Dynamic Response Parameters and Damage Assessment of Educational Building located in Earthquake Prone Area

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SUMMARY:
According to the modern approach of the post-seismic investigation, the building's damage assessment should be clearly foreseen and properly planned in order to obtain dynamic parameters for the analysis. In this context, determining the fundamental period of building oscillation and comparison with the original data is a first comprehensive method for assessing the variation of stiffness building due to the earthquake. The paper presents a case study of a university building from Bucharest. Using seismic instrumentation results the safety condition of the building was assessed in three phases of work: before the earthquake of 1977, after strengthening of the 80s, and after the earthquake from 1990 until today. Also, structural intervention scenarios to enhance global security using genetic algorithms are presented. Based on this method, the strengthening solutions were identified and the need of seismic joints was emphasized.

Keywords: educational building, seismic instrumentation, dynamic response parameters

1. INTRODUCTION

In Romania, Vrancea earthquakes occur every few decades, and approximately 60% of territory is affected by them. There are buildings that were designed decades ago, after the less stringent provisions. Thus, when the earthquake occurs there are many cases where buildings are badly damaged.

The university centres shelter large concentrations of young intellectuals which in the near future are assumed to take over most the society duties. Besides education, in universities are carried out scientific research activities for the modern technology of society. For that reason, seismic protective measures of the university buildings according to the new requirements are necessary as well as drawing up some assistance strategies and interventions for emergency situations similar with those already existing in the technologically advanced countries. The priority for the university centres is to respect the clause 1.1.2 of the Romanian Code P100-1:2006 which provides avoiding of human loss, maintenance of the activities and limitation of damages.

Currently, there are no specific programs for university building inspection to verify the compliance with new requirements of safety standards and no organized programs in emergency areas such as in countries like U.S.A. and Japan. For this reason the article tries to present a method for assessing the vulnerability of university buildings through a case study for the building that houses the Faculty of Land Improvement and Environmental Engineering in Bucharest.

2. NEED FOR SEISMIC INSTRUMENTATION OF UNIVERSITY BUILDINGS

Behaviour analysis of different types of buildings and the earthquake effect evaluation on them, in addition to a detailed visual inspection of building's state and recording the damage found, in many cases, involves a series of tests and experimental research. These are made for both the hidden effect detection and to specify the real characteristics of materials and structural components that have suffered damage.

In Romania seismic protection was provided by P100: 1992 and from 2006, and 2008 respectively, the code P100 was in forced with parts 1:2006 and 3:2008 - which is made in accordance with Eurocode 8. In Romania the Ordinance no. 20/1994 was promulgated, which includes intervention measures on existing buildings and the Government Emergency Ordinance no. 21/2004 which has institutionalized the National System of Management of Emergency Situations. But now there is no specific legislation to protect university buildings which according to codes above mentioned are included in 2nd Class of importance.

In Romania, the seismic design code, P100-1: 2006 sets out in Annex A, the following aspects regarding the future seismic instrumentation on buildings in Romania:

- In areas where seismic design acceleration value a_g with IMR $\geq$100 years is $a_g \geq 0{,}24g$, the buildings with a height over 50 m and more than 16 storeys or having a surface of over 7,500 m^2, will be instrumented with a digital acquisition system and minimum 4 (four) axial sensors for acceleration.
- This minimal instrumentation will be located as follows: a sensor in the open field near the building, a sensor in the basement and two sensors on the top floor. Instruments will be located so that access to equipment to be possible at any time.
- Instrumentation, maintenance and operation are financed by the owner of the building and are performed by authorized organizations.
- The records obtained during strong earthquakes should be available to competent authorities and specialized institutions in 24 hours after the earthquake.

The cost of seismic data acquisition system is low compared to the total amount of a modern tall building, with finishes, endowments, facilities and modern equipment, or to an industrial investment, which would otherwise be decommissioned pending traditional expertise.

Proper understanding by the designer of the importance and influence of various factors on structural dynamic response, and their correlation with the objectives of interest to the beneficiary, leads to a choice and a suitable distribution of the seismic monitoring systems' components in the building.

3. DYNAMIC PARAMETERS DETERMINATION THROUGH SEISMIC INSTRUMENTATION

In terms of dynamic, a building can be modelled as an elastic system embedded in the ground through a rigid foundation and the ground can be modelled as elastic half space.

The ground motion is usually a chaotic feature and for this reason the time variation of various kinematical parameters can't be described in mathematical terms by simple analytical functions. Such phenomena must be modelled by so-called random functions, defined as functions of time for which the values at a time are random variables.

Spectral composition of these oscillations is influenced by the nature of disturbances. It is necessary that the excitation meets a fundamental condition to allow emphasis on the response of the dynamic characteristics of the building. This condition refers to the spectral density of excitation, which should be "broadband", with a constant value on a range of frequencies (pulses) as large as possible.

The use of experimental determinations to identify proper periods, as well as other dynamic characteristics of the constructions, is based on theoretical developments in dynamic structures. Between the period (the term most often used in engineering practice), frequency and pulse exists the simple relationship, as Eq. 3.1.

$$T = \frac{1}{f} = \frac{2\pi}{\omega}; \quad f = \frac{1}{T} = \frac{\omega}{2\pi}; \quad \omega = \frac{2\pi}{T} = 2\pi f \tag{3.1}$$

An important element involved in calculating the building subjected to seismic forces, is the proper vibration period of the building, whose value, determined experimentally, can give an indication of the stiffness and resistance capacity level of these structures to horizontal seismic forces.

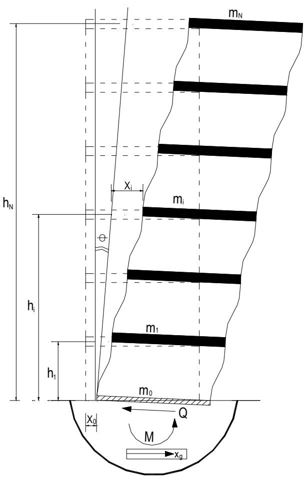


Figure 3.1. Structure-ground dynamic model

During the earthquake all buildings behave beyond the elastic range, which implies changing of all dynamic characteristics. It is obvious that after the ground motion ends, the structure will remain with modified physical and mechanical characteristics. Thus from the degradation caused by the earthquake, the building' stiffness decreases, the proper periods are increased and the percentage of critical damping increases. So the higher a building is damaged, the higher are the proper periods than their initial ones. But the rigidity and proper period values of the constructions are influenced not only by visible degradations, but also by a series of deformations and invisible cracks accumulated in the building structure, which can be important. Such deformation occurs sometimes later, as observed after the earthquake of 03.04.1977, when to the number of damaged buildings, it was found later, long after the earthquake, an increased occurrence of cracks or appearance of new ones.

Therefore, measuring of proper vibration periods of the buildings in their different situations, namely: after being released to service, before the earthquake, after the effect of the earthquake that caused damages and weakened the structure, or after the strengthening and reinforcement so it allows a determination of the rigidities and therefore very useful assessment of the degree of damage and resistance capacity of buildings.

When one wants to determine the proper rotation periods in the horizontal plane, known as proper period of overall torsion is necessary to perform a series of recordings of synchronous oscillations in pairs of points located at large distances from the stiffness centre assessed by the experimenter, on the same floor of the building (preferably the top floor). If the floor has a rotation movement in plane, the extreme points of selected pairs will move in phase opposition.

Similar processing methods of the above sum and difference of signals for the mentioned pairs, because of chosen movement points, allow the determination of their rotation periods in the horizontal plane (torsion). In most common cases, in which the fundamental mode of oscillation is predominant, the determination of their basic forms (for oscillations in the two main planes of the building) can be easily done.

Experimental determination of fractions from critical damping can be achieved based on the autocorrelation function properties of the response.

The rotation influence of foundations on the field may have important effects for buildings located on land with higher deformation. Share rotating on the field from total response of the building can be determined based on experimental data. Conclusions that can be drawn refer only to the linear behaviour for both land and building.

The method for determining the foundation rotation consists of seismometers recording the vertical oscillations of the building, at the foundation level, in two main points in main vertical plane, where oscillations of the building are considering, located wherever possible, at its extremities.

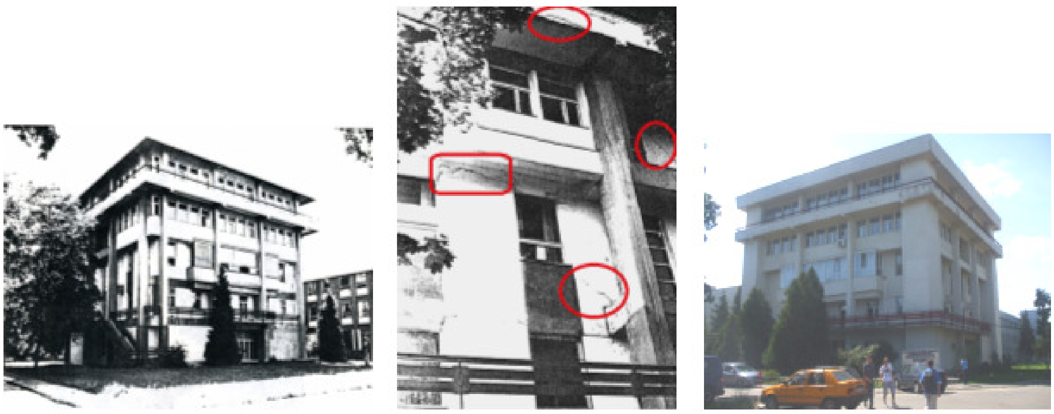
Floors deformation in dynamic conditions can be emphasized by seismometers located in a large number of points, located on the floor level, on a straight line, method that allows obtaining the floor deformations at different times. The deformation occurs mainly in constructions with special shapes in plane, with large openings of the floors, and it is very important the way horizontal forces are transmitted to the vertical resistance structure.

According to the modern approach of preparedness, the post-seismic interventions should be clearly foreseen and properly planned in order to avoid additional damages and fatalities as well as to save what remained worth to be further used. The post-seismic interventions should be designed and organised according to the provisions of the ISO13822:2001. The clause 7.4 regarding the plausibility of interventions should be carefully considered. It can be also extended on the rehabilitation of building environment after a comparative analysis of existing solutions. All the aforementioned ideas are illustrated through a study case.

4. CASE STUDY – BUCHAREST F.L.R.E.E. BUILDING

Analysed building is located in Bucharest, in the University of Agricultural Sciences and Veterinary Medicine on Blvd. Marasti. The building belonging to the Faculty of Land Reclamation and Environmental Engineering consists of three bodies labelled A, B and C. The three bodies have reinforced concrete frames structures, designed in the '70s, according to Norm P13-70 (see Fig. 4.1). This case study shows the evolution of dynamic parameters for the body A, from putting in work to date.

Although the height regime is low (H = 20.33 m) and the in plane form is regular, the earthquake of March 4, 1977 has caused damages, especially in structural elements, due to insufficient stiffness for the protection of partition elements.



a) initial structure - 1973 b) damages after 1977 earthquake c) actual structure - 2011

Figure 4.1. Faculty of Land Reclamation and Environment Engineering building in different stages

Later to the 30/31 August 1986 earthquake, INCERC has determined the dynamic characteristics of this building. Strengthen works were completed in 1990, after the earthquake of May 30. As such, it was performed a new experimental determination of dynamic characteristics of the building changes due to cumulative effect of building works and the earthquake of May 30, 1990.

The results of these measurements revealed an increase in overall stiffness by 37% in the transverse direction, with 76% in the longitudinal direction and 64% for the overall torque.

After P100-92 Code entered into force, further strengthening works of the structure were carried out , bringing the building to its requirements regarding the maximum allowable relative deformations level for protection of non-structural elements.

This consolidation works executed up to level 4, are likely to meet these requirements. To verify the effectiveness of these works, University of Agriculture Sciences and Veterinary Medicine requested the determination of dynamic characteristics of body A of the Land Reclamation and Environmental Engineering building.

To identify the dynamic characteristics to a higher level of stress, measurements were made during building demolition by implosion of the former home, at about 50 m of body A, on October 11, 1996.

These results and the micro-seismic level, performed at the same time, are very useful for assessing the effect of latest consolidation works carried out in 1997.

Table 4.1 shows the time evolution of proper periods of body A of F.L.R.E.E. Bucharest, with records available by INCERC Bucharest from 1986 to 1998.

Table 4.1. Time evolution of proper periods of body A of F.L.R.E.E. Bucharest

Data	Type of excitation	Direction of oscillation	
		Transversal	Longitudinal
3.12.1986	Micro-seism (after earthquake in 30/31 August, 1986)	0.62	0.57
19.11.1990	Micro-seism (after earthquake in May 30, 1990)	0.53	0.43
11.10.1996	Micro-seism (between blast)	0.50	0.44
11.10.1996	Blast – maximum excitation	0.57	0.50
11.10.1996	Blast – free oscillations	0.53	0.44
13.02.1998	Micro-seism (after structural intervention in 1997)	0.42...0.44	0.40...0.42
21.12.2009	Micro-seism (after entered into force of Romanian Code P100-1:2006)	0.35	0.42

Below are presented the records made with GBV GeoSIG 316 device (see Fig. 4.2) in 2009, when the new design code P100-1: 2006 entered into force. Records were made on the 4th floor of body A of F.L.R.E.E. building. Processing's were performed with GeoDAS program that leads to the displacements, velocities, accelerations, time varying accelerations and the oscillation fundamental periods of the building (see Fig. 4.3).

Figure 4.2. GeoSIG GBV 316 device

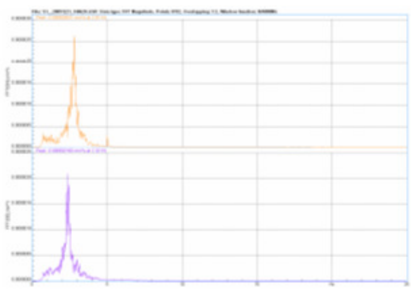


Figure 4.3. F.F.T. on 2 horizontal directions

It's found that the oscillation period of the building was reduced by approximately 19% compared to values measured in 1998. It is estimated that this reduction is due to the processes of cooperation of the various parts, old and new, from the structure and also due to the earthquake of magnitude Mw = 6.0, which took place on October 27, 2004 in the Vrancea seismic zone, which may contributed to structural transfer efforts from the four concrete caissons to the structure.

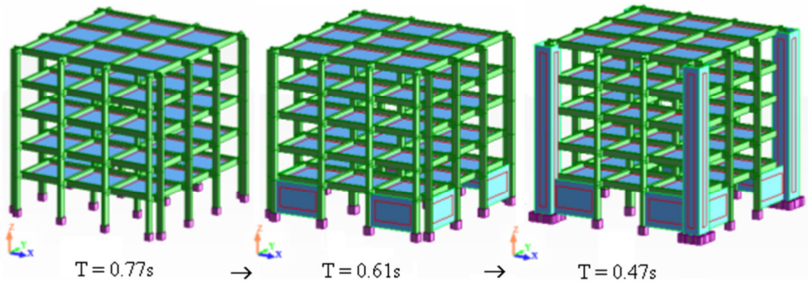


Figure 4.4. A-body structure in three hypotheses: initial (left), after first structural intervention (centre), actual (right)

In Fig. 4.5 are presented the results of structural analyses performed with the program Robot Millennium in three structural hypotheses: first in 1973, after the first strengthening, in 1986 and existing building in 2011. The results indicated an increase in overall stiffness of the structure with 72% of initial stiffness. However, the values obtained by calculation in all three structural hypotheses differ from values obtained from seismic instrumentation of the building, especially in the second hypothesis (after the first consolidation).

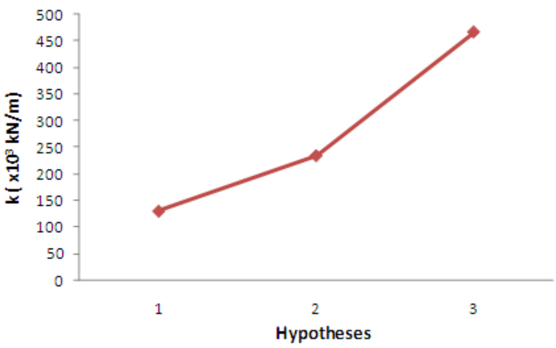


Figure 4.5. Structural stiffness variation in three hypotheses

For F.L.R.E.E. building - Bucharest there is a geotechnical study stating that the foundation soil contains clay contractile. It notes that the project developed in 1972, contains small isolated foundations, made to the minimum depth allowed by law.

During the strengthening in 1996, for the corner caissons of body A, the foundation depth was lowered. In these conditions the ground-structure interaction has changed over time.

Considering these aspects, there were also taken into account the two structural hypotheses: 1. building bodies are separated by seismic joints, and, 2. building bodies are connected. These assumptions are applied for both - rigid and elastic foundation.

The results of analyses made with the ROBOT program were validated through dynamic parameters of the structure, which are the oscillation periods and frequencies, determined by measurement.

The conclusion of the comparative analysis shows that the real behaviour of the structure corresponds to the structure with elastic foundation hypothesis (there is a ground-structure interaction) without seismic joints (see in Fig.4.6).

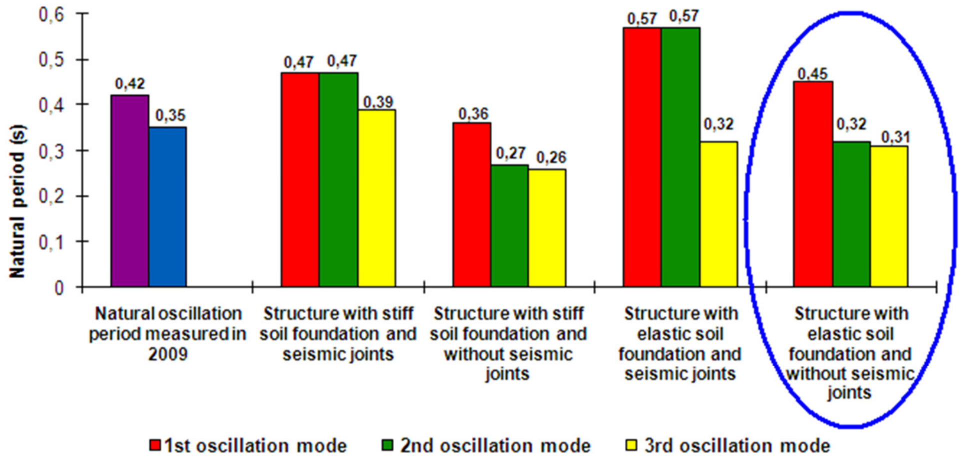


Figure 4.6. Comparative results regarding natural periods for first three oscillation modes

By closing the seismic joints the distance between the two intrinsic centres has increased significantly, as can be seen in Fig. 4.7 and 4.8. This increasing of the calculation eccentricity leads to an increased torque and therefore to major efforts in the structure.

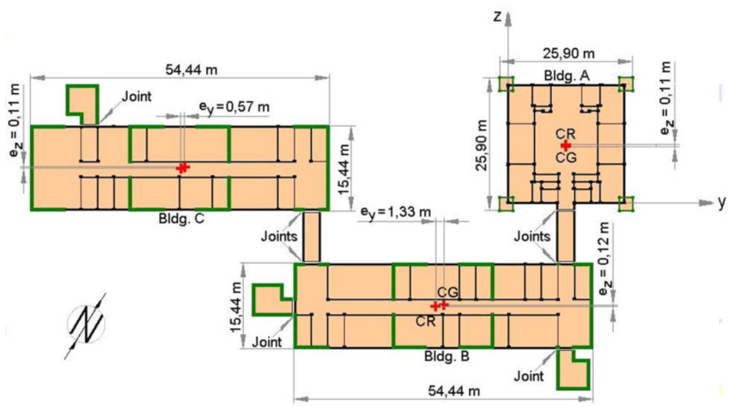


Figure 4.7. Eccentricity between two intrinsic centres after structural interventions-hypothesis with seismic joints

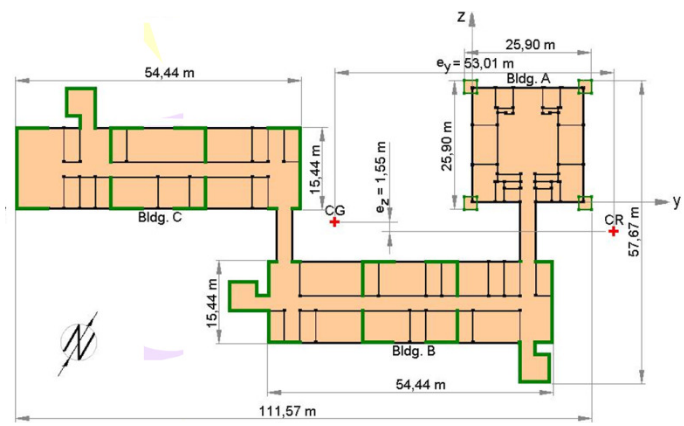


Figure 4.8. Eccentricity between two intrinsic centres after structural interventions-hypothesis without seismic joints

In conclusion we can say that the structure was reinforced in 1972 compared with the initial structure, but closing the seismic joints will lead to significant structural damages from future earthquakes. This conclusion is accentuated by the cracks appeared in the old joints after the earthquake of October 27, 2004 (see Fig. 4.9).

a) Seismic joint between A and B bodies

b) Seismic joint between B and C bodies

Figure 4.9. Damages around seismic joint area

The influence of the ground-structure interaction on the coupling phenomenon is considered in the comparative study regarding the relationship between their first two oscillation modes which are bending and the third mode which is twisting. All these modes have been obtained by calculation using the ROBOT program and are validated by recent measurements with specialized instrumentation.

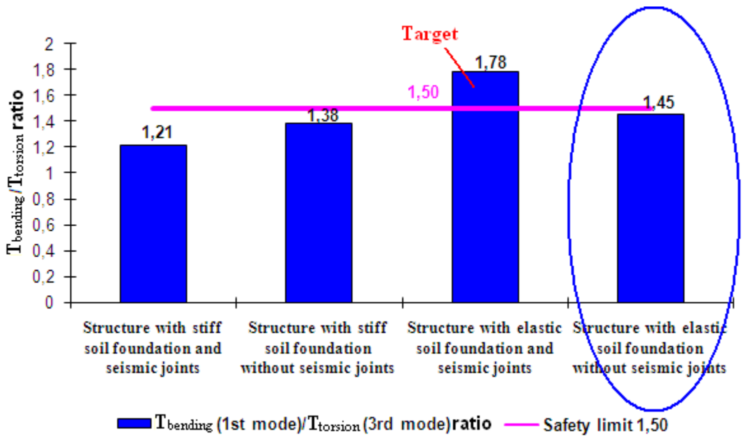


Figure 4.10. Relationship between 1st oscillation mode and the 3rd oscillation mode of buildings

It ascertained that:

1. From the comparison of 1st (bending) and 3rd (twisting) modes in the hypothesis of structure with rigid foundation and seismic joints the two modes are appropriated at a ratio of 1.21 and the danger of instability through the coupling exists.
2. In the same situation above, comparison of 1st and 3rd modes, but in the hypothesis of structure with rigid foundation without seismic joints, the situation is improving in that the ratio increases to 1.38, but the danger of instability through the coupling is maintained.
3. From comparison of 1st and 3rd modes in the hypothesis of structure with elastic foundation without seismic joints, which is the current situation, the ratio between bending and twisting is 1.45, but still remains below the safety limit of 1.5.

4. Only in the hypothesis of structure with elastic foundation and seismic joints, when comparing the oscillation modes 1 with 3, we obtain a favourable upper limit of 1.78 > 1.5, which motivates the practice of seismic joints between body A and other bodies.

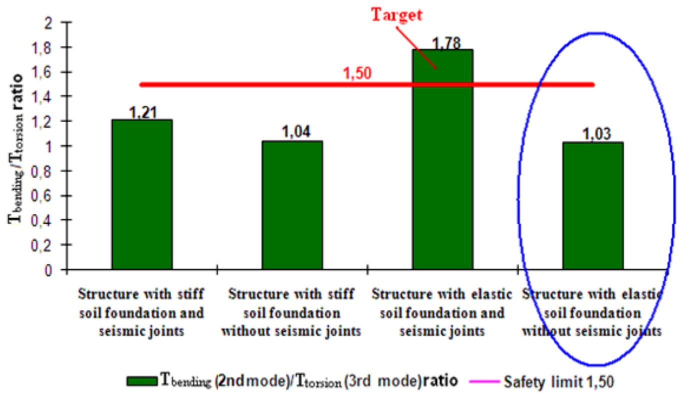


Figure 4.11. Relationship between 2^{nd} oscillation mode and the 3^{rd} oscillation mode of buildings

5. By comparing the oscillation modes 2 and 3 in both cases with rigid foundation and without seismic joints, the ratio of dynamic parameters remains well below 1.5.
6. Even in the hypotheses of structure with elastic foundation without seismic joints, which is the real situation, the ratio of two modes 2^{nd} (bending) and 3^{rd} (twisting) the ratio is only 1.03 showing the danger of instability through the coupling.
7. To be noted however that in the hypotheses of structure with elastic foundation and seismic joints, the ratio of modes 2 and 3 remains above 1.5, which is a strong argument for the practice of seismic joints between existing bodies of the building.

5. CONCLUSION

Proper period of vibration measurement may reveal a number of structural damages that has incurred the structure until the measurement; a measurement of this size before and after the earthquake, represents a global method for assessing the stiffness variation of a construction due to the seismic stress, except that stiffness such highlighted, corresponds to the low levels of stress.

Consequently, seismic instrumentation of buildings is a form of specific monitoring and is a modern, complex and multilateral seismic data acquisition system, both on the seismic characteristics of the sites and also on the dynamic characteristics response of structures.

Regarding the case study is found that after strengthening interventions, the joints were closed and therefore the construction was constrained, all 6 degrees of freedom were cancelled. Although trough the strengthening interventions the improvement of the situation was desired, by closing the joints the situation was complicated because the dynamic conditions were not met (see Fig. 4.10 and 4.11).

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