IOP Conf. Series: Materials Science and Engineering **365** (2018) 052017 doi:10.1088/1757-899X/365/5/052017

Construction strengthening in historical wooden cupolas restoration

Yury Yuzhakov and Alexander Belkin

Moscow State University of Civil Engineering, Yaroslavskoye Shosse, 26, Moscow, 129337, Russia

E-mail: an.belkin@mail.ru

Abstract: There are many architectural monuments with wooden cupolas, included in cultural heritage of our country. Cupolas in Russian architecture appeared with the adoption of Christianity as an indispensable element of the Byzantine, and now Russian, church. In recent years, Central Scientific-Restoration Design Workshops of the Ministry of Culture have carried out natural research and restoration of wooden cupolas of more than thirty architectural monuments of the late XVIII - early XX centuries located in Moscow and central regions of Russia.
Cupolas made of wooden elements present a spatial framework with a round or polygonal plan and a different pattern forming the shape of the profile. The paper gives a general description of the types of constructive solutions and their elements. Wood is the most vulnerable material of structures, with poor quality and unsatisfactory operating conditions, is prone to lesions in the form of house fungi and woodworm beetles, leading to the destruction of the material with a weakening of the working sections. Moreover, rotting and burning do lead to the destruction of the structure. Therefore, when restoring, it is necessary to carry out a complex of measures to restore the original form of the cupola and the original elements of the structures.
As an example, four objects of cultural heritage are examined from the experience of Central Scientific-Restoration Design Workshops. This is the main house of the Ostankino manor in Moscow (1792-98, the architects A.Mironov and P.Argunov), the Petrovsky Travel Palace in Moscow (1775-96, the architect M.Kazakov), the building of the Guardian Council in Moscow (1823- 26th, architects D. Zhilyardi and A. Grigoriev, was rebuilt in 1846-49 by architect M. Bykovsky), the Church of the Transfiguration of the Lord in the village of Snoved in the Nizhny Novgorod Region (1800, unknown).
The characteristics are given for each of them: the original design of the cupola; its current state, based on engineering and chemical and technological research; adopted and implemented restoration measures aimed at restoring the shape and reinforcement of structures. In conclusion, on the basis of the generalizations made, methods for the restoration of wooden cupolas are formulated: prosthetics and strengthening of individual elements, the arrangement of duplicating and supporting elements, the complete reconstruction of the form with the preservation of the original design, the complete restoration of the form with a change in the original design.

1. Introduction

Cupolas appeared in Russian architecture after the Christianity acceptance as an inevitable element of Byzantium, then Russian temple. «Byzantium cupola above the temple symbolizes firmament, vaulted the earth» [1]. Considerably later, in XVIII century cupolas began to be used in the secular architecture of Russia. Vaulting dwelling or public building, they lost rich symbolic meaning of religious architecture, but saved the role of the most important element in a composition. Cupola, as a crown of a

building, reconciled its heaviness to the heaven, provided its gradual dissolving in the air, gave the building grandeur of a monument. «… The form of the cupola, which crowns it, mostly expresses the greatness of a monumental construction dominating over a city. The idea of the closed central form of roofing is also perfectly embodied in the quiet, spherical surface of a cupola. These two properties of a sphere allow us to recognize the cupola as a higher architectural form of roofing which creates total unity of the external volume of a building and its internal space...» [2].

Great quantities of the architectural heritage of our country are the historical buildings with wooden cupolas. Currently, Central Scientific-Restoration Design Workshops of the Ministry of Culture (CNRPM) fulfilled field observation and restoration of the wooden cupolas of more than thirty monuments of architecture in Moscow and central regions of Russia dating from the end of the 18th to the beginning of 20th centuries.

Wooden cupolas are the spatial structure with round or polygonal plan and various profiles, making a form. There are 3 types of wooden cupolas designs:

1. Without a central support (with a "light" tholobate) – when the underlying premises are lit through structures of a dome;
2. With a central support (with a "blind" tholobate);
3. With bearing structures consisting of mutually perpendicular roof trusses or arches.

Depending on the type of wooden cupolas, they consist of: curve pieces (meridian ribs), roof trusses having triangular configuration, curb plate and dome drum, ring binding rafters, central support with angle braces, shell made of slanting timber planking.

Field observation was held in accordance with State Standards 31937-2011 «Buildings and structures. The rules of observation and monitoring of technical condition» in terms of complex observation to determine wooden construction technical condition, to examine destruction and damage causes, followed with elaborating of projects proposals for restoration and exploiting of an object of cultural heritage in whole. The methodic of observation includes preliminary (visual) and detailed (instrumental) examination of the wooden cupolas constructions. On the first, preliminary constructive scheme of a cupola was made, schematic measures of construction gabarits were held, unsafe areas were pointed up (in the case of destruction), and fotofixation was fulfilled. On the second, constructive scheme of a cupola was detailed, precise measures of construction gabarits and sections were held, detailed fotofixation was fulfilled. The samples for examination of durability and physical-mechanical characteristics and for mycological analysis of construction timber were selected. The quality of construction timber was determined in accordance with State Standards 16483.3, 16483.7, 16483.10, 16483.18. Testing calculation of the construction strength was based on the general results of observations.

2. Materials

Let us analyze several examples of cupolas structures observation and restoration.

The main house of Ostankino estate in Moscow [Fig. 1] was erected in 1792-1798 as a project of architects A. Mironov and P. Argunov. The building is a unique monument of wooden architecture. However, the plastered walls imitate a stone structure. The cupola is located over the central part of the building, diameter of the cupola – 13.56 m; rising height – 3.6 m. Bearing structures of the cupola are made in the form of two main mutually perpendicular timber arches with cross-sections bxh = 140x180mm; 190x180mm; 180x200mm; 140x240mm.

Figure 1. The main facade of the manor house in Ostankino, present condition

The main arches consist of semi arches of triangular configuration and horizontal tie of beam with cross-sections bxh = 170x230mm; 170x180mm; 170x160mm; 150x200mm. The ends of the upper and lower chords of the semi arches are cut in the rectangular timber of the central support with cross-sections bxh = 300x300 mm (in the center) and four beams Ø280 mm (in external angles). The support serves for flagstaff fixing. Between the main arches there are intermediate building structures resting with one end on the upper support contour, and another - on the external framing ring. The shell made of timber planking lays on the upper chord of the arches. The external framing ring of belvedere rests on the ledger of frame rectangular timber walls.

Complex analysis of the results of the investigations showed that wooden cupola support and framing constructions are in satisfactory condition. Laboratory research of the timber samples, choose after taking of a plaster, was done.

It was revealed, that some uprights of belvedere walls and some boards of the floor have surface rotting and damage caused by wood fretters and need prosthetic appliance. The testing of dome construction to bear permanent load and temporary load has shown that there is an overstress of 41,5 % in one of the elements in the upper multiangle construction. There is an overstress of 18 % in the lower inclined element of the intermediate rafter, weakened with junctions. The stresses in the other elements are below rated, in the floor beams deflection is below limit.

In the course of the cupola restoration the following was performed:

- reinforcement of tightening of the main arches and elements of the framework by means of steel tension bars with stop channel bars and splice pieces of wood boards **[Fig. 2]**;

Figure 2. The main house of Ostankino estate. Reinforcement of tightenings of the mainarches and elements of the framework by means of steel tension bars with stop channel bars and splice pieces of wood boards

- reinforcement of the intermediate rafter, overstressed in the middle, with wood boards on both sides;
- taking the bark of some elements.

Petrovsky Putevoy Dvorets in Moscow [Fig. 3] was erected in 1775-1796 as a project of the architect M. Kazakov. This is a brick two-storied building with cellars. The cupola is located over the central part. The existing cupola was restored in 1818-1823 as part of the repairs after the fire in 1812.

Figure 3. Petrovsky Putevoy Dvorets in Moscow; present condition

Diameter of the cupola – 16.86 m; rising height – 5.5 m. The cupola consists of two hemispherical cupolas - external and internal (decorative), located one above another. Bearing structures of the external cupola are made of two parallel triangular trusses Ø 250 mm with interval 3300 mm. The external cupola formed of wooden curve pieces 70 mm thick, covered with roof steel over wood boards 30 mm thick. Wood boards are laid with angle 450 to the framing ring. Curve pieces of the cupola are supported by inclined two logs with section Ø 220 mm, with toothed coupling along the length. Bearing structures of the decorative cupola are made of wooden curve pieces 2x70 mm, boards which are covered from below, plastered and coated with painting.

Complex analysis of constructions revealed biological and entomological decay of some elements (greyish-brown rot and white mould), caused the deterioration of physical-mechanical characteristics of wooden cupolas constructions. Separate elements, including the central support - flagstaff base, have rotting and damage from wood fretters [Fig. 4].

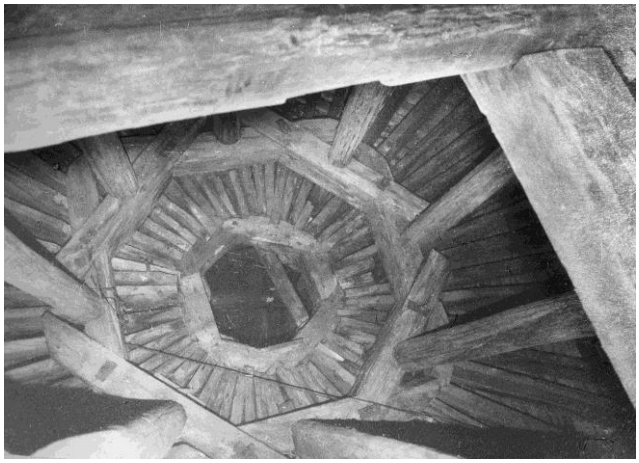

Figure 4. Petrovsky Putevoy Dvorets in Moscow. Separate elements, including the central support - flagstaff base, have rotting and damage from wood fretters

Physical wear of the external cupola below 20%, of the decorative cupola below 30%. General condition of wooden constructions is restrictedly durable. Some pieces are unsafe. The unsafe is caused with:

- absence of the ventilation of supporting ends of constructions;
- Condensation between the external and decorative cupolas, leads to biological decay;
- the roof leaks, the absence of hydro and steam isolation in framing constructions.

Testing calculations of external cupola constructions to bear permanent and temporary load has shown that there is over allowed deflection of triangular trusses of external cupola.

During the restoration of the cupola, the following was fulfilled:

- reinforcement of rafter trusses with installation of two three-hinge frames made of laminated wood with the section 100x500 mm, in parallel to historical trusses;
- replacement of some upper and lower knee braces and installation of bracings along the top and bottom chords of the trusses to include new trusses in the work of the whole structure.

The Building of the Board of Guardians in Moscow [Fig. 5] was constructed of brick as a project of architects D.I. Zhilyardi and A.G. Grigoriev in 1823-1826. Architect M.D. Bykovsky in 1846-1849 reconstructed and partially changed the architecture of the facades and interiors. The building is crowned with a cupola placed on the light drum, which is erected in the central part of the building over the front stairs. The volume of the stairway is arched directly over spherical cupola with a sky-light.

Figure 5. The Building of the Board of Guardians in Moscow; present condition

As a result of field observation it is established: diameter of the cupola – 13.26 m, rising height – 3.88 m; the bearing structures of the cupola consist of two cupolas - external and internal (disassembled in 1846), located one above another.

The bearing structures of the external cupola are created from 61 curve pieces made of 60 mm board. The cupola is installed on supports of a light drum the height of which is 6.7 m. Curve pieces are covered with roof steel over wooden boards. Curve pieces of the internal cupola also rest on supports of the light drum. There are no decorations on the curve pieces. There are no tightening of the curve pieces. The thrust is sustained by two curb plates with 100 mm thickness.

Dissemblance of the internal cupola changed the static scheme of a truss, broke the work of elements and junction, and caused numerous defects and damages. Nevertheless, main damages are the result of a long exploitation (more than 180 years [Fig. 6].

Figure 6. The Building of the Board of Guardians, destruction of the wood

Owing to destruction of wood and under the influence of the thrust, an opening is created of conjunctions of segments of curb plates and there is bending and shearing of wrought nails in the nodes.

The testing of the external cupola framework to bear permanent load and super-load has shown that the existing section of the elements is not enough to resist loads and these elements should be strengthened. The calculation of the nodes of the curb plates revealed that the insufficient number of the driven in nails resulted in bending and, here and there, shearing of nails.

The engineer A.N. Gustova on the timber samples fulfilled the research of building and finishing materials in laboratory conditions choose after taking of a plaster. It was revealed, that some upright timber and some boards of the floor have surface rotting and damage caused by wood fretters and need prosthetic appliance. The sawn wood ends have trademarks stamped by a hammer [Fig. 7].

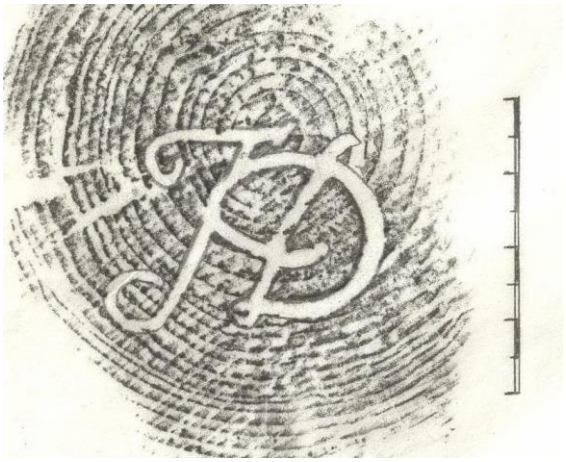

Figure 7. The Building of the Board of Guardians. The sawn wood ends have trademarks stamped by a hammer

The decision to partial changing and prosthetic appliance of some elements was adopted, based on the results of engineer-constructive and chemical-technological research. In the course of the cupola restoration the following was performed:

- full reconstruction of the original (authentic) framework of the internal cupola using whole timber, δ=60 mm; junction of the elements with stub tenon [Fig. 8];
- addition of spatial bracings made of whole timber between the arches of the external and internal cupolas with the formation of crescent-shaped semi arches;
- replacement of wrought nails in nodes by bolted connection.

After the reconstruction of the inner cupola, the construction is the following:

- cupolas consist of 61 curve pieces (each) of board, δ=60 mm, with 4 elements in every curve piece, step of curve pieces 480-660 mm;
- external cupola has a curve upper plane, and internal cupola has a curve down plane, R = 6,81 m;
- curve pieces of external and internal cupolas are based on wooden uprights, 60x350 mm in section, 5.9 m and 2.0 m in length external and internal cupolas adequately. Lower ends of uprights are connected with saddle beam by stub tenons;
- drum inner row uprights and the cupolas bases have pole strut of beams Ø150 mm in width, 3.3 m in length, organized radially from a wooden platform of the bay window.

Figure 8. The Building of the Board of Guardians. Full reconstruction of the original (authentic) framework of the internal cupola using whole timber

The Cathedral of the Transfiguration of Christ in vil. Snoved was constructed in 1800. The Cathedral was crowned with a massive dome with a canopy. The building is a unique monument of wooden architecture. Outwardly it imitates a stone structure [Fig. 9].

Figure 9. The Cathedral of the Transfiguration of Christ in vil. Snoved. Historical picture. 1966

As a result of field observation it is established:
- at the time of observation (2007) the wooden structures of the cupola and the structures of the building partially had been brought down [Fig. 10];

Figure 10. The Cathedral of the Transfiguration of Christ in vil. Snoved. At the time of observation the wooden structures of the cupola had been brought down

- diameter of the cupola – 10.46 m, rising height – 5.18 m.
- the bearing structure of the cupola is created by two segmental truss made of timber. The lower truss belt has 350x370 mm in section, three uprights have a step 1850 mm and section of 270x330 mm; the section of two upper belts is 180x220 mm;
- truss height is approximately 4960 mm, span is approximately 7400 mm;
- curve pieces of the cupola were made of 120x450 mm timbers connected by treenails 40 mm over, and were covered by roof steel over boards.
- «zenith» ring with diameter 1000 mm is made of two steel strips 90 x 20 mm, connecting up and down curve pieces ends;
- junctions of the elements are made with stub tenons and suspensions of steel strip 90 x 20 mm;
- cathedral structure state was estimated as ruined.

Laboratory research revealed that timber was damaged by dry rot (Poria vaporaria and Coniophora cerebella). Humidity of beams and board facing is very high (30-50%). The walls of the Cathedral had extensive places of rotting and damage from wood fretters that caused the structures of the cupola to be brought down. The engineer N.A. Syomina on the samples of timber held the research of materials.

Laboratory endurance test and research of physical-mechanical characteristics made on the 45 samples, sawed from timber-blocking, upper and lower rings and curve pieces of cupola, revealed, that endurance of timber is not adequate to the demands of the State Standard. Basing on the results of engineer-constructive and chemical-technological research, the decision was adopted to change totally timber-blocking on the existing stone basement [Fig. 11].

Figure 11. The Cathedral of the Transfiguration of Christ in vil. Snoved

Now the Cathedral is restored out of wood. In the course of the cupola restoration the following was performed:

- restoration of the cupola shape by means of computer modeling with the use of archival drawings from 1849 and full-scale measurements;
- full reconstruction of main structures of cupola made of bentwood semi trusses with the section 120x400 mm, saving the historical forged elements.

3. Conclusion

Thus, now in Russia the following methods of restoration of wooden cupolas have been developed and put into practice, including the methods with participation of Yury Yuzhakov:

1. Prosthetics and strengthening of separate elements using:
- whole timber or laminated wood, steel rolled elements, polymer concrete (epoxy resins) with built-in reinforcement.
2. Installation of backup and supporting elements made of laminated wood or steel rolled elements.
3. Full reconstitution with preservation of original (authentic) framework using whole timber or laminated wood.
4. Full reconstruction with change of original (authentic) design using:
- whole timber or laminated wood, steel rolled elements, concrete components.

References

[1] Kuznetsov A V. Arches and their decoration / A V Kuznetsov. - M: Izd. V. Shevchuk, 2003. - 420 p.
[2] Trubetskoy E N, Speculation in paints / E N Troubetzkoy. - M: publishing house of Moscow Patriarchate of the Russian Orthodox Church, 2012. – 147p.
[3] General history of architecture, ТомVI. Architecture of Russia, Ukraine and Belarus XIV – first half XIX centuries. - M: Stroyizdat, 1968. - 568 p.
[4] Piatnitski A A, Makhov I O, Pyltsin M A, Strengthening of vaulted overlappings of a building-monument / Bulletin of civil engineers. 2014, № 3 (44). - p. 92-95.
[5] Pashkin E M, Bessonov G B, Diagnostics of deformation of monuments of architecture / E M Pashkin, B G Bessonov. - M: Stroyizdat, 1984. - 151 p.
[6] Kramina T A. Reconstruction of the arched and vaulted systems in the monuments / T A Krumina / Design review. 2009. No. 1/4. - p. 59-62.
[7] Bessonov G B. A study of the deformation calculation of bearing capacity and structural strengthening of ancient trust systems. Methodical recommendations. - M: Soyuzrestavratsia, 1989. - 171 p.
[8] Lakhtin N K. Calculation of arches and vaults / N K Lakhtin. – St. Petersburg: 1911. - 106 p.
[9] Statsenko V G. Parts of buildings / V G Statsenko. – St. Petersburg: 1912. - 523 p.
[10] Dmitrieva S L. Development of methods of solution, dome structures in the architecture of religious buildings of the Italian Renaissance / S L Dmitrieva. The World of science, culture, education. 2010. No 5 (24). - p. 18-21.