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Changes in the Dynamic Properties of an Experimental Building by Ambient Vibration and Forced Vibration Analysis

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Abstract: In this paper, ambient and forced vibration records are analyzed to determine the dynamic properties (mode shapes and characteristic frequencies) of a five-story experimental building constructed at full scale within the Charles Lee Powell Laboratory at the University of California, San Diego (UCSD). This was the first full-scale building, built in 1992, to perform seismic resistance testing in the United States. Vibration records were obtained during the three stages of the building's physical conditions: a newly constructed building, a damaged building with simulated seismic loading, and a repaired building. Both ambient and forced vibration analysis results show changes in its dynamic properties due to stiffness degradation in the damaged building and stiffness recovery in the repaired building.

Key words: experimental building; Charles Lee Powell laboratory; ambient vibration; forced vibration; modal forms; characteristic frequencies

1. Introduction

In 1992, the first full-scale seismic resistance testing facility in the United States was built. The project was funded by the National Science Foundation (NSF), the Department of Energy, the concrete industry, specifically the Masonry Association of California and Nevada, and the Masonry Institute of America. The five-story experimental facility was constructed within the Charles Lee Powell Laboratory at UCSD. The Applied Engineering Seismology group of the CICESE Department of Seismology participated collaboratively in this project at the invitation of Dr. J. Enrique Luco, a professor at UCSD. CICESE provided seismic instrumentation during the seismic resistance tests, with the goal of studying changes in the building's dynamic properties through vibration analysis. The results presented in this work consist of the identification of characteristic frequencies and mode shapes of the experimental building, employing classical methods of spectral analysis and transfer functions (admittance, coherence, and phase shift) between the different faces and levels of the building in its three stages: undamaged building, referring to the newly constructed building; damaged building, referring to the building damaged by means of a seismic load simulation using a system of lateral loads applied with ten servo-controlled hydraulic actuators; and repaired building, using repair techniques for concrete block buildings. This set of observations, both ambient vibration and forced vibration, has been used for educational purposes and, typical of a good set of observations, its educational value has increased over the years. Therefore, this work is presented in commemoration of the 35th anniversary of the Center for Seismic Instrumentation and Recording, A.C. (CIRES), to illustrate how these types of seismic instrumentation and recording experiments, contemporary to the creation of CIRES, as well as classical spectral analysis methods, have prevailed over the years to identify the modal shapes of a building and, where appropriate, to interpret changes in its modal shapes (e.g., De-la-Colina and Valdés-González, 2021; Pepi et al., 2021; Motamedi et al., 2021; Khanmohammadi et al., 2021; Chakra-Varthy and Basu, 2021; Inci et al., 2021; Souici et al., 2021; Casas-Guzik, 2019; Henao et al., 2014).

2. Background

2.1 Building undamaged

The building (Figures 1 and 2) is made of rebar-reinforced concrete block, as shown in Figure 1. The levels refer to the base of each wall, starting with level 0 at the base and ending with level 5 at the roof. Level 0, or the base, is made of reinforced concrete, and below it is the floor of the Charles Lee Powell Structural Systems laboratory at UCSD.

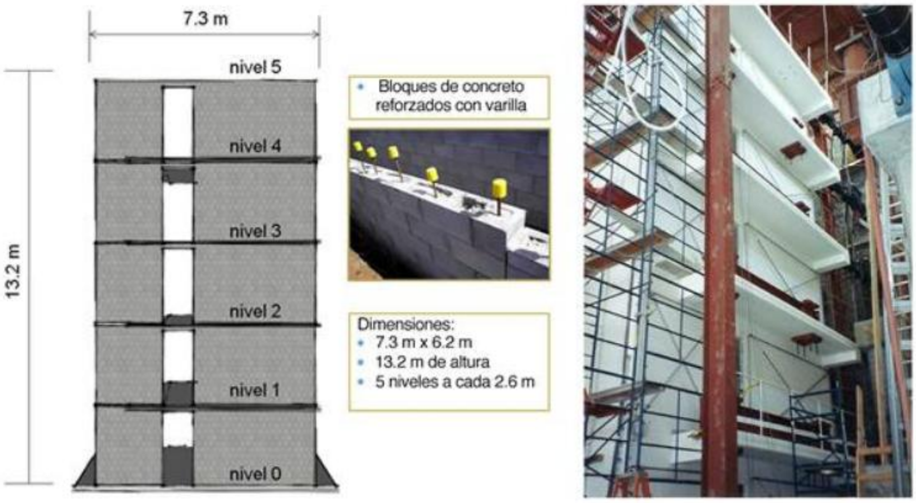

Figure 1. Front facade (east face) and building dimensions. In the background of the building photograph, a reaction wall with hydraulic actuators is visible, applying forces along the east face on each of the levels from 1 to 5. Photograph: Luis H. Mendoza 1992.

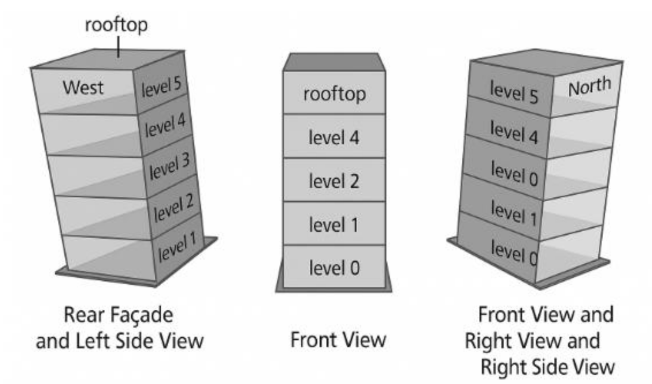

Figure 2. Front, rear, and side views of the building

The north face of the building was built parallel to a reaction wall, which supports a set of hydraulic actuators to apply loads to the building at each floor or level. The reaction wall and the distribution of the hydraulic actuators are shown in Figure 3. Note that the west face has no wall at any level because the building is merely a module, or subsection, of a symmetrical box-type structure formed by vertical and horizontal panels connected to provide continuity, as schematically illustrated in Figure 4.

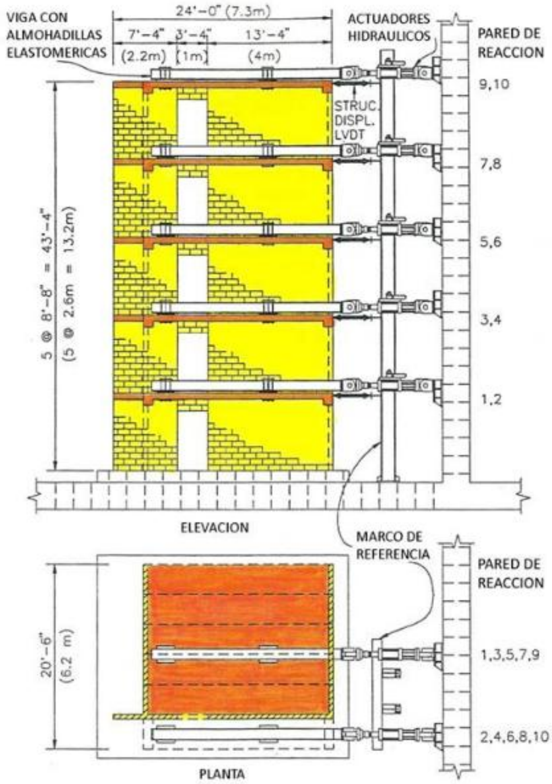

Figure 3. Reaction wall and hydraulic actuator distribution on the north side of the building. Figure modified from Seible et al. (1994). The numbers along the reaction wall refer to the corresponding hydraulic actuator number.

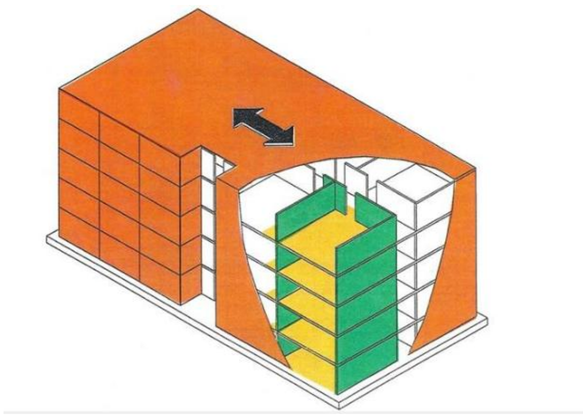

Figure 4. Building as part of a typical symmetrical structure for a concrete block office or apartment building. The arrows on the building's roof indicate the direction of the simulated seismic load to damage the building with hydraulic actuators. Figure taken from Seible et al. (1994).

The building was created under the initiative of the United States - Technical Coordinating Committee for Masonry Research (U.S.-TCCMAR), with the objective of designing concrete block buildings in seismic zones, considering that, under the most severe seismic design requirements, a concrete block structure must:

1. Withstand a displacement of at least four times the maximum expected without deteriorating stiffness.

2. Dissipate seismic energy in its principal response modes through damping caused by its ductile structural components.

3. Inhibit fractures caused by shear stresses associated with the building's normal modes.

The reinforced concrete block building provided a unique experimental platform for investigating the structural seismic response of a building at the limit of its linear state.

The walls in the tension and compression directions with respect to the hydraulic actuator loads have different strength and stiffness characteristics due to differences in steel distribution. The steel framework is denser in the wall responding to compression (east face). The structure of these walls is schematically illustrated in Figure 5.

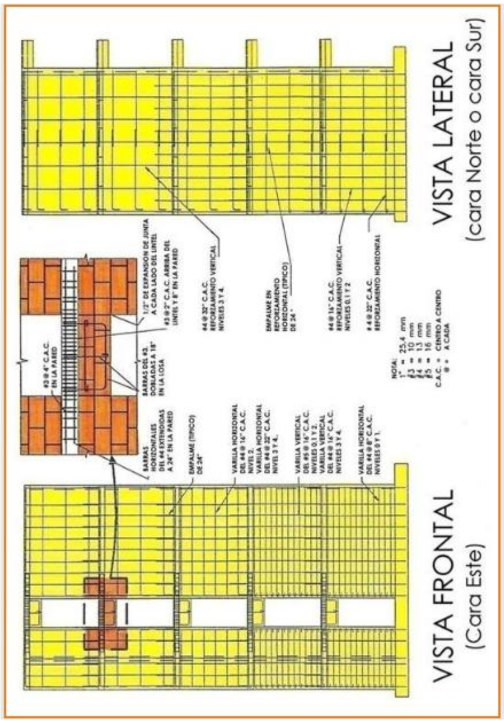

Figure 5. Structural reinforcement of the building walls. Figure modified from Seible et al., (1994).

The design standards used for the building correspond to those indicated by the National Earthquake Hazards Reduction Program Part I and II (NEHRP); FEMA, 1988a,b. These design standards constitute the most comprehensive design codes that the U.S.-TCCMAR required in 1992 for the design of the building.

Bond Beam concrete block, 6x8x16 inches or 150x200x400 mm, with a single opening, was used on all walls of the building, as shown in Figure 6.

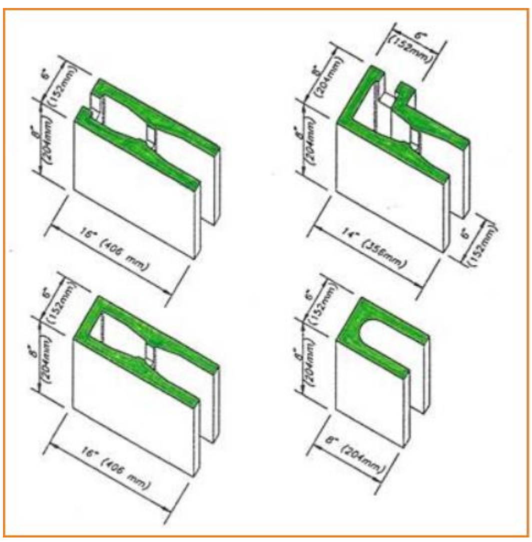

Figure 6. Concrete block units used in the building. Figure taken from Seible et al., (1994).

2.2 Building with damage

To damage the building, seismic loads were simulated using a system of lateral loads applied with ten servo-controlled hydraulic actuators; a pair of actuators at each level of the building, as shown in Figure 3.

The acceleration records from the historical earthquakes used to program the displacement of the hydraulic actuators with which the building was sequentially deformed until reaching the limit of its linear state were: the 1971 San Fernando earthquake (Magnitude Mw = 6.6), and the 1979 Imperial Valley earthquake (Mw = 6.8). Six segments of the acceleration records from the aforementioned events, obtained at different locations, were used and joined together to construct a synthetic seismogram that practically coincided with the UBC (Uniform Building Code; 1991) design spectrum, within a period range of 0.2 to 0.6 s, which is the expected range of the building's fundamental response.

Greater loads were introduced at the lower levels, considering that these levels naturally experience greater load concentrations. Lateral forces were distributed across the slab area at each level by rigid loading via two beams (W 18 × 97) at levels 1 through 5, connected to the slab by 12.7 mm (1/2 in) flexible elastomeric pads. The two beams provided uniform load distribution between the two loading points at each level. Force transfer between the slab and the elastomeric pads was accomplished by a frictional connection provided by four high-strength exterior bars, which held the load-bearing beam and slab together with a normal force of approximately 224 kN (50 kip) per pad or per support. An example of cracking in the building's walls and slabs resulting from loads induced by the hydraulic actuators is shown in Figure 7.

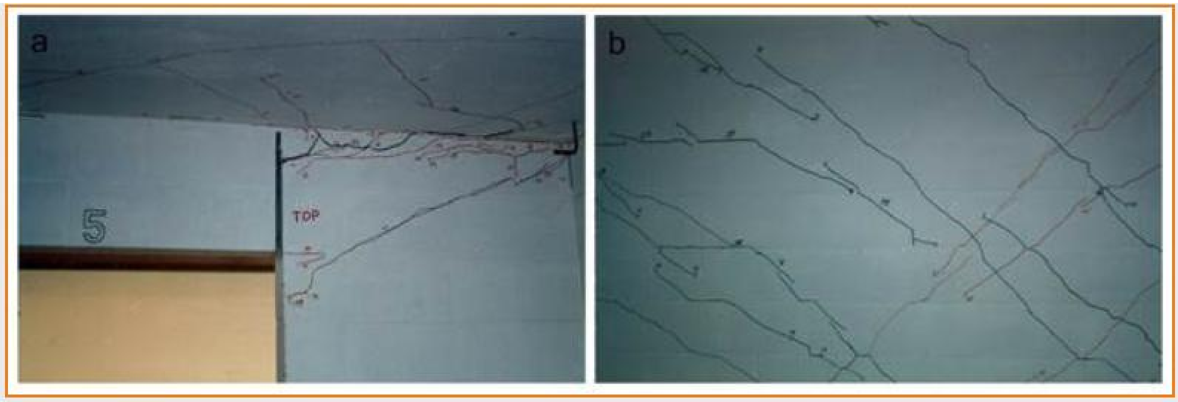

Figure 7. Cracks or fissures in the roof slab or level 5, and in the east wall of level 2. Compressive cracks are indicated in black, and tensile cracks are indicated in red. Photograph: Luis H. Mendoza, 1992.

To evaluate the effectiveness of repair techniques for these structures and adapt new methods to existing building codes, new repair techniques for concrete block buildings were implemented in the building. It is worth noting that the building was designed and constructed to absorb damage once a seismic load was applied, reinforcing the east wall, where the exit door is located, and the north and south faces are reinforced to a lesser extent, as shown in Figure 5. This type of reinforcement increases the building's deformation capacity by facilitating bending and reducing its shear stress.

The techniques used to repair the building were:

-Use of polymer-based concrete to patch the most affected cracked concrete areas, such as at the base of walls and door lintels.

-Injection of "epoxy resin" into the cracked joints between the floor slab and the base of the wall.

-Reconstruction and reinforcement at the base of the joints between the walls of level 0 of the building.

-Reinforcement of floor slabs to withstand shear stress using various methods: synthetic foam, sealants, and a structural mortar, "Silka Grout 212".

-Reinforcement of the lintels.

-Carbon fiber layers in the walls corresponding to the first two levels to cover the critically damaged walls in order to reduce shear deformation and increase wall rigidity.

The complete report of the experimental building, describing the structural details, as well as the controlled damage and repair techniques, can be found in: "The U.S.-TCCMAR Full-Scale Five-Story Masonry Research Building Test", in its V volumes (e.g., Seible et al., 1994; Weeks et al., 1994).

2.3 Instrumentation for recording building vibrations

The seismometers were installed in July 1992 in the undamaged building; in November 1992 in the damaged building; and in August 1993 in the repaired building. Vibration data were recorded with the Kinemetrics SSR-1 portable Solid State Recorder system using Mark L-4C velocity sensors (Figure 8). The recordings correspond to vibrations in the north-south, east-west, and vertical directions. The instruments were provided by the Applied Seismology for Engineering Laboratory of CICESE.

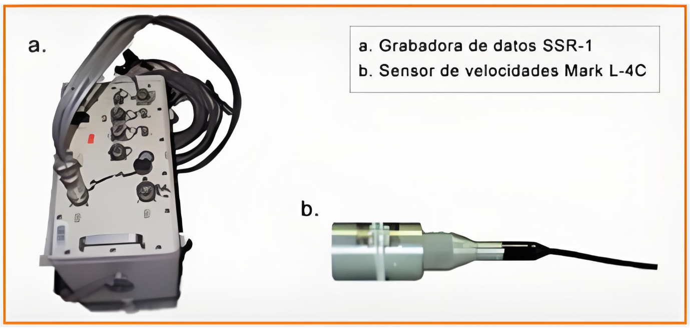

Figure 8. Instrumentation equipment used in the building

Four horizontal component sensors were placed on each of the five levels of the building; two in the north-south direction and two in the east-west direction, oriented along the walls. At the base or ground level of the building, in addition to the horizontal sensors, vertical sensors were placed at each of the four corners. The sensor locations are indicated in Figure 9. This same sensor location was used in the damaged and repaired buildings for both the ambient and forced vibration tests. For the forced vibration tests, a shaking table oscillating in the north-south direction was placed 8 m away from the southeast corner of the Charles Lee Powell Laboratory, as shown in the Appendix.

Figure 9. Location of the vertical and horizontal sensors in the experimental building.

2.4 Data acquisition

Thirty-seven ambient vibration tests, three forced vibration tests, and, incidentally, one earthquake record were obtained during the first stage or newly constructed building. The ML 3.2 magnitude earthquake was located 155 km from the Charles Lee Powell Laboratory southeast of Yucca Valley, California, occurring at a depth of 2.2 km at 02:17:59 UTC on July 12, 1992 (USGS catalog). Table 1 indicates the schedule of vibration observations. For redundancy, different data sets corresponding to the same experiment were obtained.

Table 1. Summary and schedule of vibration observations in the building

Building stage	Date	Test type	Test number	Number of	Number of	Total number
No damage	10/07/92	AV	6	20	4	24
	11/07/92	FV	1	20	4	24
	11/07/92	AV	2	20	4	24
	11/07/92	Earthquake	1	20	4	24
With damage	20/11/92	AV	7	18	--	18
	21/11/92	AV	5	18	--	18
	21/11/92	AV	5	14	4	18
	21/11/92	FV	1	18	--	18
	21/11/92	FV	1	14	4	18
Repaired	03/08/93	AV	6	18	3	21
	03/08/93	AV	6	17	4	21

Ambient Vibration: AV, Forced Vibration: FV.

The sampling interval for all ambient vibration and forced vibration recordings is 0.01 s and the duration of each recording is 150 s (2.5 min).

The frequencies at which the vibrating table oscillated in all forced vibration tests were selected from the results of the ambient vibration tests, observing the frequencies at which the building vibrated with the greatest amplitude. Specifically, 62 tests were required, one for each selected frequency, to complete a sweep in the vicinity of each of the selected frequencies, ranging from 1.9 Hz to 13.50 Hz.

One day before recording began, simultaneous ambient vibration observations were obtained at the building, as well as at the reaction wall and roof of the Charles Lee Powell Laboratory to confirm that the characteristic frequencies of the reaction wall and roof of the Charles Lee Powell Laboratory were not affecting or coincided with the characteristic frequencies of the building. The results of this phase are described in the Appendix.

3. Methodology

3.1 Identification of characteristic frequencies and modal shapes of the building

To observe the typical vibration patterns of the building or modal shapes, the frequency response of each of the faces and levels with respect to Level 5 of the North face was obtained. The frequency response between two levels of the building is defined as (Bendat and Piersol, 1971):

$$\boldsymbol{Respuesta} = \frac{\langle S_{xy}(f)\rangle}{\langle S_{xx}(f)\rangle} = \frac{\left\langle X^{*}(f)Y(f)\right\rangle}{\left\langle X^{*}(f)X(f)\right\rangle} = \frac{\left\langle |X||Y|e^{i(\theta_y-\theta_x)}\right\rangle}{\left\langle |X|^{2}\right\rangle} = \boldsymbol{H}e^{i(\quad)} \qquad (1)$$

In equation (1), *X(f)* and *Y(f)* are the Fourier transforms of *x(t)* and *y(t)*, respectively; the asterisk indicates the corresponding complex conjugate. *Sxx* is the power spectrum or autospectrum of level 5 of the North face, and *Sxy* is the cross-spectrum of level 5 of the North face with any other level and face of the building. The angle brackets indicate the assembled average per frequency band of each of the spectral estimates corresponding to the different samples or segments into which the records *x(t)* and *y(t)* were subdivided.

The response for each frequency is a complex number whose magnitude or admittance *H* indicates the spectral quotient or relative amplitude of any other point in the building with respect to level 5 of the North face. The phase of the response is the phase difference of any other point in the building with respect to the phase of level 5 of the North face.

To quantify the constancy of the building's response in each of the spectral estimates, coherence, also known as square coherence (Bendat and Piersol, 1971), was calculated:

$$0 \leq Coherencia = \frac{\left\langle S^{*}{}_{xy}(f)\right\rangle \langle S_{xy}(f)\rangle}{\langle S_{xx}(f)\rangle \langle S_{yy}(f)\rangle} \leq 1. \qquad (2)$$

Coherence depends on the stability of the spectral ratios across different spectral segments or partitions. Frequency band coherence reaches its maximum value if both the phase differences and the amplitude ratios remain constant across the different segments. However, coherence decreases as the variation in both the phase differences and the amplitude ratios across the different segments increases.

The main modal shapes expected to be identified are a first horizontal translational mode or fundamental mode and a torsional mode, as schematically illustrated in Figure 10.

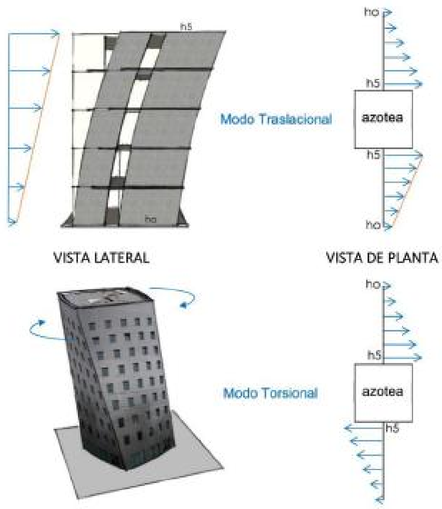

Figure 10. Facade view and schematic view of the first horizontal translational mode and first torsional mode of a building. The vectors indicate the magnitude of the admittance modulated by its corresponding phase *Real*($He^{i(\ )}$), intended to describe the modal shape.

4. Results

4.1 Characteristic frequencies of the undamaged building

In the spectra resulting from the different vibration tests (Figure 11), three characteristic frequencies are identified: one of 4.43 Hz, which is common to all tests (environmental, forced and earthquake), on the four faces of the building; another of 6.79 Hz on the north and south faces that is only observed in the ambient vibration tests; and another of 8.01 Hz, on the north and south faces, which is observed in both the ambient and forced vibration tests.

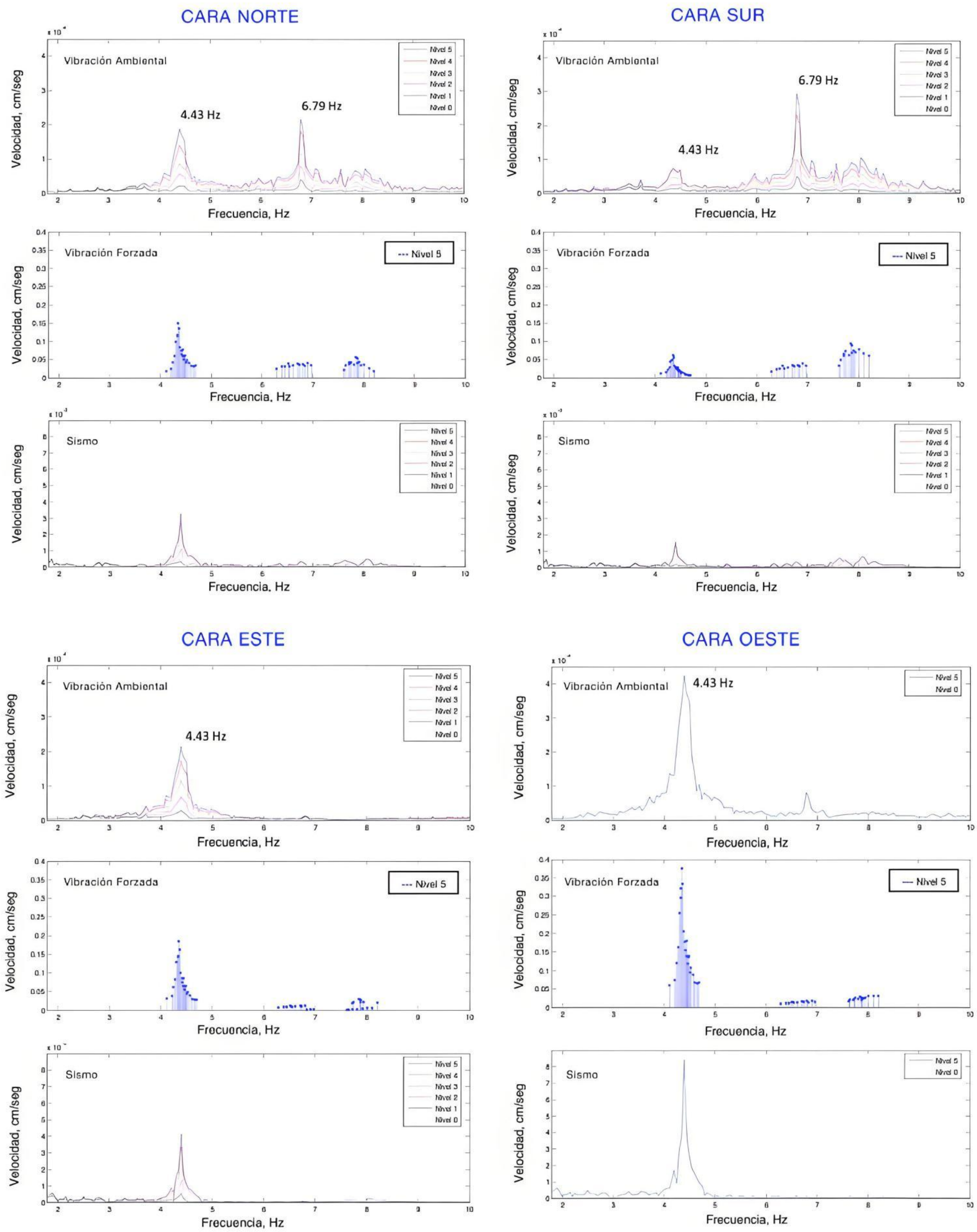

Figure 11. Amplitude spectra of velocity observations at different levels on the four undamaged building faces obtained from ambient vibration, forced vibration, and earthquake. North and south faces (horizontal component in the E-W direction). East and west faces (horizontal component in the N-S direction).

The fact that the 6.79 Hz spectral peak in the ambient vibration tests is observed only on the north and south faces indicates the possibility of a modal shape of the building in the east-west direction. In the forced vibration spectrum, a pronounced spectral peak at 6.79 Hz is not observed because the forced vibrations were generated by a shaking table located to the south of the building, which would explain why these vibrations did not activate a mode in the east-west direction. This spectral peak is also not observed in the earthquake recording. The spectral peak at the 8 Hz frequency observed only on the north and south faces, although of very low amplitude compared to the amplitude at the 6.79 Hz frequency, indicates the possibility of a second mode in the east-west direction.

4.2 Modal shapes of the building without damage

The modal shapes corresponding to the characteristic frequencies of 4.43 Hz, 6.79 Hz and 8.01 Hz were calculated with the response spectra obtained from the ambient vibration and forced vibration tests.

The spectra for the frequency of 4.43 Hz (Figure 12) qualitatively show two modal shapes: a first translational mode in the North-South direction and a torsional mode. Note that the admittance, coherence and phase values in h5N are always (1,1,0), to redundantly indicate that all cross-spectra were made with respect to level 5 of the North face.

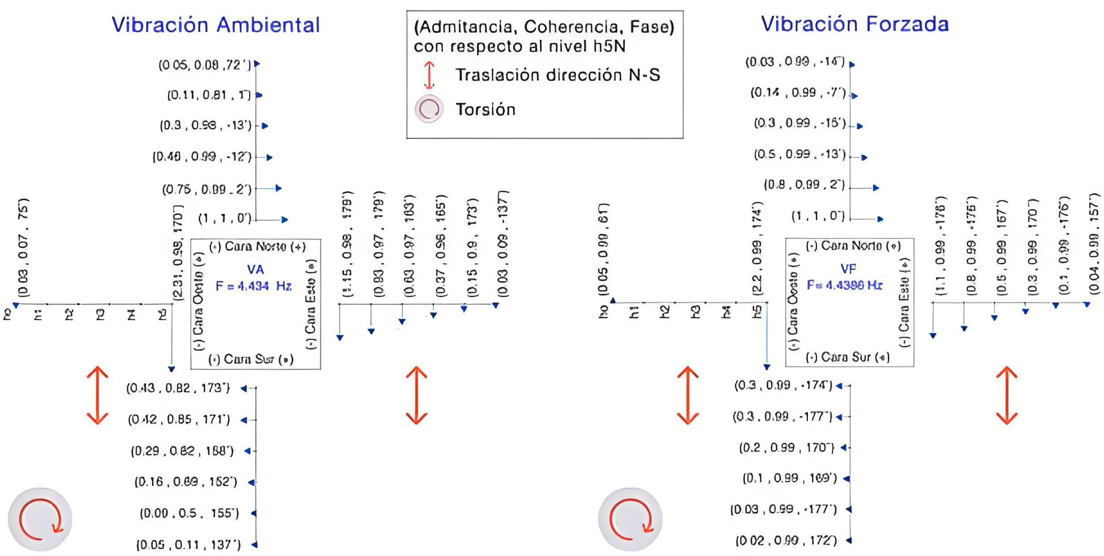

Figure 12. Response of the undamaged building to the spectral components of ambient vibration (AV; left panel) and forced vibration (FV; right panel) at 4.43 Hz.

At the frequency of 6.79 Hz (Figure 13), a first translational mode is observed in the East-West direction, and at the frequency of 8.01 Hz the existence of a mode composed of torsion and translation in the East-West direction is confirmed (Figure 14).

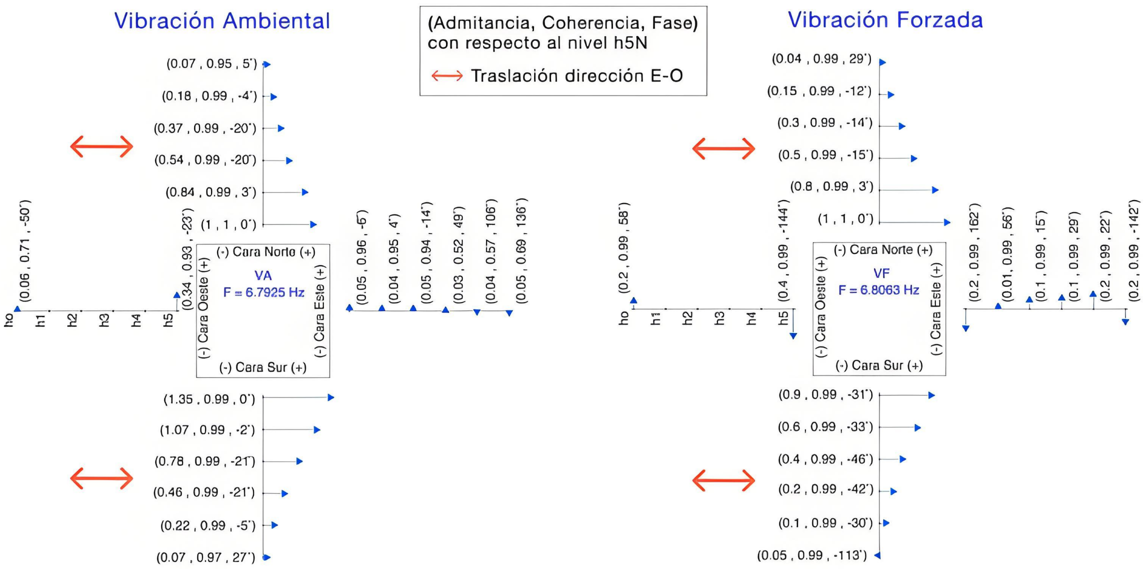

Figure 13. Response of the undamaged building to the spectral component of ambient vibration (left panel) at 6.79 Hz and forced vibration (right panel) at 6.80 Hz.

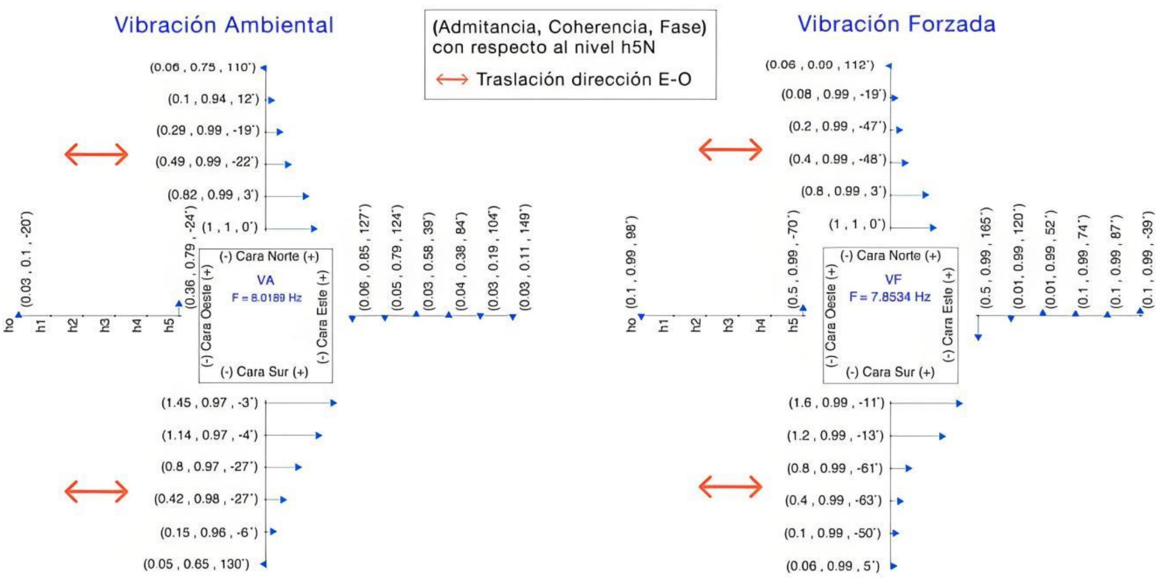

Figure 14. Response of the undamaged building to the spectral component of ambient vibration (left panel) at 8.01 Hz; and forced vibration (right panel) at 7.85 Hz.

The high coherence (>0.9) in the forced vibration and ambient vibration response spectra, corresponding to the characteristic frequencies of 4.43 Hz, 6.79 Hz, and 8.01 Hz, indicates the persistence of the building's mode shapes. Note that in all ambient vibration tests, the coherence is comparatively low at the zero level on all faces of the building. This is due to the random nature of the ambient vibration forcing the building at its base. Whereas, the high coherence (0.99) in the forced vibration tests, at all levels of the building, including the zero level on all faces, is due to the monochromatic nature of the forcing vibration.

As can be seen in Figures 11 to 14, the characteristic frequencies and corresponding mode shapes obtained from the ambient vibration and forced vibration analysis are practically identical and adequately describe the building's mode shapes. However, for simplicity, only the analysis of the ambient vibration recordings is presented below.

4.3 Changes in characteristic frequencies and modal shapes

The methods used to detect damage with ambient vibration testing are based on observing changes in the dynamic behavior of the structure. In general, damage to a building is associated with a degradation in its stiffness, which in turn is identified by a decrease in the frequency of its normal modes or, where appropriate, by an increase in frequency when the building is repaired or reinforced. In this case, the results (Figure 15) show changes in the characteristic frequencies of the damaged and repaired building compared to the undamaged building.

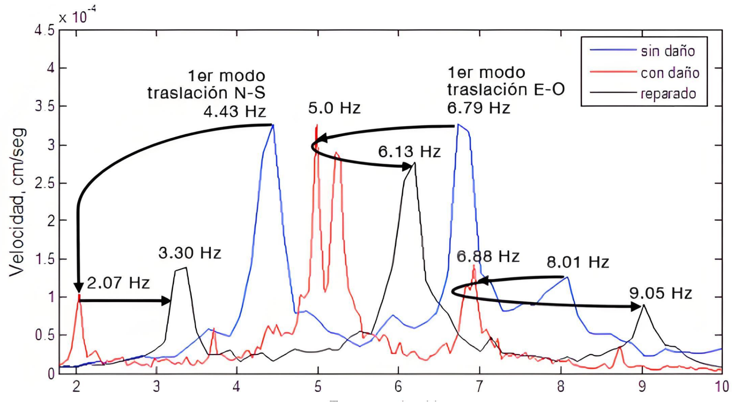

Figure 15. Amplitude spectra of ambient vibration observations from level 5 of the building's north face in its three stages: undamaged, damaged, and repaired, respectively. The arrows indicate the change in frequency of each of the building's normal modes.

The first translational mode in the north-south direction, with a frequency of 4.43 Hz, decreases to 2.07 Hz after the building was damaged, and increases to 3.30 Hz once the building was repaired or reinforced. The same behavior occurs with the translational mode in the east-west direction at a frequency of 6.79 Hz, whose frequency decreases to 5.0 Hz in the damaged building and increases to 6.13 Hz in the repaired building. The highest frequency mode (8.01 Hz) in the undamaged building corresponds to a low-amplitude translational mode in the east-west direction. This mode is not observed in the damaged building, but instead a torsional mode is observed at a frequency of 6.88 Hz; and a higher frequency torsional mode (9.05 Hz) is observed in the repaired building.

In order to identify the building levels where the greatest damage occurs, emphasis is placed on observing the modal shape at the frequency of 4.43 Hz on the east face of the undamaged building (Figure 16), to contrast it with the corresponding modal shape of the damaged building, where it can be seen how the relative amplitude is amplified at levels h3, h4 and h5, and how a "node" appears at level h2 of the east face, a level where coherence decreases from 0.96 in the undamaged building to 0.5 in the damaged building. The same Figure shows how the greatest damage inflicted on the building by tension and compression was recorded between levels h0, h1 and h2, on the east face, because the reaction wall of the hydraulic actuators is located parallel to the north face of the building. Once the experimental building was repaired, the shape of the first north-south translational mode on the east face can be seen to have recovered; however, its corresponding frequency only recovers up to 3.3 Hz, indicating that stiffness has been restored, but not completely. In fact, Seible et al. (1994) indicate that 50% of the original stiffness has been recovered.

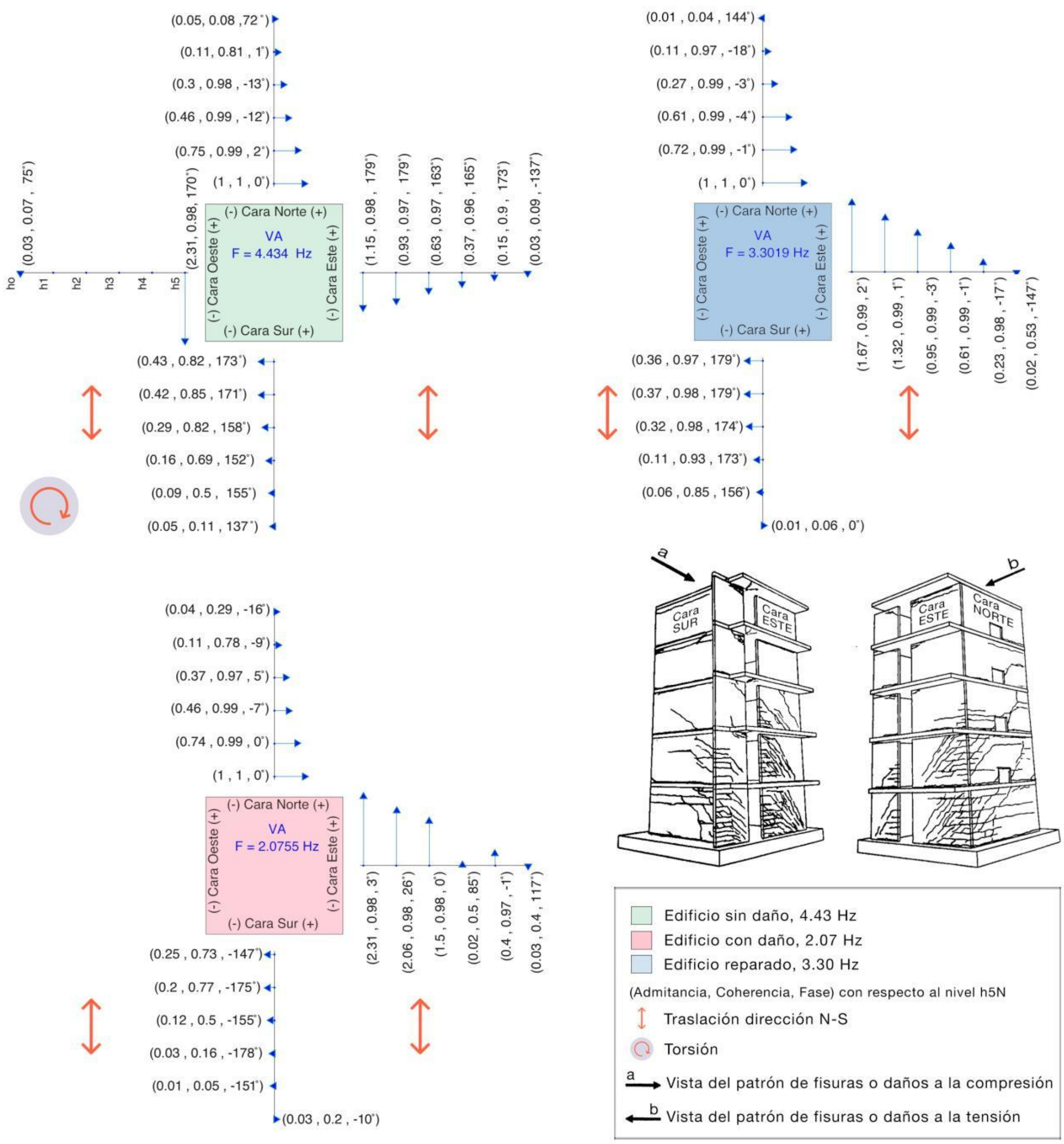

Figure 16. First translational mode in the north-south direction in the undamaged (4.43 Hz), damaged (2.07 Hz), and repaired (3.30 Hz) buildings, for the ambient vibration spectral component. The building schematic shows the pattern of cracks or damage due to hydraulic actuators (Seible et al., 1994).

In the east-west direction, no significant changes in modal shape were observed across the three stages of the experiment (Figure 17). Only changes in frequency were observed, consistent with the degradation and recovery of its stiffness.

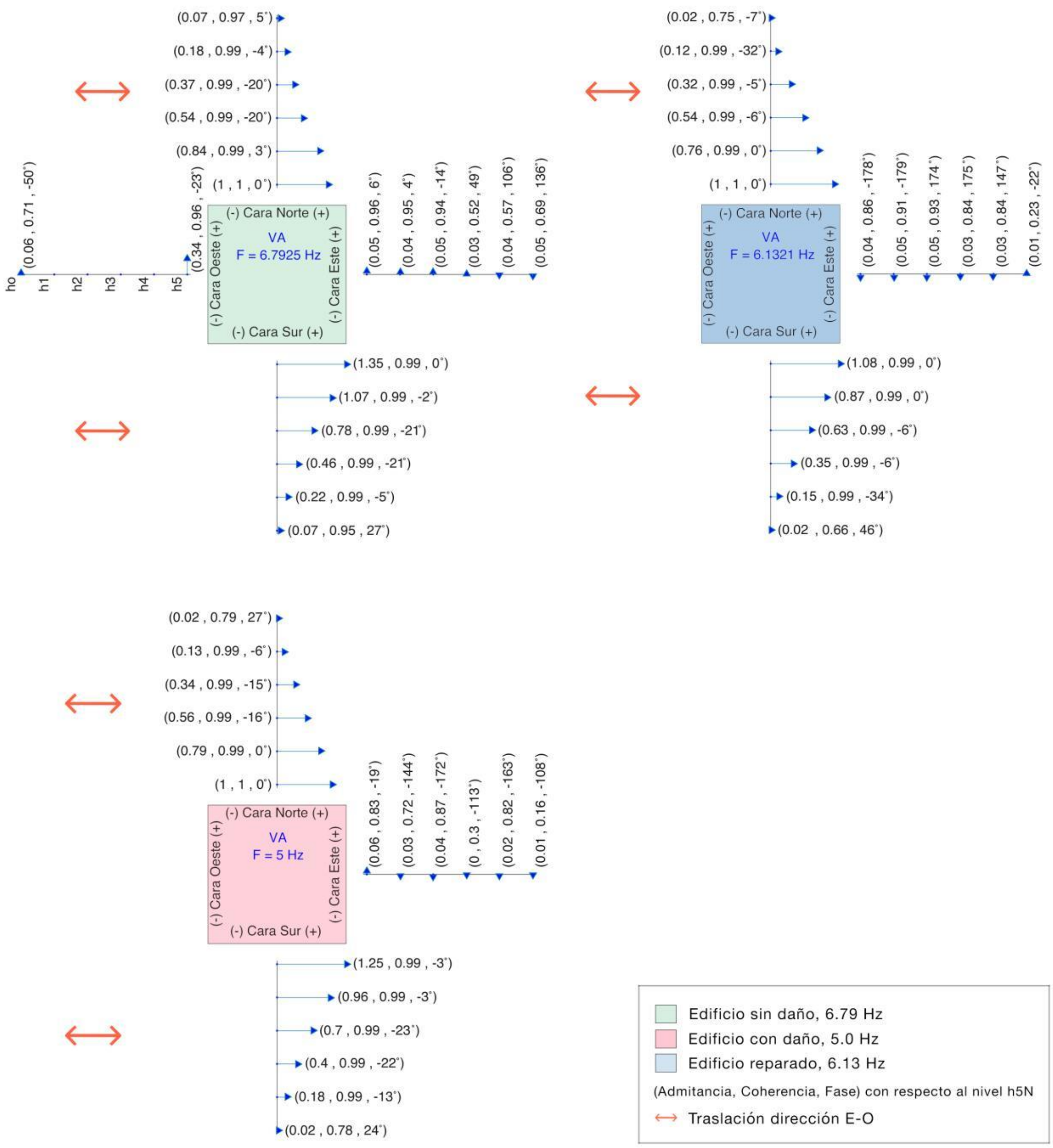

Figure 17. First translational mode in the East-West direction in the undamaged (6.79 Hz), damaged (5.0 Hz), and repaired (6.13 Hz) buildings, for the ambient vibration spectral component.

In the higher frequency mode shapes (Figure 18), it can be seen how the east-west translational mode (8 Hz) changes to a dominant torsional mode (6.88 Hz) once the building has been damaged. However, while torsion is clearly observed at all levels of the north and south faces and at levels h5, h4 and h3 of the east face, a "node" is observed at level h2 of the east face, similar to the "node" observed in the first translational mode at the frequency of 2.07 Hz in the damaged building. Note that the node observed at level h2 of the east face coincides in its location with the damage observed in the walls corresponding to levels h0, h1 and h2 of the east face, which is the face where the greatest damage due to the hydraulic actuators was recorded.

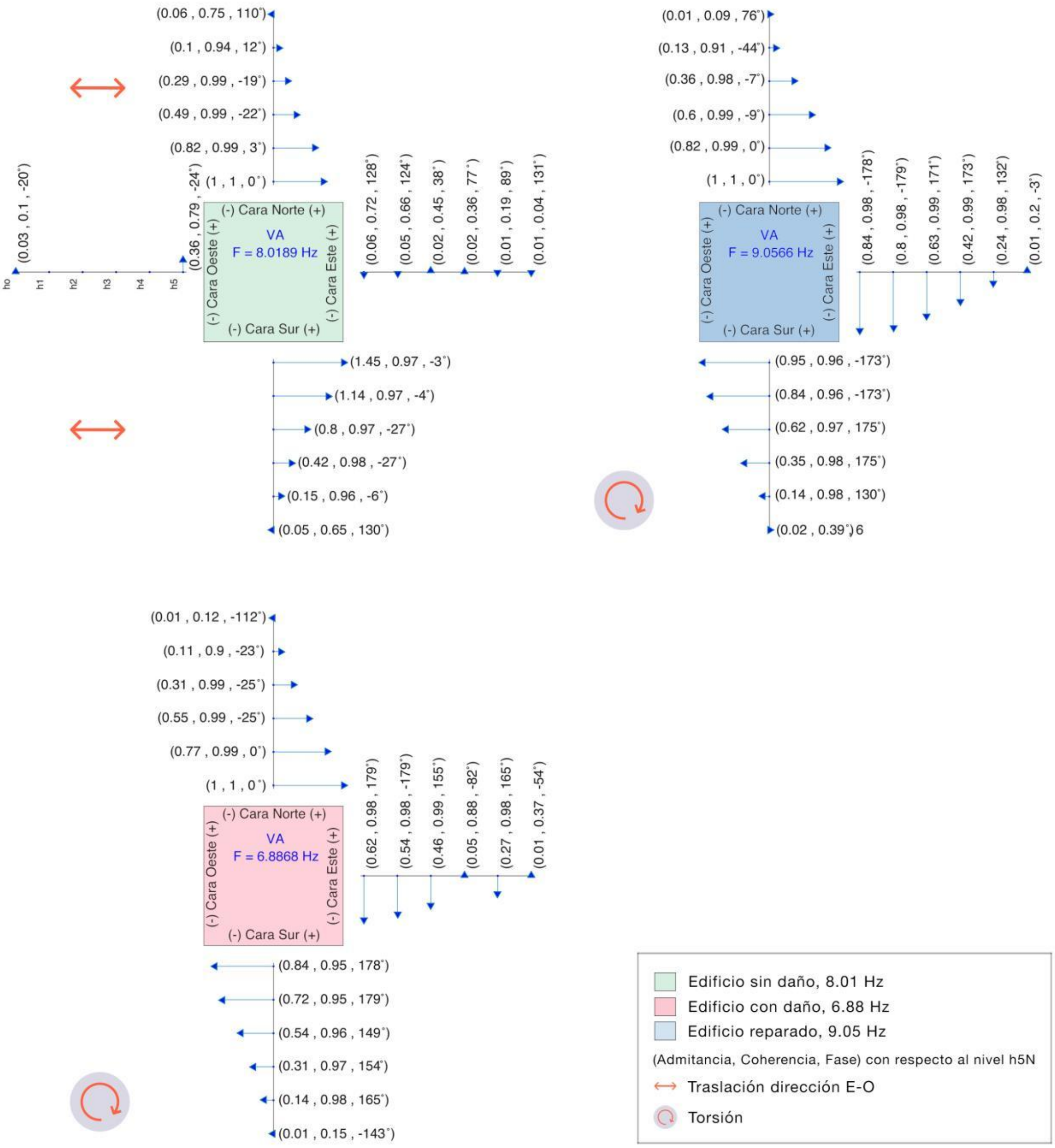

Figure 18. Response of the undamaged (8.01 Hz), damaged (6.88 Hz), and repaired (9.05 Hz) building to the ambient vibration spectral component.

The change in the frequency of the modal shape, from 6.88 Hz to 9.05 Hz, once the building has been repaired, could be indicating that this mode does not correspond to the previous ones because it exceeds the frequency of 8.01 Hz observed in the first stage of the building, as if the stiffness had increased after the repairs.

5. Conclusions

Ambient vibration records, like forced vibration records, were suitable for analyzing the dynamic properties of the experimental building. Obtaining and analyzing ambient vibration records is faster and less expensive than forced vibration records. In this particular work, we had the opportunity to experiment with both types of records, which allowed us to verify once again that ambient vibration records are sufficient to identify both the characteristic frequencies of a building and its mode shapes. Furthermore, this work obtained a record of an earthquake during the first stage of the experimental building (newly constructed), whose analysis confirmed the characteristic frequencies obtained through both the ambient vibration and forced vibration analyses.

The observed changes in the frequencies of the building's normal modes during its three stages (undamaged, damaged, and repaired) confirm the hypothesis that damage to a building is associated with stiffness degradation, which in turn is associated with a decrease in the frequencies of its normal modes, or, if applicable, with an increase in frequency when the building is repaired or reinforced. At the same time, the observed changes in the building's modal shapes once damaged allow for a qualitative identification of the faces and levels where the damage occurred.

Systematic monitoring of a building's vibrations would allow us to determine its structural integrity by verifying the consistency of its characteristic frequencies and modal shapes, or failing that, it would allow us to observe changes in its stiffness, whether due to natural causes such as seismic stress, changes in soil properties, or perhaps simply due to its lifetime.

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Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix

Analysis of the Charles Lee Powell Laboratory building, reaction wall, and roof

The objective of this test was to identify the characteristic frequencies of the building, the reaction wall, and the Charles Lee Powell Laboratory, in order to verify that the structures' vibrations do not resonate with the experimental building. In this case, only ambient vibration observations were used. These recordings were made one day before the ambient vibration tests began.

Sensor location

Due to the type of instruments and the amount of wiring needed to record the vibrations of the three structures at the same time, four horizontal component sensors were placed on level 4 of the experimental building oriented along the walls, two horizontal sensors on the reaction wall, and three horizontal sensors on the roof of the Charles Lee Powell Laboratory, as shown in Figure A.1.

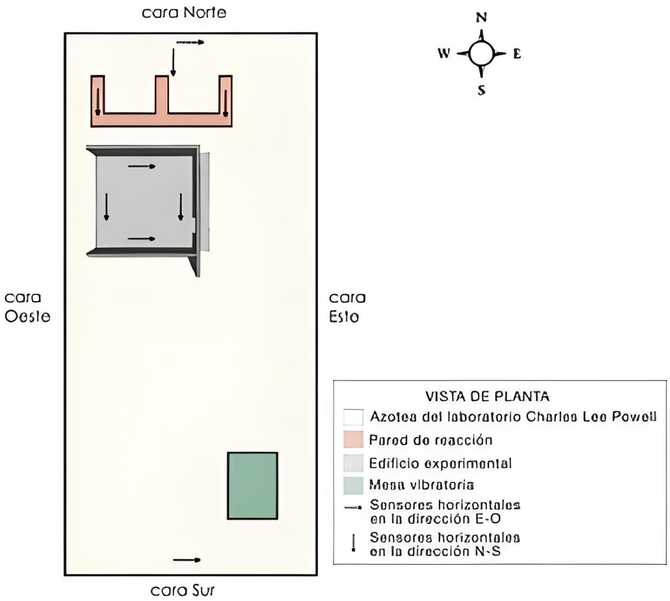

Figure A.1 Schematic plan view of the experimental building, reaction wall, and shaking table location within the Charles Lee Powell Laboratory, and location of horizontal sensors for the ambient vibration test.

identification of characteristic frequencies

The resulting ambient vibration spectra in the three structures are shown in Figure A.2:

- On the roof of the Charles Lee Powell Laboratory, in the sensors parallel to the north and south faces, we observe a prominent peak at the frequency of 2.2 Hz (Figure A.2a), while in the sensor oriented in the longitudinal direction no prominent spectral peak is observed, indicating that the laboratory oscillates preferentially in the transverse direction (East-West).

- In the spectra of level 4 of the experimental building (Figure A.2b), we observe a peak at the 4.5 Hz frequency that is present on all four sides of the building and is of greater amplitude on the east and west sides, indicating a preferential oscillation in the north-south direction. We also observe energy in the 7 Hz to 8 Hz frequency band that is only observed on the north and south sides, indicating preferential oscillations in the east-west direction. These results are consistent with those in Figure 13, which identifies the characteristic frequencies of the undamaged building.

- In the reaction wall, as in the building, we find energy in the frequency band between 7 Hz and 8 Hz (Figure A.2c). However, in contrast to the building, the oscillations are of lower amplitude and the reaction wall oscillates naturally in the north-south direction, while the building oscillates preferentially in the east-west direction. It is possible that the oscillations in the reaction wall are forced by the building, since, due to its design, the reaction wall's natural oscillation frequency is very high.

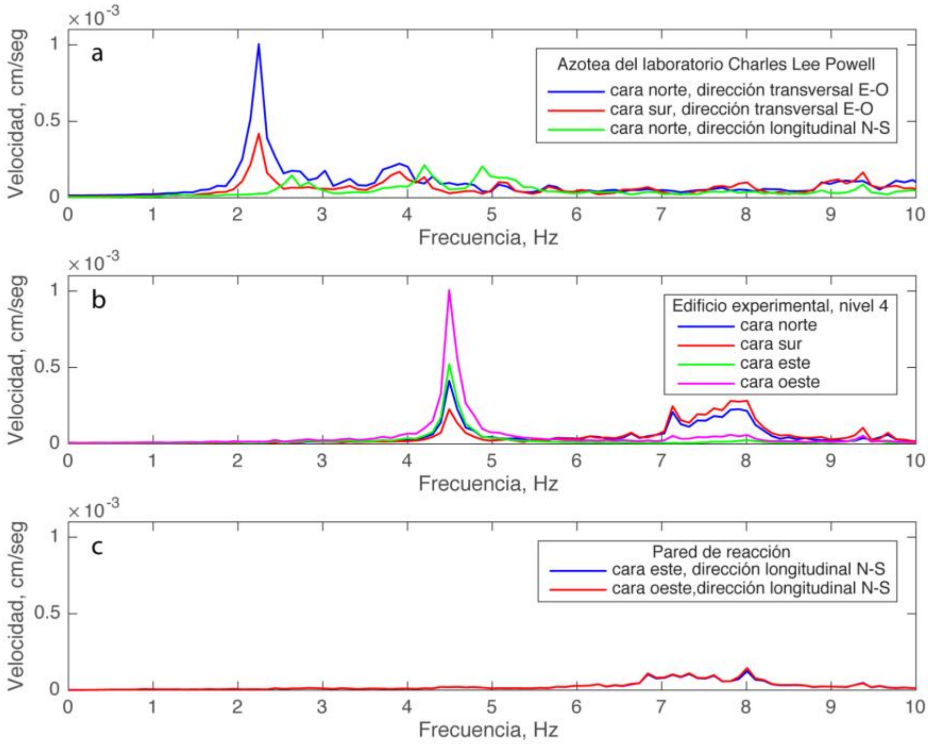

Figure A.2 Amplitude spectra from velocity observations on: a. Roof of the Charles Lee Powell Laboratory. b. Experimental building. c. Reaction wall obtained from ambient vibration recordings.