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Review

Thin sheet metal suspended roof structures

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A B S T R A C T

Metal membrane suspended roofs are used considerably less than other type of suspended roofs. Russia possesses an undoubted priority in this type of structures. At present time, all theoretical and practical problems are solved, but in spite of this, few design offices and project organizations would undertake the design and supervision of construction of large-spanned membrane metal suspension roofs. In the paper, brief information on the history of emergence of metal suspended roofs is presented, and general information on structural features of membrane roofs is given. As illustrations, the most outstanding membrane roofs erected in Russia are shown and description of some existing tension fabric membrane structures built in Austria, Canada, Japan, China, and other countries is presented.

1. Introduction

Membrane roofs of large dimensions are very complex structures both from a point of view of forming and analysis and from a point of view of their erection and maintenance. Combination of load-bearing and protecting functions in the same material is a distinctive feature of membrane roofs as compared with other types of suspended structures. At the same time, membrane roofs require the greater expenditure of metal than cable-stayed structures. The Central Research Institute of Building Structures (TzNIISK im. V.V. Kucherenko, Moscow) initiated the mass introduction of membrane roofs in the practice of construction in Russia. A group of specialists of ZAO “Kurortproekt” (Moscow) under the leadership of N.V. Kanchely worked out the main units and details of membrane roofs. As a result, all theoretical and practical problems of arrangement of the thin sheet metal suspended roof structures were solved, for example, folds appearing in the angle zones of membrane roofs were liquidated. It was proved that steel membrane roofs can serve accident-free for a long time in the Russian climate even under great design snow load in winter.

Economic efficiency of membrane structures increases with increase of span. However, at present time, few design offices and project organizations would undertake the design and construction supervision of large-span membrane metal suspension roofs and strip coverings, although all theoretical problems are solved.

2. General information and definitions

Metal membrane suspended roofs [1] or simply *membrane roofs* are spatial structures consisting of *thin metal sheet* and *rigid support contour*. A thin sheet possesses small flexural rigidity, and that is why it works only in tension, hence, membrane roofs can be considered as suspended structures. In *suspended structures* external load is carried by cables (wire ropes) [2], chains and stays [3], standard (rolled) sections and sheet membranes [4]. Some architects also consider tent [5,6] and air-supported pneumatic structures as membrane roofs [7,8]. Structures, called “membrane roofs” in Russia, are called “*tensile metal membrane roofs*” in other countries. *The drop shaped metal reservoirs* can also be considered as *membrane structures* but not as suspension structures.

The Russian “Recommendations for Design of Membrane Roofs on Rectangular Plans for Reconstructed Buildings and Structures” [9] notes that membrane system is a spatial structure made of thin metal sheet fixed on the contour. The main advantages of membrane structures are reduction of material consumption from 10% to 75% [10] due to the spatial work of thin steel sheet in tension and due to the combination of bearing and isolating functions in the same material, reduction of working hours of their manufacturing and erection from 5% to 70%, reduction of cost from 7% to 65%, reduction of time of building due to the application of large-size rolled panel of factory making, considerable reduction of dead weight of the covering, comparative simplicity of their assembling, the opportunity of covering of considerable spans without intermediate supports. Membrane roofs have additional advantages in comparison with traditional structures in the cases of reconstruction in constrained conditions of a functioning enterprise.

According to the method of erection of membrane roofs, they are divided into two types: strip membranes and membrane shells. *Strip membranes* are formed by separate strips that are not interconnected and work like single-layer cable structure [11]. More rigid systems

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made of strips interweaved in the two mutually perpendicular directions are also attributed to this type. In *membrane shells,* the separate strips are connected in a continuous space structure by means of welding, high-strength bolts, or rivets, and this thin-walled structure can carry shearing forces. So, membrane shells possess greater bearing capacity and rigidity in comparison with strip membranes and require less amount of materials for a span structure. Membrane shells can have a form of surfaces of zero Gaussian curvature (cylindrical and conical); positive Gaussian curvature (spherical and in the form of elliptical paraboloid), and of negative Gaussian curvature (hypar).

The term “*membrane shells*” often means that the shells are analyzed according to a membrane (momentless) theory of shells [12].

3. Some structural features of membrane suspended roofs

In Russian building practice, *two methods of erection of membrane roofs* are used. According to the first method, steel panels forming the membrane are laid out and connected together on the horizontal surface on the ground level, and after this, the whole membrane is lifted up to the project position. According to the second method, separate panels are lifted up and laid out to the project position on the scaffolding bed frame (Fig. 1, a). Steel strips, beams, or light suspension trusses are located along the directions of lines of principle curvatures and fix the designed geometrical form of the roof surface. Simultaneously, the guide elements of the bed ensure the stabilization of the roof.

Membrane roofs and cable systems are stabilized by putting additional load on the roof. The choice of a method of stabilization of the membrane roof is governed by the type of membrane roof, its dimension, by the form of its plan, and by the design of the support contour.

Cylindrical membrane needs stabilization of the surface like no other type does, but this form is sufficiently stable when the membrane edges are connected to the support contour along the whole perimeter, and the self-weight of the membrane is of the same order of magnitude as the snow load. Usually, cylindrical surfaces are taken for membranes on rectangular plans. Loading of plane membrane with rectangular plan

a

b

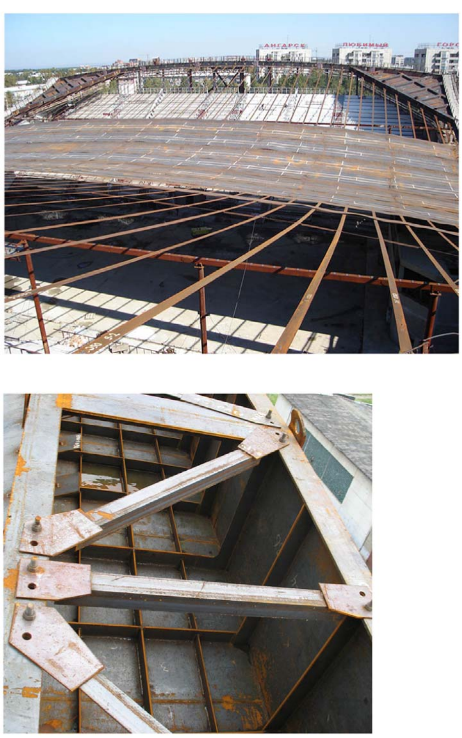

Fig. 1. Ice Palace of Sport “Ermak” in Angarsk (Russia) in the process of building. a) Lay of the steel panels on the temporary elements of the bed. b) The support contour before placement of concrete.

to its design form yields buckling of the sheet in the corners and formation of folds. The formation of folds can be prevented by arrangement of brackets of considerable extent in the angles (Fig. 1, a) or by prestressing of single-layered membrane. Prestressing is the most effective process of stabilization of membrane roof structures but it leads to complication of erection work and to increase in inner forces.

Forms of tensile membrane structures cannot be arbitrary selected, therefore, the first step of designing these structures is to determine surface that satisfies static equilibrium equations and architecture need [13].

Suspended membrane roofs on the round plan are the most efficient type of membrane roofs. The form of the middle surface of the shell is defined by the geometry of the bed on which the membrane is assembled. Bearing capacity of membrane roof increases when concavity of the membrane is increased. A membrane meridian has the form of the second order parabola if elements of the bed and rectangular panels of membranes are placed mutually perpendicularly to each other [14]. A membrane meridian has the intermediate form between quadratic parabola and cubic parabola under radial-and-circular arrangement of the elements of the bed in the plan and if the membrane panels have trapezoidal form [14]. Membranes on the round plan can have also the form of spherical or cone surface. Conical membranes are rational if an external force is imposed at the vertex of a cone or along the perimeter of tensile inner ring. Conical membranes are considerably less rational in comparison with spherical membranes under the action of uniformly distributed load. Conical membranes are recommended to use when spans are less than 60 m. The opportunities of spherical membranes are considerably wider.

Supporting contour taking up large forces from membrane and passing them to the supports and foundations is of great importance (Fig. 1, b). Depending on the form of the structure, supporting contour can be plane or spatial, rectilinear or curvilinear, closed or opened, propped up along the length or free from span supports. The cost of supporting contour can make up considerable part of the whole cost of a suspended roof. The process of defining shape of a structure under tension is a very important and difficult action. Minimal surfaces for suspended tensile membranes with spatial curvilinear contours are the most preferable [15] but they are difficult of realization. Lewis in his book [16] discusses the role of stable minimal surfaces in finding optimal shapes of suspended tensile membranes. Philipp et al. [17] studies the form-finding for the catenoid membrane.

Tusnin and Kondrashov [18] state that membrane structures on rectangular plan with inner supports provide considerably wider opportunities of for the design of new types of buildings. The main idea of such structures is redistribution of loads from the support contour that is in complex stress state on inner supports. Basing on the fundamental solution, the dangerous places of the structure have been detected. The largest stress jumps occur at the points of connection of steel sheets to metal columns. These stress concentrations lead to the necessity of strengthening the places of leaning. “It is necessary to pay special attention to the method of fixing of separate panels of the membrane roof between themselves. The membrane thickness is several millimeters. Welding, high-strength bolts, and rivets are the most wide-spread methods of connection. The panels are jointed in continuous space structure that resists the shearing forces. But welding of the elements of such small thickness is rather difficult and, in addition, the temperature actions can be a reason of formation of local buckling zones. If bolted connections are used, the water proofing of the joints becomes the most important problem. Special waterproofing strips are inserted between the two steel sheets at the joint of the two membranes increasing the friction coefficient when high-strength bolts are tightened. A double-sided mounting tape can also be used providing the necessary level of water proofing (typically for the structures with small column spacing)” [18].

The experience of building membrane structures has shown that they can successfully compete with other metal structures at small and