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DYNAMIC TESTS OF A REINFORCED CONCRETE BUILDING SUBJECTED TO FORCED VIBRATION

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ABSTRACT

This paper presents results of dynamic tests conducted on a four-story reinforced concrete building. Responses of the building to ambient and forced vibration were used to study the application of identification techniques and the torsional response. Using an identification technique that only uses response signals, it was possible to identify some of the most important building frequencies and modal shapes. Results of the torsional response corroborate the importance of the excitation frequency contents on the torsional response of the building.

Introduction

It is well known that, in general, three types of dynamic tests on structures can be conducted: free vibration, ambient vibration, and forced vibration (actually ambient vibration is a singular type of forced vibration but it is not usually considered as such). In the last type, the structure can be excited with either mechanical exciters or actual earthquakes. Previous studies on building testing include those carried out by Trifunac (1972), Foutch et al. (1975), Foutch (1978), and Yu et al. (2006). Real-scale building tests with mechanical exciters are useful to determine structural dynamical properties. These tests can also be used to improve the definition of analytical models for buildings as well as for the assessment of identification techniques and building code recommendations. There are some reasons, however, that preclude a wider use of dynamic tests with force vibration generators. For instance, the low force capacity of these exciters limits its use to small structural responses. Also, the type of excitation generated by these devices is constrained to harmonic forces, limiting its application for the simulation of narrow-band excitations such as those caused by earthquakes in soft soils.

The tests reported in this study were focused to both 1) the identification of the dynamic properties of the building (frequencies, modal shapes and damping) for two types of excitation (ambient vibration and forced vibration) and 2) the assessment of the frequency content of the excitation force on the torsional response of the building.

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Building Description

The four-story reinforced concrete building is located on firm soil in the city of Toluca, the capital of the central state of México. The building was designed for offices of the federal government transportation department. The structure consists of orthogonal frames with rectangular columns separated at 6 m each and story heights equal to 4 m. The structure is only the right portion shown in the right picture of Fig.1. Along one direction the building has 4 bays in the lower two stories, three in the third story and only two in the upper one. Along the perpendicular direction, it has three bays in all stories as seen in the left picture of Fig. 1. Floors consist of a 300 mm-thick waffle slabs supported by beams. The foundation is a solid 300 mm-thick slab with beams along the frames. The structure was tested without non-structural elements such as separation walls, windows, doors, ceilings, installations, etc. Moreover, the structure did have neither stairs nor slab openings.

Figure 1. Studied building structure.

Force Generator and Measuring Devices

In addition to the ambient vibration tests, the structure was dynamically excited with a mechanical force generator (shaker or exciter). It is known that this simple device uses two equal eccentric weights rotating at opposite directions to generate a force with magnitude *P* given by the following Eq. 1

$$P = 2\ m\ r\ \Omega^2 \sin(\Omega\ t) = 2\ (Wr/g)\ \Omega^2 \sin(\Omega\ t) \tag{1}$$

where m is the mass of each rotating weight W, r is its eccentricity, Ω is the rotation frequency of both masses, g is the gravity acceleration, and t is the time. The exciter used in the tests is shown in Fig. 2 and can reach force magnitudes P close to 3 ton for an operation frequency Ω equal to 3 Hz. As for the measurement equipment, the characteristics of both accelerometers and recorders are summarized in Table 1.

Table 1. Description of the equipment used for measurements.

Equipment	Brand	Model	Characteristics
4 Accelerometers	*Kinemetrics®*	*EpiSensor®* / FBA ES-U2	Uniaxial
3 Accelerometers	*Kinemetrics®*	FBA-11	Uniaxial
Digital recorder	*Kinemetrics®*	SSR-1	6 channels
Digital recorder	*Kinemetrics®*	*Altus/K2®*	6 channels
Accelerograph	*Kinemetrics®*	*Altus/Etna®*	Triaxial

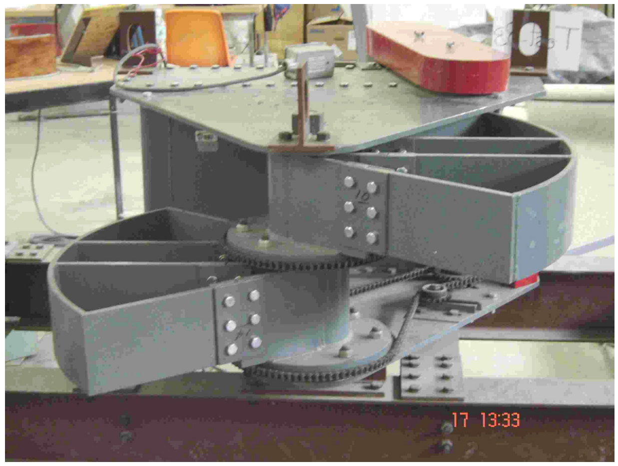


Figure 2. Eccentric-masses force generator.

Description of Tests

The force generator was placed at two positions of the building roof (shaded area), as indicated in Fig. 3. Position A is located at the geometrical center of the roof, while position B is 2 m eccentric. Configurations of masses were set to obtain force resultants along three directions: north-south (N-S), east-west (E-W), and northeast-southwest. In this work, however, only the directions N-S and E-W were considered.

As for the location of the measuring devices, all accelerometers were placed along the axis A (west facade). Four schemes of accelerometers at this axis were used for testing, as indicated in Fig. 4. For both locations (A and B) (and for each direction of the force resultant), six frequencies of the force generator were used (Ω = 1.5, 3.0, 3.5, 4.0, 4.5, and 5.0 Hz); however, in all cases the rotating masses were constant with $W \cdot r$ = 2,301.1 kg-cm (Eq. 1).

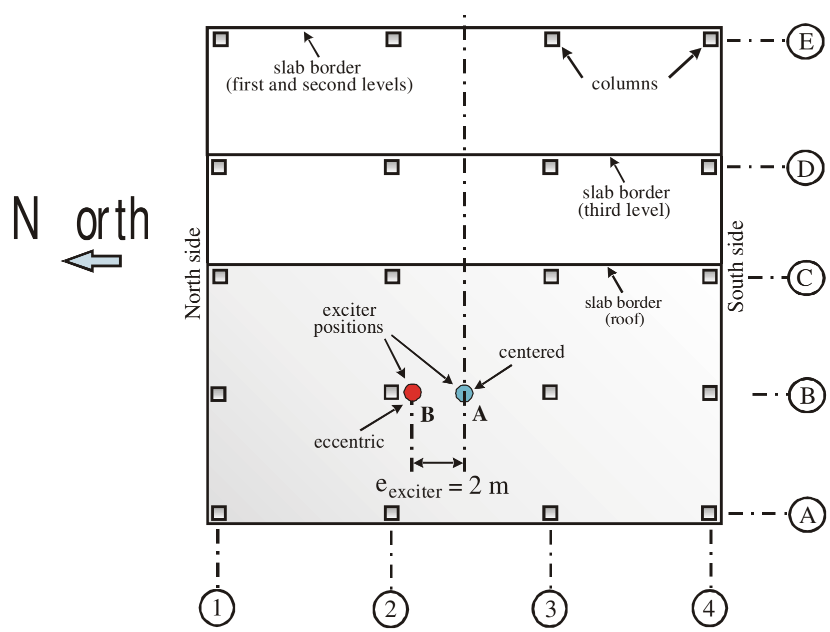


Figure 3. Plan view of the structure showing the testing positions of the exciter.

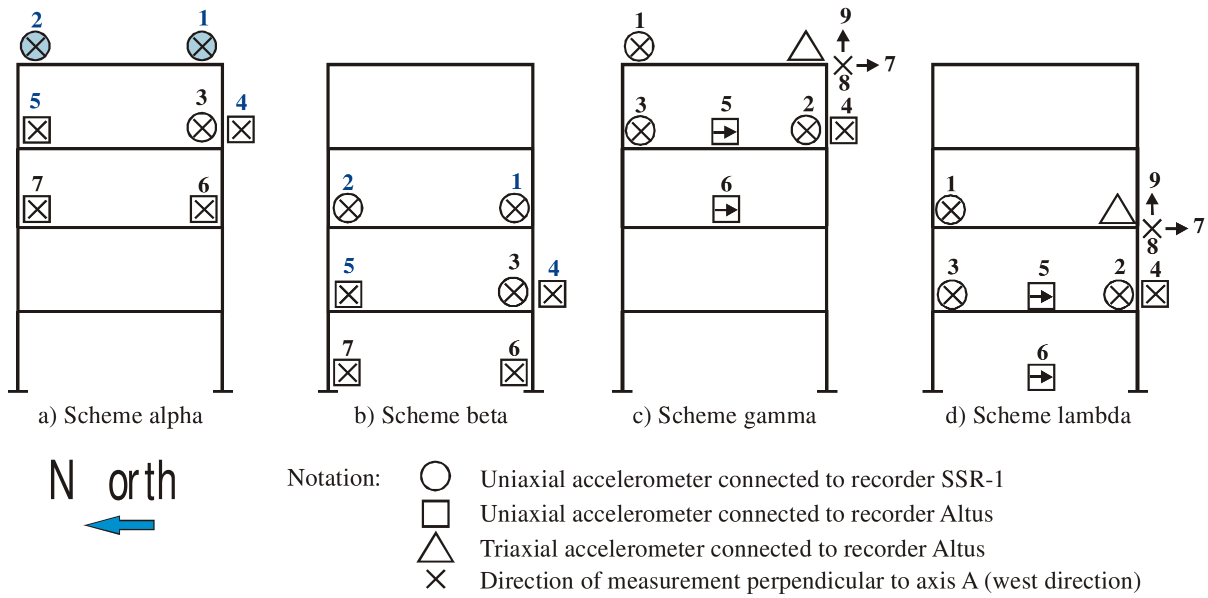


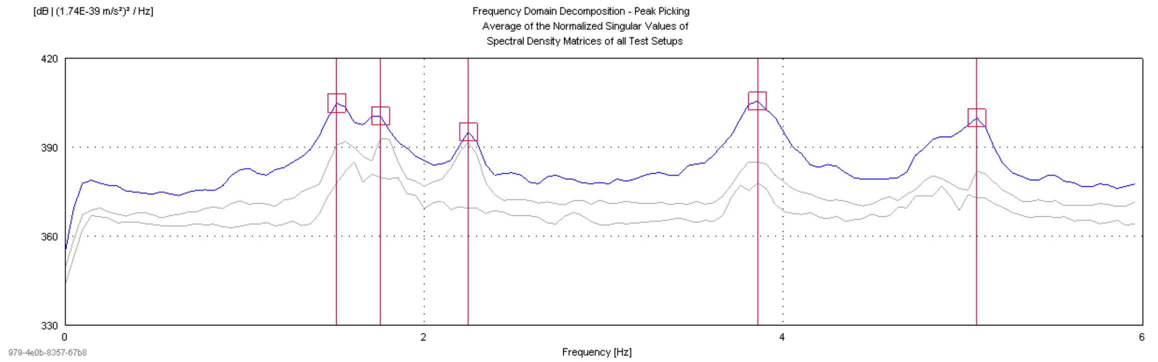
Figure 4. Schemes of locations for accelerometers.

Identification of the Building Dynamic Properties

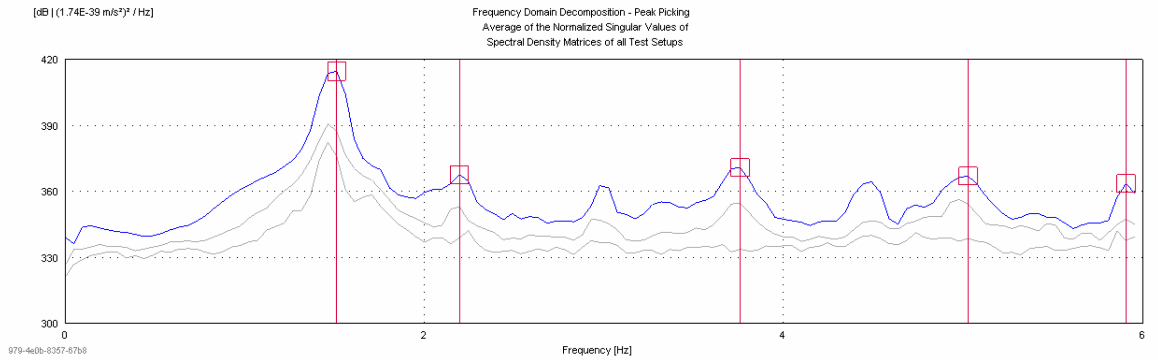
Among the techniques for nonparametric identification, there is one that theoretically can be used for this particular case wherein the signal of the generated force is unknown. It is based on the coherence $\gamma(f)$ between two signals, where f is the frequency. Although initially depicted as the coherence between an input signal (excitation) and an output signal (response), it is possible to use this scalar function with two output signals. According to Paultre et al. (1995), who applied this technique for the identification of dynamic properties of bridges, good estimation of natural frequencies is obtained when a reference accelerometer is chosen (instead of the input signal) at a location where motion is most likely to occur for the first few modes. It is known that $\gamma(f)$ varies between 0 and 1, and that a high value of it suggests a linear relationship between input and output signals. Therefore, natural frequencies could be identified at those values of f with a high coherence value. This technique was initially applied taking into account the recommendation by Paultre et al. (1995); however, it was difficult to identify the first few frequencies satisfactorily for the forced vibration tests.

There are some other available techniques for estimating structural dynamic properties that use the structure response records for a specific excitation. For this paper, a frequency domain decomposition technique was used. It estimates the structure dynamic properties with the average of the normalized singular values of the spectral density matrices for different response records (ARTeMIS Extractor, Release 4.0, package software).

This technique was applied using separately four different tests. One with ambient vibration, and the other three with forced vibration at two frequencies (Ω=1.5 Hz y Ω=4.5 Hz), two exciter location (points A and B) and two excitation directions (N-S and E-W). Each one of these four tests was composed of three different sets of response records that have in common only one register point (translation along E-W direction of the second floor). Three degrees of freedom were considered for each floor (two translations along E-W and N-S directions and the floor rotation multiplied by the distance between the center of mass and the corner of the fourth floor (RL for Fig. 7)). For each floor, the degrees of freedom were concentrated at the plan projection of the roof center of mass (point A of Fig. 3). Figure 5 shows plots of the average normalized singular values of the spectral density matrices for each test. The identified modal frequencies are indicated in the corresponding plot with square marks.



a) Test 1 (ambient vibration).



b) Test 2 (Forced vibration, Ω = 1.5 Hz, excitation along the E-W direction, position B)

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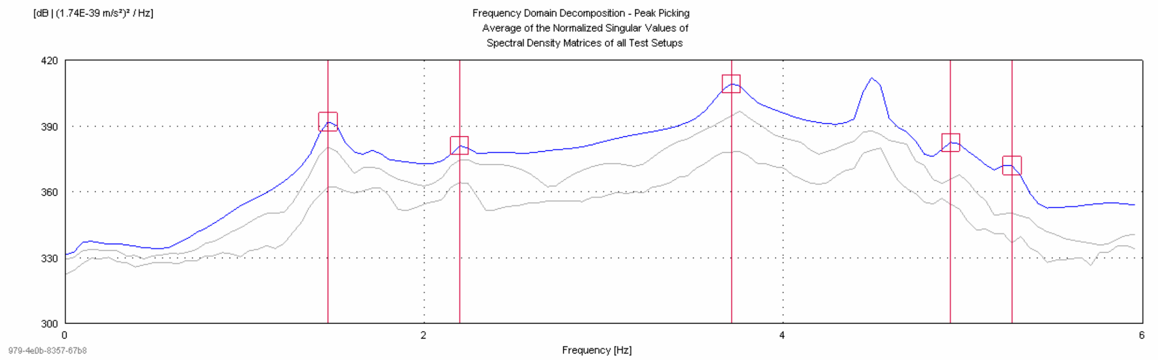
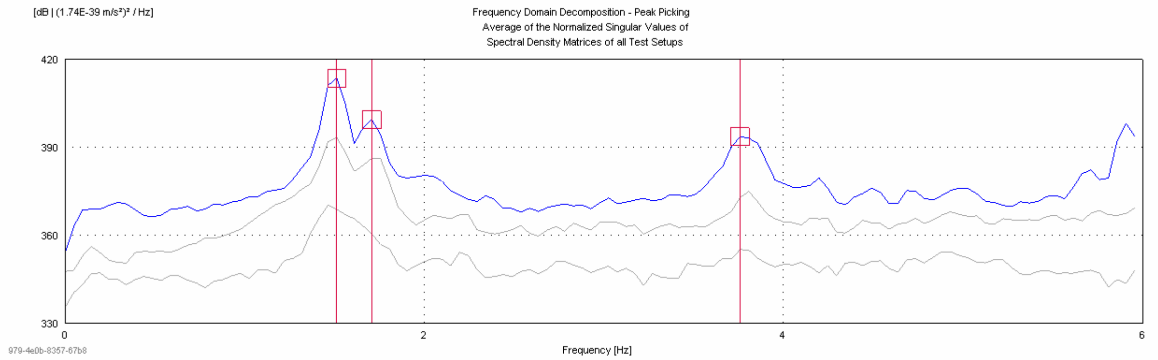


c) Test 3 (Forced vibration, Ω = 4.5 Hz, excitation along the E-W direction, position B).



d) Test 4 (Forced vibration, Ω = 1.5 Hz, excitation along the N-S direction, position A).

Figure 5. Average normalized singular values of the spectral density matrices.

As a frame of reference, a three-dimensional finite element model of the building was done with the properties (geometry, materials, etc.) of the nominal building design. The only special consideration was to assume live load equal to zero, because that was the actual condition during tests. The analytical model was calibrated so that its first frequency was set equal to the first frequency obtained from the ambient vibration test. The calibration was achieved by increasing the elasticity modulus about 20%. The first six modes obtained with the analytical model (shapes and frequencies) are illustrated in Fig. 6.

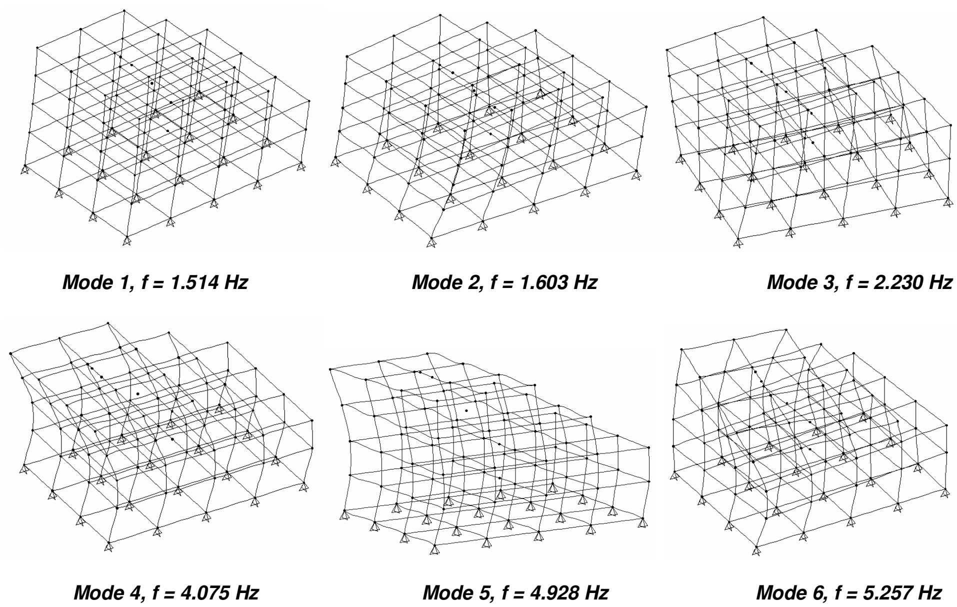


Figure 6. Natural frequencies and modal shapes computed with a finite element building model.

Table 2 shows the first six identified modal frequencies for the four tests and for the analytical model. None of the four tests conducted to the identification of the first six frequencies. Each one of tests 1 and 3 permitted to identify five frequencies, test 2 identified four frequencies and the test 4 identified three frequencies only. It is interesting to observe that tests 2 and 3 (forced vibration along E-W) could not identify the second frequency associated to the translation along the N-S direction. Test 4 (with force along the N-S direction) identified correctly frequencies 1 and 2 related to the translation along N-S and E-W directions, respectively. Test 2 identified three frequencies (2.979 Hz, 4.492 Hz and 5.908 Hz) that are not structural frequencies (see Fig. 5b). The identification of these non-structural frequencies shows that the used method can be influenced by the excitation frequencies. Moreover, this technique also identified the harmonics of the excitation frequency ($n \times \Omega$, n = 1,2,3,…). Similarly, test 3 (Fig. 5c) identified the frequency of the excitation (Ω = 4.492 Hz) as a structural frequency. In general, it is observed the necessity of taking into account the results of the different tests (ambient vibration and forced vibration) to identify the most of the structural modes. It is also important to combine the experimental results with the analytical results to identify the actual structural modes from the excitation frequencies.

Table 3 shows the absolute values of the differences between the analytical frequencies with those obtained from tests 1 and 3. Because the identified frequencies with one test does not necessarily correspond to the same number of modal frequency obtained with either other test or the analytical model, the computed differences shown in this table could be mixed among modes.

Table 2. Identified frequencies (in Hz) with ambient vibration, forced vibration, and analytically.

Test 1: Ambient vibration	Test 2: Forced vibration Ω=1.5 Hz (E-W, position B)	Test 3: Forced vibration Ω=4.5 Hz (E-W, position B)	Test 4: Forced vibration Ω=1.5 Hz (N-S, position A)	Analytical model
1.514	1.514	1.465	1.514	1.514
1.758	Not identified	Not identified	1.709	1.603
2.246	2.197	2.197	Not identified	2.230
3.857	3.760	3.711	3.76	4.075
5.078	5.029	4.932	Not identified	4.928
Not identified	Not identified	5.273	Not identified	5.257

Table 3. Absolute values (in %) of the differences between the analytical and experimental results.

Test	*f* = 1.514 Hz	*f* = 1.603 Hz	*f* = 2.230 Hz	*f* = 4.075 Hz	*f* = 4.928 Hz	*f* = 5.257 Hz
1	0.00	9.66	0.71	5.34	3.04	-
3	2.98	-	1.47	8.93	0.08	0.30

Some modal shapes obtained from ambient vibration tests are shown in Fig. 7. For the identified mode with *f* = 1.514 Hz the translation along the E-W direction governs the response. The translational response along the perpendicular direction is associated to the mode with *f* = 1.758 Hz; however, this modal shape was not identified due to the arrangements of sensors (and therefore is not shown in the Fig. 7). It is clear that for the mode with *f* = 2.246 Hz, torsion governs the response at most floors; while for the mode with *f* = 5.078 Hz, torsion governs only at the first floor.

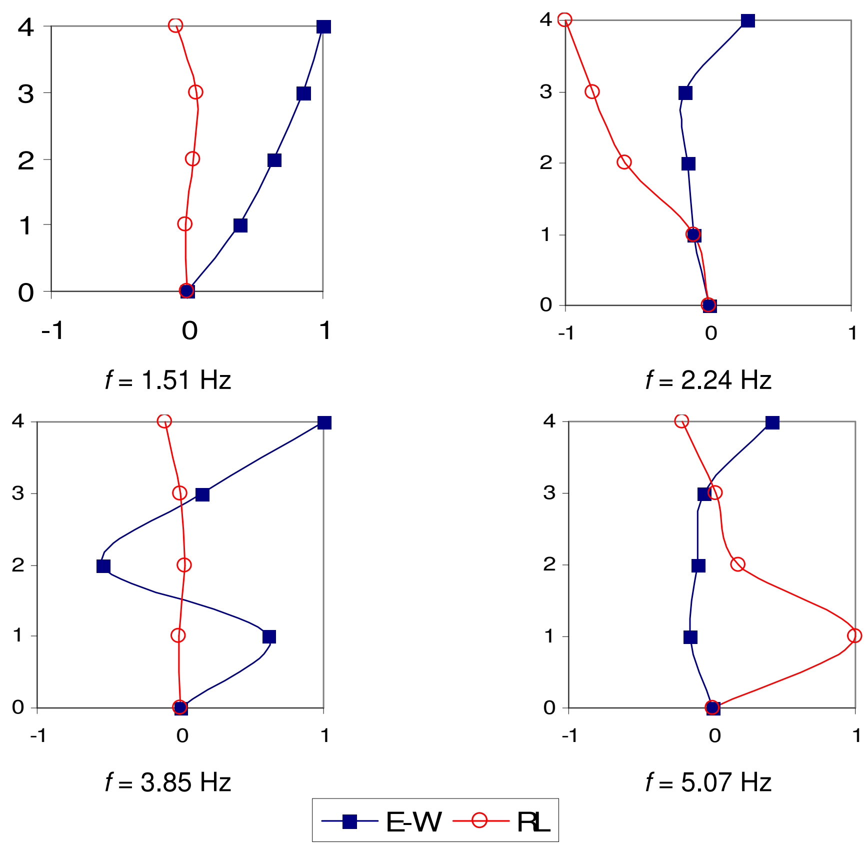


Figure 7. Modal shapes obtained from the ambient vibration test.

Building damping, in terms of the damping ratio ξ, was estimated with the logarithmic decrement method (Clough and Penzien 1993) applied to the acceleration records obtained from the free vibration response after the exciter was turned off. The average value of damping resulted to be close to 1.0%. This small value is justified by both the elastic behavior and the lack of non-structural elements during the tests.

Building Torsional Response

Some tests results are presented to show some aspects of the building torsional response. By brevity, only results at the exciter operation frequencies Ω = 1.5 and 4.5 Hz are shown. Results of accelerometers 1, 2, 4 and 5 of schemes alpha and beta were processed (Fig. 4), however only records 1 and 2 of scheme alpha (blue circles in Fig. 4) are presented. The selection of these schemes, which correspond to accelerations along the east-west (E-W) direction measured at frame A (Fig. 3), is because the pairs of records required for computing the slab rotations of a given level are connected to a common recorder. This selection is important for the synchronization of signals. To avoid errors caused by a double integration (and filtering), results are not given in terms of displacements, but only in terms of accelerations, which were both filtered (band pass filter) and baseline corrected.

As an initial step to verify that the structure did not have significant accidental eccentricities, the force generator was placed in the position A (Fig. 3) with the force acting along the east-west direction. Roof accelerations at south and north sides are shown in Fig. 8 for two exciter frequencies (Ω = 1.5 and 4.5 Hz). North and south side accelerations (along the east-west direction) are shown in the left and right side of the figure, respectively. These records show that the structure did not have any eccentricities. Notice also that the shape of the records changes with the excitation frequency. For Ω = 1.5 Hz the peak acceleration occurs at the initial part of the record, while for Ω = 4.5 Hz the peak occurs at the final part.

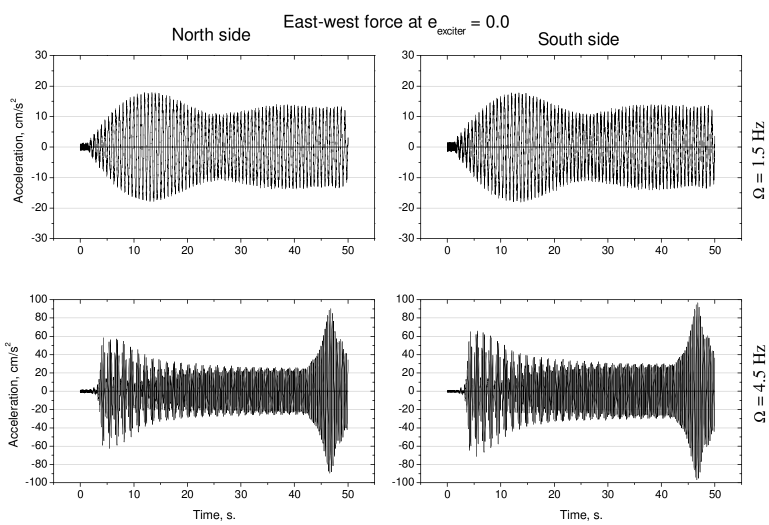


Figure 8. Roof accelerations along east-west direction (exciter at A and force along E-W direction).

The rotational accelerations of the roof around a vertical axis (torsional accelerations) are preferred to study torsion because the signals of Fig. 8 can have time shift. In that case, even for similar signal shapes, torsion would be present. The differences of accelerations between both sides of the roof slab, taken here as a measure of the building torsion, are shown in Fig. 9. Moreover, acceleration differences for Ω = 4.5 Hz were divided by 9.0 = $(4.5/1.5)^2$ to obtain amplitudes comparable to those for Ω = 1.5 Hz. This normalization permits to appreciate the effect of the excitation frequency on the torsional response, by eliminating the effect of the excitation force amplitude (see Eq. 1). Notice that peak values of these small normalized acceleration differences are close to 1.0 cm/s^2 for both excitation frequencies.

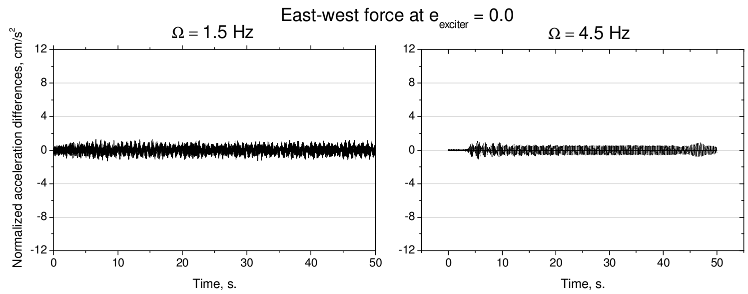


Figure 9. Roof normalized acceleration differences (exciter at A and force along E-W direction).

When the force generator is located with an eccentricity = 2 m (position B in Fig. 3) with the force acting along the east-west direction again, the normalized acceleration differences obtained are those shown in Fig. 10. For this eccentric position of the exciter, the normalized acceleration differences are significantly larger than those for the exciter at position A. Moreover, it can be observed that the torsional response for Ω = 4.5 Hz is about 3.0 times larger than that obtained for Ω = 1.5 Hz. This larger response for Ω = 4.5 Hz is due to the nearness of the force generator frequency (working at Ω = 4.5 Hz) with that estimated for a torsional mode (f = 5.257 Hz for mode 6 in Fig. 6).

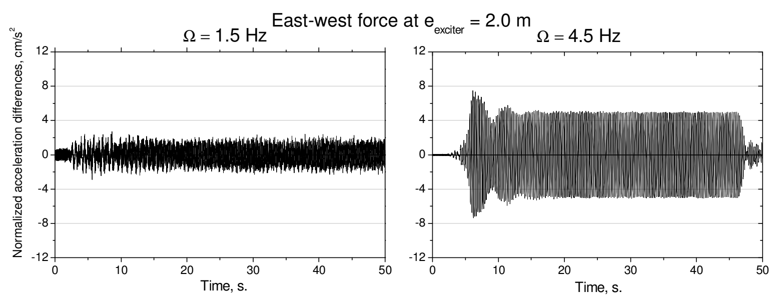


Figure 10. Roof normalized acceleration differences (exciter at B and force along E-W direction).

When the exciter is located at A, but with the force resultant acting along the N-S direction, the normalized acceleration differences result as shown in Fig. 11. As expected, the setbacks of the upper stories induce torsion in the structure when the force resultant has a component along the north-south direction. Again, the torsional response for an exciter frequency Ω = 4.5 Hz resulted to be larger than that for Ω = 1.5 Hz.

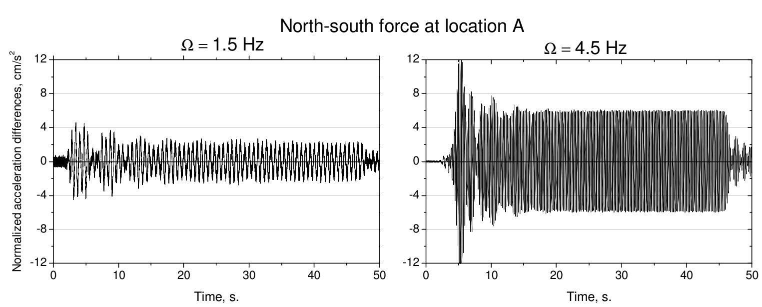


Figure 11. Roof normalized acceleration differences (exciter at A and force along N-S direction).

Conclusions

An analysis of the rotational accelerations corroborated that the magnitude of the torsional response not only depends on both the shear lateral force magnitude and the structural eccentricity but also on the frequency content of the excitation.

The identification technique based on the coherence between response (output) signals gave good results for the ambient vibration test. However, for forced vibration tests, this technique only identified some modes.

The frequency domain decomposition technique based on the average of the normalized singular values of the spectral density matrices for different response records showed some contamination caused by the excitation frequency. Therefore, it is recommended to use this technique in combination with an analytical model.

As for the instrumentation schemes based on a limited number of synchronized channels, it was observed the necessity of maintaining at least one record point for all tests and for all instrumentation schemes.

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