Chapter 6
Shell Domes

6.1 Introduction

The striving for the use in the operation of dome structures of all the elements creating the dome: ribs and the plank shell led to the creation of a dome having the form of a thin-wall rotating shell. **Thin-wall domes were called such domes in which of an essential importance in the load capacity of the structure is the shell from planks nailed onto the meridionally laid assembly ribs**. The dome's geometry was formed using assembly ribs, creating at the same time a technological scaffolding of the plank shell. The use of meridional technological ribs also allowed to maintain the computational, mathematical shape of the shell. The ribs, upon consolidation with the shell from several layers of planks, substantially increased the load capacity of the complex structure of the dome.

Thin-wall shells from wood were built from several layers of planks connected using nails. The system of planks of the sheathing and the structure of plank ribs was differentiated depending on the required dome's diameter. Thin-wall, complex spatial structures were built in which all layers of the shell and the ribs participated in the transfer of loads. The thin-wall domes are characterized by the shape nearing a sphere, the spatial stiffness, a favourable indicator of the material consumption for the construction in relation to the surface covered by it, as well the minimum surface of the casing in relation to the projection's area. The minimalist form of shell domes was also favourable in relation to the load from wind. Shell domes of a tiny eminence were built in Central and Northern Russia over gas tanks, at a height of 33.0 m above the ground level in regions exposed to strong and frequent winds [1] (1937).

In the axially symmetrical thin-wall domes from wood discussed in this chapter the ratio of the rise of arch (height) f to the diameter of the base's circle according to the proportion: $\frac{f}{L} = \frac{1}{4} \div \frac{1}{6}$ was adopted.

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Depending on the required strength of the shell and ribs, thin-wall domes, axially symmetrical, were built in four systems. A designation was adopted for each system in this publication, emphasizing the essential load-bearing element of the system. Depending on the features of the complex section,[1] thin-wall domes were split into:

- smooth shell domes, on ribs from one, flat plank,
- smooth shell domes, prestressed with steel tie rods,
- ribbed domes on layer ribs (from three planks),
- ribbed shell domes, on ribs having the form of bipolar girders.

6.2 Shell, Smooth Domes

The three-layer thin wall plank shell was built on meridional ribs from a single plank being tangential to the sphere. The lower sections of ribs were connected using steel clamps with the lower supporting ring. The upper sections of ribs were built into central rings, made from several layers of arch centres. Meridional arches in the domes of a projection's diameter up to 20.0 m were made from one plank.

Shown in Fig. 6.1 is the assembly method of the system 1 thin-wall domes. The meridional plank ribs **2′** were laid along the radius. The ribs were based on the lower ring **1** and bent to the shape of the plank shell into the position **2**.

The conical profile of the ribs **2′** in Fig. 6.1a illustrates the initial position of assembly ribs from planks which, upon bending downwards, adopt the shape of the circular section's arc.

The bent ribs **2** were connected by means of the central rings **6**, **7**, **8** (Fig. 6.1c), supported on a light scaffolding from arch centres. Upon fastening the ribs **2** in the lower and upper ring, the rib was undergoing a prestressing.

The ribs **2** shown in Fig. 6.1b are assembly planks and were used in order to obtain the proper geometry of the dome.

The even number of meridional ribs **2** from 3.0 cm thick and 12.0 cm wide planks was adopted. The number of ribs was calculated according to the lower supporting crown, adopting a spacing of circa 0.80 m to 1.5 m between them. The lower supporting ring **1** was built from three beams laid vertically—Fig. 6.2c. Meridional ribs **2** were disposed on the lower beam of the crown **1**. In order to prevent the shift of ribs **2**, spacing beams were arranged between them, that is the spacing beam, of the supporting crown **1**,—Fig. 6.2c. The lower and the central beam of the ring **1** were used to fasten and to adjust the spacing of plank ribs **2** of the dome. The task of the upper beam of the ring **1** was to hold down from above the ribs **2**, as well as to prevent the tearing-off of ribs from the supporting ring during the formation of the dome's shape.

[1]The designation "structure of the rib consolidated by the shell" defines the structure type and not the connection type.

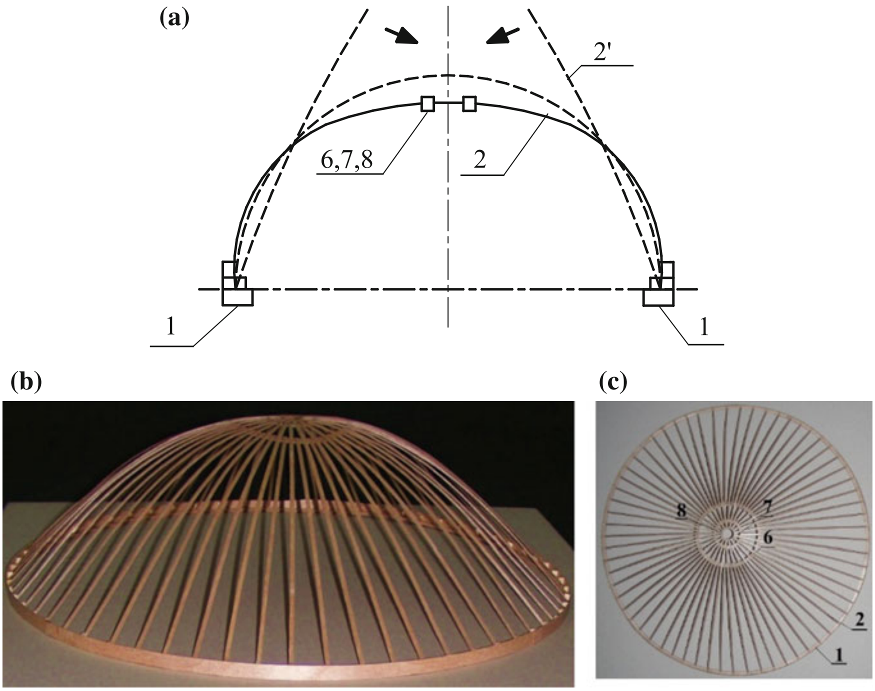

Fig. 6.1 Building rule of structures from flat ribs for thin-wall domes according to [2], **a** schematic diagram of the assembly of the dome's scaffolding: **2′**—initial arrangement of planks, **2**, position of planks after the bending, **b** assembly scaffolding 2 shown on a model, **c** structure of ribs with the top view of the, central rings 6, 7, 8 to connect flat ribs

The rings **6**, **7**, **8** were also used to make such a connection of the ribs that every second meridional rib passed beyond the ring. The rings **6**, **7**, **8** were built from two layers of arch centres that embraced the bilaterally flat planks of the ribs **2**. Each ring let pass every second flat rib of the dome. The longest ribs were connected in the key block by means of the last ring **8**.

The three-layer shell from planks was nailed onto the bent flat ribs **2**. The direction of the layer was determined in parallel to the generatrix of the dome passing through the upper ring **8**. The generatrix of each layer was reversed in relation to the generatrix of another layer by 60°. The construction of the three-layer shell, made according to [2], is shown in Figs. 6.2, 6.3, and 6.4. Three inclined sheathings **3**, **4**, **5** were built from planks of a thickness of 1.9–2.5 cm and an 8–12 cm width. All the three sheathings were connected with nails of a dia. 5 mm diameter between them and the meridional ribs. Each layer of the floor from planks was laid on the sphere in parallel to the generatrix passing through the upper ring of the dome, creating an arch along the meridian.

To illustrate the building technology of the dome's structure two models at a scale 1:50 were made, as shown in Figs. 6.3, and 6.4.

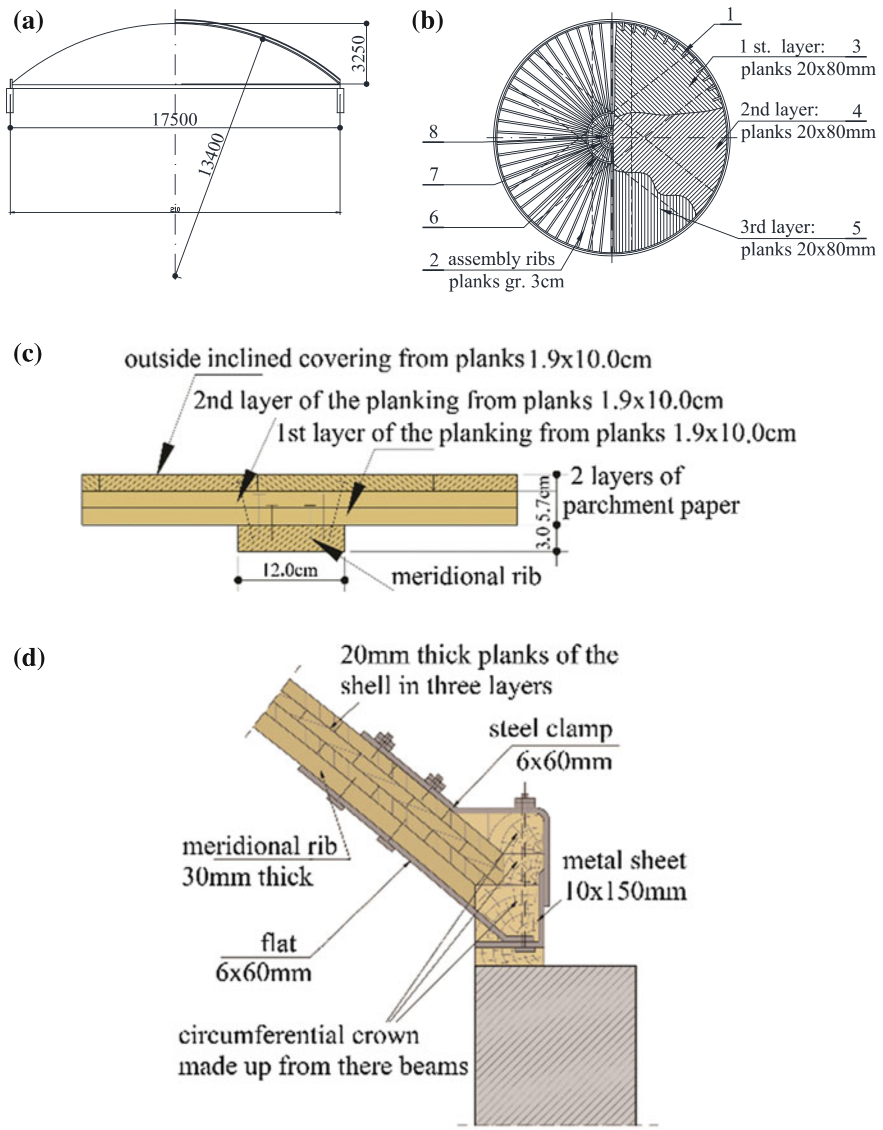

Fig. 6.2 Structure of a dome from planks of a 17.50 m span and a 3.25 m height according to [2], **a** section of a shell dome of a 17.5 m diameter, **b** schematic diagram of the plank shell's projection, 6, 7, 8—upper rings to connect the meridional ribs of the assembly layer, **c** section of a meridional rib, **d** supporting node of a dome using steel flats

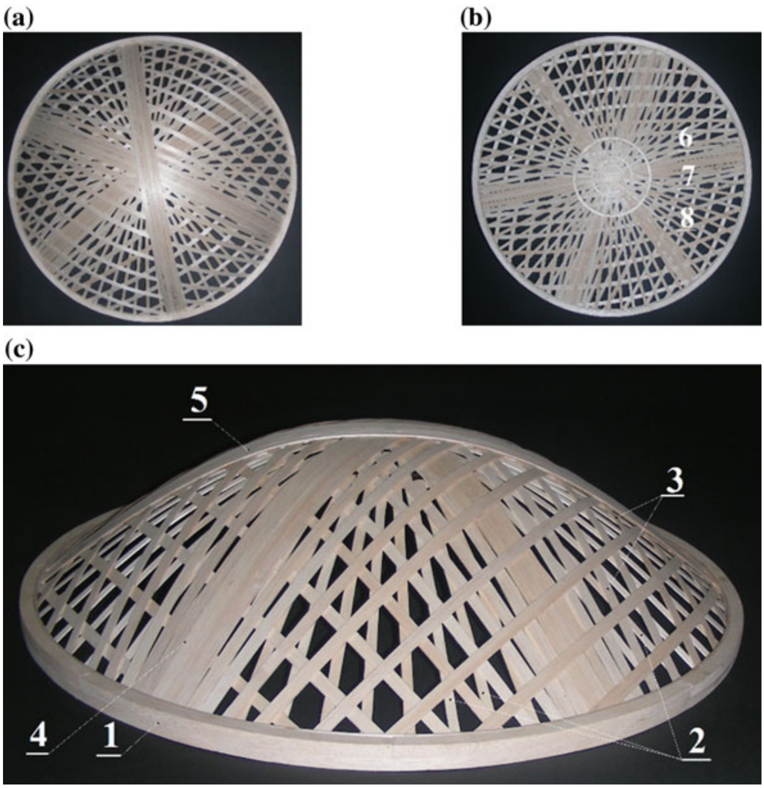

Fig. 6.3 Shell dome from three layers of planks according to [3], **a** top view, **b** view of the palate, **c** side view of the dome

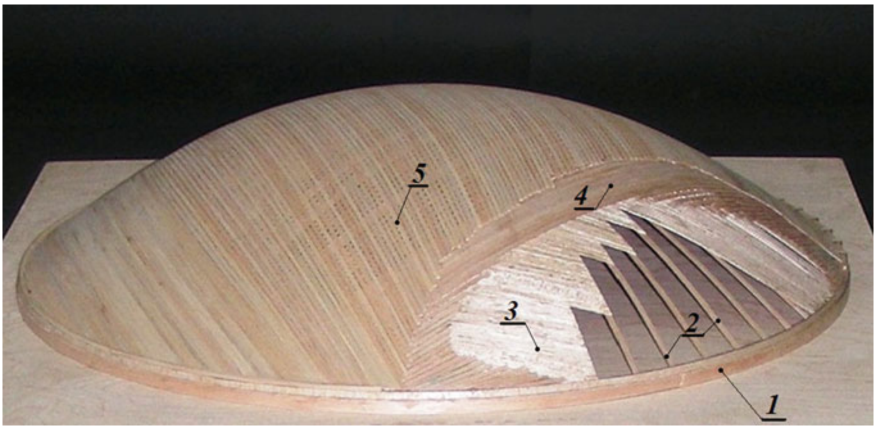

Fig. 6.4 Model of a shell dome of a 17.5 m diameter at a scale 1:30 according to [3]

Three arches intersecting at 60° are shown on the model (Fig. 6.3), each of them being positioned in a different layer. Each layer of the sheathing was fabricated from long planks branching off fan-wise from the arch passing through the dome's peak towards the lower supporting ring. As they go off from the main direction of the layer's arch, the position of planks was nearing the meridional direction. Due to the need to maintain the continuity of the shell, the planks were hewn, or the sheathing was fabricated from planks of a fixed length, with the inclusion every several rows of hewn planks in form of flat wedges.

The model shown in Fig. 6.3 illustrates three layers of the sheathing from planks parting fan-wise from the peak towards the lower crown.

The operation of this dome may be presented in the following way: in each sheathing the layer of planks, positioned along the meridian passing through the upper ring of the dome, creates an arch and takes over the meridional forces in the shell. In this way three main arches in the dome are formed. Depending on the deviation of planks from the meridional direction, the planks of sheathings gradually approach the meridional direction, taking over the circumferential forces in the shell of the dome (Fig. 6.3c).

As verification of the correctness of the reconstructed system, another similar model of a dome of a 17.50 m diameter at a scale 1;30 was made, as shown in Fig. 6.4. The elements of the floor from planks were designated with numbers: lower ring **1** built from three planks, meridional ribs **2**, as well as the layers of the plank floor **3**, **4**, **5**.

The models presented were used for the analysis of the operation of shell domes. On the basis of Fig. 6.2 and the models fabricated, the weight of wood required to make thin-wall shell domes was assessed. The results obtained are very attractive in comparison to how much wood is necessary to build domes in other systems or from other materials, also including those from glued laminated timber. The volume of wood required to make ribs, rings or the three-layer shell of the dome of a 17.50 m diameter totals according to Fig. 6.2 circa 14.45 m^3. The area of the dome's horizontal projection totals 240.41 m^2. **The** weight **of solid wood as calculated per m^2 of the dome's projection amounts to circa 30.0 kg/m^2. The amount of the steel consumed for nails required to join the layers of planks is also lower. It totals circa 1.5 kg per m^2 of the dome's projection**.

The amount of wood required to make the construction and the casing of the facility is much lower than that required to make domes from other materials. The cheapest type of wood used for the construction are planks. The three-layer shell built according the foregoing description allows an additional use of planks without the expensive selection, even the building-in of planks of a worse quality. The execution of plank shell from solid wood is not associated with such a huge mass of waste of structural elements from layer-wise glued laminated timber, requiring the elimination of natural defects of wood. The selection of natural wood in the production of layer-wise glued laminated timber is associated with the production of a huge mass of waste.

6.3 Shell Domes Prestressed with Steel Tie Rods

The system of shell domes prestressed with tie rods from steel bars was patented in Russia under the number 14822, cl. 37a,6, **in 1907, by the engineer Kaliepa** [4] (1947). In accordance with this patent, the dome that covered the building having a rectangular projection did not have a thrust ring and is made up of two layers of planks. The next authors: Wiazemski O. W., Smrczek L. L., Wiesolowski W. W, Chamasuridze G. W, in the authors' certificate 68,121, cl. 37a, 6, from 1947, I quote after Tshichachiev [4], propose using a dome roof shown in Fig. 6.5 as a removable roofing of the hydroelectric power plant's generator. **In practice, the roof was removed during the assembly and the next reviews of the equipment**. **In summer, the roof was raised for ventilation** [4]**. It is also known that the shell domes were raised and positioned above gas tanks**.

The three-layer thin-wall plank shell as discussed in Sect. 6.2 was built on meridional ribs from a single plank, bent to the shape of a sphere with steel tie rods. The systems of shells prestressed with steel tie rods were built on projections at the level of a lower thrust ring having a diameter of circa 20.0 m. The solution as described in the paper [4] demonstrates the use of the prestressing of plank ribs, round steel rods of a 8 mm diameter, bending the ribs from planks and taking over the additional horizontal strutting forces. The schematic drawing of the construction of a shell dome using ribs from planks prestressed with steel tie rods is shown in Fig. 6.5.

In Fig. 6.5, the number designations are: **1**—triple, lower circumferential ring, **2**–**3**.0 cm thick, 12.0 cm wide ribs, bent using a tie rod **9**, and **3**, **4**, **5**—layers of a shell from planks, **9**—steel tie rod, **10**—hook to raise the dome, **11**—steel ring to hold together tie rods, **12**, **13**—steel clamps of the supporting ring.

The structure of shell domes prestressed with steel tie rods allowed a comfortable assembly of the roof covering using cranes. It is known from historical descriptions that the shell of the domes as described in Sects. 6.2 and 6.3 may be made up of a higher number of layers than it was described in the examples specified. The minimum number of the applied layers of planks amounted to 2.

The approximate calculation of such shells was conducted following the algorithms known since the beginning of the 20th century. The central sheathings of each layer were separated, as marked off with dotted lines in Fig. 6.2b. Those chords were considered to be the basic load-bearing element of a thickness equal to that of the plank in each layer (2.0 cm up to 2.5 cm). Owing to the consolidation (through the connection using nails) of all the layers of the shells, the planks of the layer were considered in increasing the stiffness of the chord being calculated.

The shell dome systems discussed (Figs. 6.2, and 6.5) bring to mind the connotations with the contemporary realizations of Swiss facilities having a structure designed by Natterer [5] (1991). In the solution shown in Fig. 6.6 the flat meridional assembly ribs were eliminated, using just the shell from two layers of planks.

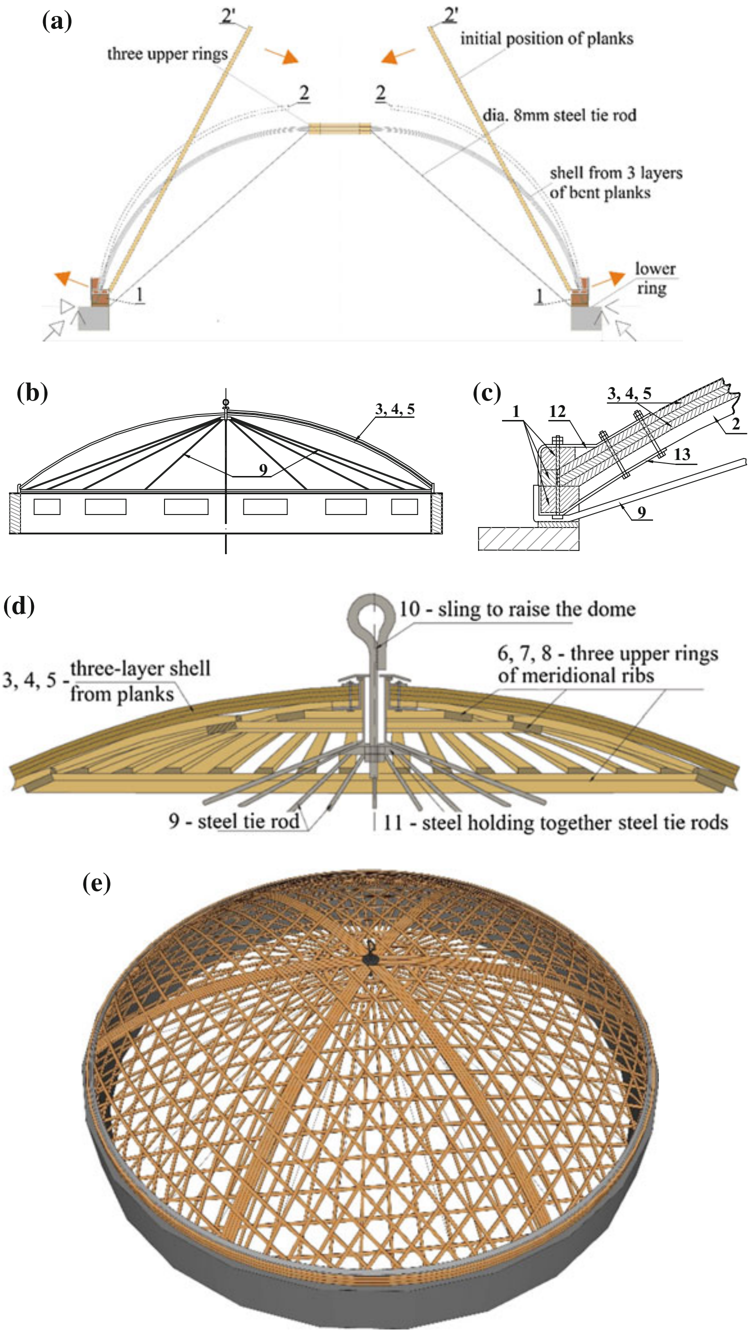

Fig. 6.5 Shell dome prestressed with steel bars according to [4], **a** schematic diagram of the structure, **b** section of the dome, **c** supporting node, **d** anchoring of tie rods in the upper node, **e** reconstructed view of the dome

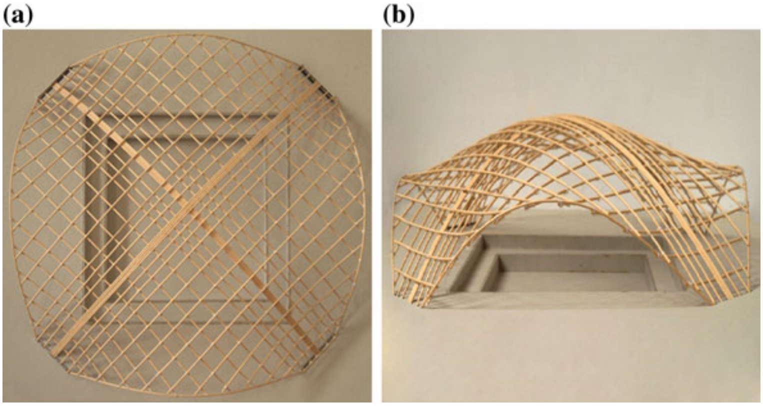

Fig. 6.6 Model of the shell by Natterer J. made from wood, [6], a projection of the shell, b side view

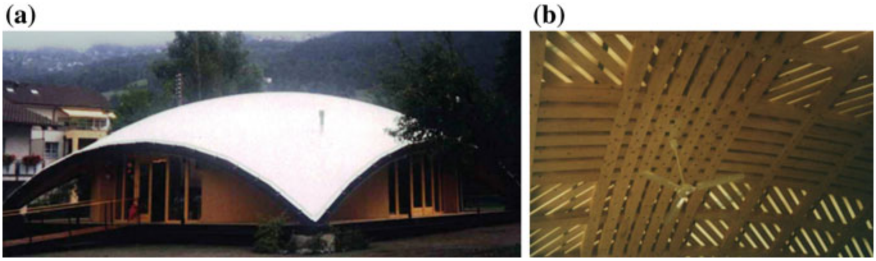

Fig. 6.7 Kindergarten's building in Lausanne roofed with a shell from planks, a view of the building, photograph by the author, b view of the plank shell from the inside, photograph by the author

Hidden ribs were made in the shell along the diagonal of the square projection. Two main load-bearing arches were made along the generatrices of the shells, shifted in relation to each other at 90° (Fig. 6.6a). The planks of the floor were laid in parallel to the central arches.

Shown in Fig. 6.7 is the covering of the kindergarten's building near Lausanne, Switzerland, built in 1998, according to the design project described in [5] (1991). The construction of the shell was made following the rules presented in Fig. 6.6.

Steel tie rods were eliminated from the structure of the roofing, and the strutting from main ribs was taken over onto the pyramidal reinforced concrete supports in four supporting corner points of the shell.

6.4 Shell-Ribbed Domes

In this system the three-layer thin-wall shell was built on meridional ribs from three planks tangential to the sphere. Such systems were built on circular projections having a diameter of 19.5 m up to 40.0 m [3].

Shown in Fig. 6.8 according to [2] is the example of a thin-wall dome built in the shell-ribbed system, of a diameter of 30.0 m and a height of 6.0 m. The technology of the dome's assembly is similar to that discussed in Sect. 6.1 and illustrated therein. The difference consists in the introduction of multi-layer meridional ribs (Fig. 6.8c) and a different structure of the layers of a shell from planks. In the domes of a 20.0 m up to 35.0 m diameter arches were built from several planks (three or four), laid flat one on another and connected using nails. The distance between the axis of ribs on the lower supporting ring was adopted to be circa 1.0 m. In the example from Fig. 6.8 the distance of 1.27 m was adopted.

In the shell-ribbed domes the ratio of the height of the meridional rib **h** to the dome projection's diameter **L** within the range of $h/L = 1/200 \div 1/270$ was used. The dome shown in Fig. 6.8 was built on seventy-four meridional ribs from three 4.0 cm thick planks of a total height of 12.0 cm, a width of 15.0 cm. The ratio of the height **h** of the meridional rib's section to the dome projection's diameter **L** is $\frac{h}{L} = \frac{1}{250}$. The ribs were bent to the dome sphere's radius (e.g. in Fig. 6.8 this is the radius 21.75 m) and connected at the top at the height of 6.0 m using a ring made from arch centres shown in Fig. 6.9.

The connection of ribs with the upper ring followed on an assembly scaffolding. The sections of the connection spots of meridional arches were moved over the length of ribs, whereby the contact spots of the upper and lower plank were disposed not closer to 3–4 m from the upper ring made from arch centres.

Ring-shaped sheathings were nailed onto the bent meridional planks of ribs, which helped shaping the sphere as well as protected the fragile load-bearing ribs against lateral translocations.

The ring-shaped (meridional) sheathings were used in order to transfer the compressive and tensile, meridional forces. They were built from two layers of planks: the lower layer laid directly on the meridional arches of the dome, and the upper layer, covering the contact spots of the lower layer. This first layer of 19.0 cm thick planks stiffened the scaffolding from meridional ribs. The accurate positioning of the first layer determined the geometry of the whole dome. The slight assembly inaccuracies of the first layer's planks nailed onto ribs introduced the horizontal translocations of ribs, which resulted in a deformation of the dome's sphere. Such deviations became particularly dangerous at the occurrence of non-symmetrical loads. In order to prevent this, a second latitudinal layer was nailed, shifted in relation to the first latitudinal layer by one half of the plank's width. The contact spots of the ring-shaped sheathing's planks were placed in the axis of meridional

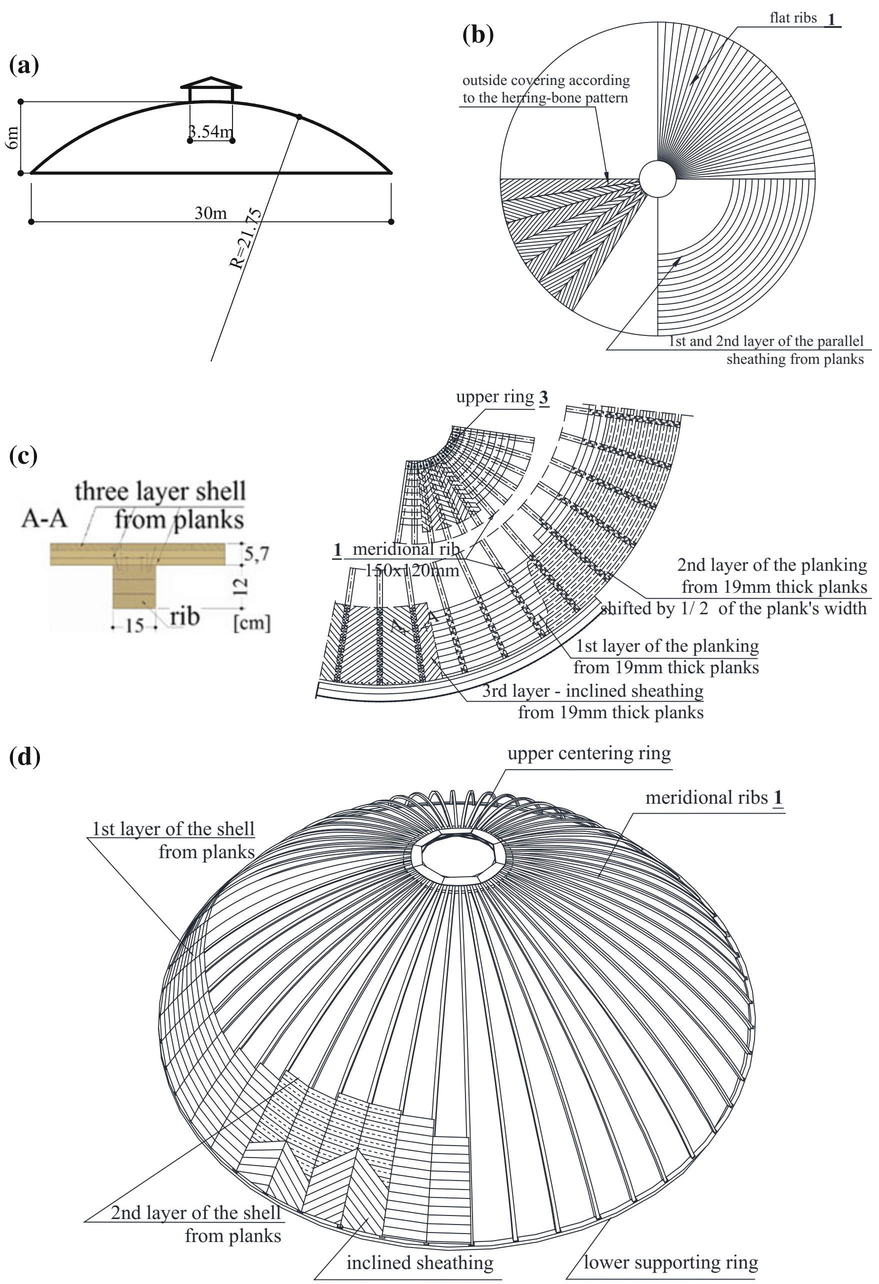

Fig. 6.8 Shell-ribbed dome of a diameter of the circular projection of 30.0 m according to [3], **a** schematic diagram of the dome's section, **b** projection of the dome, **c** lay-out of ribs and planks of the floor, **d** reconstructed view of ribs and the sheathing from planks

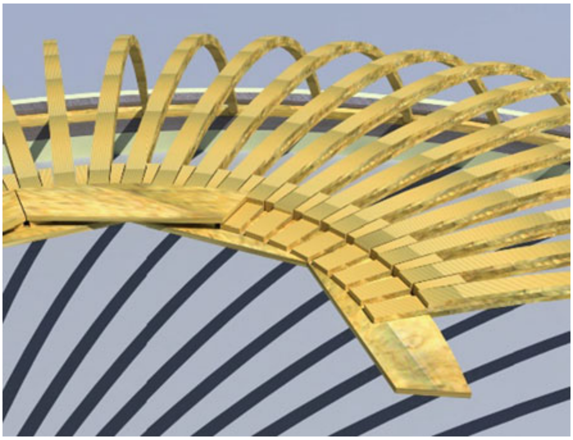

Fig. 6.9 Building of the central upper ring of thin-wall domes

ribs. Both the layers of the ring-shaped sheathing were connected using nails of a 5.0 mm diameter, up to the meridional ribs of the dome. Usually, the thickness of 1.9–2.5 cm, the width of 10–16 cm width of the planks of the ring-shaped sheathing was adopted. In the upper part of the dome, at the arch centre ring, the duplicated ring-shaped sheathing was substituted for a single sheathing from planks of a thickness equal to the sum of the thicknesses of the duplicated sheathing.

The elasticity of ribs produced a reciprocal meridional and circumferential tightening of the shell, from the lower supporting ring up to the upper crown. The shape of the dome was maintained owing to the reciprocal equilibrium-maintaining prestressing of the planks of ribs and those of the three-layer shell.

The sloping (outside) sheathing was used to transfer the shearing forces resulting from the non-symmetrical load of the dome. They were laid on latitudinal rings at 45°. They were built from one layer of planks of a 1.9 to 2.5 cm thickness, positioned at circa 45° from one meridional arch to another one. In the outside view, the inclined sheathing fell on the dome into the “herring-bone” pattern.

The upper arch centre ring that anchors meridional ribs and assumes the forces from meridional arches (Fig. 6.9) were made from two or more chords of arch centres embracing the central plank of three-layer, flat of meridional arches. If the number of arches was adopted to be m, and the width of a plank b, then the diameter of the arch centre ring was calculated from the formula $d_0 = \frac{mb}{\pi}$. In order to reduce d_0, a slight undercutting of the planks of arches was used at the place of their junction with the arch centre ring. The layers of the arch centres of the central ring were connected with the meridional ribs using steel bolts of a 12 mm diameter. The view of the upper ring and the junction of the arch centres of the ring with the planks of ribs is shown in Fig. 6.9.

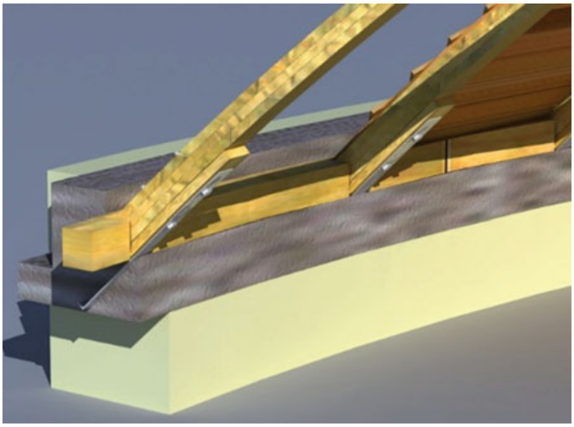

Fig. 6.10 Connection of ribs with the wall plate and the lower reinforced concrete crown

The opening of the upper arch centre ring was covered with a skylight. In some solutions a lantern with a wooden roof was placed on the ring. The weight of the lantern whose walls were placed on the arch centre ring favourably influenced the maintenance of the shape of the dome.

The lower support of the meridional ribs of the shell constituted a circumferential reinforced concrete crown—Fig. 6.10. The supporting ring—the lower circumferential ring of the dome, operating on the extension originating from the strutting of the dome, was made as a reinforced concrete, steel or wooden triple ring (for domes of a diameter up to 20 m, Fig. 6.2d). In this crown, using steel flats, the supporting triple wooden ring of the dome's diameter was anchored. The flat ribs of the dome were fastened in it following the rules and the figures described in Sects. 6.1 and 6.2. The bent planks of the ribs were protected against tearing-off with steel flats of a thickness of circa 5–6 mm. The connection was fabricated with dia. 2 mm bolts. In order to reconstruct the modern (unfortunately forgotten) structure of the dome, the view of the structure of ribs and the covering was reconstructed using incomplete sketches from the referenced literature [3] (1943), [1] (1937), and demonstrated in Fig. 6.8.

Following the above-discussed rules, the dome of the gas tank building of the Berezhnikovsky Chemical Complex in Russia, having the structure as shown in Fig. 6.11, was also reconstructed. The designer of the dome was the engineer Milvitsky [1] in the thirties of the 20th century. The dimensions of the dome were as follows: the diameter of 32.50 m, rise f = 7.20 m, the proportion of the rise **f** to the projection's diameter **L** was adopted: $f/L = 7,2/32,5 \div 1/4,5$. The shell was built, following the rules discussed in the previous example, on eighty-eight meridional ribs, spaced every 1.15 m on the lower supporting ring.

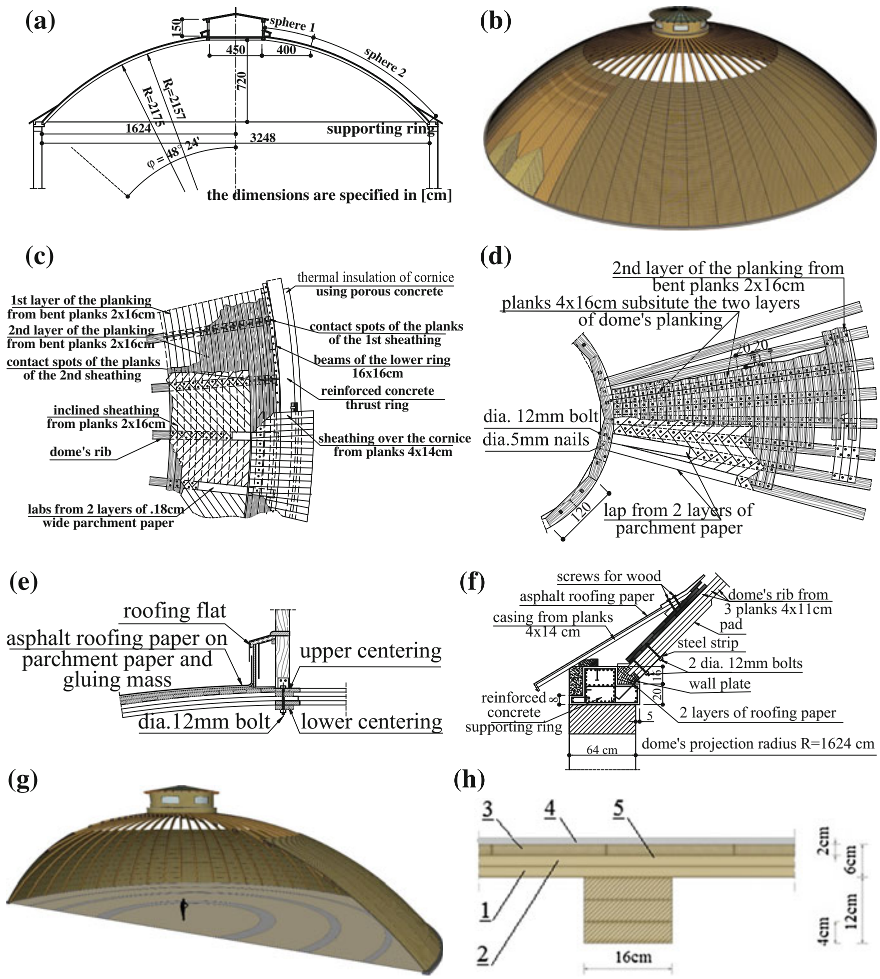

Fig. 6.11 Structure of the Berezhnikovsky's dome of a 32.48 m diameter according to [1], **a** section, **b** general view of meridional ribs and the three-layer shell, **c** shell at the lower supporting ring, **d** shell at the upper supporting ring, **e** connection of the layers of the floor shell with meridional ribs and connection of the meridional rib with the dome's upper ring, **f** supporting ring, **g** reconstructed section of the dome, **h** section of the rib joint with the shell: **1**, **2**—1st and 2nd layer of the latitudinal sheathing, **3**—3rd layer of the inclined sheathing, **4**—covering using roofing paper, **5**—spacers from 2 layers of parchment paper

6.5 Ribbed-Shell Domes

The ribbed revolving domes developed from thin-wall shells and were used for domes of a higher stiffness when in order to raise the stability of the shell ribs should have been given a higher stiffness. Besides, the stiff ribs proved correct as an assembly skeleton when erecting the dome. Such systems were built on circular projections of a diameter of 35.0 m up to 60.0 m.

In the ribbed-shell system the three-layer shell from planks was built from two ring-shaped layers and one inclined layer, like in the thin-wall shells described in Sects. 6.3 and 6.4. In the ribbed shell domes the ribs raise the load capacity to bending, and are characterized by a massive structure as compared to the flat ribs of shell ribbed domes. At the higher diameters of shell domes the stiffness of meridional ribs driving the dome's geometry was increased through spreading apart the chords tangential to the sphere and through introducing a web from two planks between the chords. The main load-bearing ribs were given an I-section, and over the length along the meridian, a form of bipolar coordinates. Meridional intermediate ribs from several planks bent to the sphere's curvature were placed between the stiff main ribs. A three-layer shell from planks like in the system discussed in Sect. 6.4 were nailed on the main and intermediate ribs. The three-layer shell jointly with the stiff and intermediate ribs operated as a complex element.

The forms of ribbed-shell domes, dimensional dependencies and the construction of intermediate ribs and of the dome are assumed to be the same as in thin-wall domes. The difference consists in the introduction of meridional ribs of a higher stiffness and bipolar coordinates. The main meridional ribs of domes required at their erection a support on the central scaffolding in the vertical axis of the facility.

In 1930, a ribbed-shell dome of the circus in Saratov (Russia) was built, as described by Kashkarov K.P. in his paper [1] (1937). The author does not specify the precise description of the dome. It is limited just to some pieces of information. I quote: "Crescent-shaped meridional ribs of the dome were made to have an I-section and a height of 1.00 m in the highest section, which in relation to the diameter L = 46.0 m totals $h/L = 1/46$". Attached to the text was one photograph that, presently, is almost illegible. On the basis of the intuition and the data on other ribbed-shell domes a model at a scale 1:50 was made, which recalls the view of a light structure of the Saratov dome. Perhaps it looked like as shown in Fig. 6.12. Due to lack of information (at the present-day stage) about the construction of the lower supporting crown of the dome, it was designed in such a way as to suggest a solution meeting also the requirements of the modern user. Let us hope that the model will recall and rescue from oblivion the subtle and modern construction of the Saratov dome.

Shown in Fig. 6.13 is the structure of the ribbed-shell dome as described by Karlsen G. G. in [3]. A facility of a 50.0 m diameter was designed on shuttering bipolar ribs and a plank shell consolidated with them. A ring-shaped shell from two layers of 2.5 cm thick planks laid latitudinally and a third 1.9 cm thick inclined layer was made on 32 meridional ribs and 96 flexible intermediate ribs (from three planks) (Fig. 6.12e).

The main, bipolar rib of the dome shown in Fig. 6.13a was made with the upper chord of a curvature conforming to the radius of the dome's sphere, i.e. 31.85 m. Demonstrated in Fig. 6.13b is the lay-out of the main ribs on the dome's projection. The main meridional ribs were disposed every 6.04 m as measured on the lower ring of the dome. The flexible ribs, made from flat laid planks of the sectional

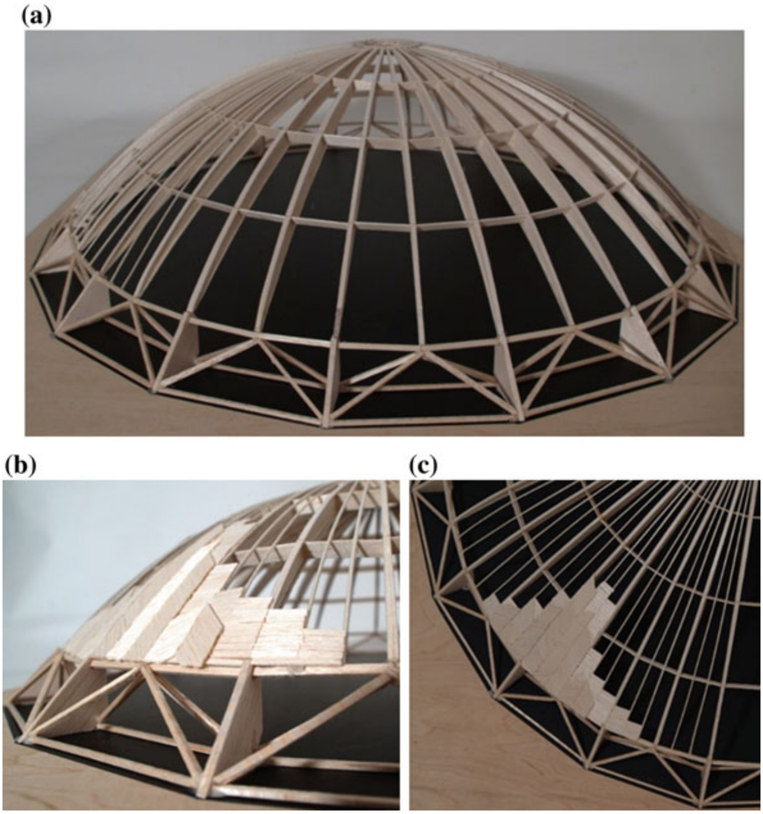

Fig. 6.12 Model of a shell-ribbed dome of a 46 m diameter according to [1], **a** structure of ribs and the supporting ring, **b** detail of overlaying the layers of the sheathing, **c** main, intermediate ribs and the covering

dimensions, 15 × 16 cm width x height, were placed between them every 1.51 m. Each of the intermediate ribs was composed of four 40.0 mm thick and 150.0 mm wide ribs each (Fig. 6.13e). The spacing of the intermediate ribs resulted from the length of planks required to make the meridional layers of the shell.

Shown in Fig. 6.13d, e is the structure of a shell made up of two ring-shaped layers from 25 mm thick planks, and of a third, inclined layer from 19 mm thick planks. Quarterings of 40 mm × 40 mm dimensions, in a spacing of 50.0 cm as battens from zinc-plated sheet were nailed on the three-layers of the shell. Figure 6.13c–e depicts the view and the section of meridional ribs: the main rib and the intermediate rib. The upper and the lower chord of shuttering meridional main ribs were built from four planks of a section of 80 × 40 mm each, and the web from two layers of 2.5 cm thick planks laid at 90° one to another. The support of meridional ribs on the lower thrust crown was made on a massive reinforced concrete ring. The connection of the main ribs at the top in the key was made on a

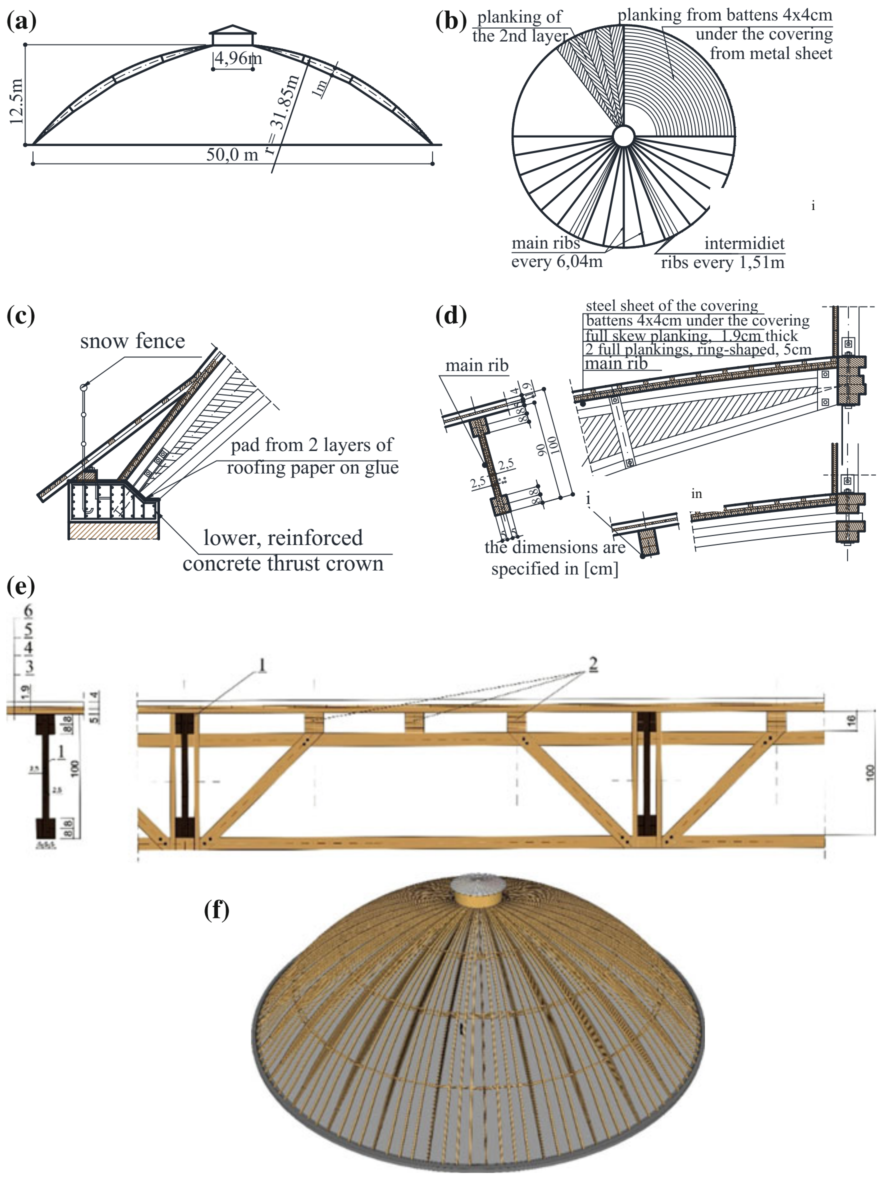

Fig. 6.13 Ribbed shell dome of a 50.0 m diameter according to [3], **a** schematic diagram of the dome, **b** lay-out of ribs and planks of the floor as well as of battens under the covering from metal sheet, **c** structure of the supporting node, **d** structure of the load-bearing and intermediate rib, **e** structure of the latitudinal brace rib between meridional ribs, 1—main rib, 2—intermediate rib, 3—latitudinal planking from planks 2 × 2.5 cm, 4—inclined planking from 1.9 cm thick planks, 5—battens from 4.0 cm thick quarterings, 6—covering from metal sheet, **f** reconstructed view of the dome with meridional ribs demonstrated

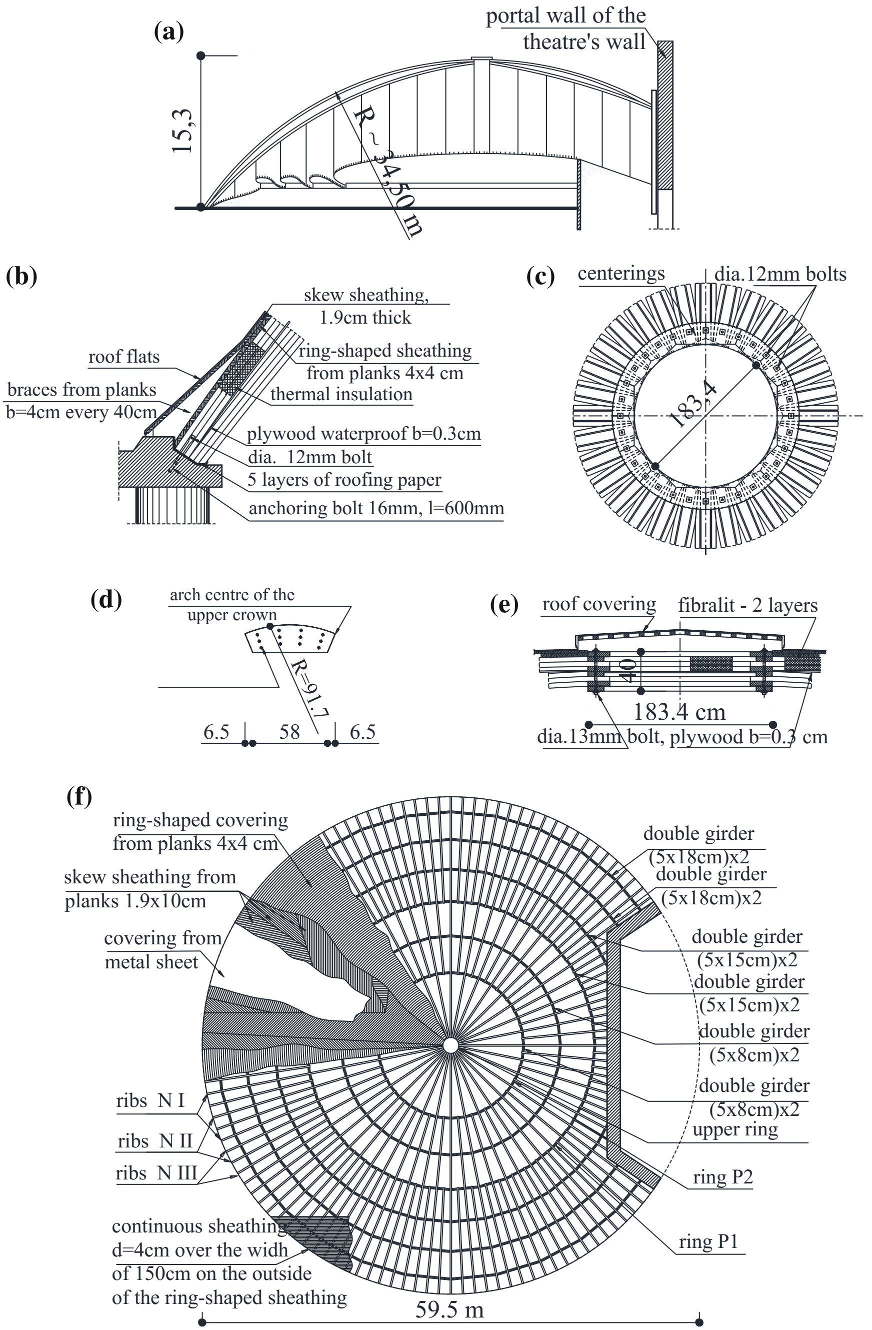

Fig. 6.14 Dome of a 59.50 m diameter on the building of the Simonov Palace of Culture in Moscow according to [1], **a** section of the dome, **b** structure of the supporting node, **c** upper ring, **d** arch centre from which the upper ring was fabricated, **e** section of the upper ring, **f** horizontal projection of the dome, **g** main rib No. NI, **h** construction of latitudinal struttings of main ribs NI and intermediate ribs NII, NIII, **i** section of the load-bearing rib N1 in the middle of the span, **j** supporting section of the load-bearing rib, **k** reconstructed view of the structure of ribs and the shell, **l** section of the facility crowned with a dome

wooden ring built from five layers of flat laid arch centres. The view in Fig. 6.13e shows the span of a meridional angle brace strutting between the main ribs, preventing the twist of the main ribs. The braces of the meridional strutting were placed under the meridional intermediate ribs.

In 1933, at the Central Research and Development Centre of Industrial Structures the engineer Kashkarov [1] was the author of the design project of the ribbed-shell dome of the Simonov Palace of Culture in Moscow. The section of the dome is shown in Fig. 6.14a. The diameter of the dome's projection was 59.5 m, and the height was 15.3 m. The ratio of the dome's rise to the diameter amounts to: $f/L = 15.3/59.5 \approx 1/4$.

The dome was built from one hundred and twenty-eight meridional ribs of which thirty-two are brought to the central upper ring. Thirty-two longest load-bearing ribs are designated in Fig. 6.14f, g with the symbol **N1**. Figure 6.14c, d presents the section of ribs, and Fig. 6.14 the disposition on the dome's projection of the ribs **N1**, the ribs of an average length **N2**, as well as the shortest meridional ribs **N3**. All the ribs **N1**, **N2**, **N3** were fastened on the lower thrust ring in a distance of circa 1.45 m when calculated over the circumference of the crown. The upper supporting sections of the meridional ribs were connected using ring-shaped latitudinal ribs **P1**, **P2**. Only every second meridional rib was let pass beyond the rings. The last longest meridional ribs were connected in the upper, central ring of the dome. The main meridional ribs **N1**, having in the side view the form with bipolar coordinates, are shown in Fig. 6.14g. They were designed as having a length of circa 30.0 m and the maximum height in the middle of the length h = 1.15 m, which yields a ratio of the rib's height to the dome's projection diameter of $h/L = 1.15/59.5 \approx 1/52$.

The cross section of the meridional rib is made up of an upper chord and a lower chord from planks of 5.0 × 10 cm and 4.0 × 5.0 cm dimensions. The web to connect the chords is duplicated and was made from a 6 mm thick plywood—Fig. 6.14h–j. The meridional, intermediate ribs, similarly to the example demonstrated in Fig. 6.13, are made up of three planks of 5.0 × 8.0 cm dimensions using nails. The ring-shaped sheathing of the first meridional layer of the shell was made from quarterings of a 4.0 cm × 4.0 cm section and placed on the meridional ribs. Three inclined layers from 1.9 cm thick planks each were fastened using nails onto the latitudinal layer (Fig. 6.14f). The structural elements: ribs, the shell, the upper crowning ring and the lower supporting ring were designed following the building rules for ribbed-shell domes and shown in Fig. 6.14.

In the dome of the Simonov Palace of Culture in Moscow 58.3 kg of solid wood were used for the construction and the casing per m^2 of the projection. Steel fasteners were used in the connections: dia. 5 mm nails and dia. 12 mm bolts whose total mass was 1.71 kg per m^2 of the dome's projection [1] (1937). This is such an economical consumption of steel that its repetition in a contemporary produced dome was a failure.

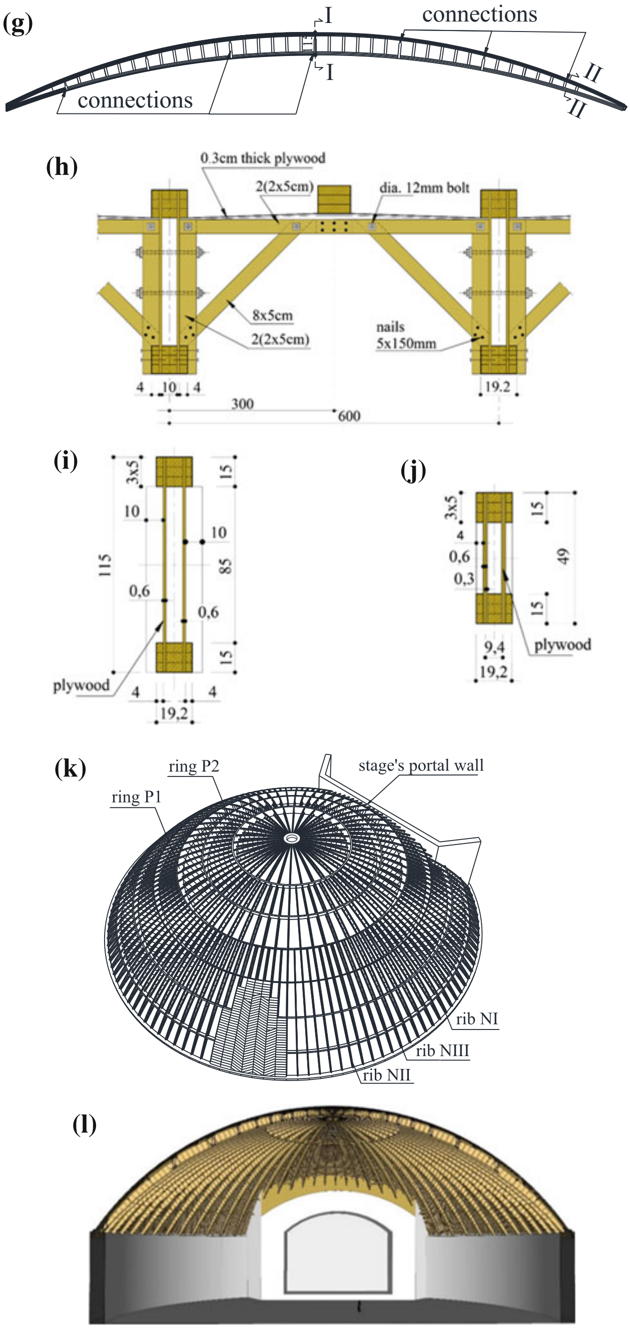

Fig. 6.14 (continued)

6.6 Conclusions

The domes from solid wood described in this chapter constitute an important stage in the search for an optimum structure of roof coverings of a small and average-sized span, as well as of a low eminence. **Among the most important advantages of those rational and economical, worth recalling and reusing structures are**: (1) low consumption of wood and metal fasteners, (2) possibility to use low-grade materials, (3) limitation of wood selection and reduction in waste amount, (4) increase in the span of domes even up to 60.0 m, without changing the assembly technology, (5) increase in the height of load-bearing ribs through nailing several layers of the covering's planks, (6) possibility to join the plank shell with assembly ribs, which considerably increases the load capacity and the stiffness of the construction, (7) possibility to build domes of a low eminence amounting to **h/L = 1/3 up to 1/6** of the base's diameter. According to the recommendations in the paper [1], the rise of the dome should not be, however, lower than 1/6, (8) possibility to limit the scaffoldings at the stage of the dome's erection, (9) possibility to make openings in the shell and reinforcements around the opening even after the building of the dome, (10) possibility to bend planks to the required shape of ribs or the shell.

The system of the layers of covering's planks stiffened the shell in tangential planes, making it almost homogenous, and prevented the translocation of ribs in the plane tangential to the shell, whilst the flexibility of the construction allowed a uniform translocation of forces, created due to thermal and moisture-related deformations. After the consolidation of the three-layer shell with meridional ribs the elements of the central scaffolding to support the central rings were relieved. In the examples discussed in Sect. 6.4 the mass of the lantern placed on the upper ring counterbalanced the prestressed dome's ribs that were tending to straighten.

The fundamental load-bearing element of thin-wall domes are flat ribs made up of three to four planks, bent along the meridians, of a slenderness counted by the ratio of the rib's height **h** to the dome's diameter **L** amounting to **h/L = 1/200 ÷ 1/270**. The ribs were disposed every 1.0–1.5 m over the circumference of the lower supporting crown. The two or three-layer shell, joined with ribs, built from 1.9 to 2.5 cm thick planks, of a total thickness of 5.7 up to 9.7 cm, complements the load-bearing structure of the system.

Steel fasteners of a type: nails, bolts and cast iron clamps were used in order to introduce the mechanical pressure. In the zones of the highest extension, e.g. on the lower supporting ring clamps from steel metal sheet were used, embracing, and not cutting through the wood of the shell's rib.

The production of shell domes and ribbed-shell domes was distinguished by the use of meridional ribs as assembly scaffoldings to be consolidated with the plank shell, prominently increasing the load capacity of the dome. After the years, the light and economical shell systems, shell-ribbed systems, ribbed-shell systems fell into a total oblivion jointly with the people who built them. They were reconstructed after 90 years and described in this work.

In the shell systems domes of a span up to 60.0 m were built (dome of the Simonov Palace of in Moscow), without using steel nodes, which may be considered as a large structural achievement.

The engineers: Kaszkarov K.P. and Sventistky G.W. used plywood for the first time in the construction of domes of a projection's diameter higher than 50.0 m. Worth noticing is the note written in the paper [1] (1937), I quote: "The possibility to use plywood, like in other cases, is dependent on the total exclusion of its moistening after the commissioning".

The described constructions of shell domes and ribbed-shell domes constitute exquisite examples that should presently inspire to work on the solutions of environmentally beneficial contemporary domes.

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