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ANALYSIS OF HAGIA SOPHIA USING NONDESTRUCTIVE MESUREMENT

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In this paper, the structural behavior of Hagia Sophia was analyzed by use of vibration records of the structure. The vibration records were measured by the micro tremor meters. The recorded data was utilized not only to define the mode shape but also to evaluate the structural problems. Firstly, the vibration characteristics of the main building were analyzed by combining the vibration records. Secondary, the deformation characteristics and the structural functions of the second cornice were investigated in the same manner as the main building. In case of main building, from the frequency domain analyses, the natural frequency of the main building was analyzed and the obtained natural frequencies were compared with the results of the previous researches. The vibration modes were investigated as well. From these results, the characteristics of the total structure were clarified and the structural problems were detected. In case of the second cornice, the base at the corner where was the junction of the main pier and the sub-dome connecting to the semi-dome showed the movement of the embedded stone. To investigate such phenomena, the same non destructive measurements were applied. Then, applying the finite element method to solve such structures, the structural behaviors were clarified and the health monitoring was performed.

Keywords: Vibration, FDD, FEM, Measurement, Structural behavior.

1 INTRODUCTION

Hagia Sophia (Figure 1), Istanbul, was constructed in 537 as the church and was changed the usage as the mosque since 1453. Since 1935, Hagia Sophia has been opened as the museum. Their structural characteristics and the function of each structural element have been studied by many researchers (Mainstone 1988, Çakmak, *et al.*, 1995, Hara *et al.*, 2015, etc.). The building shows particular characteristics. Huge dome was supported by the main arches, the tympanums and the piers. To resist the horizontal thrust from the main dome, the semi domes, the buttress and the pendentives were arranged. These were also supported by the complex structure.

In spite of many earthquake attacks, Hagia Sophia has been survived and has shown the ancient status as the world heritage. However, the deformation of the structure has grown after completion of the building and several structural problems have been found.

To maintain such structure in the future, the appropriate renovations or the restorations are the important matter. The structural assessments are also required by use of nondestructive methods.

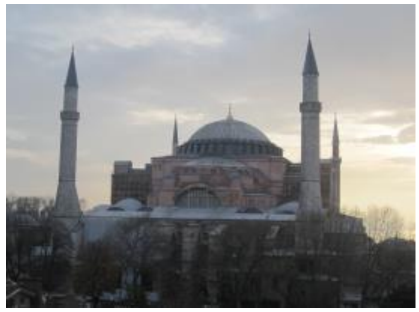


Figure 1. Hagia Sophia.

In this paper, the structural behavior of Hagia Sophia was analyzed by use of vibration record of the structure. The vibration record was measured by the micro tremor meters. Firstly, the vibration characteristics of the main building were analyzed by use of FDD. Secondary, the deformation characteristics and the structural functions of the second cornice were investigated in the same manner as the main building. In case of main building, the natural frequency of it was analyzed and the obtained natural frequencies were compared with the results by other researches (Çakmak, *et al*, 1995 and Hidaka 2004). Then, the vibration modes were investigated. From these results, the characteristics of the total structure were clarified and the structural problems were obtained as well. In case of the investigation of the second cornice, the base at the corner where was the junction of the main pier and sub-dome connecting to the semi-dome shows the movement of the embedded stone. To investigate such phenomena, the same nondestructive measurements were carried out. Combining the finite element analyses, the structural behaviors were clarified.

2 DYNAMIC ANALYSIS OF MAIN BUILDING

From the drawing by Van Nice (1965), the height of the roof top is about 56m and the diameter of the main dome in N-S and EW directions are 31.805m and 30.855m, respectively. The main dome is supported by four main arches and the arches are placed on four main piers. The thrust induced into main arches and the piers is reacted by the buttresses in N-S direction. The thrust induced into arches and the piers in E-W direction is also reacted by the semi-domes on the second cornice. The structure of Hagia Sophia consists of many structural elements and provides huge spaces in the dome (see Figure 2). The structure is constructed using the bricks and stones up to the gallery layer and the masonries are used for building upper structures.

The building has been attacked by the strong earthquake in several times and by the penetration of the water and moisture. Therefore, several problems, such as cracking of the walls and the domes, inclination of the columns and water penetration, are detected.

In addition, due to the different depth of the bed rocks and the large deformation of the materials, the building structure shows a lot of damages on the surfaces and represents the incredible structural deformation. To restore and to conserve such a huge heritage structure, the detail structural inspections are required.

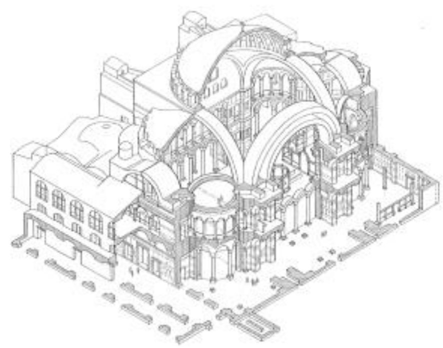


Figure 2. Structure of Hagia Sophia (Mainstone 1988).

Figure 3. Micro tremor meter.

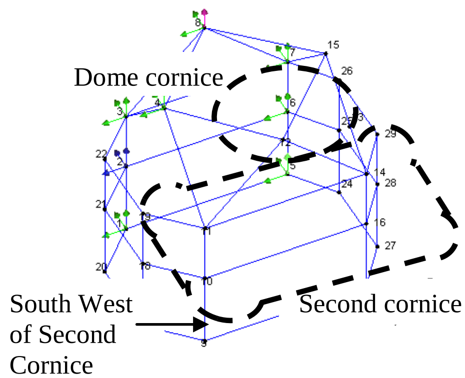


Figure 4. Measuring model.

2.1 Measurement Procedure

The purpose of the dynamic measurement is to acquire the structural data of existing building and to access the structural performance or structural deficiencies. To obtain the structural data, the acceleration tremors were measured. Then the natural frequencies and the vibration modes of the main building were determined. Eight micro-tremor meters (Figure 3) were applied in this analysis. Each tremor meter consists of three acceleration pickups and measures the accelerations in orthogonal direction simultaneously.

Figure 4 shows the measuring model and nodal points in this investigation. The main structure shown in Figure 2 is transformed into skeleton as shown in Figure 4. Measuring point numbers are denoted at each node. Each tremor was measured 40Hz sampling frequency and 3600 second time duration. One micro-tremor meter is fixed on base floor and the other 7 micro-tremor meters are moved on point by point.

Firstly, the tremors at the base floor, the gallery level, the second cornice and the dome cornice on the northern side of main building were measured. Secondary, tremors on the southern side of main building were measured as the same manor. Finally, the piers at the entrance gate and the piers under apse dome were measured. The tremors are totally measured at 29 nodes. All the tremor data obtained in this measurement were collected and were analyzed by FDD (Frequency Domain Decomposition) and the natural frequency and vibration mode were obtained.

2.2 Dynamic Characteristics of Main Building

Using the FDD analysis, the frequency domain expressions of four measuring record sets were combined and represented. From the measurement, the first two frequencies 1.85Hz and 2.09Hz were obtained. These were the same results obtained by Hidaka (2004) and Çakmak (1995). 1.85Hz and 2.09Hz are natural frequency for the predominant vibration in N-S direction, respectively. However, in addition, in this analysis, the peak frequencies 2.93Hz and 3.06Hz, were obtained respectively. The vibration modes of 2.93Hz is shown in Figures 5. In case, the building at south west pier moves, even it is a column base. Çukmak (1995) reported that the southern portion of the building has deeper foundation than the northern portion. It may cause the column movement mode.

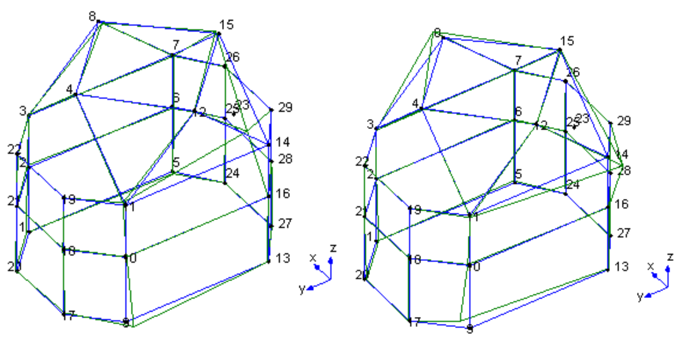


Figure 5. Vibration mode shape (2.93Hz).

Figure 6. Problems at the south west second cornice.

3 DYNAMIC ANALYSIS OF THE SECOND CORNICE

In Hagia Sophia, there is the main dome at the center and the main dome is supported on four main arches. Two arches are supported by the buttress in northern southern direction. Also, other arches are supported by the semi-domes in eastern western direction. Each semi-dome has two sub-domes. The second cornice is attached to the sub-dome placed on the exedra. At the eastern corner on the south west cornice (see

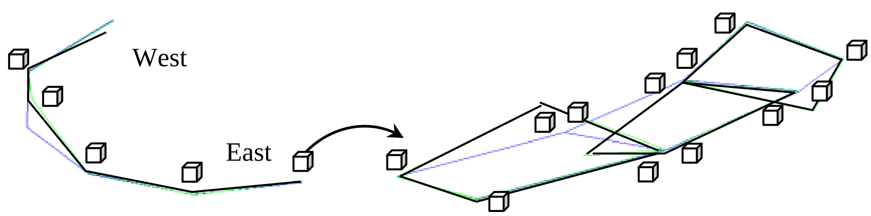
Figure 6), the deformation of the second cornice and the movement of the composing stones were detected. From the observation, the same phenomena were detected at each corner of the second cornice on the main piers. There are particular deformations. Therefore, the movement of the cornice at south west corner was investigated as an example. Figure 6 shows the picture of the problem of the south western cornice.

3.1 Measurement of Acceleration Tremor

In this analysis, firstly, six tremor meters were placed along the cornice with equidistance. Each tremor was measured 40Hz sampling frequency and 3600 second time duration. Then, the movement of each stone on the cornice was measured.

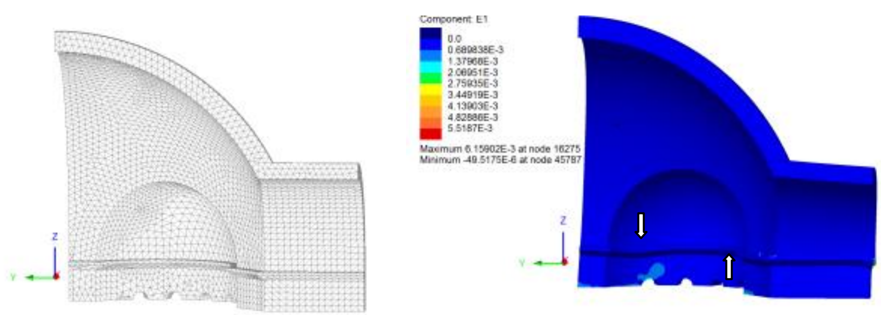
The total movement of the cornice shows large amplitude at the center with the natural frequency 9.70Hz (Figure 7(a)). Also, at the east end of the south west cornice, three stones vibrate independently with natural frequency 2.91Hz (Figure 7(b)). The movement of the stones was detected at the east end of the south west cornice.

The local deformations shown on the south west cornice incorporate with the global deformation bring us information to understand and to maintain the building structure.



(a) Total vibration (b) Brick vibration at east

Figure 7. Vibration of second cornice (□ tremor meter).



(a) FE Mesh (b) Equivalent stress by FE Analysis

Figure 8. FEM analysis.

3.2 Numerical Deformation Analysis of the Cornice

To represent the deformation and stress states of the cornice around the south west sub-dome under complex stress states, the finite element analyses were performed (Hara *et al*, 1913, 1914, 2015). Figure 8(a) shows the FEM model adopted in this analysis.

Considering the symmetry of N-S and EW directions, a quarter of the model was adopted. Applied load was the self weight and the lateral load on the x-z plane that was applied as the dome thrust. The boundary condition at the bottom was fixed in the vertical direction and the symmetrical boundary conditions were applied to other cutting edges. Figure 8(b) shows numerical results as well. The cornice did not deform at west end and moved upward on the western part of the cornice and sank downward on the eastern cornice. The cornice did not move at the east end by the main pier. Therefore, the cornice deforms vertically as like S shape. Also, the deformation shape was similar to the deformation obtained from the vibration mode shown in Figure 6(a). The cornice at the left end on the exedra shows higher equivalent stress (Figure 8(b)).

4 CONCLUSIONS

In this study, the vibration characteristics of the main building and the second cornice were analyzed experimentally. From the analysis, following conclusions are obtained.

1. FDD analyses of recorded data show the vibration characteristics of the structure precisely.
2. Hagia Sophia shows the global type of deformation of the structure. Also, several particular deformations and the local failures have been detected on the cornice.
3. The local deformations appear on the south west cornice incorporate with the global deformation.

The recorded data will be utilized to obtain the response of structure precisely by using FE Analysis with combining the earthquake record. The local deformations shown on the south west cornice bring us the information to understand and to maintain the building structure.

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