Chapter 3
Multi-Shell Domes

3.1 Introduction

The Renaissance brought into the Western-European building masonry two-shell domes, lighter than the massive, one-shell Roman concrete or masonry domes from stone or brick. When the requirements for prestige led the dimensions of two-shell domes to a weight exceeding the load capacity of scaffolding systems from wood known at that time, it was necessary to introduce lighter and slimmer double masonry domes. Such shells, susceptible to non-symmetrical and concentrated loads, required a shielding structure to protect against the load by wind and atmospheric precipitation. Outside wooden scaffoldings as shielding structures were introduced. It has been shown in this chapter how the systems deriving from the scaffolding building practice affected the development of the construction of domes.

3.2 Wooden Scaffoldings for the Building of Masonry Structures from Stone or Brick

The daily practice of the building of masonry facilities from stone or brick included various types of ceilings, vaults and masonry shells that were erected on light and resistant supporting structures. Also, smaller stone and ceramic domes were constructed on wooden scaffoldings. Inventive bar structures were erected, having static schemes allowing to transfer high loads. The shaping methods of scaffoldings, proven at the building of heavy masonry vaults, were imitated and propagated. The building of wooden scaffoldings started the optimization process of light engineering structures from wood. Those systems were sort of prototypes of wooden dome structures.

B. Misztal, *Wooden Domes*, https://doi.org/10.1007/978-3-319-65741-7_3

Along with the development of technology and the new challenges of successive epochs, more and more interesting solutions of wooden structures appeared. It may be presumed that the building technology of wooden scaffoldings moved to the general building trade owing to carpenters knowledgeable in various structural solutions, their knowledge practiced in masonry building. The role of bricklayers and skills of carpenters in the forming of masterpieces of architecture is not to be underestimated.

Various wooden truss systems were used for the building of scaffoldings. Shown in Fig. 3.1a) is a sketch of a scaffolding compiled on the basis of the manual by the French architect Eugène Violet-le-Duc according to [1]. He reconstructed the historical solutions of scaffoldings structures used for the building of shells and vaults. The scaffoldings exhibited were used for the building of masonry vaults of a span up to a dozen or so metres.[1] The floor from planks was built on a scaffolding, with an upper chord from arch centres, with outside edges cut according to the radius of the vault curvature. The vault bricks, connected with mortar, were laid on the floor from planks.

An example of a wooden scaffolding shaped for a heavy, masonry cross vault is shown in Fig. 3.1b according to [2]. The scaffoldings bars were made from several layers of arch centres cut out from planks, according to the methods shown in Fig. 3.2. Load-bearing ribs (bars) were consolidated with the plank shell, creating ribbed shells on which vault bricks were laid. In the example shown (Fig. 3.1b), in order to strengthen the scaffolding, the nodes of bars from arch centres were supported with pillars. Wooden tie rods were applied at the base of the arches of the wooden scaffolding, in order the transfer expansion forces at the stage of bricklaying.

The skill of cutting out arch centres from straight planks and their connection into arch elements affected the development of the building technology of wooden structures. Shown in Fig. 3.2 are the methods of cutting out arch centres from planks and the option of their connecting in flat arches - Fig. 3.2c. The planks cut as in Fig. 3.2a, b were laid and connected with nails as in Fig. 3.2c. Ribs, built from two or more layers of arch centres, constituted the load-bearing structure of the planking to construct headers, cylindrical or ribbed vaults, tiny cupolas or as upper chords of the trusses that supported plank shells of large spans required in the building of massive masonry structures.

The constructing of arched ribs from arch centres also allowed to build apparent vaults in more modest sacral, dwelling or temporary facilities, e.g. built on the occasion of local feasts. The interpenetrating cylindrical shells from wood were used as various cross vaults in sacral facilities. An example of a wooden vault is that of the cathedra of 1192–1280 in the cloister at the Cathedral in Lincoln in UK

[1] *Dictionnaire raisonné de l'Architecture française* of 1854–1868.

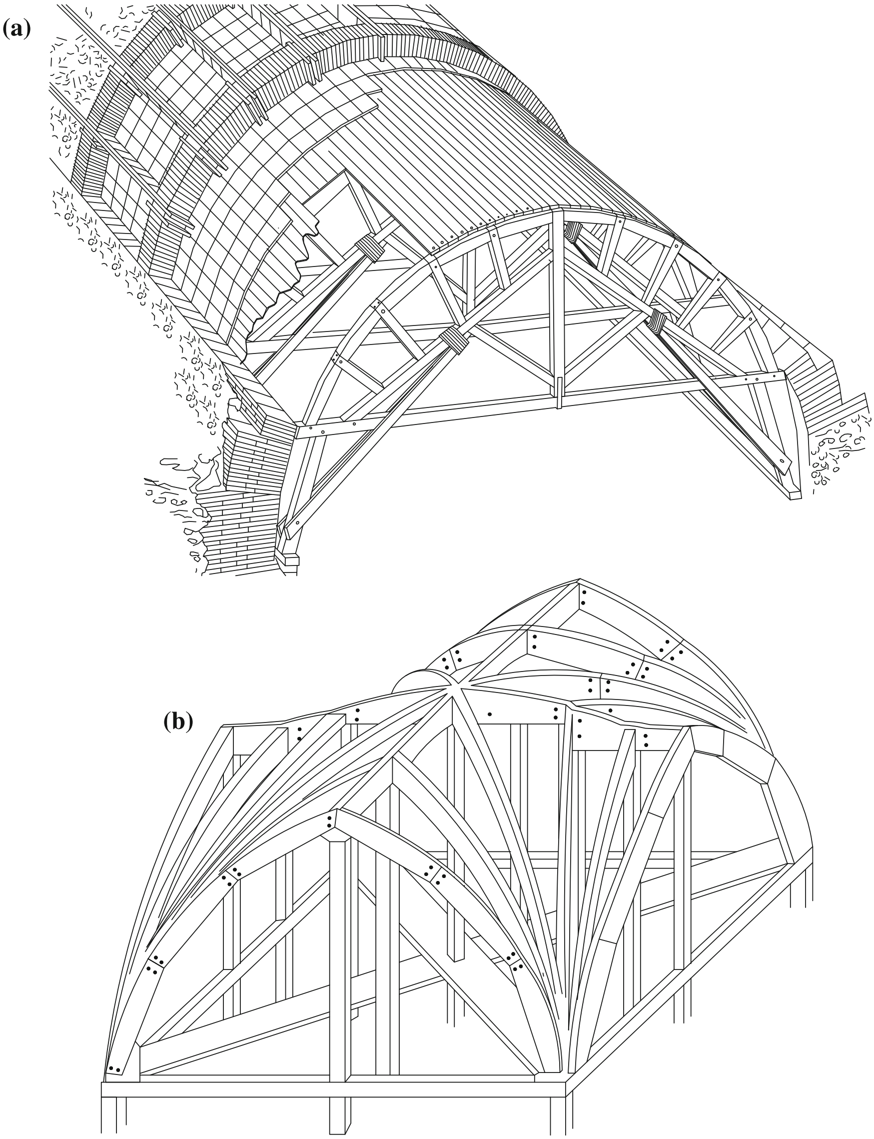

Fig. 3.1 Scaffoldings for the building of vaults, **a** masonry cylindrical vault [1], **b** masonry cross vault according to [2]

[1], as presented in Fig. 3.3. The shell-ribbed vault made in wood in the 13th century has been an instructive example of an open shell roof covering until today.

The architect Philibert de l'Orme, who lived in the years of 1510–1570 in France, introduced to the building trade, arches from arch centres, cut out from

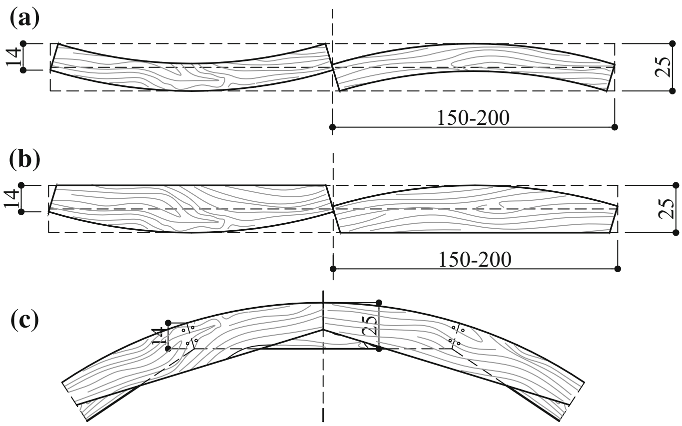

Fig. 3.2 Rules of constructing arches from arch centres [13]: **a**, **b** methods of cutting out arch centres from straight planks, **c** connecting method process of arch centres into a scaffolding bar. The dimensions are specified in [cm]

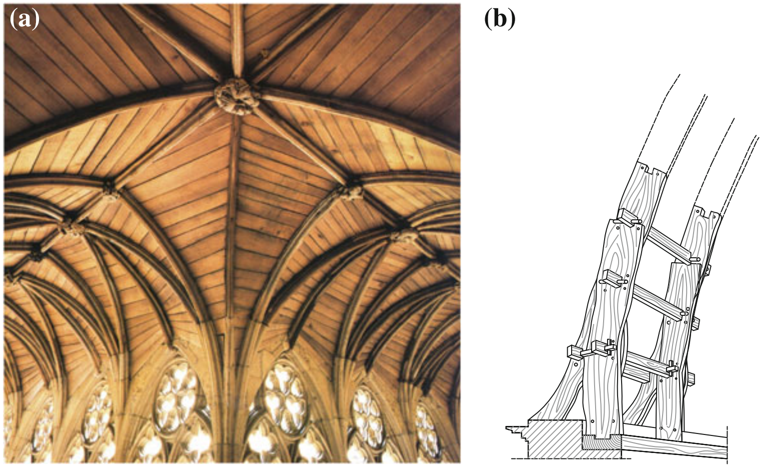

Fig. 3.3 Example of application of arch centres in construction: **a** wooden vault from the 13th century in the cloister at the Cathedral in Lincoln, UK [1], **b** arch by Philibert de l'Orme according to [6]

straight planks following the rules shown in Fig. 3.2. They appeared as single and connected pair-wise arches, as shown in Fig. 3.3b. Double arches from planks were used by de l'Orme to build cylindrical vaults and roofs in the 16th century in France.

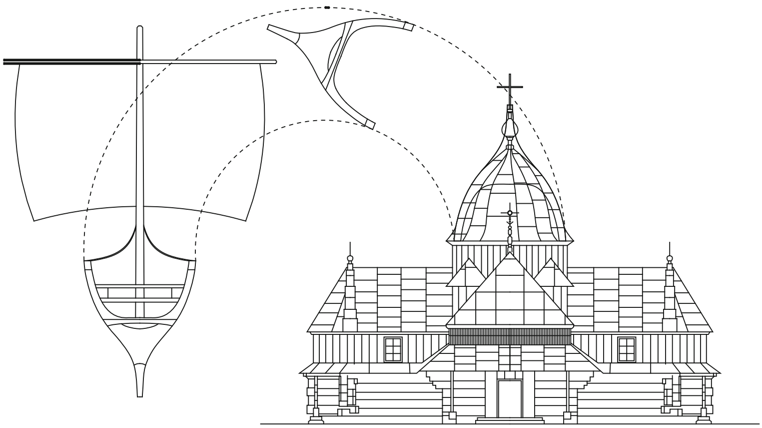

Fig. 3.4 Transfer of experience in sailing into building according to [3] vol. 2

The solutions from various fields of technology were mutually inclusive. Taras J. describes in his work [3] (2007) a solution known from the building of ship ribs encountered in the structure of church domes in north-eastern Europe—Fig. 3.4.

In the International Maritime Museum in Hamburg (*Internationales Maritimes Museum Hamburg, Hafen City*) exhibits were demonstrated illustrating the process of the material selection for the building of ship structures. The criterion of the wood species choice is ignored. Owing to the exposure, it is possible to learn which tree trunks from a wood were selected to fabricate the ribbed structure of vessels. Trees having the shape close to the geometry of ship ribs were looked after, e.g. such as in the example in Fig. 3.4. Shown in Fig. 3.5 are the photographs of the models from the exposure in the International Maritime Museum in Hamburg illustrating how the load-bearing ribs of a ship from selected tree trunks were cut out.

The shaping of ship structures demonstrate that ship carpenters were aware of the meaning to maintain the fibrous continuity of the wood structure. They tried to build the structure using the natural arrangement of wood fibres in selected tree trunks. Intuitively, they appreciate the anchoring of fibres in the mass of parenchymatous cells (visco-elastic matrix). Owing to this, they obtained the elements of the ship structure of an increased strength. The durability of ribs was provided by the cutting-out of elements from the central, heart-wood part of the trunk. The meaning of the maintenance of the natural wood structure, built from fibres anchored in the visco-elastic matrix, is explained by the author basing on the works by Kowal Z. in Chap. 9 of the monograph.

The proven ribbed structure of a boat adapted to overcome the forces of the sea element was introduced to the building trade where considerable climatic loads occurred and a higher load-bearing capacity and durability of the facility was required.

Fig. 3.5 Exposure in the International Maritime Museum in Hamburg illustrating the selection process of trees having a shape favourable for the building of ship rib structures. Photograph by the author, 2017

3.3 Wooden Covering Domes Developed from the Wooden Scaffoldings of Masonry Domes

The scaffoldings used to erect heavy vaults and masonry domes were separated in the course of time as independent wooden structures. Originally, the structure of the scaffolding was just used to support the masonry cylindrical shell or the cross vault (Fig. 3.1). As the structure of the scaffolding was perfected, they started to be used also to cover and strengthen the masonry dome from the outside. The outside wooden structure, covered the inside single-shell or double-shell masonry dome, protecting it against destructive weather effects.

3.3.1 Multi-shell Domes Built in the Middle East

In the 7th and 8th century AC, two and three-layer structures of wooden domes were built in the Middle East. Shown in Fig. 3.6a is the location of the domes discussed in this chapter: the Dome of the Rock and the Al-Aqsa Mosque in Jerusalem and the mosque in Isfahan, Iran.

Its designer, surely a Byzantine, consciously used the option of splitting outside and inside loads, in order to accomplish the concept of the two-shell dome. 745 years before the construction of the two-shell dome of the Santa Maria del Fiore Cathedral in Florence, an unknown builder designed and executed a two-layer dome.

Probably, this is the first in the history bar structure in which the wooden outside structure transfers climatic loads, and the other shell, the inside one, transfers its own weight and the interior decorations. The two-layer structure of the dome is

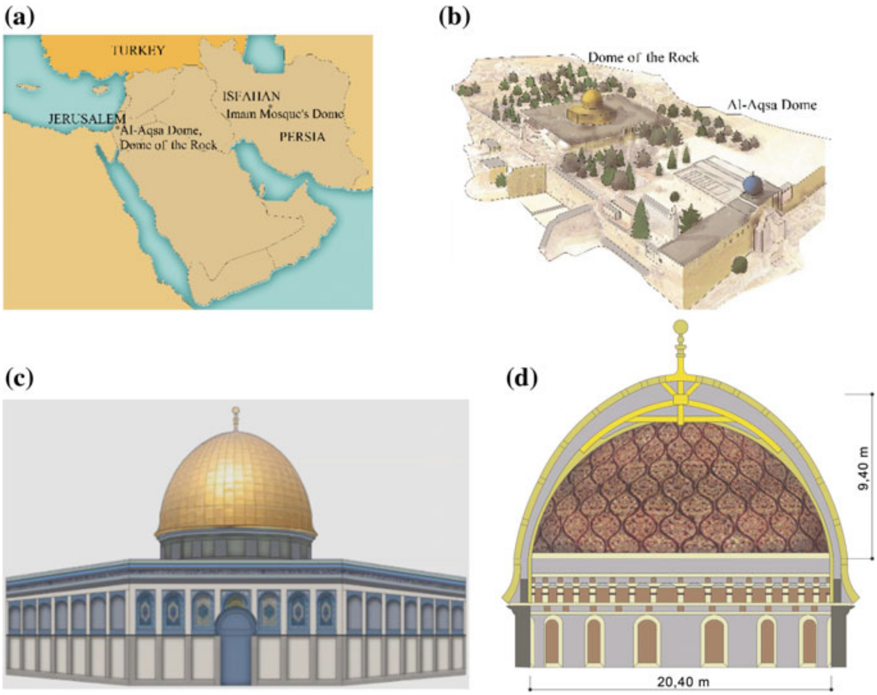

Fig. 3.6 The Dome of the Rock in Jerusalem built in the years 687–691 AC, of a 20.40 m diameter, according to [1, 4], **a**, **b** location of the domes, **c** view of the temple crowned with the Dome on the Rock, **d** vertical section of the structure of the dome ribs and shells

made up of: an outside shell, having the structure of a roof truss arch, and an inside dome connected in the key block using a stiff node with the outside dome. The stability of the structure is provided by a stiff node in the dome key block. It is not known whether this building method was brought in the territories by Arab builders from the areas abounding with woods, or those are examples to confirm the high civilization or technological development of the Byzantine culture.

In Jerusalem, in 715 AC, a two-shell wooden dome was built, crowning the Al-Aqsa Mosque, shown in Fig. 3.6 [4]. Its structure is exceptional due the static operation. It was built from two canopies, made as ribbed shells from planks, and was placed axially the one in the other. The support ring fastening meridional arches was set on a masonry ring of a 11.5 m diameter. The eminent outside canopy transfers the climatic load, the semi-spherical inside canopy transfers the own weight. The outside canopy was made by cutting off the sphere below the equator. The ribbed inside canopy was made as one-half of the sphere. The skilful choice and juxtaposition of the outside and inside canopies led the builders to reduce the horizontal forces on the structures of the supporting walls, built, maybe, from a weak brick dried in the sun. Such shaping of the domes gives evidence of the advanced knowledge of their builders.

The effects of the interference of the compression forces in the ribs of the outside dome were reduced, by introducing sloping bracings—crossheads to protect outside meridional ribs, against buckling. The statics of the dome, legible and simple, creates an exceptionally beautiful structural solution.

The beauty of the dome is exhibited by the model made on the basis of [4] at a 1:50 scale, presented in Fig. 3.7.

Wood in Arab countries was used sparingly. Only in prestigious facilities, erected as a proof of significance and richness, wooden bars to transfer stretching and bending were introduced to the structure. An example is the dome of the mosque Masjed-e Shah in Isfahan originating from the years 1612–1630, shown in Fig. 3.8, developed on the basis of [1]. Two thin-wall, masonry dome canopies were connected with an internal scaffolding from wood. The lower masonry dome of a 21.40 m diameter rises up to the height of 36.3 m above the floor level. The outside dome reaches the height of 51 m from the skewback to the key. The inside wooden bar structure was also used as a scaffolding required to erect and strengthen both the domes. The outside dome was constructed on it. Upon completion of the construction, the scaffolding was left as a bar membrane supporting the light masonry shell, shielding the inside sphere. The split masonry shells were joined with a bar structure from wood and adapted to the transferring of various loads, mainly load by wind by the outside shell and the own weight by the masonry inside dome (Fig. 3.8). The scaffolding from wood also transfers the forces of strutting, stretching and bending.

The significance of the structure shown in Fig. 3.8a, b consists in the creation of the brick-wooden joined domes in which the wooden scaffolding to the joining of the outside and inside brick shell of the dome is used. This concept was initiated by Byzantines in the 7th–8th century, afterwards it was perfected by other, talented builders.

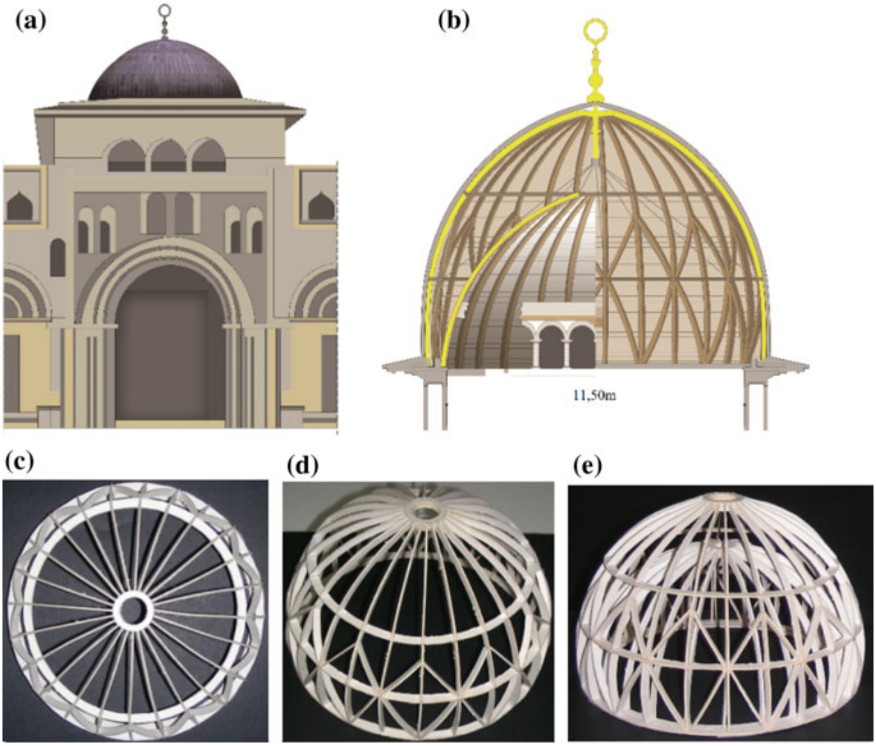

Fig. 3.7 Figure and model of the structure of the dome of the Al-Aqsa Mosque built in Jerusalem in 715 AC to [4], **a** view of the Al-Aqsa Mosque **b**, two-shell structure of the dome of a 11.50 m diameter, **c** model—top view of the outside dome, **d** model—side view of the outside dome, **e** model—view of the inside and outside dome

It is worth noticing the quantity and variety of masonry domes used as roofs of various building structures in Persia—Fig. 3.8c, d. Visible on the photographs are the 3 domes of mosques and those of other building structures. They were generally built due to their effectiveness, from the most available material in those areas—brick from clay dried in the sun.

Perhaps the statics of the domes as presented in Sect. 3.3.1 derives from the need to save wood as construction material, and from the need to reduce horizontal loads on load-bearing walls, also from the wick brick dried in the sun. The brick, the most frequently used as the most available material in the given area, fixed the template of the dome occurring in the architecture of the southern Europe and the Middle East. Shown in Fig. 3.9 and developed according to [5] are the most often achieved forms. It may be presumed that the specific shape of arches, e.g. of Grenada and Cordoba, shown in Fig. 3.9, is not just a decoration characteristic of that architecture, but it follows from the careful use of the system and the material.

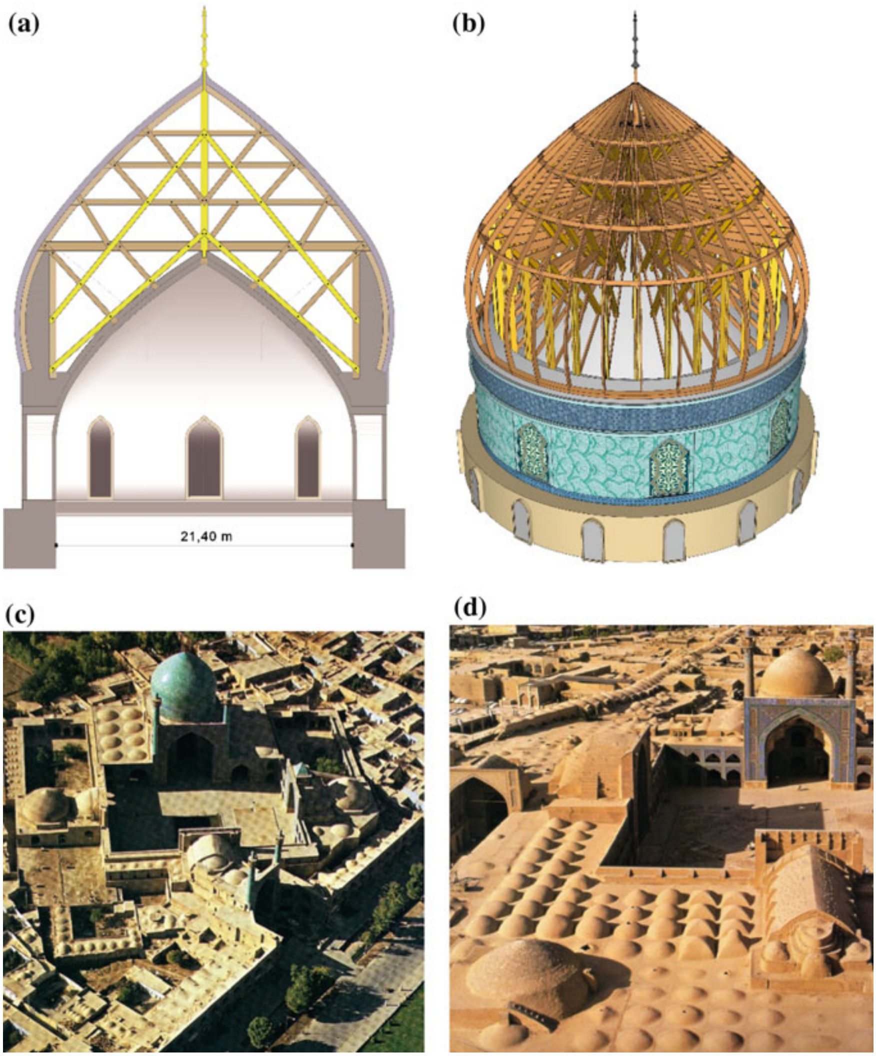

Fig. 3.8 The domes covering the building structures in Isfahan, Iran to [1]. **a** Section of the structure of the central dome of the Masjed-e Shah Mosque, **b** visualization of the structure, **c** top view of the central dome and those in the surroundings of the Masjed-e Shah, **d** top view of the central domes and those in the surroundings of the Friday Mosque in Isfahan [16]

3.3.2 Multi-layer Domes Built in Europe

On the basis of the references retained, it may be noticed that the invention of the two-shell masonry dome in shells joined using an internal scaffolding has been known in Europe since the Middle Ages. At that time, the central bar structure

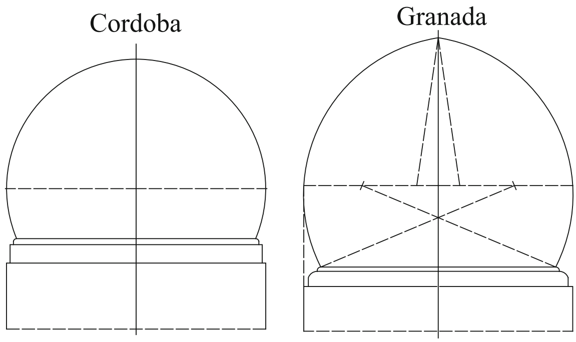

Fig. 3.9 Shapes of the arches of Cordoba and Grenada [17]

(Fig. 3.10b) covering the inside masonry dome and stiffening the outside dome, bricked or shaped on meridional arches from arch centres, was introduced. The lower masonry shell transferred its own weight and that of the interior decorations, the upper outside shell rested on a wooden scaffolding. The bar structure from wood was constructed so as to transfer the load from the lantern—the conical part of the bars—Fig. 3.10d. The latitudinal ribs supported with pillars with angle braces, supported meridional arches from arch centres on which the latitudinal shell from planks for the elements of the outside roof covering were made. In this way the solutions of three-layer domes, lighter than those of heavy masonry one or two-shell domes were formed. An example are the domes of 1063-1031, as described by Heinle E., Schlaich I. in the work [4] (1996), characteristic of the Saint Mark's Basilica in Venice. The view and the section of the domes are shown in Fig. 3.10. In the crosscut of the aisles of the church, three-layer domes were built, having two shells: an inside masonry shell, an outside shell on ribs from arch centres. A scaffolding from wood was made between the outside shell and the inside shell—Fig. 3.10b. In this way five domes were built, of which the largest, central dome has a span in projection of 13.0 m. Shown in Fig. 3.10c, d is the view and the structure used in the building of the lateral dome of a 10.0 m diameter.

Figure 3.11 shows the three-layer dome crowning the Saint Paul's Cathedral in London to [4]. Upon destruction during a fire of the earlier roof of the tower, the builders feared to erect the conventional heavy masonry structure of the new dome on fire-weakened pillars of the building.

This resulted in a need to assume a lighter structure. The new dome of the Saint Paul's Cathedral in London came into being in the first decade of the 18th century, about 1710, in accordance with the project design by the astronomer and architect Christopher Wren. Two masonry domes and the third outside shell were made on a wooden scaffolding, as a wind shield for two inside domes. The height from the floor level to the highest section of the steel cross positioned on the lantern totals 108.0 m.

The masonry inside domes of the Saint Paul's Cathedral in London: the semi-spherical and the conical dome (Fig. 3.11) operate in tandem in the transfer of vertical loads. The conical dome supports the load of the lantern, transferring the

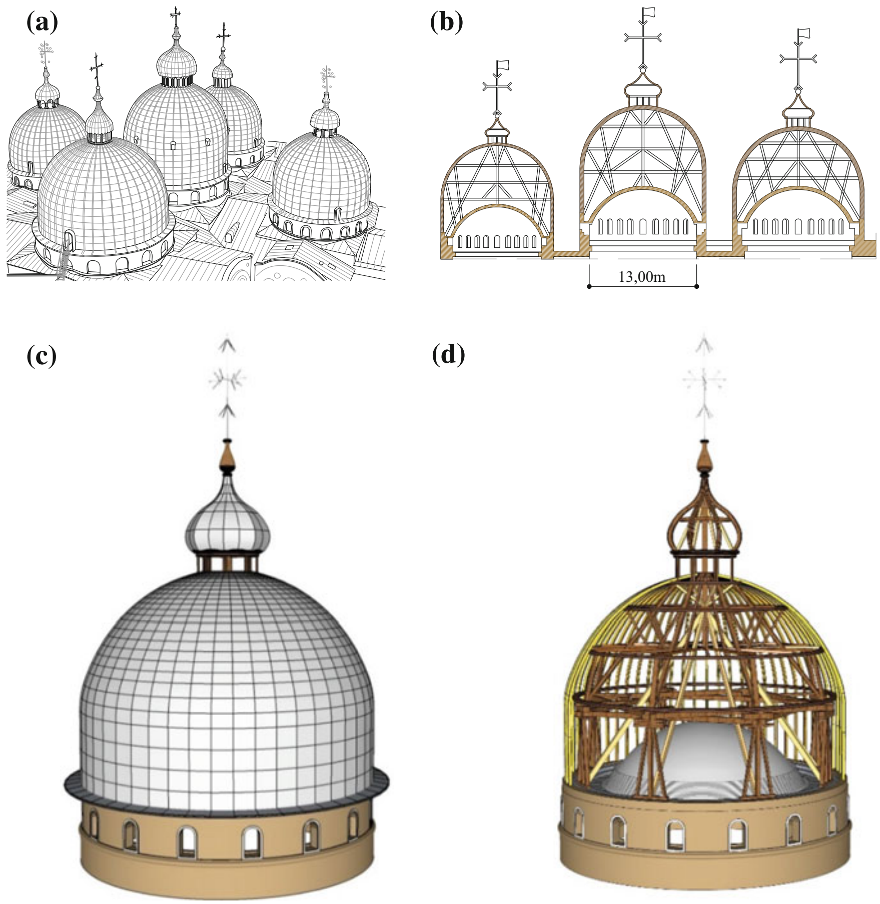

Fig. 3.10 Venice—Saint Mark's Church, 1063-1031 according to [4, 6], **a** view of the roof, **b** cross-section of the three domes, **c** view of the side dome of a 10.0 m diameter, **d** visualization of the dome's structure

vertical forces onto the circumferential ring common with the semi-spherical internal dome, built as a masonry double ring. The bottom dome, of a circa 32.0 m diameter of the horizontal projection, transfers the load by own load and the rich architectonic detail giving evidence of the rank and function of the facility. The pillar-purlin structures of the outside scaffolding, surrounding the conical dome, were helpful at the stage of building both the masonry domes, later on as a shield against the load by wind. The outside arch elements of the domes on which the coating was laid burdened the separate, outside, tensile support ring.

The dome of the Invalids Church in Paris also has a three-layer structure (Fig. 3.12). The outside wooden dome of an 80 ft, i.e. 25.0 m diameter of the horizontal projection and a height 16.0 m to the lantern basis [6] was designed by

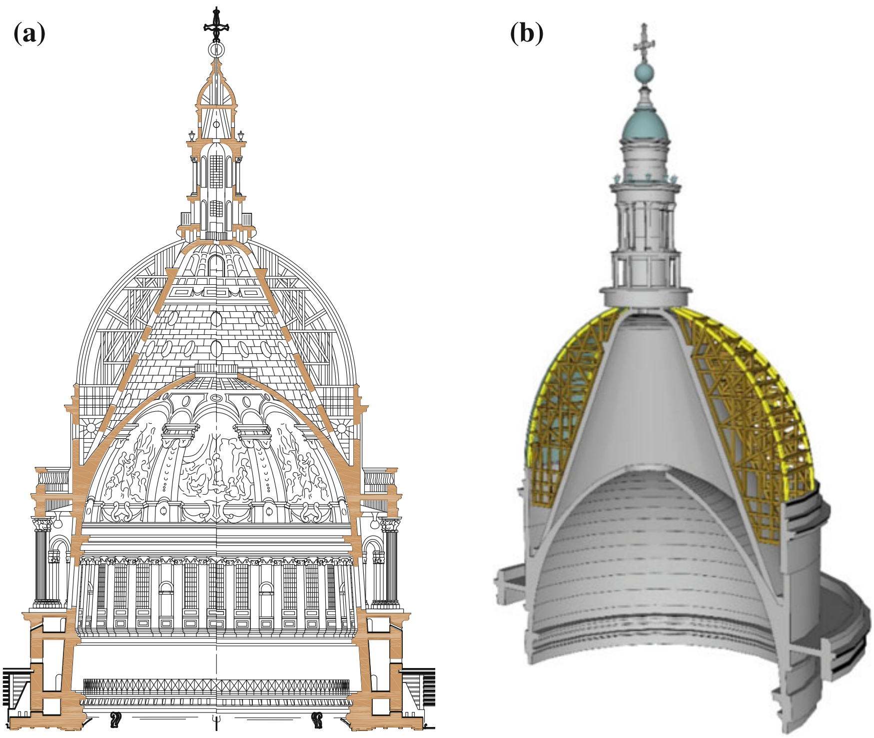

Fig. 3.11 London—St Paul's Cathedral, 1710 to [4], **a** section of the dome, **b** visualization of the structure

the engineer Mansart J. [5], and was built in 1693 until 1706. This talented designer of wooden roofs resolved the outside, wooden bar structure so that it could transfer the vertical load with the lantern and the horizontal load from wind. Two masonry inside domes, set up on a ring of a 25.0 m diameter, have transferred the own weight and the load by the décor of the inside.

The outside dome of the Saint Nicholas' Church in Potsdam (Fig. 3.13) in the wooden version was designed by the master builder and painter Karl von Schinkel [7]. The wooden construction had to shield the inside masonry dome of a 10.0 m diameter.

The outside element of the scaffolding giving the shape to the dome in Potsdam were ribs from arch centres of the dimensions: 5 cm thick, 30 cm wide each. The total thickness of the meridional rib from arch centres amounted to 15.0 cm. On the meridional ribs, at the spacing of 1.50 m each, latitudinal stiffenings from three arch centres of the 5 × 25 cm dimensions were designed. Finally, the wooden dome was not built due to the interest in iron that at that time was introduced to the building trade. The design of the wooden dome was replaced with another one. The dome was built in 1830–1849 from cast iron [7]. The bar structure of the inside

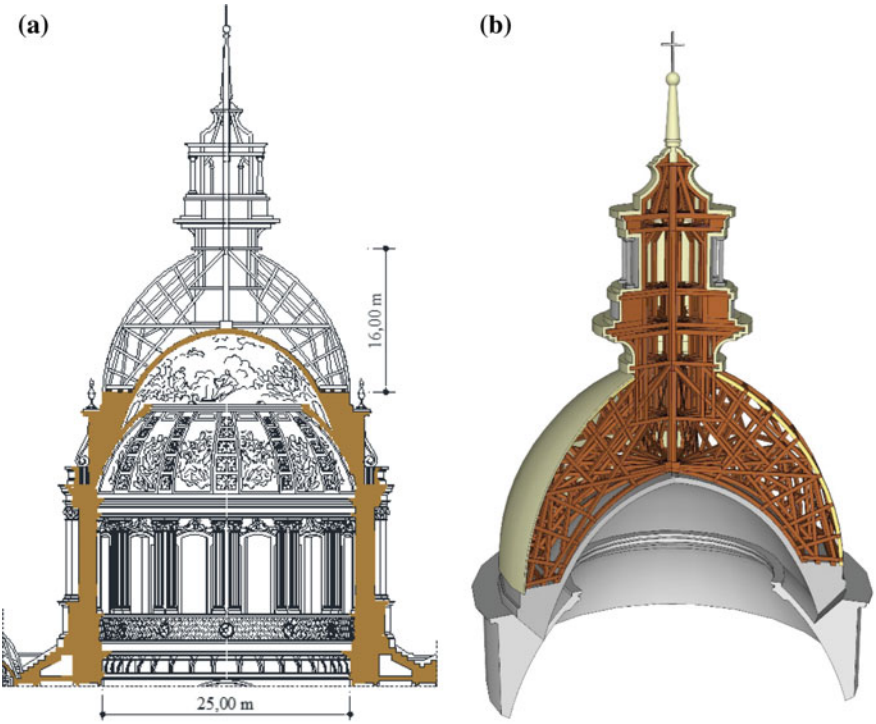

Fig. 3.12 Dome of the Invalids Church in Paris, 1693–1706, design project by the engineer Mansart J. Ch. to [4], **a** section of the dome, **b** visualization of the structure (Bourget P., Cattaui G. *Jules Hardouin Mansart* Éditions Vincent&Co, Paris)

casing of the masonry dome of the diameter of the horizontal projection of 10.0 m was made so as it could transfer the vertical loads from the lantern and the horizontal forces from wind.

The data collected in this work on the multi-layer structures of the wooden-masonry domes are incomplete. **The detailed inventory of paintings and the décor, as existing in the referenced literature, is not related to the information on the structure on which those works came into being**. Such is the situation in the majority of domes completed. The data on the structure, especially the outside load-bearing wooden dome, are inaccurate, without numerical sizes. Sometimes, those are fragmentary figures, as for instance in the case of the dome of the church shown in Fig. 3.14 according to Durand J.N. (1800). An interesting structure of the outside dome is shown fragmentarily. One may presume that it was constructed from arches of two chords interconnected with pillar lacings. **The fragmentary figure exhibits, however, that by chance,** (without paying special attention), **one of the most important technological events of the epoch was shown: the structure of the two-layer shell of a wooden dome**.

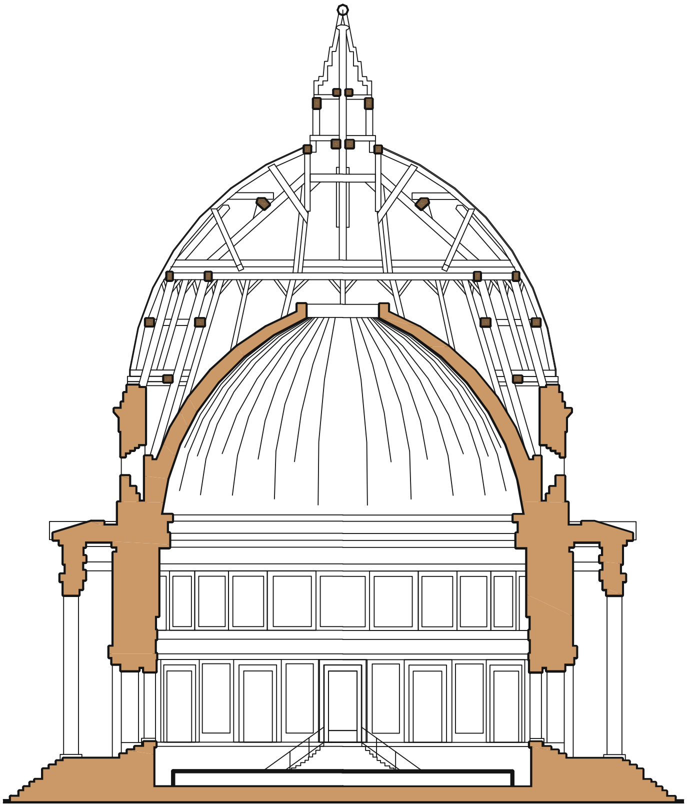

Fig. 3.13 The duplicated structure of the dome of the church in Potsdam according to [7]

In 1631, in Venice, the construction of the Santa Maria della Salute Basilica started. The designer was the Italian architect and sculptor Baldassare Longhena. The basilica is shown in Fig. 3.15. This is a structure in the style of the Venetian baroque, crowned with cupolas, the central cupolas having the diameter of 60 Venetian feet[2] each, i.e. 20.63 m. The two-coating canopy is supported on an octagonal tambour. The presbytery adjacent to the central part was roofed with a dome of a lower diameter (Fig. 3.15a). The structure of the outside casing from wood of a 23.0 m diameter [6] shields the central inside masonry dome of a circa 20.60 m diameter. The multi-layer dome of the Longhena's basilica was built following the rules discussed in the previous examples. The view is shown in Fig. 3.15a, b, the schematic of the section is shown in Fig. 3.15c), whilst in Fig. 3.15d the visualization.

[2]1 Venetian foot is equal to 34.38 cm.

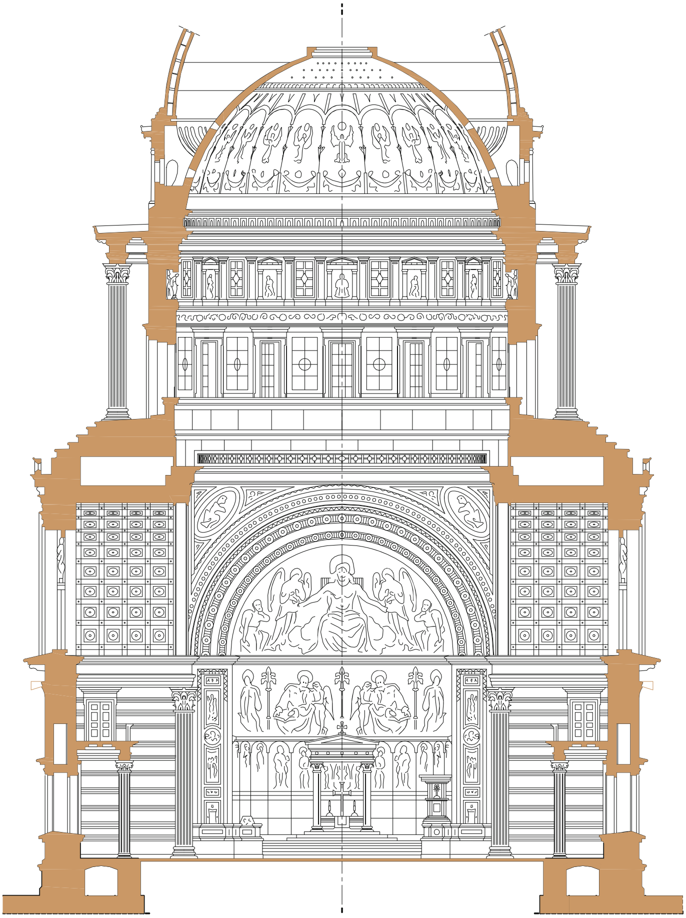

Fig. 3.14 Rich inventory of the church interior to Durand J.N.L. 1800 (Durand J.N.L. *Recueil Parallèle des Édifices de Tout Genre Anciens et Modernes,* Chez l'Auteur, à l'École Polytechnique. 1800)

The Santa Maria della Salute Basilica as shown in Fig. 3.15 was the inspiration for the founders of the church in Gostyń, Poland, in the 18th century [8]. A masonry dome was ordered from Longhena B., of a diameter of 60 ft, like in the Santa Maria della Salute Basilica in Venice. After the construction, it turned out that the dome had an internal diameter of 17.20 m, and an external diameter of 20.0 m. In Poland, when building the dome, 60 ft were measured, but these were Cracow (crown) feet.[3]

[3]1 Cracow foot, also called a crown foot totals 29.30 cm.

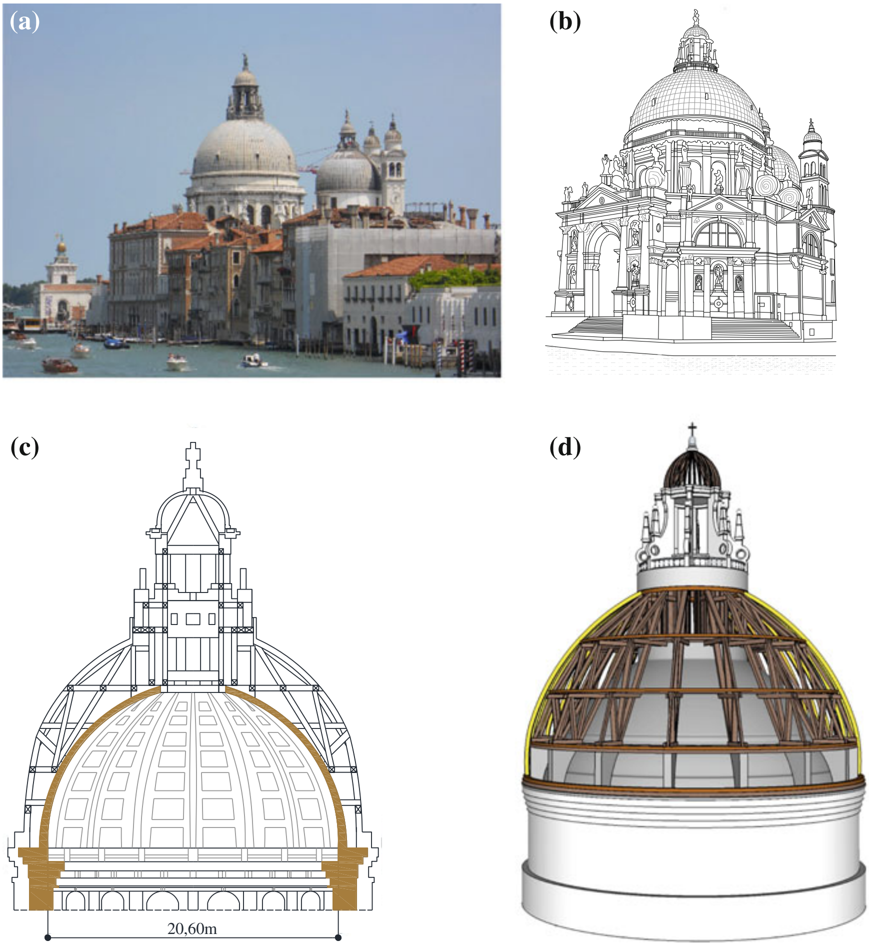

Fig. 3.15 Venice—**a** domes of the S. Maria della Salute Cathedral according to the project by Baldassarre Longhena from 1631 to 1687 [4], photo by the author, **b** view of the central dome, **c** section of the central dome, **d** visualization of the dome's structure [4, 6]

One of the most eminent designers of baroque domes was the architect Balthasar Neumann born on 27 January 1687 in Würzburg [9]. He designed and built in South Germany. He was the Chief Architect of the town of Würzburg. He also died over there on 19 August 1753. Shown in Fig. 3.16a is the view of the Schönborn Chapel in Würzburg, and in Fig. 3.16b the structure of the dome of a 20.0 m diameter crowning the building built in 1722.

A next example of the introduction of meridional trusses to the construction of domes is that of the Saint Mark's dome of a 16.0 m diameter, in Berlin, shown in Fig. 3.17 according to [10]. The design project was completed in 1846–48 by the

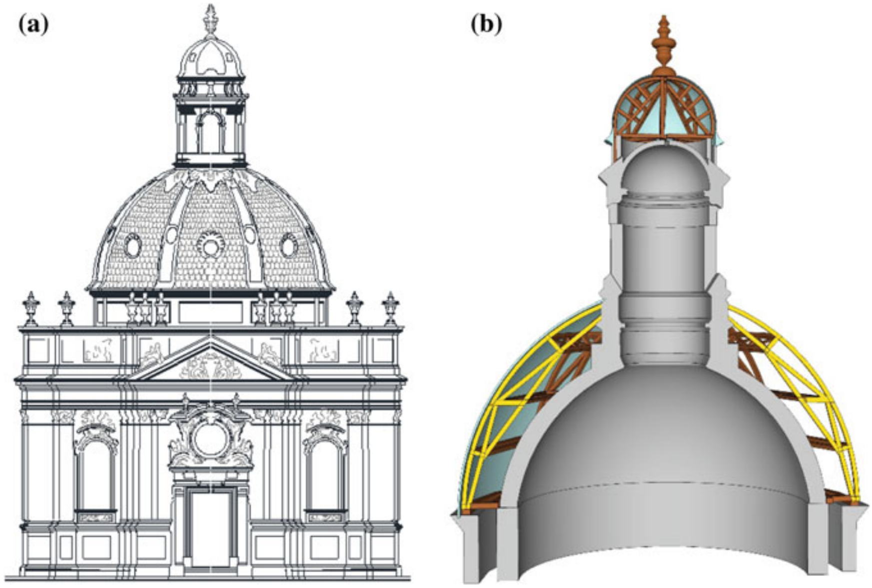

Fig. 3.16 Würzburg—Schönborn Chapel by the architect Balthasar Neumann, 1722, [9], **a** view of the chapel, **b** visualization of the structure

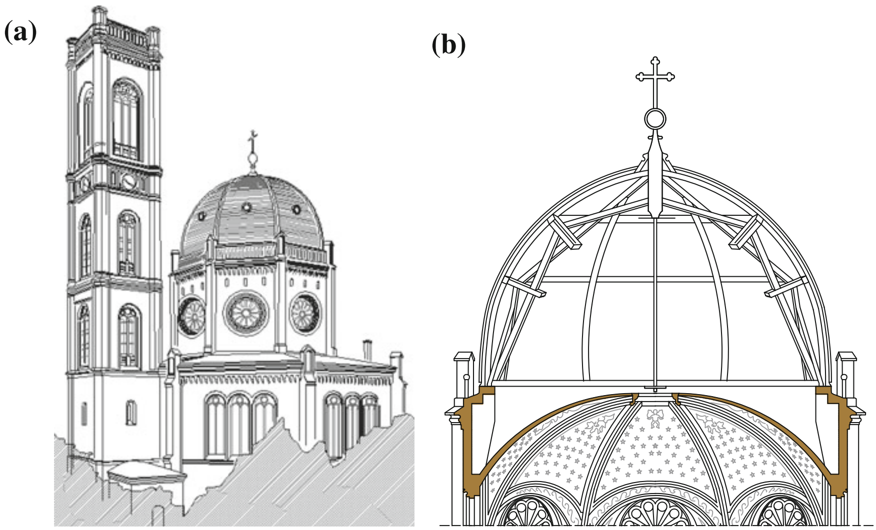

Fig. 3.17 Saint Mark's Church in Berlin built in 1855 [10], **a** view of the church, **b** structure of the dome

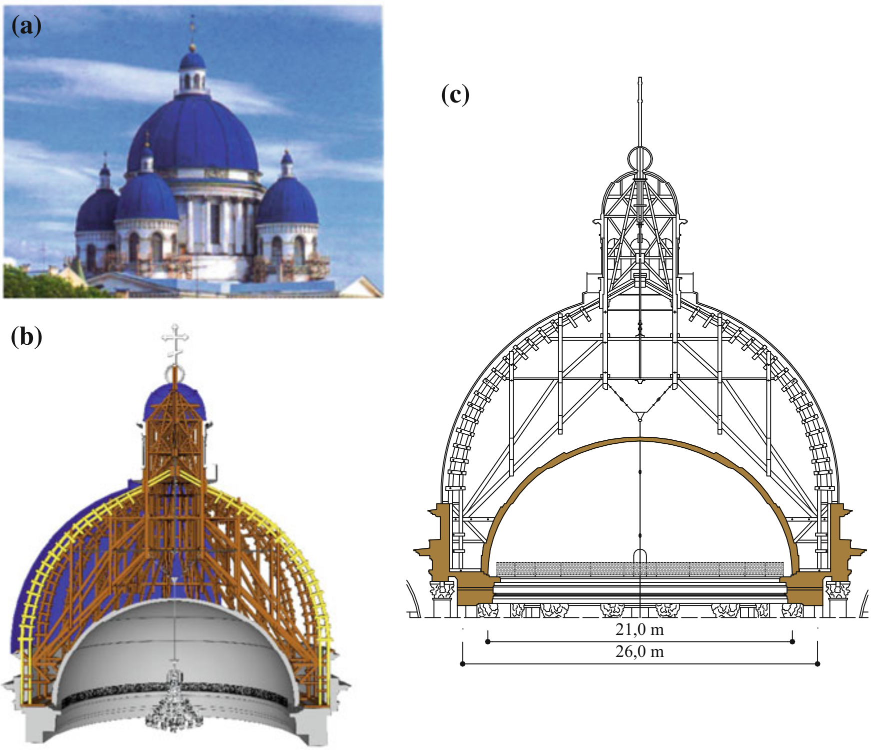

Fig. 3.18 Domes of the Trinity-Izmailovsky Cathedral in Saint Petersburg according to the project by the architect Stasov V.P. [11], **a** view of the domes before the fire, **b** visualization of the structure, **c** view of the structure of 1826

architect Friedrich August Stüler.[4] The building was erected in 1848–1855. In the solution of the wooden outside dome shielding the masonry canopy roof trusses were used. The reconstruction of the structure was made on the basis of the data acquired from the work [10].

Figure 3.18 a presents five domes that crowned the building of the Trinity-Izmailovsky Cathedral in Saint-Petersburg, designed by the architect Stasov W.P. [11]. The building was erected in 1826. The largest central dome was built to the height of 83.0 m. It is made up of two separate shells. The outside shell, having a wooden structure from arches with two parallel chords interconnected with lacings had a diameter of 26.0 m. Underneath there was a masonry dome of a 21.0 m diameter, 22 cm thick in the key block and 64 cm thick in the supporting

[4]Börsch-Supan Eva, Müller-Stüler Dietrich, *Friedrich August Stüler 1800–1865,* Deutscher Kunstverlag, München Berlin 1997, p. 530–531.

zone. The data on this wooden dome were obtained from the paper [11] written on the subject matter of the inside masonry dome after the fire that totally destroyed the wooden structure of the outside dome. The masonry dome was saved, after the wooden one a sketch was left, as well as the view of the dome before the fire, as shown in Fig. 3.18.

Visible on the sketch of the structure of the wooden dome (Fig. 3.18b) are meridional load-bearing ribs. They form a two-chord load-bearing system not encountered in other, previous solutions of dome structures. Maybe this is the historically first bar system characteristic of the dome form developed in successive years, e.g. by the Karlsruhe school. The inside, conical bar system transfers the load from the lantern. The connection of sloping pillars at the lantern base with steel bars allows to suspend heavy chandeliers of the temple lighting system to the roof structure, without burdening the sensitive masonry dome by concentrated forces.

In multi-shell domes built in the 18th century transformations of the outside, wooden bar structure shielding the inside masonry dome are noticed. Eminent architects introduced trusses with an arched outside chord from arch centres with a curvature adapted to the dome radius.

3.4 Multi-shell Domes with an Outside and Inside Wooden Dome

In 1546, the Italian architect Andrea Palladio, known from the design projects of truss systems in the building of wooden bridges, designed the structure of the dome of the Il Redentore Church in Venice of a 14.50 m diameter [12] as shown in Fig. 3.19. The meridional load-bearing arches were executed as two-chord arches, interconnected with studs and crossheads (Fig. 3.19b). The latitudinal bracing was made from horizontal trusses.

It may be presumed from the inaccurate sketch from the work [12] that the outside arch chords were made from plank arch centres, adapted to the dome radius. The two-chord structure of meridional ribs allows the production of a spherical vault also on the inside, creating a resistant two-layer combined structure. The shell from planks nailed latitudinally on meridional ribs was made on the dome's outside and inside. The combined structure transferred the load by the lantern, own weight and non-symmetrical climatic loads.

The building of wooden multi-layer domes was taught in the 17th century at schools of building trades [1]. The handbook example of a two-shell structure from solid wood is shown in Fig. 3.20. The figure was made on the basis of the building handbook of 1691, by D'Aviler A. C. *Cours d'Architecture*.

As the demand for dome-roofed prestigious facilities was growing, their dimensions were also increased. In order to limit the weight of the structure, heavy

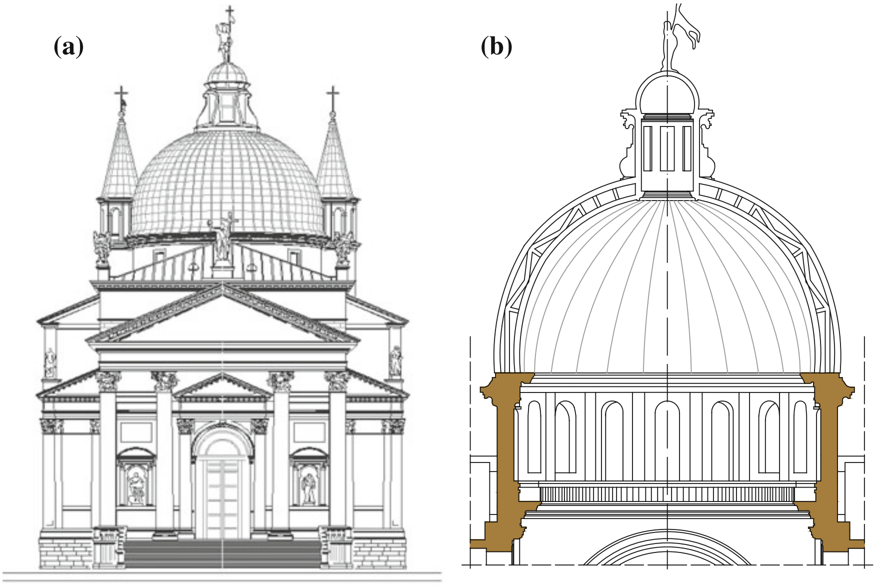

Fig. 3.19 Il Redentore Church in Venice, **a** view of the church, **b** section of the dome [12]

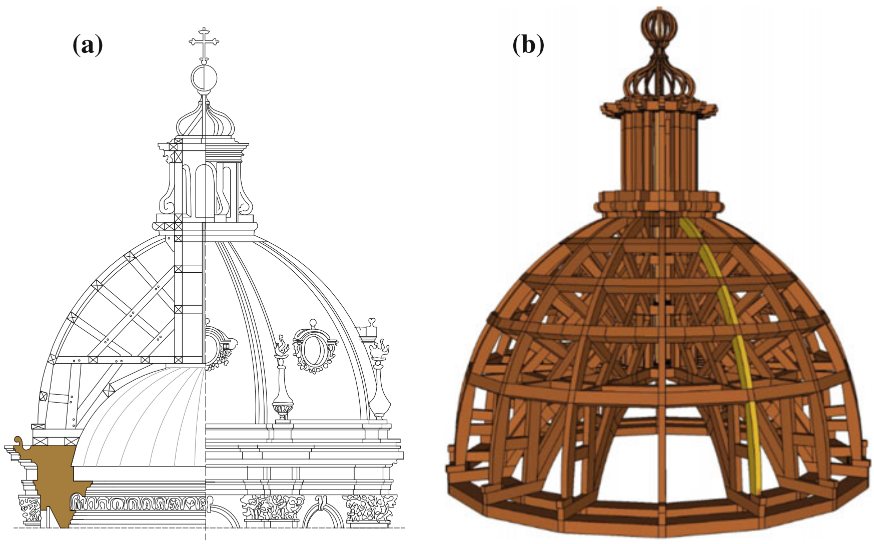

Fig. 3.20 Figure of the dome structure according to [1], **a** section of the dome, **b** visualization of the dome's structure

scaffoldings were replaced with lighter bar structures. Trusses with an outside arched chord from arch centres of the outside edge conforming to the radius of the dome sphere were introduced. The inside chord was shaped according to the radius of the sphere of the inside vault being designed. An example of such a structure of the Saint Stephan's Church in Karlsruhe designed by the architect Friedrich Weinbrenner, built in 1808–1814, is shown in Fig. 3.21.

The dome in Karlsruhe (Fig. 3.21) of a span of 30.0 m was built from twenty main meridional truss ribs with upper and lower arched chord made from arch centres. The outside chords were interconnected with studs and crossheads. Three intermediate meridional ribs were built in between each pair of main ribs. In total, eighty wooden ribs, arranged along meridians were made. The main ribs were connected upside with a central ring of a 6.0 m diameter. The latitudinal, truss rib at the middle of the dome height stiffened the structure, constituting, at the same time, a support for meridional intermediate ribs.

The arch centres that connect the outside nodes of meridional ribs shape the dome and maintain the covering (Fig. 3.21). The arch centres that connect inside nodes form the vault, maintaining plasters and paintings. Each of the trusses that form the dome by Weinbrenner F. is based at the bottom on a skewback support by six truss systems. Arches supporting the circumferential construction were made under the trusses. The supporting wooden structure of the dome was encased with a masonry wall. The arrangement of arches over the circumference of the facility allows to unburden the masonry structure of walls, and the adding to the central room of adjacent aisles of a 12.0 m width [13].

This type of the supporting structure for the dome—a lower ring resting on arches of the first storey was developed in successive Western-European building crowned with domes.

The dome as shown in Fig. 3.22 crowned the building erected on the Nordic Exhibition in Copenhagen in 1888 [13]. The dome was set up on the crossing of the longitudinal and cross aisle, close to the main entrance over the representative central hall. The projection of the dome is inscribed into a square of a 26.50 m side. The tambour rests on the arches of lateral aisles of a 17.50 m height. The tambour resting on the arches has a height of 6.0 m. The dome, from the tambour to the top ring, has a height of 11.50 m. A lantern of a 8.0 m height rests on the central top ring. The lantern structure is made of cast iron. At a height of 20.0 m under the tambour a 2.0 m wide circular gallery was located, constituting, at the same time, a horizontal stiffening of the tambour's structure. The clear diameter of the top ring of the dome totals 9.50 m. Meridional trussed rafters were led out from the four corners of the rectangular projection, the chords of which were interconnected with studs and crossheads in each field along the diagonals. The arches are fastened in the supporting zone by several cast iron anchors. The height of the meridional main ribs of a shape approximating a quarter of a circle, the outside chords of which are created from arch centres, totals 1.75 m.

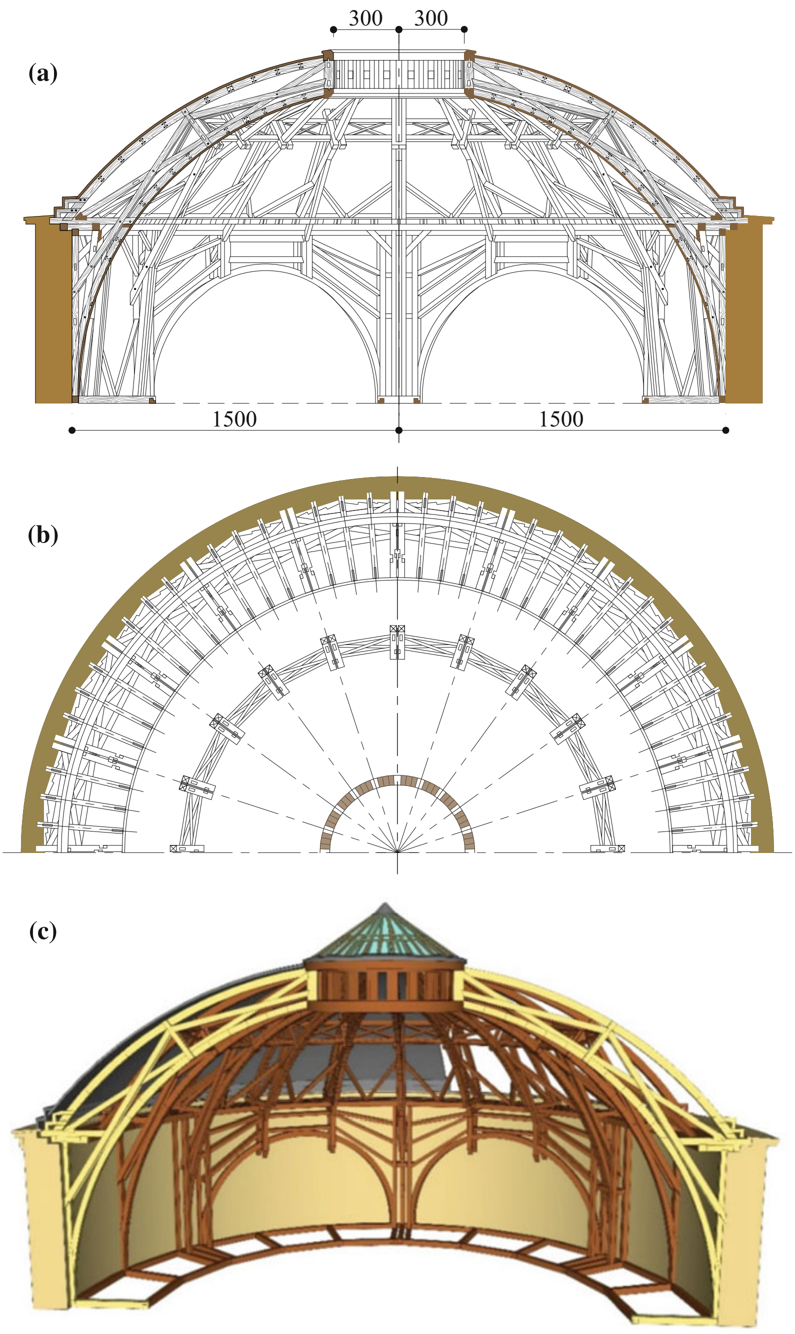

Fig. 3.21 Section and projection of the dome of the church in Karlsruhe by Weinbrenner F. according to [14], **a** section of the dome's structure, **b** projection of the structure, **c** visualization of the structure

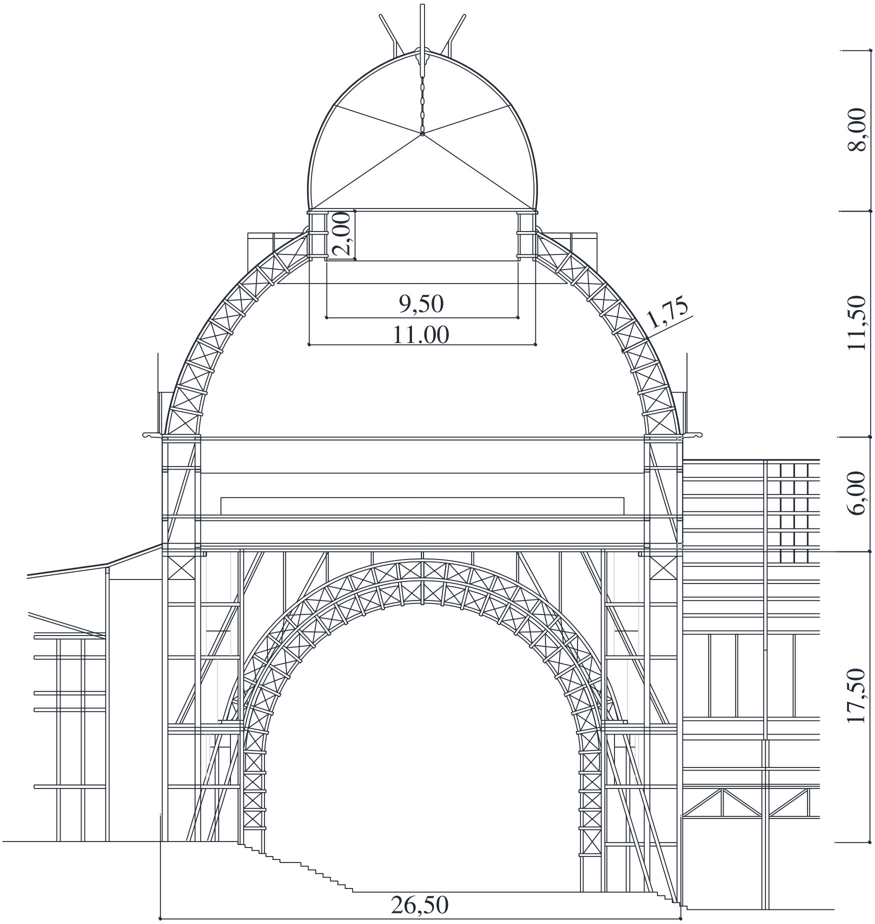

Fig. 3.22 The dome of a temporary facility in Copenhagen was built in 1888 [13]

3.5 Ribbed Domes from Arch Centres

The transformation of the inside scaffolding supporting the meridional arches from arch centres giving the shape to the outside canopy into a meridional-latitudinal system of load-bearing trusses was a breakthrough moment. **The meridional ribs with outside chords conforming to the dome radius were later used by other architects. Weinbrenner F., Neumann B. propagated in the Western-European building trade the dome structures in which already separated load-bearing, both meridional and latitudinal, appeared, characteristic of the dome form as**

shown in Figs. 3.16, 3.17, 3.18, 3.19, 3.20, 3.21**, and** 3.22. The meridional-latitudinal systems of trusses with an outside and inside arched chord made from arch centres were adapted to the radius of the outside and inside sphere. Such structures made possible the execution of two-layer domes deemed more solid.

One of the first structures exceeding the barrier of the 30.0 m diameter in which a wooden arch centre had been used for centuries became a separated load-bearing element is shown in Fig. 3.23, the dome structure by Georg Moller of a diameter of 33.5 m [13], built in 1827 for the catholic church in Darmstadt, Germany. A modern, one-layer was built that, according to Prof. Otto Warth from Karlsruhe, constituted simultaneously “a roof and a ceiling”, which was considered more as its defect than success. The dome’s structure rests on a tambour supported by twenty-eight columns.

In the axially symmetrical dome by Moller arched load-bearing ribs in the meridional direction were used and stiffened with latitudinal ribs. One hundred and four meridional ribs were used, including: fifty-two main ribs, and fifty-two intermediate ribs and eleven meridional ribs. One hundred and four meridional ribs were built from several layers of planks of a 5 × 38 cm section and a 1.60 m length. The main ribs were made from five layers, the intermediate ribs were made from three layers of arch centres, each of a 5 × 38 cm section. Up to the sixth, lower rib, the main meridional rib was made up of five layers of planks, above the sixth latitudinal rib all meridional were built from three layers of planks. Above the ninth main latitudinal rib, every second was cut off latitudinally, bringing one half of meridional ribs to the top ring of the dome.

The meridional ribs were mounted on a foundation from oak wood laid on walls of the lower storey. The meridional ribs were mounted jointly with the latitudinal ribs, as they were erected. In the first order, in order to support the main ribs, the meridional ribs from a single plank of a 1.25 × 10 cm section perpendicularly to the plane of the lower stiffness of the meridional rib were mounted. In order to counteract the buckling of arch centres of the meridional ribs, in the contact sections with the meridional ribs, horizontal “plugs” were used, double at the main ribs, single at the intermediate ribs—Fig. 3.23b. **Both the ribs and the “plugs” were made from dry oak wood. Each stage of the dome’s erection process was closed with latitudinal ribs with two chords: an outside and an inside chord from young oak wood**.

Every second circumferential latitudinal rib was made as a beam having two concentric chords, embracing meridional main ribs and intermediate ribs, Fig. 3.23b–d. Those ribs were made from beams of a 2.5 × 10 cm section from young oak wood. The latitudinal chords of the hoop were connected from drawn iron wire of a 10 mm diameter. **This encountered a critic by Prof. Otto Warth who wrote in his work [13] that rather wooden fasteners should have been used**. In order to prevent an uneven settlement of meridional ribs, horizontal, outside, latitudinal chords were let into meridional ribs to a depth of 1.25 cm, by making cuts in the arch centres of meridional ribs, as shown in Fig. 3.23d.

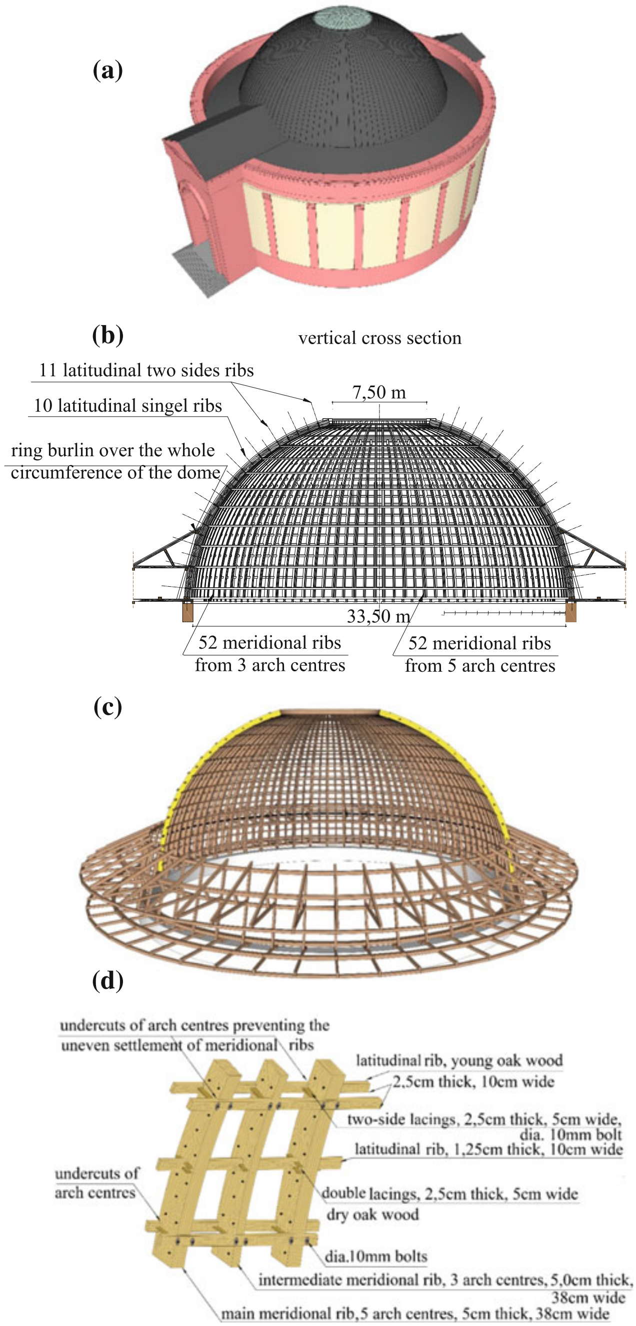

Fig. 3.23 The Moller G.'s Dome in Darmstadt, Germany, of a 33.5 m span according to [13], **a** view of the Saint Louis Church in Darmstadt, **b** vertical section of the structure, **c** visualisation of the dome' structure, **d** details of the connection of the dome's meridional and latitudinal ribs

The horizontal chords surrounds the dome like hoops, protecting it against horizontal distortions and ensuring the mating of mating meridional ribs at an uneven vertical settlement.

The main meridional load-bearing ribs were connected at the dome's peak with a wooden ring of a 7.5 m diameter, made from horizontal beams in which meridional ribs were introduced. This connection method protects ribs against a horizontal shift.

The lower roof of a triangular section shown in Fig. 3.23b, c constitutes a ring that prevents a horizontal shift of the dome. The sloping pillars support a latitudinal double beam that creates a permanent and immobile ring to buckle the meridional ribs in the sphere of the lower dome. The subtly designed and made, geometrically invariable structure ensures a spatial mating of all dome's elements.

The realization of the structure innovative in the 19th century by Moller G. triggered a discussion in the engineering environment. **The use of a single-layer construction and the introduction of iron connectors in rib connections was criticized**. In his work [13] Prof. Otto Warth from Karlsruhe describes two examples of dome structures that he considered correct, as shown in Figs. 3.24 and 3.25. Shown in Fig. 3.24 is the first didactic example placed in [14] of a dome made up of two self-supporting shells: an outside wooden shell of a diameter of ca. 12.0 m, another masonry dome of a 11.0 m diameter. The outside dome has a pure ribbed structure from arch centres, as the dome by Moller G. built in 1827 in Darmstadt (Fig. 3.23). The wooden structure comprises thirty-two main arches made from two arch centres, 4 cm thick and 25 cm wide each, having the character of de l'Orme's arches. The arched ribs of the dome were connected in the key block with a ring of a 3.0 m diameter, at the bottom they were anchored in a masonry wall with cast iron anchors. The stiffening of the wooden ribbed structure constitutes three horizontal latitudinal ribs in a spacing of ca. 2.0 m, also made from arch centres. The connection of vertical ribs and horizontal ribs is shown in Fig. 3.23d.

While comparing the Moller's dome and that shown in Fig. 3.24, Otto Warth wrote so, I quote from his work [13]: "The structure of the dome that creates, at the same time, both the ceiling and the roof is less worth recommending, i.e. the Moller's dome, since in the case of domes it is difficult to recognize leaks of the hardly connected covering since its inside area and its decorative outfit is easily exposed to a damage. Hence, in order to maintain the building it is justified to set one dome above the other so as to be able to recognize necessary repairs on the outside dome in the right time."

Facing up such expectations for the solutions of lighter domes like that shown in Fig. 3.24, Warth O. suggests the other example, i.e. with the two-layer dome from wood shown in Fig. 3.25. Its advantage is the protection of the inside shell against the effects of inundation by precipitation water due to lack of tightness of the outside shell, and the option of using the space between the shells for ventilation,

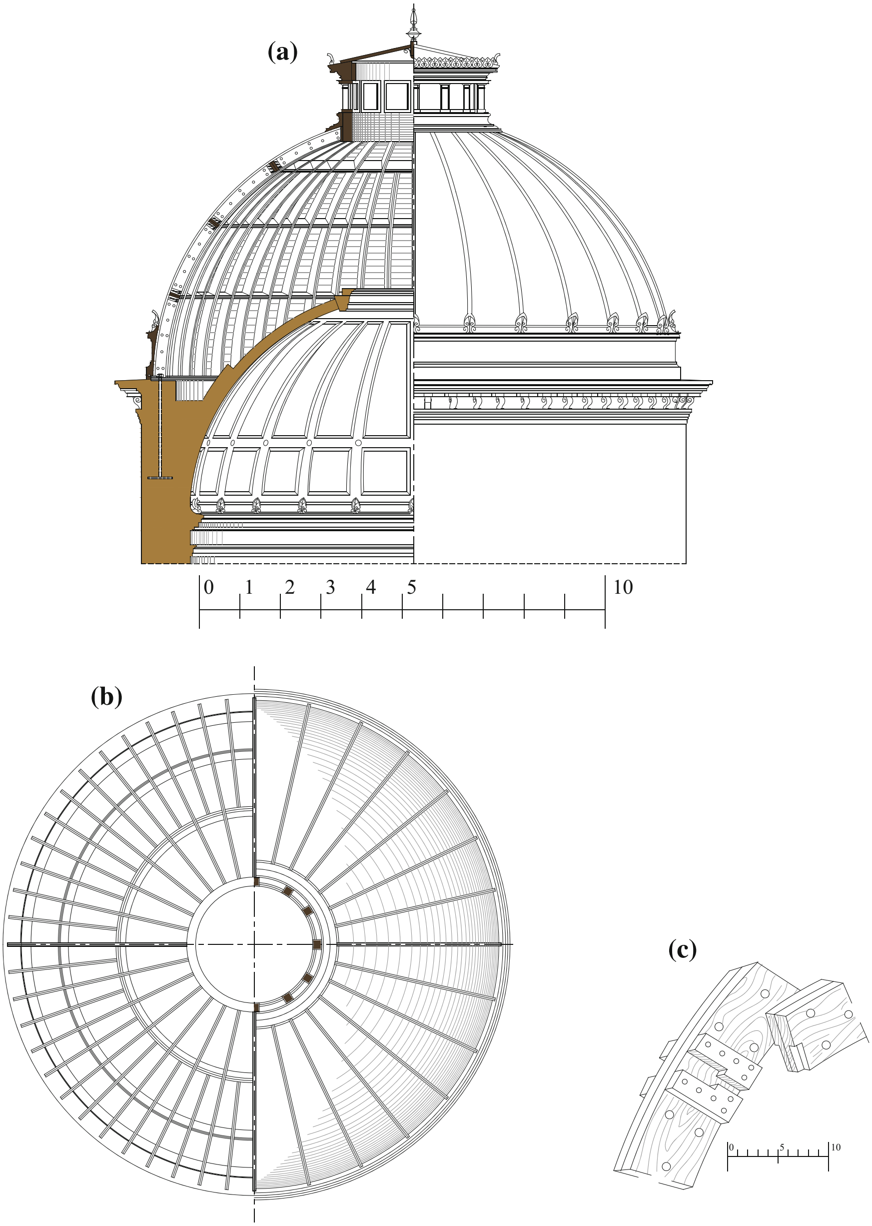

Fig. 3.24 Example of a two-layer dome of a 10.0 m diameter to [14], **a** view and section of the dome, **b** projection and view of the roof covering, **c** connection of meridional and latitudinal ribs in a node

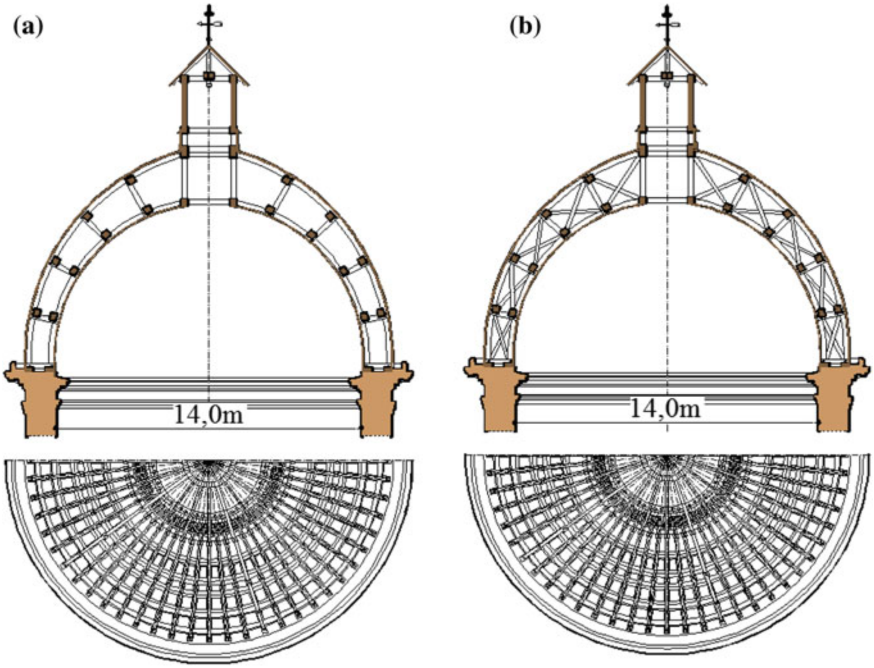

Fig. 3.25 Example of the two-layer dome of a 14.0 m span, with the lantern according to [13] **a** section with the view of meridional ribs, **b** section with the view of the main meridional ribs

maintenance and overhaul purposes. **An essential issued raised by Warth O. is to create conditions for an effective air replacement and ventilation between wooden shells**.

In the structure, meridional ribs from arch centres creating two layers of bars connected with studs were proposed—Fig. 3.25a. The inside diameter of the dome projection is 14.0 m, and the top horizontal stiffening ring under the lantern—ca. 2.30 m. The two-shell dome constitutes both the structure under the roof covering elements and the ceiling over the room covered. Shown in Fig. 3.25a is the section and structure of intermediate ribs. Shown in Fig. 3.25b are meridional, main roof trusses with the dual diagonal framework. The dual-chord, truss meridional bracings in each node of meridional trusses, shown in section, ensure the spatial mating of the meridional elements of the system. At the same time, the calculation of sectional forces was possible without taking into account the effect of displacements. Meridional ribs were embedded on the wall using oak rings from logs. Meridional ribs from logs of 12 × 25 cm dimensions at a spacing every ca 1.0 m were proposed.

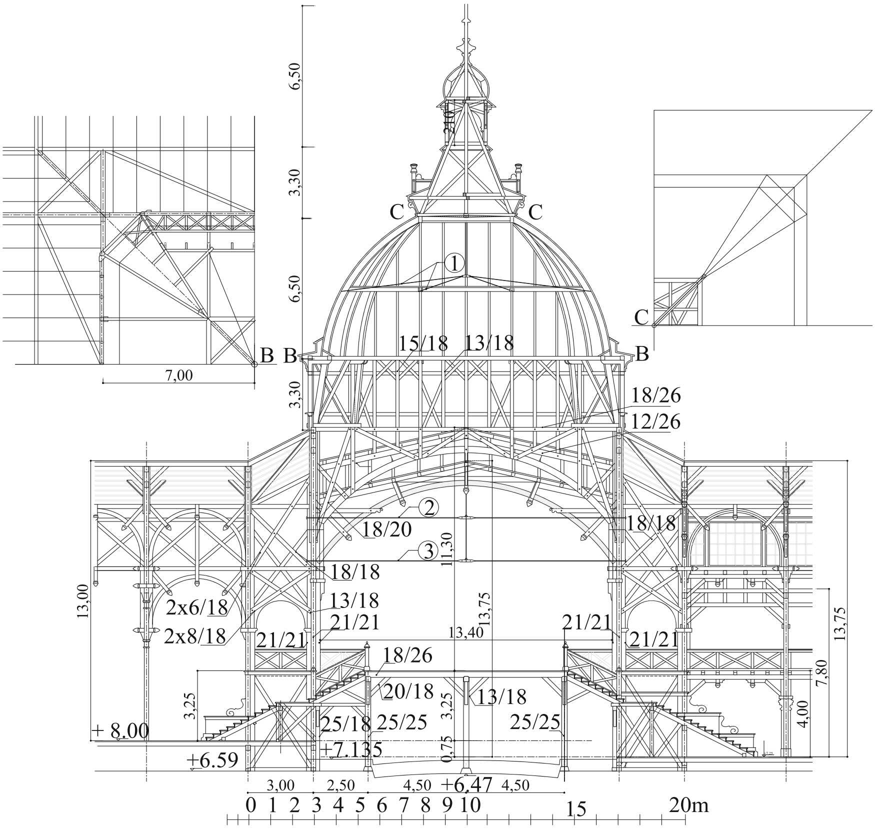

Fig. 3.26 View of the structure crowned with the dome in Görlitz as described in Deutsche Bauzeitung 1885. Steel tie rods are designated with numbers 1, 2, 3 [13]

Shown in Figs. 3.26, 3.27, and 3.28 are the examples of later facilities built in the 19th century, having the structure from solid wood, crowned with domes, developed on the basis of the work by Otto Warth [13]. The already illegible drawings have been reconstructed in order to remind of those exceptionally subtle structure, of the sections of load-bearing elements of a height not greater than 30.0 cm and a thickness of several planks.

In Figs. 3.26 an industrial-craftsman's building erected in Görlitz in 1885 is shown. The dome was built over the central room that had been designed on the intersection of the main hall with the cross hall. This fact was designated on the outside through a higher construction crowned with a dome. In the middle of the dome's height steel tie rods were used, anchoring the vertical mast crowning the lantern. Another pair of cast iron tie rods was used at the level of supporting arches of the side aisles supporting the load-bearing tambour of the dome.

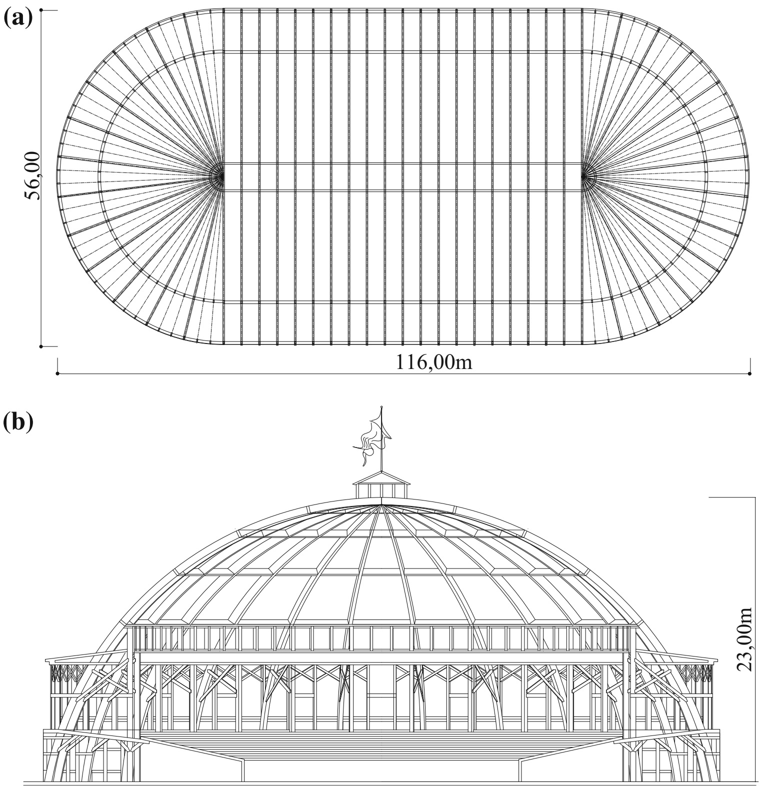

Fig. 3.27 Auditorium built in Vienna in 1890 [14], **a** horizontal projection, **b** section

Beside the dome-crowned buildings, free-standing hall buildings of imposing dimensions were built using ribbed arch centres. Shown in Fig. 3.27 is the auditorium built for the German Federal Festival of Singers in Vienna in 1890. The hall had a span of 56.0 m, a length of 116.0 m and a height of 23.0 m [14]. The hall was dedicated to 20,000 spectators.

The structure was made from arches stiffened with horizontal and meridional beams. The feet of the posts were seated on logs.

Shown in Fig. 3.28 is the section of the building erected for the North-German Industrial Exhibition in Königsberg in 1895. The main entrance led to the central room of a 21.0 m height, crowned with a dome of a 19.0 m diameter. Meridional load-bearing ribs were built from arches from arch centres of 8 $\times$ 30 cm dimensions.

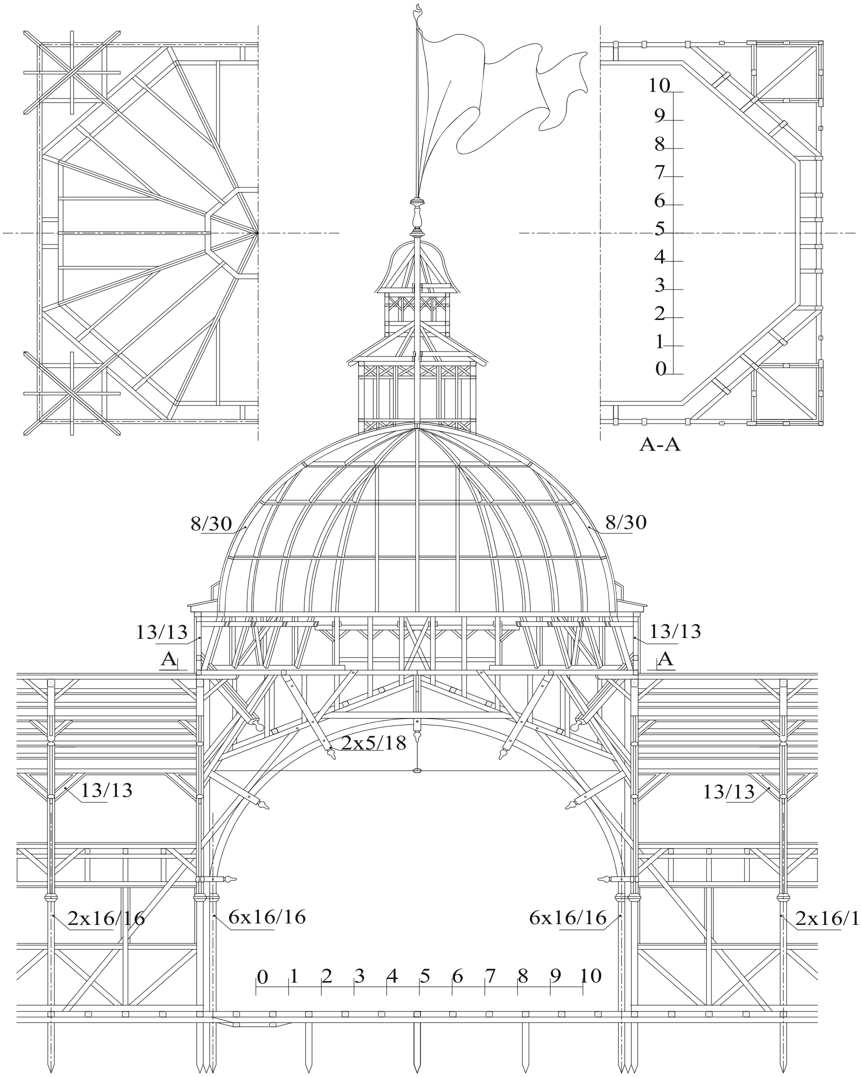

Fig. 3.28 Section of the dome of the building in Königsberg for the North-German Industrial Exhibition 1895 [13]

Fig. 3.29 Dome of the Alhambra Palace, Granada: **a** location, **b** view of the dome-roofed inside [18], **c** details in close-up, **d** dome palate, photo by the author

3.6 Conclusions

The lasting centuries of the building of facilities using meridional-latitudinal structures led to the optimization of the structural characteristic of the dome form. While maintaining the geometrical invariability the system and the connections of wooden elements was perfected, which led to a simple and legible meridional-latitudinal structure designed and built by Moller G.

Saint Louis Church in Darmstadt is the first facility described in the referenced literature [13] (1900) roofed with a single-layer wooden dome of a 33.5 m span, made as a regular ribbed structure. The structure designed by Moller is the result of a regular experience in the building of wooden scaffoldings for the building of masonry ceilings and domes. An arch centre, being an outside element of the scaffolding supporting the outside canopy, became an autonomous load-bearing rib of the dome. The scaffolding supporting it vanished. The introduction of a latitudinal stiffening as shown in detail (Fig. 3.23b, c), created the first, ribbed load-bearing system of the dome.

The division of structures into meridians and lines of latitude introduced a legible picture of the distribution of forces in a dome and facilitated the statistical calculations of load-bearing elements.

Today, the Moller's dome arouses admiration due to its subtle sections of the wood used for the construction and its purposeful application. Ripe wood was used for meridional ribs, young wood was used for latitudinal ribs, using differences in the properties of young and old oak wood. Basing on the today forgotten criteria, a wood species was selected to be used for pre-stressing elements or connectors. It is worth quoting here what Moller G. himself, subjected to a critic, wrote on the subject matter of rules applied to increase the durability of a structure. I quote from the work by Otto Warth in Karlsruhe: "The foundations on which meridional ribs from arch centres rest are made from oak wood, the latter standing with their footing not in the plug hole where rain water could collect but in an open and a little bit steep cavity. The entablature that supports the foundation has dilatation openings so that it could quickly dry up in case it got wetted. Located between the rib heads, as near as possible to the top lantern, are dilation openings (in the top ring) having the form of openwork rosettes since, over the roofs, the outside side of the dome is not planked, then long channels are naturally formed between ribs from arch centres, which has to directly contribute to the maintenance."

The Moller's idea was perfected in successive realizations of the facilities roofed with domes.

The susceptibility of wood to the environmental interference produced that for centuries various method of its protection has been used, and Prof. Warth O. called attention to the problem of the durability of wooden domes. He emphasized the meaning in that process of the ventilation of the structure.

Various methods were used, and the most effective turned out to be those methods that protected against corrosion, without destroying the specific anatomic structure of wood. An example of the facility preserved owing to the proper maintenance and operation is the wooden dome made as a roofing of one of view towers of the Alhambra Palace in Grenada shown in Fig. 3.29. The dome was made in 1320, having the dimensions in projection of 3.55 m $\times$ 3.55 m and the height of 1.90 m. It was made from cedar and poplar wood commonly considered as a non-durable species. Owing to the skills of its creators, the dome has subsisted for 700 years and may be admired in the pavilion of the Islamic Art Museum in the Pergamum Museum on the Isle of Museums in Berlin. Shown in Fig. 3.29 are the photographs taken by the author in the museum in Berlin.

An essential role in the issues of durability is played by the conditions under which wood operates in a building facility. Wood located under the settled conditions of temperature and humidity has an unlimited durability. A confirmation of this is the dome shown in Fig. 3.29, as well as wooden items counting several thousands of years, originating from Egyptian tombs [15].

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