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ПРИНЦИПОВІ ПІДХОДИ ДО УРАХУВАННЯ РОБОТИ ВУЗЛІВ В РОЗРАХУНКАХ НАДІЙНОСТІ ВИСЯЧИХ СТЕРЖНЕВИХ ПОКРИТТІВ

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Анотація. Проаналізовано проблеми надійності великопрольотних висячих покриттів. Описані принципові підходи до урахування надійності вузлів в розрахунках надійності висячих стержневих покриттів. Як розрахункові прийняті опорні вузли кріплення гнучко-жорсткої нитки до зовнішнього і внутрішнього контуру, проміжні вузли верхнього і нижнього поясів несучої нитки, вузли кріплення вертикальних і горизонтальних зв'язків до несучих ниток покриття. В аналізі прийняті логіко-імовірнісні методи оцінки надійності вузлів і методи, засновані на математичній статистиці. Проведений структурний аналіз надійності вузлів висячих покриттів показав, що вони в основному описуються послідовними схемами із включенням паралельних з'єднань залежних елементів, відповідних багатоелементним сполукам, підібраним з запасом. Врахування кореляції між елементами структурних схем вузлів внаслідок спільності зусиль і міцності сталі дозволяє скоротити число врахованих у схемі елементів і підвищити підсумкову оцінку надійності.

Ключові слова: просторово-стержнева висяча оболонка, згинально-жорсткі нитки, вузол, показники надійності, напружено-деформований стан, логіко-імовірнісні методи.

ПРИНЦИПИАЛЬНЫЕ ПОДХОДЫ К УЧЕТУ РАБОТЫ УЗЛОВ В РАСЧЕТАХ НАДЕЖНОСТИ ВИСЯЧИХ СТЕРЖНЕВЫХ ПОКРЫТИЙ

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Аннотация. Проанализированы проблемы надежности большепролетных висячих покрытий. Описаны принципиальные подходы к учету надежности узлов в расчетах надежности висячих стержневых покрытий. В качестве расчетных приняты опорные узлы крепления изгибно-жесткой нити к внешнему и внутреннему контуру, промежуточные узлы верхнего и нижнего поясов несущей нити, узлы крепления вертикальных и горизонтальных связей к несущим нитям покрытия. В анализе приняты логико-вероятностные методы оценки надежности узлов и методы, основанные на математической статистике. Проведенный структурный анализ надежности узлов висячих покрытий показал, что они в основном описываются последовательными схемами с включением параллельных соединений зависимых элементов, соответствующих многоэлементным соединениям, подобранным с запасом. Учет корреляции между элементами структурных схем узлов вследствие общности усилий и прочности стали позволяет сократить число учитываемых в схеме элементов и повысить результирующую оценку надежности.

Ключевые слова: пространственно-стержневая висячая оболочка, изгибно-жесткие нити, узел, показатели надежности, напряженно-деформированное состояние, логико-вероятностные методы.

FUNDAMENTAL APPROACHES TOWARDS JOINTS OPERATION AT RELIABILITY DESIGNS OF SUSPENSION BAR ROOFS

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Abstract. The problems of reliability of large-span suspension roofs have been analyzed. The fundamental approaches to regard of joints reliability in designs of reliability of suspension bar roofs have been described. The bearing joints of sheeting of curved and rigid filament to the external and internal outline, interstitial joints of the top and lower chords of bearing filament, sheeting joints of vertical and horizontal connections to the bearing filaments of the roof have been accepted as the designed data. The logical and probabilistic methods of estimation of joints reliability and methods based on the mathematical statistics have been accepted in the analysis. Carried out structural design of reliability of joints of suspension roofs has shown that they are mainly described by sequential schemes including parallel connections of dependent elements corresponding to multi-elementary connections selected in store. Correlation regard between the elements of structural schematic drawings of joints in consequence of generality of intensification and strength of steel allows to reduce quantity of elements in the scheme and increase resulting estimation of reliability.

Keywords: space and bar suspension shell, curved and rigid filaments, joint, reliability indices, stressed-strained state, logical and probabilistic methods.

Introduction

The problem of reliability of structures is a constituent part of a science of building elements uniting problems of design, designing work, production, erection and operation of building and constructional structures.

Reliability of metal structures of buildings and constructions representing themselves statistically determined and non-determined systems of components was investigated by many researchers. The separate problems and samples were considered in papers of V. V. Bolotin, P. L. Vizir, B. N. Koshutin, V. D. Reiser, A. R. Rzhanitsyn, A. V. Perelmuter, V. P. Mushchanov, G. Schpete, G. Augusti, A. Baratt, R. M. Bennet, M. Vorlitchek, etc. [7, 8, 10, 11, 13, 14].

In the engineering theory, reliability evaluation of complex systems is usually reduced to examination and analysis of two principal kinds of joints [11]:

a) series connection, failure-free work probability of which at independent components is determined as

$$P_m = \prod_{i=1}^{m} P_i , \quad (1)$$

where P_i is probability of failure-free work of i-component;

b) parallel connection

$$P_m = 1 - \prod_{i=1}^{m} (1 - P_i) . \quad (2)$$

Series connection in probabilistic meaning can be used for description of statistically determined system, e. g. trusses.

But a practical evaluation of real structures reliability cannot be reduced to application of simple equation (1) in consequence of availability of correlation between resistance conditions of components.

Activities of statistically non-determined systems is definitely associated with parallel connection, but evaluation of their reliability cannot be done according to (1) because of redistribution of forces in the system after failure of separate components which are dependent. Thus, reliability evaluation of statistically non-determined structures requires thorough and careful analysis of character of their activities and failure under load and discount of distinguishing features of failures of the components and the system on the whole.

Reliability analysis of statistically non-determined system is usually done by the following methods and techniques: a method of states, a probabilistic method of limiting equilibrium, a Monte-Carlo method, a Markov model of reliability analysis [14].

Gradual perfection of the numerical techniques of stressed-stained state of building structures was stipulated by the swift development of computer engineering in 1960s and 1980s. T. A. Cruse, J. C. Lachat, F. J. Rizzo, A. S. Henry C. E. Massonet, N. M. Belyaev, I. Ya. Shtaerman, N. I. Musknelishvili, G. N. Savin, B. N. Zhemochkin, A. P. Sinitsyn, A. M. Kalandiya and other scientists were occupied with the given problem.

The problem of reliability especially concerns unique large-span structures. Among these are suspension shell which have increased level of responsibility on application denial from which can bring to severe economic results and social consequences. During their designing there are problems exceeding the limits of existing regulatory documents. Novelty of technical conceptions demand from a structural engineer profound specific knowledge, an experience of designing work of such kind of structures is required. Requirements of reliability, technological and economic efficiency have to be realized in full volume, in this connection, environmental and social factors should be considered.

Nowadays, one of the most dynamic developing kinds of space, large-span structures interesting in architectural and structural relations are the stationary, suspension roofs (Fig. 1).

The bases the shells design were founded in the XIXth century. The intensive progress of the shells design has been started since the 1930s. B. G. Galerkin, V. Z. Vlasov, S. P. Timoshenko, A. I. Lurier, I. N. Vekua, S. Ph. Pichugin, V. Ph. Mushchanov, V. I. Trofimov, P. G. Yeremeyev, Donnell have greatly contributed to the design theory of three-dimensional large-span shells [6, 9, 17].

The joints occupy the significant part in composition of structures. Application of numerical simulation permits to investigate the impact of structural schematic drawing to the joints operation and accumulate of necessary base of statistic materials on stressed-strained state of such kind of joints. At the same time, contemporary status of computer engineering development opens possibilities for determination of reliability estimation of joints of suspension roofs, bearing in mind parameters of stressed-strained state and correlation links between functions of bearing capacity of joints elements.

A. R. Vegner, Yu. V. Sobolev, M. N. Mukhortov, A. P. Mishchenko, R. A. Shafeyev and others [1, 11] dealt with investigations of stressed-strained status of steel structures joints. The steel joints abroad were investigated by W. F. Chen, K. W. Patel, S. V. Johnes, P. A. Kirbyt, M. V. Walles, E. K. Rossow, G. A. Morris.

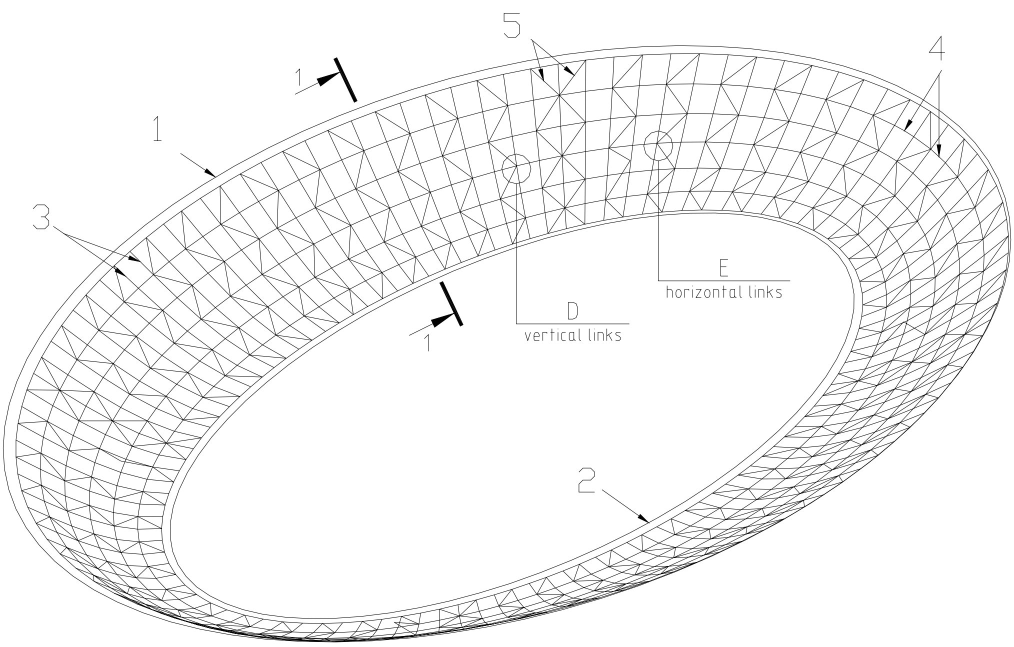


Figure 1. Structural schematic drawing of spatial and rod roof: 1, 2 – external and internal contours, 3, 4, 5 – radial, annular and diagonal components.

The hot topic of provision of required level of reliability at design work of large-span roofs, in particular of suspension and bar shells, in many aspect determining the efficiency of large-span roofs construction, has obtained its operational permit [10] in which the method of design and design work of rigid filaments of through section based on determination of numerical exponents of reliability of designed structure has been made (Fig. 3). But the given paper does not touch upon the problem of joints operation records in composition of a shell at determination of reliability level of the roof.

Nowadays, practically there are no investigations to estimate reliability of roofs on the whole and reliability of their joints, that stipulate of urgency of estimation problem of stressed-strained state and reliability of welded joints of roofs and working-out of recommendations concerning such structures on the basis of obtained data.

The main objective at the given stage is to study the fundamental approaches to determination of joints reliability of suspension roofs by numerical methods.

In the capacity of a fundamental example, let us consider the joints reliability of large-span roof with large cut on the elliptic plan designed with application of the method Mushchanov–Priadko [10] (Fig. 1, 2). The choice of the given method provides its perfection with further regard of joints operation in composition of a shell at determination of the reliability level of the roof.

Let us consider the fundamental approaches to regard of reliability of the main joints of system of the roof determining its structural form. We can relate to them the following: bearing joints of curved and rigid filament to external outline «A» and internal outline «B», interstitial joints of upper and lower chords of carrying filament «C», fastening joints of vertical constraints to the filaments «D» and fastening joints of horizontal constraints to the filaments «E» (Fig. 4, 6). In this connection, it is necessary to note that denial not each joint may bring to cave-in all the roof. On the basis of it, let us appoint the types of connections of joints in the roof (sequential or parallel connection) given in the Table 1.

In accordance with accepted in logic and probabilistic simulations notations [11], the conditions of trouble-free operation of elements let us denote by X, failure conditions by X'. The joint operation on whole let us describe by the function of introduced logical variables – the function of Boolean algebra (FBA) y $(X_1, X_2, ..., X_n)$ called as the condition of the system capacity (a joint).

The shortest way of successful functioning (SWSF) describing probability of trouble-free operation of minimum set of elements necessary for trouble-free of the system is expressed in the form of conjunction (logical multiplication) of elements:

$$P_i = \Lambda_{i\in(K_{pl})} X_i, \qquad (3)$$

where K_{pl} – is a set of elements entering into the given way.

Starting from the above-mentioned, the condition of the system capacity (a joint) is described in the form of disjunction (logical adding) of all d having in the system the shortest ways of successful functioning (SWSF):

$$y(X_1, X_2, ..., X_n) = V_{i=1}^{d} P_i = V_{i=1}^{d} [\Lambda_{i\in(K_{pl})} X_i]. \qquad (4)$$

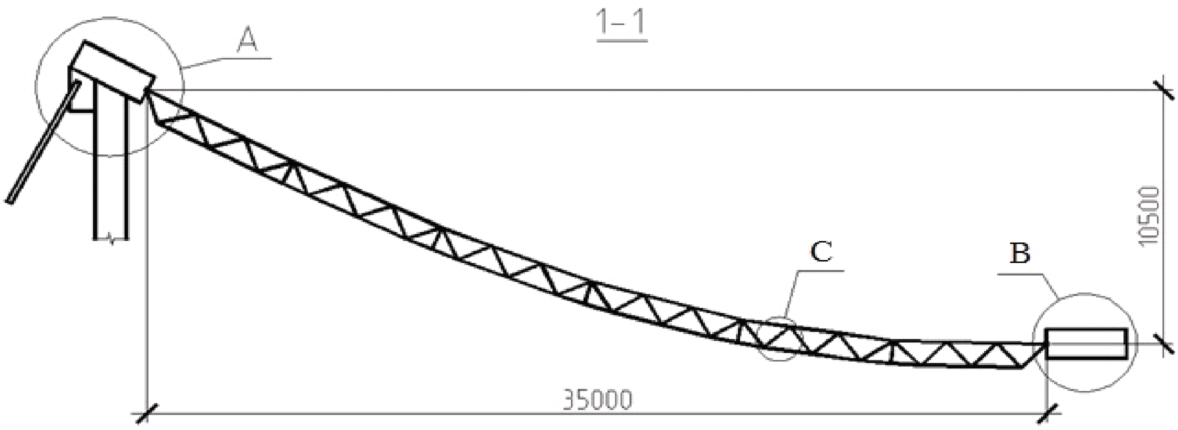


Figure 2. Structural schematic drawing of space and bar roof. Open-cut mine 1–1.

Table 1. Caving of joint elements

Notation of joint	Type of caving of joint elements	Type of connection of joint elements	Type of connection of joint in a roof
«A» (Fig. 4)	See above	(Fig. 5)	Sequential
«B» (Fig. 6)	1 – caving of a sheeting gusset of carrying filament to the internal outline because of failure of bearing welds; 2 – a sheeting bolt shearing of carrying filament to a gusset; 3 – loss of stability of sectional elements of the internal bearing outline; 4 – caving of internal outline because of failure of sheeting welds of sectional elements of outline.	Sequential Sequential Parallel Parallel	Sequential
«C» (Fig. 6)	1 – caving of row braces of filament because of failure of welds of their sheeting to chords.	Sequential	Parallel
«D» (Fig. 6)	1 – caving of vertical connections elements (top chord, bottom chord, braces, posts) because of failure welds of their sheeting to filament chords; 2 – caving of sheeting gusset of vertical connection to the chord of filament because failure of welds; 3 – bolts shearing of guy sheeting of a gusset of vertical connection to the chord.	Sequential Sequential Parallel	Parallel
«D» (Fig. 6)	1 – caving of horizontal connections elements because of failure of welds of their sheeting to the top chord of filament; 2 – caving of horizontal gusset of connections elements sheeting to the top chord of filament because of failure of the welds.	Sequential Sequential	Parallel

Lets start with bearing joint of suspension roof to the outer bearing outline «A» (Fig. 4).

Enumerated failures are represented in a form of elements in a total structural schematic drawing (Fig. 5). In this connection, it would be unjustified the presentation of twin welds in poses of 4, 7 and 11 in the form of parallel connection because in the latest ones each element enables to carry out a function rested on a connection. In examined joint, one of two welds, obviously, cannot perceive double load and a twin weld is actually a single weld superimposed by two plots reflected in series connection X4, X7, X11.

In bolted connections of poses 2, 6, 10 especially if the number of bolts has been determined structurally from the condition of their distribution, the operational regard of connection after failure of the first and consequent bolts is possible. But, in this connection, the load to the rest of the bolts increased sharply, the character of their operation is changed and can be reflected by the parallel dependent elements. The condition of the system capacity reflecting the operation of a joint (Fig. 5) is described in the form:

$$y(X_1, X_2..., X_{11}) = X_1 \cdot (X_{21} \cdot VX_{22}VX_{23}VX_{24})\times$$
$$\times X_3 \cdot X_4 \cdot X_5 \cdot (X_{61} \cdot VX_{62}VX_{63}VX_{64})\times$$
$$\times X_7 \cdot X_8 \cdot X_9 \cdot (X_{101} \cdot VX_{103}VX_{104}) \cdot X_{11}. \qquad (5)$$

For conversion from logical function to probability one, the analysis of correlated bonds between the elements can be implemented. One can take approximately that all the forces in the joint are proportional to a load from the roof (main roof and snow one), thus in the condition of non-destruction of all the elements

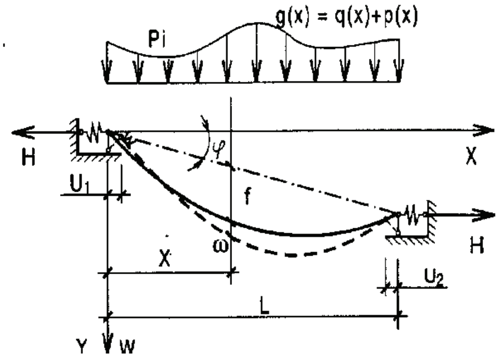
$$Y_i = X_i = R_i - S_i = \sigma_{Ti} - \sigma_{qi} \geq 0, \qquad (6)$$

parameters σ_{qi} are connected functionally. The second parameter σ_{Ti} obviously coincides for details 3, 5, 8, 9 and welds 4, 7, 11. Thus, corresponding conditions of the trouble-free operation X_3, X_5, X_8, X_9, X_4, X_7, X_{11} have tight correlative connection with $r \approx 1$. In consequence of it, at conversion from FBA (5) to probabilistic form the pointed out groups of elements have to be presented by «the weakest units» with P_{imin}.

Probability properties of steel of details 3, 5, 8, 9; of bolts 1, 2, 6, 10 and of welds 4, 7, 11 are obviously

1. Engineering analysis of the roof

1.1. Analysis of the bent and rigid thread



Equation of thread equilibrium

$$EI\frac{dw}{dx^4} - H\frac{d^2(f+\omega)}{dx^2} + q(x) = 0$$

Forces in thread components

$$N_{ВП} \approx N\cdot\frac{a_{НП}}{h} + \frac{M}{h}\cdot\alpha\cdot k$$

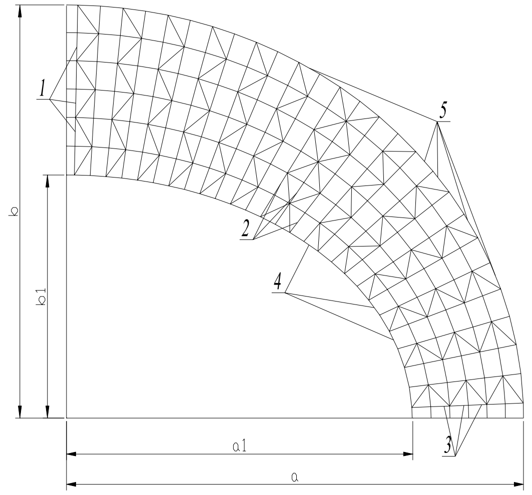
$$N_{НП} \approx N\cdot\frac{a_{ВП}}{h} + \frac{M}{h}\cdot\alpha$$

Improved values of forces

$$N^y_{ВП} = k'_\sigma k''_\sigma N_{ВП} \quad N^y_{НП} = k'_\sigma k''_\sigma N_{НП}$$

$$N^y_P = k'_\sigma k''_\sigma N_P$$

1.2. Structural analysis of the roof



1. Assignment of geometry parameters of the shell;
2. Snow load S requirement of $\overline{D_1}, \overline{D_4}, \overline{W}, \overline{U}$;
3. $\overline{D_1}, \overline{D_4}, \overline{W}, \overline{U}$ determination;
4. Determination of N and M forces from dependences of $\overline{D_1} = f(\overline{M}, \overline{W})$, $\overline{D_1} = f(\overline{N}, \overline{W})$ $\overline{D_1} = f(\overline{M}, \overline{U})$, $\overline{D_1} = f(\overline{N}, \overline{U})$

2. Numerical analysis of the shell in the software SCAD
(determination of trace to failure)

3. Probabilistic design of the roof

3.1. Lower limit of reliability

– Series connection (a brittle model);
– Random quantities: $\tilde{A}$, $\tilde{\sigma}_y$;
– Calculation of the reliability indices based on using the unique Monte Carlo method;
– Identification of the law of distribution of the random quantity density and determination of its boundaries.

3.2. Higher limit of reliability

– Parallel connection (a plastic model);
– Random quantities: $\tilde{A}$, $\tilde{S}$, $\tilde{M}$, $\tilde{N}$, $\tilde{\sigma}_y$,

$$\tilde{\sigma}(\tilde{M}, \tilde{N}, \tilde{A}) = \overline{\sigma}_N\cdot(1+\nu_N-\nu_A) + \overline{\sigma}_M\cdot(1+\nu_M-\nu_A);$$

– Safety characteristics of Rzhanitsyn

$$\gamma = \overline{(\sigma_y - \sigma)} / \sqrt{\hat{\sigma}_y + \hat{\sigma}};$$

– Calculation of the reliability indices of the roofing
1-Psis=(1-Pspan)×(1-Pext.con.)×(1-Pint.con.)

Figure 3. Block-scheme of the determination technique numerical indices of reliability of suspension roof.

should be taken independent, as such kind of an offer goes into reliability factor of the joint. In consequence of it, the correlations between the elements X_i and X_j in accordance with [14] are determined as:

$$r_{ij} = \frac{\hat{\sigma}_q^2}{\sqrt{\hat{\sigma}_T^2 + \hat{\sigma}_q^2}}. \qquad (7)$$

Using total expression for standard ratio $\hat{\sigma}_T^2$ and $\hat{\sigma}_q^2$, with regard for variability and standardized deviations of designed value γ_T and γ_q for snow and fixed load [11] with regard to above-mentioned concepts about correlation connections, we get correlation coefficients $r_{ij} \le 0.5$ between conditions of joint elements failure with independent strength of steel. At such comparatively weak correlation, the failure of elements can be considered independent [11].

On the basis of above-mentioned facts, conversion from FBA (5) to the formula of probability of trouble-free operation of the bearing joint «A» (Fig. 4), we get in the form of

$$P_A = P_1 \cdot min(P_3, P_5, P_8, P_9) \cdot min(P_4, P_7, P_{11}) \times$$
$$\times\, min((1 - Q_{21} \cdot Q_{22} \cdot Q_{23} \cdot Q_{24}), (1 - Q_{61} \cdot Q_{62} \cdot Q_{63} \cdot Q_{64}),$$
$$(1 - Q_{101} \cdot Q_{102} \cdot Q_{103} \cdot Q_{104})). \qquad (8)$$

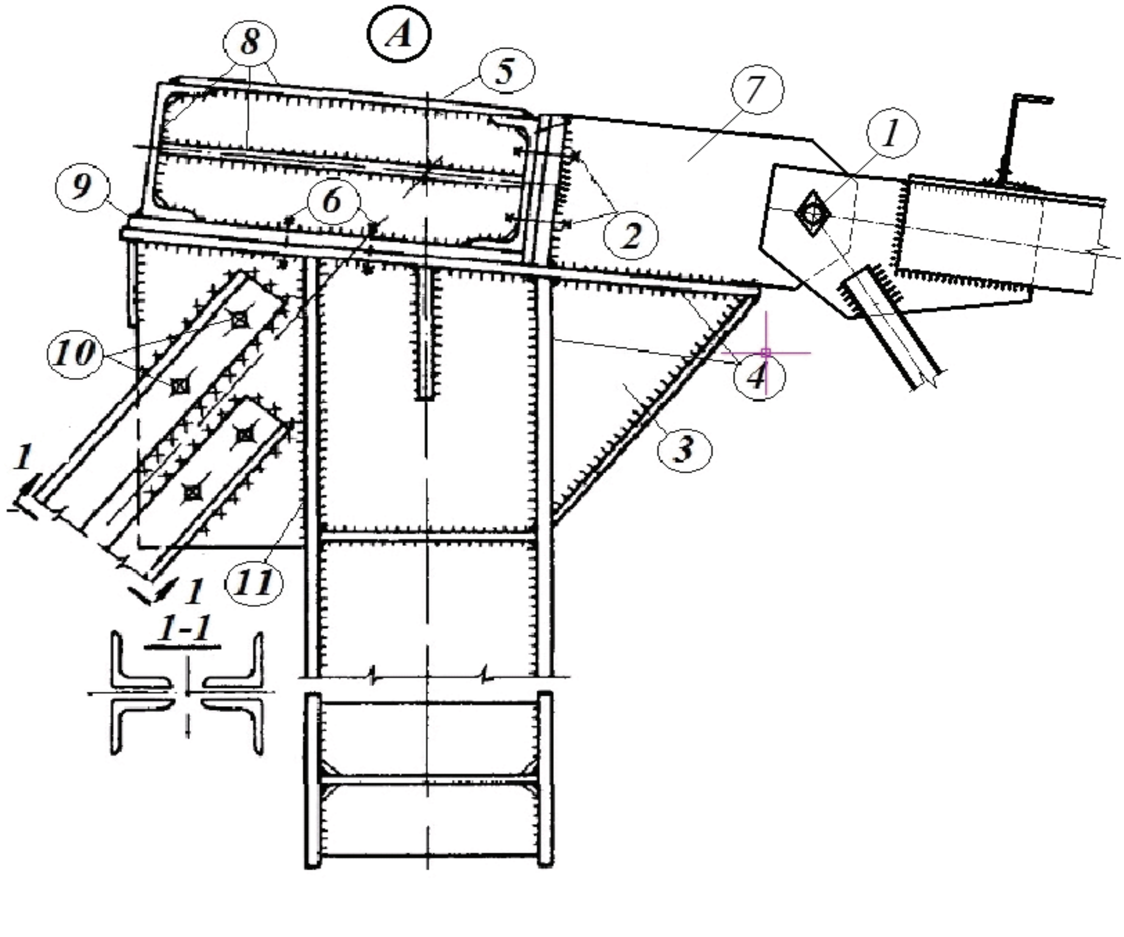


Figure 4. Bearing joint of suspension roof with carrying elements of rolling steel. Starting from the actual operation of such joint, its failure can occur in consequence of: 1 – a sheeting bolt shearing of carrying filament to a gusset; 2 – a break of sheeting bolts of a bearing flange to the external metal outline of a rectangular section; 3 – bearing strain of an assemble table; 4 – caving of an assemble table because of failure of welds of sheeting of a table to a column; 5 – loss of general stability of external bearing outline (in a span); 6 – a break of sheeting bolts of the external outline to a column; 7 – caving of a gusset of a sheeting of a carrying filament to the external outline because of failure of sheeting welds; 8 – loss of stability of sectional elements of the external bearing outline; 9 – bearing strain in the spot of a resting of the external bearing outline to a column; 10 – bolts shearing of guy sheeting to a gusset; 11 – caving of guy sheeting gusset to a column because of failure of sheeting welds to a column.

Let us make similar analysis for the rest above-mentioned joints of the roof. Their structural conceptions are given on the Fig. 6.

Starting from the operation of the given joints, the Table 1 enumerated possible failures of the elements entering into joints and types of their connections taken into account at reliability design.

On the basis of above-mentioned information, the formulae of probability of trouble-free operation of joints have been obtained:

$$P_B = min(P_1,(1-Q_{41}\cdot\ldots\cdot Q_{45}))\cdot P_2\cdot(1-Q_{31}\cdot\ldots\cdot Q_{35}), \quad (9)$$

$$P_C = P_1, \quad (10)$$

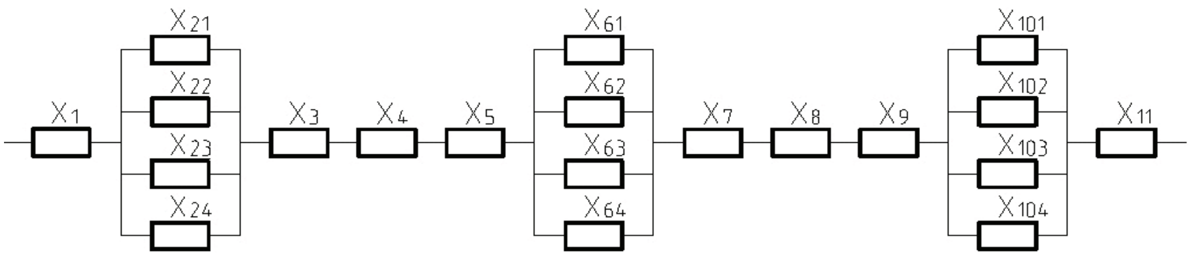


Figure 5. Reliability of a bearing joint of a suspension roof. Structural schematic drawing.

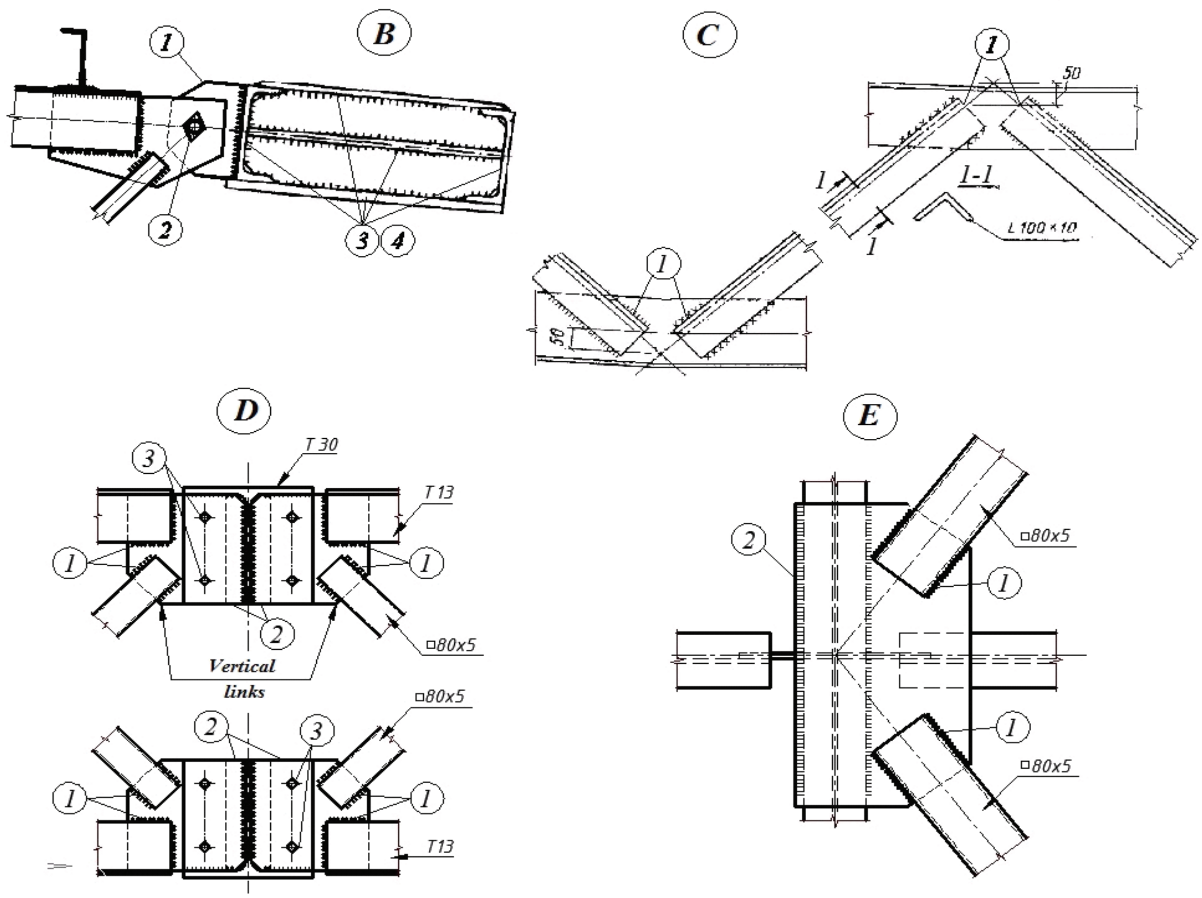


Figure 6. Suspension roof joints (Fig. 1, 2).

$$P_D = min(P_{11},\dots,P_{18},P_2)\cdot(1-Q_{31}\cdot Q_{32}), \quad (11)$$

$$P_E = min(P_{11},P_{12},P_2), \quad (12)$$

where P_B, P_C, P_D, P_E are corresponding to probability of trouble-free operation of joints «B», «C», «D», «E».

With regard to accepted types of joints connections (Table 1), probability of trouble-free operation of the system of joints takes the following form:

$$P_{sis\ y} = P_A\cdot P_B\cdot(1-Q_{C1}\cdot\ldots\cdot Q_{Cn})\times$$
$$\times(1-Q_{D1}\cdot\ldots\cdot Q_{Dm})\cdot(1-Q_{E1}\cdot\ldots\cdot Q_{Ek}), \quad (13)$$

where n, m, k – are the number of designed joints «C», «D», «E» respectively.

Values of n, m, k are determined to the moment of destruction of roof span part [10].

At the given stage of investigations the fundamental approaches to definition of reliability of joints of suspension roof were determined by numerical methods.

The further investigations assume on the basis of the method of Mushchanov–Priadko [10] to originate the method of design and designing work of suspension roofs, based on determination of numerical indices of reliability of designed structure with regard to joints operation in composition of a shell at determination of roof reliability.

Conclusions

1. Carried out structural design of reliability of joints of suspension roofs has shown that they are mainly described by sequential schemes including parallel connections of dependent elements corresponding to multi-elementary connections selected in store.
2. Correlation regard between the elements of structural schematic drawings of joints in consequence of generality of intensification and strength of steel allows to reduce quantity of elements in the scheme and increase resulting estimation of reliability.
3. Reliability of joints of suspension roofs depends on the number of bearing elements entering into them: with increase of the number of elements, the reliability is decreased, low-element joints have greater reliability. The important factor is also homogeneity of strengths of elements: joints reliability results the least if reliability of the elements should be considered as independent one. Such kind of situation appears if the elements are produced from different types of steel by various producers, at comparison of fabricated and field joints, etc.
4. In consequence of its multi-elementary nature, the joints can be less reliable than elements themselves (bars of columns, span parts of suspension filaments, etc) that should be considered at estimation of reliability of structures on the whole.

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