

Thermal Capacity Masonry Shell Modeling and Simulation of Byzantine Monuments in Greece.

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Abstract

Masonry buildings, when subjected to external temperature fluctuations, tend to regulate them either by storing heat in their thermal mass or by offering it back to the interior, with a time lag depending on the thermal capacity of the building and characterized mainly by the overall mass of the masonry. This time lag may vary from a few hours when lightweight masonry is concerned to several days for masonry buildings of large mass. The scope of this work is to calculate the thermal capacity of Byzantine (334 – 1453 AD) monuments in Greece and to show how their thermal capacity affects their internal temperature temporal profile. The analysis will be based on a typical 6th AD century Byzantine Church in Thessaloniki Greece, dedicated to the Holy Wisdom of God our Lord (Aghia Sophia).

1. Introduction

The energy efficiency problem in building design has been paused very early in the history. The main parameters of this design were the orientation of the building, the solar heating and the thermal inertia of the building. From the Geometric Period of the Greek History (9th to 6th centuries BC) there is a tendency (e.g. small village of Vroulia in Rhodes) of taking advantage of the benefits of the winter sunshine and of avoiding the strong Northern winds. For example, in Athens, the Holy Island of Delos, Olynthos and Priene there was a tendency of positioning the windows to the South or Southeast, whereas the building walls were oriented in a way that would cover the building from strong winds. The same of course holds for urban planning, too. Towns are oriented to the South or Southeast and inclined areas are being preferred, in order to take full advantage of the wind and the sunshine. This philosophy is to be found in the Memoirs of Xenophon, where Socrates describes the so called 'Solar House' and gives instructions for its orientation.

Moreover, examples of thermal storage and thermal inertia philosophy are also to be found in ancient Greece. Santorini island is a very good example dating back to the 15th century BC. There solid bricks and stones were used for constructions.

In the present work, the thermal capacity of Byzantine (334 – 1453 AD) monuments in Greece is analyzed and the way their thermal capacity affects their internal temperature temporal profile is shown. The analysis is based on a typical 6th AD century Byzantine Church in Thessaloniki Greece, dedicated to the Holy Wisdom of God our Lord (Aghia Sophia).

1.1 Thermal Capacity

By definition the thermal capacity of masonry is its capability to save thermal energy by storing it in its mass during the heating period. The amount of heat stored depends on the temperature difference between the masonry and the air surrounding it, the thermal capacity of the masonry, and the masonry mass. The masonry thermal capacity is determined by:

i. The specific thermal capacity c , which is determined as the amount of heat required to increase the unit mass by 1° K.

ii. The thermal capacity coefficient C , which is determined by the amount of heat stored in a m² of masonry when the temperature difference is 1° K. It is usually defined, for a harmonic temperature variation, as the amplitude of the heat flow q divided by the temperature amplitude θ on the surface of the masonry and the radial frequency ω or the period T of the variation.

$$C = \frac{q}{\omega\theta} = \frac{Tq}{2\pi\theta} \quad (1)$$

iii. The thermal diffusion a is defined as the thermal transmittance coefficient λ divided by the density ρ and the specific thermal capacity c

$$a = \frac{\lambda}{\rho c} \quad (2)$$

iv. The active masonry mass is defined by the surface of the masonry A and its thermal capacity coefficient C divided by an arbitrary specific thermal capacity $c_c = 1000$ J/KgK.

$$m^* = A \frac{C}{c_c} \quad (3)$$

2. Historical Data and Description of the Church

The church of Aghia Sophia, as all Greek Orthodox churches, is oriented from West to East and is a very heavy cubic building with an almost square plane view, its basic dimensions being 30,92 m wide by 28,90 m long or 40,06 m if the Sanctus tri-folio niche is included. Its interior forms a cross-like nucleus covered by a large cupola that is based on masonry friezes supported by four cylindrical bows. These bows are based on four large masonry pillars. Lateral naves and church-porch with balconies surround the three sides of the central nucleus in a π -like shape. On the upper structure the cupola largely extends over the whole wooden roof, covered with ceramic roof tiles. It stands on a heavy masonry drum base, cubic-shaped outside and rather ellipsoid inside, its two N-S and E-W main diameters being 11,60 m and 10,95 m respectively. The average diameter of the cupola is 10,16 m and it is illuminated by twelve bow-like windows, three on each side of the cupola. The square base of the cupola is quite shorter than the cupola itself forming a balcony.

The three folio vaulted Holy Altar forms a somewhat architecturally independent unit with respect to the rest of the cubic church. The Sanctuary, paced at the center of the Holy Altar, is covered by a semicircular masonry bow (kamara) and it ends to a semi-hexagonal niche. On the left and right side of it are two squares covered by semi-spherical domes placed of fringes. Five large windows illuminate the Holy Altar.

The masonry of the church is distinguished in four periods.

The initial masonry is made of five high, parallel, horizontal zones of roughly carved stones 1.15 cm high followed by five rows of fired clay solid bricks 40.0 x (30.0 to 32.50) x (4.50 to 5.00) cm. Although the stones used are of limestone or sandstones have an inferior quality, the fired clay bricks are of excellent quality. The mortar consists of very cohesive well graded, milled fired clay of excellent quality. The milled fired clay offers excellent hydraulic performance of the mortar, together with fast humidity absorption.

The masonry of the 2nd period resembles that of the initial period, the only difference being in that the carved stones are substituted by non-carved ones. The bricks are of various dimensions and the bows are exclusively made of fired clay bricks 3.00 to 3.50 cm high.

The masonry of the 3rd period consists of non-carved stones and joints filled with small stones and very small quantities of brick splinters.

The masonry of the 4th period is also made of series of non-carved stones and series of bricks. The mortar consists of lime, milled fired-clay, grit and ceramics broken to very small sizes. Compared to the mortar used during the 1st period, it contains smaller quantities of crusted fired-clay.

Figure 1a-e show different views of the church.

3. Results and Discussion

The thermal characteristics of the masonry units used are shown in Table 1.

Table 1. Thermal characteristics of the masonry units

Characteristic	Clay Brick	Natural Stone	Mortar
λ (W/mK)	1.09	1.09	0.87
ρ (kg/m ³)	1900.00	1900.00	1900.00
C (J/kgK)	790.00	790.00	1000.00

Table 2 shows the geometrical characteristics (m), the thermal resistance (m²K/W), the thermal transmittance (W/m²K), the active penetration depth (m), the thermal capacity (KJ/m²K) using the analytical method proposed by CEN TC89 WG4 and the time lag (h) of the masonry types mentioned above. Table 3 shows the total power losses (W/K), the total thermal capacity (MJ/K) and the total time lag (h) for the East, West, South and North sides, the Roof and for the whole building.

Table 2. Geometrical and thermal characteristics of the masonry used

Masonry Type	W [m]	R [m ² K/W]	U [W/m ² K]	d* [m]	c [KJ/m ² K]	τ [h]
Bricks	0.85	0.780	1.055	0.141	203.23	22.98
Bricks	2.35	2.516	0.430	0.141	203.23	63.53
Stones	0.85	0.570	1.353	0.162	207.82	20.10
Stones	2.45	1.644	0.522	0.162	207.82	57.93
Bricks*	0.85	0.814	1.018	0.141	203.23	22.98
Bricks*	1.15	1.090	0.795	0.141	203.23	31.09
Bricks*	1.30	1.227	0.717	0.141	203.23	35.15
Bricks*	1.55	1.457	0.615	0.141	203.23	41.91
Bricks*	1.70	1.594	0.567	0.141	203.23	45.96
Bricks*	2.15	2.007	0.460	0.141	203.23	58.13
Bricks*	2.35	2.190	0.424	0.141	203.23	63.53
Bricks*	2.45	2.282	0.408	0.141	203.23	66.24
Stones*	0.85	0.605	1.293	0.162	207.82	21.05
Stones*	1.15	0.806	1.026	0.162	207.82	28.48
Stones*	1.30	0.907	0.930	0.162	207.82	32.20
Stones*	1.55	1.075	0.804	0.162	207.82	38.39
Stones*	1.70	1.175	0.744	0.162	207.82	42.11
Stones*	2.15	1.477	0.608	0.162	207.82	53.25
Stones*	2.35	1.612	0.562	0.162	207.82	58.21
Stones*	2.45	1.679	0.541	0.162	207.82	60.68
Window	.004	0.004	5.804	0.004	5.00	0.14
Door	0.10	0.250	2.390	0.065	32.60	2.94
Roof	0.30	0.435	1.657	0.129	71.73	0.89

*the indoor side is covered with mortar.

The temperature fluctuation period equals 24 and the decrement factor D ranges between 2.45×10^{-3} and 6.02×10^{-3} for the clay brickwork, between 5.20×10^{-3} and 2.97×10^{-3} for the natural stonework and equals 0.46 for the roof.

Table 3. Thermal Characteristics of the building's sides

Orientation	\sum_{UF} [W/K]	\sum_{cF} [MJ/K]	τ [h]
West	894.05	81.46	25.31
South	749.09	97.21	36.05
East	785.99	120.61	42.62
North	856.35	93.51	30.33
Roof	1644.70	331.89	3.22
Overall	4930.18	724.68	40.83

From Table 3 it is evident that the masonry walls largely contribute to the thermal capacity of the building and consequently to its thermal inertia. The overall thermal inertia of the building is 724.68 MJ/K, which for 18°C (291°K) equals 210881 MJ. This gives a time lag of 40.83 h or almost two days. Taking into account:

- i. That for Thessaloniki the average maximum temperatures for July and August are 31.6°C their corresponding average minimum temperatures are 18.2°C and 17.9°C and the corresponding average absolute average temperatures (1% probability) are 36.6°C and 36.0°C respectively.
- ii. The average duration of a Greek Orthodox Mass is of the order of two hours, twice-a-day

It is evident that no artificial cooling is required in summer.

Moreover, taking into account that for Thessaloniki the absolute minimum temperature for the winter is -12.8°C whereas the corresponding design minimum temperature is -5°C, it can be seen that the 40.83 h

thermal lag can regulate all external temperature short term fluctuations reducing the heating cost to a minimum, if of course the heating system is specifically designed and tuned for these large thermal capacities.

4. Conclusions

The above analysis has indicated that the temperature variation damping increases exponentially with the width, and consequently the mass, of the masonry. For wall of large width, as those of Aghia Sophia, the damping is very large. This leads to an almost constant temperature, which, if heating is not applied, is almost equal the average external temperature. On the other hand the temperature fluctuation hysteresis increases linearly with the masonry width.

Historic buildings as the analysed church show the importance of the thermal mass for the comfort of the occupants resp. heating and cooling costs. This fact is still valid for modern buildings, underlining the advantages of massive buildings built with clay bricks and blocks as opposed to the lightweight houses. Nowadays the aim is to find a optimum between the thickness of the wall, the thermal mass and the corresponding heating and cooling requirements.

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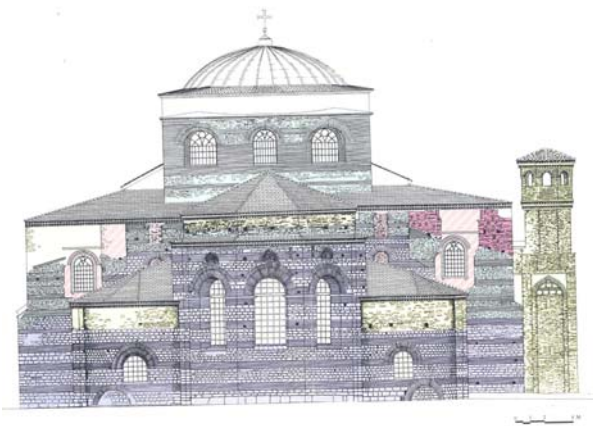


Fig1a. East side view of the monument

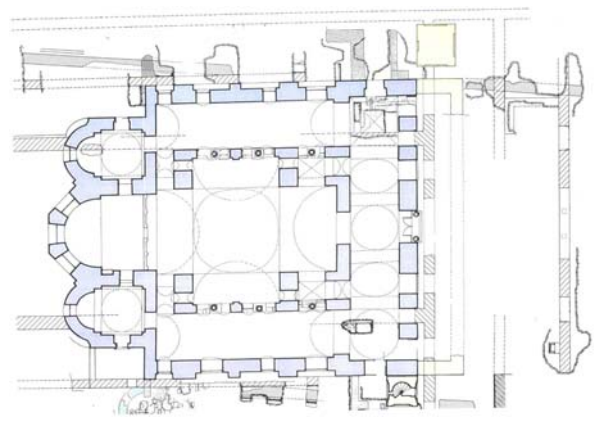


Fig. 1e. Plane view of the monument

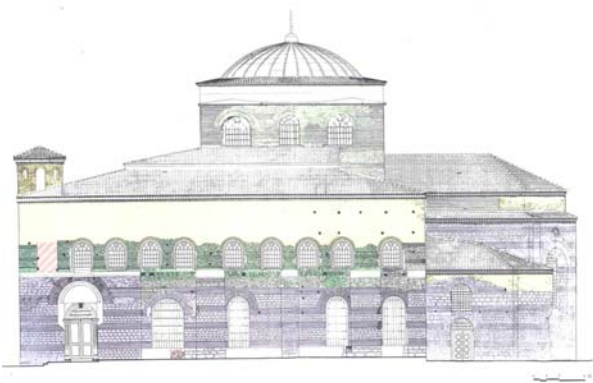


Fig1b. South side view of the monument

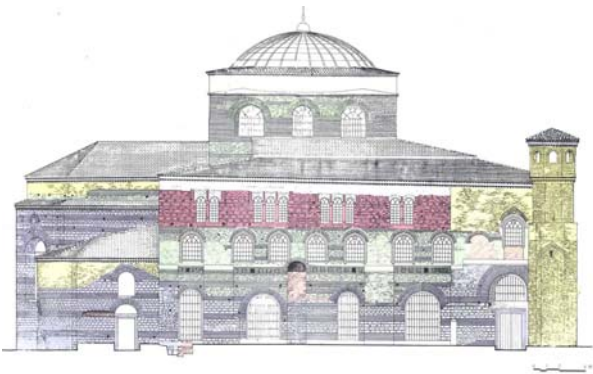


Fig1c. North side view of the monument

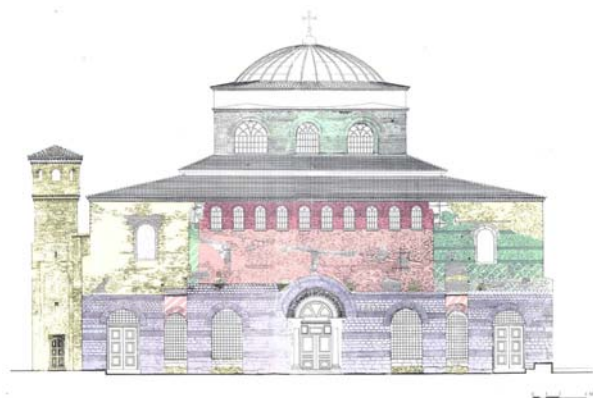


Fig1d. West side view of the monument