Measured seismic response of the Mexico City Cathedral

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ABSTRACT: Results from 16 seismic events, recorded in the first three years of operation of a strong motion instrumentation network, provide a significant insight about the seismic performance of the Mexico City Cathedral and other similar buildings. Due to soil-interaction effects, and to great differences between dominant frequencies of the induced motion and fundamental frequencies of the building vibration; seismic effects on this and similar buildings are much smaller than those induced in most modern constructions. On the other hand, several parts of the building show important local vibrations, particularly the main façade and the bell towers. Results indicate that in its present state the building has an acceptable level of seismic safety.

1 INTRODUCTION

1.1 Seismic performance of monuments

Mexico possesses both a large wealth of extremely valuable historical buildings, and a long history of damage and destruction of them, by severe earthquakes frequently affecting most of the country. The most recent experience comes from the June 1999, Tehuacan earthquake (Magnitude, M=7.0), that damaged about 1800 historic buildings, most of them being colonial temples and convents of the central states of Puebla and Oaxaca.

Sources of weakness of historic buildings, typically heavy masonry structures, are rather well known, nevertheless, procedures for evaluating their seismic safety are not well established, and quantitative information about their behaviour and response is very scarce. Seismic response of historic buildings is significantly different from that of common modern structures. Differences come from their form and structure, and from their basic constituting materials, which are weak in tension, thus making it almost impossible to provide continuity within and between structural members, and lending to specific mechanisms for resisting seismic actions, different from those of modern construction.

Despite of their seemingly inherent weakness to earthquakes, historic buildings in Mexico City have shown a rather good performance under the many earthquakes that have shaken the city during their existence; specifically, in the great 1985 Mexico earthquake (M=8.1), they performed much better than most, supposedly more resistant, modern structures. In particular, the Mexico City Cathedral has successfully survived earthquakes until now, nevertheless it shows some signs of distress that arise suspicion about its safety under future events.

1.2 The Cathedral of Mexico City

The Mexico City Cathedral (Fig. 1) is one of the most important colonial monuments of the Americas, and was built over the remains of several Aztec constructions, on the very soft soil deposits underlying most of the ancient city. Since the beginning of its construction, in 1565, the temple suffered extreme subsidence, forcing the builders to significant adjustments to the geometry, and being a major reason for the protracted period of construction (240 years). The lack of uniformity in the degree of consolidation of the soft clay layers underlying different parts of its foundation, generated great differential settlements.

Figure 1. The Cathedral of Mexico City

The Cathedral has five longitudinal naves; the central one is covered by a cylindrical vault, and the lateral ones by spherical domes. Two rows of eight columns support the central nave and its heavy central dome. A close array of robust masonry walls divides the extreme naves into small chapels constituting, along with the facade walls and some buttresses, a very stiff peripheral belt that provides great lateral strength to the structure (Fig.2). The building foundation consists of a grid of foundation beams, and a thick masonry mat over a dense array of short timber piles.

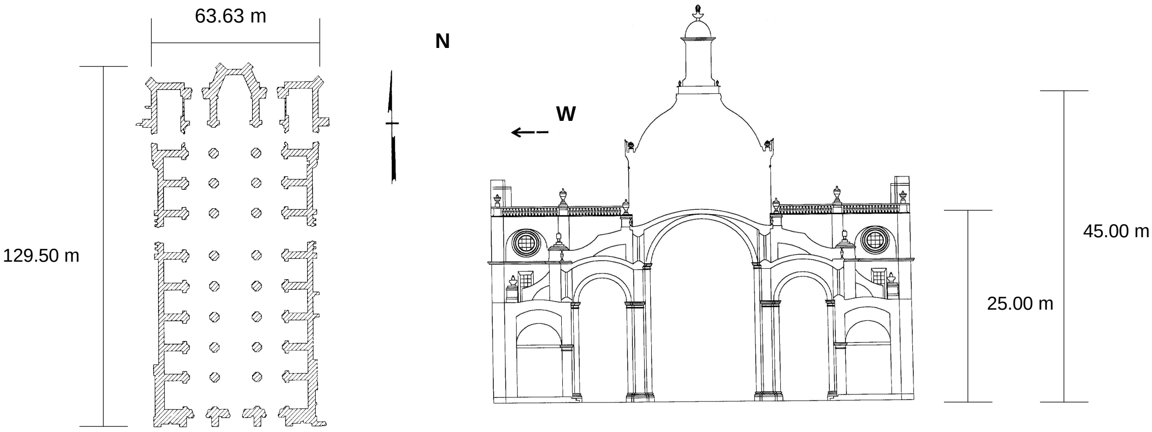

Figure 2. Main features of the Cathedral

The distortion of the building produced by the differential settlements, that reached a maximum of 2.4 m, seriously undermined its structural safety. The four columns supporting the central dome were between 2 and 3 % out of plumb, generating large eccentricities to the heavy vertical loads that are transferred from the roof to the base level. Severe cracks in the roof, floor and walls constantly reappeared in spite of frequent repairs.

A major rehabilitation project was started in 1991, aiming at reducing differential settlements through a technique called underexcavation, and by subsequently making more uniform the deformability of the soil through injections of mortar in the softer zones, and finally at repairing the most significant structural damage. The main geotechnical aspects of the program can be found in Ovando and Santoyo (2001), and the structural ones, in Meli and Sánchez R. (1997).

The rehabilitation program has been supported by numerous studies, as well as by direct determinations of properties and extensive monitoring of its response. As a part of this program, a seismic network was installed in 1996, to measure the vibration induced by the frequent earthquakes felt in the city.

2 STRONG MOTION INSTRUMENTATION

2.1 Instrumentation network

Seismic instrumentation of buildings has shown to be the most effective way to validate design procedures and determining the main characteristics of seismic response of special buildings. Many structures have been seismically instrumented in different parts of the world, but only a handful of them are historic buildings. Therefore, the results obtained by this network are of great value not only for the study of the Cathedral itself, but also of other similar buildings, mainly the colonial temples in the Americas.

Instruments are tri-directional accelerographs that are automatically triggered to provide a continuous record with a common time basis. The initial array was composed of one instrument located in the free-field, on the ground, about 10 m outside the foundation of the building; three instruments were placed at the foundation level in order to measure the motion directly induced to the building and its possible differences along the building plan; four instruments were located on the roof to measure the building response at different points. The array is schematically shown in Fig 3. After the first year, two of the instruments at the basements were removed and placed on a bell tower, to study its local seismic response. More recently, some of the instruments were moved to other buildings, and a five instruments array has remained in place.

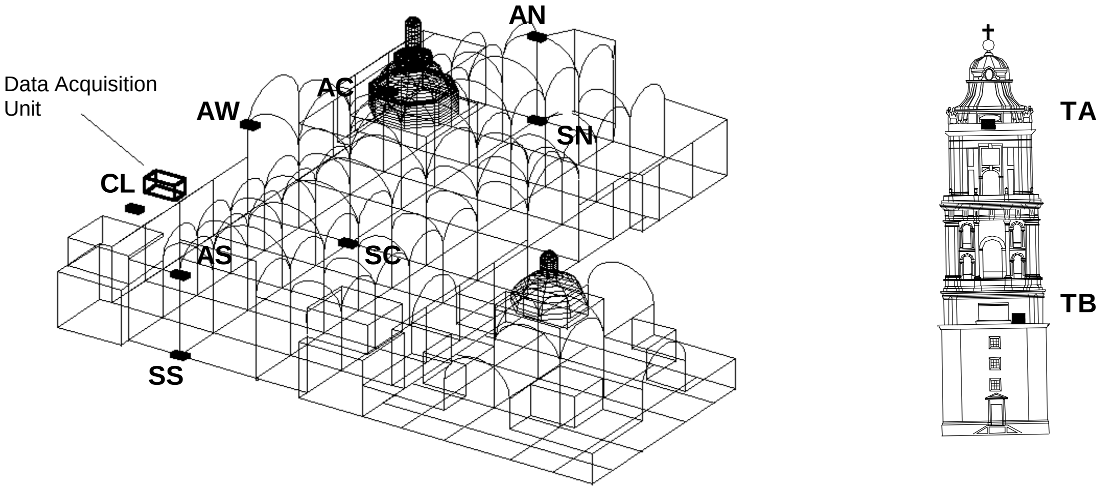

Figure 3. Schematic view of the instrumentation network

2.2 Seismic records obtained.

From January 1997 to December 1999, 16 seismic events were recorded by the network; only four of them are discussed in this paper. In all cases epicenters were located at least 100 km away from the Cathedral site, and in most cases they were subduction earthquakes generated in the Pacific Coast, at a distance of more than 300 km from Mexico City. Due to the great epicentral distances, the intensity of the ground motion and of the building response was quite low, even if the magnitude of some of the events exceeded 7.0 in the Richter scale.

Table 1. Maximum accelerations recorded in the four main events

Event	Magnitude (Mc)	Component	AC	AN	AS	AW	SC	SN	SS	CL	TB	TA
01/11/97	7.3	N-S	14.99	14.31	17.48	13.46	12.64	12.40	12.69	14.84	-	-
E1		V	4.74	-3.72	-4.37	4.89	-3.81	-3.54	-4.08	-5.75	-	-
		E-W	15.89	13.65	15.43	18.09	12.47	12.15	12.54	-14.21	-	-
04/22/97	5.9	N-S	-3.67	3.45	-6.02	3.56	-2.78	-2.71	-2.76	3.86	-	-
E2		V	2.73	2.23	2.05	1.81	1.86	1.92	1.91	2.09	-	-
		E-W	-5.41	4.57	4.90	6.50	3.69	-3.72	3.90	4.12	-	-
07/19/97	6.3	N-S	-2.09	-2.05	-2.37	-1.99	-1.88	-1.89	-1.91	-2.01	-	-
E3		V	0.64	0.52	0.65	0.72	0.56	-0.56	0.59	-1.91	-	-
		E-W	-1.88	-1.68	-1.88	-2.03	-1.40	-1.54	1.40	1.86	-	-
04/20/98	5.4	N-S	2.87	2.57	4.09	2.59	1.77	-	-	2.87	-3.71	14.26
E4		V	-2.47	-1.68	-1.56	-1.54	-1.48	-	-	2.04	-1.63	-1.95
		E-W	3.10	2.32	3.70	3.45	1.48	-	-	1.68	4.61	16.23

Accelerations in gal

Main features of the four selected events, and maximum measured accelerations at different points, are summarized in Table 1. Maximum ground acceleration corresponds to event E1, and equals 14.84 gal, while maximum recorded acceleration on the building, for the same event, is 18.09 gal, corresponding to less than 2 % of the gravity acceleration. Typical acceleration histories, presented in Fig. 4, show a very long duration and an almost harmonic vibration.

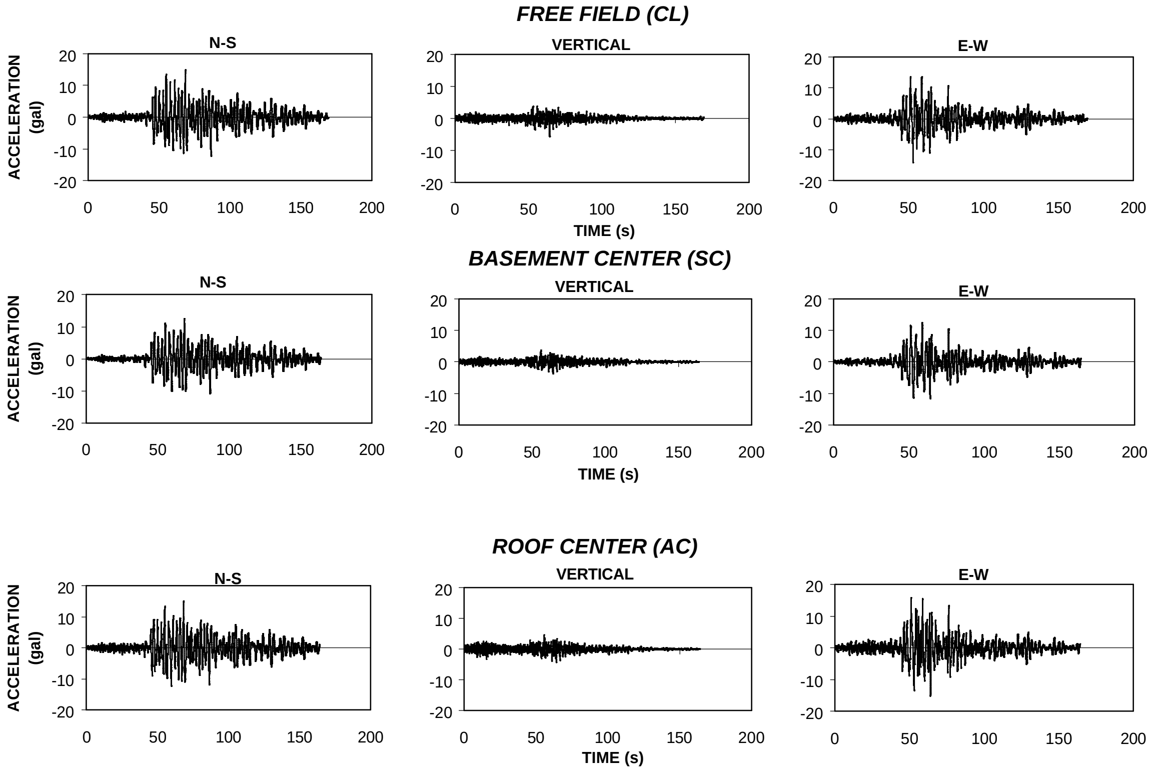

Figure 4. Strong motion records for event E1

All seismic records were analysed in the frequency domains, obtaining Fourier and response spectra as well as correlation and transfer functions of the motion at different point. From analyses in the time domain, histories of absolute and relative displacements between different points were obtained.

3. MAIN RESULTS

3.1 Ground motion at free-field

For engineering purposes, characteristic of the seismic ground motion are usually studied through acceleration response spectra for 5% damping. A set of these spectra is shown in Fig 5 for the two main horizontal directions. As it can be seen, spectral form changes with earthquake size, and the earthquakes of highest intensity show significant response amplification for long periods. This is attributed to the higher content of long period waves in motion of large earthquakes travelling long distances from their source. These long period waves are amplified by the thick deposits of very soft clay underlying the Cathedral site and most of the central part of the city.

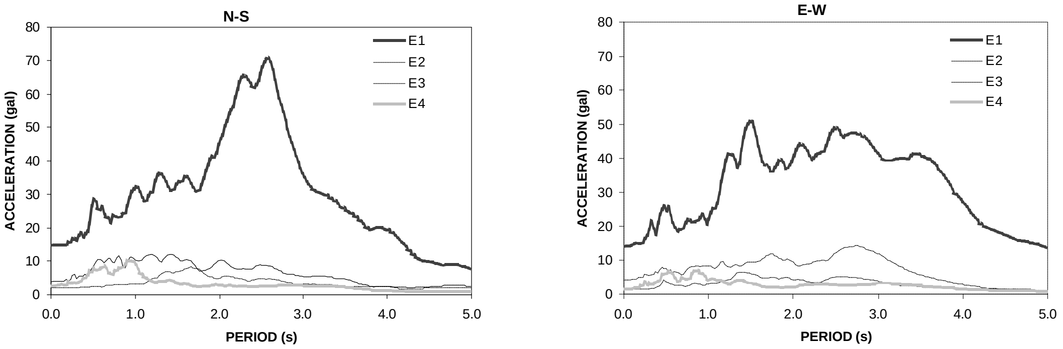

Figure 5. Acceleration response spectra of records at free field (CL*)*

To better identify the site effects, transfer functions of the Fourier spectral amplitudes were obtained between the Cathedral site and a station in a site of firm ground in Mexico City, where the same events were recorded (CU). These functions, shown in Fig. 6 for all events and for both horizontal directions, allow to clearly identify the first mode of the soil deposits at the site, as 0.38 and 0.37 Hz for the N-S and E-W directions, respectively. A second modal frequency is found at 1.76 and 2.08 Hz, for the same two directions.

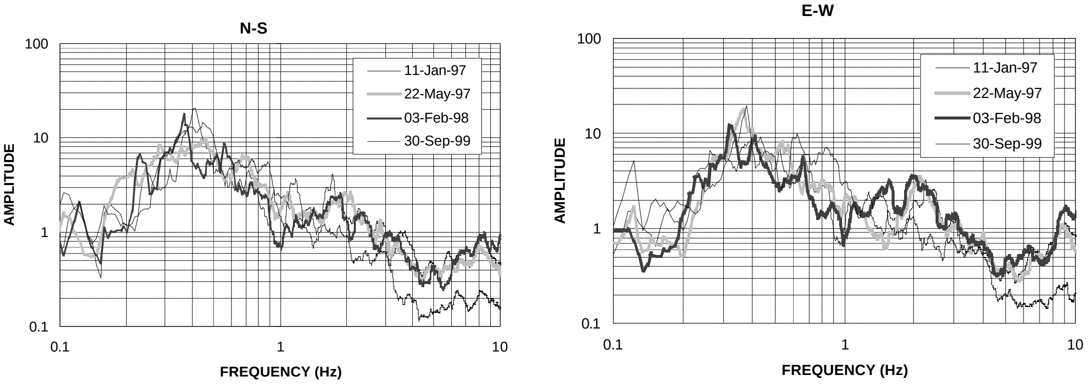

Figure 6. Transfer functions between the Cathedral site (CL) and a station in firm ground (CU)

Monumental structures have fundamental periods of vibration usually not exceeding 0.5 s, very far from the dominant periods of vibration of the soft soil of Mexico City. This is particularly beneficial for the seismic performance of these buildings, which do not experience the great amplification of vibration due to near-resonance response that has been the main cause of the great damage suffered by many modern buildings in the 1985, Mexico earthquake (Rosenblueth and Meli 1986). Nevertheless, it must be noticed that the natural period for the second mode of vibration of the soil deposits (around 0.85 s) is not far from the fundamental period of many historical buildings, and, therefore, some response amplification can be expected around this period.

3.2 Motion at building basement

It is important to assess if and how the presence of the building alters the motion of the ground, thus producing a shaking at the building basis that is different from what could be obtained from motions recorded in open ground.

To study this issue, transfer functions between the ordinates of Fourier spectra corresponding to ground motions recorded at the three stations of the basement, and those for the free-field spectrum, were computed. Fig. 7 shows the average of the three main events at the three locations, for the two horizontal directions. A drastic decrease in response amplitudes at the basement can be appreciated for frequencies exceeding 1.1 Hz. Specifically, for a frequency of 2.5 Hz (corresponding to the fundamental period of the structure, that is approximately 0.4s, as will be demonstrated shortly) spectral ordinates of the motion at the basement are on average 50 % and 40 % of those at free-field, for N-S and E-W directions, respectively.

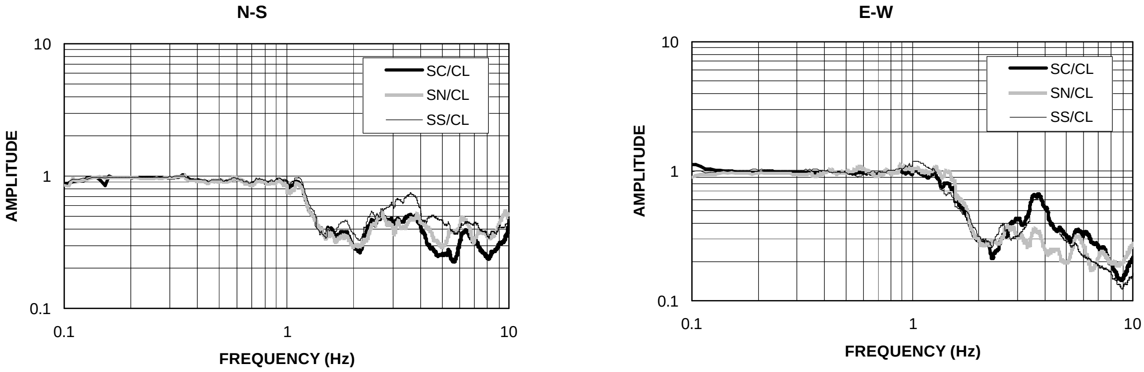

Figure 7. Average transfer functions of spectral amplitudes for events E1, E2, E3, at the three points of the basement with respect to free field

The reduction in the amplitude of motion is due to soil-structure interaction, and primarily to the filtering of short length waves by this very heavy and stiff building: As shown in Fig 7, waves whose frequency is higher than 1 Hz are filtered and dampened when crossing the building.

The above mentioned phenomenon is particularly beneficial for the seismic safety of the Cathedral, and, similarly, for all historical buildings located in the central area of Mexico City on soft soil. It has been probably the main factor for their survival to the many high intensity earthquakes they have experienced though the centuries.

Another aspect to be studied is the uniformity of the motion induced at the three points of the foundation. Spectral ordinates and transfer functions do not show significant differences, nevertheless time histories of relative displacements computed from the records show bending of the base, mainly in the vertical direction, but also longitudinally. Maximum relative vertical displacement, between the north end of the basement and its central point, is approximately 20 % of the maximum total vertical displacement at the center. The significant distortion of the building basement is probably due to the large cracking that exists both in the foundation and in the structure; nevertheless, these relative displacements do not generate significant differences in accelerations induced in different parts of the structure.

3.3 Motion at the roof

Maximum accelerations recorded at the roof are only slightly greater than those at the basement (17 % for event E-1), showing that the building essentially follows the motion of the ground, with very little amplification.

Transfer functions of the spectral ordinates of the horizontal motion at the four points on the roof, with respect to the corresponding points at the basement, are shown in Fig. 8. A first peak of roof response is appreciated at about 2,5 Hz, for both directions, corresponding to the fundamental mode of vibration of the building (0.35 s and 0.40 s period, for N-S and E-W, respectively). The second mode of vibration of the building is found at a frequency around 6 Hz. The peak at 1.1 Hz corresponds to the fundamental mode of vibration of the bell towers, as will be shown in section 3.5.

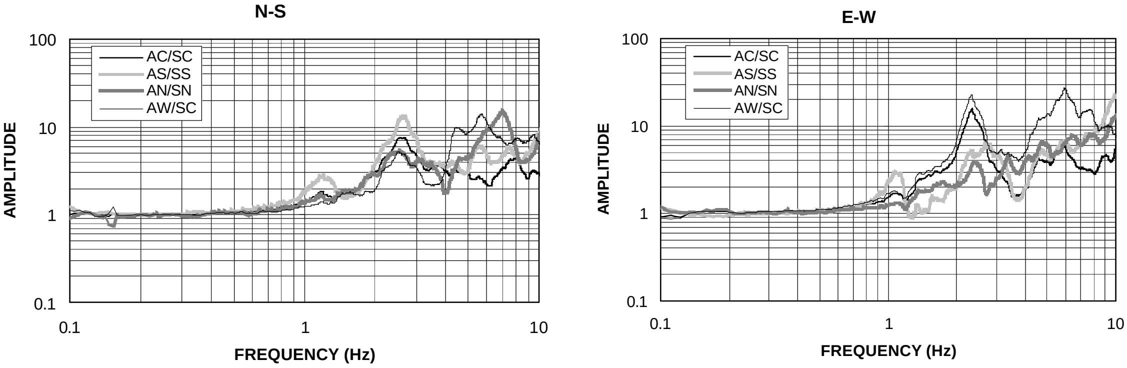

Figure 8. Transfer functions of spectral amplitudes of the four points on the roof with respect to the basement

Significant differences exist among the amplitudes of the motion at the four points on the roof. In general terms, they are due to the large cracks crossing almost completely the roof in the longitudinal and transverse directions. The main difference is the amplification of the motion at the south end of the roof, over the façade, at a frequency of about 6 Hz, due to the vibration of the two tall and heavy bell towers which move together with the main façade, partially, separated from the rest of the building by a great transverse crack. The west side of the roof also shows important amplification (E-W), due to out-of-plane vibration of the longitudinal façade, also separated from the rest of the building by a large crack crossing almost entirely vaults and foundation.

Transfer functions of spectral ordinates of the vertical motion at the center of the roof with respect to the other three points on the roof, are shown in Fig. 9, as an average for three events. The peak at 6.5 Hz indicates a local vertical vibration due to the motion of the heavy central dome supported by the four leaning central columns. This same frequency has been obtained for the mode of vertical vibration of the dome, from the analysis of a finite element model of the whole building.

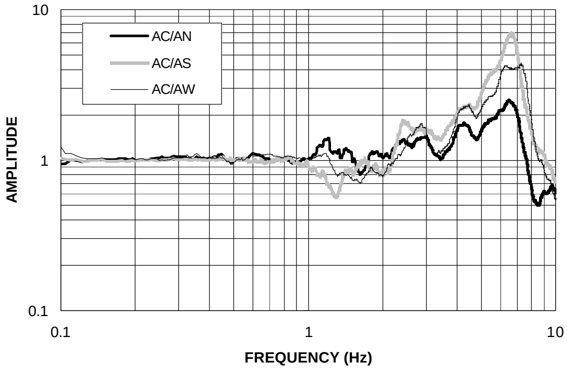

Figure 9. Transfer functions of spectral amplitudes of vertical motion at roof center with respect to other points of the roof. Average for events E1, E2, E3.

3.4 Motion of the bell tower

Acceleration time histories recorded at the basement, roof end top levels of the southwest bell tower for event E4 are shown in Fig. 10. Maximum acceleration a the top is 7.5 times greater than that at the basement, while this ratio for the roof level is about two. From the spectral transfer functions (Fig. 11) , fundamental modes of vibration of the tower are found to be at 1.25 and 1.15 Hz, for N-S and E-W, respectively. A second peak of the transfer function corresponds to the first mode of vibration of the building as a whole (about 2.5 Hz), and a third peak to the second mode of the tower (4.5 and 7.5 Hz in N-S and E-W, respectively) A two degrees of freedom spring model was analysed in order to identify the mass and stiffness required to match recorded response. Properties identified in this way approximately correspond to those of a system composed by the tower itself plus one half of the main façade, suggesting that both towers vibrate with the façade, as a structure almost independent from the rest of the building. The large amplification from the top to the roof levels of the tower reveals an appendix-like vibration, due to the high flexibility of the upper part of the tower.

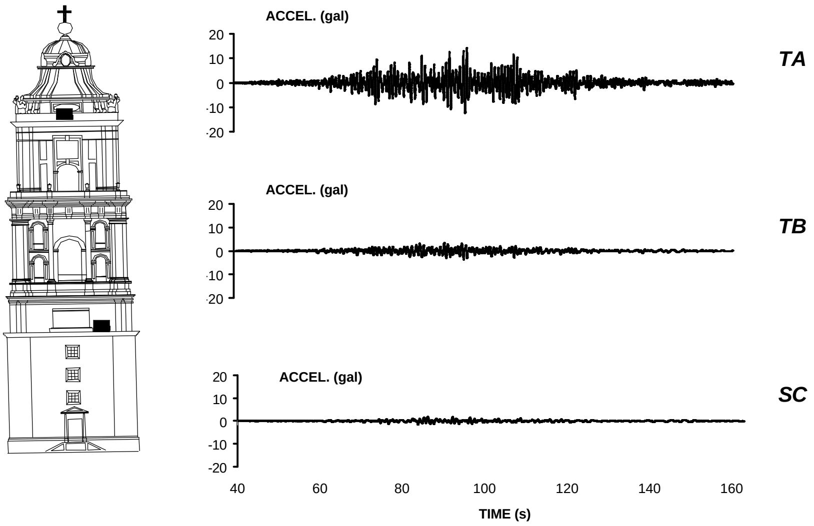

Figure 10. Response of SW tower at different heights, Event E4.

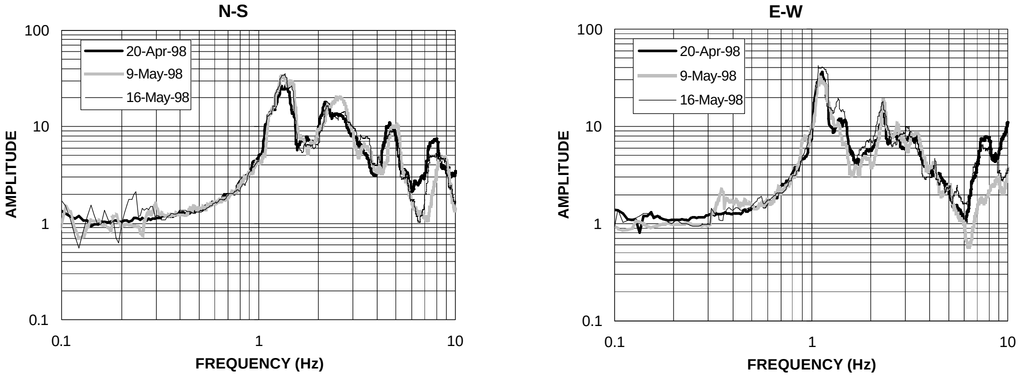

Figure 11. Transfer function of spectral amplitudes at the top of bell tower (TA) with respect to basement (SC)

4. CONSIDERATIONS ON THE SEISMIC SAFETY OF THE CATHEDRAL

Motion induced by the 16 seismic events recorded by the network corresponds to earthquakes from small to moderate intensities. In order to estimate the building response to the maximum intensities the building should be able to withstand, first the expected ground motion at the basement, and then the building response to this motion should be evaluated.

Reasonably accurate estimations of the ground motion at the site and the basement for great earthquake intensities are feasible, because it has been demonstrated that the behaviour of the soil layers remains linear elastic for a very wide range of wave amplitudes. Therefore, an estimation can be based on the measurements at a station (CU) in another part of the city where not only records of the same events measured by the network at the Cathedral are available, but also those of the great earthquake of September 19, 1985 which has been considered as a reference for a so called “design earthquake”.

Ground motion that should have occurred at the Cathedral site in the 1985 earthquake could be estimated by multiplying the ordinates of the spectra obtained at CU by the ordinates of the transfer function between the spectra at the two stations, obtained from the E1 event. A great number of records obtained in different sites throughout the city show that such transfer functions remain rather stable for a wide range of seismic intensities (Reinoso et al. 1999).

Acceleration response spectrum computed in this fashion for the basement of the Cathedral is shown in Fig. 12, along with the response spectrum corresponding to the most severe ground motion recorded in 1985 in the area of soft soil of Mexico City (SCT). As it can be seen, the response spectrum for the Cathedral has drastically smaller ordinates than that at SCT. Specifically, for a period of 0.4 s corresponding to the fundamental mode of vibration of the Cathedral, the spectral ordinate is 53 gal for the Cathedral and 235 gal for SCT, where the maximum ordinate for a period of 2.0 s is about 1000 gal. Again, this large reduction explains the good seismic performance of the monument.

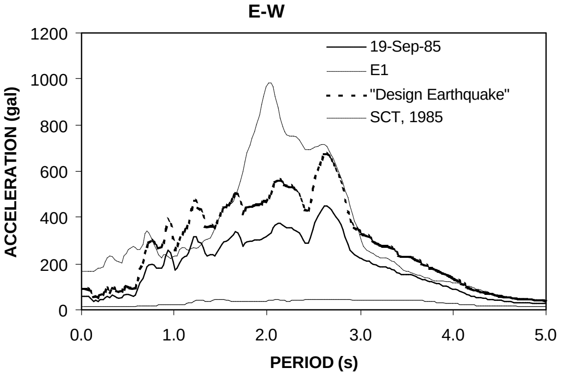

Figure 12. Comparison of acceleration response spectra

Present seismic design criteria for Mexico City require that buildings of great importance, as the Cathedral, be able to withstand an earthquake 50 % more intense than that of 1985; accordingly, a “design spectrum” for the Cathedral could be obtained by increasing 1.5 times the ordinates of the one previously estimated for 1985.

Regarding the estimation of the building response, it must be considered, first, that the main indices of measured response remained rather stable within the wide range of seismic intensities of the 16 events recorded; therefore an attempt could be made to extrapolate results to much greater intensities; nevertheless, they could be considered only as rough estimates, because it must be recognized that important changes should occur of the basic parameters of the response due to the additional cracking expected under very large intensities.

Expected response for the design earthquake could be estimated by multiplying those derived from the records of event E1 by the ratio between ordinates of the two response spectra corresponding to the period of the mode of vibration governing that response. For instance, the maximum horizontal displacement at the top of the columns supporting the central dome, derived from the motion of the roof for event E1 was l.7 mm; the ratio of spectral ordinates of the design and the E1 earthquakes, for the fundamental period of the roof vibration (0.4 s) is 5.5, therefore an horizontal relative displacement of 9.5 mm could be expected for the design earthquake. Estimated responses are in all cases rather small, and even if actual values could be significantly increased by stiffness softening of the structure under higher levels of solicitations, they should remain amply smaller than those the structure has suffered due to differential settlements, and should not impair the structural safety.

5. CONCLUDING REMARKS

The seismic network installed at the Cathedral could be considered very successful, in terms of the number and quality of records gathered in a limited time span. From the several conclusions derived from the study the following could be pointed out.

A favourable interaction between the structure and the soil reduces to less than one half the amplitudes of the seismic waves for frequencies that are critical to the structure. Moreover, these frequencies are very far from the predominant frequencies of seismic waves at the site. Both factors explain the good performance of historical masonry buildings on the soft soil of Mexico City.

The building as a whole vibrates essentially as a rigid body, the roof showing only a 17 % amplification of the acceleration at its basis. Nevertheless, some parts of the structure show local vibrations that could be harmful to the structure. Front and lateral façades have significant out-of-plane vibrations. Central dome has an important vertical vibration inducing vertical forces on the drum and on the supporting arches. The upper part of the bell towers shows a significant amplification of lateral displacement.

Even if more significant non-linear structural response is expected under stronger earthquakes than on recorded events, approximated extrapolations could be made for seismic intensities similar to those expected for a “design earthquake”. It could be concluded that displacements and stresses will still lay within limits corresponding to reasonable performance, except maybe for the safety of the bell towers.

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