Chapter 5
Ribbed Domes

5.1 Introduction

The examples of ribbed domes designed by the eminent architects: Neumann B., Weinbrenner F., Moller G. are described in Chap. 3. They introduced to the Western-European building trade the load-bearing systems, still imitating the scaffoldings to build masonry vaults, but also such systems in which separated meridional and latitudinal load-bearing systems already appeared. The impact of the stiffness of the plank floor on the load capacity of the system was omitted considering it to be slight in comparison to the main structure of meridional ribs and latitudinal bracings.

Moller G. (Fig. 3.23), while using the arch centre known for centuries and eliminating the bar systems supporting it, designed in the middle of the 19th century the first modern, ribbed load-bearing system of a dome. By introducing the latitudinal stiffenings, he applied the division of the structure into meridians and lines of latitude. He proposed a legible structural system corresponding to the distribution of forces in the dome, also facilitating the static calculation of load-bearing elements.

5.2 Ribbed Domes Built in Switzerland and Germany

The G. Moller's idea was perfected in successive realizations of many facilities crowned with domes. Shown in Fig. 5.1 is a facility covered with a dome, built in Bern in 1914 for the World Food Products Exhibition. The dome's diameter as measured at the floor level totals 31.0 m. The meridional load-bearing arches were made as full-wall arches from planks. The dome was placed at the height of 22.0 m, on a wooden supporting crown backed on four arches (Fig. 5.1). Each arch starts the adjacent side bay of a 18.0 m span. The photograph of the construction from the paper [1] is shown in Fig. 5.1.

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Fig. 5.1 Food products hall at the national exhibition in Bern in 1914 [1]

Figure 5.2 presents the structure of the dome of the hall in Geißweid near Singen made at the beginning of the 20th century using a light Kallenbach's structure.

In the structure presented in Fig. 5.2 the meridional load-bearing ribs were made from flat-arranged planks, glued into an I-section. The supporting piers of arches

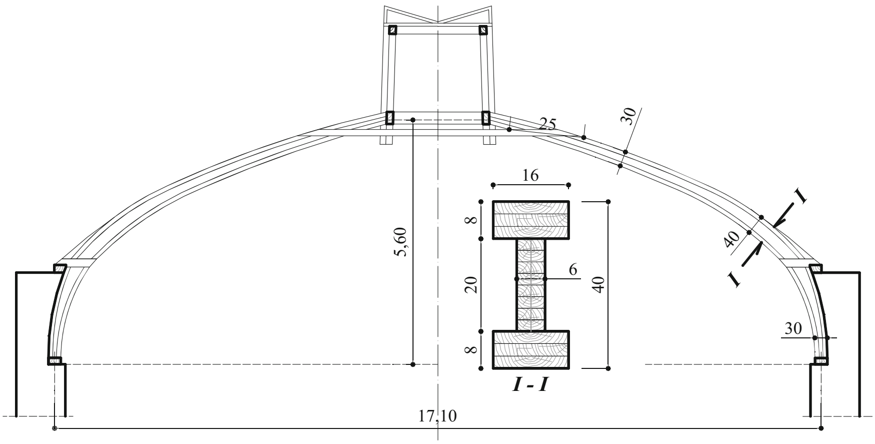


Fig. 5.2 Ribbed dome of a 17.10 m diameter according to the Kallenbach's system [1]

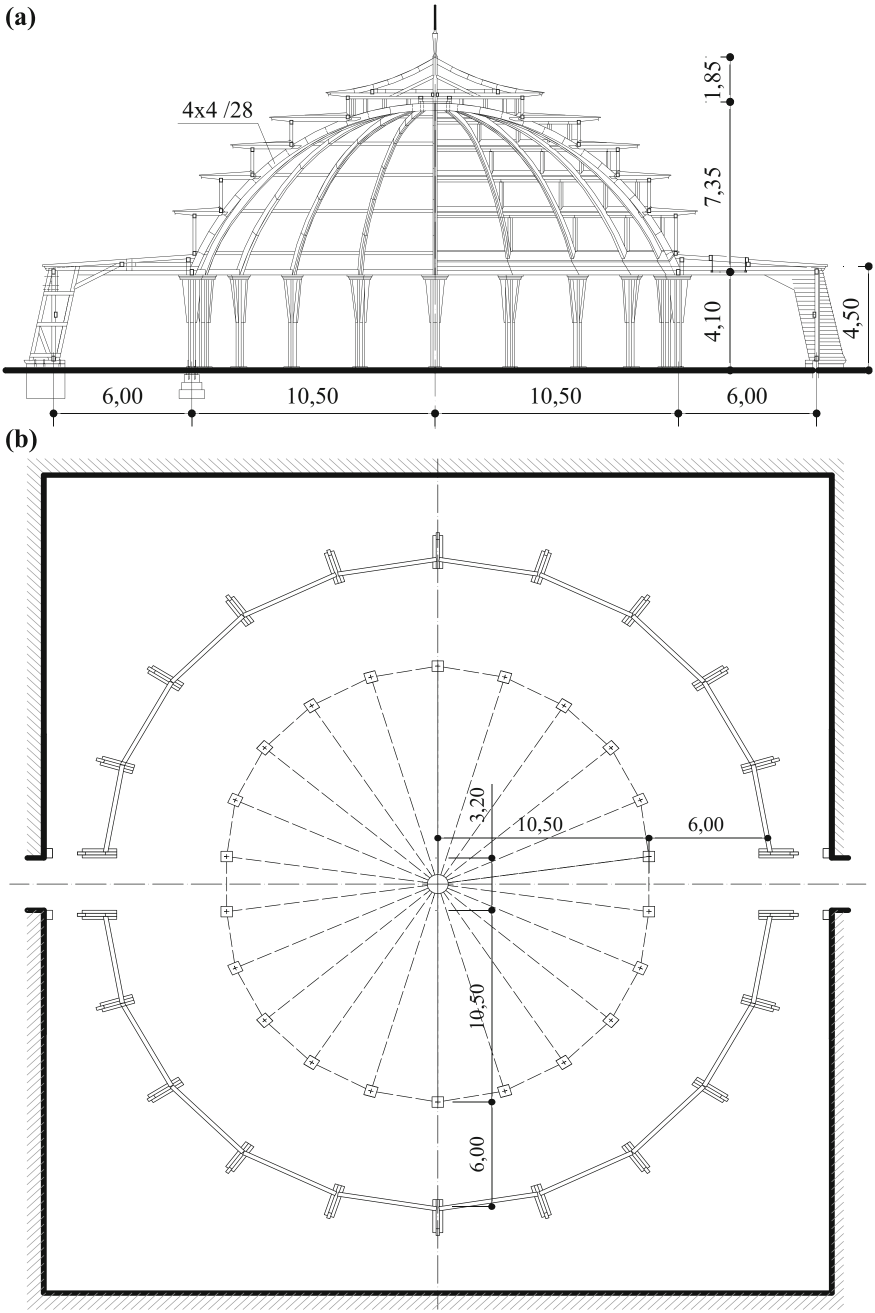


Fig. 5.3 Dome by Hatz F. from 1925 in Munich according to [1], **a** vertical section, **b** projection at the level of the ground floor

were made from concrete reinforced with steel bars. In the supporting section the wooden ribs were reinforced with laps from cast iron. In the static calculations the load of 160 kg/m^2 for own weight, that of snow and wind, including 60 kg/m^2 for own weight itself was assumed. **The characteristic feature of this structure is the use of load-bearing ribs from glued planks forming an I-section**.

The Mail Coaches Hall of an oval dome's horizontal projection is presented in Fig. 5.3. The facility was built by Franz Hatz in 1925 on the occasion of the German Communications Exhibition in Munich. On the ground storey of the building, at the height of 4.10 m (Fig. 5.3a), a dome was situated, having a ribbed structure and a horizontal elliptic projection. The diameters of the ellipse total 21.0 and 24.20 m, respectively, the height from the supporting ring to the upper plate that connects the meridional ribs is 7.35 m.

Twenty-two load-bearing ribs were based on the lower supporting crown made at the height of 4.10 m. At the height of 11.85 m the meridional ribs were connected using a ring-shaped plate from planks. In his paper [1], Kersten C. does not describe the structure of such a board. Boards from planks used as a stiff node, connecting the meridional ribs of ribbed domes, were made familiar from the description by the engineer Kashkarov K. P. in his paper [2] and discussed in Sect. 5.3 following the example of the dome in Baku of 1930.

The additional lighting system and the concentric rings of the casing visible in the section in Fig. 5.3a resemble the section of the Centennial Hall in Wroclaw described by Niemczyk E. in his paper [3] (1997).

5.2.1 Ribbed Domes Built in Russia

In the thirties of the 20th century, the largest domes from solid, and not glued laminated timber were built in Russia. Shown in Fig. 5.4 is the location of just two of them. To reach the paperwork of other facilities ended with a failure.

In 1930, a ribbed dome of the circus-theatre was built in Baku, having a projection's diameter of 67.0 m and a height of 27.0 m [1] (Fig. 5.5). The subtle structure of the dome was reconstructed on the basis of the paper [2], and shown in Fig. 5.6.

The author of the design project was the engineer Kashkarov K. P. The lower supporting ring was made at the height of the second floor of the building. The supporting ring taking over the dome's strutting was connected with the reinforced concrete structure of the ceiling above the 2nd floor. The main gate of the theatre's stage, shown in the section (Fig. 5.5a, h) infringes the symmetry of the dome, at the same time, it constitutes a framework that increases the stability of the dome. Meridional load-bearing arches A were eliminated over the length of the lock of the stage's portal, replacing them with a cylindrical structure based on that of the stage through the intermediary of shorter arches B. The transverse arches are based on shortened lattice arches B, transferring the reactions onto the columns of the stage's

Fig. 5.4 Location of the largest domes from solid wood built in Russia in the thirties of the 20th century

portal. The lay-out of main ribs A and B is shown in Fig. 5.5c. Two arches B are based on the columns of the stage's portal.

Twenty-one main arches A (Fig. 5.6a, b) were disposed along the lower ring every 8.09 m and connected in the key block using the central, multi-layer upper plate shown in Fig. 5.5f, g. The arches A have the form of an arch of bipolar coordinates. The maximum height of the section in the middle of the length of the main meridional arch totals 1.50 m, the width 30.0 cm. The supporting section of the arch has the dimensions of A 30 × 40 cm. The ratio of the maximum height ratio of the main rib h = 1.50 m to the dome's diameter L = 67.0 m is $\frac{1}{45}L$. The lower and upper chords of the section of the meridional load-bearing ribs A and B were made from 5.0 cm thick planks—the upper chord, from four thick planks—the lower chord from five planks (inside chord—Fig. 5.5i). On the whole, the upper chord was made of 20 × 30.0 cm dimensions, and the inside lower chord of 25 × 30.0 cm dimensions. Duplicated posts and crossheads of a 2 × 5 × 8 cm section were inserted between the layers of the chords.

The intermediate ribs were built from three 10 cm wide and 4.0 cm thick planks, which yielded the total height of the rib of 12.0 cm. The meridional intermediate ribs, required in building of the plank shell of the sheathing were disposed on the latitudinal nodes of the stiffening ribs shown in of the dome's projection 5.5f.

The meridional structure was stiffened horizontally with two latitudinal stiffening chords. The one being latitudinal with parallel chords connected with cross braces, the other having parallel chords with angle braces conducted to the section of the crossing with intermediate meridional ribs, called a brace chord. The view of a brace girder is shown in Fig. 6.13. The latitudinal girders: truss girders and brace girders were connected in nodes with load-bearing ribs. A covering was assembled to the latitudinal girders. The upper ring connecting the meridional ribs A and

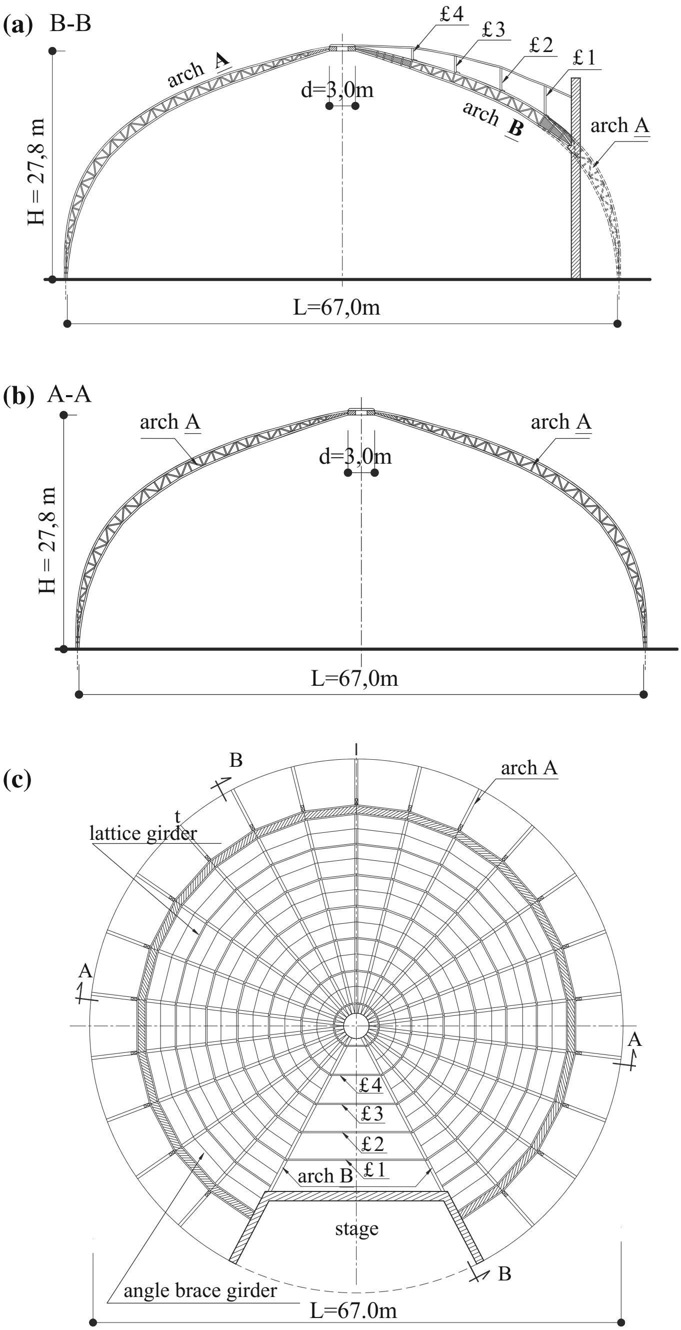
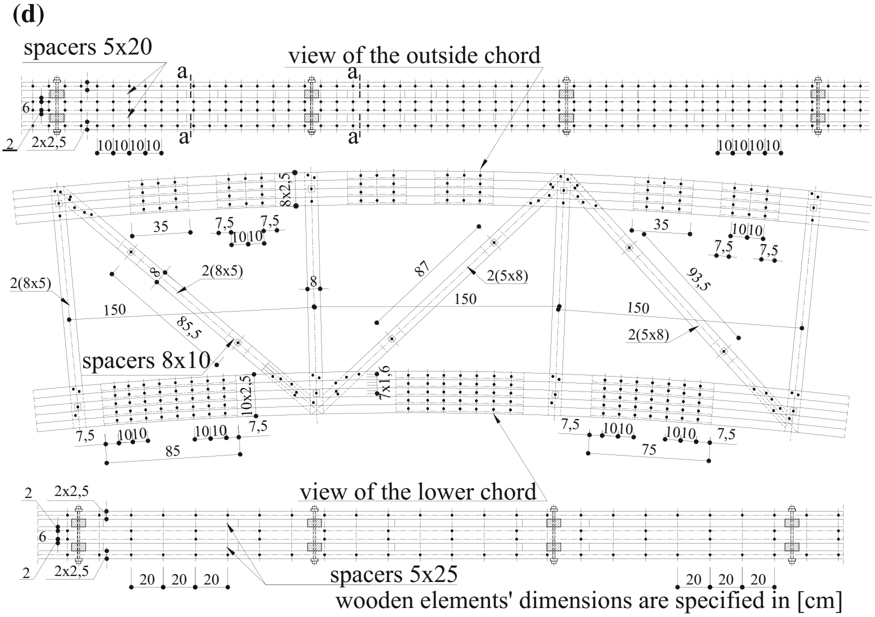


Fig. 5.5 Structure of the Baku dome according to [2], **a** section B-B with the view of meridional arches A and B, **b** section A-A, **c** projection of the dome's structure, **d** structure of the meridional load-bearing rib, **e** structure of the supporting node of the meridional load-bearing rib, **f** structure of the dome's upper plate connecting the meridional ribs, **g** section of the dome's upper ring, **h** view of the reconstructed dome, **i** visualization of the dome's main meridional arch A of a 67.0 m diameter



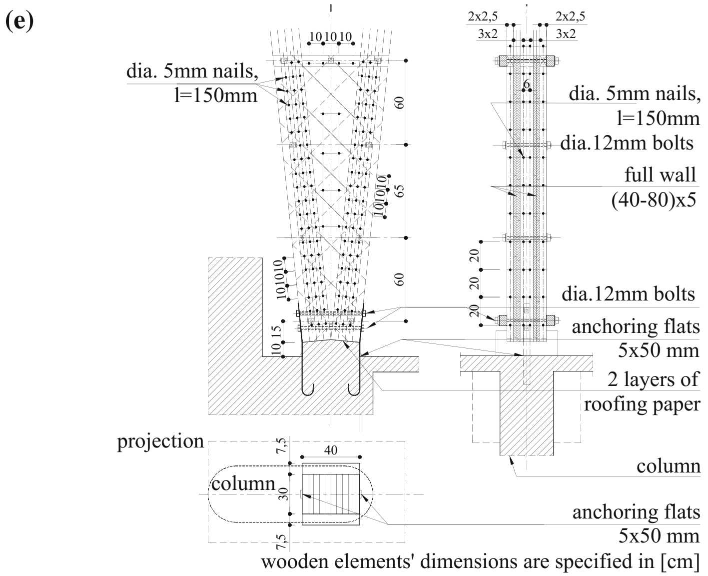
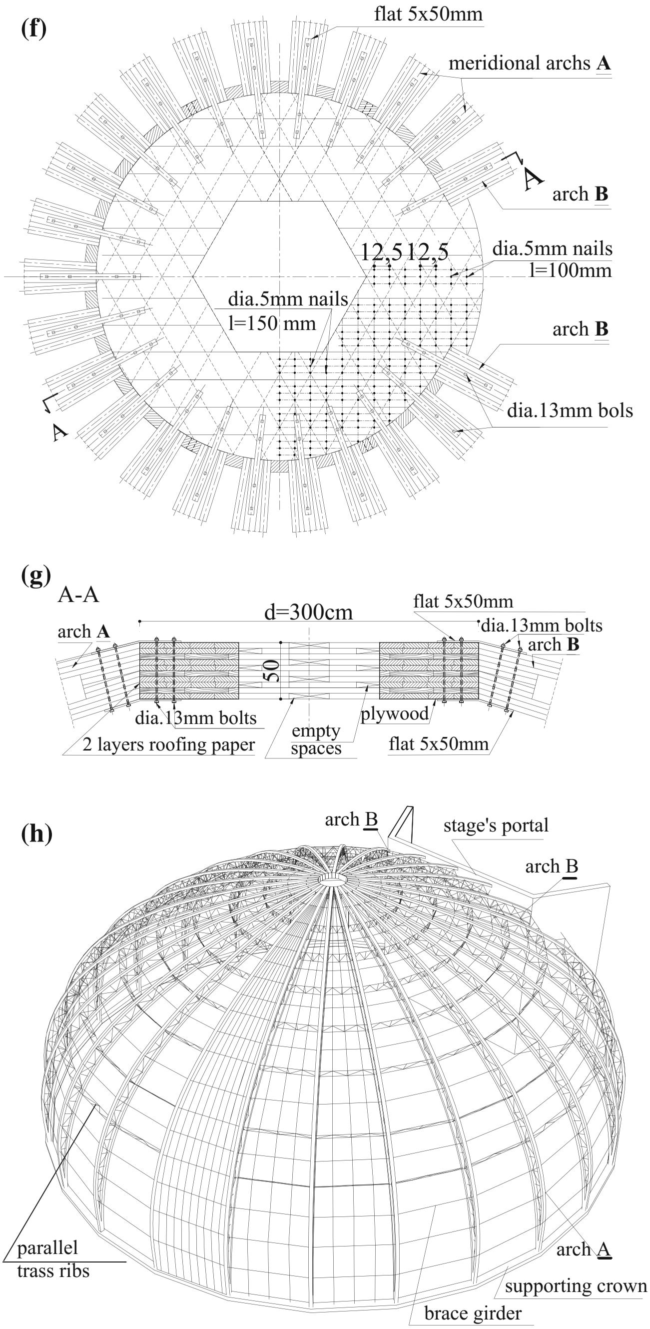


Fig. 5.5 (continued)



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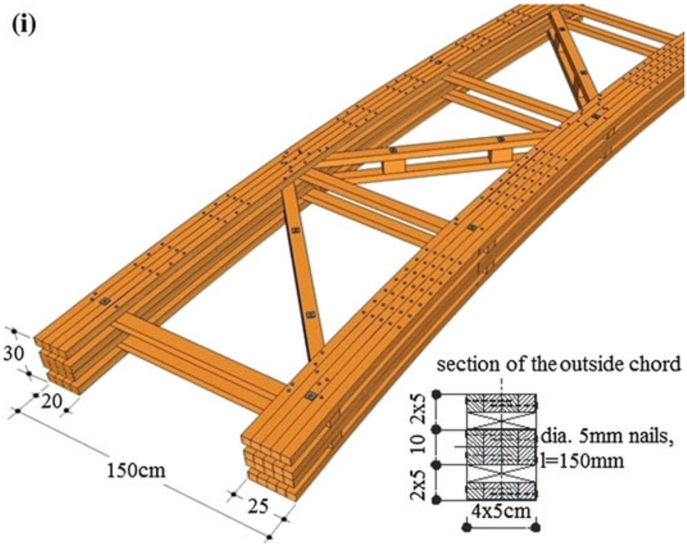

Fig. 5.5 (continued)

B was connected in form of a stiff disk of a 3.0 m diameter, made up of 10 layers of crossed 5.0 cm thick planks. The construction of the ring is shown in Fig. 5.5f, g. It is essential that in the plate of the upper ring empty spaces in various layers and directions have been left as ventilation openings ensuring the exchange of air and moisture on the dome's outside.

The roof sheathing was made from planks in several layers. 2.5 cm thick planks of the first layer were nailed on the outside of the meridional ribs and from below (on the dome's inside) onto the chords of 10 cm wide and 12 cm high latitudinal ribs. The chords of latitudinal ribs jointly with the covering formed a box panel. An inclined roof covering from 1.9 cm thick planks, arranged with an inclined chord over all the arches A, was nailed onto the outside layer of the covering from 2.5 cm thick planks. This is the first example described in the reference literature of the application of box panels from wood as a load-bearing partition constructed to transfer climatic loads.

To connect planks from which the dome's structure (Fig. 5.5) nails of a 5 mm diameter and 150.00 mm long were used. **The consumption of steel for fasteners as calculated per square metre of the dome's projection did not exceed 2.0 kg. Such low consumption of steel for fasteners is not encountered in the presently built wooden structures**. The largest steel fastener used in the node of the lattice construction of meridional ribs are steel bolts of a 12 mm diameter. The steel flats shown in Fig. 5.5d, e connecting the multi-layer upper plate with the meridional load-bearing ribs of the dome were laid on the wooden element. **The most laden supporting sections of bars were embraced with 5 mm thick, 5.0 cm wide metal sheet (uncut)**.

An essential issue associated with the discussed domes from solid wood is the ventilation of the structure. Enormous importance was attached to the correct ventilation of elements from wood. Solutions of the exchange of air in the dome's structure are specified in the description of the Baku dome included in [2]. The figures of the ventilation of meridional arches 5.6a and latitudinal arches 5.6b were compiled according to them. After a closer perusal it is visible that **ventilation ducts along meridians and lines of latitude were built from planks, in a position corresponding to the main ribs of the structure. The dome was covered on the outside with a network of ventilation ducts helping to maintain the thermal and moisture conditions favourable for wood**. Since the durability of the facility depended on the proper ventilation of all wooden elements, especially of the load-bearing structure. The solution of the ventilation of the load-bearing ribs of the Baku dome, built in the thirties of the 20th century is shown in Fig. 5.6.

The method of the drying ventilation of the main ribs of the Baku dome is worth propagation also in the contemporary wooden structures, not only of domes from wood.

In the thirties of the 20th century, steel entered into a broad application in the building trade. The new material was also eagerly used in wooden structures. One of the first examples of the application of steel in the wooden building is the structure of the Ivanovo dome.

The dome of the circus in Ivanovo, Russia, designed by the engineers Minofiev S., Lopatin B., [4] was built from solid wood in the years 1930–1931. The dome has a diameter of the projection of 50.0 m and the height from the floor to the key block of 24.80 m. On the basis of the information from the papers [2, 5, 6], the figures of the dome's construction were reconstructed (Fig. 5.7) and its computer visualization was compiled (Fig. 5.8).

The dome was built from thirty-two ribs disposed along the meridians.

The assembly of the dome followed using a tower situated in the middle of the horizontal projection. In the building process of the dome in Ivanovo, the strengthening of the assembly tower with inclined posts was used (Fig. 5.7) in order to reduce the horizontal forces acting on the central tower. The assembly of main ribs followed pair-wise on the one and the other side of the tower. The one-sided assembly of more than one half-arch was not permitted.

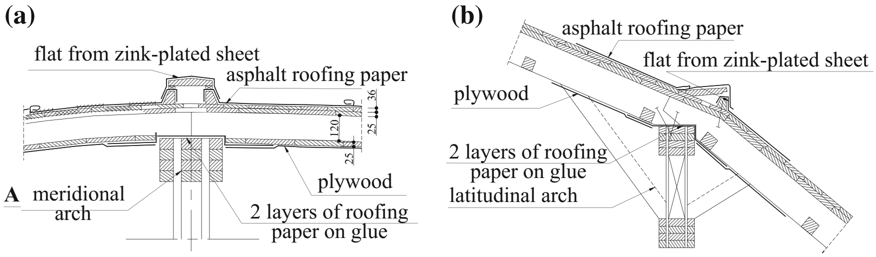

Fig. 5.6 Examples of the ventilation of load-bearing arches in the Baku dome according to [2], **a** ventilation of the main arch A, **b** drying opening on latitudinal girders

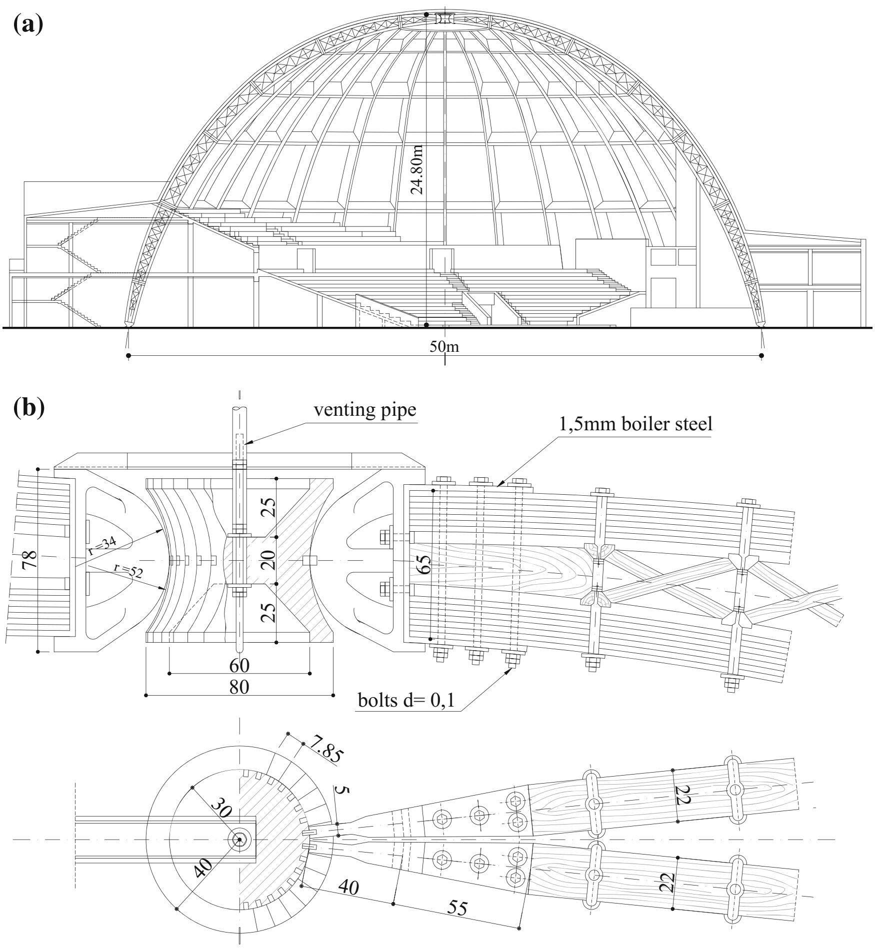

Fig. 5.7 The ribbed Ivanovo dome of a 50.0 m diameter [5, 6], **a** section of the dome, **b** upper steel node connecting 32 ribs of the dome, **c** supporting node of each rib, **d** fragment of the truss of the dome's rib, **e** node to connect cross braces with the chords in the truss of the dome's load-bearing rib

The number of main ribs was determined on the lower supporting crown by dividing the circumference of the dome's projection into circa 4.91 m long sections. The outside chords of bipolar meridional ribs were built from seven 25 mm thick and 220.0 mm wide planks. The planks of the chords were connected using steel clamps, twisting them with steel posts and connecting with wooden crossheads (Fig. 5.7b, d). The multi-layer outside chords of the lattice rib were connected using posts. Crossheads from quarterings as in Fig. 5.8 were built in the field between the posts.

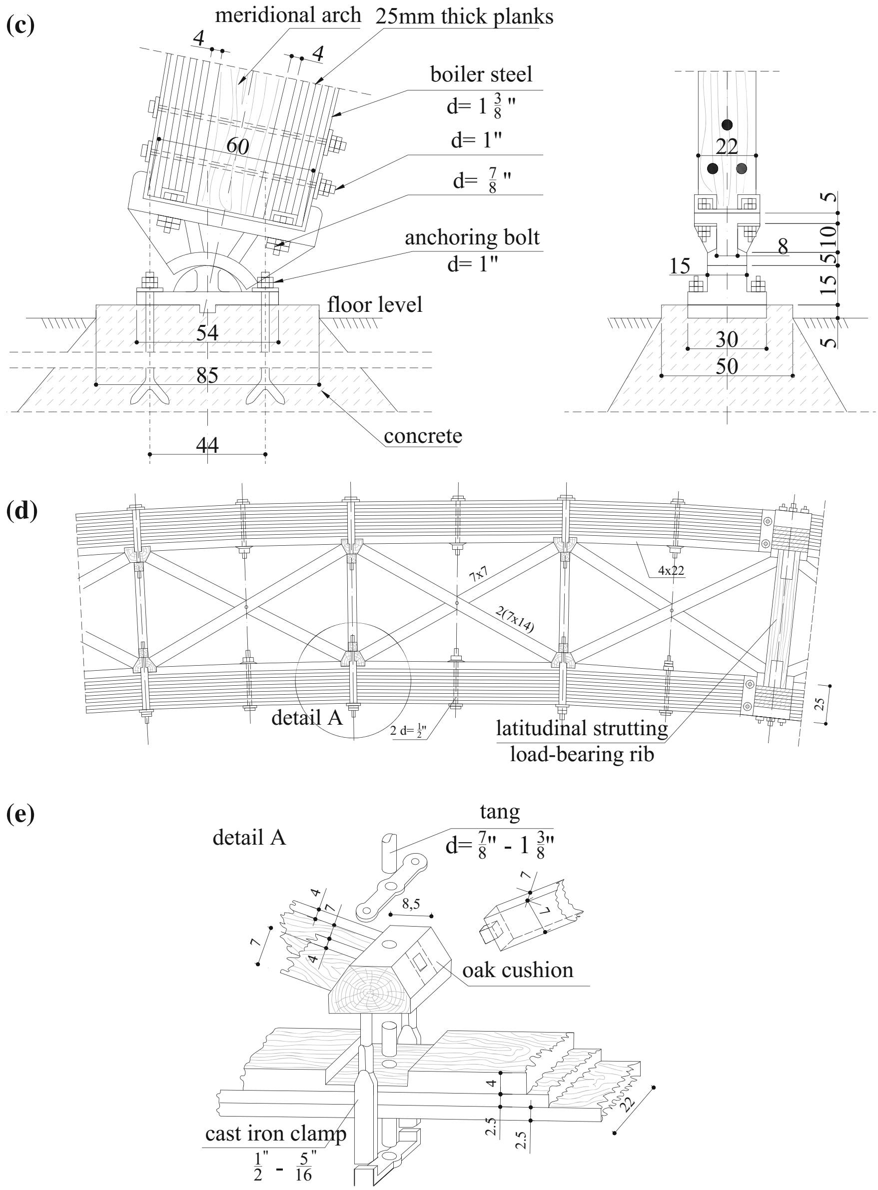

Fig. 5.7 (continued)

The main load-bearing ribs of the Ivanovo dome are trusses of a variable moment of inertia of the section. The maximum height of the section of the dome's meridional rib, in the middle of its length, totals 1.30 m, which in relation to the dome's diameter L = 50.0 m yields $\frac{1}{38}L$.

(a)

(b)

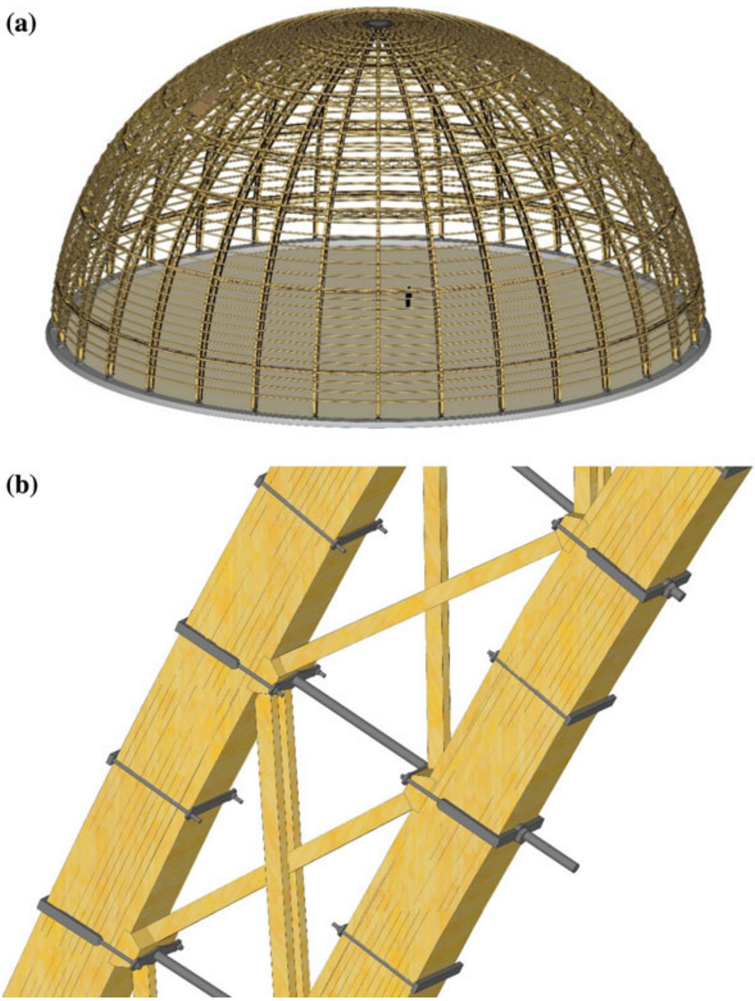

Fig. 5.8 Visualization of the Ivanovo dome according to [6], **a** visualization of the structure, **b** visualization of the structure of ribs

The meridional truss ribs were stiffened in the horizontal line with five latitudinal struttings in form of angle brace girders of parallel chords shown in Fig. 5.8a. Depending on the direction of the occurring deformations of main meridional ribs, the latitudinal struttings operated on compression or extension. Meridional intermediate ribs rested on the outside nodes of angle brace girders, three ribs each between the main meridional ribs.

In the highest node of the dome a steel hinge having the shape of a spool was mounted, in which all meridional load-bearing ribs concurred—Figs. 5.7b and 5.10a. The ends of the ribs connected in the upper hinge were strengthened under a

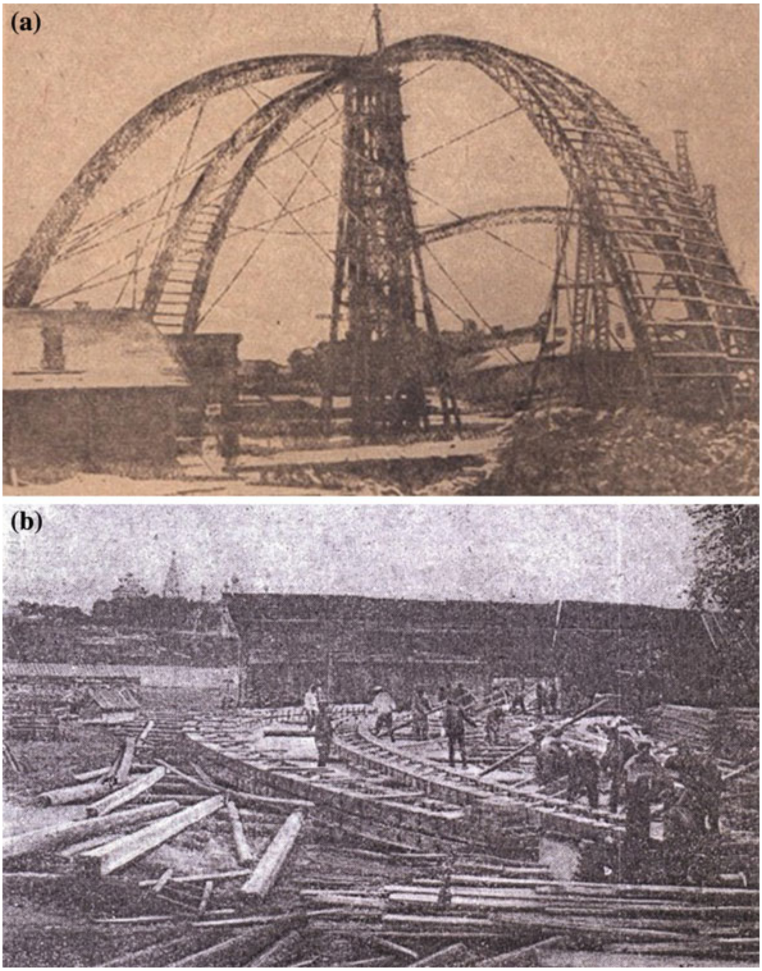

Fig. 5.9 Photographs of the building of the Ivanovo circus dome, **a** pair-wise assembly of the dome's load-bearing arches, [5], **b** construction yard

local pressure with steel clamps. The assembly of the highest node of the dome followed on tower scaffoldings having a vertical axis (Fig. 5.9a). The lower supports of arches were fabricated in form of cast iron hinges (Fig. 5.7c).

In Figs. 5.7, 5.8, 5.10 attention should be drawn to the application method of steel elements in the nodes of the dome. **The characteristic feature of this structure is the shape of nodes from steel and the connection of wood using steel elements. None of the steel elements was pasted in the wooden section**. Steel was used only in sections having the highest local pressure or as clamps introducing the mechanical pressure to increase the load capacity of the wooden element. In the key block and on the lower supports cast iron end pieces embraced

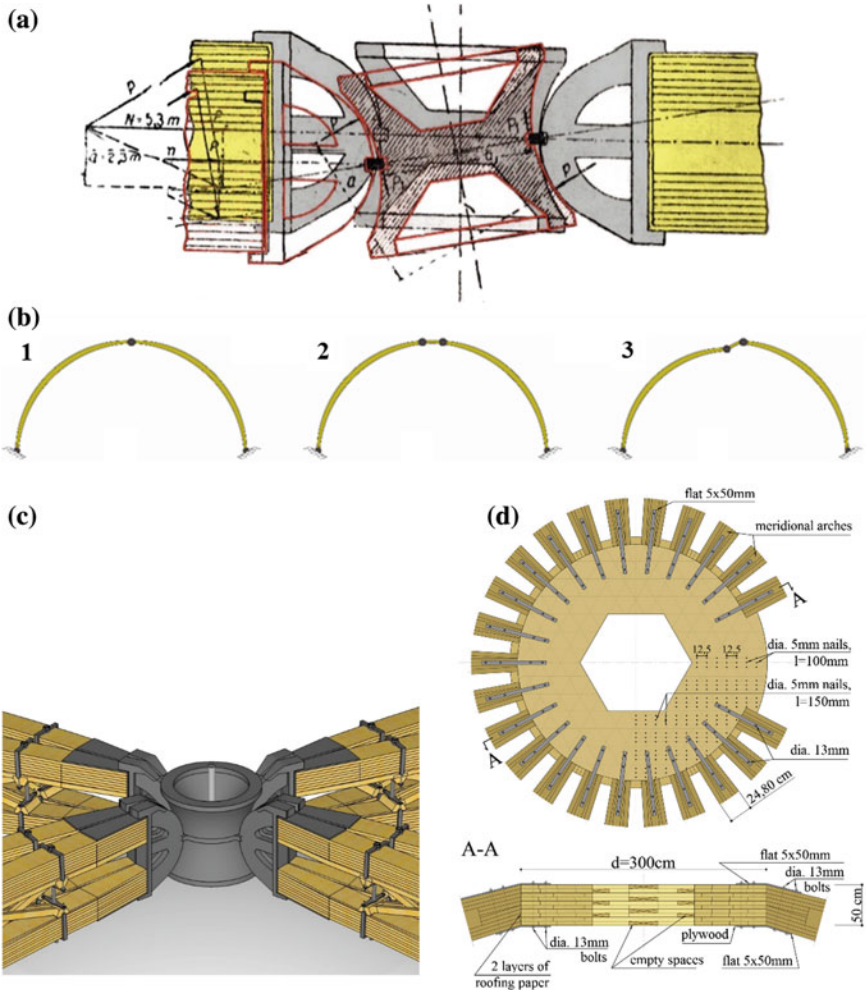

Fig. 5.10 Comparison of the nodes of the domes in Baku and Ivanovo, **a** loss of stability of the upper node of the Ivanovo dome [5], **b** static arrangement of the arches of the Ivanovo dome: 1—arrangement designed, 2—arrangement made, 3—arrangement translocated, **c** steel hinge node not resistant to twist in the Ivanovo dome, **d** upper stiff node from a multi-layer plate from planks made in the Baku dome

the extreme sections of wooden load-bearing ribs. **By using steel, an outside circumferential reinforcement of the section was introduced, protecting wood against delamination**. The historical description of steel included in Fig. 5.7b, 'boiler steel' [6], reminds that to protect extreme sections of wooden bars steel of an increased load capacity was used (also resistant to high temperature), used at that time (in the thirties of the 20th century) to build steam-operated industrial boilers. In the calculations of ribs the mating of the plank sheathing with ribs was not considered. However, in the realization, the plank sheathing was coupled with ribs in order to increase the stiffness of the dome. It was recommended to use the two-layer latitudinal sheathings on which, additionally, the planks of the third layer were nailed in form of a herring-bone pattern at the angle of 45° and 135° in relation to the latitudinal layer.

During the building of the Ivanovo dome—Fig. 5.9, there occurred a failure [5], consisting in the twist of the upper cast iron node, laid on a sand cushion placed on the central assembly tower. The scheme of the node's twist is shown in Fig. 5.10a, b. This happened after the assembly of arches and after the installation of 50% of the sheathing from planks. The arches curved in the horizontal direction. After a discussion of the problem with Professor Karlsen, a decision was taken to stiffen the arches with meridional trusses and to change the structure of the sheathing from planks. In the design project the sheathing from planks was supposed to be fabricated as a two-layer direct sheathing on meridional arches.

In order to stiffen the dome a two-layer sheathing [5] having a nature of a panel made on the outside and inside chord of meridional arches was introduced. The sheathing was made in the following way: on the arches, on the outside, planks with notches were laid latitudinally, from the centre another latitudinal layer was laid. A two-layer shell was formed, stiffening and, at the same time, effectively ventilating the wooden construction. On the outside, the metal sheet covering of the dome was made.

Upon completion of all the works, the central assembly scaffolding was removed. The vertical translocation of the central upper node was measured. It totalled 25.0 mm.

Conclusions related to the failure of the Ivanovo structure, related to the building of the central upper ring, were drawn. They were used in the structure of the Baku dome, as shown in Fig. 5.6. It consisted in the fabrication of a stiff node in form of a plate from 5.0 cm thick planks, laid in ten layers.

The paper [5] specifies the weight of the materials used to produce dome's load-bearing elements. **According to the compilation attached to [5], 5.45 m^3 of wood and 869.5 kg of steel and steel fasteners per meridional load-bearing arch were used When calculated per m^2 of the dome's horizontal projection, this yields the wood consumption of circa 40.0 kg/m^2 and steel consumption of circa 15.0 kg/m^2. Such minimum consumption of materials does not occur in the contemporary realization of domes from layer-wise glued laminated timber**.

5.3 Conclusions

The structure of ribbed domes from solid wood constitutes an essential stage in the development of wooden domes, falling on the thirties of the 20th century. In the calculations of the structures of such domes the coupling of load-bearing ribs with the plank floor or the box panels of the covering was not considered. In reality, the planks of the covering connected with ribs participated in the spatial operation of the dome, essentially relieving the load-bearing ribs [5]. Kashkarov K. P. specifies in his paper [2] that the own weight of ribbed domes of a span of 20.0–50.0 m totals 50–75 kg per m^2 of the dome's horizontal projection, without the roofing material and thermal insulation. **An essential element of the structure of the Baku dome, as described by the engineer Kashkarov K. P., is the use of low-dimension fasteners and lack of steel nodes, like for instance in the Ivanovo dome**.

In the thirties of the 20th century, in the domes of the projection's diameter of 50.0 m and more metres, builders started to introduce steel elements, mainly in the supporting zones of the dome's meridional ribs. However, steel was used sparingly. The consumption of steel in the papers by Kaszkarow [2] and Łopatin [5] is minimal and not encountered in the structures from glued laminated timber—Table 14.1. Attention should be drawn to the shape of steel elements used in the nodes of the domes in Baku and Ivanovo: Figs. 5.5, 5.7, 5.8, 5.10. **Cast iron fittings embrace bars from planks, not destroying by the intersection wood fibres and the matrix of the domes' load-bearing elements**.

The mechanical pressure applied increased the load capacity of bars from planks. In this way the wooden load-bearing bars were protected against the delamination of fibres.

The Baku dome, of a 67.0 m circular projection's diameter, closed the development of domes from solid wood built without using steel nodes.

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