Nadja Kurtović-Folić, Vesna Stojaković

THE ORIGIN OF THE STRUCTURAL CONCEPT OF HAGHIA SOPHIA IN CONSTANTINOPLE

Introduction

The essence of exploration of architecture from past periods reserve to the qualification of the same problems that builders are dealing today. These problems could be defined trough the following questions: what task was given to the builder, how he decided to solve it and what tools he used to solved it? The information available from the building past are primarily aimed to show of what kind and what extent could be the relation between a problem and its solution. The main question repeating all the time trough history is: Why a structure belonging to a certain period looks the way it does and not in a different way? There are reasons why any shape existing in the space looks like it does and not differently. The basic elements of logic contribute to this.[1]

In the past building structures were created by perceptioning as the time went by which was accompanied by numerous attempts and mistakes. Every builder appeared to be bolder than the previous one. Some of the old experiences within limited period of the Late Antiquity and Early Middle Age and in the territory that covered Byzantine Empery are one of the most representative examples.[2]

The climax in shaping of Byzantine structures is represented by Saint Sophia church in Constantinople from the VI century AD. As far as it structure is concerned it is divided into two rather independent space units. The internal core consisting of piers, arches, conch, semi-domes and a central dome is functioning as a central canopy, a kind of "heaven" which establishes even the spiritual vertical of the structure. The lateral ails, nartex, and the gallery are almost independent from this effect of the central core. Somehow, this structural solution represents the VI Century continuation of Roman building tradition merged with inovative Christian ideas.

---

1 Ch. Norberg-Schulz, *Intentions in Architecture,* MIT Press, Cambridge, Mass., 1965.

2 J.Fitchen, Building Construction Before Mechanization, The MIT Press, Cambridge, Mass, 1986.

Analyzing this structural approach, we can try to do this by comparing two churches from the same period, but different in size, the church of SS. Sergius and Bacchus and the church of Hagia Sophia, both built in Constantinople. The conclusion could be of great interest for the history of building technology, as there is the possibility that the same authors made the designs for both churches, using the experience of building the smaller church to build one of the most important structures ever. Another question of interest could be how mathematics and physics could help in solving building problems, because Anthemius and Isidorus, the authors, were well known as scientists and become architects by using the knowledge of mathematics and physics.[3]

We must add the eternal love towards order, good proportions and meaning of the building declared by Justinian the Great as the key to understanding the structural origin of Hagia Sophia.

The later forms of the Byzantine churches were represented by a cross-inscribed base with one or fife domes, and this structural design was recognized as more appropriate for religious doctrine and financial potential of Byzantine orthodox clergy and aristocracy.[4]

Structural relations and similar concept of the churches ss. Sergios and Bacchos and Hagia Sophia in Constantinople

Many authors have already stressed out that the plans of SS. Sergios and Bacchos and Hagia Sophia in Constantinople belong to the same building type.[5] We owe the miracle of Hagia Sophia to the vision of Justinian the Lawgiver, fourth Christian Roman Emperor (482-565, Emperor 527-655). It is also known that the plan for Hagia Sophia was evolved by Anthemius of Tralles (Aydin) and Isidore the Elder of Milletus. It may well be that Anthemius solo, or together with Isidore, designed some other buildings in Constantinople, specially SS. Sergius and Bacchus.

Anthemios and Isidore lived in the first half of the sixth century. Anthemios was born in the ancient city of Tralles in Asia Minor and probably studied in Alexandria, speaking Greek. An experimental scientist and theoretician, he easily assumed mastery over the technical aspects of architecture. Although a splendid artist, Anthemios gained most recognition for his design of the Hagia Sophia on which he worked with Isidore.

An engineer, architect and scholar, Isidoros was born in Miletus in Asia Minor and presumably received his education in Constantinople. Although historians often consider him Anthemios's engineer, he probably worked as an ar-

[3] M. Salvadori, *Why the Buildings Stand up, The Strength of Architecture*, New York, 1980.

[4] Even this plan, in the rudimentary shape, was known and applied in VI Century Christian architecture of Near East. It was in the X[th] Century when this plan entered in the religious architecture of Byzantine Empire as the main building type.

[5] R. Krautheimer, *Early Christian and Byzantine Architecture*, Harmondsworth, 1986, C. Mango, *Byzantine Architecture*, New York, 1976,

chitect-engineer with Anthemios assuming the role of senior partner. Although the two probably worked on several projects together, their only certain team work occurred with the Hagia Sophia.

Some authorities avoid calling Anthemios and Isidoros architects in the traditional sense of the word, but their innovative work on the Hagia Sophia marks them as more than engineers. Borrowing from Roman Imperial, late antique, and early Christian concepts, they designed and built the major monument of Byzantine architecture. They were called *mechanicos* as they both were excellent in mathematics and physics, but in different, yet complementary fields.

Very important for the future design of Saint Sophia is the fact that Anthemios was the first to described the construction of an ellipse with a string fixed at the two foci. In his famous book *On Burning Mirrors* he also describes the focal properties of a parabola. Heath gives one of his problems which leads to the ellipse construction. „*To contrive that a ray of the sun* (*admitted through a small hole or window*) *shall fall in a given spot, without moving away at any hour and season“*. And Anthemius's solution is: *„This is contrived by constructing an elliptical mirror one focus of which is at the point where the ray of the sun is admitted while the other is at the point to which the ray is required to be reflected at all times.*“[6]

Anthemius studied the focal properties of the parabola and proves that: *„.. parallel rays can be reflected to one single point from a parabolic mirror of which the point is the focus. The directrix is used in the construction, which follows, mutatis mutandis, the same course as the above construction in the case of the ellipse“.* He compiled a survey of remarkable mirror configurations in his work *On remarkable mechanical devices* which was known to certain of the Arab mathematicians such as al –Haytham. Where this knowledge was applied in his architectural achievement?

Hagia Sophia was a stunning architectural achievement that combined the longitudinal shape of the Roman basilica with domed central plan. Two centuries earlier the Emperor Constantine had used both the dome and basilica in the Church of the Holy Sepulcher in Jerusalem, but he had not joined them into an organic unity. In the earlier dome buildings such as the Pantheon, Torre Pignatarra, Santa Constanza, the dome rested on a circular drum. That gave the dome solidity but limited its heights and expansiveness. (Fig. 1)

Anthemius and Isidore solved this problem by the use of pendentives, space triangles, that carried the weight of the dome on massive piers rather than straight down to the drum. In the Church of Saint Sophia, the central dome was abutted by two half dome so that a person looking down at the building from above might see a nave in the form of an oval instead of a quadrangle. (Fig. 2)

Some other Roman buildings were stabilized by using the outside conques, such as could be seen at *Nymphaeum* in *Horti Liciniani* (so called *Minerva Medica*). This construction gives the building necessary stiffness and stability and was elaborated later in different variations, including the inverse plan, designed by structuring the conques (apses) inside and shortened them to

---

6 S. Huerta, "Oval Domes, History, Geometry and Mechanics", *Nexus Network Journal*-Vol 9, No 2, 2007, 211-248.

Fig. 1 The Roman domes rested on a circular drum: Pantheon, Torre Pignatarra, chiesa di Santa Constanza

Сл. 1 Римске куполе на кружном тамбуру: Пантеон, Торе Пињатара, црква Св. Констанце

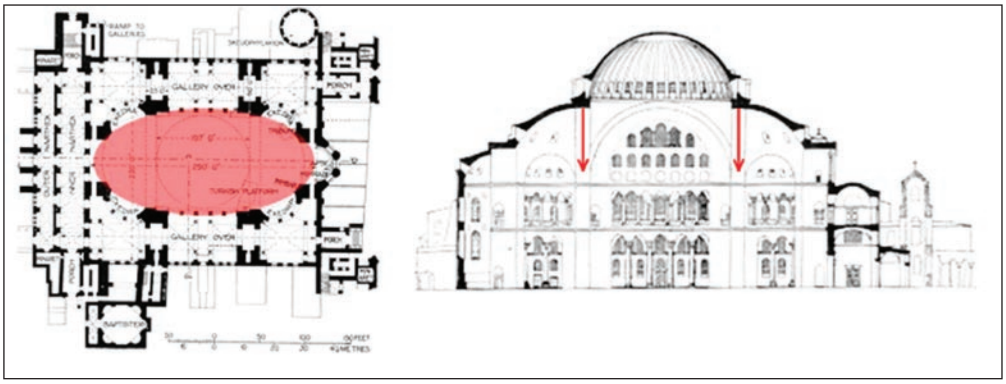

Fig. 2 Ground plan and longitudinal cross-section of the church Hagia Sophia

Сл. 2 Основа и подужни пресек цркве Св. Софија (према J. Mainstone)

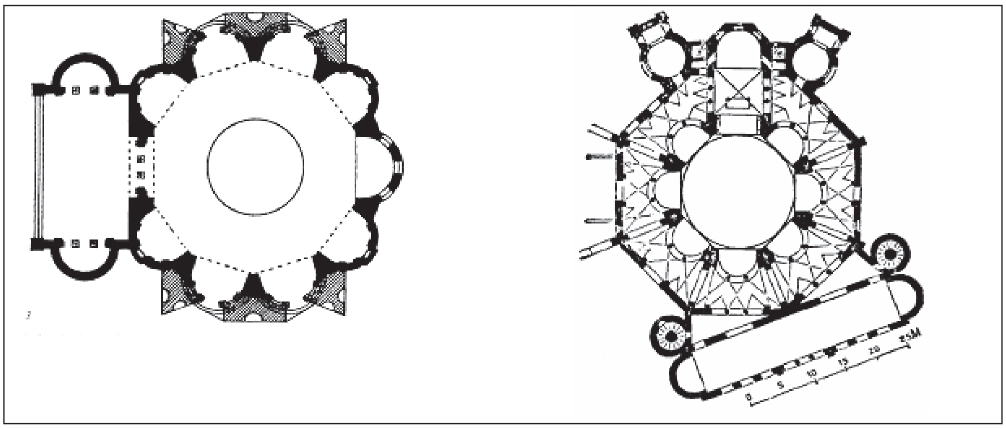

Fig. 3 Ground plans of "Minerva Medica" in Rome and San Vitale in Ravenna

Сл. 3 Основе „Минерве Медике" у Риму и Сан Витале у Равени

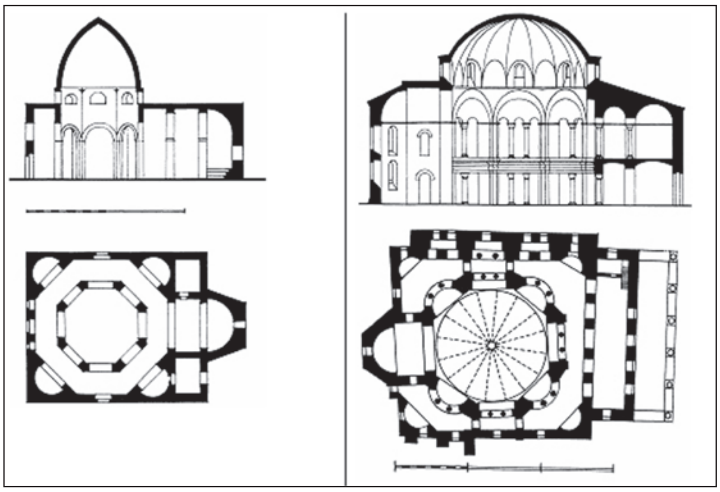

Fig. 4 Ground plan and cross section of the Church Saint George in Es'ra and the Church of SS. Sergios and Bacchus in Constantinople

Сл. 4 Основа и попречни пресек цркве Св. Ђорђа у Езри и цркве Св. Сергија и Вакха у Цариграду

act as small blind semi domes supported by columns, as in the Early Christian church of San Vitale in Ravenna.[7] In design this church is an octagonal building, roofed with a dome and enclosed by a rectangle, with a narthex along the west side. This was a favorite type of ecclesiastical architecture, in which Justinian and Theodora were interested. There, however, the octagonal interior is placed within an octagonal enclosure, so even the structural concepts are similar, the building forms are different. (Fig. 3)

In the small town of Es'ra, in far southern Syria, stands even today the Church of St. George. This is not just any church of St. George, for the relics of the saint are in a corner niche in this church.[8] This particular church dates back to the 6th century, is a somewhat unique in its architecture. The outside appears squarish and fortresslike. The nave of the church is octagonal and sits completely underneath the over sized beehive dome. A gallery extends around the outside of the nave, meeting at the iconostasis. There is a great similarity with the concept of the Church of SS. Sergius and Bacchus in Constantinople.

As construction of the Church of SS. Sergius and Bacchos started as soon as Justinian ascended the throne in 527, we could think of how the process of plan transformation into the much elaborated plan of Hagia Sophia was evolved. For better understanding the idea of composing such a huge interior, with the vast dome floating with apparent weightlessness over the main room, some must think about the learning and skills that helps the builders to realize that dream of Justinian. Both builders were Greeks by origin, and they were not trained to build. They were known as mathematicians and physicians, but now they are highly estimated as great architects. Anthemius skills seem also to have extended to engineering for he is said to have been employed to repair flood defenses at Daras.[9]

---

7 San Vitale was founded in 526, a year before SS. Sergius and Bacchus

8 There is a church in Israel that claims the same thing.

9 G.L, *Huxley „Anthemius of Tralles". Dictionary of Scientific Biography 1: 169-170. New York, 1970.*

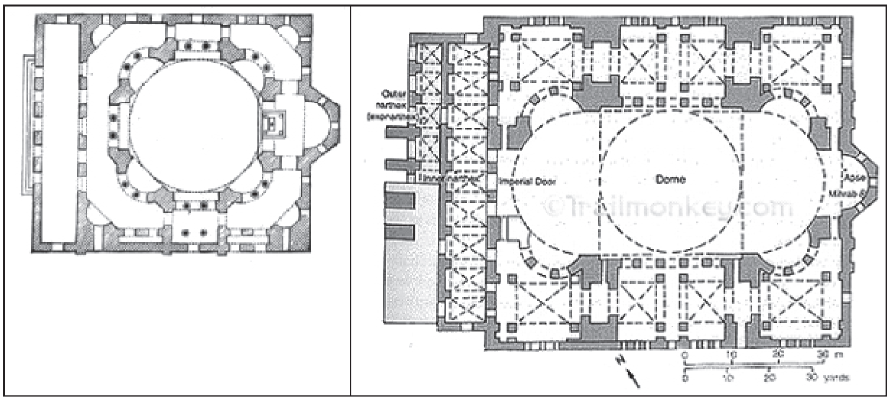

Fig. 5 – Plans of Church of SS. Sergius and Bacchus and Hagia Sophia

Сл. 5 Основе цркава Св. Сергија и Вакха и Св. Софије у Цариграду

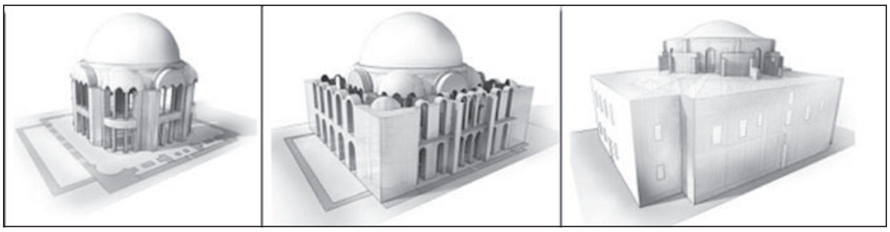

Fig. 6 – 3D model of Church of SS. Sergius and Bacchus representing: dome; structural system and the building in the whole

Сл. 6 – 3Д модел цркве Св. Сергија и Вакха: купола, конструктивни склоп и цела грађевина

The Church of SS. Sergius and Bacchus is one of typical samples of central planned, first period Byzantine churches in the capital Constantinople. Narthex lies at the west and semi-hexagonal shapedapse lies at the east side of the irregular, rectangular planned church. The octagonal planned center area, which was placed in the irregular rectangle, was enlarged and stabilized with semi-circle shaped niches. The location integrity has been ensured between the center area and apse by placing polygonal shape pillars to the corners of this center area and two each column among these pillars.

In terms of plan there are very similar characteristics with Saint Georges in Es'ra, and some with San Vitale in Ravenna, and with other examples of minor interest, but it is completely different at third dimension. (Fig. 4)

In the central area, there is 16 sectioned dome carried by eight big pillars on its corners. Eight of these sections are plain and eight of them are concave. The upper surface of the corridors providing passage from the center area to rectangular form takes shape of a gallery at the upper floor. At the gallery floor, the upper surface of the exedras are furnished with semi - domes carried by three arches.

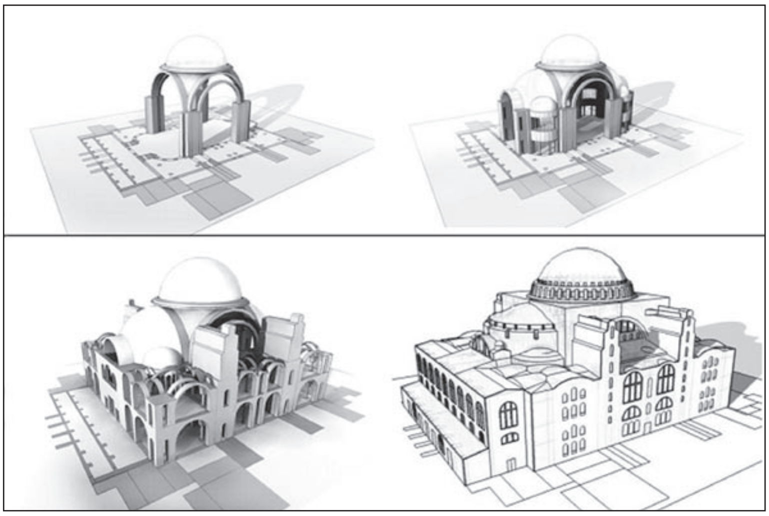

Fig. 7 – 3D model of Hagia Sophia representing: dome; central dome and west and east semi domes; structural system; the building as the whole

Сл. 7 – 3Д модел цкве Св. Софије: купола, централна купола са западном и источном полукуполом; конструктивни склоп; цела грађевина

The plan of Hagia Sophia suggests that of SS. Sergius and Bacchus cut in two, with a lofty dome on pendentives over a square plan inserted between the halves (Fig. 5, 6, 7, 8). Thus was secured a noble and unobstructed hall of unrivalled proportions and great beauty, covered by a combination of half-domes increasing in span and height as they lead up successively to the stupendous central vault, which rises more than 54 m into the air and fitly crowns the whole. The imposing effect of this low-curved but loftily-poised dome, resting as it does upon a crown of windows, and so disposed that its summit is visible from every point of the nave (as may be easily seen from an examination of the section), is not surpassed in any interior ever erected. Technology of our days could help us, by making the animation of 3D model, to repeat, step by step, the way how the concept of the Church of SS. Sergius and Bacchus was ingeniously enlarged to fit the needs of the Church Hagia Sophia, done on a scale unprecedented in human history.

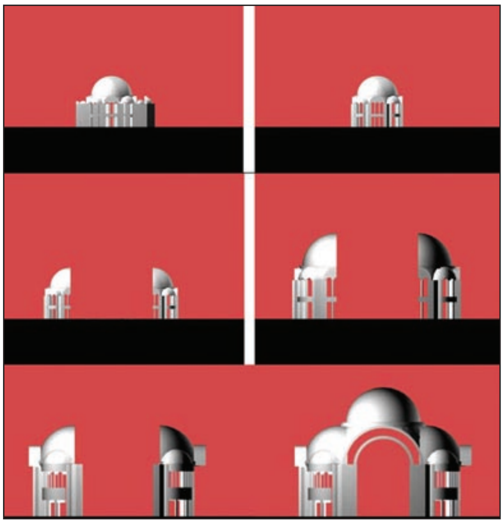

Fig. 8 – 3D model representing transformation of the structure of SS. Sergius and Bacchus to the structure of Hagia Sophia.

Сл. 8 – 3Д модел који представља трансформацију структуре цркве Св. Сергија и Вакха у структуру Св. Софије

The original plans of Hagia Sophia have been lost without a trace. For hundreds of years, experts have tried to fathom just how the scientists and artists working in the 6th century managed to construct a freely suspended dome measuring almost 56 meters high and 31 meters wide, supported only by four pillars.[10]

[10] Çakmak, A, Taylor, R.M, Durukal, E, "The Structural configuration of the first dome of Justinian's Hagia Sophia (A.D. 537-558): An investigation based on structural and literally analysis", *Soil Dynamics and Earthquake Engineering 29*, 2008, 693-698.

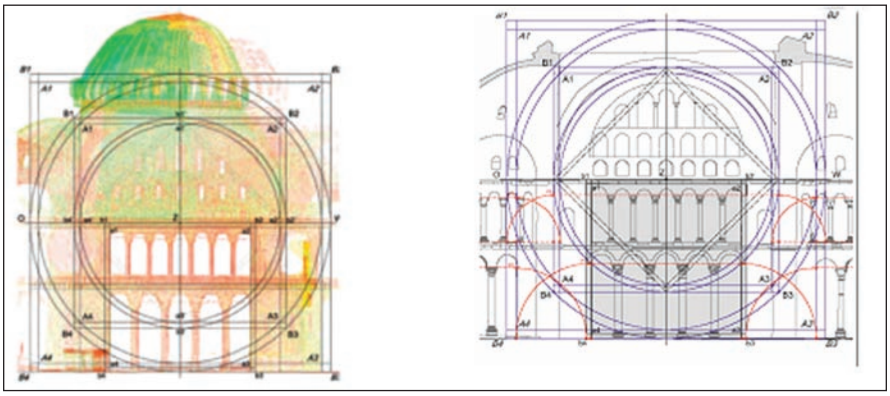

Fig. 9 - The secret of the design principle was deciphered by Volker Hoffmann, professor at the Institute for Art History at the University of Bern, by using state-of-the-art HDS laser technology from Leica Geosystems

Сл. 9 – Тајну пројектантског принципа дешифровао је Фолкер Хофман, профессор историје уметности Универзитета у Берну, применом технологије студије случаја ХДС ласера Лајка геосистема

In 2005 every point of Saint Sophia's main dome was recorded in 3D in HDS laser scan file. Using the Cyclone software from Leica Geosystems, it was possible to view and measure the building from various perspectives on the PC 10. The "master plan" was deciphered by Volker Hoffmann and Nicholaos Theocharis of the University of Bern.[11] According to them the entire Hagia Sophia is based on the proportions of a double circle and a double square (Fig. 9).

Volker Hoffmann and Nikolaos Theocharis in a research project sponsored by the Swiss National Fund found that the entire design of Saint Sophia is based on an *Analemma.*[12] This is a projection technique that was described by *Ptolemaeus*. This technique made it possible to interconnect the earth and the canopy of heaven in accordance with the view of the world at the time: the sphere representing the sky, god and the church, and the cube representing the earth with its four directions, above and below, and the Emperors realm. For Saint Sophia, according to Volker Hoffmann's findings, Anthemios and Isidoros

[11] Der geometrische Entwurf der Hagia Sophia in Istanbul, Bilder einer Ausstellung / Herausgegeben von Volker Hoffmann, Peter Lang AG / Europäischer Verlag der Wissenschaften;, Leica Geosystems AG: Deciphering the 'Eighth Wonder of the World', Report 52

[12] Claudius Ptolemaeus (Greek: Klaudios Ptolemaios; A.D. circa 85 - circa 165), was a Greek astronomer who probably lived and worked in Alexandria in Egypt. His mathematical theories, most valuable in the field of trigonometry, are preserved in his *Analemma* and *Planisphaerium*. Vitruvius, also, working from earlier Greek manuscripts now lost, constructs the analemma from the known height of a gnomon and the known length of its equinox shadow. The result of the geometric construction is a projection of the winter and summer solstice shadow lines (known as the zodiacal plaques) and the vernal and autumnal shadow lines. To complete the design of the sundial a further projection, constructed 90¡ to the meridian, provides added day and hour lines for the entire year (Book IX).

devise an overlapping double-square analemma as a uniform design shape for the ground plan and the elevation of the church, penetrating each other three dimensionally in the form of a cube and sphere.

The explanation could be again found in the knowledge that Isidore of Milletus possessed as he had earlier taught physics in Alexandria and then later at Constantinople, and had written a commentary on earlier books on building. He had also collected and published the writings of Eutocius, which were commentaries on the mathematics of Archimedes and Apollonius, and consequently helped to revive interest in their works. Furthermore, he was also an able mathematician, and to him we owe the T-square and string construction of a parabola and possibly also the apocryphal Book XV of Eucild's Elements.

Concluding remarcs

The Hagia Sophia of the Christian mysteries, to which concept and building participated an emperor, two mathematicians-engineers, 10000 workers and 100 overseers, is gone. The message of the building is now purely intellectual and emotional. Those who understand its pure stuctural essence can do so better now than ever before. Even than R.J. Mainston stated that „Of all structures that have survived to the present, Hagia Sophias' is possibly the most difficult to analyze".[13]

It is only through the opening of the building to modern structural engineers and new technologies that the problems and their fascinating solutions could be understand and used as the messages from the past.

Нађа Куртовић-Фолић, Весна Стојаковић

ПОРЕКЛО КОНСТУКТИВНОГ КОНЦЕПТА СВ. СОФИЈЕ У ЦАРИГРАДУ

Порекло конструктивног концепта цркве Пресвете мудрости у Цариграду повезује се са низом наслеђених облика из римске античке архитектуре, хришћанске архитектуре Блиског истока, али и са веома надахнутим идејама двојице градитеља, Антемија из Трала и Исидора из Милета, које је цар Јустинијан био ангажовао за овај историјски подухват. У раду се њихова идеја о конструкцијском склопу Св. Софије доводи у непосредну везу са склопом цркве Св. Сергија и Вакха, што је уочено од стране многих истраживача, али се кроз декомпозицију склопова и 3Д модела показује како је било могуће раздвојити структуру цркве Св. Сергија и Вакха, транслаторно померити те две половине и у средину убацити конструкцију централне, велике куполе. На тај начин могуће је објаснити положај полукупола са западне и источне стране, као и све остале елементе који учествују у стабилизацији језгра са великом куполом.

Поред тог предлога решења порекла конструкцијског облика, кроз приказ дешифровања пропорцијског система од стране професора Хофмана указано је на потребу примене савремених технологија, како би се разјаснили многи, до данас, непознати елементи обликовања цркве која још увек представља недостижни узор инвентивности и довитљивости градитеља.

---

[13] R. J. Mainstone, *Hagia Sophia: Architecture, Structure, and Liturgy of Justinian's Great Church*, New York, 1997, 25