of steel structures of several metallurgical plants gave the following values of constructive corrections:

- crane trusses (by deflections) $k = 0.67...1.00$;
- crane beams (by deflections) $k = 0.53...1.07$;
- crane beams (according to stresses) $k = 0.51...0.87$.

At the same time, the great difficulties of field research in operating workshops, especially metallurgical ones with their exceptionally intensive mode of operation and highly aggressive internal environment (high temperatures, gassing, dynamic crane effects, etc.) are obvious. It should be noted that the majority of the received constructive corrections turned out to be less than one, that is, they had the opposite character to the data of G.A. Shapiro. It is possible that this indicated the available reserves in the studied beams and the possibility of some increase in the coefficient of working conditions. According to data obtained experimentally in the 1960s, the constructive correction for deflections of welded crane beams is in the range of 0.85...1.00.

The most complete data on constructive corrections of transverse frames was obtained by G.A. Shapiro during large-scale field tests of production buildings (OVB) in the 30s...50s of the last century [8]. Some of the obtained results are shown in the Table 4. Workshop No. 1 – Marteniv shop, built at the beginning of the 20th century, with a hinged connection of crossbars with columns and riveted steel structures. Workshop No. 4 is also Marteniv shop, designed in the 1940s, with rigid transverse frames and lattice crossbars. As can be seen from the Table. 4, constructive corrections for transverse displacements were found to be very small compared to the calculation of a flat free-standing frame, which clearly indicates the significant approximation of this calculation model. After taking into account the spatial calculation model, the constructive correction was significantly increased, although it still does not reach unity, which indicates the incomplete perfection of the spatial model of the OVB of the 1940s..1950s.

Table 4 – Constructive corrections of OVB frames according to transverse displacements

No work-shop	Marking the place of displacement measurement, m	Transverse braking of a bridge crane		Horizontal force on the marks of the trusses bottom or the head of the rail	
		Flat frame	Spatial system	Flat frame	Spatial system
№1	25,7	0,12	0,60	0,21	0,80
	18,5	0,16	0,80	0,15	0,58
№4	15,2	0,09	1,00	0,08	0,51
	12,4	0,06	0,90	0,10	0,57

As field tests of OVB steel columns have shown, theoretical and experimental values of normal forces differ slightly, constructive corrections are close to unity (Table 5). Constructive corrections of columns in terms of moments are much smaller due to their more complex nature (uncertainty of lateral forces of cranes, eccentricity of crane beams support, complex construction of trusses and work platforms, etc.).

Table 5 – Constructive corrections of steel columns

Column type		Constructive corrections	
		by normal forces	by bending moments
Heavy (with branches from folded I-beams)	Extreme row	0,91…1,01	0,66…0,74
	Average row	0,76…1,00	0,44…0,67
Light (with branches from rolled corners)		0,87…1,03	0,64…0,74

Probabilistic estimates of the coefficient of working conditions of steel structures. The substantiation of the coefficients of working conditions, in addition to the assessment of constructive corrections, can also be based on probabilistic studies and assessments of the structures reliability.

Let's consider the justification of the coefficient of the working conditions of steel stepped columns. The peculiarity of column structures is, in particular, that several random loads of different probabilistic nature (permanent, atmospheric, crane) act on them. Therefore, the assessment of the reliability of such structures is quite difficult, it was obtained in studies conducted at the department of KMDiP PoltNTU over several years [9, 10]. These studies made it possible, in particular, to estimate the reserves of the bearing capacity of OVB steel columns, which did not take into account the current codes, and to propose a new coefficient of working conditions.

To obtain specific results, a number of characteristic stepped columns of industrial buildings, designed according to codes [3], were tested, part of the obtained results is illustrated in *Table 6*, in which the following designations are adopted: L – span of the transverse frame of the industrial building; B – pitch of columns; l_2, l_1 – lengths of the upper and lower parts of the column, respectively; $Q_2(t)$, $Q_1(t)$ are the failure probabilities, respectively, of the upper and lower parts of the column for the service life of t = 50 years, which were determined approximately by the number of emissions $N_+(t) \leq 1$.

As can be seen from Table 6, columns were considered in a wide range of parameters: with rigid and hinged connections of columns with crossbars, for frames with spans of 24...36 *m* and pitches of 6 and 12 *m*, with warm and cold roofs with profiled flooring and reinforced concrete panels, with overhead cranes with a load capacity of 30/5...125/20 *t* of modes 4K-6K and 7K, with snow and wind loads of I, II and III districts; all columns are selected according to the calculation without reserve.

Information of the Table 6 show that the upper parts of stepped columns have the same failure probabilities as columns of constant section and rafter beams with a heavy roof, so we can speak for approximately equal security of this group of steel structures. At the same time, systematically, both with a rigid and with a hinged connection of the crossbars with the columns, the reliability of the lower parts turned out to be significantly greater than the upper ones. This is a consequence of applying to the lower part a greater number of random loads, in particular, a vertical crane load.

This provision made it possible to estimate the reliability reserves of the lower parts of the columns and from the condition $Q_1(t) \approx Q_2(t)$ to find the reduced cross-sectional area and the coefficient of the working condition, which was equal to γ_c = 1,15…1,53 for the tested versions of the columns. This coefficient, determined on the basis of the criterion of equal reliability of parts, can be recommended to be introduced into the calculation formulas for the columns of OVB equipped with bridge cranes. The obtained data made it possible to assign, in the first approximation, the coefficient of working conditions γ_C = 1.15 for the lower parts of steel stepped columns with a margin of the lower calculated values and to recommend it in the codes of design and reinforcement of steel structures. When developing DBN V.2.6-198:2014 "Steel structures. Design codes" [3] this recommendation is carefully considered in the form γ_C = 1.05 for OVB columns equipped with bridge cranes.

Let's proceed to the justification of the coefficient of the working conditions of statically indeterminate frames. In the theory of building structures reliability, the calculation of statically indeterminate systems (beams and frames, multi-story and multi-span buildings) is considered one of the most difficult problems. The reason for this is the complex nature of the destruction of statically indeterminate systems (SIS), which differs from the nature of the destruction of a statically determined system. After the failure of one or even several elements of the SIS, it can maintain an operational state. Therefore, the destruction of a statically indeterminate system can occur, as individual elements fail, by transitioning through different operational states corresponding to different schemes and probability parameters of the system. As a result, the assessment of SIS reliability is a rather cumbersome task, the degree of complexity of which increases rapidly in accordance with the complexity of the system. The researches conducted at the department of KMDiP PoltNTU [11 – 13] managed to overcome the indicated difficulties and to develop methods for assessing the reliability of SIS, suitable for practical use, and to propose a new scale of coefficients of working conditions for such systems.

Table 6 – Reliability assessment of stepped columns of industrial buildings

Variant	Connection of the crossbars with the columns	Geometric parameters		Loads					Failure probabilities		Coefficient of working conditions
				Roof	Cranes		Districts		Upper part	Lower part	
		$\frac{L}{B}$	$\frac{l_2}{l_1}$		Q, t	Mode	Snow	Wind	$Q_2(t)$	$Q_1(t)$	γ_c
1	rigid	$\frac{24}{12}$	$\frac{3,97}{16,4}$	warm concrete panels	15/3	7K	III	I	0,48	$0,96\times 10^{-2}$	1,15
2	rigid	$\frac{36}{12}$	$\frac{6,6}{12,4}$	warm concrete panels	125/20	4K-6K	III	II	0,023	$4,15\times 10^{-4}$	1,15
3	hinged	$\frac{30}{12}$	$\frac{6,1}{11,0}$	warm profiled flooring	100/20	4K-6K	III	II	$9,83\times 10^{-4}$	$2,24\times 10^{-7}$	1,32
4	rigid	$\frac{30}{12}$	$\frac{6,4}{14,2}$	warm concrete panels	100/20	4K-6K	III	II	0,054	$6,5\times 10^{-5}$	1,25
5	hinged	$\frac{36}{12}$	$\frac{6,02}{14,4}$	warm concrete panels	80/20	7K	III	II	0,213	$1,71\times 10^{-6}$	1,18
6	hinged	$\frac{24}{12}$	$\frac{5,23}{17,0}$	warm concrete panels	50/10	4K-6K	I	III	0,54	$5,0\times 10^{-8}$	1,19
7	hinged	$\frac{24}{6}$	$\frac{3,25}{9,75}$	cold concrete panels	30/5	7K	II	I	0,71	$2,78\times 10^{-12}$	1,32

The researches conducted at the department of KMDiP PoltNTU [11 – 13] managed to overcome the indicated difficulties and to develop methods for assessing the reliability of SIS, suitable for practical use, and to propose a new scale of coefficients of working conditions for such systems.

A comparative analysis of SIS reliability calculation methods was carried out: state method, logical-probabilistic method, limit equilibrium method. On this basis, the probabilistic limit equilibrium method (PLEM) was developed. A full assessment of the probability of failure of the SIS with random strength and load was obtained as a result of the development of the PLEM variant, which is based on the kinematic method of limit equilibrium. A variant of this method was used, called the "method of combined mechanisms", which consists of the main mechanisms of SIS destruction: beam, floor (sliding) and nodal. The method is implemented in the form of an algorithm and a computer program, during the calculation of which combined mechanisms with a different number of plasticity hinges are formed, statically unacceptable (excessive) and unlikely mechanisms are rejected. The assessment of the probability of failure of the SIS as a whole was defined as the disjunction of the correlated failure conditions of the main mechanisms, corresponding to the increased probability of destruction.

Using the developed methods and programs, a numerical experiment was performed to determine the reliability of 140 statically indeterminate frames of various purposes and configurations, with the number of floors varying from one to three, the number of spans also from one to three. It has been quantitatively confirmed that the elastic-plastic calculation of the considered SIS leads to material savings of 10...15% compared to the elastic calculation.

In addition, for the first time, the SIS reliability reserve was quantified compared to individual elements and statically determined systems. This reserve is proposed to be taken into account by the newly introduced "schematic reliability coefficient γ_S", similar to the coefficient of the working conditions of the current codes. The justification of the values of this coefficient is based on taking into account its probabilistic nature and the condition of equal reliability of the SIS, according to which the probability of the system failure as a whole is equal to the probability of failure of individual elements.

The analysis showed that as the mechanism of SIS destruction approaches the beam mechanism, the coefficient γ_S decreases, and increases to the shear mechanism; the maximum values of the coefficient γ_S are obtained for the complete destruction mechanisms, the partial mechanism leads to a decrease in the coefficient γ_S. The obtained schematic reliability coefficients are in the interval γ_S = 1.18...1.27 (Table 7), they indicate significant reserves of the SIS's carrying capacity, which do not take into account the current codes. This coefficient of SIS working conditions is intended for use in calculations of the load-bearing capacity of of SIS elements sections, taking into account the plastic stage of operation.

Table 7 – Calculated values of the working conditions coefficient γ_S **of statically indeterminate steel frames**

Number of spans	Number of floors		
	1 floor	2 floors	3 floors
1 span	1,18	1,21	1,21
2 spans	1,19	1,26…1,27	–
3 spans	1,24	–	–

Conclusions

The article is devoted to issues of substantiation and normalization of the coefficient of working conditions - an important factor in the methodology of calculation of building structures according to limit states. A systematic analysis of changes in the normalization of this coefficient in the design codes of steel structures, starting from the 1950s to the present time, was carried out. Emphasis is placed on the constructive correction - the experimental basis of the coefficient of working conditions, the results of the relevant field tests of steel structures of the operating workshops are given. The perspective of probabilistic methods for substantiating the coefficients of the working conditions of stepped columns and statically indeterminate systems is shown.

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