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Improved numerical methods in reliability analysis of suspension roof joints

Усовершенствование численных методов расчета надежности узлов висячих покрытий

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Key words: roof; suspension devices; suspension system; suspensions; civil engineering; constructions; buildings; roof joints; reliability indices; stress-strain analysis

Ключевые слова: покрытие; висячие конструкции; висячие системы; висячий; гражданское строительство; сооружения; здания; узлы крыши; показатели надежности; анализ напряженно-деформированного состояния

Abstract. Modern structures require more complex designs. There is an increased need for accurate approaches to assessing uncertainties in loads, geometry, material properties, and operational environments. However, information is scarce on the reliability of suspension roofs together with their joints. There is an urgent need for estimating stress-strain state and reliability of welded joints, so recommendations can be given based on the obtained data. In this paper, reliability of large-span suspension roofs was investigated and a fundamental approach is proposed for reliability determination of these joints at the design phase of suspension rod roofs. In this work, several joints were investigated: supporting joints between rigid threads and external/internal contours, intermediate joints of top /lower chords of supporting threads, as well as joints between vertical/horizontal links and supporting thread of a roof. To measure reliability of joints, logic and probabilistic methods were used conjointly with other methods based on mathematical statistics. The proposed approach can be applied to design of suspension roof systems and help to develop better designs for better safety, quality control and efficiency of these structures, providing economic and social benefits.

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Аннотация. Проектирование современных конструкций требует комплексного подхода, обусловленного учетом большого количества факторов при расчете, а также оценки неточностей нагрузок, геометрии сечений, физических свойств материалов и условий эксплуатации. Отсутствие необходимых для оценки надежности покрытий в целом исследований надежности их узлов обусловливает актуальность задачи оценки напряженно-деформированного состояния и надежности сварных узлов покрытий и выработке рекомендаций относительно таких конструкций на основе полученных данных. В связи с этим в статье проанализированы проблемы надежности большепролетных висячих покрытий и 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. Описанные подходы могут применяться при проектировании новых висячих покрытий, способствуя получению более сложных конструктивных форм с повышенной надежностью несущих элементов, а также на стадии эксплуатации, обеспечивая надежность существующих конструкций.

Introduction

Structural reliability is a fundamental part of building structures, which combines design problems, work planning, production, erection and operation of buildings and structures. Reliability of steel structures in buildings and statical determined and non-determined systems have been investigated by several researchers, such as G. Augusti, A. Baratt, V. Bolotin etc. The major problems and some examples are described by S.F. Pichugin [1] and G. Shpete [2].

In civil engineering, reliability measurement of complex systems is usually concerned with examination and analysis of two principal kinds of joints:

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

$$P_m = \prod_{i=1}^{m} P_i \,, \tag{1}$$

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

b) parallel connection

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

Series connection in probabilistic sense can be used to describe statically determined systems, e.g. trusses, though practical assessment of reliability of real structures cannot be reduced to application of a simple equation (1) due to the correlation between resistance indices of components.

Activities of statically non-determined systems are definitely associated with parallel connections, but reliability assessment cannot be defined by (1), because of the redistribution of forces in a system after the failure of its individual components, which are dependent. Thus, reliability assessment of statically non-determined structures requires a thorough and careful analysis of the stress-stained state and failure under load, and also consideration of distinct features of component failures and the system as a whole.

Reliability analysis of a statically non-determined system is usually made by the following methods and techniques: a method of states, probabilistic method of limiting equilibrium, Monte-Carlo method, Markovian model of reliability analysis [1]. Analytical and computational methods used in the technical reliability theory for computation of complex systems, which can be applied for reliability analysis of statically indeterminate systems, are shown in Figure 1.

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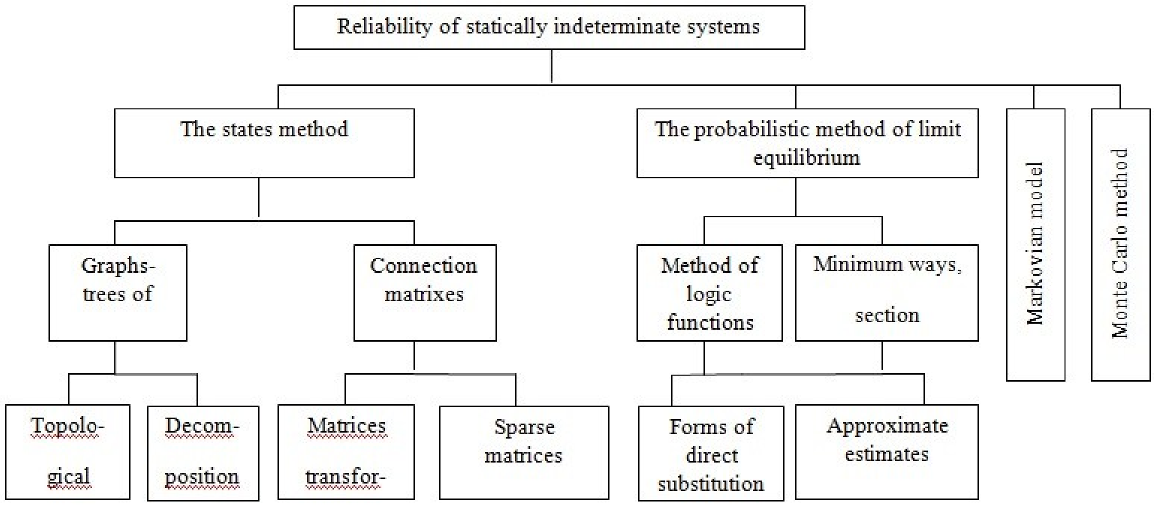


Figure 1. Methods for assessing reliability of statically indeterminate systems

Reliability of steel structures of buildings and constructions representing the statically determined or undefinable systems of elements was reviewed by several research studies by F. Otto, G. Behnisch etc. Certain problems and examples were considered by several researchers, as described by Z. Kala [3]. T. Guo et al. [4], K. Kwon and D.M. Frangopol [5] and Z. Wu et al. [6] achieved good results in determination of the reliability parameters of unique structures.

Relevant scientific experience in the field of structural reliability assessment has been provided by Y. Luo et al. [7] and N. Xiao et al. [8], while Z. Qiu et al. [9] in the field of probabilistic interval reliability of structural systems.

The problem of reliability is especially concerned with unique large-span structures. Suspension shells are among the ones having an increased level of responsibility and their failure can lead to serious economic and social consequences. In the design phase, some problems can occur that are not described in existing regulatory documents. The novelty of technical conceptions demands that a structural engineer should haveprofound specific knowledge and experience in designing such kind of structures. Requirements of reliability, technological and economic efficiency must be met, as well as the environmental and social factors should be considered.

Nowadays, one of the most dynamic type of large-span structures in architectural and structural view are suspension roofs (Fig.2 and Fig. 3).

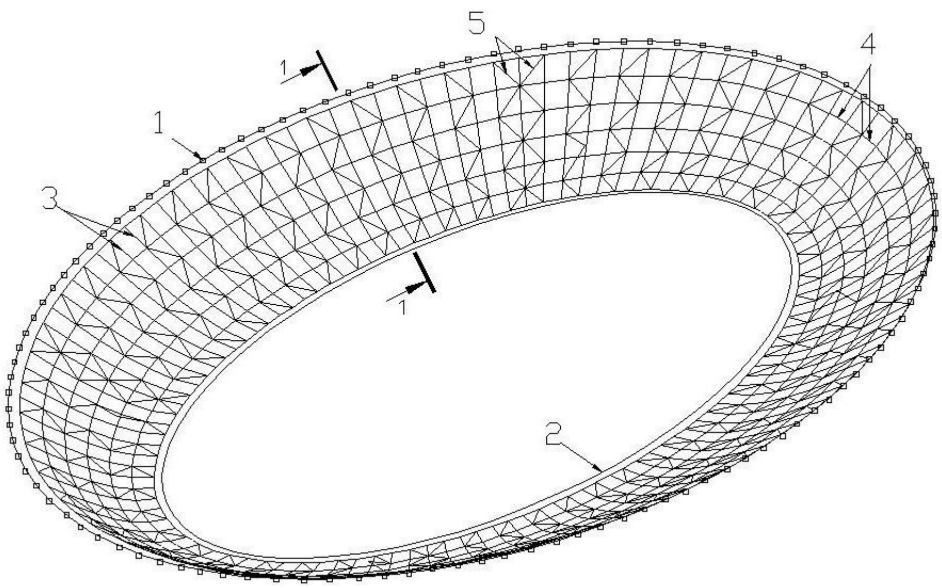


Figure 2. Structural schematic drawing of spatial and rod roof:
1, 2 – external and internal contours, 3, 4, 5 – radial, annular and diagonal components

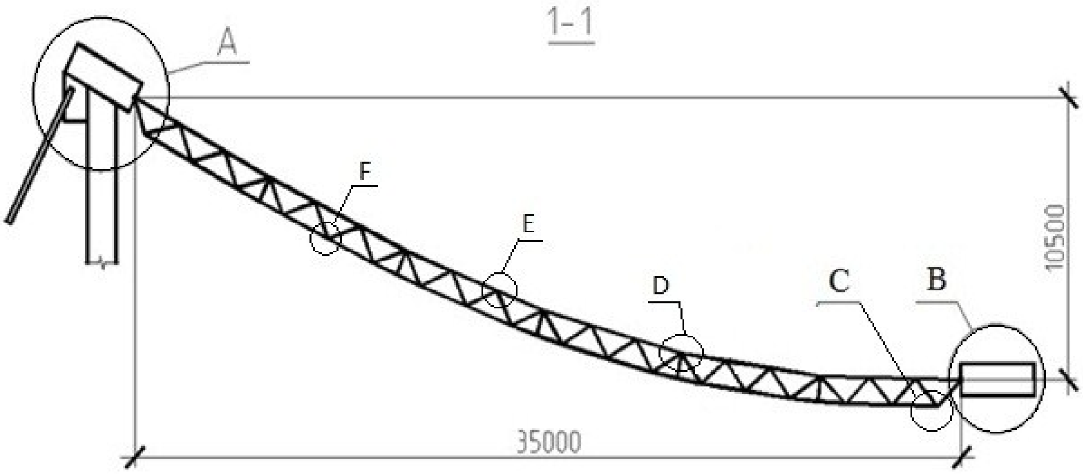


Figure 3. Structural schematic drawing of spatial and rod roof. Open-cut mine 1–1

Large-span roofs have a higher level of responsibility as their failure can lead to serious economic and social consequences. In this context, the design of these unique structures should be based on an integrated approach of rational selection of design solutions. These solutions are related to functionality, architectural design, manufacturing and installation techniques, and operating conditions. The requirements for reliability, manufacturability and cost-effectiveness, given environmental and social factors, should be fully implemented.

The history of shell design goes back to the 1890. Shell design has progressed since the 1930s, and important contributions to the design theory of large-span spatial shells were made by several authors, such as A. Kotli, L. Donell etc. Today, this issue has been pursued by E. Gorokhov, V. Mushchanov, I. Priadko [10] and I.N. Rudneva [11].

Over the last 15 years in particular, the advent of powerful computers and the development of sophisticated nonlinear CAE software (ADINA [12], ABAQUS [13] among others) have enabled engineers to utilize suspension roofs in complicated large scale structures, some of them classified as unique examples of civil engineering excellence [14].

Probabilistic assessment of reliability is one of the most important tasks to be taken into account in structures with high responsibility. The main property that determines the reliability of these structures is their ability to save the pre-defined operational quality during its lifetime. The quantitative characteristic of this property is the probability of failure-free operation.

Several authors from the CIS countries have been working on the reliability assessment of large-span suspension devices and cable-stayed structures, such as V. Muschanov [10], A.A. Sventikov [15], D.Yu. Drobot [16]. Big contribution in stress-strain analysis was made by D. Dol et al. [17], V.V. Eremin [18], D.B. Kiselev et al. [19]. The issues of failure-free operations of the large-span roofs were described by M.I. Farfel [20] and I.V. Smelyanskiy et al. [21].

Among the foreign researchers who made relevant investigations in the area of large span structures V. Goremikins et al. [22], O. Blazevica-Juhnevica et al. [23] should be pointed out.

Joints play a significant role in the composition of structures. Their application in numerical simulation permits to investigate the impact of structural forces on the joints operation and gather the necessary base of statistic stressed-strained state of such kind of joints. At the same time, modern approaches in computer engineering give a chance to assess reliability of joints in a suspension system, bearing in mind the parameters of stressed-strained state and the correlation between the function of structural supporting capacity and elements of joints.

N. Chowdhury [24] and M. Skorupa [25] investigated the stressed-strained status of steel structural joints. However, some questions remain about the stress-strain state (SSS) of suspension roof joints.

Nowadays, there are few investigations on the reliability of roofs and their joints as a whole, though there is an urgent need to assess the stressed-strained state and reliability of roof welded joints, in our view, as well as to create guidelines for these structures.

Provision of required levels of reliability at design work for large-span roofs is a topical issue, in particular regarding suspension and rod shells, which strongly determine the efficiency of large-span roof structure. This issue has been investigated by E. Gorokhov, V. Mushchanov and I. Pryadko [26], together with the design method of rigid threads with through section, based on the determination of numerical indices of reliability. The framework of this method is shown in Figure 4. The reference values of this method are presented in Table 1.

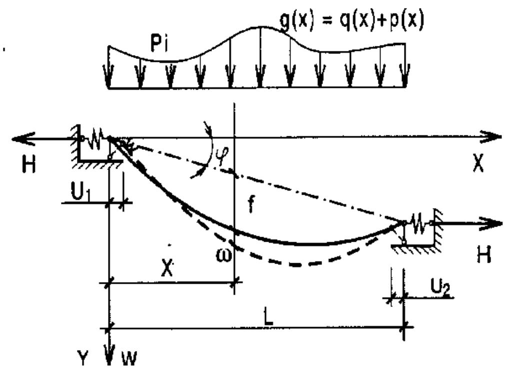
The proposed method provides a sequence of solutions for some problems, as follows: how to determine rational geometric parameters of a structure; how to obtain appropriate rigidity characteristics of major supporting elements; how to determine a track of elements' destruction for a typical roof diagram, followed by evaluation of stressed and strained state of a structure; and how to determine the numerical safety indices of a structure (lower and upper safety limits).

Table 1. The reference values of the method described in Figure 4.

h	– height of the threads section;
a_{ub}, a_{lb}	– distance from the center of gravity of the composite section to the center of the cross section of the upper and lower thread chords respectively;
α, k, k′, k″	– correction coefficients;
$\overline{D}_1, \overline{D}_4, \overline{W}, \overline{U}$	– dimensionless spatial and stiffness parameters;
$\widetilde{A}, \widetilde{S}, \widetilde{M}, \widetilde{N}, \widetilde{\sigma}_y$	– random values of supporting contour section, snow load, forces and stresses in the elements respectively;
v_N, v_M, v_A	– random values of the area section of supporting contour, of the snow load, of the forces and stresses in the elements respectively;
P_{syst}, P_{span}, $P_{ext.con}$, $P_{int.con}$	– probabilities of failure of roof system, load-supporting threads, external and internal contours respectively.

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

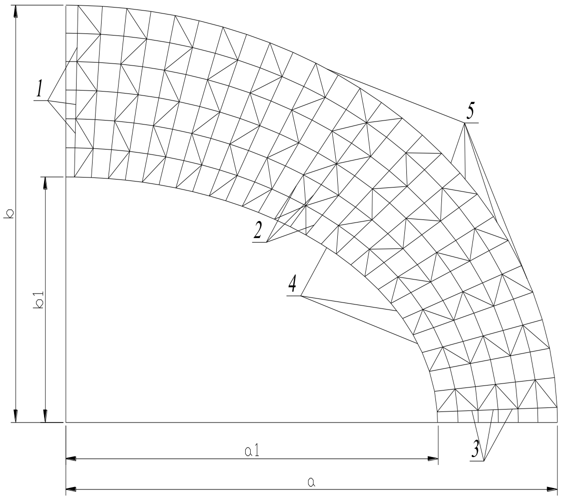
$$N_{UB} \approx N\cdot\frac{a_{UB}}{h} + \frac{M}{h}\cdot\alpha\cdot k$$

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

Improved values of forces

$$N^{y}_{UB} = k'_{\sigma}k''_{\sigma}N_{UB} \quad N^{y}_{UB} = k'_{\sigma}k''_{\sigma}N_{UB}$$

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 SCAD software (determination of trace to failure)

↓

3. Probabilistic design of the roof

3.1. Lower limit of reliability

– Series connection (a brittle model);

– Random quantities: $\widetilde{A}$, $\widetilde{\sigma}_y$;

– Computation of the reliability indices based on 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: $\widetilde{A}$, $\widetilde{S}$, $\widetilde{M}, \widetilde{N}$, $\widetilde{\sigma}_y$,

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

– Safety characteristics of Rzhanitsyn

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

– Computation of the reliability indices of the roofing $1\text{-}P_{syst}=(1\text{-}P_{span})\times(1\text{-}P_{ext.con.})\times(1\text{-}P_{int.con.})$

Figure 4. Method for determination of numerical indices of reliability for a suspension roof

The above-described method also has shortcomings. It does not take into account shell joints for determination of roof reliability, which opens new areas for research. To overcome this limitation, the first step was already made with the introduction of this new approach. Some issues have already been considered [27], where the fundamental concerns were to determine the reliability of suspension roofs joint by numerical methods, though only with the aid of common approaches for typical joints of suspension roofs. In this work, the abovementioned method was used for joints of suspensions, and subsequently modelled in modern CAD software.

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The main objective at this stage is to get better understanding of the fundamental approaches to determine the reliability of suspension roof joints by numerical methods, using modern CAD system simulation.

Methods

To apply the method (Fig. 4), a new roof was designed using standard football stadium roof dimensions. To perform the structural analysis the following dimensions were used: a = 186 m; b = 136 m; a1 = 123 m; b1 = 85 m (Fig.2). The main load-supporting elements of the roof are external contour, supported by stadium columns or walls; internal unsupported contour supported by thrust; rigid threads with a truss form (Fig. 5). The roof contours are designed by welded box-section from steel sheet. All the other elements of the supporting structure are made by box-shaped profile. Two types of design load are considered: a constant load (structure weight) and a temporary load (snow), which is 160 kg/m^2 for Donetsk (Ukraine) [28], as the test was done at Donetsk. After completing all the necessary computations, the design scheme was created in AutoCad 2014 for the macro-analysis. As shown in Figure 2, the external contour is fixed along its length, though the internal contour is not fixed and is only supported by the thrust. The obtained scheme was successfully transported to Abaqus/CAE 6.13-1 to perform the macroanalysis and determine the forces and deformations in the rods. At the same time, the 3d models of the joints of the roof (microanalysis) was created using SolidWorks 2014, and also transported to Abaqus/CAE (Fig. 5).

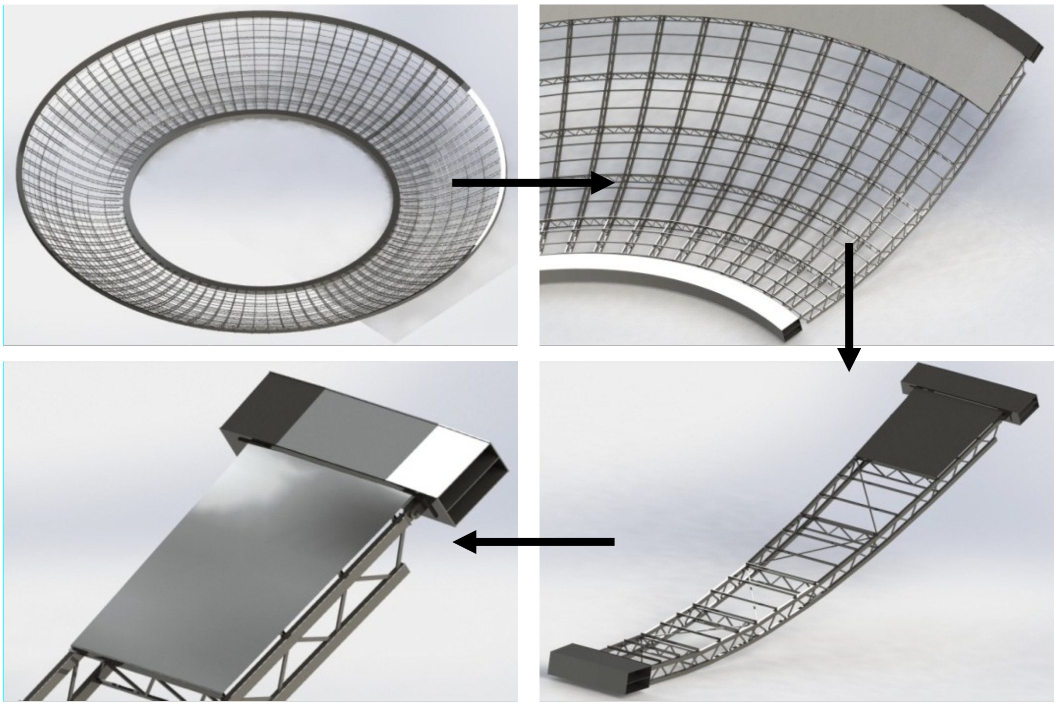

Figure 5. Suspension roof of the stadium with a cut on the elliptic plan (transition from the rod scheme to 3D model)

Additionally, critical external loads and the internal forces were applied in the clipping element zones of model joints, to obtain the critical stresses in the elements and the irreversible deformation, as it is necessary to obtain the deformability of the model and identify the most vulnerable areas. Furthermore, the displacements with all fastenings were applied to the 3d models in order to determine the stress and strain state (Fig. 2, 6). All joint element connections were welded. The exception is the joint connection between the pin and the truss, respectively "A" and "B". In this case, the contact interaction was slipping without friction. Models were divided by grids with a mesh size of 30 mm to perform microanalysis. The simulation results are shown in Figures 7, 9, 10, and 11.

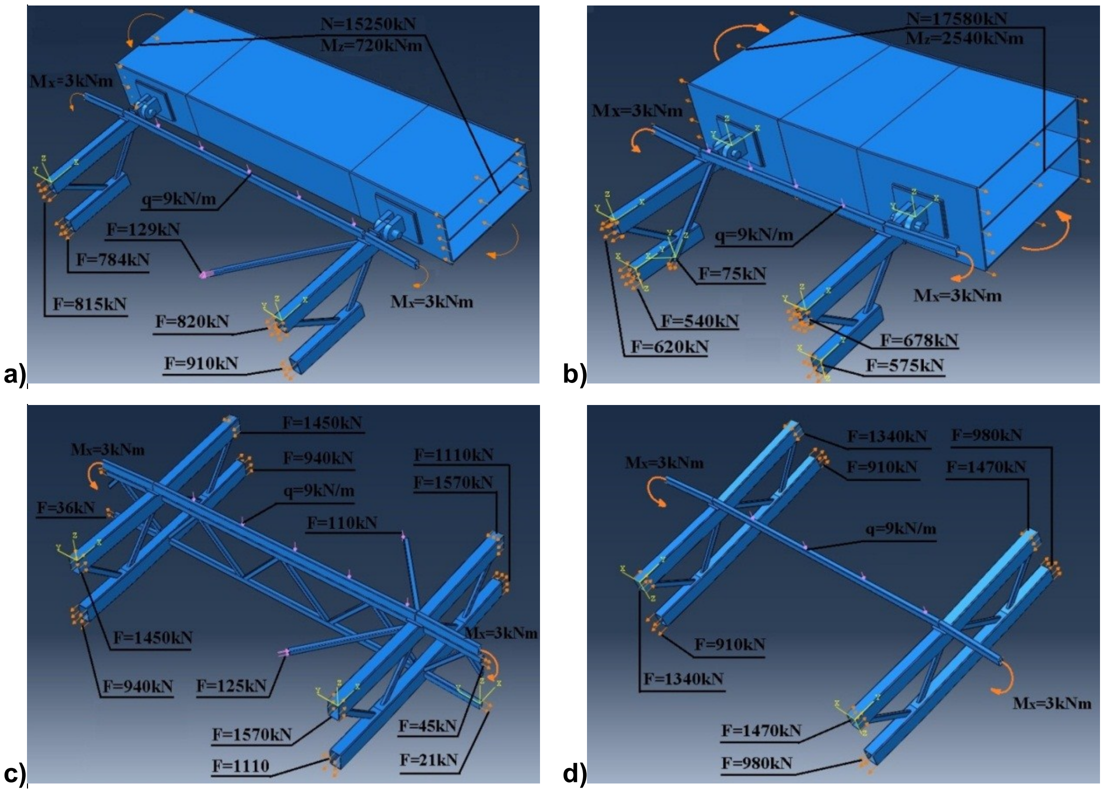

Figure 6. 3D models of the roof joints:
a) Joints A and C; b) Joints B and C; c) Joints D and F; d) Joints E and F

Let us consider the fundamental approaches to reliability of the major joints of the roof to determine its structural form. There are supporting joints of rigid thread to external contour A (Fig. 7) and internal contour B (Fig. 9), connecting joints of the supporting brace with the lower chord of the truss C (Fig. 7), intermediate joints of upper and lower chords of supporting threads D, E and F (Fig. 10 and 11). Not every joint collapse will lead to the collapse of the entire roof, and Table 1 shows the types of connections of the joints in the roof (sequential or parallel connections).

According to theaccepted logic and probabilistic simulation rules [1], the requirements for trouble-free element operation are indicated by X, and failure cases by X'. The joint operation described by the function of the included logical variables – the function of Boolean algebra (FBA) y (X_1, X_2, …, Xn) is named as the case of the system capacity (a joint).

The shortest way for successful functioning (SWSF), describing the probability of trouble-free operation of a minimum set of elements, is necessary for trouble-free operation of the system, expressed in the form of conjunction (logical multiplication) of elements (3):

$$\mathrm{P_i} = \wedge_{\mathrm{i}\epsilon(\mathrm{K_{pl}})} \mathrm{X_i}, \tag{3}$$

where $\mathrm{K_{pl}}$ – is a set of elements included in the given equation.

The condition of the system capacity (a joint) is described in the form of disjunction (logical adding) of all d shortest ways of successful functioning (SWSF) in the system (4), as follows:

$$\mathrm{y}(\mathrm{X_1}, \mathrm{X_2}, \dots, \mathrm{X_n}) = \vee_{i=1}^{\mathrm{d}} \mathrm{P_i} = \vee_{i=1}^{\mathrm{d}} \left[\wedge_{\mathrm{i}\epsilon(\mathrm{K_{pl}})} \mathrm{X_i}\right] \tag{4}$$

Results and discussion

Lets start with the supporting joint of the suspension roof to the outer supporting contour "A" (Fig. 7).

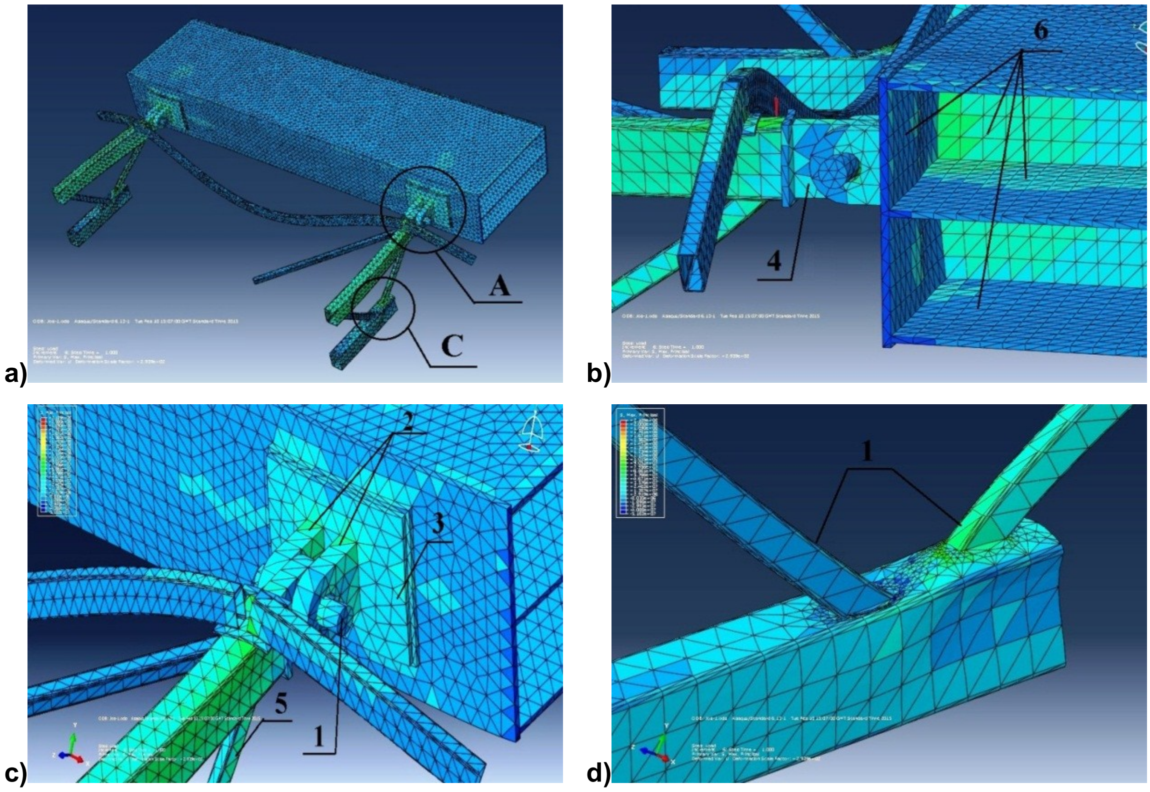

Figure 7. Deformed 3d model in the supporting zone of the external contour:
a) General view; b) Joint A (View 1); c) Joint A (View 2); d) Joint C

Regarding the actual operation of this joint, its failure can occur in consequence of several factors, as follows:

1 – a pin crushing;

2 – break of the fasteners between the thread and the contour;

3 – break of the mounting plate between the contour and the truss;

4 – break of the fasteners between the upper chord element and the pin;

5 – collapse of the supporting brace;

6 – loss of stability of the support contours elements.

These failures are represented in the form of elements in a common structural scheme (Fig.8). In this case, there is no sound base to represent twin welds in the form of parallel connections, as each element enables to carry out a function of strength capacity. In the investigated joint, one of the two welds cannot take a double load, and a twin weld is actually a single weld superimposed by two plots affecting the connection.

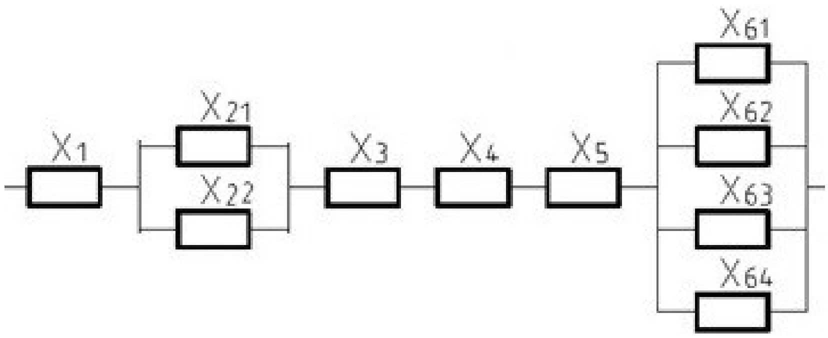

Figure 8. Reliability of joint A. Structural schematic drawing

In the conection 2, if the pin has a stop at the edges, the redistribution of the stresses will be possible after one of the fastening elements fails. However, this will dramatically increase the impact on the remaining elements, which can be affected by a parallel connection of the dependent elements. A similar situation can be observed in connection 6: whenever one of the contour elements loses the stability, the load will be distributed to other elements.

The system operation capacity affecting the operation of the joint (Fig.7) is described in equation 5, as follows:

$$y(X_1, X_2, \dots, X_{11}) = X_1 \cdot (X_{21} \vee X_{22}) \cdot X_3 \cdot X_4 \cdot X_5 \cdot (X_{61} \vee X_{62} \vee X_{63} \vee X_{64}) \quad (5)$$

For the conversion from a logical to probability function, the analysis of the correlated bonds between the elements can be carried out. Given that approximately all the forces in the joint are proportional to the roof load (main roof and snow load), the case of non-destruction of all the elements: can be described by equation 6, as follows:

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

where parameters σ_{qi} are functionally connected, and .the second parameter σ_{Ti} is the same for details 1, 6 and welds 2 to 5. Thus, the corresponding requirements of the trouble-free operation X_1 to X_6 have tight correlation connections with r ≈ 1. As a result, converting FBA (5) to a probabilistic form, the outlined groups of elements can be presented by the weakest units with $P_{imin.}$

Probability steel properties of details 1 to 6 and welds 2 to 5 should be taken independently, due to the reliability factor of the joint. Consequently, the correlations between the elements Xi and Xj accordingly to [1] can be determined by equation 7:

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

A common expression for the standard ratio $\hat{\sigma}_T^2$ и $\hat{\sigma}_q^2$, with regard to the variability and standardized deviations of designed values γ_T and γ_q, respectively is used for snow and fixed load [28]. Taking into account the abovementioned concepts about correlation connections, we get correlation coefficients $r_{ij} \leq 0.5$ between the conditions of joint elements' failure with independent strength of steel. Bearing in mind such a comparatively weak correlation, the failure of elements can be considered independent.

Conversing from FBA (5) to the probability equation of trouble-free operation (1) of the supporting joint A (Fig. 7), we obtain equation 8, as follows:

$$P_A = P_1 \cdot (1 - Q_{21} \cdot Q_{22}) \cdot \min(P_3, P_4, P_5) \cdot (1 - Q_{61} \cdot Q_{62} \cdot Q_{63} \cdot Q_{64}) \quad (8)$$

A similar analysis of the other abovementioned joints of the roof is illustrated in Figures 9, 10 and 11.

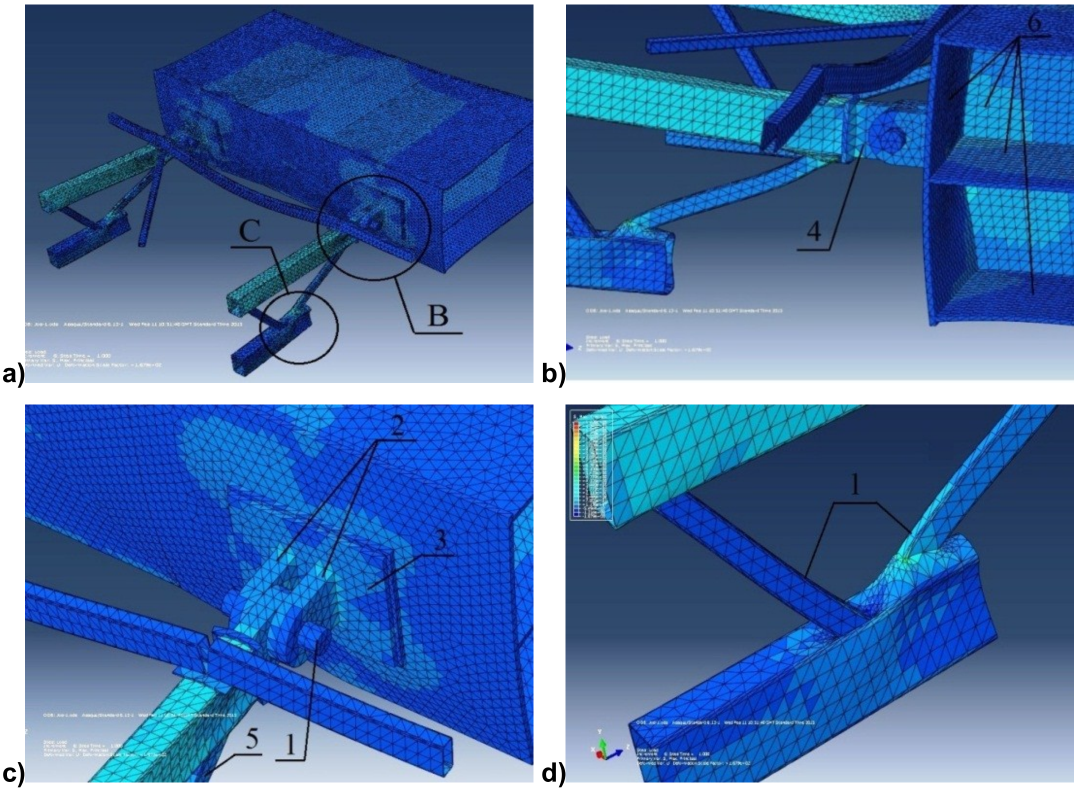

Figure 9. Part of deformed 3D model of unsupported internal contour:
a) General view; b) Joint B (View 1); c) Joint B (View 2); d) Joint C

Figure 10 shows the simulation results of 3d models of joints D and F.

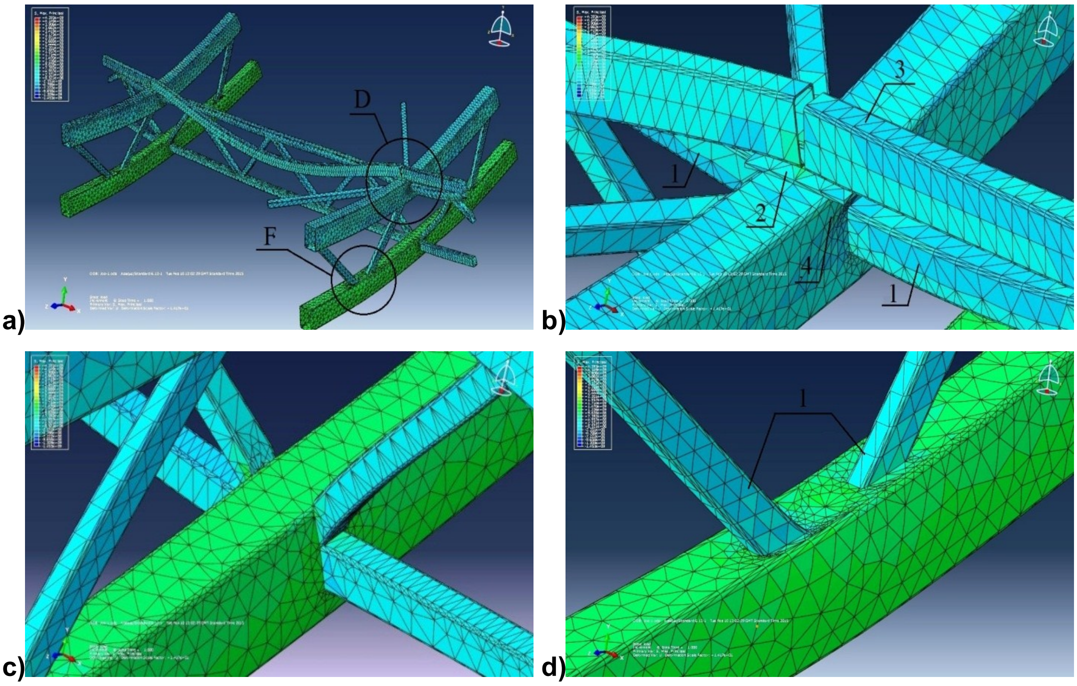

Fig.10. Deformed 3D model in the zone of fastening vertical links to the trusses:
a) General view; b) Joint D (View 1); c) Joint D (View 2); d) Joint F.

Figure 11 shows the simulation results of 3D model of joint E

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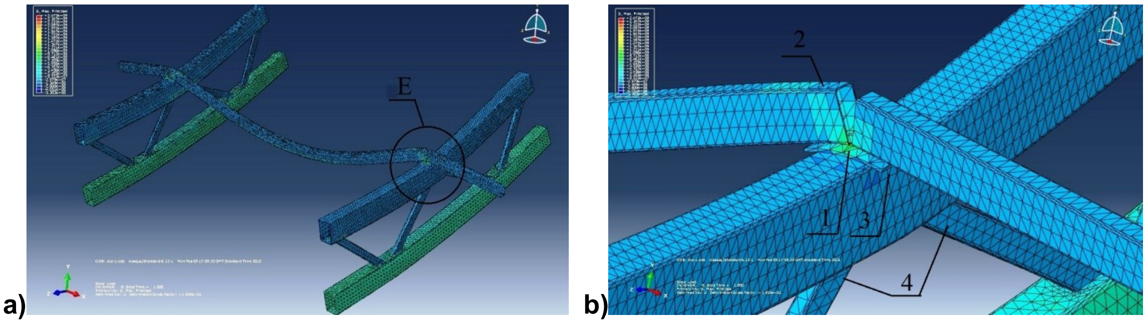

Fig.11. Deformed 3d model in the zone of fastening beam to the upper chord:
a) General view; b) Joint E

Starting from the operation of the abovementioned joints, Table 1 describes possible failures of the elements in the joints, as well the types of their connections at reliability design stage.

Table 2. Failures of joint elements

Notation of joint	Type of failures of joint elements	Type of connection of joint elements	Type of connection of joint in the roof
A (Fig. 7)	See above	(Fig. 8)	Sequential
B (Fig. 9)	1 – a pin crushing; 2 – break of the fasteners between the thread and the contour; 3 – break of the mounting plate between the contour and truss; 4 – break of the fasteners between the upper chord element and the pin; 5 – collapse of the supporting brace; 6 – loss of stability of the support contours elements.	Sequential Parallel Sequential Sequential Sequential Parallel	Sequential
C (Fig. 7)	1 – collapse of the welds between the supporting brace and the lower truss chords	Sequential	Parallel
D (Fig.10)	1 – collapse of the welds between the elements of vertical linkages and truss chords; 2 – collapse of the intermediate plate between the beam and truss chord due to local buckling or failure of welds; 3 – beams collapse due to failure of welds. 4 – local buckling of the upper chord at the place of fastening to beams. 5 – collapse of the intermediate trusses braces due to the failure of welds or local buckling.	Parallel Sequential Sequential Sequential Parallel	Parallel
E (Fig. 11)	1 – collapse of the intermediate plate between the beam and truss chord due to local buckling or failure of welds; 2 – beams collapse due to failure of welds. 3 – local buckling of the upper chord at the place of fastening to beams. 4 – collapse of the intermediate trusses braces due to the failure of welds or local buckling.	Sequential Sequential Sequential Parallel	Parallel
F (Fig. 10)	1 – collapse of the intermediate plate between the beam and truss chord due to local buckling or failure of welds;	Parallel	Parallel

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

$$P_B = P_1 \cdot (1 - Q_{21} \cdot Q_{22}) \cdot \min(P_3, P_4, P_5) \cdot (1 - Q_{61} \cdot Q_{62} \cdot Q_{63} \cdot Q_{64}), \quad (9)$$

$$P_C = P_1, \tag{10}$$

$$P_D = \min((1 - Q_{11} \cdot Q_{12}), (1 - Q_{51} \cdot Q_{52})) \cdot \min(P_2, P_3) \cdot P_4, \tag{11}$$

$$P_E = (1 - Q_{41} \cdot Q_{42}) \cdot \min(P_1, P_2) \cdot P_3\ , \tag{12}$$

$$P_F = 1 - Q_{11} \cdot Q_{12}, \tag{13}$$

where P_B, P_C, P_D, P_E, P_F – correspond to probability of trouble-free operation of joints B, C, D, E, F.

With regard to the accepted types of joint connections (Table 1), the probability of the trouble-free operation of the joint system may be described in the following way:

$$P_{sis\ y} = P_A \cdot P_B \cdot (1 - Q_{C1} \cdot \ldots \cdot Q_{Cn}) \cdot (1 - Q_{D1} \cdot \ldots \cdot Q_{Dm}) \cdot (1 - Q_{E1} \cdot \ldots \cdot Q_{Ek}) \cdot (1 - Q_{F1} \cdot \ldots \cdot Q_{Fh}) \tag{14}$$

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

Values of n, m, k, h are determined when the roof span part is destructed.

At this stage, the fundamental approaches to define the reliability of the joints in suspension roof were determined by numerical methods.

Further investigation is needed, based on the method of Mushchanov-Pryadko [10], to develop a new method to design suspension roofs, founded on realiability numerical indices of designed structures taking into account joints' operation. This method can be applied in 2 stages:

a) Analysis of the systems' reliability at the macro level, considering the geometric characteristics of the sections of the main structural elements;

b) Analysis of the reliability of the system at the micro level, when a reliability analysis of the most strained structural elements is performed, based on the analysis of the behavior of joints.

Conclusions

The reliability of large-span suspension roofs was investigated and a fundamental approach is proposed to determine reliability of their joints at the design phase. Some major principles are laid down in these conclusions:

1. Structural design of the reliability of joints in suspension roofs shows that these joints are mainly described by sequential schemes including parallel connections of dependent elements, corresponding to multi-elementary connections selected at the design scheme.

2. There is a correlation between joint elements in the structure, due to the same steel strength properties which allow reducing the number of elements and increase the final reliability of the joints.

3. The reliability of the joints of suspension roofs depends on the number of its supporting elements, as an increase in the the number of elements leads to reduction in its reliability, while low-element joints have greater reliability. Other important factor is the homogeneity of strengths of elements: reliability of joints is lower whenever the reliability of elements is independent. This situation is true if the elements are produced with different types of steel, by various producers, if different types of welding are used, etc.

4. Due to theirmulti-elementary nature, joints can be less reliable than elements themselves (rods of columns, span parts of suspension threads, etc), so they should be considered when reliability of structures is assessed.

5. The proposed approach may be used for suspension and convex rod shells with similar design joint solutions.

6. After performing the reliability analysis of joints, there is a need to increase the supporting capacity of the structure in zones with fixed critical stresses by increasing the weld sizes, installing additional bolts, additional elements or using high strength steels, etc.

7. The proposed approach can be applied to the design of suspension roof systems providing economic and social benefits. Design companies and customers will benefit from this approach by using a reliability-based model that allows efficient management of complex systems and maintenance of sufficient reliability and functionality levels of such systems.

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