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USE OF STRONG MOTION DATA FOR THE ASSESSMENT OF THE EARTHQUAKE RESPONSE OF HISTORICAL MONUMENTS

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ABSTRACT

Strong motion networks installed in two historical monuments, in the Hagia Sophia museum and in the Süleymaniye mosque, yielded valuable information regarding their time-domain and frequency-domain dynamic characteristics. The buildings with similar structural systems have quite different responses especially in the vertical direction at the crowns of the main arches. While the Süleymaniye behaves along the lines of the results of the finite element modeling , the excessive vertical vibrations at the crowns of the main arches of Hagia Sophia can not be explained with standard analytical means. The earthquake specific variation of the modal frequencies common to both structures is also remains to be explained. Strong motion networks prove themselves as valuable tools for capturing information about dynamic behavior of historical structures

KEYWORDS

Historical monuments; strong motion instrumentation; system identification; earthquake response.

INTRODUCTION

Structural preservation of historical buildings in seismic areas has evolved to being one of the important and relatively new issues in earthquake engineering. The development of high dynamic range digital accelerometer systems paved the path to monitor and to study the dynamic response of historical monuments under actual earthquake ground motions. The results allow for the comparison of the dynamic behaviour of architecturally similar structures with different structural systems and/or different material properties and to make projections regarding their future earthquake performance under scenario earthquakes. The prerequisite to a reliable and optimal strong motion instrumentation is to conduct a through study of the structural system of these monuments. This study should encompass the linear dynamic analysis, ambient vibration testing, soil and foundation investigations and the identification of zones of previous repair, weakness, cracking and other structural discontinuities. The number of sensors, their locations, orientations and common timing needs of the strong motion array can then be assessed in a reliable and optimal manner. The dynamic range and the frequency band of the accelerometers can be determined on the basis of the modal frequencies of vibration and the physical parameters of the scenario earthquake. The strong motion network directly measures the absolute accelerations at sensor locations. The total absolute velocities and displacements can be obtained with proper integration techniques. Under common timing the differential motions between the sensor locations can be easily computed. Further augmentation and redundancy of the earthquake response measurements can be realized with the installation of laser reflectometers, laser interferometers, displacement meters, short (for existing cracks) and long baselength strain gages, tilt- or inclinometers and triggered high-resolution time-lapse photography. The strong motion measurement system can also be extended to the foundation media through bore hole accelerometers, tiltmeters and, if appropriate, piezometers to measure the pore water pressure.

Strong motion data obtained from the accelerometer networks in structures are used in structural system identification. Spectral system identification techniques are widely used by the engineering community, whereas parametric system identification techniques are relatively less preferred. The aim at the application of the technique is to estimate the natural vibrational characteristics of the building in question experimentally. The results can be used to calibrate numerical models, such as finite element models, which in turn yield valuable information about the static and dynamic behavior of the structure, hint on the reasons of past structural damages and deformations, if there are any, and can help to estimate the dynamic response during a seismic event or the feasibility and the reliability of structural interventions for restoration purposes. The spectral system identification makes use of Fourier amplitude, power, cross-power and phase spectra as well as transfer functions and transfer function phases for the identification of natural modes of vibration and natural modal frequencies. The parametric system identification, on the other hand, consists of choosing a parametric model, such as ARX or ARMAX models, calculating the model parameters using the input-output or output data, depending on the model chosen and data available, and validating the model by methods like zero-pole cancellations, comparing the real output with calculated output, calculating the residuals and their auto- and cross-correlations with the input. The on-line identification, which can be explained as determining the system parameters at every time step starting from an initial guess, can be a powerful tool for tracking the changes in the system parameters or in other words the non-linearity (Durukal and Erdik, 1994).

A strong motion recording system and the attendant investigations has been initiated by joint teams from Princeton (USA) and Bogaziçi (Turkey) universities (Mark *et al.*, 1992) for the Hagia Sophia Museum. Similar investigations were then extended to Süleymaniye Mosque (Selahiye *et al.*, 1995). Both of the edifices are in Istanbul and constitute important monuments of the world's architectural heritage. In this paper results obtained from the strong motion arrays and the consequent analytical/numerical investigations will be covered, anomalous dynamic behaviors will be identified and a comparative study of the earthquake response of these two historical monuments will be presented.

HAGIA SOPHIA AND SÜLEYMANIYE

Dedicated in 537 after 5 years of construction Hagia Sophia has been an inspiring architectural and engineering marvel throughout the ages. Being one of the most important buildings of the world heritage, today it requires urgent concern due to the high seismic hazard in the western part of the North Anatolian Fault Zone in addition to the scars of many past earthquakes left on the building. A network of strong motion accelerometers consisting of nine interconnected Kinemetrics SSA-2 units has been operational in the structure since August 1991 as part of the efforts for the determination of its earthquake worthiness (Fig. 1). The instruments cover three levels. One instrument is at the ground level; four of them are located at the cornice level at the springing points of the four main arches; and the final four are at the dome base level on the crowns of the main arches.

The Süleymaniye mosque was constructed between 1549-1557 and is celebrated as one of the biggest achievements of the Ottoman architecture. It survived several earthquakes without any apparent structural damage since then. An accelerometer system consisting of 8 individual Kinemetrics SSA-2 units has been operating in the Süleymaniye mosque since February 1994 (Fig. 2). The positioning of the instruments is similar to the case of Hagia Sophia except that there is no instrument at the ground level.

As for the physical characteristics of the two structures, the Hagia Sophia is 32 m wide and 80 m long in plan. Its dome of 31 m diameter rises 56 m above the ground level. The dimensions of the Süleymaniye in

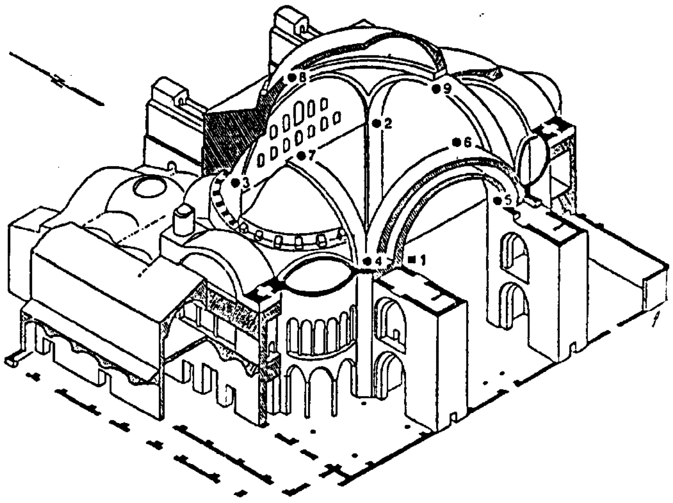

Fig. 1. The main structural system of Hagia Sophia and the strong motion network

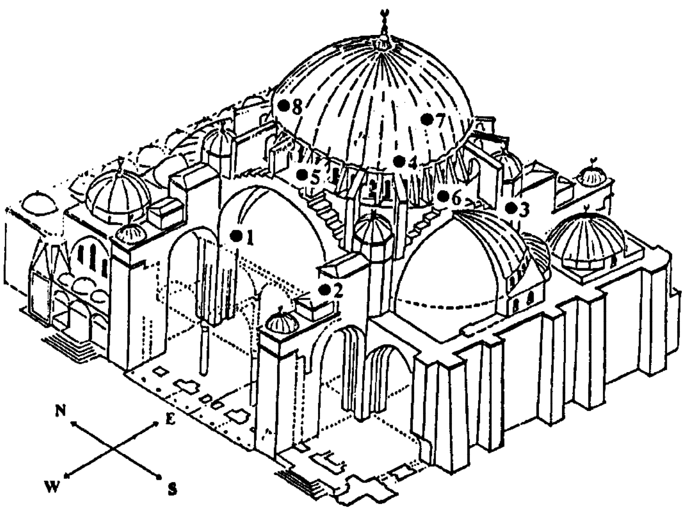

Fig. 2. The main structural system of Süleymaniye and the strong motion network

plan are 63 m x 73 m. It has a dome of 27.5 m diameter that is 48 m high. The vaulting systems of the two are similar. The differences can be cited as follows; in the Hagia Sophia the diameters of the main dome and the semidomes are the same whereas in the Süleymaniye the semidomes are smaller in diameter relative to the main dome. The main arches are probably of cut stone in the Süleymaniye while they are of brick masonry in the Hagia Sophia. There are no galleries on each side of the Süleymaniye along its longitudinal axis, such that the connections between the main-and the buttress piers are only above the aisles unlike in Hagia Sophia, but they are more substantial and rise toward the dome in steps. The use of brick masonry with thick mortar layers starting from too low a level has been replaced by the use of cut stones with closer joints. Excessive reductions in the cross-sections of the main piers at the Hagia Sophia's gallery level have also been corrected since there is no gallery in the Süleymaniye (Mainstone, 1993).

A comparison of the dynamic behavior of these two monumental buildings is justified due to the resemblance of their structural systems and to a minor extent their materials in contrast to their age difference of 1000 years.

STRONG MOTION DATA AND THEIR PROCESSING

As of December 1995 the two arrays have provided data pertaining to events with magnitudes varying between 3.9 to 4.8 M_b and epicentral distances between 22 to 140 km. The biggest event recorded by the Hagia Sophia array occurred on 22.12.1993 with M_b=4.8 at an epicentral distance of 59 km to the north of Istanbul. The biggest event recorded by the Süleymaniye array occurred on 8.2.1995 with M_b=4.4 at an epicentral distance of 140 km to the southwest of the city.

Data processing applied uniformly to all records involves baseline correction, high-cut filters at 10 Hz and low-cut filters at 1 Hz.

Maximum acceleration recorded in Hagia Sophia is 13 cm/s^2. In Süleymaniye a maximum acceleration of 28 cm/s^2 was recorded on 8.2.1995. Unfortunately the 8.2.1995 event was not recorded by the Hagia Sophia array because the trigger levels throughout the array were increased before that date since a satisfactory number of low magnitude earthquakes had already been obtained and records from relatively high magnitude earthquakes are necessary. Hence, a direct comparison of the two structures based on records obtained during the same event is not possible at this stage.

In addition to the time domain observations regarding the general dynamic behavior, spectral techniques have been applied for system identification. Transfer functions and transfer function phases have been utilized for Hagia Sophia records since in Hagia Sophia a ground level station exists in addition to a free field station 170 m to the west of the building. For the case of Süleymaniye Fourier amplitude and phase spectra have been preferred because there are only upper level stations in this building.

RESULTS AND DISCUSSION

Time Domain Characteristics of Earthquake Response

The 12.12.1993 event yielded maximum response amplitudes recorded in Hagia Sophia so far. The records in three directions are presented in Fig. 3. Looking at the figure there are two observations which can be made immediately: (1) the different response characteristics of the SW pier relative to the other three piers, (2) the high amplitudes in the order of lateral vibrations at the crowns of the main arches in vertical direction. It should be mentioned that these two observations are not specific to this earthquake, but can be found consistently in all records obtained so far.

The excessive lateral vibrations of the SW pier, which can also be observed in Fig. 4 in frequency domain, can be due to the soil conditions at the base of this pier, due to a foundation problem or due to localized structural or material problems. The bedrock topography beneath the main arches has been determined by Gürbüz *et al.* (1993). According to this study the bedrock is approximately 1 m below the ground level beneath the NW and NE piers. It dips towards south, such that the foundations of the SW and SE piers are at about 3 m below the ground level. This 2 m difference might have been an explanation if the SE pier had behaved similar to the SW pier as well. Emerson and Van Nice (1943), looking at the almost symmetrical structural deformation of the four main piers (an average of 0.15 m outwards in the E-W direction and an average of 0.45 m outwards in the N-S direction for a single pier), conclude that this can not suggest any differential foundation material behavior neither statically nor as a result of earthquakes. It remains only as one possible explanation, that this atypical behavior is because of localized structural or material problems. It is almost impossible that materials different from other piers were used in the construction of the SW pier. Whether there is a structural detoriation or damage from the past earthquakes can not be studied at the moment since the body of the SW pier is covered with marble panels. Hence, whatever the reason, this behavior remains to be explained..

The vertical vibrations of the crowns of the main arches are in the order of their lateral vibrations recorded at the same level. In almost all of the cases in Hagia Sophia maximum accelerations were obtained in the vertical directions at the crown of the east main arch. Vertical vibration of the arches could not be simulated by the finite element technique, although the lateral dynamics of the building could be captured satisfactorily using this method. The behavior is also remarkable considering the dynamics of an arch. At this point it is appropriate to discuss the case of the Süleymaniye. Unlike in Hagia Sophia, in Süleymaniye the vertical motions at the crowns of the main arches are considerably lower relative to the lateral vibrations at these locations (Fig. 4). In both structures the vertical responses at the springing points of the main arches are comparable. The main reason for the anomaly should lie in the difference of the construction materials of the arches in the two buildings. In Hagia Sophia the arches are composed of brick masonry with thick mortar joints, whereas in Süleymaniye stone masonry is used in the arch construction. The results of the finite element modeling are similar to the vertical data from the top of the arches. All these considerations point at the need for further study on the engineering behavior of the brick masonry.

The Süleymaniye presents a much more uniform, simple and stable picture as far as its time domain dynamic response is concerned which lessens the possibility of unexpected localized effects during stronger ground motions.

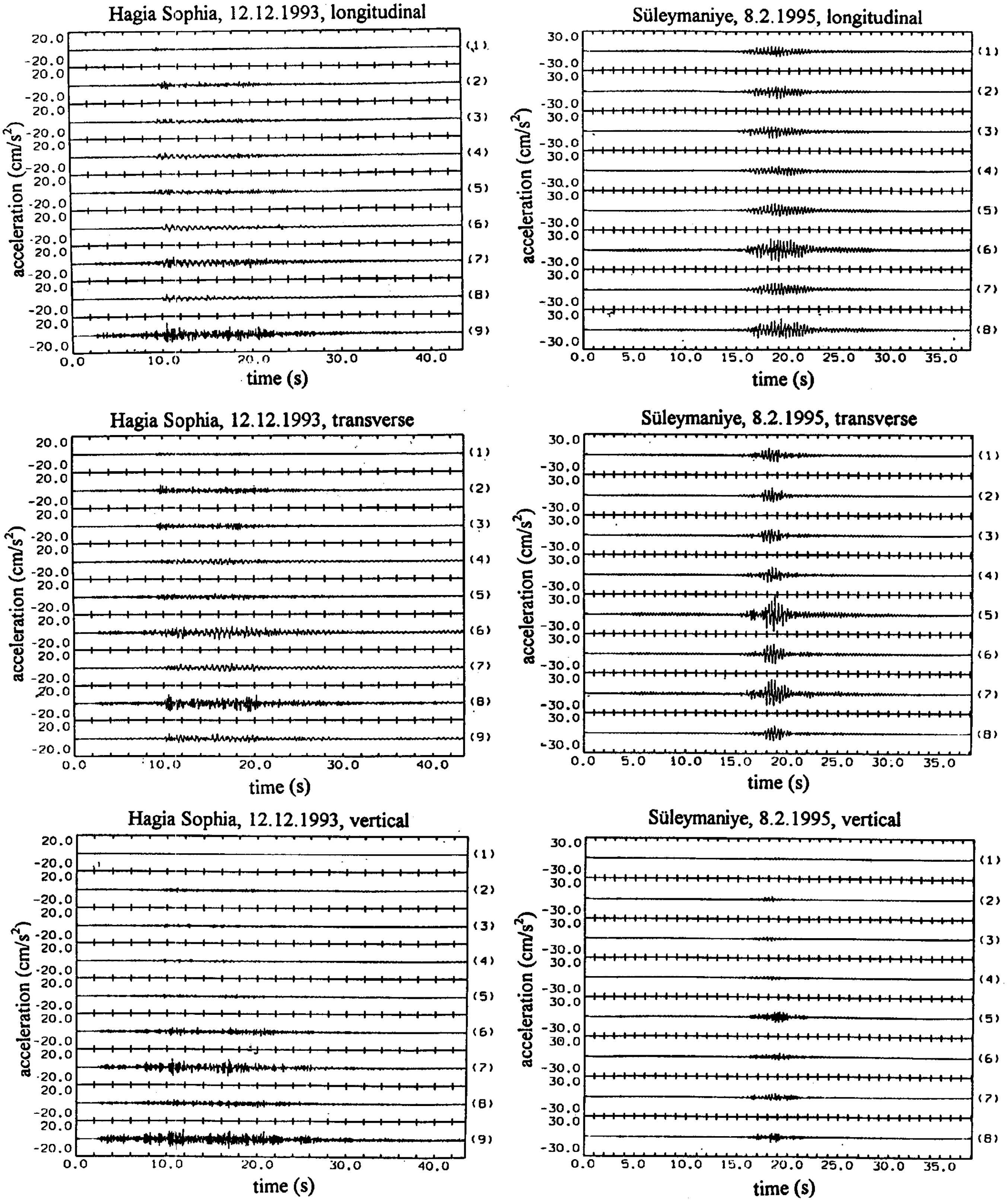

Fig. 3. The corrected acceleration time histories obtained during the 12.12.1993 event in Hagia Sophia (on the left) and during the 8.2.1995 event in Süleymaniye (on the right). The numbers in paranthesis on the right of each subfigure indicate the stations. The reader is referred to Fig.'s 1 and 2 for the station locations in the two buildings.

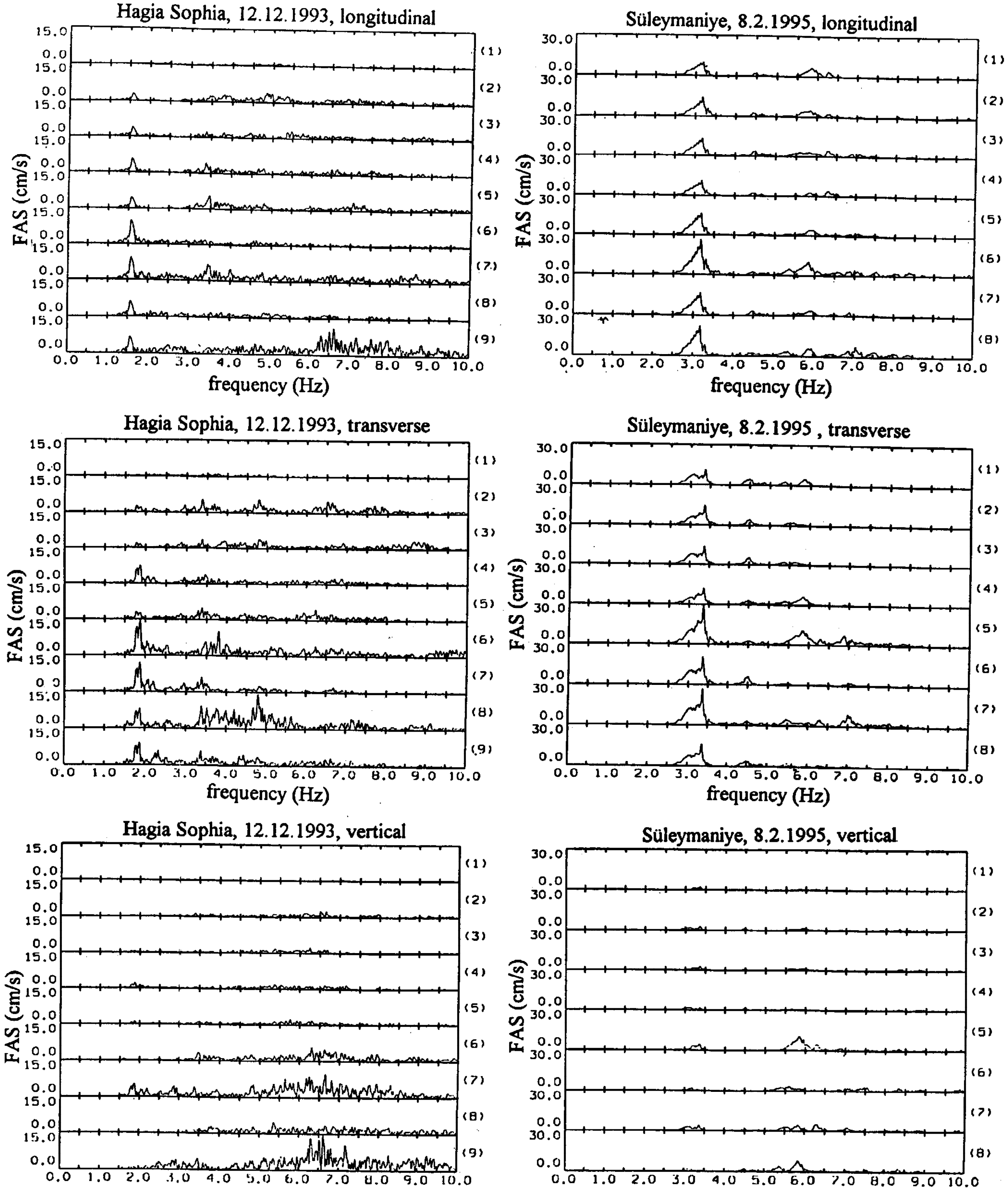

Fig. 4. Fourier amplitude spectra of the 12.12.1993 records obtained in Hagia Sophia (on the left) and of the 8.2.1995 records obtained in Süleymaniye (on the right). The numbers in paranthesis on the right of each subfigure indicate the stations. The reader is referred to Fig.'s 1 and 2 for the station locations in the two buildings.

For consistency the E-W axis of Hagia Sophia and the N-S axis of Süleymaniye will be called longitudinal axis hereafter. Similarly the N-S axis of Hagia Sophia and the E-W axis of Süleymaniye will be named as their transverse axis.

The Fourier amplitude spectra of records from 12.12.1993 and 8.2.1995 events are presented in Fig. 4. Although transfer functions are utilized for identification of the Hagia Sophia data, Fourier amplitude spectra are shown in Fig. 4 for uniform presentation.

From the analysis of ambient vibration data 1.85 Hz and 2.10 Hz have been identified as the modal frequencies of Hagia Sophia by Durukal and Erdik (1994) along its longitudinal and transverse axes respectively. 2.35 Hz has been identified as the torsional modal frequency. They found that there is an earthquake specific variation of modal frequencies of Hagia Sophia. The highest values are obtained from the ambient vibration studies. They tend to drop with the increase in the acceleration level and with the increase of the duration of the strong motion part of the record. The first modal frequency of 1.85 Hz drops as low as 1.56 Hz during the event on 12.12.1993 and the second frequency of 2.10 Hz drops to 1.77 Hz. Analyzing the records of a single event by separating the data into three parts called pre-, co- and post strong motion parts, it can be shown that the variation can actually be tracked during a single specific event and that the modal frequencies recover their pre-strong motion values after the co-strong motion part dies out. The phenomenon can also be shown using the on-line parametric system identification technique, as in Fig. 5, which presents the variation of the second modal frequecny of Hagia Sophia based on records from station 6. This had been an unexpected observation considering the low amplitude ground motions experienced by the structure. The reason was attributed to the micro-cracking throughout the structure (Durukal and Erdik, 1994) and to the existence of a jelly-like material in the mortar of Hagia Sophia specific to the era in which Hagia Sophia was constructed which has the ability to emit the vibrations and indeed improves the earthquake performance of the building (Çakmak, 1995).

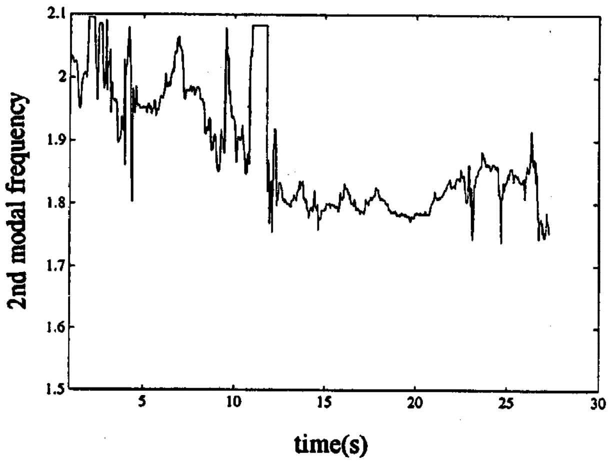

Fig.5. The variation of the second modal frequency of Hagia Sophia based on records from station 6.

A similar study on the data from the Süleymaniye yielded however that the variation is not specific to Hagia Sophia, but exists in Süleymaniye with stone masonry arches unlike Hagia Sophia as well. 3.35 Hz and 3.50 Hz have been determined as the first two natural frequencies along the longitudinal and transverse axes of the structure from the ambient vibration data using the procedure given by Gavin *et al.*, 1992. Analysis of the earthquake data shows that the first two modal frequencies drop as low as 3.17 Hz and 3.36 Hz respectively. The drop of the values in accordance with the increase in the ground motion amplitudes is also evident from the Süleymaniye data. It is clear that the explanations for the case of Hagia Sophia regarding the drop in these frequencies (Durukal and Erdik, 1994, Cakmak, 1995) are not sufficient for both cases now, since they were based on the assumption that the effect is due to the response of the brick masonry.

Presently the common reason causing the decrease of natural frequencies in both structures is unknown. Clearly the material non-linearity can not be the only explanation for the phenomenon.

CONCLUSIONS

The strong motion accelerometer networks prove themselves as valuable tools for monitoring of historical structures. They can help to show localized problems such as in the case in Hagia Sophia, on a quantitative basis they can hint on similarities and differences between two structural systems which otherwise seem similar to many; augmented with appropriate analytical/numerical tools, the data obtained from such strong motion arrays can indicate possible reasons for the past collapses of structures; and they can bring up new phenomena the explanation of which may not be possible with our present knowledge and need to be investigated in more detail. It is expected that such networks will become a standard tool for investigations towards the preservation of historical buildings in seismic areas in the future.

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