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## A NEW APPROACH TO THE DESIGN OF SUSPENSION ROOF SYSTEMS

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Over the last century, the suspension roofs design has progressed until the advent of the shells theory in the first half of the 20th century, due to a rapid pace in technological advancement. A paradigm shift emerged with the new trend in structural design towards a new design process that cooperatively integrated economy, efficiency, and elegance. Different approaches in computation, design and reliability assessment of roof structures are discussed in this work to identify the key conditions that have significantly contributed to modern suspension roof design principles. A new algorithm to assess the reliability of suspension roofs at the design stage is proposed and a novel method for computational design and reliability evaluation of suspension roofs is presented in this paper. This method enables to solve some topical issues, such as assignment of initial geometric roof parameters and relevant problems, like numerical determination of reliability indices for statistically non-determined systems of suspension roofs with a big cut on elliptical plan.

**Keywords:** suspension roof, stress-strain state, computational methods, reliability indices, roof failure.

### 1. Introduction

The esthetic superiority and the overall structural performance of suspension roofs are well known by Otto [1] and Rabinovich [2], since these structural systems combine stability, economy and satisfaction of special architectural demands, while their application is closely related to major engineering challenges. Based on inspiration and intuitive conception quality, distinguished pioneer engineers have designed and realized numerous buildings with suspension roofs as their main structural component (Mies van der Rohe [3], Tange and Nervi [4], etc. Starting from the famous Crown Hall at the Illinois Institute of Technology between 1950 and 1956 [5, 6], the Tokyo Small Olympic Arena from the early sixties [7, 8] and the Paper Mill at Mantua, Italy [9], there are many applications of suspension roofing system, like that in Dulles

International Airport (Washington DC 1962), Stadthalle (Bremen 1964), Europahalle (Karlsruhe 1983), PA Tech Laboratories (Princeton 1986) and Church of Fatima (Brasilia 1988) must be quoted [4].

A valuable contribution to the theory and design of large-span spatial shells was done by many scientists [10]. In the last 15 years the advent of powerful computers and development of sophisticated nonlinear computer-aided design (CAD) software [11, 12, etc.] have enabled engineers to utilize suspension roofs in complicated large scale structures, some of which can be classified among unique examples of engineering excellence. A comparative presentation of earlier and recent applications of suspension roofs is shown in Fig. 1, where the



(a)



(b)



(c)

Fig. 1. Four classical applications of suspension roofs: (a) Dulles Airport, United States [13]; (b) PA Tech Lab, United States [14]; (c) Oquirrh Park Speed Skating Oval, United States [15]

last image (Fig. 1(c)) refers to the Oquirrh Park Speed Skating Oval, belonging to the facilities of the Salt Lake City site for the XIX Olympic Winter Games of 2002 [4].

Supporting elements of suspension roofs are most often made by flexible or rigid threads (guys). The guys can be made from conventional rolled steel, trusses, rebar rods, strand of high-tensile wire and cables, etc. These roofs are different from others due to the lack of prestressing process. It is also possible to obtain the necessary roof rigidity with a low constant and high temporary load. The material in suspension shells works in two directions. In addition, shells can also withstand shear forces.

Large-span roofs have a higher responsibility level as their failure can lead to serious economic and social consequences. In this context, design of these unique structures should be based on an integrated approach of rational choice of design solutions [16, 17, 18]. These decisions are related to functionality, architectural design, manufacturing and installation

techniques as well as operating conditions. The requirements of reliability, manufacturability and cost efficiency as well as accounting the environmental and social factors should be fully implemented.

Probabilistic assessment of reliability is one of the most important tasks in roofs researches in the objects with high responsibility. The main property that determines the reliability of these structures is their performance and ability to save the pre-defined operational quality during the lifetime. Quantitative characteristic of this property is the failure-free operation probability [18, 19].

Existing design codes [20-22] do not include large-span roofs reliability quantification requirements. It is assumed that the computational requirements implementation provides a sufficient reliability level. However, this level can vary within very wide limits depending on load variation characteristics and material properties; constructive scheme; number of structural elements; type of relations between the forces in the elements and the loads.

Reliability of metal structures in buildings and constructions represent statistically determined and non-determined systems that were investigated by many researchers. The major problems and samples were considered [23, 16] and reliability assessment of the large-span suspension roofs and cable-stayed structures was investigated [24, 25, 26].

It should be mentioned that joints between the supporting elements of bearing structures, such as trusses or beams, are a significant issue in the supporting elements composition, because their failure could lead to the start of the damage of the whole roof. Application of modern numerical simulation techniques, like ADINA and ABAQUS [11, 12] enables to investigate the effect of structural schemes on the joints operation and to accumulate necessary statistical data on stressed-strained state of joints. At the same time, contemporary status of computer engineering development opens possibilities for estimating the reliability of joints in suspension roofs, bearing in mind parameters of stressed-strained state and correlation links between functions of joints elements supporting capacity. Investigations of stressed-strained state of joints in steel structures was performed [27, 28], however lot of issues related to stress-strain state (SSS) of suspension roofs joints should steel be studied.

## **2. Aims and Scope**

The main objective of this study is to present a broad perspective of using a novel method for computational design and reliability evaluation of suspension roofs, as they are often used in construction of modern stadiums. It is related to the fact that UEFA puts forward strict requirements to ensure comfort for spectators of world or continental football championships. One of the requirements is high-quality roofs over the stadium tribunes for protection against external influences, such as rain, snow, wind, sun, etc. The choice of this type of the stadium roofs is due to their numerous advantages. Thus, the present paper reviews the existing modern design approaches and ways for ensuring proper reliability of long span suspension roofs.

Consequently, the main objective at the given stage is developing fundamental approaches for determining reliability of stadium roofs joints by numerical methods, using microsimulation in modern CAD.

### 3. Structures as art: from concept to design

Over the past few decades, a lot of large-span shells have been designed and constructed all over the world. Each of them represents a unique architectural form and based on different approaches in design of supporting structures roof.

#### 3.1. Types of tension roof structures

In order to achieve adequately stiff and stable tensile cable or membrane roof structures the following possibilities are known [24]:

1. Using gravity stiffness
2. Pre-stressing
3. Using air pressure support
4. Combination with rigid elements such as beams, trusses, arches, plates, grids, columns.

Simple suspension cables, synclastic shells and membranes are otherwise flexible. If loaded by heavy slab or shell elements, the resulting tension system can be imparted adequate stability and stiffness though it is an antithesis to the tension structures 'lightness'. An alternative concept is to design pre-stressed or 'counter-stressed' tension systems as shown in Fig. 2 [25].

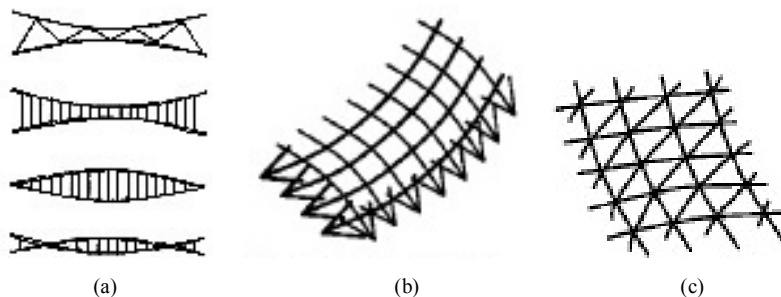


Fig. 2. Typical roof supporting tension systems[29]:  
(a) trusses, (b) two-way net; (c) tri-diagonal net.

It is recommended to use rigid threads without pre-stressing to improve the stability in suspension roofs [24]. This decision significantly reduces the roof weight, applies light prefabricated flooring and simplifies the construction. Rigid thread is easiest to produce rolled, preferably from the high-strength steel.

An important element of suspension roofs is the supporting contour [10]. Normally a supporting contour has a rectangular cross section and is made of reinforced concrete in a monolithic and/or modular form. The supporting contour is used for fastening the suspension roof that transmits the tensile forces from the trusses fixed by hinges to the supporting contour. These contours may be designed either closed or opened. In case when the contour is opened, the thrust force is transmitted by struts, buttresses, delays with anchors and other to

foundations. Big forces appear in these elements from the guys thrust and they require higher material consumption. Therefore, the closed contours are more economical. At the same time, the supporting contour has the highest material consumption in the roof (about 35 ... 60%).

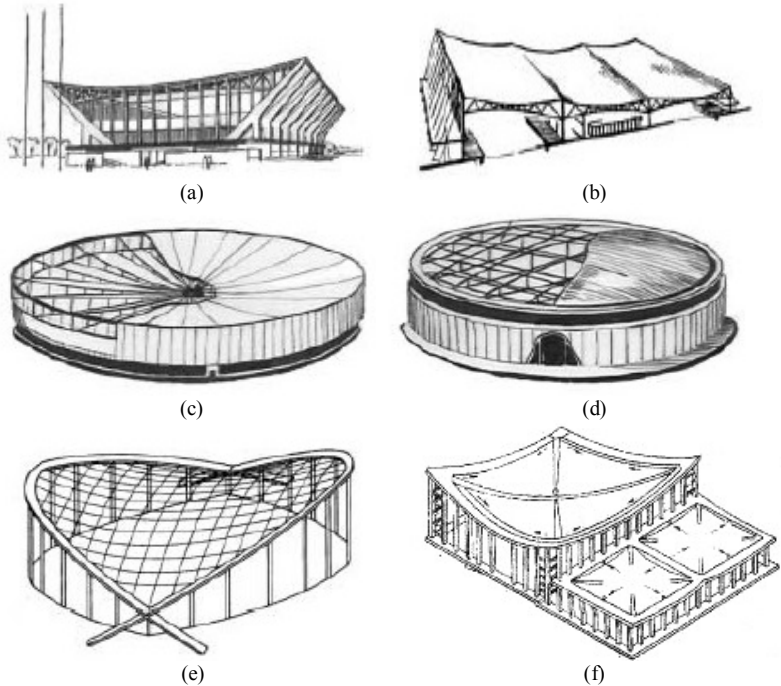


Fig. 3. Typical tension roof systems [31, 29]: (a) one-chord system; (b) two-chord system on rectangular plane; (c) two-chord system on round plane with cut; (d) two-chord system on round plane without cut; (e) typical saddles strained nets; (f) metal membrane

There are planar or spatial covering shells which together with a membrane or cladding form the basis of a roof system. Both gravity loaded or pre-stressed roofs have to be combined with elements such as beams, trusses, arches, plates, grids and columns. Typical structures [25] are shown in Fig. 3. Some known examples are worthy of discussion such as the roof of the Munich Olympic stadium in Germany, roof of the ice-skating rink in Munich, Germany, convertible roof over the Roman arena in Nimes, France, convertible roof of the Montreal Olympic stadium, Canada, the glass-grid dome of the Neckarsulm indoor swimming pool, the Olympiakos Stadium in Athens, Greece, the new suspended cable roof of Braga Stadium, Portugal, the Thessaloniki Olympic sport complex, Greece, the new Juventus Stadium in Turin, Italy etc. [30, 25, 26]. The present review is focused on landmark buildings that have a determined suspension roofs shape on a rectangular, square, elliptical or circular planes.

### 3.1.1. Suspension roofs of round or elliptical plans

Shukhov Rotunda (Fig. 4 (a)) is a unique round steel pavilion, constructed by V. G. Shukhov for the Russian Industrial and Art Exhibition in Nizhny Novgorod in 1896 [4]. Rare structure with a diameter of 68 m has a roof in a form of strongly stretched suspension annular mesh shell with a steel membrane and has a diameter of 25 m in the central part. It was the world's first membrane (suspension) structure of roof buildings.

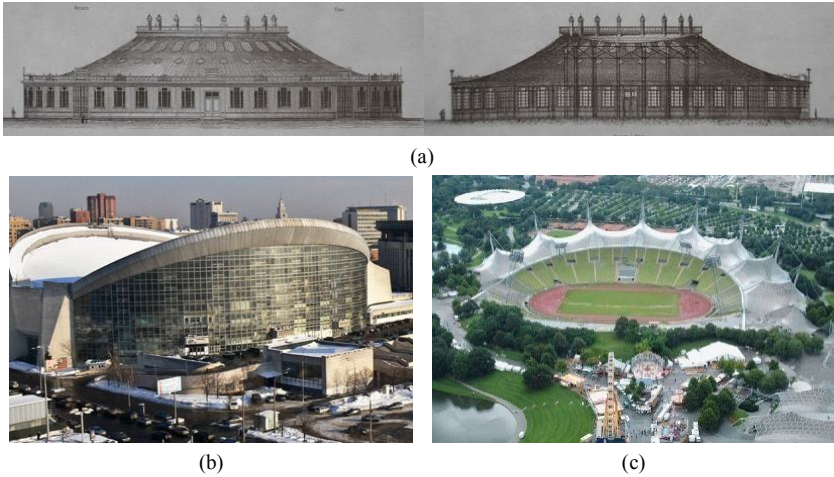


Fig. 4. Suspension roofs with round and elliptical plans:

(a) Shukhov Rotunda, Russia [32]; (b) Olympic pool in Moscow, Russia [33]; (c) Olympiastadium in Munich, Germany [34]

As example of an external thrust systems, where the thrust forces are transmitted to the foundation or anchor, is the roof of the Olympic pool [35] on the Mira-street in Moscow, Russia (Fig. 4 (b)). It has a rigid supporting contour in a form of two arches. The bases for the roof construction solution are rigid threads made in a form of trusses and parallel to the short axis of the building with a step of 4.5 m. Profiled sheeting panels are installed on the trusses to provide suitable stiffness. Insulation, screed and roof waterproofing are placed on the panels. Another example of rigid threads functional application is their using as stabilizing system components of large-span membrane roof (for example, that of the covered stadium on Mira street in Moscow, Russia [35], where the radial elements of the stabilizing system were designed as 2.5 m height suspension trusses).

Olympia stadium [36] (Fig. 4 (c)) is a unique multifunctional stadium in the heart of the Olympic Park in Munich, Germany, that was constructed in 1972. The tribunes are covered by a giant suspension shell that was designed by architect Frei Otto. Large canopies of acrylic glass and steel cables were used for the roof construction. Moreover, they were used for the first time in such a quantity for construction of sports facilities.

### 3.1.2. Suspension roofs of square and rectangular plans.

As a roof with rigid threads, one can distinguish the pavilion of USSR at the World Exhibition in Montreal, Canada, constructed in 1967 [25, 36], which was later dismantled and imported to the USSR in 1975. The structure of the pavilion (Fig. 5 (a)) is represented by stretched corner trusses that transmit the supporting forces to the powerful V-shaped pylons-spacers. At the bottom of the structure supported on hinges are installed special vertical ties that are loaded from the opposite side by the mass of the structure and pre-stressing for providing structural stability.

A modern stadium with a unique suspension roof on a rectangular plan and flexible threads is the stadium in Braga, Portugal. It is included in the top 20 unique stadiums of the world [39]. The Braga Stadium was one of the stadiums constructed in Portugal for the 2004 European Championship (Fig. 5 (b)). The most outstanding element of the structure is its very flexible suspension roof, which is formed by pairs of full locked coil cables spaced 3.75m apart from each other, supporting two concrete slabs over the stands of the stadium. This infrastructure was built for the 2004 European Football Championship. The stadium was designed by Eduardo Souto Moura in conjunction with the “Afassociados” consultancy office and has been considered by many a masterpiece of modern architecture. In the west stand, the concrete walls are anchored in the rock and the roof cable forces are transmitted to the foundation by pre-stressing tendons embedded in the concrete [40].

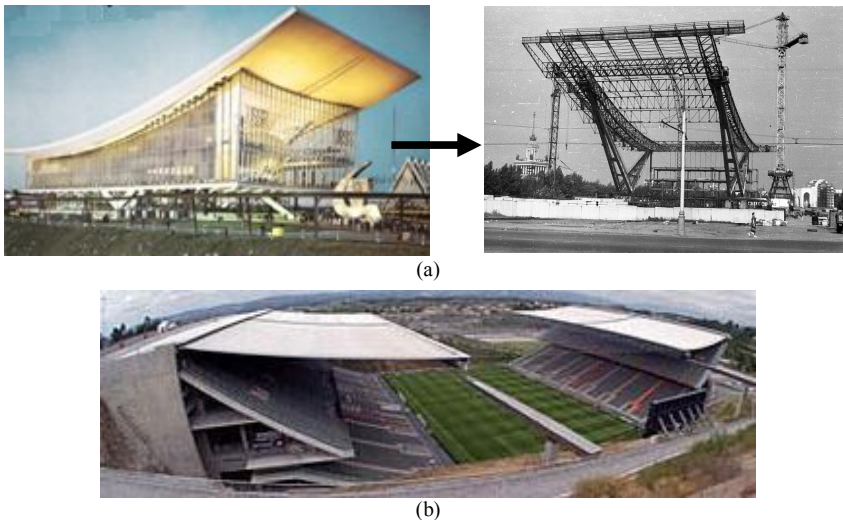


Fig. 5. Suspension roof on the square and rectangular plans:  
(a) Pavilion of USSR in Montreal, Canada [37]; (b) The Braga Stadium, Portugal[38]

After considering all the variety of suspension roof design solutions, one can conclude the following remarks about their advantages:

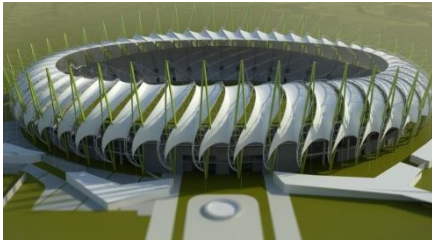
- architectural and structural expressiveness;
- constructive form of suspension roof is quite common in large -span structures;
- materials consumption in metal suspension roofs is much less than in arched type structures, where the main part of the metal is consumed in arch supporting;
- the opportunity of constructing roof structures by parts, is important for the financing big construction projects.

### 3.2. Necessary conditions

Current trends should be taken into account in the design and construction of new roofs. There is a large number of both realized and pending projects of stadiums with suspension roofs in the world [41]. Figure 6 illustrates some of the new projects in different countries around the world.



(a)



(b)



(c)

Fig. 6. Modern design solutions of suspension roofs of stadiums: (a) Vladikavkaz, Russia [42]; (b) Basra, Iraq[43]; (c) Durban, South Africa[44]

#### 3.2.1. Structural principles

The history of architecture has involved countless styles and trends, but the rationale behind the structural art has not changed significantly no matter the scale of a structure; it always features a search for a cost-effective and performance-efficient design without losing elegance [5, 7, 10]. The aesthetic expression of a structural form is neither a pure desire to find a shape for decoration nor a subordination of its function; otherwise a structure would be overdesigned without any appearance of structural art [45]. Stadiums and their roofs exteriors should comply with the culture and the area where they are located. Examples of roof projects that consider the local culture are shown in Fig. 7. The Muslim Qatar stadium roof for the World Cup 2022 in Qatar is fully integrated into the traditional architecture ( see Fig. 7(a)); similarly, the Muslim



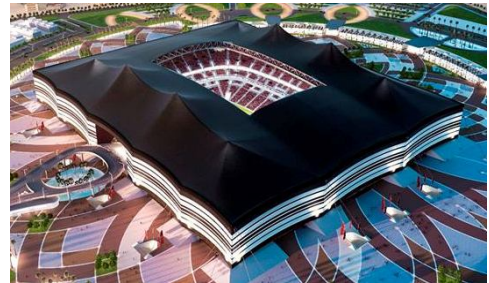
style arches were used in Uzbekistan (Fig. 7(b)), stadium roof in Turkey (Fig. 7(c)) that looks as a crocodile [46].

Studies from the historical point of view have shown how design evolved to achieve an efficient and economic structure by understanding structural principles. Further, bio-inspired or biomimetic design (Fig. 8) inspires engineers to find a cost-effective structural form with elegant appearance and also presents emerging challenges, including design of smart and intelligent structures. Review on these topics is available [50–52].

F. Leonhardt [56] formulated ten rules for structural design and M. Troitsky [57] mentioned ten requirements for structures aesthetics. These rules could be sorted into two groups: to improve the elegance of structures and to improve their harmony with the environment. Although the rules cannot guarantee the elegance of a structure, but at least they can help designers to avoid certain kinds of unattractive designs.

### 3.2.2. Competitive environment

Quality function deployment (QFD) has been widely used as a multi-functional design tool to translate customer requirements to a product's technical attributes. QFD originated in the late 1960s and early 1970s in Japan [58] and the topic is investigated till today [59]. At the beginning of QFD development, the primary QFD functions were product development, quality management, and customer needs analysis. Thus, QFD was used to help design teams to develop products with higher quality to meet or surpass customer requirements. With the



(a)



(b)

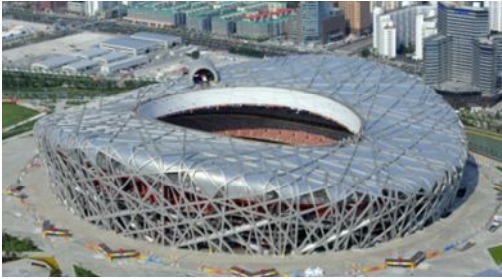


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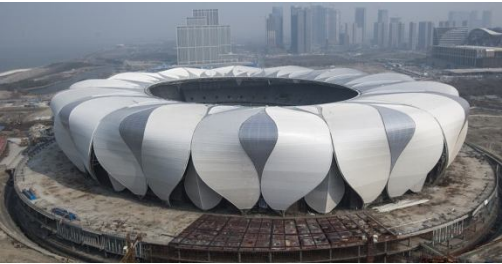
Fig. 7. Exteriors of stadiums roofs: (a) Al Khor, Qatar [47]; (b) Tashkent, Uzbekistan [48]; (c) Bursa, Turkey[49]

development and widespread use of QFD, its application areas expanded to much wider fields, including design, planning, decision-making, engineering, management, teamwork, timing, costing and so on. The inherent incentive of the widespread use of QFD is its benefits to practitioners. Researchers have mentioned the benefits of QFD correctly rating the importance of every customer requirement is essential to the QFD process because it will largely affect the final target value of a product's technical attributes [60 - 63]. Traditionally, capturing customer requirements involves three steps in QFD:

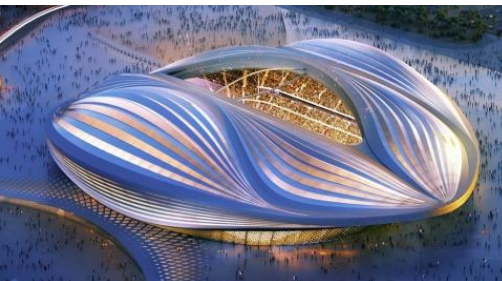
1. Identifying customer requirements;
2. Structuring customer requirements;
3. Determining the importance weight for the individual customer requirements.



(a)



(b)



(c)

Fig. 8. Biomimetic architecture of stadiums. (a) Beijing, China [53]; (b) Hangzhou, China[54]; (c) Al Wakrah, Qatar[55]

The first two steps are usually accomplished via market survey, combined with expert opinion. Many researchers have proposed several mature methods on this topic. Presently, the success of a product in a competitive market place depends either on how well it meets the customers' requirements, or how it compares with competitors' products. Therefore, it is important to integrate competitive analysis into product design and development.

A new customer requirement ranking method that takes competitor information into account was proposed [64]. This method focuses on the voice of the customer and also considers the competitive environment. The method helps in finding out the most important customer requirements, and provides a way to combine them

with the importance weights from a customer's viewpoint. The proposed rating method will provide the final weight from three perspectives: competition, performance and customers. The conceptual process of this model is presented in Fig. 9.

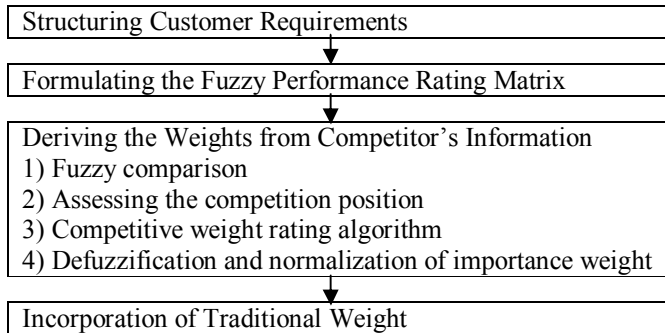


Fig. 9. Conceptual process according to the proposed model

Competition is a factor that can improve the result in works on structural art. European countries such as Switzerland and Germany have elevated modern structural design to an artistic level by making the design process itself competitive. It is reported that competition between structural artists pushed designs to become works of art, such as Thomas Telford and John Rennie in the age of iron, Isambard Brunel and George Stephenson in the design of unique structures, or Othmar Ammann and David Steinman in the design of long-span suspension bridges [65]. Hines and Billington have studied the design process of the winning bridge for the competition of the Ingolstada Bridge in 1998 and showed how design competition pushed structural engineers to exceed the norms of practice and design a work of art [66]. Overall, structural form based on competition can drive the conceptual design process, leading to a highly developed vision of the design and a form that could not have been conceived by structural theory alone.

### 3.2.3. Materials efficiency

The development in structural materials is a prime factor, leading to a revolution that has taken place in suspension structure development and use. The roof cladding which may have used animal skins in the primitive applications can today be chosen from a wide variety of possibilities. Corrugated sheeting from metals—galvanized iron, aluminum alloys, stainless steel—plain or corrugated, and sheets from non-metals such as fibre reinforced glass or plastic, timber planks, concrete slabs, and fabrics of different type, and, produced to a high degree of sophistication are available. The development in the capacity to carry direct forces or flexure is even more dramatic.

The basic tenet is the enormous increase in the strength-weight ratio. In compression and flexure elements, timber and stone have given way to high strength steels [67], high performance concrete [67], pre-stressed concrete [67],

corrosion resistant high yield reinforcing steels [67], etc. For tension elements which initially used natural vines and creepers, and then cast iron chains, there is now abundant use of high tensile strength steel wire ropes and strands [67] and opportunity of using carbon reinforced plastic fiber [68].

Increase in the strength–weight ratio has enabled a substantial growth in the capacity of a structure or its elements to carry live and superimposed loads [67]. Furthermore, improvements in technology have led to enhanced corrosion resistance of metals and their products, as well as development of high strength non-metallic materials which are inert to the effect of corrosion [67]. Thus from the humble beginnings of small exotic suspension systems, the way has been paved for the large scale application of suspension structures.

Alongside typical construction materials such as steel and concrete, today's innovative materials are finding their way into the designs of new structural form, such as fibre reinforced polymer (FRP) composites. With its high strength and durability, it has been recognized as a competitive material for suspension construction [69]. However, its optimal structural forms have not yet been fully explored, nor has its material potential been achieved. Attempts to use laminated composite in the shape of thin shells, membranes and woven webs were investigated [17, 68, 70]. Keller [71] reviewed the multifunctional use of FRP composites that offer the potential to meet the need of a new generation of infrastructures, such as lightweight and high sustainability. It is important to develop material-adapted forms, meaning efficient forms that exploit the unique properties of a material [72].

The requirements for the roof material are described in the International Building Code 2006 (IBC), chapter 15, [73].

### **3.3. Failures of the large-span roof structures due to design mistakes**

Collapse examples of different large -span roofs types can be used to learn the errors in design or improper construction. Putting forward ideas should be technically and economically justified in the design of unique large-span structures. Requirements for reliability, manufacturability and cost-effectiveness, environmental and social factors should be performed in full.

The modern building codes are based on structural reliability theory [22]. Theoretically, the structural failure probability should be in the order of  $10^6$  per year. However, failures occur and are in general caused by:

- Unfavorable combinations of circumstances like extreme snow load on a roof structure in combination with an unfortunately low structure strength.
- Unforeseen load conditions like for example explosions. It is quite rare events and precautions can be done to reduce the consequences like design against progressing collapse.
- Gross human error in the design, material production or construction phases. To minimize or avoid human errors, different actions can be taken like for example education, good working environment, complexity reduction, self-checking and inspection.

Violation of existing rules can lead to accidents. Some illustrative examples of large -span roofs are shown below.

In December 2010, 50 centimeters of snow fell in the western part of USA and the temperature dropped to minus 18 degrees [74]. Therefore, a huge inflatable roof collapsed over the stadium Metrodome in Minneapolis. The unique domed roof was made of fiberglass. The whole structure was maintained by overpressure of air. During the collapsing process first, a hole formed in the roof; second, the roof crushed under the snow weight on the field of the stadium (Fig. 10 (a)).

Roof of one of the FC Twente, Netherlands, stadium tribunes collapsed in 2011 [78]. The roof has collapsed during the stadium reconstruction in order to expand its capacity. The collapse was due to mistakes during construction and installation works. As a result, two supporting beams lost their load-supporting capacity (Fig. 10 (b)).

Siemens Super Arena is a multifunction sports hall. The arena was formally run by the Danish Bicycle Union and a cycle-racing track was one of the main features. The structure was built in 2001 and inaugurated in February 2002. The “fish-shaped” main trusses with a spacing of 10.1 m have a span of 72 m. On the morning of 3 January 2003 the truss in line 4 (Fig. 10 (c)) suddenly fell to the floor [79]. The Siemens Arena case differs from many other cases in that it was due only to design errors made by Albeit Many that was working under a tight time pressure and without supervision. Formally third control party by an approved independent structural engineer was hired, but what he did apart from putting his signature on the front page of the computations and his bill is difficult to see [79].

Nowadays, civil structures become more and more wind and snow sensitive, because of the trend towards lightweight



(a)



(b)



(c)

Fig. 10. Collapse of stadiums roofs  
(a) Minneapolis, USA [75]; (b) Twente, Holland[76]; (c) Ballerup, Denmark [77]

construction and the evaluation of exact wind loads acting on such structures, frequently characterized by complex geometries, requiring expensive experiments in wind tunnels or semiempirical methods. The dynamic nature of wind action can cause oscillations and deformations, which can compromise the performance of the roof and, in the worst cases, its structural stability. On the other hand, the static effect of snow represents a dominant load for this type of structure, even reaching as high as 70%-80% of the total load. One of the primary collapse causes (corresponding to approximately 45% of the cases analyzed) lies in an erroneous evaluation of the loading conditions and of the structural response [18]. A number of studies and analyses have been carried out on structures that have completely or partially collapsed:

- due to snow, e.g. the Hartford Coliseum (1978), the Pontiac Stadium (1982), the Milan Sports Hall (1985) and the Montreal Olympic Stadium (1992);

- due to wind, e.g. the Montreal Olympic Stadium (1988).

From the observation of such collapse events significant information has been collected, and design specifications have been obtained for verification of these structures in ultimate and serviceability limit states. In particular, the great difficulties in assessing and simulating real load conditions have emerged and some considerations about such problems are described [80, 81].

Among the facts, related to the work of suspension threads and hard errors in their design, one can identify the following examples:

1. Swimming pool of Olympic sports complex in Moscow, Russia (Fig. 4b) [35]. Following the publications of the appropriate commissions that have studied the reasons of these events, the influence of concrete creep and changes in the shell geometry on buckling of RC thin-walled shells was not properly considered in the design. Iskhakov and Ribakov [82] focused on buckling of such shells, taking into account geometrical and physical nonlinear behavior of compressed concrete. The critical buckling loads for the shells are obtained. It was shown that these loads are lower than the actual ones and therefore the shells' buckling was unavoidable. To prevent brittle shell failure, they should be designed using other dominant failure modes that appear before the buckling. It was concluded that possible failure schemes of real RC shells can be predicted using dominant failure modes obtained by laboratory testing of scaled models. Rigid threads (suspension trusses) are the main load-supporting structural elements of the roof mounted on the support contour. The error in the geometry of the support contour at this facility led to significant changes in the stress-strain state of threads. It has led to violations of their design geometry and operating problems of the roof.

2. Covered stadium on Mira street in Moscow, Russia, [35]. Rigid threads (suspension trusses) are part of the radial-ring stabilizing system. It is working together with the membrane roof in perception of non-equilibrium loads. Considering of geometric nonlinearity was performed incorrectly. It has led to necessity correction of the roof geometry in the final stages and cutting

(essentially it is generate failures) of the separate elements of the lower chords of suspension trusses.

Consider addition of the case regarding the airport terminal roof collapse in Paris.

Terminal 2E of the Charles De Gaulle International Airport (Paris) collapsed unexpectedly in the early morning of Sunday, 23-May-2004. According to an initial enquiry, the metal support structure had pierced the concrete roof, causing it to split and fall in. The new terminal collapse was “linked to the perforation of the vault by thes, that was a consequence of a design errors” [83].

Long span coverings were subjected to partial and global failures as that of the Hartford Colisseum (1978), the Pontiac Stadium (1982) and the Milan Sport Hall (1985) due to snow storms, the Montreal Olympic Stadium due to wind excitations of the membrane roof (1988) and snow accumulation (1995), the Minnesota Metrodome (1983) air supported structure that deflated under water ponding, the steel and glass shell sporthall in Halstenbeck (2002).

These examples describe the importance of considering the nonlinear effects (geometrical, physical, structural, genetic) in more accurate computation and proper design of similar roofs, and as result, ensuring the reliability of rigid threads.

The problems with general poor quality in the building industry are not new and were investigated [84]. It was identified that there are five main drivers for change, four processes on which to focus improvement and seven targets for improvement with for example an annual targets for capital cost of 10% (see Fig. 11.). In Sweden, a commission has published a 400-page report, describing a building sector with many problems, like illegal cartels and other market manipulating activities, macho culture and short time for planning design even for very complex structures [85]. According to the report more than 60% of the shortcomings in the finished structure are related to shortage in documents that the client has the responsibility for. These problems have resulted in poor quality and high prices.

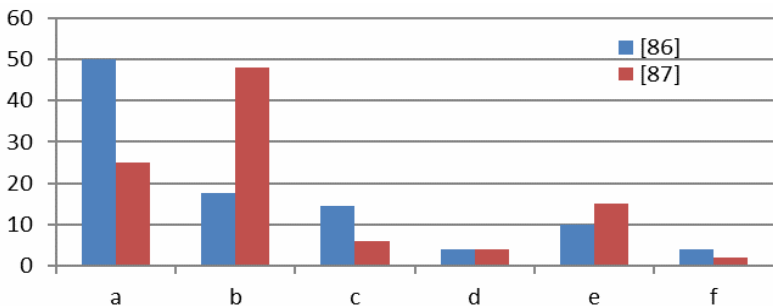


Fig. 11. Cause of accidents in building in percentage following [86, 87]:  
 (a) design errors; (b) manufacturing and installation errors; (c) poor materials quality;  
 (d) shortcomings in codes; (e) incorrect operation; (f) other

After considering various examples of accidents it can be concluded that there are different causes of accidents [88]. The available data are presented in Fig. 11. The difference of these data can be explained, apparently, by lack of statistical data, imperfect methodology for assessing the accidents causes, etc. However, a large proportion of design errors is alarming.

These cases are the lessons that should be learned as the causes and mechanisms of accidents. Methods of structural analysis of roofs to eliminate the possibility of structures failures in the future should also be improved.

#### **4. Modern methods of computation and providing reliability in design of suspension roofs**

Effective solution of the designing problem in modern construction is highly depends on considering of real construction work in the computation and construction.

##### **4.1. Computation methods for stress-strain state evaluation in spatial rod shells formed by threads**

There are various methods for computation of stress-strain state (SSS) of spatial rod shells. Detailed information about it is given in [10].

Analytical computation methods of spatial rod shells lead to solution of problems described by a system of nonlinear differential equations. Solutions of these problems can be implemented using the following methods [23]:

- methods of solution of boundary problem together with the boundary conditions;
- methods of energy functional minimization;
- linearization method.

Particular attention should be paid to the computation of shell structures considering the geometrical and "structural" nonlinearity, because considering of the design scheme that changes during the construction (as built) is required for computation and design.

Numerical computation methods of spatial rod shells have been widely applied due to the rapid development of computer technology. Among them are the finite difference method, finite element method (FEM), the variational-difference method, and others [35]. FEM allows solving problems with the changes in the design scheme. It is important for the large -span structures, which during the construction change the distribution of internal forces, and also the direction of displacements in the main load-supporting elements.

Currently, particular wide application among numerical methods has the finite element method. This is due to a number of important advantages for this case:

- the ability to consider a large number of structural elements with specified analytical models (finite elements) and a wide range of analytic representation;
- boundary conditions and random load can be considered;
- the size and stiffness characteristics of the finite element may be variable, depending on the geometry of the structure, as well as operational and technological characteristics;



- properties of structural elements and materials may be different, that allows to analyze structure with multi-modulus materials.

There are different manufacturing and computation methods for estimating actual design performance of rigid threads with varying degrees of accuracy [10, 24, 25, 89], etc. However, all the above methods do not consider the difference between computation of solid threads as well as threads with through-section. Furthermore, they do not consider the type of lattice, and its stiffness characteristics. It yields forces redistribution in the elements, but particularities in structural behavior under dead and live loads are not fully considered.

#### **4.2. Modern methods for providing reliability of suspension roofs in design stage**

The problem of reliability especially concerns unique large -span structures. Among these are suspension shells that have increased level of responsibility on application denial that may lead to severe economic results and social consequences (as it was discussed in section 3.3). During design there are problems exceeding the limits of existing regulatory documents. Novelty of technical concepts, specific knowledge and experience in design of such kind of structures is required from a structural engineer. Requirements of reliability, technological and economic efficiency should be fully realized in this case, as well as environmental and social factors should be considered.

##### **4.2.1. Requirements of modern codes for providing strength, rigidity and stability of roofs structures and their elements**

Strength, stiffness and stability of suspension roofs and their elements are regulated by current standards [20-22] and provided by computation, performed assuming that entire load is perceived by threads and transmitted to supports. Considering the strength and stiffness of beams is required for determining the roofs deformations and displacements, caused by temporary load.

Computation of the suspension system should include:

- finding the maximum force for all elements under any possible loads combination;
- finding the cross-sections of all elements in the suspension system and supporting structures;
- finding the deformation of the roof and supporting structures under the possible loads combinations;
- verification, if necessary, to special effects: thermal stresses, supports displacement, seismic loads, fatigue, dynamic stability, etc.

The computation is recommended in the following order:

A. Selecting the type and the main parameters of the roof system: spans, supports location, etc. The shape taken by the system under the action of the full design load is determined.

B. Computation of strength.

Forces in the supporting threads and the supporting structures under the full load and the actual roof geometry are calculated. Cross sections of threads are found accordingly. After that, the dimensions of the support structure are assigned.

### C. Computation of deformation.

The computation is required to determine the sections of stabilizing structures that together with the supporting threads provide the necessary stiffness and stability of the suspension roof. It is advisable to separate the deformation to elastic and kinematic. The suspension roof stiffness is achieved by increasing the supporting threads sag and cross section.

The type and section of the stabilizing structures are determined by the terms of the maximum allowable kinematic displacements of the roof under the uneven payloads. After that, verification of the shell stiffness is performed (elastic deflection under the temporary load is determined).

Verification of the supporting structures with the unfavorable mounting load is performed. Computation of the systems and support contour under the uneven temporary load is performed. The analysis of rigid threads is performed in a geometrically nonlinear formulation.

Despite the demands of modern codes for providing strength, rigidity, stability of roof structures and their components, the system of partial reliability coefficients for structures with high responsibility level is not normalized [22]. Therefore, it is most logical to analyze the roof structure using direct reliability theory methods, which can later become a basis for normalization of reliability coefficient for the required level. This method is described in paragraph 4 below.

#### **4.2.2. The methods of reliability theory of building construction in providing reliability requirements at the design stage**

Uncertainty analysis in engineering should ideally be a part of routine design because the variables and supposedly constant parameters are either random or known with imprecision. In some cases the uncertainty can be very large, such as in case of natural actions provoking disasters or modeling errors leading to technological disasters. To estimate the risk of a given engineering problem, cumulative distributions functions (CDFs), defining the input variables, are traditionally used and then, by means of analytic or synthetic methods (i.e. Monte Carlo) the probability of not exceeding undesirable thresholds, is computed [90, 91].

One of the main problems in applying the probabilistic approach is that the CDFs of the input variables are usually known with imprecision. This is normally due to the lack of sufficient data for fitting the model to each input random variable. For this reason, the parameters of the input distributions are commonly known up to confidence intervals and even these are not wholly certain. This hinders the application of the probability-based approach in actual design practice [19]. Even if the information is abundant, there remains a problem of high sensitivity to usually small failure probabilities to the distribution functions parameters [86]. Such a sensitivity is due to the fact that the probability density function estimation from empirical data is an ill-posed problem [87, 92]. This means that small changes in the empirical sample affect the parameters, defining the model being fitted, with serious consequences in

the tails, which are just the most important zones of the distribution functions for probabilistic reliability methods [93, 94].

These and other considerations have fostered the research on alternative methods for incorporating uncertainty in the structural analysis, such as fuzzy sets and related theories [95], anti-optimization or convex-set modeling [96], interval analysis [97], random sets [98], ellipsoid modeling [99,100] and worst-case scenarios [101]. Comparisons have been also made between probabilistic and alternative methods [102] or their combination has been explored [103, 104]. Analytical and computational methods used in the technical reliability theory for computation of complex systems, which can be used for reliability analysis of statically indeterminate systems are shown in Fig. 12.

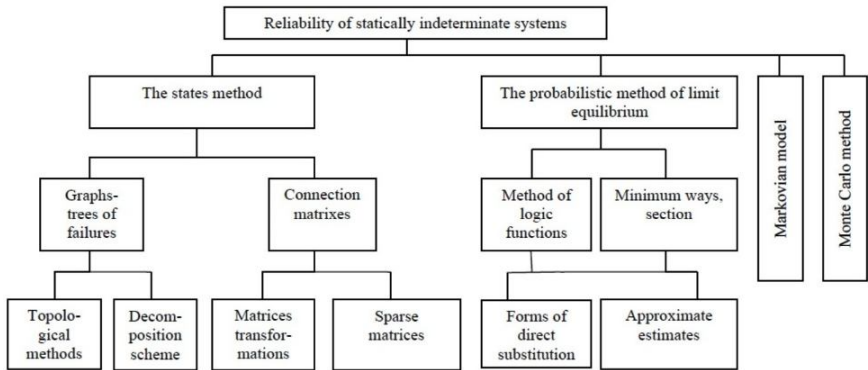


Fig. 12. Methods for assessing the reliability of statically indeterminate systems

In the engineering theory, reliability evaluation of complex systems is usually reduced to examination and analysis of two principal kinds of joints [23]:

a) series connection, failure-free performance 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 performance of component  $i$ ;

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

A special technique of construction reliability level estimation has been developed [10]. This technique is a good example of computing the reliability of large -span roofs, as systems with series of elements connections.

Failure probability of was adopted as the quantitative characteristics to evaluate the reliability of suspension structures [105].

The survivability term should be noted together with reliability. Survivability is the ability of an object to keep (perhaps with a degradation of performance) working condition, even with damage of some parts. The term of construction survivability is directly related with that of sensitivity. As a rule, the last one is used for design purposes. There are various methods for sensitivity analysis, based on certain restrictions and conditions in the algorithm for design of structures using FEM [23]. Therefore, finite element computation algorithm is needed to analyze the survivability and sensitivity of construction. In the investigation of the survivability of the Ice Palace "Luzhniki" roof in Moscow, Russia, failure of individual components was simulated and construction functionality was estimated [10].

### **5. Method of determining the reliability indices at the design stage**

It can be concluded, that current design standards do not contain demands on quantitative estimation of reliability of large -span roofs. Various approaches and structural design concepts, particularly for metal structures, have been significantly developed and justified however, nevertheless, there are no convenient and sufficiently simple methods for determining reliability of parameters for a structures in evident form. Known design solutions, based on ultimate state method, cannot be properly compared by the design concepts' reliability.

The hot topic of providing the required reliability level in design of large -span roofs, in particular suspension roofs and rod shells, in many aspects, determining the efficiency of large -span roofs construction, was considered and approved [24]. The design method of and design work of rigid through section threads based on determining numerical exponents of designed structure reliability has been made (Fig. 14).

The developed calculation and design technique of three-dimensional rod roof with a cut on elliptical basis can consider such problems as assigning the initial geometric parameters of the roof, initial selection of the section with further refinement using a finite elements model under different loading combinations. It also allows numerical calculation of reliability indices for statistically non-determined systems in a form of suspended shell with a big cut

on elliptical plane – a problem that was not considered previously in design methodologies, based on the ultimate state method.

This type of roof corresponds to modern requirements of aesthetics and biomimetic architecture. Suspension rigid threads may be compared with the lianas, whole roof system with the bird's nest, where these lianas are the supporting elements (Fig. 13) [106]

The main load-supporting elements of the roof system: a) external contour, supported by columns or walls of the stadium; b) internal unsupported contour, supported by thrust; c) rigid thread with the form of trusses (Fig. 13).

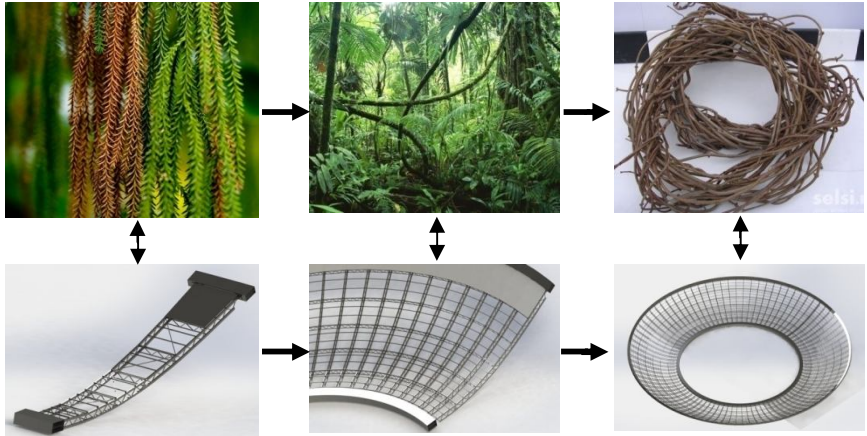


Fig. 13. Long-span suspension roof with rigid threads

The proposed method provides solution for the following problems:

- finding rational geometric parameters of a structure;
- obtaining appropriate rigidity characteristics of basic supporting elements;
- finding a track of elements failure for typical roof diagram with following evaluation of stressed and strained state of the object;
- finding of numerical safety indices of a structure (finding the lower and upper safety limits).

The described method has been applied to obtain the reliability indices of the stadiums roofs of FC «Schakhtar» in Donetsk, Ukraine [24]. It was shown that the obtained values of reliability indices for a roof structure satisfy the European codes requirements [20,22].

A design procedure of roof reliability can be described by a scheme presented in Fig. 14. The values designations of this scheme are shown in Table 1.

The above-described method has also shortcomings. It ignores issues related to the joints' action as part of the shell when calculating the roof reliability level. This issue opens a new research areas. The first steps in this direction were already made [82]. Fundamental approaches for providing reliability of

suspension roof joints by numerical methods were determined. The authors suggest that creation of new computation and design methods for suspension roofs based on recently developed technique [24] will enable to improve the quality of computation methods and increase the reliability and durability of such type of structures. It will be based on the definition of numerical reliability indicators of the designed structure taking into account the performance of joints in the roof.

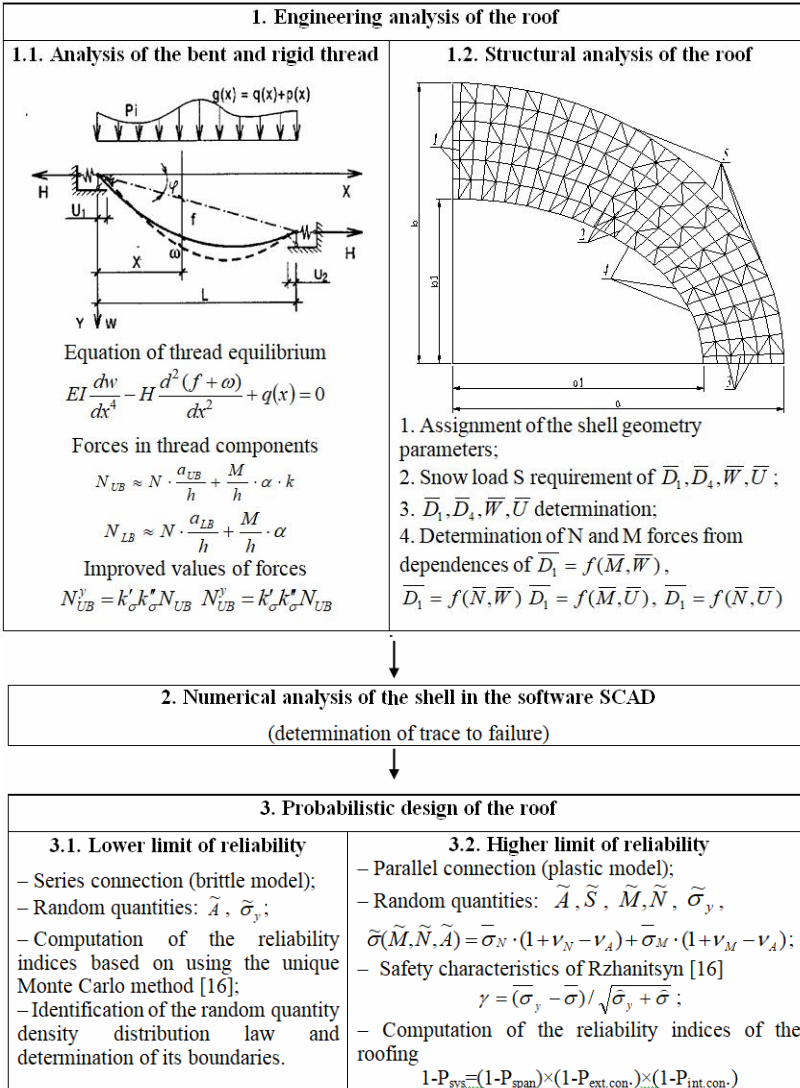


Fig. 14. A scheme for finding the numerical indices of suspension roof reliability

## 6. Results and Discussion

From the above-mentioned procedure the reliability indices of a spatial structural block of shell “G” as a constituent of the section NC of the “Donbas-Arena” Stadium in the city of Donetsk were determined according to the actual fact of the construction [24]. The span of the roof block is a spatial bar shell of a double curvature and variable height. The basic dimensions are: the shell external profile – 59.9 m, the shell internal profile – 31.7 m, the span – 61.2 m. The structure height varies and is 1.99 m – 5.3 – 3.1 m.

From the results of analyses carried out at the maximum normative snow load  $160 \text{ kg/m}^2$  there was fixed the most stressed element, but stress  $\sigma$  in it was therewith  $108 \text{ MPa} < \sigma_r = 440 \text{ MPa}$ . To reach the limiting state of the elements this load was being increased step-by-step and reached  $535 \text{ kg/m}^2$  when the failure tracing of the shell block elements was fixed, see Fig. 15.

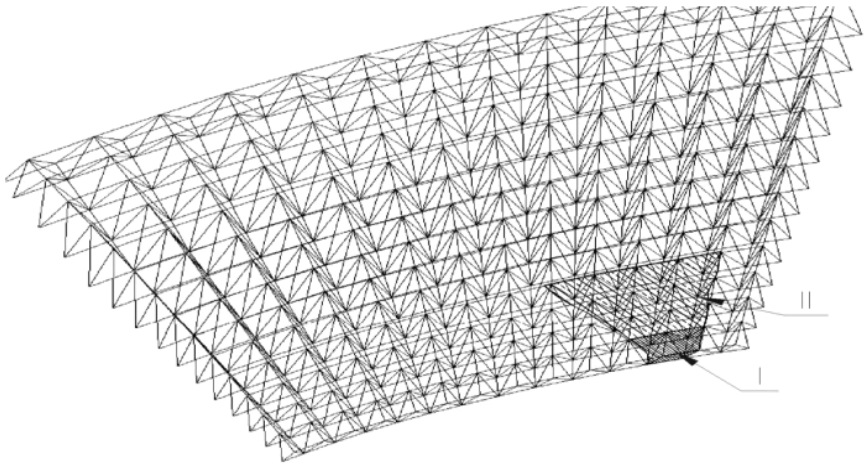


Fig. 15. A shell section being failed [24]:  
(I) a ruptured zone of the shell; (II) a predicted zone of the next failure of the shell

## 7. Conclusions

The paper reviews the latest issues and developments in suspension roofs, touches upon the historical perspective. It particularly addresses the latest design trends and concepts as well as ways for providing reliability of suspension roofs.

The proposed method provides solutions for the following problems: obtaining rational geometric parameters of a structure; finding appropriate rigidity characteristics of basic supporting elements; determining the elements failure trajectory for typical roof diagram with the following evaluation of stress - strain state of a structure; calculating numerical safety indices of a structure (determining the lower and upper safety limits).

The method enables to find the zones, where failure will be initiated. It offers an opportunity to create additional strength and reliability of structures, located in dangerous places, such as bearing joints of the connecting trusses to

external contour and internal contour, the braces to the lower chord of the trusses, intermediate joints of upper and lower chords of supporting trusses etc., at the stage of design and construction.

Large-span roofs have increased liability level, since their failure can lead to severe economic and social consequences. In this case, the design of these unique structures should be based on complex approach for selecting the rational structural concept related to the structure's function, architectural concept, manufacturing methods, construction, etc. Reliability requirements, adaptability to manufacture, economic efficiency, ecological and social factors should be also fulfilled.

Young engineers should be inspired by the great structural forms of the past and be encouraged to study more works from our generation to spark improved designs in the future.

Based on the above, we can recommend to young researchers the universal algorithm, based on:

- preliminary computation;
- analysis of survivability;
- design according to the limit states requirements;
- design based on the numerical reliability indicators.

It will allow improvement of computation methods quality and more accurate analysis of roof structures. Using this approach also leads to increasing of reliability and durability of such types of structures and minimizes mistakes in design and computation.

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#### **A NEW APPROACH TO THE DESIGN OF SUSPENSION ROOF SYSTEMS**

Over the last century, the suspension roofs design has progressed until the advent of the shells theory in the first half of the 20th century, due to a rapid pace in technological advancement. A paradigm shift emerged with the new trend in structural design towards a new design process that cooperatively integrated economy, efficiency, and elegance. Different approaches in computation, design and reliability assessment of roof structures are discussed in this work to identify the key conditions that have significantly contributed to modern suspension roof design principles.

A new algorithm to assess the reliability of suspension roofs at the design stage is proposed and a novel method for computational design and reliability evaluation of suspension roofs is presented in this paper.

The proposed method provides solutions for the following problems: obtaining rational geometric parameters of a structure; finding appropriate rigidity characteristics of basic supporting elements; determining the elements failure trajectory for typical roof diagram with the following evaluation of stress - strain state of a structure; calculating numerical safety indices of a structure (determining the lower and upper safety limits).

The method enables to find the zones, where failure will be initiated. It offers an opportunity to create additional strength and reliability of structures, located in dangerous places, such as bearing joints of the connecting trusses to external contour and internal contour, the braces to the lower chord of the trusses, intermediate joints of upper and lower chords of supporting trusses etc., at the stage of design and construction.

Large-span roofs have increased liability level, since their failure can lead to severe economic and social consequences. In this case, the design of these unique structures should be based on complex approach for selecting the rational structural concept related to the structure's function, architectural concept, manufacturing methods, construction, etc. Reliability requirements, adaptability to manufacture, economic efficiency, ecological and social factors should be also fulfilled.

Young engineers should be inspired by the great structural forms of the past and be encouraged to study more works from our generation to spark improved designs in the future.

Based on the above, we can recommend to young researchers the universal algorithm, based on:

- preliminary computation;
- analysis of survivability;
- design according to the limit states requirements;
- design based on the numerical reliability indicators.

It will allow improvement of computation methods quality and more accurate analysis of roof structures. Using this approach also leads to increasing of reliability and durability of such types of structures and minimizes mistakes in design and computation.

**Keywords:** suspension roof, stress-strain state, computational methods, reliability indices, roof failure.

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### **НОВИЙ ПІДХІД ДО ПРОЕКТУВАННЯ СИСТЕМ ПОКРИТТІВ ВИСЯЧОГО ТИПУ**

Протягом останнього століття проектування підвісних покриттів інтенсивно розвивалося до появи теорії оболонки у першій половині 20-го століття, завдяки швидким темпам технологічного прогресу. Зміна парадигми виникла з новою тенденцією в структурному дизайні до нового процесу проектування, який швидко об'єднав економіку, ефективність та елегантність. У цій роботі розглядаються різні підходи до обчислення, проектування та оцінки надійності конструкцій висячих покриттів, щоб визначити ключові умови, які суттєво сприяли появі сучасних принципів утворення конструктивної схеми висячого покриття.

В цій роботі запропоновано новий алгоритм оцінки надійності висячого покриття на стадії проектування, а також новий метод розрахунку та оцінки надійності висячого покриття.

Запропонований спосіб пропонує рішення наступних завдань: отримання раціональних геометричних параметрів споруди; знаходження відповідних характеристик жорсткості основних опорних елементів; визначення траєкторії відмови елементів для типової схеми покриття з певною оцінкою напружено-деформованого стану конструкції; обчислення числових показників безпеки споруди (визначення нижньої та верхньої меж безпеки).

Метод дозволяє знайти зони, де буде починатися руйнування. Пропонується створити додаткову міцність і надійність конструкцій, розташованих в небезпечних місцях, таких як вузли з'єднання несучих ферм до зовнішнього контуру і внутрішнього контуру, в'язи до нижнього поясу ферми, проміжні вузли з'єднання верхніх та нижніх поясів несучих ферм тощо, на етапі проектування та будівництва.

Великопрольотні покриття мають підвищений рівень відповідальності, оскільки їх відмова може призвести до серйозних економічних та соціальних наслідків. У цьому випадку проектування цих унікальних споруд має базуватися на комплексному підході до вибору раціональної конструктивної схеми покриття, пов'язаної з функцією конструкції, архітектурною концепцією, способами виготовлення, будівництвом та інше. Вимоги до надійності, адаптованості до виробництва, економічної та екологічної ефективності, а також соціальні фактори повинні виконуватися.

Молодих інженерів слід надихати великими конструктивними формами минулого і захочувати вивчати більше робіт нашого покоління, щоб ініціювати вдосконалені проекти в майбутньому.

Виходячи з вищесказаного, ми можемо рекомендувати молодим вченим універсальний алгоритм, заснований на наступному:

- попереднє обчислення;
- аналіз живучості;
- проектування відповідно до вимог граничних станів;
- проектування на основі числових показників надійності.

Це дозволить покращити якість обчислювальних методів та отримати більш точний аналіз конструкцій покриттів. Використання цього підходу також призводить до підвищення надійності та довговічності таких типів конструкцій і мінімізує помилки в проектуванні та обчисленнях.

**Ключові слова:** висяче покриття, напружено-деформований стан, обчислювальні методи, показники надійності, руйнування покриття.

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*Розглядаються різні підходи до обчислення, проектування та оцінки надійності конструкцій висячих покриттів. Запропоновано новий алгоритм оцінки надійності висячого покриття на стадії проектування та новий метод розрахунку висячого покриття.*

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*Рассматриваются различные подходы к вычислению, проектированию и оценке надежности конструкций висячих покрытий. Предложен новый алгоритм оценки надежности висячего покрытия на стадии проектирования и новый метод расчета висячего покрытия.*

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