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DYNAMIC RESPONSE OF A GOTHIC CATHEDRAL IN CYPRUS

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Abstract. *Within the scope of this study, dynamic response of the St. Nicholas Cathedral in Cyprus that dates back to the 13th century was assessed based on obtained earthquake records. This structure resembles to the Rheims Cathedral of France with a nave of seven bays ending in a polygonal apse, together with flanking aisles ending in apsidal chapels of similar shape. According to historical records, it sustained heavy earthquake damage twice to its roof structure and flying buttresses. The main construction material used at this structure is calcarenite. Back in 2011, a strong-motion network was installed at the cathedral, which recorded a series of small to moderate magnitude events since then. This strong motion network consisting of 10 tri-axial accelerometers is the only active structural health monitoring system in Cyprus. In this article, the time-domain and frequency-domain analysis of this data is presented.*

1 INTRODUCTION

St. Nicholas Cathedral, one of the architectural landmarks of Cyprus, is located at the Gothic city center of Famagusta on the Eastern coast line of the island. The earliest documents that mention this structure go back to 1300 [1]. The era during which the cathedral was under construction corresponds to the first period of Lusignan rule on the island that is characterized by differentiable economic prosperity [2] which was reflected to the quality of monuments produced in that period. The architectural style of the cathedral heavily corresponds to the Rayonnant style in Gothic architecture that was developing in Europe during that very same period; an indication that developments in Europe were closely followed on the island during this period. St. Nicholas Cathedral was the appointed location for the coronation of the Lusignan kings as Kings of Jerusalem after they had been crowned in Nicosia (Capital of Cyprus) as Kings of Cyprus. According to [1], it is because of this functionality that St. Nicholas Cathedral imitates architecturally Rheims Cathedral of France.

St. Nicholas Cathedral has a plan area of 24mx50m, and a height of 29m (Figure 1a). It consists of a nave of seven bays ending in a polygonal apse flanked by aisles ending in apsidal chapels of similar shape. The last bay of the north aisle communicates with a sacristy composed of two roughly rectangular rib vaulted bays (Figure 1a). Enlart [1] indicates that from this sacristy, one could go down into a cistern however the passage way to the cistern is not open today. Also being mentioned in [1] is the fact that when the author visited Cyprus in late 1890s, the northern chapel of St. Nicholas Cathedral, which was added to the building after the initial construction of the main structure, was not in place (Figure 1a). In 1571, with Cyprus entering the Ottoman rule, a minaret was added to the cathedral, interior walls were white washed with gypsum and it has been in service as a mosque since then (Figure 2a).

Today the monuments of the Gothic city center of Famagusta are in a very deprived state due to decades long lack of maintenance. The deterioration of the masonry of these monuments is due to wind carrying sea salts, considerable temperature cycles between day and night, plant and animal ingress and drainage problems. St. Nicholas Cathedral is unfortunately one of the structures at which severe effects of this decay are visible (Figure 2b and 2c). In addition to this rather poor state of the structure, it is under the risk of earthquakes. The Cathedral being located close to the eastern arm of the Cyprus Arc (main seismic source for the island), it sustained severe structural damage caused by earthquakes a number of times throughout its history: 1546 [1, 3], 1568 [1, 3], 1735 [4], and 1941 [5]. It should be underlined that there are varying accounts in the literature regarding which structural elements of St. Nicholas Cathedral sustained damage throughout its history and what caused this damage; the flying buttresses and roof structure of St. Nicholas suffered severely due to 1546 and 1568 earthquakes according to [1, 3] and were tastelessly repaired. According to the British consul Alexander Drummond [4] the 1735 earthquake damaged 2/3 of the cathedral and over 200 people were buried under its ruins as a result. By [5] it was documented that the tremor of 1941 opened up cracks between the vaulting of the nave and the main walls at the St. Nicholas Cathedral. In 1951 and 1963, the cathedral was repaired and strengthened by constructing a concrete collar and a cross tie at the roof level [6].

Within the scope of European Union funded 'Earthquake Vulnerability Assessment of Historical Monuments in Cyprus' project that was active between 2009-2011, a strong motion network was developed at the St. Nicholas Cathedral with the aim of recording this structure's behavior under future earthquakes. This network is composed of 10 Guralp CMG-5TDE triaxial accelerometers (with sampling rate 100 sps, frequency band dc to 100Hz, full scale low gain sensitivity 4g to 0.1g) that are simultaneously triggered to provide a continuous record with a common time basis. Locations of these instruments are indicated in Figure 1b and 1c.

In this article, the time-domain and frequency-domain analysis of data recorded at the St. Nicholas Cathedral between 2011-2014 is presented.

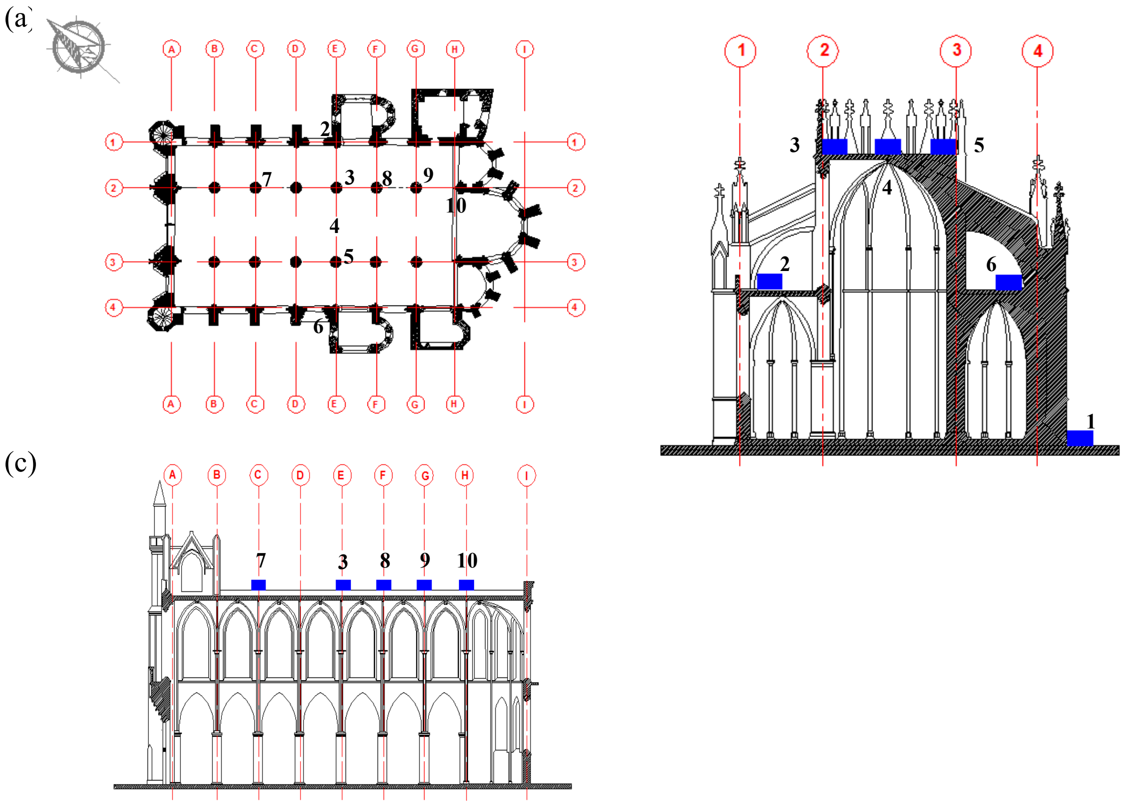

Figure 1: (a) Plan view of St. Nicholas Cathedral. (b) Transverse Section along Axis E and (c) Longitudinal Section along Axis 2 of the structure. Blue boxes indicate locations of 10 strong motion instruments installed to the St. Nicholas Cathedral for monitoring.

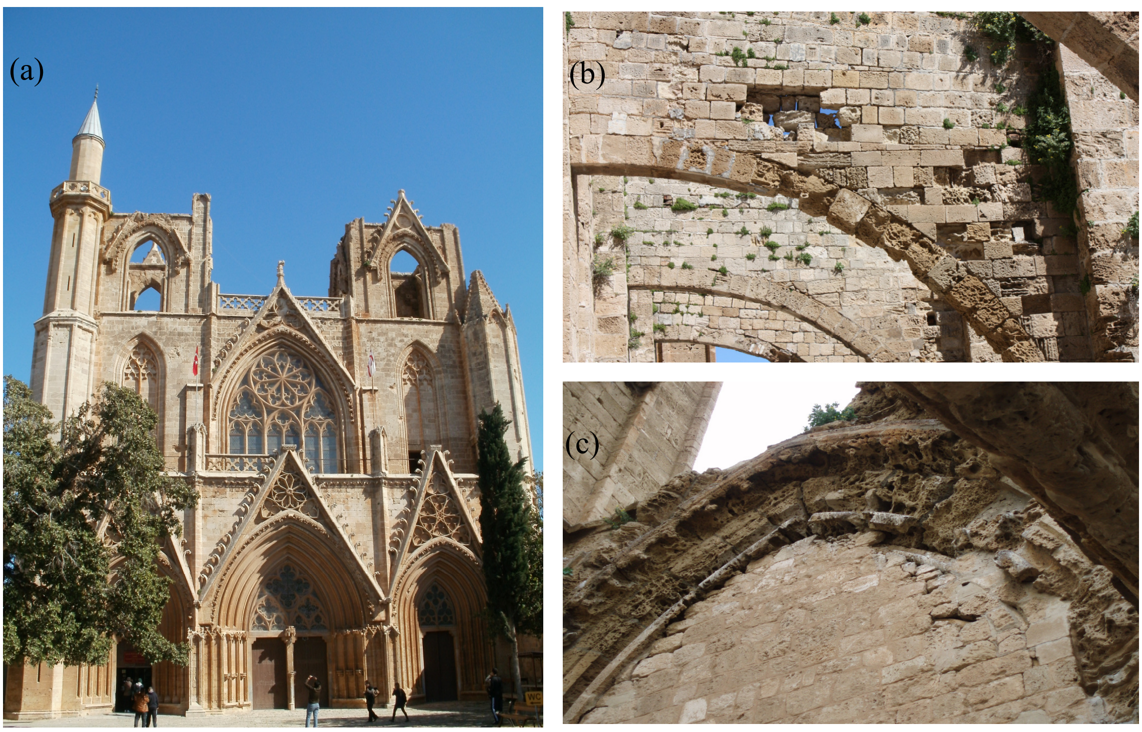

Figure 2: (a) Front (Western) façade of St. Nicholas Cathedral, (b) a close up on one of the flying buttresses of Southern façade, (c) a close up on the peripheral walls of the Northern façade. In both cases severe decay of masonry, gave the material a 'sponge like' appearance.

2 STRONG MOTION DATA

Between 2011-2014, the response of the St. Nicholas Cathedral was captured under 22 small to moderate regional events with magnitudes changing between M_d 3.1-6.0 and epicentral distances varying between 6-669 km (Table 1). Within the scope of this study all the acceleration records obtained were processed by using the USDP software [7] and following the filtering procedure suggested by [8] (a bi-directional 4 pole-4 pole Butterworth filter was used in this study; low pass and high pass cut-off frequencies were determined by observing regions of deviation of FAS computed for the accelerograms under consideration from the theoretical source spectra). The two highest acceleration values measured on the structure are 3.20 cm/s^2 and 2.28 cm/s^2 as a result of the 18 October 2012 (event 7) and 01 April 2011 (event 2) earthquakes respectively (Table 2). Based on these earthquake-recordings made at the St. Nicholas Cathedral, behavior at the locations of stations 5 and 8 were observed to be unexpected. These stations that are sitting on top of columns E3 (and southern façade axis E flying buttress), F2 (and northern façade axis F flying buttress) respectively, were observed to be associated with higher levels of acceleration when compared with data from stations at the same level such as 3, 9 and 10 (Figure 3). Different frequency characteristics were also observed in the case of recordings of these stations (Figure 4). Mainly these differences were observed for the N-S components of records that are aligned with the transverse direction of the structure.

Event No.	Date	Time	Lat	Long	Depth (km)	Magnitude (M_d)	Epicentral Distance (km)
1	26.03.2011	16:25:13	34.373	32.111	12.0	4.2	187
2	01.04.2011	13:29:07	35.514	26.580	57.1	6.0^{ǂ}	669
3	18.04.2011	12:50:42	35.048	34.444	36.7	3.7	47
4	19.09.2012	09:17:46	37.320	37.116	8.1	4.7^{ǂ}	376
5	26.09.2012	01:28:28	34.719	29.973	12.3	4.7	364
6	30.09.2012	15:52:34	34.988	33.639	54.0	3.4	31
7	18.10.2012	06:46:38	34.852	34.003	31.6	3.7	6
8	14.11.2012	23:55:48	37.266	37.100	14.8	4.9	371
9	30.11.2012	19:27:25	34.844	34.038	22.9	3.1	32
10	02.12.2012	00:21:55	34.393	32.933	5.0	3.5	123
11	12.12.2012	01:18:13	37.300	36.271	10.7	4.1	320
12	14.12.2012	00:31:19	35.409	33.336	12.0	3.3	64
13	03.03.2013	11:22:24	35.962	34.635	8.0	4.1	113
14	25.04.2013	22:54:15	37.315	37.137	6.0	4.3	377
15	10.07.2013	21:22:44	35.021	34.184	7.6	3.1	25
16	12.07.2013	08:57:38	35.179	33.897	11.2	3.2	8
17	12.07.2013	08:57:36	35.094	34.038	8.8	3.2	9
18	12.07.2013	08:58:42	34.719	34.240	25.2	3.5	52
19	08.08.2013	08:25:39	34.438	34.421	13.2	3.3	88
20	03.02.2014	18:29:44	34.833	32.560	24.8	4.1	130
21	14.02.2014	00:33:38	36.722	36.027	17.5	4.5	259
22	02.03.2014	04:25:57	36.776	35.159	7.5	4.1	214

Table 1: Recorded earthquakes at St. Nicholas Cathedral. Seismological data corresponding to recorded earthquakes was taken from Kandilli Observatory and Earthquake Research Institute's recent earthquakes database. M_d is duration magnitude. ǂMagnitude values given represent moment magnitude values taken from the European-Mediterranean Seismological Center database.

Event No.	PGA_{ground} $(gal)_{obs}$	$Direction_{ground}$	$PA_{structure}$ $(gal)_{obs}$	Location	$Direction_{structure}$
1	0.10	N-S	0.52	H2	N-S
2	0.36	N-S	2.28	H2	N-S
3	0.20	N-S	1.34	H2	N-S
4	NA	NA	0.22	G2	N-S
5	NA	NA	0.12	G2	N-S
6	NA	NA	0.17	G2	N-S
7	0.50	N-S	3.20	G2	N-S
8	NA	NA	0.08	G2	N-S
9	NA	NA	1.29	F2	N-S
10	0.02	N-S	0.12	F2	N-S
11	0.03*	N-S	0.04	H2	N-S
12	0.03*	N-S	0.09	G2	N-S
13	0.11*	N-S	0.69	F2	N-S
14	0.01*	N-S	0.17	E3	N-S
15	NA	NA	0.23	E3	N-S
16	0.02*	N-S	0.08	G2	N-S
17	NA	NA	0.35	G2	N-S
18	NA	NA	0.35	H2	N-S
19	0.07*	N-S	0.18	H2	N-S
20	NA	NA	0.53	G2	N-S
21	0.04	N-S	0.28	E3	N-S
22	0.1	N-S	0.32	G2	N-S

Table 2: Main peak acceleration characteristics of records obtained at St. Nicholas Cathedral: $PGA_{ground}(gal)_{obs}$ – Geometric mean of horizontal peak ground acceleration values recorded outside St. Nicholas Cathedral, NA – No ground level records are available, * – No ground level records are available from St. Nicholas Cathedral site however ground level accelerations measured by a nearby station (1.4km away with similar soil conditions) at Famagusta are given for comparison, $Direction_{ground}$ – direction in which maximum peak ground acceleration value was observed at St. Nicholas Cathedral site ((N-S, north-south direction which also corresponds to the transverse direction of the structure; E-W, east-west direction which also corresponds to the longitudinal direction of the structure), $PA_{structure}$(gal)obs – Geometric mean of horizontal peak acceleration values recorded on the St. Nicholas Cathedral, Location – location at which these horizontal peak ground acceleration values were recorded on St. Nicholas Cathedral (Please refer back to Figure 1 for these exact locations), $Direction_{structure}$ – direction in which maximum peak acceleration value was observed on St. Nicholas Cathedral (N-S, north-south direction which also corresponds to the transverse direction of the structure; E-W, east-west direction which also corresponds to the longitudinal direction of the structure).

The unexpected behavior above columns E3 and F2 (as detected by stations 5 and 8) are likely to be caused by deteriorated flying buttresses of Northern and Southern facades along axes E and F and to a lesser extent by poor material properties at these columns as was documented by [9] during past studies on St. Nicholas Cathedral.

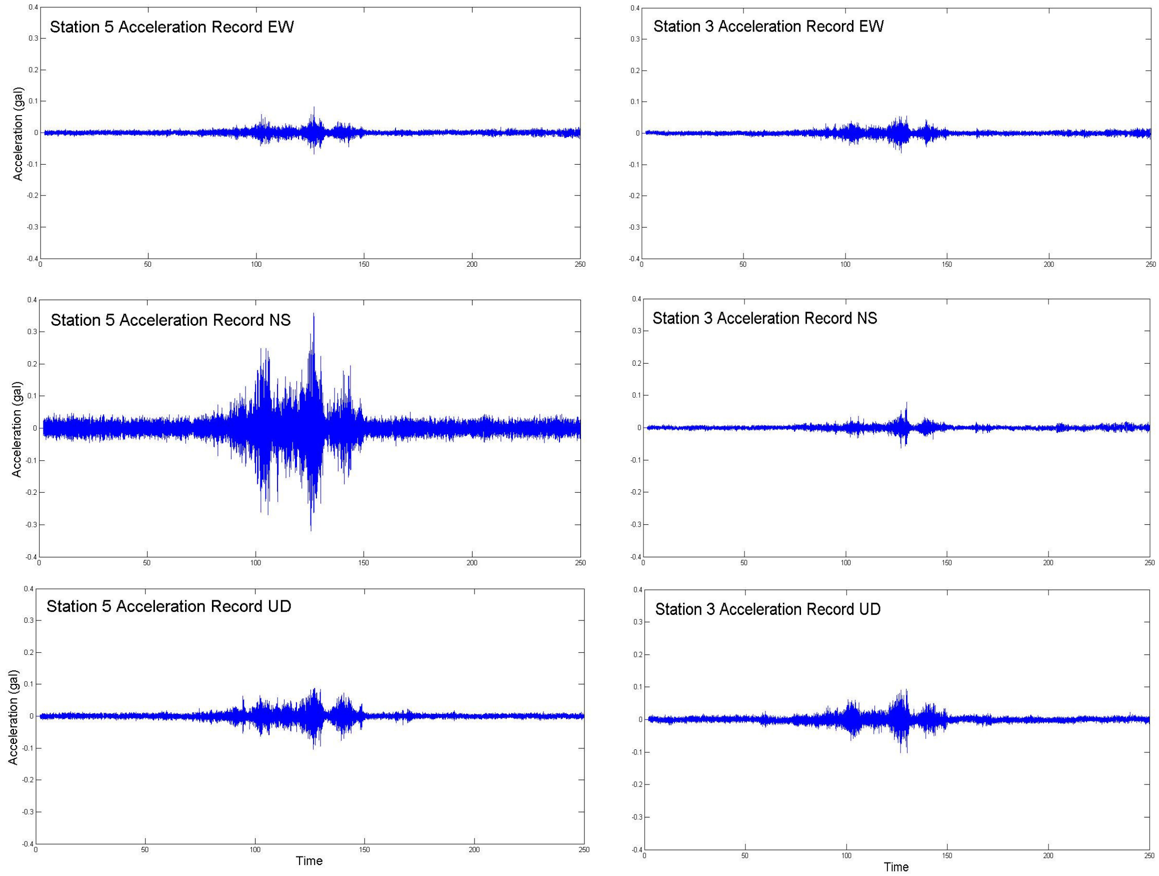

Figure 3: Acceleration records obtained at St. Nicholas Cathedral stations 3 and 5 during the 25 April 2013 Earthquake (N-S direction corresponds to the transverse direction of the structure; E-W direction corresponds to the longitudinal direction of the structure).

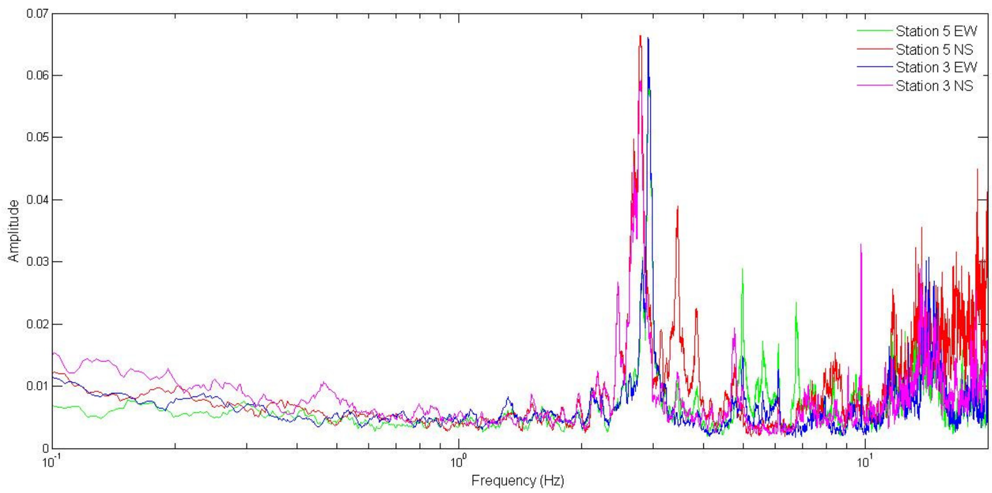

Figure 4: Comparison of Fourier Amplitude Spectra for stations 3 and 5 obtained from 25 April 2013 Earthquake acceleration records (N-S direction corresponds to the transverse direction of the structure; E-W direction corresponds to the longitudinal direction of the structure).

3 SPECTRAL ESTIMATIONS

Within the scope of this study, spectral techniques were applied to the records obtained from the 22 events given in Table 1 to identify dynamic system properties of the St. Nicholas Cathedral. Transfer functions were utilized in case of the events for which ground station of the network (station 1) yielded acceptable records (adequate signal to noise ratio values). As can be seen from Table 2, such events are rather limited in number. For the rest of the events, the power spectral density approach was preferred and only upper level stations of St. Nicholas Cathedral were utilized in this part of the study. Power spectral densities (PSD) were estimated on the basis of averaging of 10 sec. long windows with 50% overlapping. In Figure 6, the determined transfer functions based on each record (in grey) together with the overall average transfer function for each event (in red) are given. These computations were repeated for E-W and N-S direction records separately. In Figure 7, average PSDs computed for each event in E-W and N-S directions are given separately. Both in the case of Figure 6 and 7, N-S direction records yielded first vibrational modal frequencies and E-W direction records yielded second vibrational modal frequencies. Identified modal frequencies within the scope of this study from the 22 events for the presumed first and second modes are summarized in Table 3 below.

Event No.	1st Modal Frequency (Hz) Direction N-S	2nd Modal Frequency (Hz) Direction E-W
1	2.63	2.90
2	2.68	2.95
3	2.75	2.98
4	2.81	2.98
5	2.78	2.93
6	2.76	3.00
7	2.64	2.86
8	2.69	2.93
9	2.73	2.95
10	2.68	2.89
11	2.81	2.93
12	2.83	2.93
13	2.69	2.83
14	2.95	3.08
15	2.78	3.00
16	2.81	3.05
17	2.81	3.05
18	2.81	3.05
19	2.83	3.05
20	2.64	2.86
21	2.78	2.93
22	2.78	2.93

Table 3: Modal frequencies associated with the 1st and 2nd dominant vibrational modes at St. Nicholas Cathedral .

Based on the data given in Table 3, it can be stated that a correlation exists between 1st and 2nd modal frequencies determined and amplitude of recorded accelerations on the St. Nicholas Cathedral as well as between 1st and 2nd modal frequencies and event durations although the latter observed to be a weaker correlation (Figure 5). Also it should be noted that measured modal frequencies are under the effect of ambient temperature as well, as measurements were taken in different seasons and times. As temperature at the St. Nicholas Cathedral site was not recorded at the time of events, the relationship between the measured modal frequencies and temperature could not be studied in detail within the scope of this study.

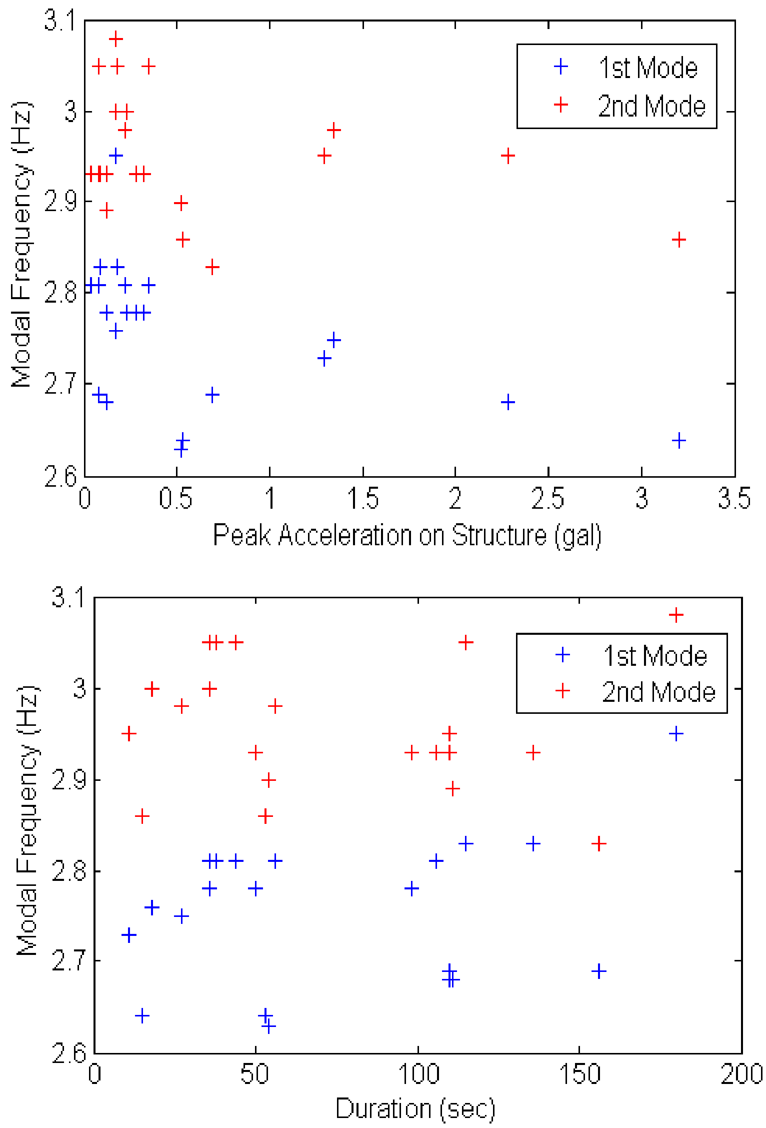

Figure 5: Relationship between measured 1st and 2nd modal frequencies and (a) observed peak acceleration values on the St. Nicholas Cathedral and (b) event durations.

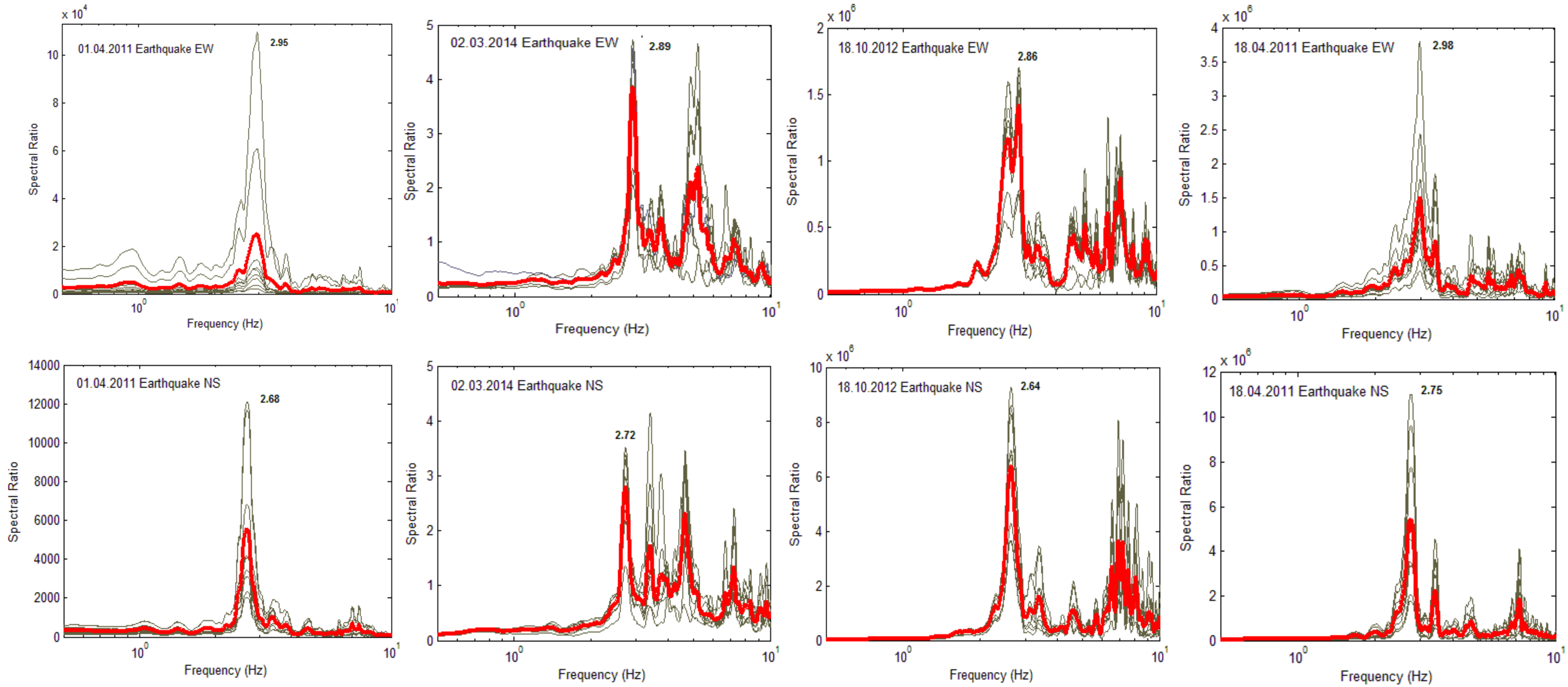

Figure 6: Estimated transfer functions for the E-W and N-S directions of St. Nicholas Cathedral for the events of 01 April 2011, 02 March 2014, 18 October 2012 and 18 April 2011. Transfer functions obtained based on individual station records are represented by grey lines. Red lines represent average transfer functions computed for each event (N-S direction corresponds to the transverse direction of the structure; E-W direction corresponds to the longitudinal direction of the structure).

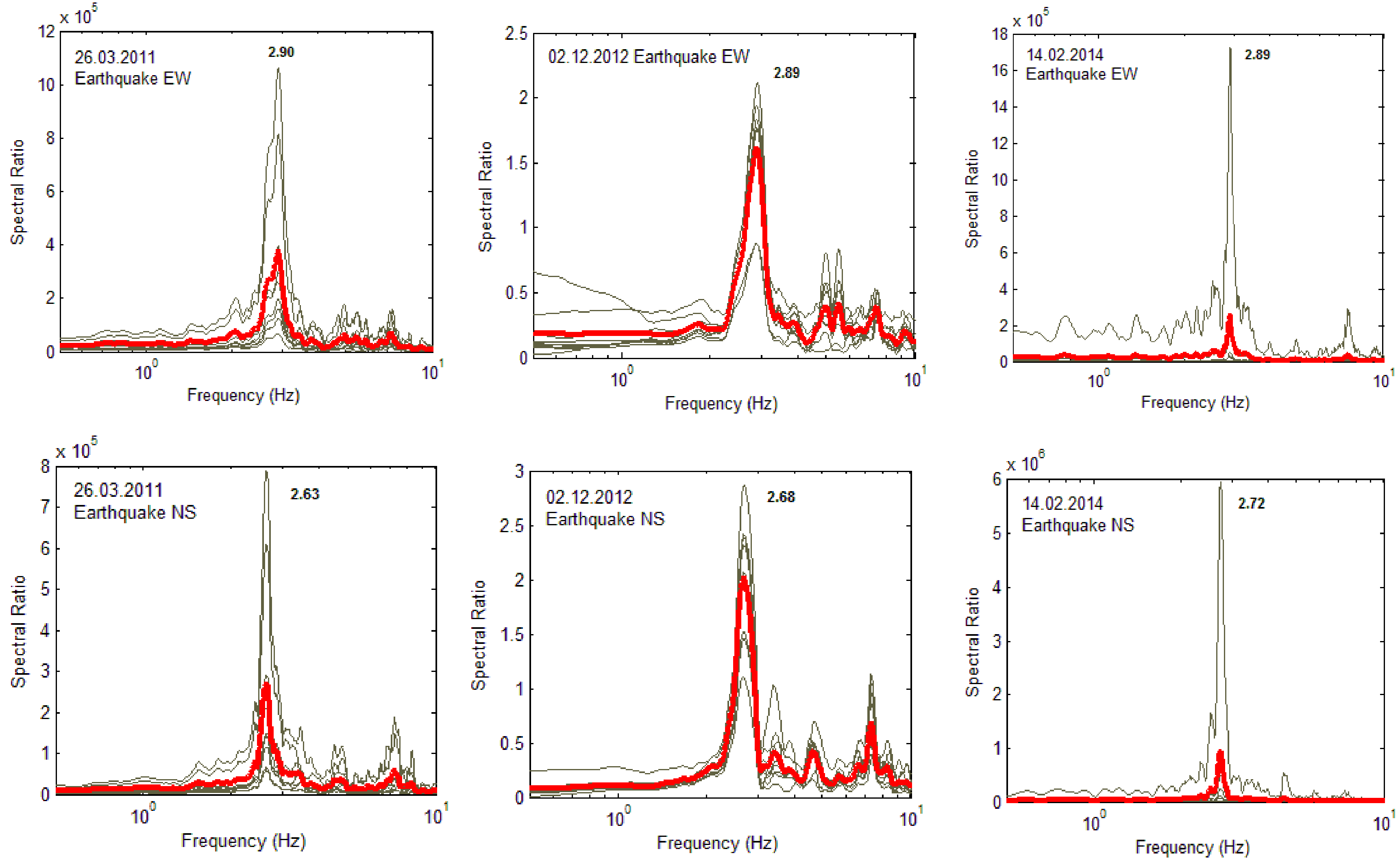

Figure 6 cont.: Estimated transfer functions for the E-W and N-S directions of St. Nicholas Cathedral for the events of 26 March 2011, 02 December 2012 and 14 February 2014. Transfer functions obtained based on individual station records are represented by grey lines. Red lines represent average transfer functions computed for each event (N-S direction corresponds to the transverse direction of the structure; E-W direction corresponds to the longitudinal direction of the structure).

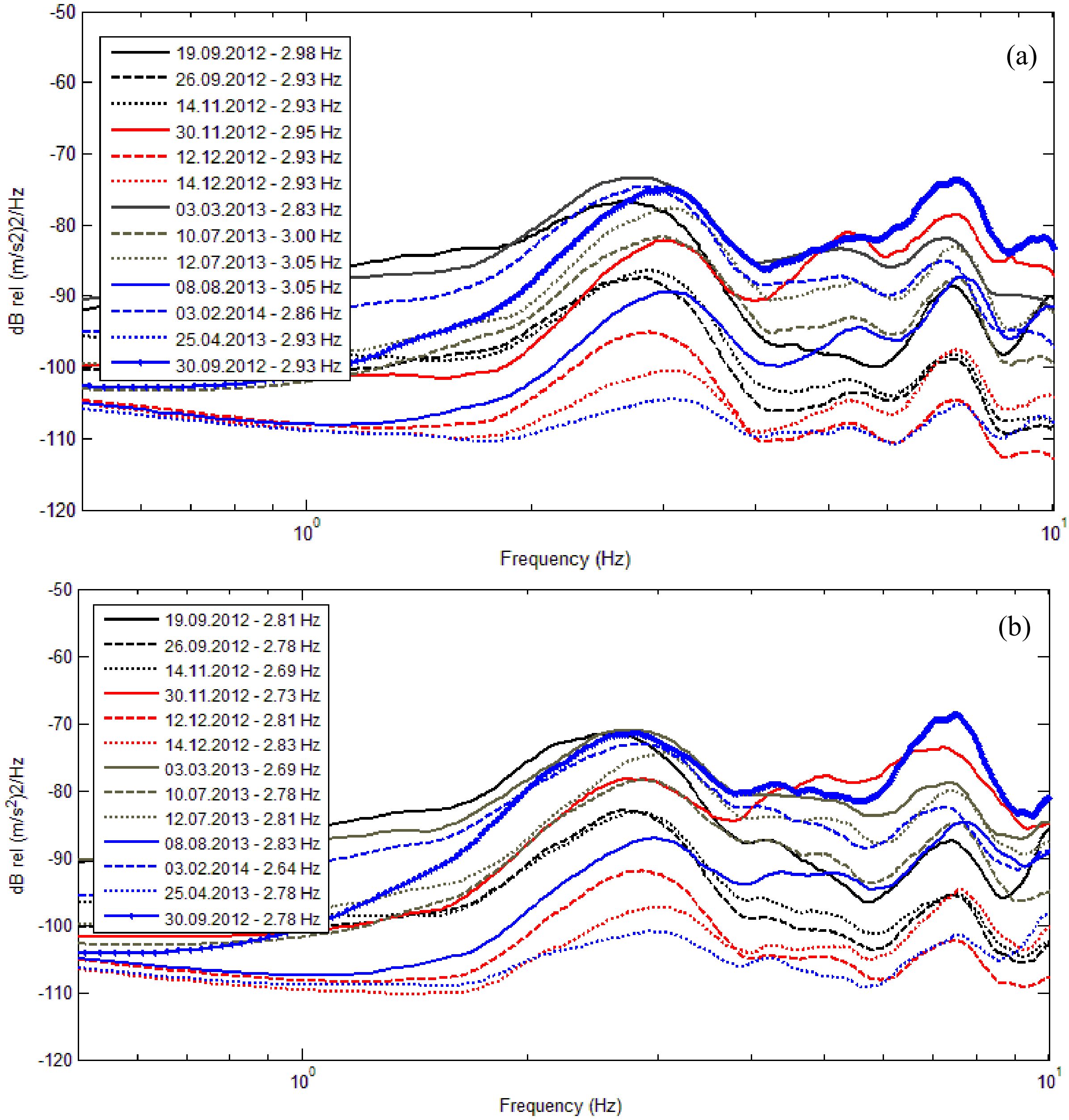

Figure 7: (a) Average power spectral densities computed for 19.09.2012, 26.09.2012, 14.11.2012, 30.11.2012, 12.12.2012, 14.12.2012, 03.03.2013, 10.07.2013, 12.07.2013, 08.08.2013, 03.02.2014, 25.04.2013, 30.09.2012 events for the E-W direction of St. Nicholas Cathedral, (b) average power spectral densities computed for 19.09.2012, 26.09.2012, 14.11.2012, 30.11.2012, 12.12.2012, 14.12.2012, 03.03.2013, 10.07.2013, 12.07.2013, 08.08.2013, 03.02.2014, 25.04.2013, 30.09.2012 events for the N-S direction of St. Nicholas Cathedral.

4 CONCLUSIONS

Within the scope of this study, the time domain and frequency domain characteristics of 22 earthquake records detected by the strong motion network at St. Nicholas Cathedral were assessed. These events that were recorded between 2011 and 2014 are rather small local and moderate distant events hence observed peak acceleration values on the St. Nicholas Cathedral remained below the 3.5 gal level. As a result processing of the obtained records proved to be rather challenging.

Based on the records obtained, it was detected that above columns E3 and F2 (at locations of station 5 and 8) the structure underwent unexpectedly high accelerations. As the N-S components of the obtained records especially observed to be unexpectedly high, it is believed that this behavior is associated with deteriorated Northern and Southern façade flying buttresses of St. Nicholas Cathedral around axes E and F of the structure (Figure 1).

Based on frequency domain analyses of obtained records, 1^{st} and 2^{nd} vibrational modal frequencies were detected for the St. Nicholas Cathedral. Previously, a finite element model of the structure was developed and calibrated based on ambient vibration tests conducted on the structure [10] and [11]. Findings of these previous studies do not fully agree with the results reached within the scope of this study based on small to moderate magnitude events recorded. In [11], the first four vibrational frequencies and their associated mode shapes were identified at 0.98 Hz, 1.04 Hz, 1.28 Hz and 1.40 Hz. Both [11] and analytical model of [10] yielded translation along the longitudinal axis of the St. Nicholas Cathedral as the 1^{st} dominant mode for the structure and translation along the transverse axis of the structure as the 2^{nd} dominant mode. Based on frequency domain analyses of this study, we did not observe peaks around 1 Hz but rather later between 2.63 Hz-2.83 Hz for the 1^{st} vibrational mode and between 2.83 Hz-3.08 Hz for the 2^{nd} vibrational mode. This study also implies that the 1^{st} vibrational mode is dominated by translation along the transverse direction of the structure and it is the 2^{nd} vibrational mode being dominantly translation along the longitudinal axis of the structure. These differences can be due to record high temperatures experienced and documented in [11] during ambient vibration tests. Also the lateral stiffness provided by the flying buttresses of the structure is probably not correctly reflected to the FEM model in [10] (modeled as higher than what the structure possess in reality). Exact conclusions, however, will be drawn when the mode shapes are extracted from the current records, so that the vibrational modes identified in both studies can be appropriately correlated.

The 22 small to moderate events recorded by the St. Nicholas Cathedral strong motion network provided valuable insight into the behavior of this structure. Before more firm conclusions can be drawn on the dynamic behavior of this structure local moderate to large events that would yield higher acceleration levels at the site of St. Nicholas Cathedral have to be recorded by this network. Nevertheless this preliminary data obtained indicates clearly the importance of such networks for fully understanding complex behavior of historical structures such as the cathedral under consideration.

5 ACKNOWLEDGEMENTS

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