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DETERMINATION OF THE ELEMENTS SIGNIFICANCE IN THE RELIABILITY OF REDUNDANT FRAMES

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Abstract: The paper attacks the problem of steel redundant structures reliability. In calculations the probabilistic method of limit equilibrium is applied. All possible mechanisms of structural failure are considered. The influence of each section on the work of the frame as a whole is taken into account. Stochastic strength and load characteristics are used in the calculations. The proposed method of calculation allows to obtain structures with a given reliability. The calculation provides an opportunity to take into account the existing reserves of frames. The numerical example uses the logic of probabilistic transformations. The graphs of specific contributions of individual sections and the most probable mechanisms of destruction are presented. The probabilistic method takes into account the correlation between the individual mechanisms of destruction. The developed method determines the limiting moments, but it is allowed to take into account the action of the longitudinal force. In this example, the task was to align the impact of the frame sections without reducing the specified reliability, but it is possible to obtain a design with the same specific contributions, which is most economically justified. Specific contributions are increased or decreased as necessary to obtain a design with equal probability of failure. In the design, the influence of destruction individual mechanisms is used, because the cross sections of the beam span or floor column do not change from the design conditions. The method provides an opportunity to obtain more optimal designs and the use of modern software systems for static calculation. Recommendations for the design of these structures have been developed. It is proposed to use the reliability coefficient of redundant steel structures.

Keywords: cross section of destruction,, mechanism of destruction, specific contribution, significance, probabilistic method, correlation, steel frame, reliability coefficient

ОПРЕДЕЛЕНИЕ ЗНАЧИМОСТИ ОТДЕЛЬНЫХ ЭЛЕМЕНТОВ В НАДЁЖНОСТИ СТАТИЧЕСКИ НЕОПРЕДЕЛИМЫХ РАМ

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Аннотация: Публикация посвящена проблеме избыточной надежности стальных статически неопределимых конструкций. В вычислениях используется вероятностный метод предельного равновесия. Рассматриваются все возможные механизмы разрушения конструкции. Учитывается влияние каждого сечения на работу рамы в целом. В вычислениях используются стохастические характеристики прочности и нагрузки. Предложенный метод вычисления позволяет получать сооружения с заданной надежностью. Расчет даёт возможность учесть существующие резервы рам. В числовом примере используются логико-вероятностные преобразования. Представлены графики удельных вкладов как отдельных сечений, так и наиболее вероятных механизмов разрушения. Вероятностный метод учитывает корреляционные связи между отдельными механизмами разрушения. Разработанный метод определяет предельные моменты, но можно учитывать и действие продольной силы. В этом примере, задачей было сравнять влияние сечений рамы без снижения заданной надежности, но возможно получить конструкцию с одинаковыми удельными вкладами, что наиболее эффективно. Удельные вклады возрастают или уменьшаются по мере необходимости, чтобы получить конструкцию с равной вероятностью отказа. При проектировании, используется влияние отдельных механизмов разрушения, потому что сечения балки пролёта или колонны этажа не изменяются по условиям конструирования. Метод позволяет получить более оптимальные конструкции при использовании современных программных комплексов статического расчета. Разработаны рекомендации для непосредственного проектирования данного типа конструкций. Предлагается использовать коэффициент надежности стальных статически неопределимых конструкций.

Ключевые слова: опасное сечение, механизм разрушения, удельный вклад, значимость, вероятностный метод, корреляционная связь, стальная рама, коэффициент надёжности

1. INTRODUCTION

The article is devoted to probabilistic estimation of steel redundant structures. Some beams and simple frames, as well as multistory and multi-span structures of industrial and residential buildings present this type of structures. The failures of these systems are various. This article attacks the problem which concern is only steel structures with the loss of carrying load capacity. Redundant structure failures occur after some member failures in the form of transmission to different workable states. These states match different designing schemes with various probabilistic parameters. Thus, the redundant structure failure estimation is a very complicated problem as depends upon the system complexity. For redundant systems in the design with a given reliability, an important step is to obtain the economic characteristics of the sections. The search for the optimum and minimum weight redundant systems dedicated a lot of research. These studies make it possible to obtain optimal frames on the bearing capacity.

2. MAIN BODY

2.1. Review of the issue status.

Evaluation of the building structures reliability is presented in a large number of works. Calculations of steel frames reliability are devoted to the work [1-10]. Consider some of these works. In particular in [1] design-by-analysis methods for steel structures are receiving considerable attention from professional engineers, researchers and standard-writing groups. Designing by analysis, termed as the Direct Design Method (DDM), is premised on the use of geometric nonlinear inelastic finite element analysis to determine the ultimate strength of steel structural frames and subsequently incorporating a system resistance factor to account for the effects of uncertainties in geometric parameters, stiffness and strength. This paper outlines the DDM in the context of cold-formed compact Hollow Steel Sections (HSS), including the reliability analysis framework at system level underpinning the Method. The system resistance factors for a series of representative 3D frames with hollow locally stable cross-sections are derived. In [2] several steel design specifications worldwide have incorporated provisions for designing through inelastic analysis of overall system behaviour. However, requirements for minimum system reliability have been implemented in such design-by-inelastic analysis methods through a simple adaptation of resistance factors originally developed from member reliability considerations. This paper [2] examines system resistance factors through a system reliability analysis of two steel moment frames subjected to combined gravity and wind loads. The frames are designed using second-order inelastic analysis and their strength and serviceability reliabilities are evaluated. The effects on the system reliabilities of system resistance factor and wind-to-gravity load ratio are examined. The paper also identifies some research issues that should be addressed prior to implementing a system reliability-based design methodology. In paper [3] a method to efficiently evaluate the reliability of elastic-perfectly plastic structures is proposed. The method is based on combining dynamic shakedown theory with Subset Simulation. In particular, focus is on describing the shakedown behaviour of uncertain elastic-plastic systems driven by stochastic wind loads. The ability of the structure to shakedown is assumed as a limit state separating plastic collapse from a safe, if not elastic, state of the structure. The limit state is therefore evaluated in terms of a probabilistic load multiplier estimated through solving a series of linear programming problems posed in terms of the responses of the underlying linear elastic model and self-stress distribution. The efficiency of the proposed procedure is guaranteed by the simplicity of the mathematical programming problem, the underlying structural model solved at each iteration, and the efficiency of Subset Simulation. The rigor of the approach is assured by the dynamic shakedown theory. The applicability of the framework is illustrated on a steel frame example. The work [4] proposes a novel data-driven optimization strategy that can efficiently handle system-level first excursion performance constraints posed on large-scale uncertain structures subject to general stochastic wind excitation. The framework is centred on defining and solving a limited sequence of decoupled optimization sub-problems. In particular, each problem is formulated in terms of information obtained from a single simulation carried out in the solution of the previous sub-problem. Two examples involving the optimal design of uncertain systems subject to stochastic wind loads are presented to demonstrate the effectiveness, efficiency, and scalability of the proposed framework. The paper [5] describes an inter-story drift reliability-based optimization method of frames subjected to stochastic earthquake loads. First, the formulas for eigenvalue and eigenvector, drift PSD functions, drift spectral moments, drift reliabilities, their first and second derivatives are derived based on random vibration theory. The computational procedure of drift reliabilities, their first and second derivatives are given in detail. Second, optimal problem of drift reliability-based optimization design is formulated in a dimensionless way. Optimal mathematic model is converted into unconstrained mathematic model using penalty function method. Gradient and Hessian matrix of penalty function are derived using drift reliabilities and structural mass, their first and second derivatives. Third, solution step of optimal problem is constructed using conjugate gradient method. Finally, optimization designs of two planar frames are demonstrated. Sensitivity analysis of optimum design indicates the drift reliability-based optimization method can obtain local optimum design. The paper [6] is focused on the development of an efficient reliability-based design optimization algorithm for solving problems posed on redundant linear dynamic systems characterized by large design variable vectors and driven by non-stationary stochastic excitation. The interest in such problems lies in the desire to define a new generation of tools that can efficiently solve practical problems, such as the design of high-rise buildings in seismic zones, characterized by numerous free parameters in a rigorously probabilistic setting. To this end a novel decoupling approach is developed based on defining and solving a limited sequence of deterministic optimization sub-problems. In particular, each sub-problem is formulated from information pertaining to a single simulation carried out exclusively in the current design point. This characteristic drastically limits the number of simulations necessary to find a solution to the original problem while making the proposed approach practically insensitive to the size of the design variable vector. To demonstrate the efficiency and strong convergence properties of the proposed approach, the structural system of a high-rise building defined by over three hundred free parameters is optimized under non-stationary stochastic earthquake excitation. The influence of different load sequences on the deterministic resistance of steel structures (in the inelastic range) is a well-understood phenomenon. However, the impact of different load sequences on the reliability of members and frames made of steel has not been specifically studied in the past. Design rules for the stability and strength checks of such elements and structures are found, e.g., in Eurocode 3 [7]. The published background shows that load sequences and amplification patterns were not systematically included in the analysis of the reliability of the design rules for steel structures in Eurocode 3. In the paper [8], the impact of different load sequences on the reliability of three design rules or procedures (the resistance of plastic cross sections, of beam columns and of portal frame structures) is studied and illustrated by means of representative examples. The results show the significance of the load sequence at the level of scatter and non-exceedance probability of resistances. The paper finally discusses the implications of the study's findings for code-making, as well as the potential of accounting for the load sequence in the reliability assessment of, e.g., existing structures. Large amounts of energy and carbon are embodied in the frames of buildings, making efficient structural design a key aspect of reducing the carbon footprint of buildings [9]. The unused mass of steel framed building could amount to nearly 46% of the total mass due to over-specification of the sections, we find a value of 36%. This value correlates with the design method, with software-aided design bringing significant improvements and with the design stage, where most of the optimization seems to occur between the preliminary and tender stage. Authors [9] find that neither the regularity of the structure nor the cost, independent of the measure used, correlate with the mean utilization ratio (ur). Conversely, we observe an apparent reluctance to design beams above a 0.8 capacity ur. This reluctance explains most of the unused mass in buildings. The rest of unused mass consists in cores, trimmers and ties (6%), some of which bear loads not captured in this analysis but are otherwise necessary for stability reasons, and in edge secondary beams (3%) which design is constrained, and should not necessarily be considered as ‘unused’ mass. Recently developed steel self-centering moment-resisting frames (SC-MRFs) have been analytically and experimentally validated as having the potential to eliminate structural damage under a design basis earthquake and restore their original vertical position following a major earthquake. Using Monte Carlo simulation, subjected three nonlinear models of prototype SC-MRFs to thousands of synthetic ground motions, and recorded peak demand responses such as story drift and beam-column relative rotation. Used this data to examine the sensitivity of SC-MRF behavior to structural properties and geometry, seeking to generate recommendations to improve the existing design procedure. A reliability-based methodology was used to assess the likelihood of reaching the limit state of post-tensioned strand yielding. The [10] study proposes modifications to the existing design procedure and illustrates a reliability-based methodology for developing improved seismic design recommendations.

2.2. General approach to solving the problem.

In the course of the study, many publications on the reliability of redundant systems were identified. But some do not include the issues of linking structural reliability calculations of steel frames with their optimization. That is, these issues remain insufficiently developed for today.

In order to obtain economic redundant steel frames with a given reliability, taking into account the plastic work of the material, the random characteristics of the material and the load, it is necessary to calculate the importance of each element in the system with respect to the reliability of the frames. It is necessary to obtain the value of the importance of the elements. Then you can adjust the existing reserves of the frame by changing the cross sections of the elements while maintaining the overall level of reliability of the structure. For existing structures, the definition of significance makes it possible to identify "weak links". During the reconstruction, this allows you to rationally influence the carrying capacity of a complex system.

The significance of the element x_i in the system $y(x_1,...x_n)$ is a partial derivative of the probability of failure-free operation of the system R_s in terms of the probability of failure-free operation of the element R_i:

$$\xi_i = \frac{dR_s}{dR_i} = \frac{R_{s1} - R_s}{R_i} = \frac{Q_s - Q_{s1}}{R_i}, \qquad (1)$$

where R_{s1}, Q_{s1} – the probability of the system failure-free operation (the probability of failure with absolute reliability of the i - th structural element); R_s, Q_s – the probability of the system failure-free operation (the probability of system

failure); R_i – the failure-free operation probability of the i-th structural element.
The criterion “significance of the element ξ_i” characterizes not only the location of this element x_i in the system structure $y(x_1,...x_n)$, but also the dependence on the probability of all system elements failure.
Consider such a characteristic as “the contribution of an element x_i” to the system $y(x_1,...x_n)$, which is equal to the product of the failure-free operation probability R_i on its significance:

$$B_i = R_i \cdot \xi_i = R_i \cdot \frac{dR_s}{dR_i} = Q_s - Q_{s1}. \qquad (2)$$

The criterion of contribution B_i characterizes the increment of the system reliability after the element restoration x_i with the actual probability of its failure-free operation, equal R_i. The contribution determines the location of the element in the system structure, the conditions of its functioning and the relationship with the probability of the system elements failure. The specific contribution of the *i*-th element to the reliability of the system can be expressed as:

$$b_i = \frac{B_i}{\sum_{i=1}^{n} B_i}. \qquad (3)$$

When calculating the failure probability of redundant systems, calculations are carried out in the region of low probability, and it is safe to assume that the failure probability of the system linearly depends on the failure probability of the element R_i. Then the increase in the reliability of the system can be determined:

$$\Delta R_s = \frac{dR_s}{dR_i} \cdot \Delta R_s = \frac{Q_s - Q_{s1}}{R_i} \cdot \Delta R_s. \qquad (4)$$

Using the formula (4), it is possible to influence the system. You can change the cross sections of elements by iteration according to significance This makes it possible to save material without reducing the overall level of reliability.
Consider the importance of elements that affect the system reliability. It is necessary to divide the structure into groups of sections. That is, you need to change the sections of the elements. So get a design with a smooth reliability of the elements. In particular, considering the work of the crossbar, the characteristics of the destruction beam mechanism are taken into account. This mechanism is based on one element. The cross section of this element is often constant along the entire length. Therefore, the change in the cross section should be done for the entire crossbar completely. Consider the surface mechanism of destruction, that is, several elements (columns). It can be assumed that the step of changing the cross sections of these elements is the same for the main mechanism as a whole.

2.3. Practical calculation.

Consider a practical example of frame calculation (Figure 1). We analyse the impact of the significance of individual elementary mechanisms (Table 1) on the system failure probability as a whole. The coefficient μ stiffness ratio was also calculated.
Calculations are performed by the probabilistic method of limiting equilibrium [11]. The significance of the elements is estimated only for the main floor and beam mechanisms of destruction. In the system of equations it will be mechanisms for No 7-12 (Table 1) number them respectively No 1-6 (Table 2).
According to the above formulas, we determine the significance, contribution and specific contribution of the frame destruction mechanisms (Table 2).
Figure 2 shows a significant difference in the specific contributions of the frame destruction mechanisms. Beam mechanisms are distinguished from them. Try to align the contributions of the elementary mechanisms in the reliability of the frame as a whole. To do this, change the ratio of stiffness in the structural elements. We will take into account the specific contribution to the reliability of the system.

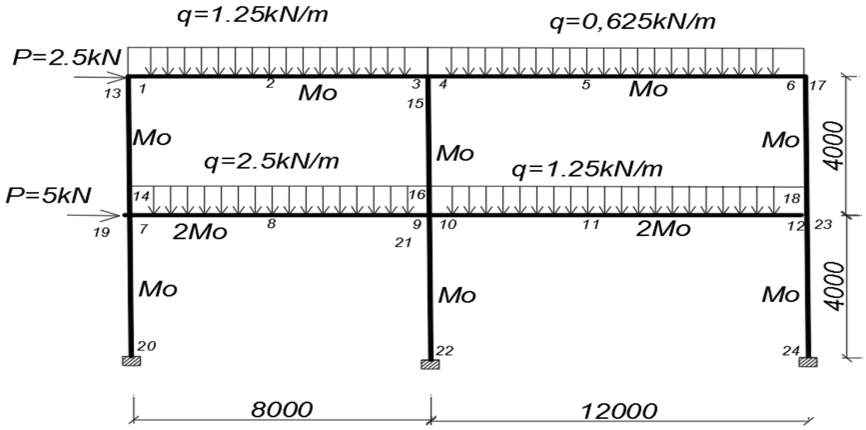


Figure 1. Scheme of the frame.

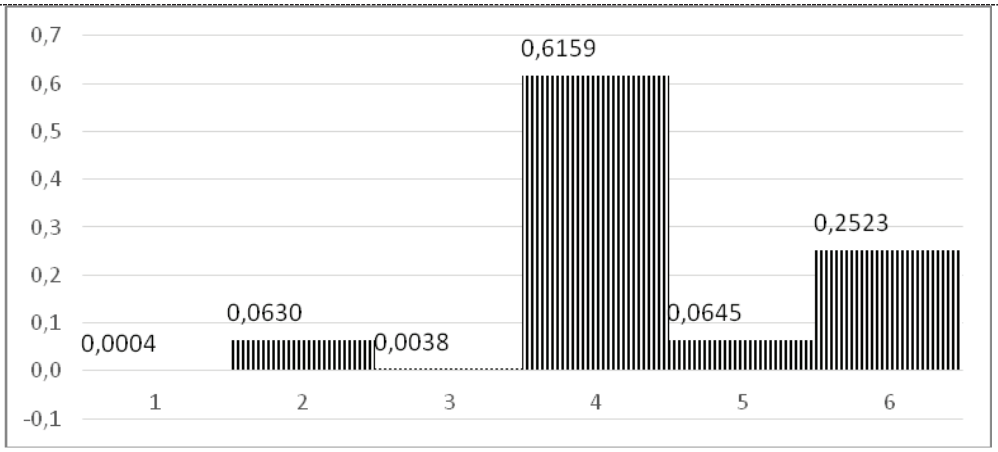
Table 1. The matrix of equilibrium conditions for elementary mechanisms.

No equation	No sections																								The right side of the equation
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	5
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	15
9	-1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
10	0	0	0	-1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11,5
11	0	0	0	0	0		-1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
12										-1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	22,5
μ	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	

The rigidity of the frame will change according to Table 3.

When analyzing the specific contributions, we note that for the floor mechanisms 1 and 2 the specific contribution is less than in the beam 3-6. The reserve is 15-20 % by the moment. It remains as a reserve for the effect of longitudinal force in determining the bearing capacity of compressed curved rods. The application of this calculating method the significance of the elements and contributions of each elementary mechanism to the reliability of the system as a whole will have a significant economic effect. That is, it is possible to obtain more economical designs of redundant steel frames. Let's show it on an example and estimate economy on values of the bending moment (Table 5).

Let us analyze the results of table 5. It should be noted that the savings on the values of the limiting moment reaches 10-55 %. This can be taken into account when solving new design problems. In addition, when reconstructing existing buildings, it is often necessary to determine whether the frame structure will withstand a given load. In this situation, it may be necessary to strengthen the structure. If we strengthen the most important element (for the frame bolt 4, 5, 6), you can get smoothly reliable design with significantly greater load-bearing capacity and a given reliability.



13-18	19-24	1,2,3	4,5,6	7, 8,9	10,11,12
Surface mechanisms		Beam mechanisms			

Figure 2. Unit contribution scheme for the main mechanisms.

Table 3. The ratio of the stiffness of the elements.

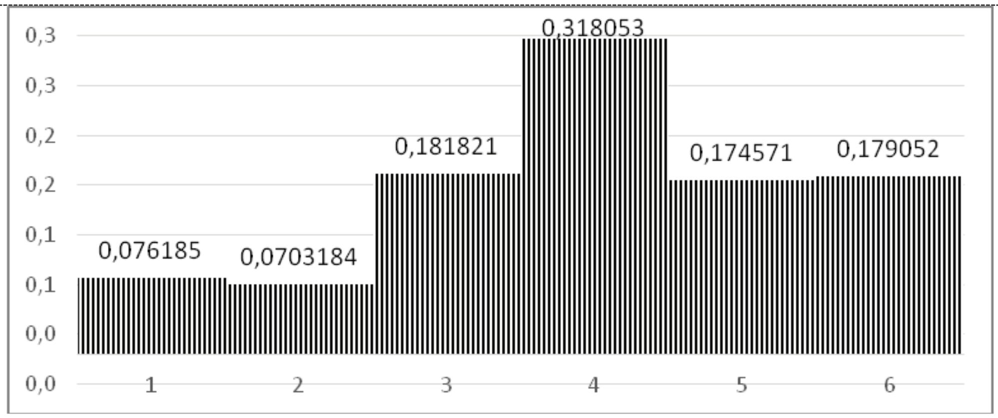
Mechanism	Initial	Final
1	1	0,5
2	1	1
3	1	0,87
4	1	1
5	2	1,59
6	2	1,78

Table 4. The calculating results of the individual basic significance mechanisms of destruction.

No.	The probability of the elementary mechanism failure	Significance ξ_i	Contribution B_i	The specific contribution b_i
1	4.393E-42	0.358951E-8	00.358951E-8	0.0761850
2	2.157E-20	0.331310E-8	0.331310E-8	0.0703184
3	8.953E-12	0.856663E-8	0.856663E-8	0.181821
4	6.763E-12	0.149853E-7	0.149853E-7	0.318053
5	6.446E-10	0.822502E-8	0.822502E-8	0.174571
6	8.1577E-10	0.843618E-8	0.843618E-8	0.179052

Table 5. The values of the limiting moments at the beginning of the calculation and after the alignment.

Mechanism	Initial value	Value after alignment	Percentage savings
1	8.89	3.99	55.1
2	8.89	7.98	10.2
3	8.89	6.94	21.9
4	8.89	7.98	10.2
5	17.78	12.69	28.6
6	17.78	14.2	20.1



13-18	19-24	1,2,3	4,5,6	7, 8,9	10,11,12
floor mechanisms		Beam mechanisms			

<u>Figure 3.</u> A diagram of specific payments is for basic mechanisms after the change of inflexibilities of elements.

<u>Table 6.</u> The significance and contributions of the frame sections.

No	1	2	3	4	5	6	7	8	9	10	11	12
Significance	.178154E-09	.325983E-09	.325983E-09	.521380E-07	.521735E-07	.521016E-07	.766320E-10	.54€278E-08	.546278E-08	.213737E-07	.213737E-107	.197929E-07
Conditional contribution	.668823E-03	.122380E-02	.122380E-02	.195735E-00	.195868E-00	.195598E-00	.287690E-03	.205082E-01	.205082E-01	.802406E-01	.802406E-01	.743062 E-01

No	13	14	15	16	17	18	19	20	21	22	23	24
Significance	.112223E-09	.535054E-08	.127898E-12	.356266E-10	.107526E-09	.161539E-08	.887752 E-10	.533849E-08	.533B49E-08	.533849E-08	.691925E-08	.533849E-08
Conditional contribution	.421305E-03	.200869E-01	.480150E-06	.133749E-03	.403673E-03	.606822E-02	.333278E-03	.200415E-01	.200416E-01	.200416E-01	.259761E-01	.200416E-01

In order to achieve this goal, the contributions of the elementary mechanisms to the reliability of the system as a whole are equalized in the calculations. To do this, change the ratio of stiffness in the structural elements, respectively, the specific contribution of each mechanism to the reliability of the system. Close to the optimum ratio of rigidity is very important for the normal static calculations of frames.

Perform the analysis of the calculation results of the contribution and value of individual cross-sections in the frame reliability. These values are calculated by the probabilistic method of limiting equilibrium [11]. The calculation results are given in Table 6, the specific contribution dependence diagram for each section is shown in Figure 4.

The diagram shows that the individual sections (1-24) contribute differently to the reliability of the system as a whole. Won give a different contribution even within the same basic mechanism. Deviations of specific contributions of sections within the main mechanisms are insignificant (the numbers of the main mechanisms are shown in the diagram in the bottom line). Therefore, it is sufficient to reliably generalize the finding of contributions for the main mechanisms, which include the elements as a whole, or a group of unified elements.

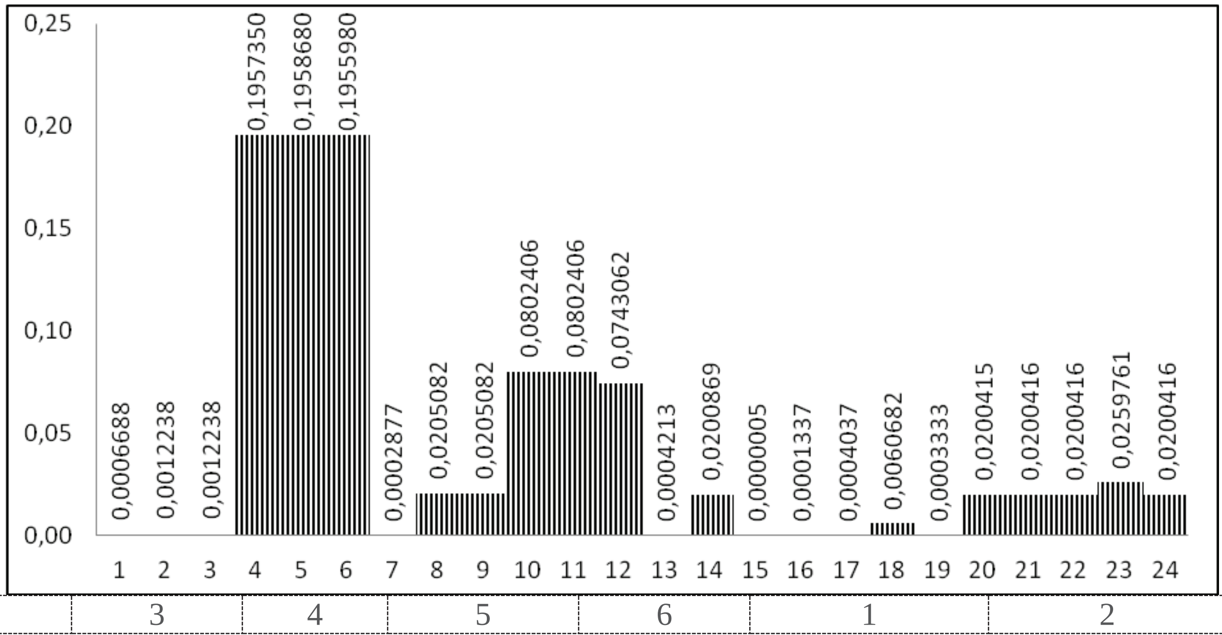


Figure 4. Diagram of the specific contribution for each section of the frame.

As you can see in the diagram (Figure 4), for the most likely mechanism "4" the specific contribution and significance of all sections are the same and equal respectively 0.196 and 0.521 E-7. Therefore, it is advisable to determine the significance and contribution for this beam mechanism as a single element.

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In fact, the most likely mechanisms of destruction may include only part of the dangerous sections relative to the main mechanism. These sections are more important for the reliability of the system as a whole than the sections that are not included in these mechanisms. The significance of individual sections can be taken into account in the state method. Thus, the work of the section is considered separately, and not in the work of the mechanisms as a whole.

According to the calculation of the probabilistic method of the limit equilibrium at the initial limiting moment is

$$M_o = 10.71kNm.$$

After the calculation we find a new value of the limiting moment (M_o = 7.978kNm). The probability of failure (for this example) is

$$Q_s = 0.305028E\text{-}07.$$

The safety factor is

$$\gamma_s = 10.71/7.978 = 1.342\ .$$

3. CONCLUSION

A method for regulating the reliability of redundant frames with a given standard probability of failure-free operation is proposed. This method is obtained by changing the value of the limiting moment and the alignment of the reliability parameters of individual elements. The ratio of the initial and the resulting limiting moment of the frames is recommended to call the coefficient of circuit reliability of steel statically uncertain frames. Its minimum value is 1.1. In the calculation of the contributions of individual elements, it is possible to obtain significantly higher values in the range of 1.1 to 1.4. This provides a significant saving of materials.

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