Alternative Dome Reconstruction Method for Masonry Structures

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Abstract. Domes first appeared in architecture in small structures such as round huts and tombs. As the need to accommodate more people became increasingly larger through the ages and the enhanced sense of symbolism of the dome became ever more important so the dome spans expanded. The construction materials switched from solid earth mounds to masonry hemispheres [1]. This growth in size has always been an engineering challenge and in many cases of masonry domed structures the dome, located at the highest point of the building, is considered to be one of the most vulnerable parts of the structure. Decreasing the weight concentrated on the highest part of the masonry structure increases the strength and durability of the structure. The aim of this paper is to present an alternative method for constructing a domed structure that was developed using computer aided design methods. This type of dome could serve as a replacement of a collapsed stone dome, usually of a church, or be fitted on a new structure.

Keywords: Church · Restoration · Reconstruction · Timber dome

1 Introduction

Reducing the mass of the architectural structures as their height increases is a common practice among architects with the intention to minimize the moment of inertia of buildings and assign to them better anti seismic qualities. In the case of churches made of stone there is a multitude of cases in which the stone domes have sustained severe damages or total collapse under the stresses developed usually in the cases of earthquakes.

Characteristic of the difficulty in building sufficiently durable masonry domes, able to withstand the earthquakes challenging the eastern part of the Mediterranean, is the multiple collapses of the Hagia Sophia dome at different years from 553 AD to 1436 AD.

The construction technology that has been developed in the last century allows architects to consider alternative methods of designing domes that could have the same appearance but significantly lighter in weight than traditional ones. Although there have been some examples in later years of light weight domes constructed from steel or wood frames these methods have not yet found their way in majority of orthodox churches and neither are they considered In most cases when a dome needs to be completely reconstructed after its collapse (Fig. 1).

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Fig. 1. Hagia Marina dome (before restoration) in Nicosia, Cyprus.

2 Selecting the Appropriate Construction Method

2.1 A Brief History of Dome Structures

To approach the matter of a new dome construction or replacement first we have to assess its history and the reasons, if there are none, to continue on building stone domes based on the current needs (structural, aesthetic or financial) of these structures.

The first stage of dome construction technology started with the solid earth mound system (usually dug underground caves) and moved to building domes with pieces of small branches or even bones.

Around two thousand years ago the technology of masonry domes started flourishing. The increasing amount of people gathering in religious buildings created a need for a constant growth of the dome's size. This growth in size has always been an engineering challenge and in many cases of masonry domed structures the dome, located at the highest point of the building, is considered to be one of the most vulnerable parts of the structure [2]. Despite the repetitive recorded failures of large stone domes in the last millennium many times the method and technology of construction remains the same (Fig. 2).

Fig. 2. Collapsed Dome in Famagusta Area, Cyprus.

2.2 Short Literature Review

One of the earliest methodical approaches to reduce the weight of the dome is that applied in the Pantheon in Rome around 126 AD by Apollodorus of Damascus [3]. In the case of the Pantheon the materials mixed in with the cement to construct the dome were gradually reduced in density as the dome's construction was moving upwards. This method combined with the molds used that when removed left the characteristic empty rectangular spaces gave the dome the durability needed to withstand the test of time for almost 2000 years.

Another attempt made to strengthen the domes structure was later made by Filippo Brunelleschi 1436 AD in the dome of Florence Cathedral [4]. In this case the Architect chose to design an arc shaped dome so that the trusts in the domes perimeter would be reduced and strengthen the dome by adding wooden rings between the double masonry walls that composed the dome.

Another example of a different kind of dome construction is that of the addition made to the original domes of San Marco Basilica [5]. The church originally had low-profile domes that were raised by an exterior wooden shell around 1260 AD. In this case a lighter structure was chosen as to reduce the additional load to the structure need to visually change the dome's exterior.

In the 17 century another alternative to dome construction was widely employed in Russia with the construction of onion shaped domes that usually had a wooden frame as their basic structure. The wooden frame was not only easier and lighter to build but also was economical as pine tree was readily available in northern Russia.

In later years we can find examples of architects that experimented with different methods of dome construction. Such an example is Imre Makovecz, a Hungarian architect that was active in Europe for the late 1950s onward [6]. A characteristic example of a wooden dome structure by this architect is the Forest Culture Center in Visegrád, Hungary, that was constructed in 1984. In this example wood was used as the frame and interior cladding for most of the building as well as the dome that covers it as to emphasize the connection that the visitor should have with nature.

2.3 Causes of Failure in Masonry Domes

One of the main issues causing total or partial failure of masonry domes is the increased weight concentrated on the higher level of the building adding static load to the structural parts beneath and increasing the momentum generated in the event of an earthquake. The second main issue is the extended thrust around the domes perimeter. In the case of total or partial collapse of domes in churches the implications go beyond the area of the dome as the structural integrity of the rest of the system is compromised due to the open shape that is left behind after the collapse.

So the restoration of collapsed domes has to be immediate, something that is not always possible due to the process of competitions, tenders and various other governmental approvals, regulations and processes that take time until completion. Then there is the question of the method and materials that should be used to restore a collapsed dome.

2.4 Parameters for Selecting a Construction Method for a Dome

Before proceeding to alternative methods of construction we should rule out the cases in which domes could only be constructed with the traditional stone method. Firstly when the dome structure is small (less than 2 m in diameter) then there is no reason to look into alternative methods because the weight of the dome [7], estimated less than 2 tons with solid limestone as the base of calculation, is small enough not to cause a major problem to the rest of the structure. Also in cases where the dome is requested to be without an internal coating and the stone is meant to be seen for the interior of the structure an alternative method of construction is out of the question. So we are left with the cases of domes that are large in span (more than 2 m in diameter) and are covered with an internal coating, which is the usual practice in churches so that the dome can be covered with hagiography. In these cases the construction material of the dome is not visible neither for the inside, due to the hagiography, nor form the outside due to waterproofing insulation of any type which cannot be avoided. So since the internal structure is not visible any type of construction is possible and can be selected based on its durability, weight and compatibility with the rest of the structure.

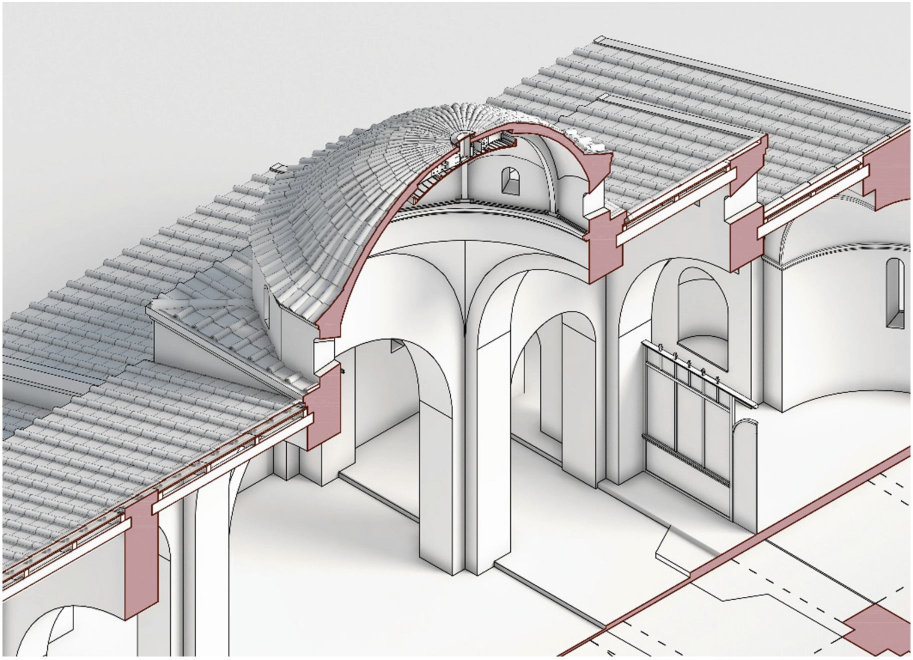

Fig. 3. Section of a sample church with a light wooden dome

Decreasing the weight concentrated on the highest part of a masonry structure and reducing the thrusts around the dome's perimeter would surely increase the strength and durability of the building. The example that will be described will suggest a light weight dome construction method that would serve both the purposes mentioned above. The technological advances of later years in laminated wood production [8] as well as the readily available stainless steel sections make the construction of such a dome possible. The ability to assemble the dome on the ground and then lift it in place also reduces the risk associated with manual labor at a height. The proposed materials and building techniques are completely compatible with masonry structures and these type of dome can serve as replacement to a totally destroyed masonry dome or can be fitted on a new masonry structure. The dome construction method to be described consists of a laminated wood frame with metallic connections that is also visible from the internal part of the building to give an aesthetic note to the dome but can also be covered completely according to the desired finished effect. A section of the whole system can be viewed on Fig. 3. The example used here is a new church to be constructed with a dome diameter of six meters. It is obvious just by observation that the section is much thinner at the part of this light dome compared to a traditional built made entirely of stone. In the case of a stone dome taking limestone with a weight of 2700 kg/m^3 for a thickness of 25 cm would weigh approximately 30 tons (30,000 kg) for a span of 6 m. In the case of the example of this light weight dome and with the basis of wood with a weigh of 600 kg/m^3 the weight comes down to less than 3 tons (3,000 kg).

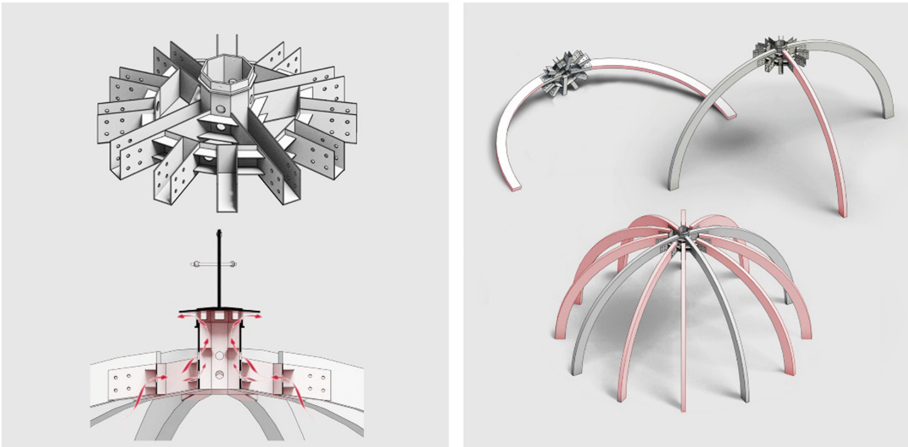

Fig. 4. Central metallic bracket and main beams installation

3 Stages of Light Weight Dome Method

3.1 Construction of the Central Connecting Bracket

Starting with the construction of the dome a metal bracket made from stainless steel is prepared to accept the twelve wooden beams that will compose the main frame (see Fig. 4). It can also be constructed from galvanized steel for cost reduction and the top final cap only can be of stainless steel. This bracket is predrilled so that the bolts can run though the beams and the bracket. The bracket has holes in the central core so that the system is breathable, avoiding moisture concentration at the top part of the dome. Also in this way the interior space can have a small scale chimney effect as to improve the buildings bioclimatic characteristics (see Fig. 4). Even with such small openings the hot air usually trapped at the highest part of the dome would be expelled based on the difference in pressure due to temperature difference between the bottom and top layer of air in the building.

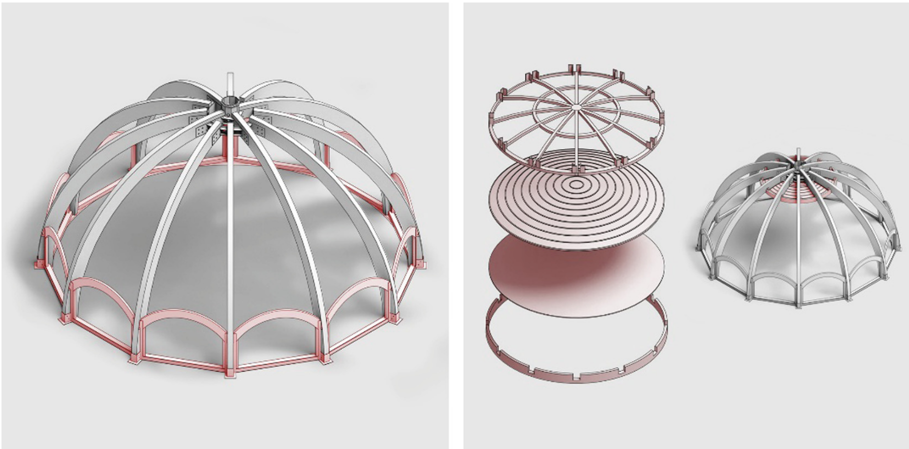

Fig. 5. Frame's perimeter completion and central spherical cap addition

3.2 Adding the Main Beams

The benefit of building a dome in this way is that it can be easily set up on the ground without the use of heavy lifting machinery. The first two wooden beams are connected to the preassembled metallic beam bracket after setting the correct distance between them and relative to the central axis. Then a third beam is bolted to the bracket so that the system can be set upright. The system of beams is completed with rest of the identical nine beams. During this stage an aerial platform should be used for the workers to be able to lift one side of the wooden beam and bolt it to the bracket.

3.3 Fixing the Geometry

The next step is to give rigidity and fixed geometry to the dome. This will serve as the layout to the next steps but also prevents the hemispherical structure to obtain an egg shape once lifted from the ground. At the bottom of the beams small brackets are bolter to each one that later will be fixed to the rest of the structure which usually ends in a rectangular stone base with a circular hole. The space between the beams as seen in the diagram (see Fig. 5) is completed with a wooden frame and galvanized steel links. In this example wood is chosen for aesthetic purposes since it will be visible for the interior space. If the intention is for this part is to be covered up or painted then metallic parts can be chosen.

3.4 Adding the Central Spherical Cap

Now the central finished interior surface of the dome is ready to be fitted. This part consists of four layers as shown in Fig. 5. The first layer also in order of construction is a metallic frame that consists of twelve bent metallic rectangular profiles following the domes radius and two rims. The central rim serves the increase of rigidity and gives a smaller bridging distance for the next layer. If the distance is larger extra rims can be added. At the bottom of this metallic frame a galvanized wire mesh is bolted and finished with plaster. After this part if bolted to the highest part of the dome a wooden ring is screwed to cover up the joints. Again this material can be metallic in case it will be painted. This spherical cap will be the centerpiece of the structure and is usually decorated with the image of Jesus Christ in case of Christian Orthodox churches. Before attaching the small spherical cap structure to the dome it can me decorated with hagiography and covered up temporarily so that the painter would not have to do this work at a height later.

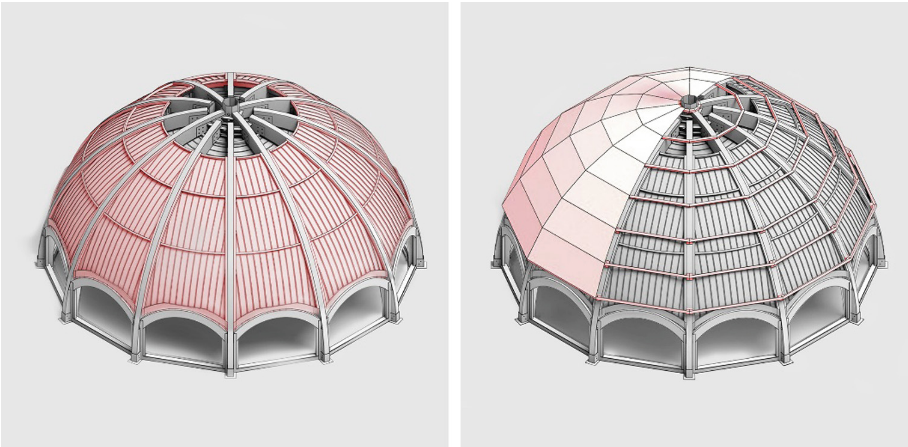

Fig. 6. Completing the interior shell and adding the insulation layer

3.5 Adding the Interior Spherical Triangles

After the spherical cap is attached the twelve spherical triangles are ready to be added as shown in Fig. 6. These parts are composed of thin metal sections that are bend to the appropriate radius to match the domes geometry. The metal sections are then covered with the same galvanized steel mesh of the spherical cap previously mentioned. Then they are covered with plaster to produce the final interior surface. The final surface can also be achieved with attaching thin gypsum boards that are cut based on the net of the curved triangles. The seams left in the gypsum boards after they are screwed into place can be taped and covered up with plaster. These spherical triangles can also be pre-assembled on a fixed location rather than in situ and follow the process of hagiography before being fixed to the main wooden beams.

3.6 Insulating the Dome

At this point the interior of the dome is finished. The step that follows is adding the thermal insulation. Secondary small wooden beams are screwed on the main beams and are covered by plywood sheets. The space between the plywood sheets and the metal frame and interior shell can be filled with mineral wool to increase the thermal and sound insulation properties of the dome. On top of the first plywood layer a second layer is added composed of small wooden beams, extruded polystyrene sheets and plywood finish (Fig. 7).

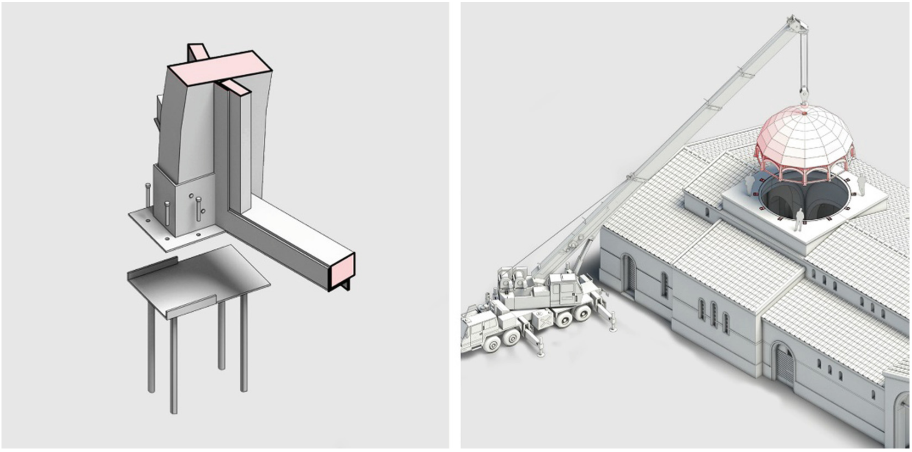

Fig. 7. Base connections and dome installation

3.7 Lifting and Fixing the Dome to the Building

With the thermal insulation of the dome completed the structure is ready to be lifted and positioned in the circular opening of the building. Twelve metal brackets are anchored into the circular perimeter of the opening in advance to serve both as landing zones for the dome and as the main connection points between the dome and the structure. At this stage a crane is needed to lift the dome into place. After the dome is positioned the final connection is made through bolting the two metal parts.

3.8 Finishing the Domes Cladding and Exterior Walls

Once the dome is fixed to the building the next step is to complete the polygonal side wall that encloses the dome. The wall can be built from any material, usually for aesthetic purposes the same as the building beneath. There will be a triangular space left between the peripheral wall and the dome and it can be filled with cement grout as to provide the appropriate slope for the water to escape freely from the roof. Covering the plywood, grout and wall surface a coating of water resistant membrane is applied. The final surface in this example ıs accomplished wıth byzantıne roof tiles but it can be constructed of any other tile of even metallic roof finish (Figs. 8 and 9).

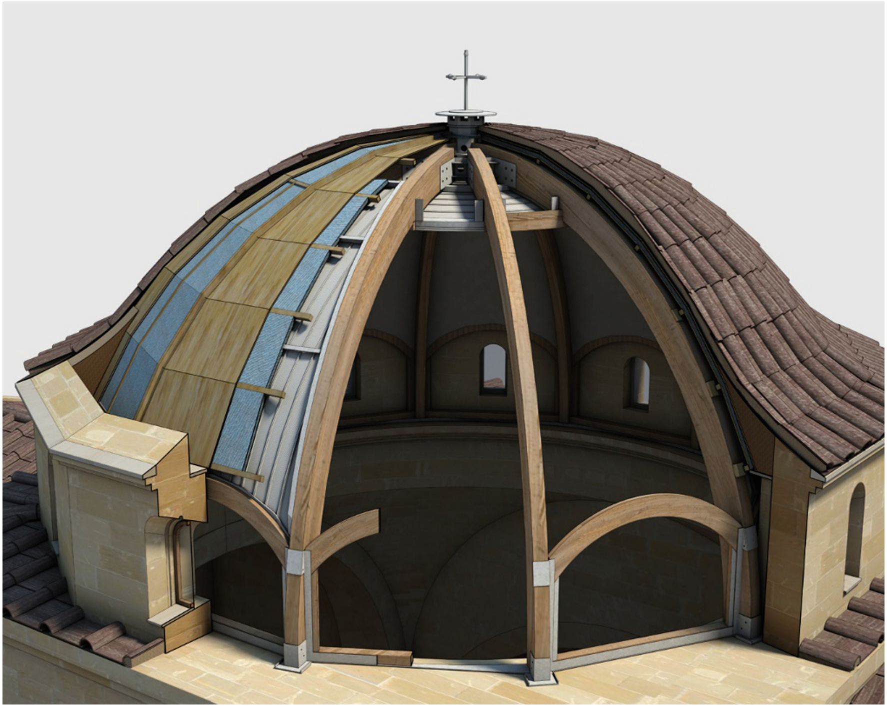

Fig. 8. Section of all the components of the dome

Fig. 9. View of the dome from the interior of the church

4 Conclusion

The example of the lightweight dome analyzed above can accept many variations both in terms of its final interior appearance as well as the construction materials of the different parts. Besides the aesthetic decisions and the various methods that can be chosen to construct such a dome the main advantage of building a dome with this design philosophy is that the weight of the dome is reduced by a great extent. This could end up determining the preservation of the interior of these structures that despite their architectural value many times carry valuable pieces of art, sculpture and decoration in their interior spaces but most importantly it could determine the safety of the people that gather in these religious buildings.

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