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Structural behaviour of historic masonry domes of major importance: an overview

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ABSTRACT

Dome was an essential structural component for all kind of public assembly edifices, from the Pantheon to Sinan's Selimiye. Computer based investigation techniques are applied to conceptualize structural behaviour of such buildings. More systematic approaches were needed, as described in the present text, to study masonry domed historic buildings.

INTRODUCTION

Social gathering and assembling have constantly been among basic needs of the mankind. Since very early times of the community life, the man searched for the feeling of the existence of others around, by sharing occupations physically and preoccupations pshycologically. Public gardens, agoras and forums existed, besides their daily functionality, also to satisfy this need. The religion generated a new order to shape this need and temples came into picture in lieu of spritual sharing.

In the specimens qualified as "masterpiece" the alliance of architectural creation with structural ingenuity has been the dominant factor.

EVOLUTION OF STRUCTURAL FORMS

Shelters were being roofed (or covered) long since. Primitive mixture of wood, stone and earth were used for this purpose. As for assembly buildings where some units had larger spans, functional requirements were solicited in a way of erecting them partly uncovered. For most of the pre-antique and antique civilizations having settled in the regions with mild climates, this solution was reliable. In the historic remainings of the agoras, forums and temples in such regions, little traces exist from covered parts. Main roofing components were formed either by straight elements or curved structural portions, namely vaults, crossing arches, domes etc... It should be underlined that "Dome" occupied a particularly prestigious place in all public edifices of major importance. Allying classical beauty of curved surfaces with an exceptional load bearing capacity, dome is considered as a unique structural component.

Speaking of the evolution of domed buildings, the "Pantheon of Roma" constituted a revolutionary progress both in form and in material aspects with extraordinary use of earth resourced material, namely pozzolana which could be considered as a kind of "antique concrete". The Pantheon is not a monument with dome; it is dome and is fully contained within itself. It is impressive by its huge spheric diameter of 43.3 m. As for engineering features of the Pantheon, searches for oversafety, unavoidable for its time (early second century) and leading somehow to overdesigned sectional sizes are merged with amazingly ingenious structural solutions. The dome of the Pantheon is a half sphere erected over a circular wall of antique concrete and lightened by a series of decorative coffers on its interior spherical surface. Exterior surface, more in the shape of a cone, is responsible for the increase of thickness of the dome towards its bottom (Figure 1). This thickness, however, overdesigned (6.6 m), is compensated by large lightening chambers scooped out of it to reduce unnecessary sizes and weights at bottom, (Mainstone[1]).

The Haghia Sophia of Istanbul, could be considered as a sample of a rather different structural approach. Imagined as a piece of historic heritage reflecting the power and superiority of the Eastern Roman Empire, the Haghia Sophia was foreseen to overpass all existing monumental buildings in majesty. Only one big dome was not sufficient to cover the gigantic inner space. Finally a series of arches were adopted to support the main dome which could also be braced by partial two symmetrical shallow portions of cupola covering some parts of the inner volumes. It is however, unfortunate that such a daring architectural concept was not allied by sound structural solutions. Th^Xxoriginal solution was readily affected by some conceptual weaknesses and partial collapses had happened during the erection of the building. No ulterior measure of additional external bracing contributed meaningfully to restrengthen the edifice that was seriously affected by almost all regional seismic events through the centuries, e.g. Mungan[2]. It is hopefully expected that clearer information would be obtained by serious and extensive future studies on assessment of this important cultural heritage.

Late middle ages witnessed rather a consecration of the vaulted forms. Romanesque and Gothic approaches in the western world and Seljoukit, Sasanit realizations in middle east regions, all dealt with small sized domes, while enlargened vaults either in pure shape or braced by ribs and cross arches were used more and more extensively. The need for overall stability

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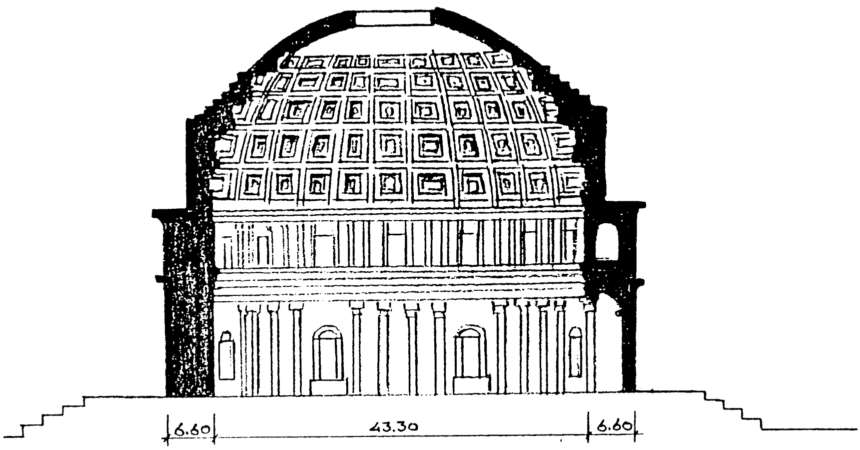

Figure 1. Descriptive Interior Section of the Pantheon

in magnified gothic structures started to constitute a crucial point, despite "flying buttress" system, characteristically used to brace them externally. Then came the series of collapses in Beauvais cathedral diluting the magic of several hundred years.

The Florence Cathedral constituted the passage from medievial structural understanding to Pre-Renaissance conceptions. Vaults were there too with wide spans, but together with a huge central construction, partly domical, partly pyramidal with a hexagonal base. The hoop and radial ribs contribute to keep the system in a state of compression, reportedly, e.g. Brebbia and Baynham[3].

SINAN AND OTTOMAN DOMED STRUCTURES

Various superb realizations were placed on the path heading from the Pantheon to Brunelleschi's Florence Dome. This extraordinary venture of development in curved structural forms was only slightly shadowed by unfortunate cases of Haghia Sophia and Beauvais.

In parallel to this evolution, a second venture certainly not less important but somewhat underestimated by western engineering architectural media has taken place in eastern mediterranean and middle eastern regions. Turks were involved actively into this movement spreading from Central Asia to Balkanic lands, including all parts of the eastern mediterranean regions. Two main flows have taken place with Turks moving west: Seljouks, first, and Ottoman's later. They had likely brought their ancestral familiarization with cylndrical and spherical forms from their origin lands to Anatolia. Seljouks had also influenced the architectural character of the beautiful medievial city of Isphahan. Bahri Memluk period's architectural sytle in Egypt is also recognized to have settled by Turkish craftsman and builders imported from Anatolia. There were meaningful products of space forms in Byzantine tradition, too, including the grandiose example of the Haghia Sophia especially. The Ottoman Empire having Istanbul as capital city in 15th. century, Turkish builders apparently merged the two traditional familiarization with the domes. Since then, Istanbul and the historic Balkan city Edirne of Türkiye became museums of dome collections.

Sinan's Approach Into Domed Structures:

Early Ottoman buildings with domes (14 th. and 15 th. century) were based either on the concept of a single dome of medium size covering the whole inner space or on the series of small domes one neighbouring the other at the same level. In both solutions, thrust and seismic actions would thus be laterally transmitted to massive exterior walls or piers, Karaesmen[4].

Sinan (1492-1588) served, for almost half a century, as the chief architect of the Empire, during which he was involved directly or indirectly in the construction of nearly five hundred works including mosques, bridges, aquaducts, hydraulic infrastructures, hospitals, palaces, schools, public baths, etc... The domes having mortared shallow bricks as constitutant material was centrally placed in some of these buildings.

Structural behaviour of domed Ottoman edifices under gravity loads is mostly governed by a mechanism of controlling thrust action around the main dome which generally lies in compression state both for meridional and hoop stresses. Surrounding partial cupolas when adequately formed and sized, contribute to this control, supporting the main dome laterally and transmitting all loads to thick external stone whereas main arches, subjected to combined effect of flexure and torsion, transfer a considerable portion of upper level loads directly to interior piers. Besides main dome and central arches, other essential components used by Sinan in major domed buildings are as described in Figure-2: drums of the main dome; strong inner piers; inclined short columns separating windows of the main dome at its lower flank; bracing surrounding partial cupolas; pendantives filling spaces between lower drum, arches and central piers; secondry arches and auxiliary inner domes of smaller dimensions. The great Masterbuilder Sinan seems to have brilliantly played with all possible combinations of arranging and associating schemes of those components.

Four major edifices taken as indicative works in evolutional path of the Sinan's domical art and science recently constituted subjects of

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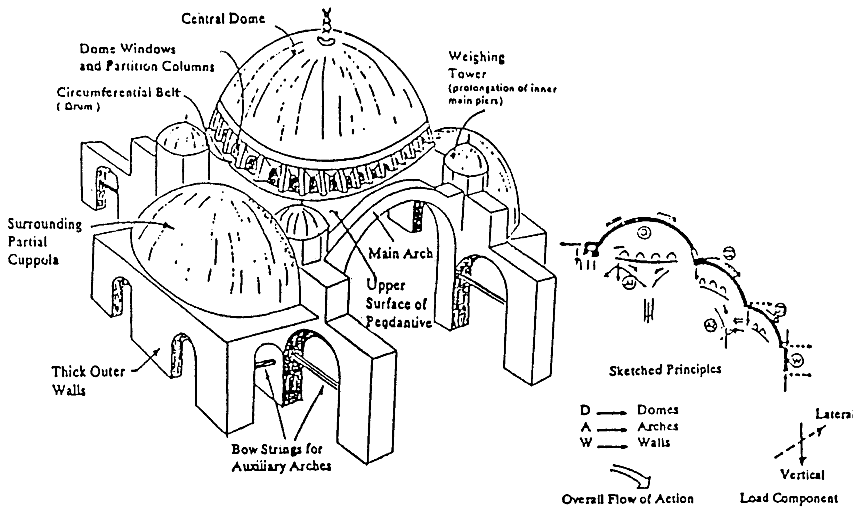

Figure 2. Representation of Typical Components and Action Flow Mechanism in Ottoman Domed Buildings

international studies to which the author was involved. These edifices and relevant findings are briefly described below, in choronological order.

Sehzade (Prince) Mehmet Mosque (1548): This edifice was a striking monument at the end of the first phase of a promising career. It represents a harmonious symmetry and the externalization of the inner spatial order. The temple was analytically investigated in several ways and some publications already were made on it, e.g. Karaesmen[4]. Engineering rightness in sizing interior piers and small inclined columns separating windows at the bottom flank of the main dome for such a heavy earthquake city as Istanbul revealed amazing superiority.

Süleymaniye Mosque (1577): Higher level of structural challenge is searched in the Süleymaniye Mosque of Istanbul which is considered as the summit of Sinan's passage to masterly period. In Süleymaniye, the radial symmetry is abolished intentionally for the sake of accordance between a majestic appearence and the beautiful hilly site suspended on the Golden Horn. There is only a bi-axial symmetry in the system and consequently the load transmission mechanism is highly daring especially with regard to the seismic conditions of Istanbul. Because of this bi-axial symmetry aspect, Süleymaniye was taken by some experts as a smaller example of the Haghia Sophia. A deeper look reveals that, structure-architecture alliance and interaction are reached in an uncomparable way. In addition the legendary story on the soil consolidation of the foundation zone is a good indication of the perfection in geotechnical engineering, too.

Mihrimah Sultan Mosque (1565): This edifice which was erected to the name of the daughter of Emperor Süleyman the Magnificent is a product of the masterly period of the Great Sinan. This edifice is recognized to have an interior space of a unique refinement. The spatial beauty of the temple is attributed to its daring structural system. There are no externally bracing partial cupolas in this extraordinary structure whose transmission of both seismic and gravity loads is ensured essentially by thin elegant arches and nice looking pendantives. The dome is known as having the largest sizes ever reached for an unbraced shell of revolution in brick with its diameter of 21 m. and its 38 m. of height from the ground level.

Various types of investigations were also applied to this temple, e.g. Erkay and Karaesmen[5]. Because of a partial hazard due to previous seismic events, studies included some detailed analysis for a better behavioural understanding of the structural system. Within this framework of a comparative analysis logic several finite element models all corresponding to the whole skeleton of the edifice were developed. A preliminary model was aiming to reduce the structure to rather simpler components with no consideration of the architectural elements at the bottom of the four main arches. These arches and pendantives of the system are descending to such unusually low levels, in a way magnifying the visual effect of these already elegant components that smaller elements of the very low levels were not looking like strongly contributive at a first glance. But, effect of the seismic action investigated with a sensitive spectral analysis was revealing as apt to cause easily the full collapse of the piers. On the other hand, the period for the prevailing (first) vibration mode evaluated to be 2,1 seconds was looking a little bit too high even for this light looking structure.

Other structural models were then needed to reflect the structural behaviour of the system more realistically. As seen in Figure 3, all bottom inner components and even one series of external small domed roof covering partly the court, and bow string arches were inserted into the model. Soil spectrum considerations and slenderness of the skeleton yielded in this modelling case in a seismic coefficient around 11 % for the first mode. It should be remembered that lack of detailed information on the shape and depth of the foundations shadowed somewhat geometrical sensitivity of the model, as it happens in most of large religions edifices. Zones of maximum tensile stresses were observed to locate in pendantives near to the middle of the main arches. Direction of the principal tensile stress was computed to be in a direction such that formation of a crack parallel to the curved axis of the arch could be expected. On the other hand, some other small cracks and displacements likely originated from static and dynamic soil behaviour are presently visible in the building. Future extensive studies, should deal with them, too.

Selimiye Mosque (1575): The structural achievement in the Selimiye Mosque at Edirne corresponds to an unsurpassable perfection. The largest masonry shell of revolution ever constructed (inner diameter 32.50) is supported by eight elegant slender columns instead of four heavy pillars occurring in his earlier works. The columns are connected, to neighbouring ones by eight arches, of light and gracious forms.

The dome rests vertically on these eight arches through a thick curved drum and is also braced externally by four partial small cupolas connected to every other arch. Unbraced for other main arches, are vertically and partly laterally supported by other systems of larger and thicker arches placed at lower levels and that would behave rather as vaults.

Domical art likely reached to its peak with the erection of Selimiye which represents also the zenith of Sinan's architectural-engineering power and the creative vision.

CONCLUDING REMARKS

Application of boundary or finite element techniques to masonry bearing systems considered as behaving elastically or inelastically contributes to get an overall assessment. But, sometimes more precise informations are needed for details of preservation-protection operations. A more systematic approach, then, is needed to evaluate behavioural features of the old masonry structures of major sizes.

International research work is undertaken with contribution of the author. Future studies will cover: i) Preliminary evalution and compilation of historic information with regard to construction type, materials. ii) Examination of geotechnical features, soil and foundation elements with non-destructive testing as well classical investigations. iii) Determination of detailed geometrical feature of the building including foundation components. iv) Establishing a monitoring system with systematic permanent measurement of deformations. v) System identification work with contribution of non-destructive testing equipment, if considered necessary. vi) Material science studies particulary intensified on mortared masonry behaviour. vii) Evaluation of a detailed structural model and full structural analysis of the system including all parameters of dynamic response. viii) Experimental studies, if considered necessary, on a laboratory model of the structure. ix) Remaining in close contact all through the studies with architecture historians and art philosopher to ensure usefulness of findings for them, too. x) Interpretation of engineering results with the objective of contributing to preservation practice.

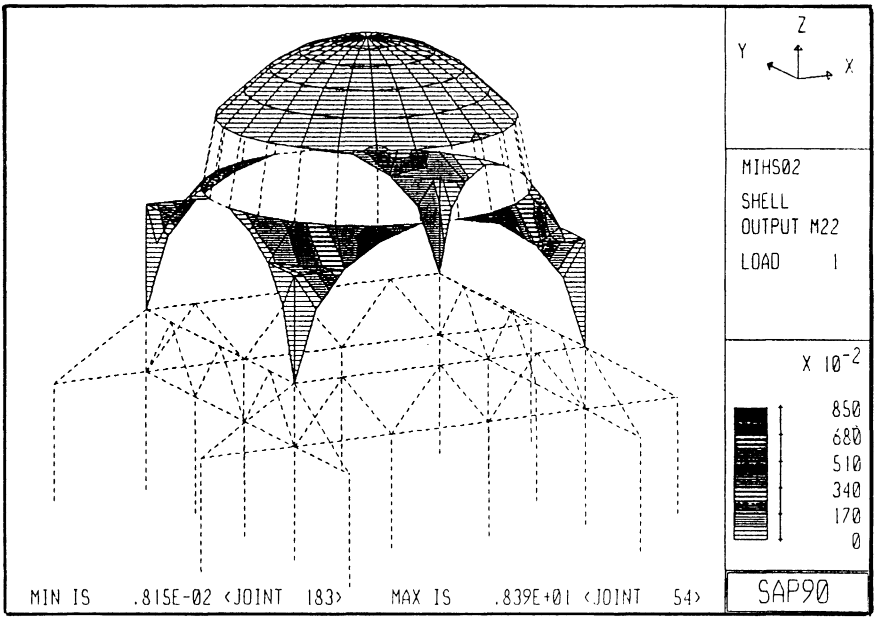

Figure 3. Mihrimah Mosque- Full Structural Model Including also Lower Components

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