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Effects of Dome System on the Seismic Behaviour of Ottomans Historical Structures

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ABSTRACT: Earthquakes are known to be natural hazards that have affected tremendously historical structures. Therefore, there is a need for a better understanding of lateral resisting systems and seismic behaviour of such structures. Generally, historical structures have very complex load carrying behaviour due to the massive and continuous interaction of domes, vaults, arches and pillars. In this study, dome systems of Ottoman historical structures will be reviewed and lateral supporting systems for the different type of domes will be classified. The seismic behaviour of the lateral resisting system with different types of dome systems are presented and analysis are performed to investigate the effect of dome system type on the dynamic characteristics of the main structure.

1 INTRODUCTION

Throughout history, earthquakes are known to be the natural hazard that have affected tremendously historical structures. Preservation of historical structures against earthquakes, necessitates a great efforts of different expertise (structural, architectural, historical, etc). There are many challenges for analysing the behaviour of historical structures under seismic loads, usually of architectural importance, due to the geometrical complexity and lack of knowledge about the inner core material. Historical structures have very complex load carrying behaviour due to the massive and continuous interaction of domes, vaults, arches and pillars. Typically these structures are more massive than contemporary structures and that usually carry their actions primarily in compression. A better understanding of the lateral resisting system and seismic behaviour of such structures is the key issue for a comprehensive earthquake structural analysis, interpretation of the analysis results and a proper intervention.

Dome systems were used extensively in the historical structures. They are very efficient since they cover the maximum volume with the minimum surface area without interrupting piers in the middle. Early Ottoman buildings with domes of 14th and 15th centuries 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, thrusts and seismic actions would thus be laterally transmitted to the massive exterior walls or piers. During sixteenth century, building techniques of Ottoman’s had been improved by allowing the construction of masonry structures with sophisticated geometries. During that period many historical structures considered to be masterpieces have been constructed. Generally the structural systems of these structures are composed of domes, transitions elements (pendatives), arches, counter weight towers, piers, walls, buttress and foundations. A very good review of Ottoman historical structures in terms of architectural and structural aspects with emphasis on the works of the great Turkish builder Sinan can be found in the proceedings of domes from antiquity to the present, IASS-MSU symposium (Ozer 1988, Gungor 1988, Karaesmen and Unay 1988, Mungan 1988).

Nowadays, with the development of computational methods, analyses of historical structures are mostly performed using Finite Element Analyses. Generating a finite element model of the structure require a good engineering experience to make a reasonable geometrical simplification of the complex geometry and a good assumption of unknown inner-core materials. During the modelling, the choice of the number, size and type of elements are matters of engineering judgement in order to represent the actual behaviour of a structural component or entire structure in mathematical terms. For historical structures located in earthquake prone areas, both static gravity forces and earthquake forces are needed to be considered in the analyses. Understanding the load transfer mechanism of static forces and lateral resisting system for earthquake forces is crucial point in analyzing these structures.

In this study, dome systems for Ottoman historical structures will be reviewed and the lateral supporting systems for different type of domes will be classified. Structural elements, load transfer mechanism for static actions and lateral resisting systems will be discussed. The effects of dome systems on the dynamic characteristics of the main structures will be studied by analyses of two masterpiece structures using the Finite Element Analysis.

2 DOME SUPPORT SYSTEMS FOR OTTOMAN HISTORICAL STRUCTURES

With the advent of improved building techniques at Ottoman empire during the sixteenth century many historical structures, considered to be masterpieces, were constructed. The structural systems are composed of domes, transitions elements (pendantives), arches, counter weight towers, piers, walls, buttress and foundations. At that period ingenious usage of different dome systems had taken in all the architectural masterpieces erected by the great Turkish builder Sinan.

Generally, dome support systems consist of a series of structural measures ensuring their stability and stretching from the square or rectangular surrounding walls of the structure. The classification of the main dome support systems used in Ottoman historical structures was done by Gungor (1998) and categorized in three systems: Square Support system, Hexagonal Support System and Octagonal Support System, as it is discussed in details below.

2.1 Square support system

This is the most popular system where the dome rests either on the walls or arches and a drum may be below it. Different support systems and structures they are applied were used and can be summarised as:

- Walls or arches on four sides: Mihrimah Mosque, Edirnekapi- Istanbul
- Walls on four sides: Haseki Sultan Mosque, Istanbul
- Wall on one side, semi-domes on three sides: Mihrimah Mosque, Uskudar- Istanbul
- Arches on two sides, semi-domes on two sides: Suleymaniye Mosque, Istanbul (Fig. 1).
- Semi-domes on four sides: Sahzade Mehmet Mosque, Istanbul; Fatih Mosque, Istanbul (Fig. 2).

2.2 Hexagonal support system

Dome rests on walls, or horizontal members replacing them, over hexagonal plan, for example Sokullu Mehmet Pasha Mosque, Kadirga-Istanbul.

2.3 Octagonal support system

- Dome rests on walls, or horizontal members substituting, over octagonal plan, for example Selimiye Mosque, Edirne (Fig. 3).

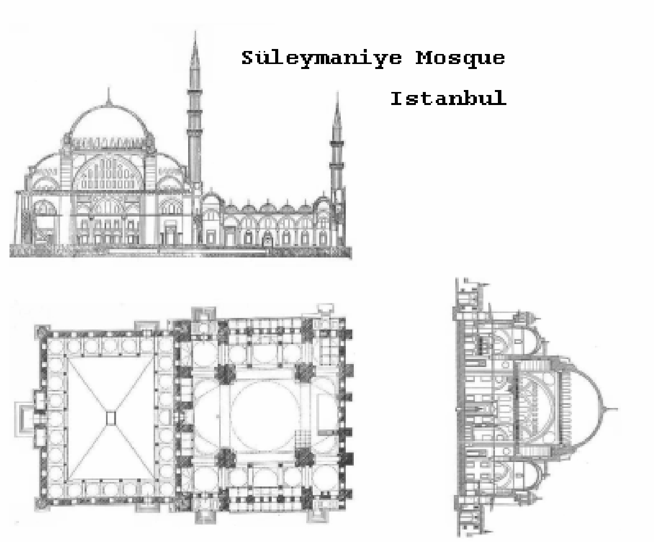

Figure 1: Square Support system for the dome, arches on two sides, semi-domes on two sides.

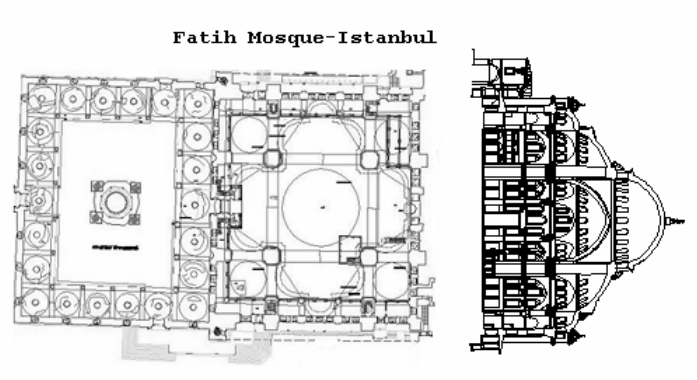

Figure 2 : Square support system for the dome, semi-domes on four sides.

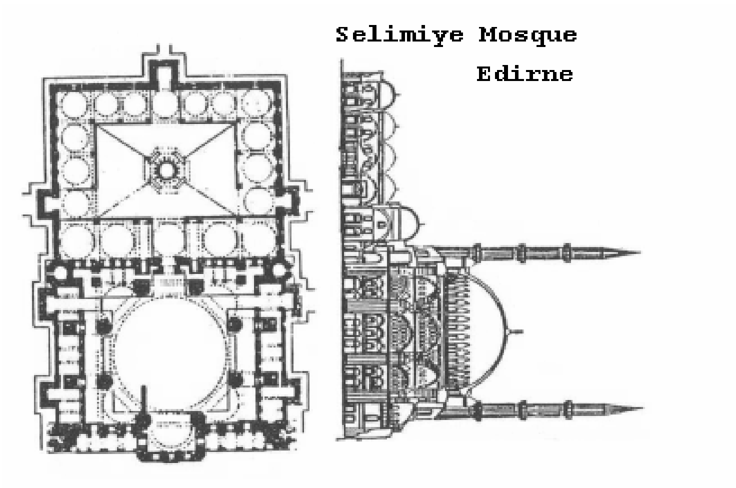

Figure 3 : Octagonal support system.

3 STRUCTURAL ELEMENTS FOR OTTOMAN HISTORICAL STRUCTURES

Historical structures have very complex load carrying behaviour due to the massive and continuous interaction of domes, vaults, arches, pillars and walls. Typically these structures are more massive than contemporary structures and that usually carry their actions primarily in compression. The structural resistance depends on the geometry of the structure, shape of the structural components and the characteristic strength and stiffness of the material used. The characteristic thickness of the masonry structural components should be able to resist compression, tension and shear stresses results from the structure's own weights and those imposed by wind and earthquake.

Major geometrical forms of Ottoman historical structural elements are arches, vaults, domes and walls. A detailed description of the load carrying mechanism of these elements can be found in (Unay 2001), and a brief summery is given below:

3.1 Arches

Arches are the structural elements that span a horizontal distance carrying its own weight and other loads totally or mainly by internal compression. The most important characteristic of the arch is that as a part of its primary action, it does always thrust outwards on its abutments as well as weighing down vertically on them.

3.2 vaults

The vault is a structural system that distributes loads by arch action through a single curved plane to continuous supports. The stresses within the vault are primarily compressive. It can be considered as a curved bearing wall enclosing a space. Lateral stability is developed within the plane of the vault, due to its continuous form.

3.3 Domes

The dome is a structural form, which distributes loads to supports through a doubly curved plane. It is a continuous geometric form, without corners or perpendicular changes in surface direction. It encloses the maximum volume with a minimum of surface area. The dome must be designed to resist compressive stresses along the meridian lines and to resolve circumferential tensile forces in the lower portion of hemispherical domes. The dome is an extremely stable structural form and resists lateral deformation through its geometry.

3.4 Load Transfer Mechanism for Gravity Forces

The main dome spreads the actions of the gravity loads' uniformly and regularly on its edge supports and pushes them in both vertically downwards and laterally outwards directions. In Ottoman masterpiece historical structures, a multitude of neighbouring domes, vaults and arches covering auxiliary spaces in the building would structurally interact with the main dome. In addition a series of window openings should be located in the flank of the dome, just at the level where the mentioned interaction would take place between the main and auxiliary structural components. The presence of external buttresses has significant contribution to release overall thrust action (Karaesmen and Unay 1988). These geometrical features lead to a complex structural system with irregular mechanism of action transmission. Therefore, ensuring the global stability of the system together with necessary strength and stability in the critical members was a big challenge as it is shown in Fig. 4.

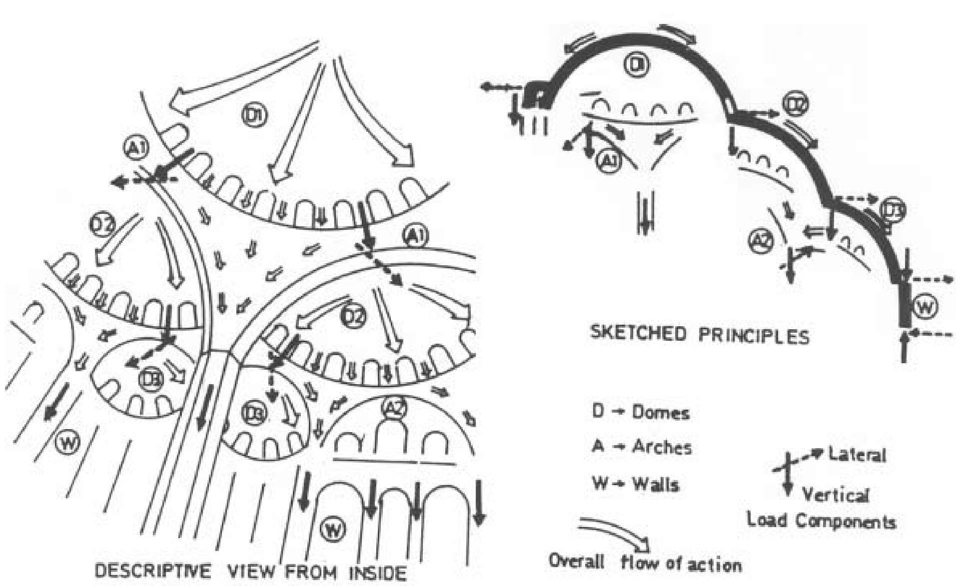

Figure 4 : Gravity load transfer mechanism in Ottoman domes (Karaesmen and Unay 1988)

4 LATERAL SUPPORTING SYSTEMS FOR OTTOMAN HISTORICAL STRUCTURES

As it is described in the previous sections, historical structures have very complex load carrying system with continuous interaction of domes, vaults, arches, pillars and walls. Most of the previous studies dealing with the load transfer mechanisms of Ottoman dome systems were considered the gravity static loads (Mungan 1988, Karaesmen and Unay 1988). Therefore, the behaviour of Ottoman historical structural systems under dynamic lateral loads are needed to be investigated to better understand overall load carrying mechanism.

In this study, general concepts of modern earthquake engineering are utilized to understand such complex lateral load transfer mechanisms. In conventional structures, the lateral resisting systems depend on sufficient horizontal and vertical diaphragms to withstand the earthquake dynamic forces. The same concept can be applied to understand the behaviour of historical structures.

Nowadays, with the development of computational methods, analyses of historical structures are mostly performed using Finite Element Analysis. Understanding the vertical and horizontal load transfer mechanism is necessary to generate reliable model of the structure and to make meaningful interpretation of the results. For dynamic lateral forces, proper cross section representing the lateral resisting system should be selected to demonstrate the analysis results. For example, the main lateral load resistant cross sections for Fatih mosque are shown in Fig. 5.

The main factors affect the seismic resistant system of such cross sections are the geometrical configuration, geometry, thickness and stiffness of the structural members and strength of the materials used. For main arch cross section shown in Fig. 5, the deformations of the main arch are needed to be studied to realize the stability of the cross section. The relative movement of the upper part of the main piers, consequently, the movement of the abutments of the main arch play the crucial rule in the stability of the arches. Huerta (2001) studied in details the effects of movements of the abutments on cracking pattern of arches. Therefore, the relative displacement between the abutments of the main arches needed to be checked in order to understand the behaviour of the main arch and the dome system in general.

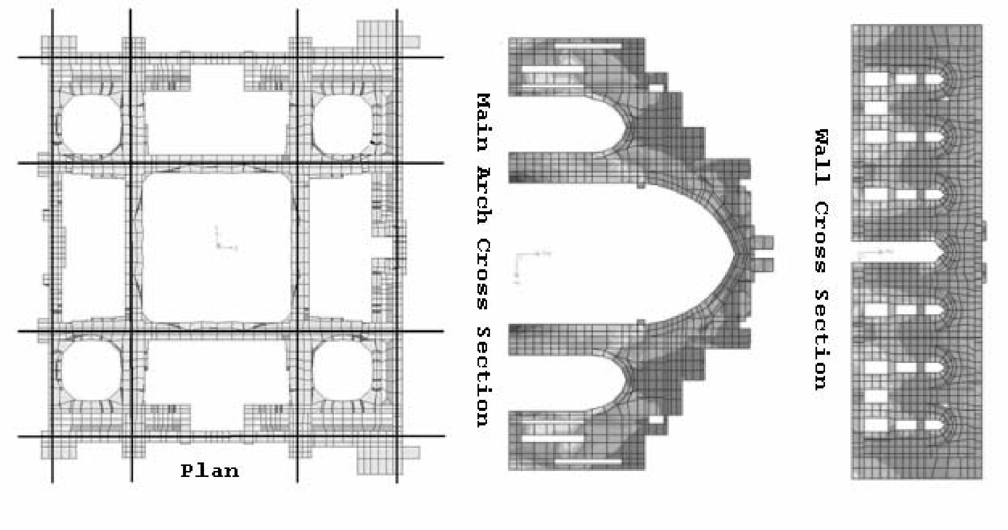

Figure 5 : Lateral load resistant cross sections for Fatih mosque

5 EFFECTS OF DOME STRUCTURAL SYSTEM

The dome structural system has major effects on the dynamic behaviour and lateral load resisting mechanism of the structures. A good dome system ensures a proper load distribution and a safe load transfer mechanism. Several parameters should be considered in understanding the dynamic behaviour of the lateral system. For example, shape and size of the main dome and half domes, size and thickness of main arches, existence of proper buttress system, height/width ratio of the main arches, etc. The most important issue to be considered for a stable structural system is whether these parameters develop a proper horizontal diaphragm that ensure stable in plane movement with acceptable in-plane deformations or not.

In this study, the dynamic characteristics of two different type of dome systems will be investigated. The modal shapes of Fatih mosque (Semi-domes on four sides) and Suleymaniye (Arches on two sides, semi-domes on two sides) are studied.

Suleymaniye Mosque was built between 1550 and 1556. It has square plan has an edge length equal to 62 m. Consequently, the base diameter of the central dome is 26m. The stiff of the four arches carrying the central dome and the rigidity of the frames supporting the arches are equal at each corner and each direction. As a result of these systems, the sub-structures and the dome itself have suffered not even the slightest damage, despite many earthquakes during its life of nearly half a millennium (Mungan 1988). The first three modal shapes of Fatih Mosque Model are given in Fig. 6.

The Fatih Mosque was built between 1463 and 1470. It was restored following an earthquake in 1509. The dome of the mosque collapsed in the 1766 earthquake and was reconstructed entirely in 1771. The Fatih Mosque has been affected by several strong earthquakes. The first three modal shapes of Fatih Mosque Model are given in Fig. 7.

The strong diaphragm concept can be noticed in Suleymaniye Mosque by studying the first three mode shapes in Fig.6. As expected, the first two modes are horizontal while the third modal shape is rotational. For Fatih Mosque modal shapes shown in Fig. 7, the absence of strong horizontal diaphragm system can be noticed especially at the third mode where a breathing mode exists.

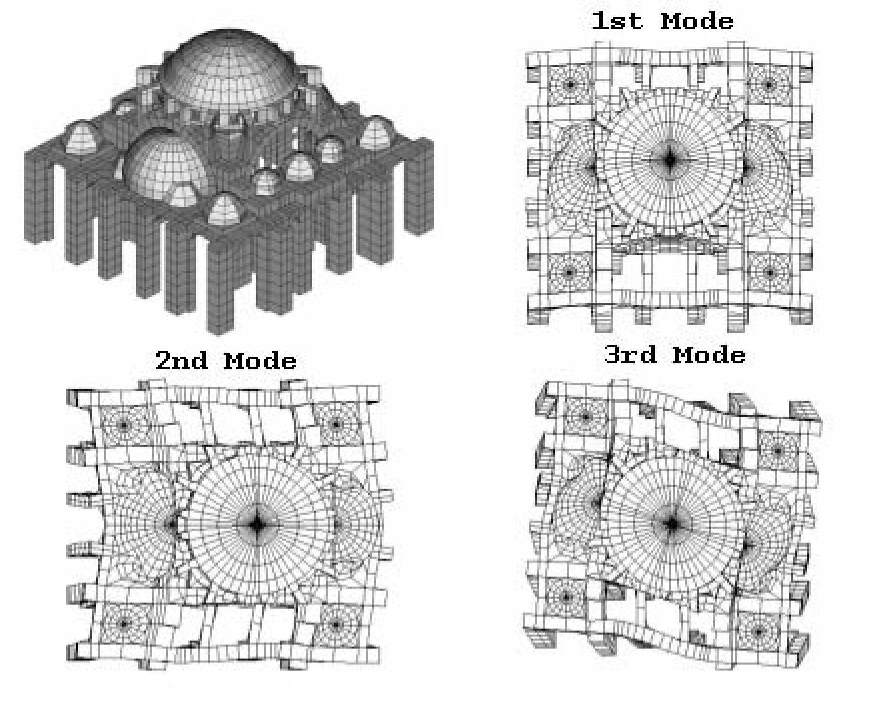

Figure 6 : Modal shapes of Suleymaniye Mosque, Istanbul.

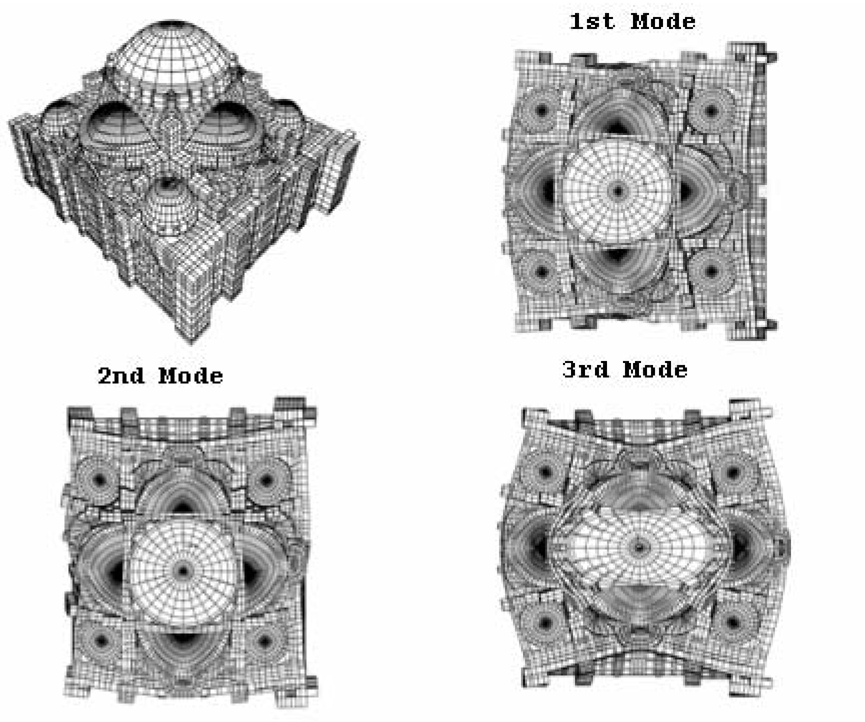

Figure 7 : Modal shapes of Fatih Mosque, Istanbul.

6 CONCLUSIONS

In this study, dome systems of Ottoman historical structures were reviewed and the lateral supporting systems for the different type of domes were categorized into three systems: square support system, hexagonal support system and octagonal support system. The complex lateral loads transfer mechanisms and the effects of dome systems on the seismic behaviour of lateral resisting system are discussed under the light of general concepts of modern earthquake engineering. The analyses of two models of historical structures representing two type of square support systems: Fatih mosque (Semi-domes on four sides) and Suleymaniye (Arches on two sides, semi-domes on two sides) were performed. The effect of dome systems with proper load transfer mechanism and strong diaphragm formation on the dynamic characteristics of the main structures was shown.

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