Case Report / Technical Paper

THE BEHAVIOR OF AXIAL-SYMMETRIC STRUCTURES AT SEISMIC MOTIONS CONSIDERING THE VARIETY OF MOTION POSSIBILITIES OF THE STRUCTURAL ENSEMBLE

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ABSTRACT

The aim of the paper is to present, in essence, the result of a research regarding the dynamic characteristics and the modal behavior of the Central ROMEXPO Pavilion, determined from ambient vibrations, considering different variations of the possibilities of motion of the structure. The retained study models are only those parametric situations, which may be considered, from the engineering point of view, as representing an important risk for the dynamic evolution of the motion process under the action of a strong earthquake.

Keywords: velocigrams; basic records combination; ovalizations

REZUMAT

Scopul articolului este acela de a prezenta, în esență, rezultatul cercetărilor privind caracteristicile dinamice şi comportarea modală a pavilionul central ROMEXPO, determinate la vibrații ambientale, considerând diferitele variații ale posibilităților de mişcare ale structurii. Modelele de studiu reținute sunt doar acele situații parametrice care, din punct de vedere ingineresc, pot fi considerate a reprezenta un risc important pentru evoluția dinamică a procesului de mişcare sub acțiunea seismică a unui cutremur puternic.

Cuvinte-cheie: velocigrame; combinarea înregistrărilor de bază; ovalizări

1. INTRODUCTION

1.1. General

The earthquake induces a spatial, random motion on the ground-structure interface points. In order to determine the equations of motion and their solutions in the case of a seismic force acting on a structure with multiple dynamic degrees of freedom – noted in short MDDF, new approaches are necessary compared to the classic ones (based on relative displacements). The simplified manner in which this subject is generally treated in codes and specialized norms is not always compatible with the real, physical phenomenon and may introduce large errors in the design phase of constructions (particularly for large-span or tall and rigid ones). When the asynchronous nature of the ground-structure interface motion becomes important, absolute displacements will be used as unknowns instead of the relative ones.

Basically, the only special characteristic of the seismic loading, compared with any other form of dynamic loading, is that the excitation is practically applied as motions of the supports instead of exterior loadings/forces.

The chosen case study for the motion possibilities of a MDDF structure is the Central ROMEXPO Pavilion, due to its special, circular-symmetric shape and also due to its rather isolated location, compared to other buildings in Bucharest.

Because inaccuracies appear between the real structure and the structural model, analyzed with ETABS, the obtained results must also be checked by dynamic measurements (multichannel digital recordings) for validation or calibration of the model. For this purpose, three layouts for placing the sensors of the data acquisition system – denoted as DAS - were created to simultaneously record the displacements of the structure at ambient vibrations on two orthogonal, perpendicular directions.

Afterwards, the main possibilities of motion of the structural ensemble could be determined (including possible ovalizations).

In the analysis presented in this paper, the asynchronous character of the motion can be recognized in the deformed shape (ovalizations) of the main ring of the structure compared to an expected compact rigid motion.

1.2. Method

The layouts for placing the sensors of the DAS are as follows:

- the first one, shown in Fig. 1, has eight sensors, placed in four points (located at 90 degrees one from the other) on the main ring of the structure;
- the second one has six sensors, placed in three points (located at 120 degrees) on the main ring of the structure;
- the third and last one has sensors placed on the entire height of an arbitrary chosen column (two for each floor).

Regardless of the chosen layout, two sensors are placed in each considered point to record signals in two horizontal perpendicular planes.

Having the first layout as a starting point, due to its increased number of sensors (compared to the other layouts) the method of basic records combination was used, considering that the symmetric and antisymmetric subspaces of motion are orthogonal. Fourier subspaces were considered with respect to an angle at the center for different order ovalizations and the distinct subspace of rotation of the structure. Practically, the eigenmodes separate the space of motion into orthogonal subspaces of one dimension. Due to this property, the position of the sensors could be established (signal recording on two orthogonal, horizontal directions). The motion recorded by the sensors represents the result of the superposition of the subspaces of the eigenmodes.

In conclusion, the basic records combination on two orthogonal directions can be summarized as the decomposition of the motion space into one dimension subspaces and, afterwards, their recombination along the directions of interest.

1.3. Objectives

The monitoring of ambient vibrations and the processing of the records have as main objective the experimental determination of the dynamic characteristics of the structure and of its motion tendencies.

The possibilities of motion considered important from the engineering point of view are:

- Translation on the E-W direction;
- Translation on the N-S direction;
- Rotation around the vertical symmetry axis;
- Second order ovalization.

For higher order ovalizations (3^{rd} and 4^{th}), the obtained results were not as clear as for the 2^{nd} order.

The vectors of recorded velocities and displacements, $u_g(t)$ and $w_g(t)$, along the two horizontal, normal axes, OX and OY and having 2x32 components, are transformed into $u_e(t)$ and $w_e(t)$, vectors corresponding to the vibration eigenmodes of translation, rotation and ovalization of the structure.

The components of the vectors are each considered separately and checked and, afterwards, compared and checked again with the results obtained from the analysis of the structural model generated in ETABS.

2. THE STRUCTURE

2.1. Layout

In 1959, the Administrative Authority of the Capital decided the erection of a modern exhibition center as a result of the economical growth of the country and its international economical expansion (Romexpo, 2012). Thus, the ROMEXPO Central Pavilion was built using avant-garde architectural solutions: a dome made of concrete, steel and glass.

The Pavilion, having a height of 42 m and a built surface of 10000 m^2, has a circular layout with a diameter of approximately 113 m and a steel dome of 95 m diameter.

On January 30, 1963, the dome, which was a replica of the one in Brno, collapsed. The roof was reconstructed based on the plans provided by Academician Professor Eng. Dan Mateescu and, during the years, the entire structure was assessed and strengthened several times. The earthquakes of 1977, 1986 and 1990 led to overall stiffness decreases, while the subsequent interventions led to stiffness increases.

On the interior, the Pavilion has three galleries situated at different elevations (3.20 m, 7.70 m and 17.30 m) supported on two rows of reinforced concrete columns. On the 32 principal columns, 32 arched trusses rest, forming the structural system of the dome. The circular platform at elevation 4.50 m, resting on 2x30 secondary columns, was added more recently and has a small contribution to the overall stiffness of the structure. The dome, as well as the entire building, was designed to allow the use of prefabricated materials.

In Figs. 1…4, the structure of the Central Pavilion ROMEXPO is presented as follows: vertical section, general view and dome images and horizontal ground floor plan.

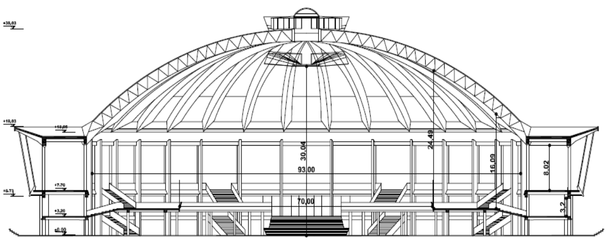

Fig. 1. Vertical section

Fig. 2. General view

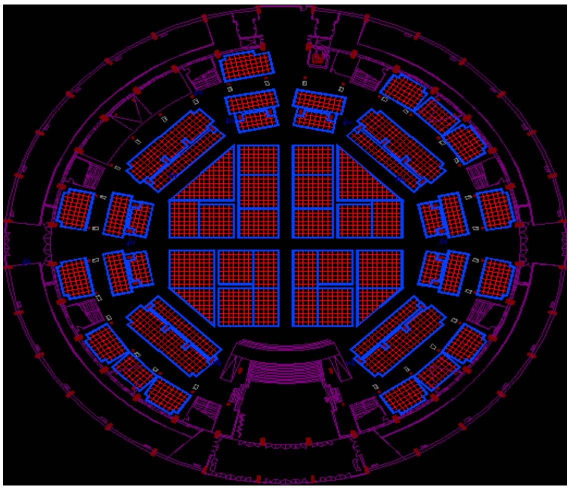

Fig. 3. Horizontal ground floor plan

Fig. 4. Dome image

2.2. Structural Model

The structural model and its linear analysis were performed using the computer program ETABS 9. The aim was to determine the natural periods and shapes of the first 12 vibration eigenmodes of the structure, needed as a comparison and validation tool for the recorded and processed data.

For the entire system, 9524 linear elements (beams, columns, steel bars etc.) and 183 surface elements were obtained. Out of these, 7136 of the linear elements were used for the dome modeling. In Fig. 5, the model of the steel dome is shown.

In Figs. 6 and 7, the ROMEXPO model with and without its dome is presented, and the plan floor at a height of 3.20 m, in which the four rows of columns, the main stair case ramp and the precast slabs can be seen.

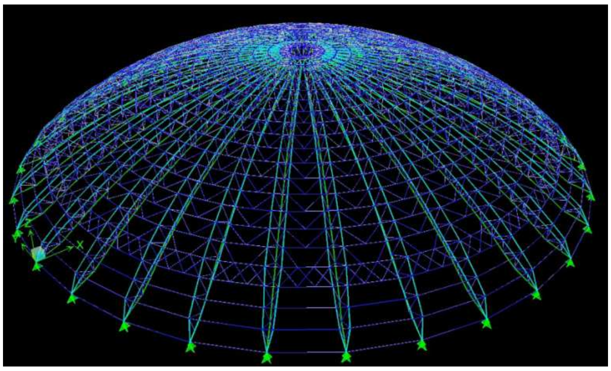

Fig. 5. Steel dome model

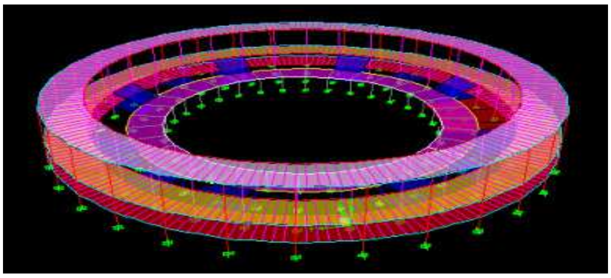

Fig. 6. Model of the pavilion without its dome

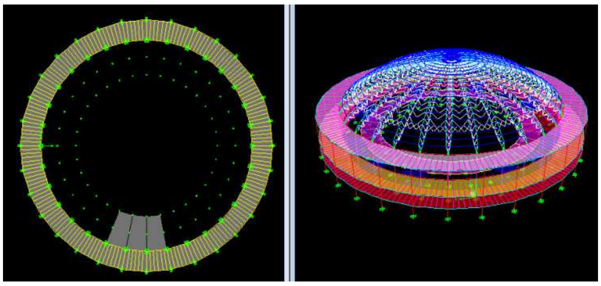

Fig. 7. General View and Floor Layout Models

Because the structure is not a newly erected one, the model has to take into account the decrease in the structural stiffness of the elements due to time and the numerous interventions on the structure.

For the dome-reinforced concrete subsystem interface, the points were modeled as hinged supports. For the ground-structure interface, they were designed as fixed supports.

Differences that may appear between the real model and the ETABS one may be due to the:

– decrease in structural stiffness of the elements;
– impossibility of knowing the exact location of the cracks in the concrete and local damage after repeated earthquakes;
– impossibility of modeling the rehabilitation/earthquake cycles;
– modeling of beams as rectangular elements instead of "T" beams, with constant sections and not varied along the height of the building, due to the lack of structural plans;
– modeling of the principal columns as having a regular rectangle shape;
– the finishes and the glass facade are considered separately as loads;
– imperfect symmetry of the structure.

Thus, the model has to be checked and calibrated using real, on site, recorded data.

3. THE FIRST SENSOR LAYOUT

Three layouts of placing the seismometers have been used for the simultaneous recording of the structural displacements at ambient vibrations (the data acquisition system records velocities which are afterwards transformed into displacement recordings and then processed into Fourier spectra) on two orthogonal horizontal directions in order to determine afterwards the possible ovalizations and the fundamental eigenshape for one of the 32 columns of the structure.

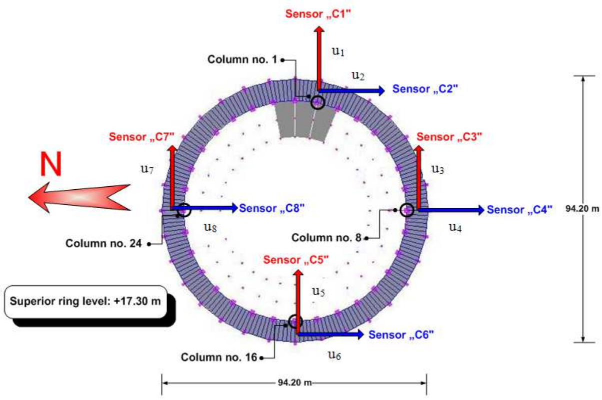

Fig. 8. First layout of the sensors

For the first layout, which offers the richest information, presented in Fig. 8, simultaneous digital recordings were done on the directions W-E and S-N at four equidistant points on the superior ring of the structure (elevation +17.30 m). The recorded results are denoted, for each direction, with:

- E: u_4 (towards E), u_3 (towards N)

- N: u_2, u_1
- W: u_8, u_7
- S: u_5, u_6

The expected motions for this layout are, for the symmetrical axis dilatation of the ring: rigid translations, ring rotations, 2nd and 4th order ovalizations (Murzea, 2012a, 2012b).

a. Symmetrical axis dilatation of the ring

Because there are only four points at which the seismoteres are placed the information is limited and the dilatation oscillations overlap with those of higher order ovalization (4, 8, etc.) The identification of the modes should be done based on the spectral analysis.

$$u_{Dil}=(u_1 + u_4 - u_5 - u_8)/4 \qquad (1)$$

b. Rigid translations of the ring along the two directions E-W and N-S, equivalent to 1st order ovalization:

$$u_{NS}=(u_2 + u_4 + u_6 + u_8)/4 \qquad (2)$$

$$u_{EW}=(u_1 + u_3 + u_5 + u_7)/4 \qquad (3)$$

$$u_\alpha = u_{WE}\cos\alpha + u_{SN}\sin\alpha \text{ (at angle } \alpha) \qquad (4)$$

c. Ring rotations:

$$u_{rot} = (u_3 - u_2 - u_7 + u_6)/4 \qquad (5)$$

d. 2nd order ovalization:

$$u_{ov2}= (u_4 - u_1 - u_8 + u_5)/4 \qquad (6)$$

$$u_{ov2'}= (u_4+u_3+u_2+u_1-u_8-u_7-u_6-u_5)/4\sqrt{2} \qquad (7)$$

$$u_{ov2\alpha} = u_{ov2}\cos\alpha + u_{ov2}\sin\alpha \qquad (8)$$

e. 4th order ovalization:

$$u_{ov4} = (u_4 + u_1 - u_8 - u_5) / 4 \qquad (9)$$

4. RESULTS

The recording process lasted 300s (for each layout) and the illustrative processed signal samples, presented in the figures below (Figs. 9-17.), are of 16s length.

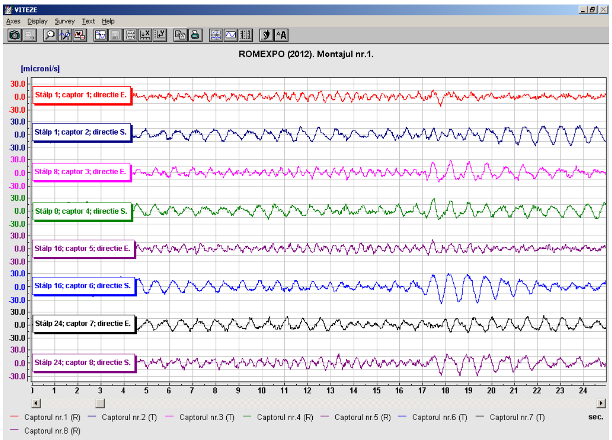

Fig. 9. The simultaneously recorded signal on 8 channels (velocities)

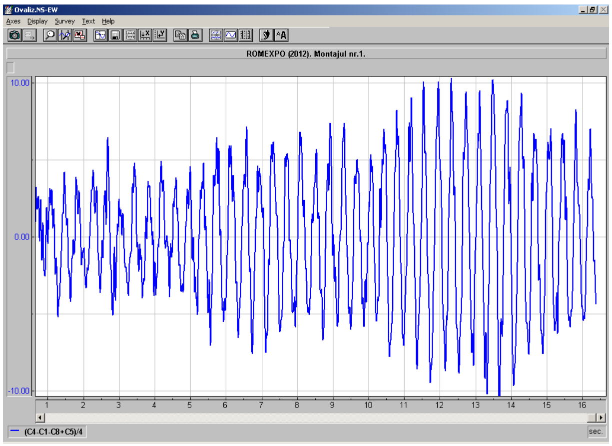

Fig. 10. 2nd Order ovalization (velocities)

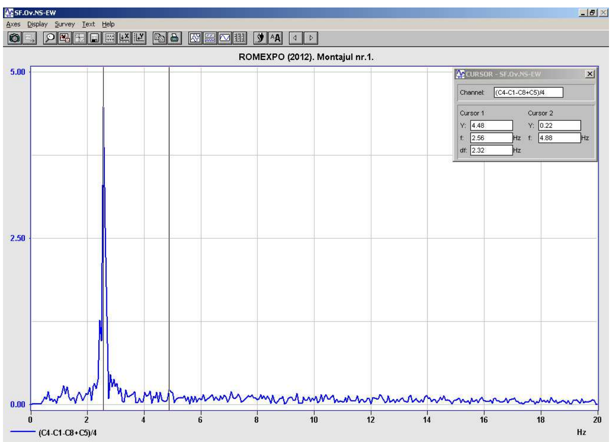

Fig. 11. 2nd Order ovalization Fourier spectrum (velocities)

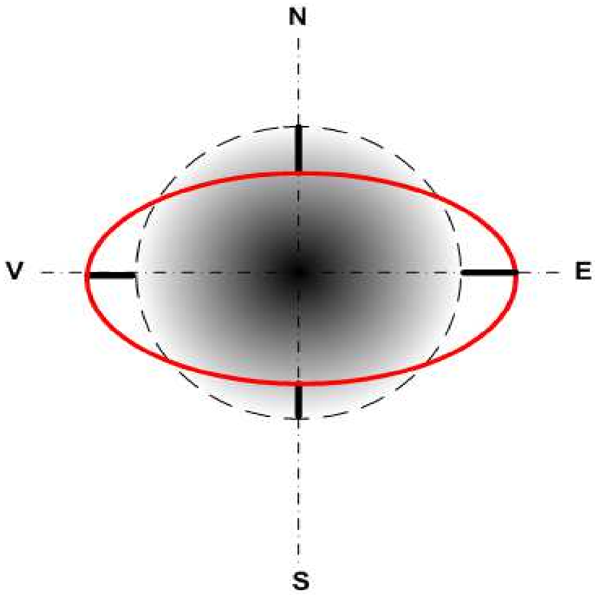

Fig. 12. Image of the 2nd order ovalization at 2.56Hz

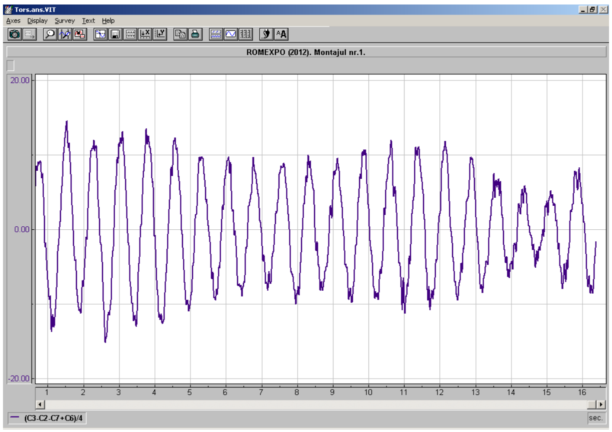

Fig. 13. Overall torsion (velocities)

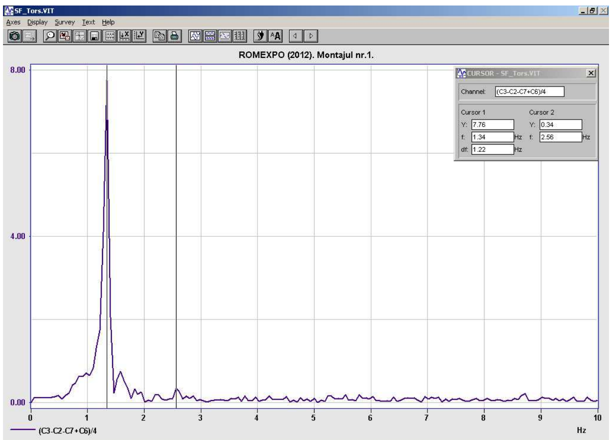

Fig. 14. Overall torsion Fourier spectrum (velocities)

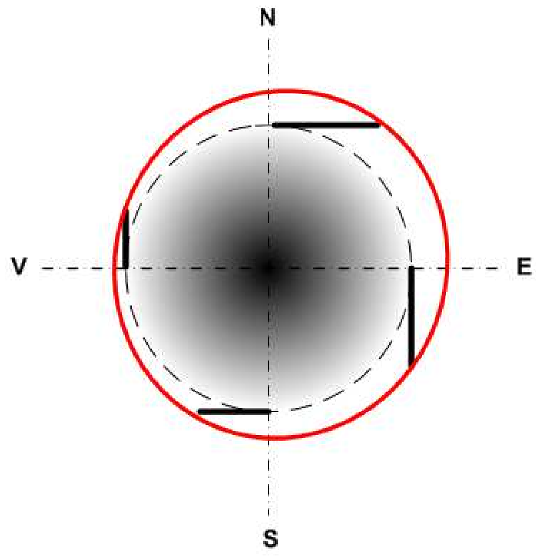

Fig. 15. Image of the overall torsion at 1.34Hz

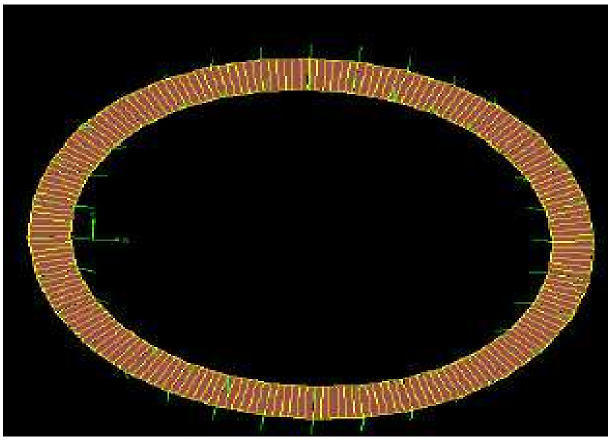

Fig. 16. 2nd order ovalization of the main ring, ETABS

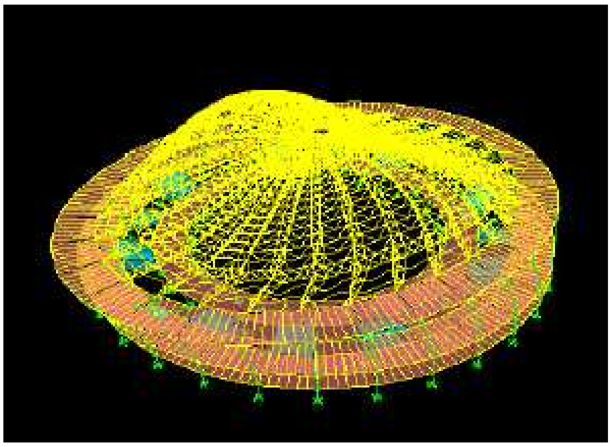

Fig. 17. 2nd order ovalization of the main ring with the deformation of the dome, ETABS

5. RESULTS

Considering its importance, the structure of the Pavilion has been carefully monitored over the years, many experimental verifications being done (INCERC, 1984; Structural SA, 2004) before and after seismic events, as well as after successive interventions on the structural system.

The obtained results, shown in Table 1, clean and with clear spectral peaks, as observed from the figures presented in the previous section of this paper, are significant for national and international code development. The codes generally recommend a 2D analysis for which the fundamental eigenmode is sufficient.

From the experimental research, it resulted that the values of the spectral peaks of the rotational motion in horizontal plane and 2nd order ovalization are visibly larger than those for the horizontal translations, thus proving that the spatial character of the ground motion when prescribing the calculation parameters should be taken into account (Murzea, 2012b).

Also, by using modern digital equipment, the obtained information is richer and can be further processed, deriving in further information. The experimental techniques based on in situ records, with highly sensitive dynamic sensors located at well-established positions, can capture with great accuracy the main tendencies of vibration/motion of the structure. These show great advantages in terms of effectiveness, accuracy and cost (Murzea, 2012b).

For the future, it is recommended to equip the structure with strong-motion accelerographs at four points below the ceiling at the elevation of +17.30 m, which will be able to simultaneously record motions on three directions, at the occurrence of strong earthquakes. Thus, an interesting comparison could be made between the behavior of the structure during/after the earthquake and the behavior of the structure under steady state micro-tremors.

Table 1. *Synthesis of the instrumental and structural analysis results obtained in 2012*

Nr. Eigen Mode	Period ETABS (s)	Deformation	Experimental (Hz)	Experimental (s)	Spectral Peaks (displ.)	Spectral Peaks (vel.)
1	0.7736	Rotation	1.34	0.746	0.52	4.2
2	0.6943	Translation	1.28	0.781	0.35	2.8
3	0.6931	Translation, dome deformation	1.28	0.781	0.32	3.2
5	0.347	2nd order ovalization	2.56	0.391	0.42	7.2

6. ACKNOWLEDGEMENT

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