ASSESSMENT OF MODAL PARAMETERS FROM EXPLOSION RECORDS

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ABSTRACT

In the year 2016, three bombing attacks took place in Istanbul. The three incidents on 12 January, 7 June, and 11 December 2016 hit the Sultanahmet and Saraçhane Squares, and the Dolmabahçe district respectively. The explosions were recorded by the accelerometric networks installed in nearby historical monuments, i.e. the Sultanahmet Mosque (Blue Mosque), the Hagia Sophia Museum, the Süleymaniye Mosque and the Fatih Mosque. The 30-channel network in the Sultanahmet Mosque, the 27-channel networks in the Hagia Sophia Museum and Süleymaniye Mosque, and the 39-channel network in the Fatih Mosque operate in real-time mode recording accelerations. One minaret of Hagia Sophia is also instrumented with a 9-channel network. This work is a study on the structural response characteristics of the four monuments using these very unique and rare datasets. The focus is on (1) time-domain response to explosions; (2) estimation of damping taking advantage of the free-decay in explosion recordings; (3) modal shapes. Findings are compared to those estimated from earthquake data.

Keywords: Historical Structures; Explosions; Structural Health Monitoring

1. INTRODUCTION

Structural vibration data stemming from explosions are rare and unique. Their analysis enables an understanding of structural response particulars during explosions. Explosions due to detonated bombs during three suicide attacks in Istanbul in the year 2016, were recorded by accelerometers installed in Hagia Sophia Museum, Sultanahmet Mosque (Blue Mosque), Fatih Mosque and Süleymaniye Mosques.

Hagia Sophia is one of the most famous structures in the world for its architectural and historical standing. The structure was constructed by Justinian as a church in less than six years between 532 and 537. It was repeatedly affected by earthquakes during its history. Parts of the main dome of Hagia Sophia collapsed three times with sections of adjacent main arches and semi domes. The minarets of Hagia Sophia on the entrance side are built by Architect Sinan in the 16th century. Süleymaniye Mosque which represents the art and political power of its time was constructed in 1549-1557 as an imperial mosque in the name of Suleiman the Magnificent. Despite experiencing several earthquakes, Süleymaniye Mosque did not have major structural damages. Fatih Mosque was built between 1463 and 1470 and was heavily and repeatedly affected by earthquakes ever since. Sultanahmet Mosque is considered to be the last great mosque of the classical period of the Ottoman Empire. It was built between 1609 and 1616. The earthquake damages to the Sultanahmet Mosque were relatively limited except its minaret.

The instrumentation for structural monitoring consists of four two-component accelerometers at the springing points of the main arches, four more at the dome level, and one accelerometer on the ground level in Hagia Sophia Museum (Figure 1) and Süleymaniye Mosque. In Sultanahmet and Fatih Mosques, locations of instruments are similar to those in Hagia Sophia and Süleymaniye except there is one more instrument at the basement level of Sultanahmet Mosque and four more accelerometers at the semi-dome level in the Fatih Mosque. The minaret southwestern minaret of Hagia Sophia is also instrumented with three instruments at different levels as shown in Figure 1(Çaktı and Şafak, 2014).

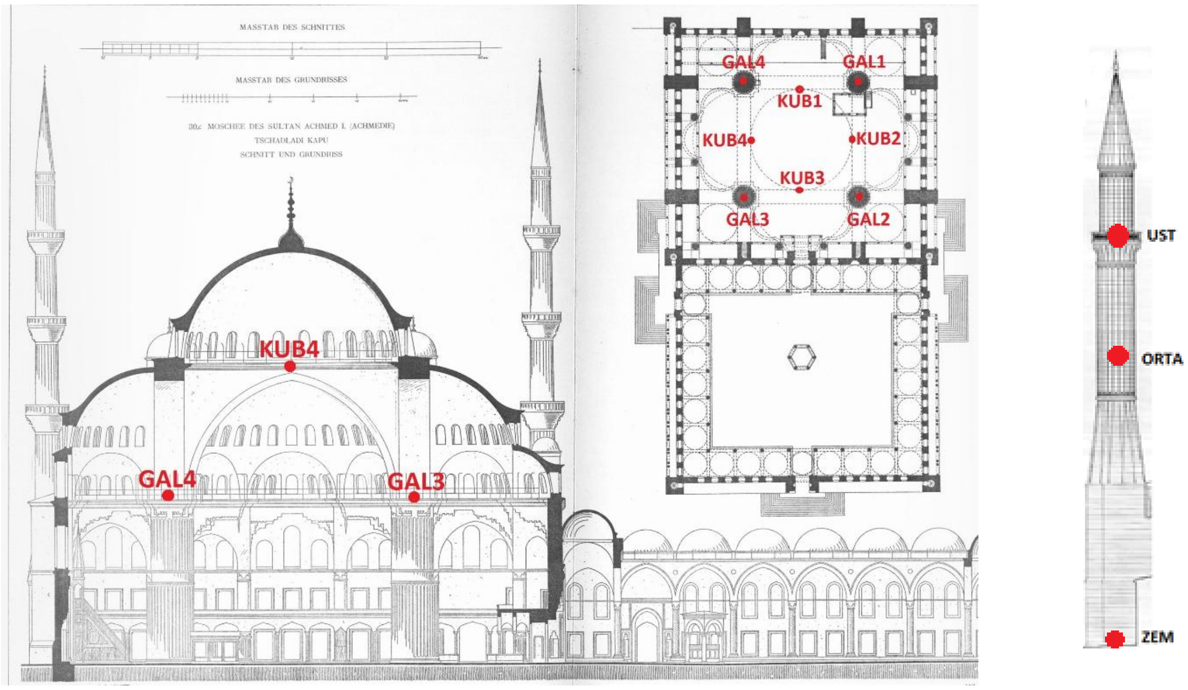

Figure 1. The accelerometer layout in Sultanahmet Mosque and Hagia Sophia's southwestern minaret (Gurlitt, 1912)

The duration of an explosion is typically short. It is up to 2 seconds. Explosions can be considered like impulsive sources. Their records obtained from structural monitoring systems consist of two parts. The first part is the explosion itself which is marked with a very short duration and sharp peaks. The second part is the free vibration of the structure controlled by modal properties. The purpose of this study is obtaining more reliable damping ratio and mode shapes taking advantage of the pure free vibration part of records which is conveniently provided by explosion data. Also, similarities and differences in both time domain and frequency domain between explosions and earthquake recordings will be discussed.

2. DATA

In Istanbul, on 12 January 2016 at 10.20 am local time, a suicide bombing attack took place in the Sultanahmet Square. About five months later on 7 June 2016, a car bomb exploded in the Saraçhane Square at around 08.40 am. The last incident in 2016 occurred on the evening of 10 December 2016 as one car bomb was detonated and a suicide bomber set off an explosive within seconds of each other near a soccer stadium in Dolmabahçe. These explosions were recorded by the monitoring networks in historical structures. As earthquake data, recordings of 25 May 2014 Gökçeada earthquake with a magnitude of 6.5 and of 7 July 2016 Çınarcık earthquake with a magnitude of 4.0 were selected.

To prevent any confusion about directions, the main entrance - mihrab/apsis axis is defined as x-direction in all structures. The axis perpendicular to x is called as y, and the up-down direction is named as z. For the minaret, the x-axis corresponds to the north-south direction, while axis y represents the east-west direction. Defined axes and the directions of explosions and earthquakes with respect to monuments can be found in Figure 2. For all the monuments and the minaret, data processing involved removing mean and high-pass filtering at 1Hz.

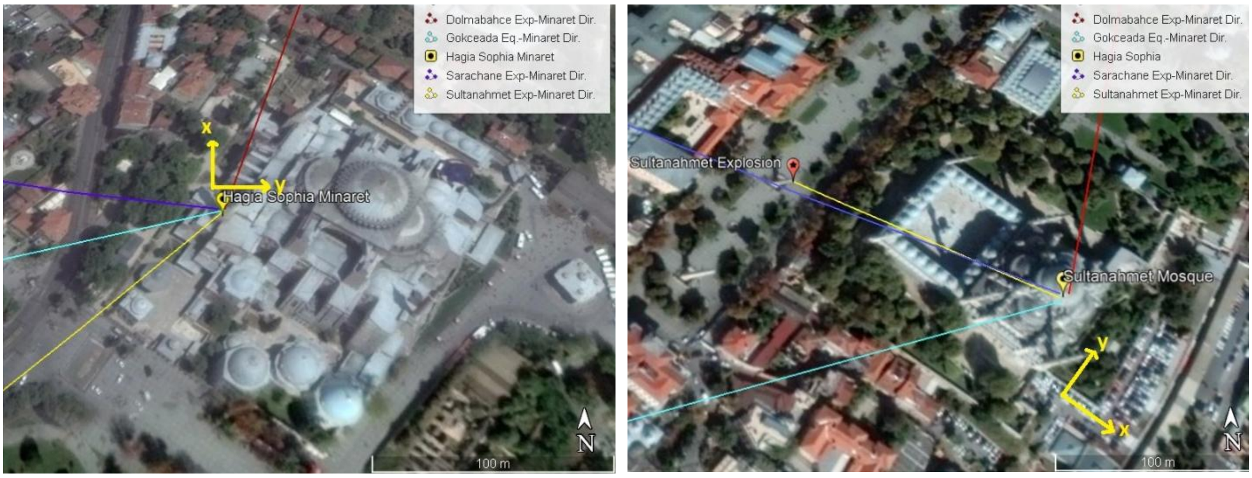

Figure 2. Defined axes used in the analysis and the directions of explosions and Gokceada earthquake with respect to Hagia Sophia Minaret (left) and Sultanahmet Mosque (right).

Due to the low signal-to-noise ratio of the Dolmabahçe explosion record likely caused by its relatively long distance to the minaret (3.62 km) and the Saraçhane explosion which happened in day-time while environmental noise is higher (with 1.5 km distance), these two explosion records couldn't be utilized on the minaret.

First general observation is that the nearby explosions can produce acceleration levels close to the ones recorded during earthquakes. As however displacement is controlled by low frequencies, this observation is not valid for displacements. Explosions are typically dominated by high frequencies whereas earthquakes' frequency content is dominated by low- to mid-range frequencies. This was best observed by comparing recordings at the Sultanahmet mosque from the Sultanahmet explosion that occurred at about 160 m distance and from the Gokceada earthquake that took place almost 320 km away from the historical structures that we evaluated.

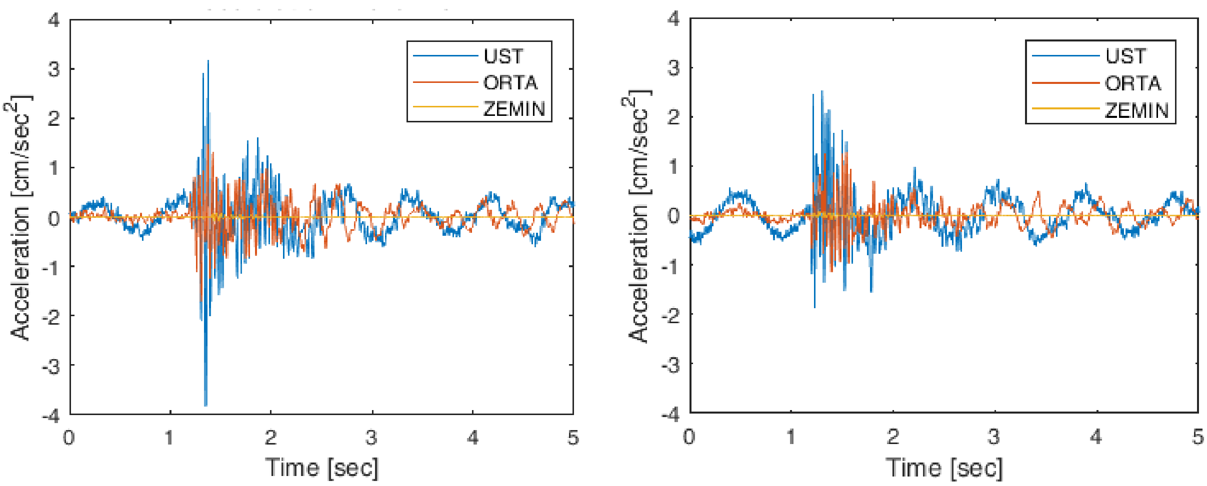

Figure 3. Sultanahmet explosion records at the Hagia Sophia Minaret for x- (left) and y- (right) directions,

Acceleration time histories on the Hagia Sophia minaret recorded during the Sultanahmet explosion can be seen in Figure 3. Accelerometers on the minaret are placed on three different levels: one at the ground level (called Zem), one in the minaret body (Orta), and another one at the balcony level (Ust), as indicated in the Figure 1. The minaret has a distinctive natural level of response evident in pre- and post-explosion parts of the acceleration record. The explosion and in particular the free decay part overlaps with the natural vibrations of the minaret. On the other hand, in the displacement time history graphs the explosion is inseparable from the natural response of the minaret. Displacement level from a night-time ambient record is in the order of 4.10^{-3} to 8.10^{-3} cm, which is the same with the peak displacement level of the Sultanahmet explosion record, 8.10^{-3} cm. It should not be forgotten that daytime ambient vibration levels are higher than those at night. Peak displacement during the Gokceada was 0.13 cm at the balcony level.

In Figure 4, the minaret's Fourier amplitude spectra for Sultanahmet explosion and Gökçeada earthquake in y-direction are given. After Gökçeada earthquake, the mid-level instrument was moved to higher location within the minaret body. Therefore the location of station Orta is somewhat different in the two subfigure of Figure 4. The first mode is at 1.172 Hz in Sultanahmet explosion, while it is 1.251 Hz in Gökçeada Earthquake. Second modes are at 3.32 Hz and 3.046 Hz, respectively. The differences in modal frequencies are interpreted to be caused by the temperature effect. It is known that frequencies in masonry structures increase with the rise in the temperature. They decrease when the temperature drops (Çaktı and Dar, 2015). Gökçeada earthquake occurred in May and Sultanahmet explosion took place in January.

In addition, it is apparent that the first mode of vibration governs the seismic response. For the second mode, mid-level station (Orta) is more responsive than the top level station (Ust) for Sultanahmet explosion and Gökçeada earthquake in line with the theoretical shape of the second mode.

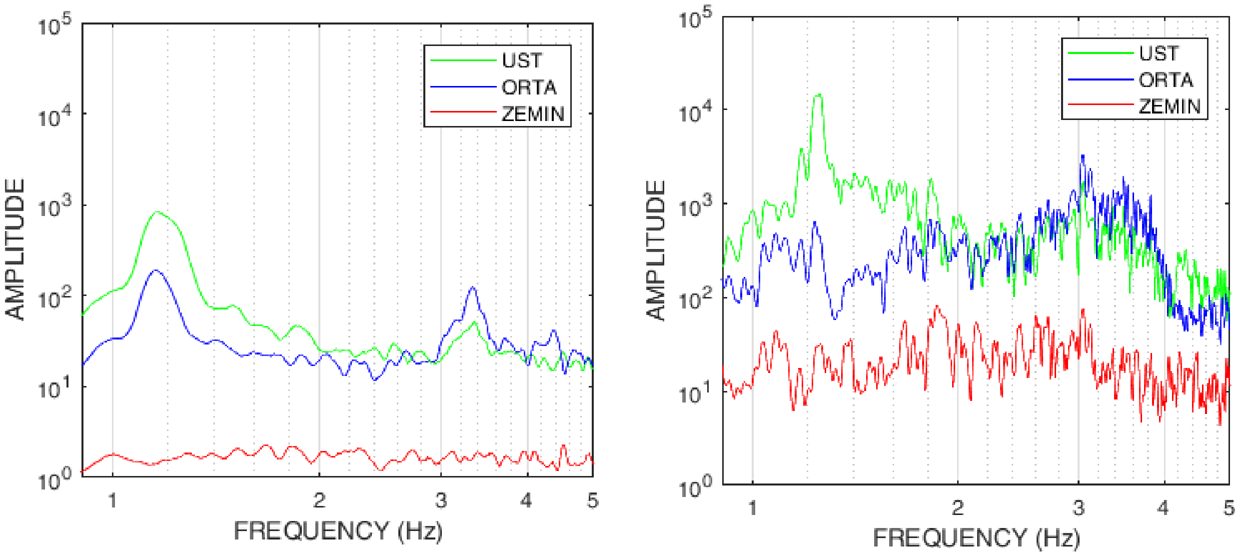

Figure 4. Fourier Spectra of the Minaret for Sultanahmet explosion (left) and Gökçeada Earthquake (right) in y-direction.

Figure 5 shows Fourier spectra of Sultanahmet explosion records for Sultanahmet Mosque in two horizontal directions without any smoothing. First and second dominant frequencies are given in Table 1. From explosion to the earthquake, frequency drop values for first and second modes are calculated as 7.6% and 9% respectively (Yenihayat and Cakti, 2017).

Figure 6 illustrates smoothed ground level Fourier Spectra of the minaret for the all explosions and the earthquake in x and y-directions. The Fourier amplitude remains consistently flat in explosion records and Gökçeada earthquake after 10Hz. Dolmabahçe explosion record has a shape similar to the ambient record. They are identical with those from Sultanahmet and Sarachane explosions. However they start to deviate after about 5 Hz. This is probably because of Dolmabahçe explosion's relatively longer distance to Hagia Sophia than other explosions.

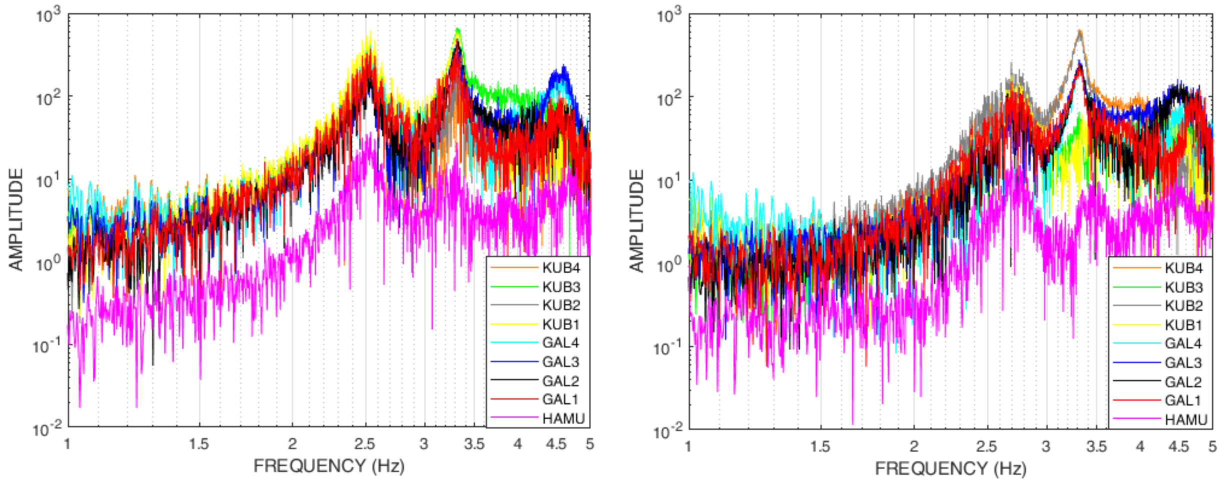

Figure 5. Fourier spectra of Sultanahmet Mosque for Sultanahmet Explosion in x-direction (left) and in y-direction (right).

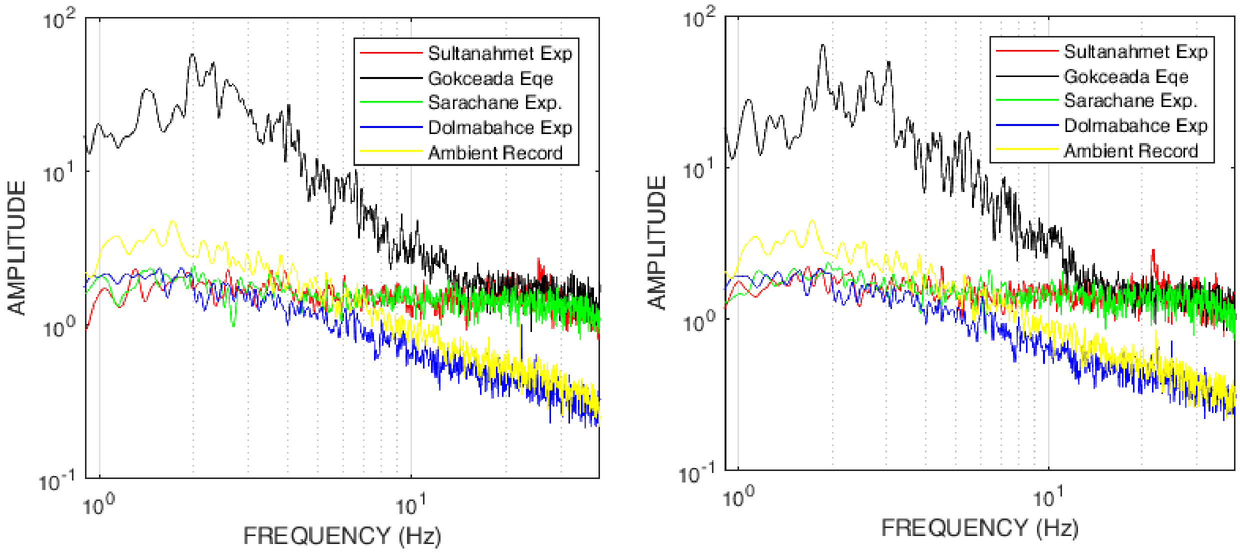

Figure 6. Ground level Fourier spectra of the minaret, in x (left) and y-(right) directions.

In Figure 7, ground level Fourier amplitude spectra in x and z-directions for Sultanahmet Mosque is given. One of the main differences between earthquake and explosion records can be observed in their Fourier amplitude spectra. While the Fourier amplitudes decay very rapidly in earthquakes, in explosions they either maintain a certain level, or increase.

3. DAMPING RATIO

As a dimensionless parameter, damping ratio identifies decaying in amplitude after an event. There are many methods to calculate it. Free decay method, logarithmic decrement method, and half power method are the most popular techniques to estimate damping parameter of a structure. First two methods use free vibration part in records. To prevent any artificial peaks, displacement records are used. Half power bandwidth method is the ratio of the difference between the two frequencies corresponding to two half power values of the peak amplitude to the frequency corresponding to the peak amplitude of Fourier amplitude spectra. To estimate damping parameter for the first and second modes, bandpass filter is applied in corresponding band ranges.

Because there is not a pure free vibration decay in the minaret, damping ratio is calculated only using the half power method. For Sultanahmet explosion, damping ratio is 3.5% to 4% approximately for the first mode, while it is 2% to 3% for the second mode in x and y directions respectively. Using Gökçeada earthquake record, damping ratio is evaluated as 1.9% and 1.1% in x and y directions.

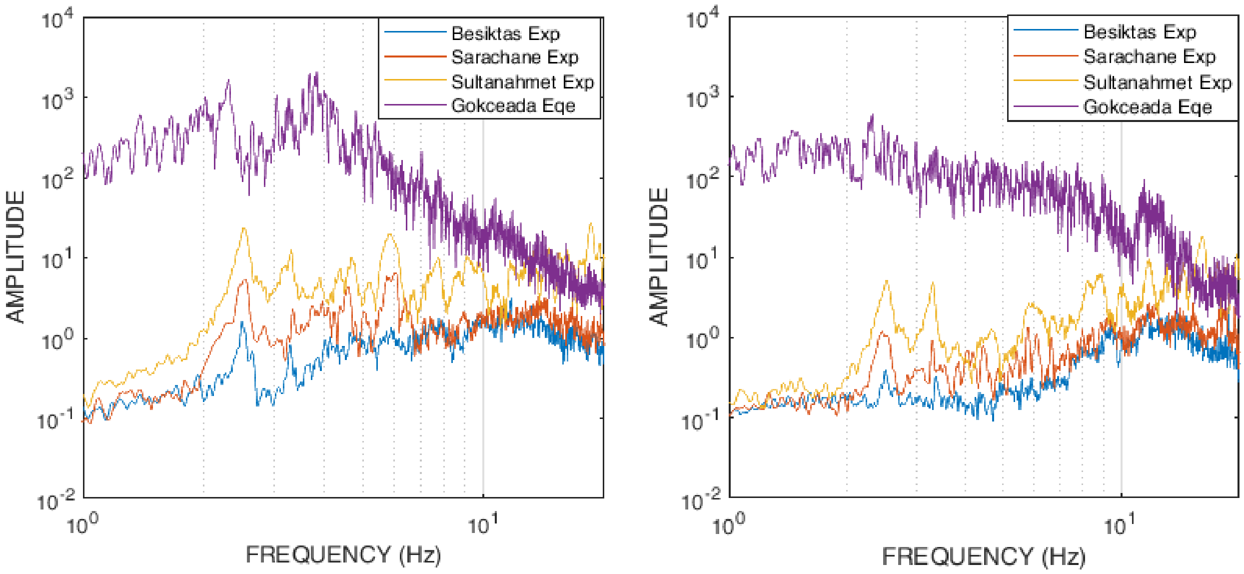

Figure 7. Fourier Spectra of ground level records for Sultanahmet Mosque, in x-direction (left) and z-direction (right).

Damping parameter of Sultanahmet Mosque is evaluated from explosion records using three methods mentioned above because the free vibration of the structure was very clear. In Süleymaniye and Fatih Mosques, Sultanahmet explosion data were not used as their signal-to-noise ratio was low. For Fatih Mosque, Dolmabahçe explosion data were too noisy and hence discarded. For Süleymaniye and Fatih Mosques, we utilized the data from the 7 July 2016 Çınarcık Earthquake with a magnitude 4.0 as well to compare modal frequencies and corresponding damping ratios. For damping ratio estimations using earthquake data, only Half Power Bandwidth Method was used, because as mentioned before, there is not a uniform decay in free vibration part. This is the main difference between earthquakes and explosions (Yenihayat and Çaktı, 2017). Results are given in Table 1, 2 & 3.

4. MODE SHAPES

Particle motions are obtained by plotting the bandpass filtered displacement response corresponding to modal frequencies. Figures 8 and 9 imply the first mode particle motion pattern of the top-level in the minaret from the records of Sultanahmet explosion and Gökçeada earthquake respectively in three directions. Band pass filtering is applied between 1-1.5 Hz for Sultanahmet explosion, and 1.13-1.3 Hz for Gökçeada earthquake. According to these figures, it is very clear that particle motion pattern is symmetric in both horizontal directions. Because displacements are very small and negligible in the vertical direction, plotting z-direction versus any horizontal axis results in practically a flat line. While x-direction is more responsive in the Sultanahmet explosion, diplacements in y-direction are generally larger in Gökçeada earthquake due to the difference in the incident angle of the two events. As a result of particle motion plots and particle videos, which cannot be shown here, it is understood that a pure translational mode cannot be isolated from recordings. The structural symmetry of the minaret and therefore the proximity of the two orthogonal modes make the separation very difficult. This results in the minaret moving in a roughly circular trajectory.

Table 1. Modal frequencies and damping ratios corresponding to the first and second modes of Sultanahmet Mosque.

Events	Sultanahmet Mosque																	
	x-direction								y-direction								z-direction	
	1. Mode Frequency (Hz)	1. Mode Damping Ratio (%)			2. Mode Frequency (Hz)	2. Mode Damping Ratio (%)			1. Mode Frequency (Hz)	1. Mode Damping Ratio (%)			2. Mode Frequency (Hz)	2. Mode Damping Ratio (%)			1. Mode Frequency (Hz)	2. Mode Frequency (Hz)
		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		
Sultanahmet Explosion	2.50	2.30	1.6	1.98	3.31	3.63	1.02	1.41	2.70	4.75	2.80	2.75	3.31	4.45	1.00	1.45	2.50	3.30
Saraçhane Explosion	2.50	6.00	3.38	3.25	3.30	4.5	1.38	1.23	2.68	5.00	3.12	3.07	3.30	3.92	1.21	1.17	2.50	3.30
Dolmabahçe Explosion	2.50	-	-	1.61	3.35	3.87	1.87	1.49	2.70	5.30	1.50	1.69	3.35	3.36	1.60	1.82	2.70	3.35
Gökçeada Earthquake	2.31	-	-	1.13	3.04	-	-	0.56	2.46	-	-	0.67	3.04	-	-	0.55	2.31	3.04

Table 2. Modal frequencies and damping ratios corresponding to the first and second modes of Süleymaniye Mosque.

Events	Süleymaniye Mosque																	
	x-direction								y-direction								z-direction	
	1. Mode Frequency (Hz)	1. Mode Damping Ratio (%)			2. Mode Frequency (Hz)	2. Mode Damping Ratio (%)			1. Mode Frequency (Hz)	1. Mode Damping Ratio (%)			2. Mode Frequency (Hz)	2. Mode Damping Ratio (%)			1. Mode Frequency (Hz)	2. Mode Frequency (Hz)
		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		
Saraçhane Explosion	3.36	3.32	2.24	2.02	4.15	2.41	0.88	1.17	3.37	3.35	1.28	1.85	4.15	2.65	1.15	1.44	3.37	4.15
Dolmabahçe Explosion	3.33	-	-	0.24	4.19	-	-	0.57	3.45	-	-	0.25	4.19	-	-	0.47	3.44	4.19
Gökçeada Earthquake	3.18	-	-	0.62	3.30	-	-		3.30	-	-	0.60	3.35	-	-	-	3.31	
Çınarcık Earthquake	3.37	-	-	0.75	4.21	-	-	-	3.30	-	-	0.85	4.28	-	-	-	3.30	4.28

Table 3. Modal frequencies and damping ratios corresponding to the first and second modes of Fatih Mosque.

	Fatih Mosque																	
	x-direction								y-direction								z-direction	
	1. Mode Frequency (Hz)	1. Mode Damping Ratio (%)			2. Mode Frequency (Hz)	2. Mode Damping Ratio (%)			1. Mode Frequency (Hz)	1. Mode Damping Ratio (%)			2. Mode Frequency (Hz)	2. Mode Damping Ratio (%)			1. Mode Frequency (Hz)	2. Mode Frequency (Hz)
Events		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		Method-1	Method-2	Method-3		
Saraçhane Explosion	2.94	-	-	8.37	3.52	3.18	3.23	2.43	2.60	-	-	4.80	2.87	4.18	1.26	1.92		-
Gökçeada Earthquake	2.58	-	-	0.86	-	-	-		2.47	-	-	0.20	-	-	-	-	2.47	-
Çınarcık Earthquake	2.47	-	-	1.34	-	-	-	-	2.62	-	-	1.77	-	-	-	-	2.60	-

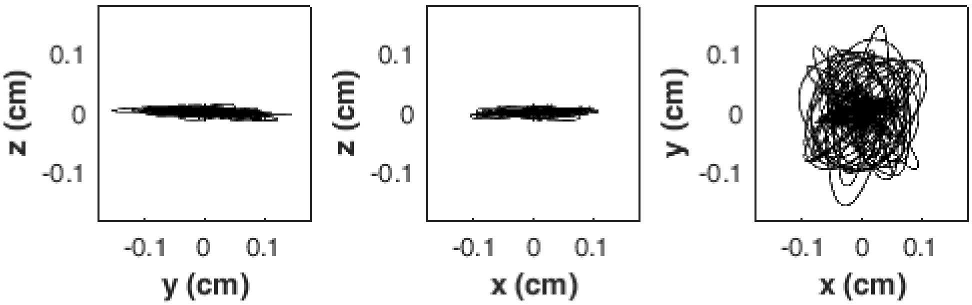

Figure 8. Balcony level particle motions of the minaret in the frequency range corresponding to first mode during the Gökçeada earthquake

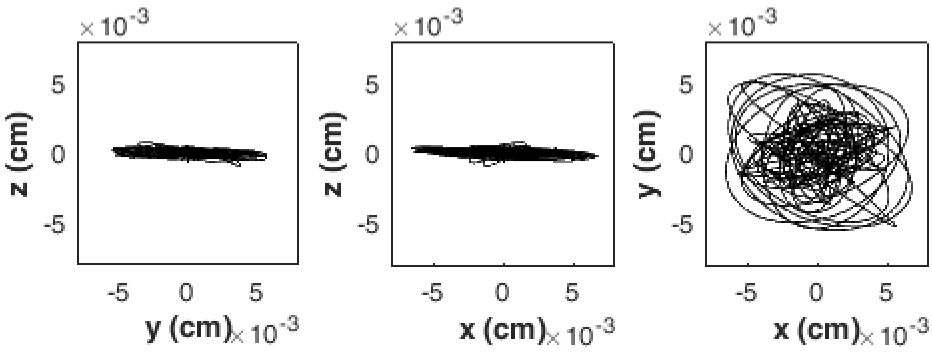

Figure 9. Balcony level particle motions of the minaret corresponding to first mode during the Sultanahmet explosion.

Figure 10 demonstrates first mode particle motions of the Sultanahmet Mosque during the Sultanahmet explosion. Black lines show the dome level movements. The particle motions at the semi dome level and at station HAMU on the basement level are shown in grey. In Sultanahmet Mosque, particle motions from explosions and earthquakes are similar, displaying same characteristic features. 3D particle motion videos of explosions show the mosque's response to the pressure wave created by the blasts. The mosque's growing and shrinking is very striking. It is particulary forthcoming in the Sultanahmet explosion. The mosque is hit by the shock wave and responds to it during the first 2-3 seconds. Following that there a relatively long and distinctive free vibration part. The dome level station Kub1 located on the mihrab side is more responsive. It experiences larger horizontal displacement and almost two times higher vertical displacements than Kub3 which is located on the opposite side ($3,5.10^{-4}$ cm and $1,9.10^{-4}$ cm for Kub1 and Kub3 respectively).

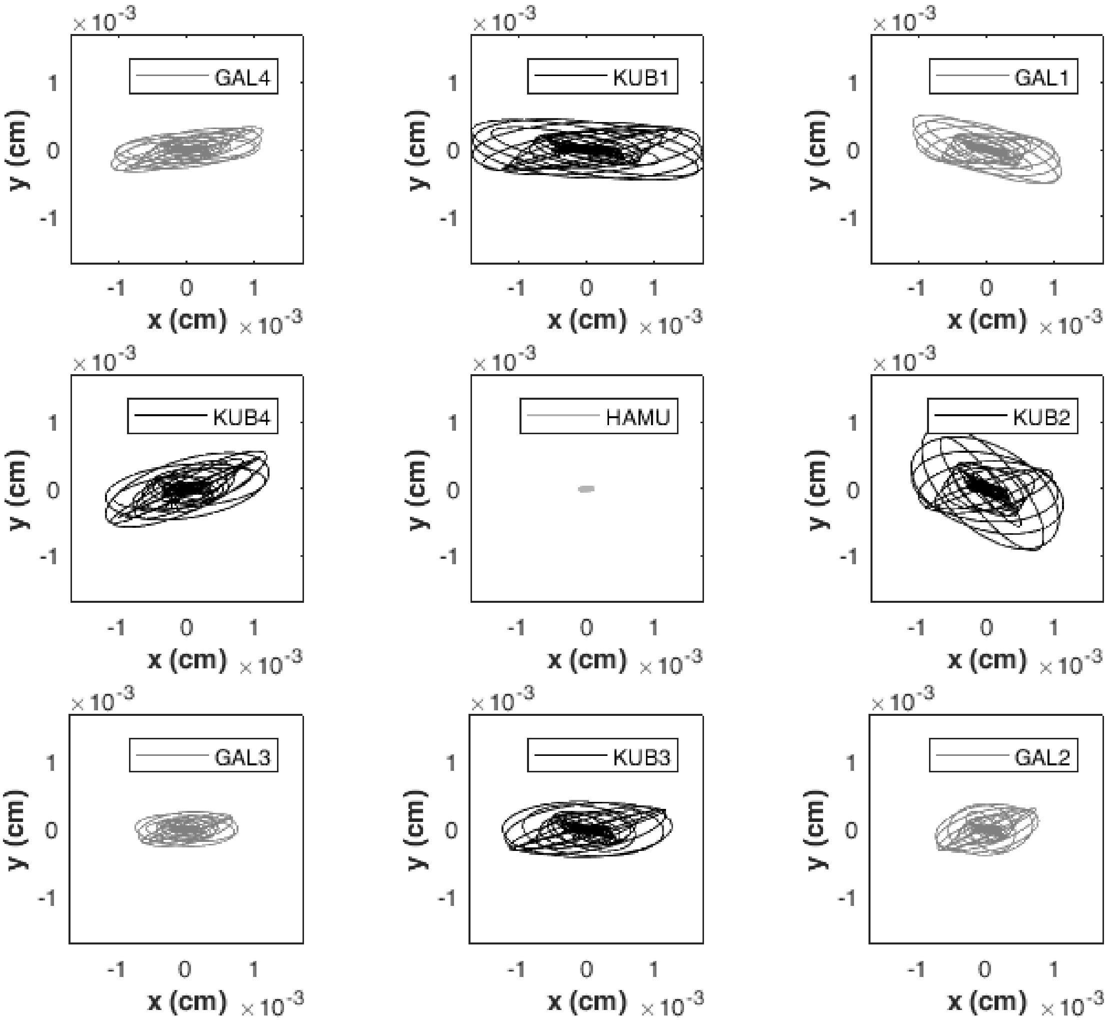

Figure 10. Particle motions at the Sultanahmet Mosque corresponding to the first mode during the Sultanahmet explosion.

5. CONCLUSION

This work is a study on the structural response characteristics of Hagia Sophia Museum and Sultanahmet, Süleymaniye and Fatih Mosques in Istanbul. Recordings of three 2016 explosions and of two earthquakes were used for this purpose. The focus was on (1) time-domain response to explosions; (2) estimation of damping taking advantage of the free-decay in explosion recordings; (3) modal shapes. Findings were compared to those estimated from earthquake data.

Ground level Fourier spectra plots highlighted the differences between earthquakes and explosions in frequency domain. For Sultanahmet Mosque, the frequency amplitudes of the explosions have a tendency to increase towards higher frequencies, while earthquakes have higher Fourier amplitudes in the low frequency range and tend to decrease towards higher frequencies. For the minaret, while the

Fourier amplitudes of earthquake decrease very sharply, explosion amplitudes remain stable.

Estimating damping ratio using explosion data provides more reliable results thanks to uniform free vibration. To calculate damping ratio, different methods were used in time and frequency domain: free decay, logarithmic decrements and half power methods. Because damping ratio is very sensitive to selected bandpass range and the applied method, their results are varied. Free decay method yielded higher damping ratios than the others. While the duration of the time window is affecting the damping estimation in free decay method, in logarithmic decrement method selected first displacement peak value has a crucial role in the results. Damping evaluation for the minaret was also attempted in this study. Damping values estimated using explosion records were higher than those estimated using earthquake records.

In addition to damping, uniform free decays in the explosion records provided an opportunity to obtain more accurate mode shapes of the historical structures we studied. Mode shape evaluations were realized with 2D plots and 3D videos of particle motions for Sultanahmet Mosque and the minaret of Hagia Sophia. Particle motion pattern corresponding to the first mode of the minaret is symmetrical in two horizontal axes which results in circular motion. Particle motions of Sultanahmet Mosque displayed the structural response to the shock wave, followed by the free vibration part. The dome level station on the mihrab side was found to be more responsive in horizontal and vertical directions than its counterpart on the opposite side.

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