13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2299

VERIFICATION TESTS AND RESPONSE OBSERVATIONS ON A NEW SPECIAL BUILDING IN VIEW OF CONTROLLING THE STRUCTURAL DESIGN AND EXECUTION

Ion VLAD[1], Mirela-Nausica VLAD[2]

SUMMARY

During the past three decades structural control has been an attractive focus of research and design and has received considerable attention both from researchers and designers.
There are the two ways of protecting structures against the effects of earthquake ground motions and wind. The first one is based on the conventional design philosophy, and the second on the structural response control. The structural systems designed for the seismic loads normally recommended by codes can survive strong ground shakings only if they have sufficient ability to dissipate seismic energy. The energy dissipated by the inelastic deformations requires adequate ductility of the elements in the structural system Olariu [1]. Two different goals of structural control must be given consideration: the utilization of control in the design of new structures, and the utilization of control to improve the seismic or wind resistance of existing structures. The problems posed by existing structures differ from the problems of designing new structures because of various constraints imposed by the fact that the building already exists. Another important aspect of Structural Control is the condition assessment of structural systems. This broad topic is usually referred to as "Structural Health Monitoring". Its goals are to detect, locate, and quantify the level of damage in typical civil systems.
In this paper *structural control* is associated with design of a new special building and verifying of the accuracy of the structural model used in design by means of instrumental investigations.
The conclusion of this paper consists of the idea that there is no structural system whose response to seismic actions can not be controlled, so that a favorable behavior in the future is assured. As it was presented in the beginning of this paper the objective is to use the combination of passive structural control to provide integrated control of structural vibrations together with instrumental dynamic investigations, as a practical application for the building above mentioned.

1. INTRODUCTION

The authors of this paper understand by "structural control" the control by design of the *response* of the structural systems of the buildings when they are subjected to earthquake and wind loadings. In the case of the design of a new building, or in the strengthening process of an existing one (damaged or

[1] Professor, Technical University of Civil Engineering Bucharest, Romania. Email: vlad@dial.kappa.ro
[2] Doctor Engineer, Technical University of Civil Engineering Bucharest, Romania. Email:vladi@itcnet.ro

undamaged by ground strong motions), the concept of structural control has to be understood as the choice and the consciously constraint of certain favorable structural characteristics in the designing stage, in view of reducing the seismic or wind effects on the structural system of the building. Thus, the main objective by means of *structural control behavior* is to obtain for a structural system, when excessive vibrations are produced by the earthquake and wind loadings, an expected response.

In this paper, structural design is considered to be the activity involved in defining the physical makeup of the structural system *only* to seismic action. Generally, the "designed" structure has to satisfy a set of requirements pertaining to *safety* and *serviceability*. Safety relates to extreme loadings that have a low probability of occurring during a building's life. The concerns here are the collapse of the structure, major damage to the structure and its contents, and loss of life, Connor [2]. Serviceability pertains to moderate loadings that may occur several times during the structure's lifetime. For service loadings, the structure should remain fully operational (i.e., the structure should suffer negligible damage and, furthermore, the motion experienced by the structure should not exceed specified *comfort limits* for humans and motion-sensitive equipment mounted on the structure).

Safety concerns are satisfied by requiring resistance of the individual structural elements to be greater than the demand associated with the extreme loading. The conventional structural design process proportions the structure based on strength requirements, establishes the corresponding stiffness properties, and then checks the various serviceability constrains such as elastic behavior. Iteration is usually necessary for convergence to an acceptable elastic structural design. This approach is referred to as *strength-based design* since the elements are proportioned according to strength requirements.

Motion-based structural design is an alternate design process that is more effective for the structural design problems just described. This approach takes as its primary objective the satisfaction of motion-related design requirements, and views strength as a constraint, not as a primary requirement. Motion-based structural design employs structural motion control methods to deal with motion issues. Structural motion control provides the conception framework for the design of structural systems, where motion is the dominant design consideration, Connor [2].

A number of imaginative approaches for improving earthquake response performance control and damage control of buildings have been developed, and other will be forthcoming in the near future, Housner [3], Hanson [4].

According to [3] and [4], these approaches were synthesized into four groups:

- *passive control systems* (this category depends on the initial design of the structural systems, base isolation and supplemental energy dissipation devices, established by a control design; a passive control system does not require an external power source);
- *active control systems* (these systems require the active participation of mechanical devices whose characteristics are made to change during the building response on the basis of current response measurements; so an active control system is one in which an external source power control actuator(s) that apply forces to the structure in a prescribed manner);
- *hybrid control systems* (these systems combine the use of passive and active control systems in a manner so that safety of the building is not compromised even if the active system fails; for example, a structure equipped with distributed visco-elastic damping supplemented with an active mass damper on or near the top of the structure, or a base isolated structure with actuators actively controlled to enhance performance);
- *semiactive control systems* (these systems are a class of active control systems for which the external energy requirements are orders of magnitude smaller than typical active control systems; semiactive control devices are often viewed as controllable passive devices.

Health monitoring is a topic which is of considerable interest in civil engineering. Health monitoring refers to the use of in-situ, nondestructive sensing and analysis of structural characteristics, including the structural response, for the purpose of establishing some knowledge of the current condition of a structure and detecting changes that may indicate damage or degradation. From the above approaches, the paper presents some aspects related only to the passive control system for a building, assured by its designing process and by dynamic instrumental investigations, as a first step of its structural health monitoring. All vibrating structures dissipate energy due to internal friction, cracking, plastic deformation and so on; the larger the energy dissipation capacity the smaller the amplitudes of vibration.

2. THE CONTROL OF STRUCTURAL DESIGN

The first stage of the design process is the one corresponding to the recommendations of the earthquake resistant code, within which the structural control consists of:

- the choice of a favorable "*spectral position*"; by spectral position it is understood the pair of values represented by the natural period of the fundamental mode of vibration, and the base shear force coefficient corresponding to the maximum strength capacity offered by the structural system considering the associated inelastic mechanism;
- the choice and the impose of a favorable mechanism for seismic energy dissipation, by fixing the positions of the zones with post-elastic deformations.

In the mean time it is necessary to take into account the following important aspects:

- the ensuring of high ductility capacities necessary in zones with post-elastic deformations;
- the avoidance of unfavorable modes of failure for the structural elements;
- the avoidance of certain instability aspects produced by excessive displacements (P - Δ effects).

The above elements refer to a direct action over the structural components by conception/proportioning and by structural analysis.

In the second stage of the controlled design, the designer can choose one of the approaches presented in paragraph 1 in order to improve the response of the structural system. Modern techniques offer supplementary possibilities, by means of which the structural system response to seismic actions can be imposed/controlled, as seismic isolation of the basis of the structural system, additional special devices for the seismic induced energy dissipation a.s.o.

The general concept of choosing and imposing of a favorable "spectral position" is also outlined by the following two situations:

(a) *The case of existing buildings to be strengthened*. A specific feature of the intermediate Vrancea earthquakes is that the predominant periods for the most exposed regions pertain to the range 0.9÷1.5 sec. (the maximum ground displacements during the destructive earthquake of 1977, derived from recorded accelerograms, were of some 20 cm). In this case, the improvement of the "spectral position" requires frequently the increase of the structural system stiffness, in view of shortening of the fundamental period of vibration, together with the increase of the seismic strength capacity.

(b) *The case of the "passive structural control" by seismic isolation of the base.* Considering the "Vrancea" types of accelerogram characteristics, on the basis of the "inelastic response spectra", it is necessary to locate the favorable "spectral position" within the natural vibration period range larger than 4.0 sec, which require horizontal displacements of the isolators greater than 40 cm.

3. STRUCTURAL CONTROL CONCEPT APPLIED FOR A NEW BUILDING IN ROMANIA

3.1 Short description of the building

In the companion paper no.1903, Vlad [5] included in the documents of 13WCEE a detailed architectural and structural description of the building was carried out. The architectural project established that the new building should have, in the horizontal plane, the shape of an equilateral triangle, having the sides of 50 m. In each of the three peaks of the triangle, structural cores (A_1, A_2 and A_3) were placed, each of them being realized with structural reinforced concrete walls. The office building has a basement and 10 stories and a *dual* type structural system, consisting of a reinforced concrete subsystem and a steel subsystem.

The superstructure of the building, of composite type, has two different parts:

- *a reinforced concrete structural subsystem* formed by the three structural cores placed in the peaks of the equilateral triangle, their main role being that of assuring the lateral strength of the building to the seismic loadings;
- *a steel structural subsystem*, having a structural role mainly towards the gravity loadings, and assuring the transmission of the horizontal seismic loadings to the three resistant and rigid vertical reinforced concrete cores.

The substructure of the building and its **foundation structure** has a unitary concept able to ensure the base fix jointing of the vertical structural elements (the columns and the structural cores).

3.2 Aspects related to design and instrumental investigations

The main stages had in mind in the design process and in the construction of the structural system of this building, from the applying of structural control point of view, underline the following aspects:

- the design of the reinforced concrete structural subsystem, imposing/controlling its response to the future seismic actions;
- the verifying of the accuracy of the structural model of analysis used in design, by means of dynamic instrumental investigations;
- the instrumental investigations for the dynamic characteristics of the building (after the construction of the reinforced concrete structural cores, after the construction of the steel structural subsystem and after the complete finishing of the office building);
- the seismic instrumentation of the building.

3.3 Structural control conferred by design

Taking into account the conceptual elements presented in paragraph 2, at the design of the reinforced concrete structural subsystem of the building the following essential aspects were kept in mind:

- the choice of a favorable "*spectral position"*;
- for the control of the inelastic response of the actual structural system it was imposed that the inelastic zones are restricted only to the bottom zones of the structural cores, for any direction of the seismic action;
- avoiding the producing of plastic deformations in the coupling beams, by assuring high ductility capacities.

a. The choice of a favorable "spectral position"

One can state that for a story height of 4.0 m and an overall height of the building of more than 36.0 m (the last two stories are only partially developed in the horizontal plane), the natural period of the fundamental mode of vibration "T_n" would result greater than 1 second, and a "*spectral displacement*" greater than 15 cm. Having in mind that the building was provided with a curtain wall system, it was imposed by design that the natural period of the fundamental mode of vibration be reduced, in view of ensuring a drift control of the structural cores subjected to seismic actions. Consequently, it was necessary to impose/control a natural period of vibration of about 0.4 seconds, thus resulting a "*spectral displacement*" of 3 cm. The accelerogram recorded during the March, 4th 1977, Vrancea earthquake, is completely different of the El Centro accelerogram, so that the philosophy of design, in case of the Vrancea earthquakes, is completely different of the design according to the El Centro accelerogram. The Romanian code for the design of structural systems to seismic actions (P-100-92) requires for the reinforced concrete structural cores of the subsystem of the building (Ploiesti town) a global base shear force coefficient "c" equal to 0.156. This value must be taken into account and, and in some cases, it can be even exceeded in the benefice of a favorable behavior of the structural system. For this particular building, the base shear force coefficient ($c_{yielding}$), corresponding to the maximum resistance capacity offered by the structural system considering the associated mechanism of plastic deformation, resulted "$c_y = 0.25$".

b. The imposing of the locations of inelastic zones

The *post-elastic controlled seismic response* is associated with the concept of *energy dissipating mechanism*. The seismic energy absorbed by structural systems is dissipated partially through damping and partially through plastic deformations. The capacity of the whole structure to dissipate energy through plastic deformations depends upon the ductility of plastic zones and upon the number and locations of plastic zones.

Each of the three reinforced concrete structural cores consists of an assembly of structural walls having a constant thickness of 35 cm (with door and window openings), being connected by coupling beams. By stiffening the coupling beams and by ensuring their elastic behavior, it was kept in mind that the structural system of a structural core acts like an elastic beam on the overall height of the building, fixed at the bottom zone, the laws of the theory of strength of materials being thus satisfied. Thus it was possible to impose the position of the plastic deformation zones at the bottom of each structural core (the horizontal sections considered at the level of the floor structure over the basement have inelastic behavior, while the other sections on the building height will behave in the elastic range).

c. The avoidance of plastic deformations in the coupling beams

The walls are bearing elements for the coupling beams. As a result of the possibilities offered by the large story heights ($H_{story} = 4.0$ m), the increase of the coupling beams thickness was possible. Thus, the coupling beams were designed to have height resistance and ductility capacities and to behave in the elastic range. Therefore the development of inelastic deformation in the coupling beams was avoided. These coupling beams, stiff and resistant, that do not have inelastic deformations make that the whole multiple connect box profile act like an elastic beam on the overall height of the building.

4. VERIFICATION TESTS IN VIEW OF CONTROLLING THE STRUCTURAL DESIGN AND CONSTRUCTION

The second part of this paper is devoted to instrumental investigations as a practical application, especially in connection with:

- the verifying of the accuracy of the structural model used in design;
- structural dynamic identification based on the vibration measurements of the building.

4.1 Objectives of instrumental investigations

The main objectives had in mind for the verification tests and response observations can be emphasized as follows:

a) the verifying of the accuracy of the structural model used in design of the three reinforced concrete cores, by means of experimental investigations, after the achievement of their construction;
b) the identification of structural properties of the whole building (after the achievement of the steel structural subsystem) from ambient vibration tests (eigenfrequencies, damping);
c) the establishing of modal characteristics for the large span floor structures, subjected to vibrations generated by different human activities.

This paper covers only the first two items.

4.2 Methodology used during the data acquisition of the experimental/instrumental data

The acquisition of the experimental data was achieved with highly sensitive modern equipment. This one was carefully selected, depending on the stated objectives of the experimental investigations and on the special conditions of performing the measurements. A particular attention was provided in order to guarantee the compatibility of the component elements of the acquisition system. The acquisition and processing systems consisted of 6 SS-1 Ranger seismometers, widely recognized as excellent short-period field seismometers, and VSS-3000, a fully portable acquisition system designed for ambient-and forced-vibration field measurements.

(a) Field procedures. Selection of measuring points.

The first step when performing experimental investigations was to select the measuring locations and orientations. Consequently, for verifying the accuracy of the structural model of analysis of the three reinforced concrete cores (after their individual construction by steel sliding formwork), 3 Ranger seismometers were positioned at the top level of each core, in three separate configurations, as shown in Figure 1.

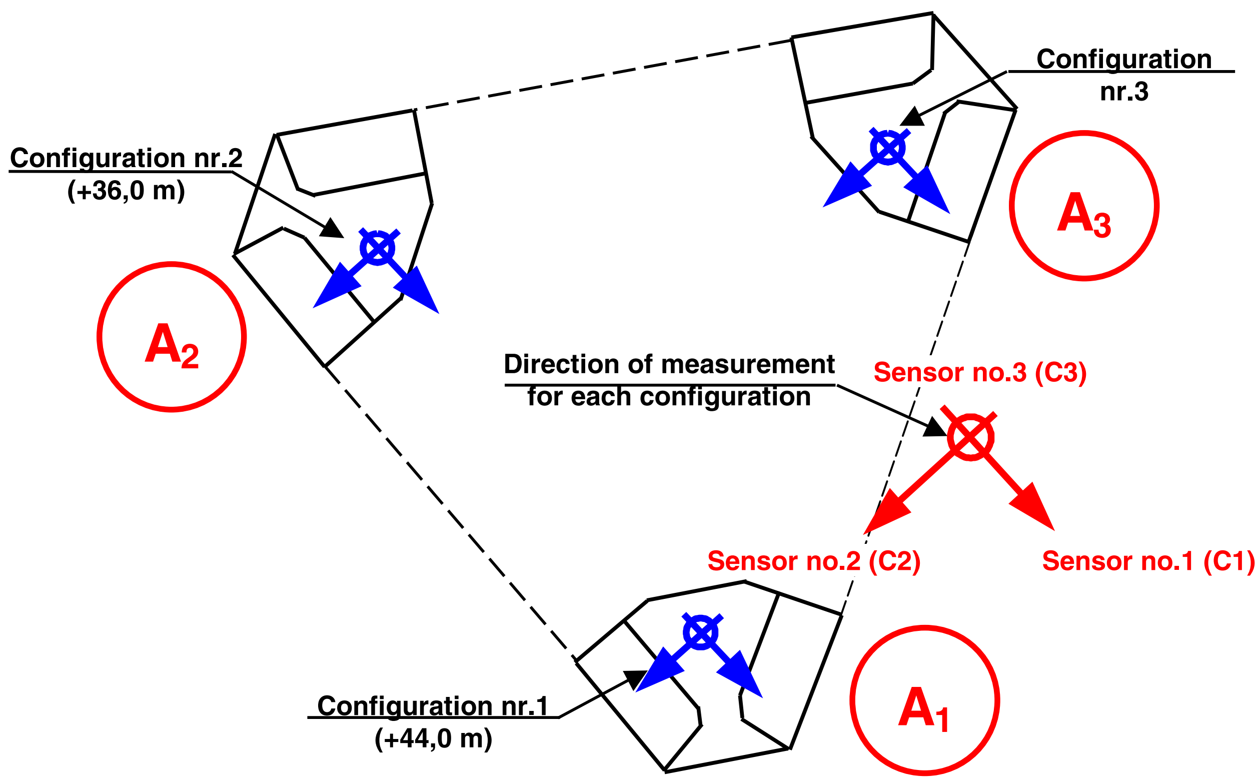

Figure 1. Location of the sensors installed at the top level of each structural core

Some samples of the outcome of the numerical process of the records are given.

In Figures 2 and 5 the time domain velocities (μm/s) for the “A_1” core and the “A_3” core (similar to “A_2” core) are presented. In Figures 3 and 6 the corresponding amplitude Fourier spectra for the “A_1” core and the “A_3” core, and in Figures 4 and 7 the auto-correlation functions are shown.

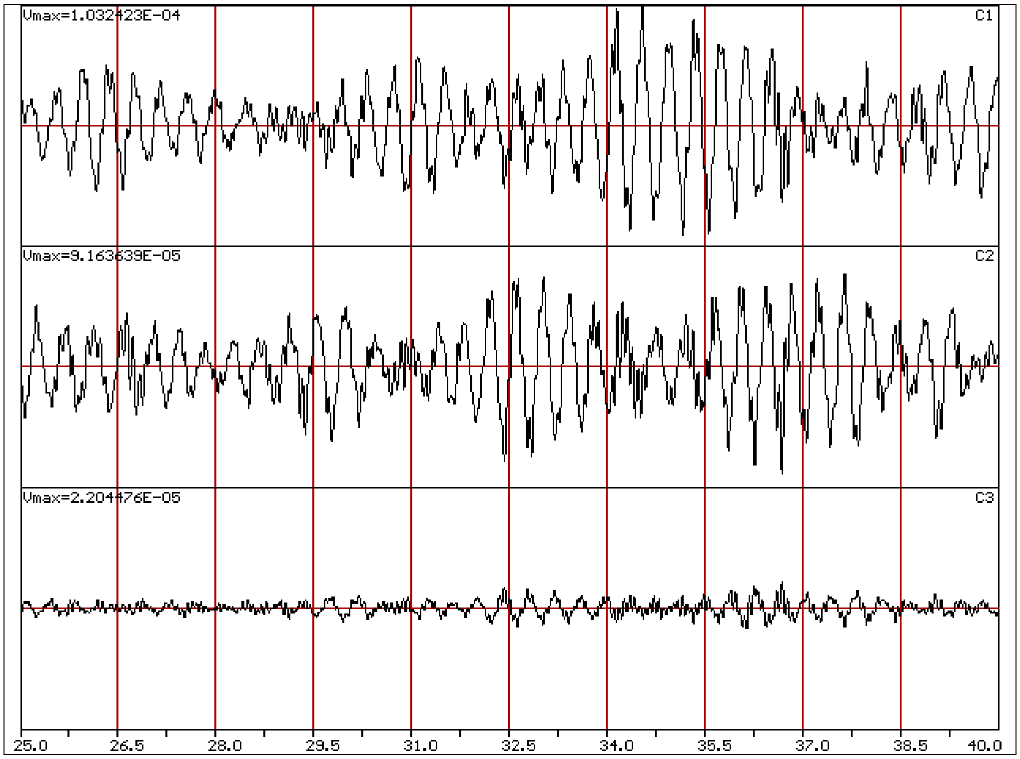

Figure 2. Structural core “A_1”. Microtremors. Time domain - velocities.

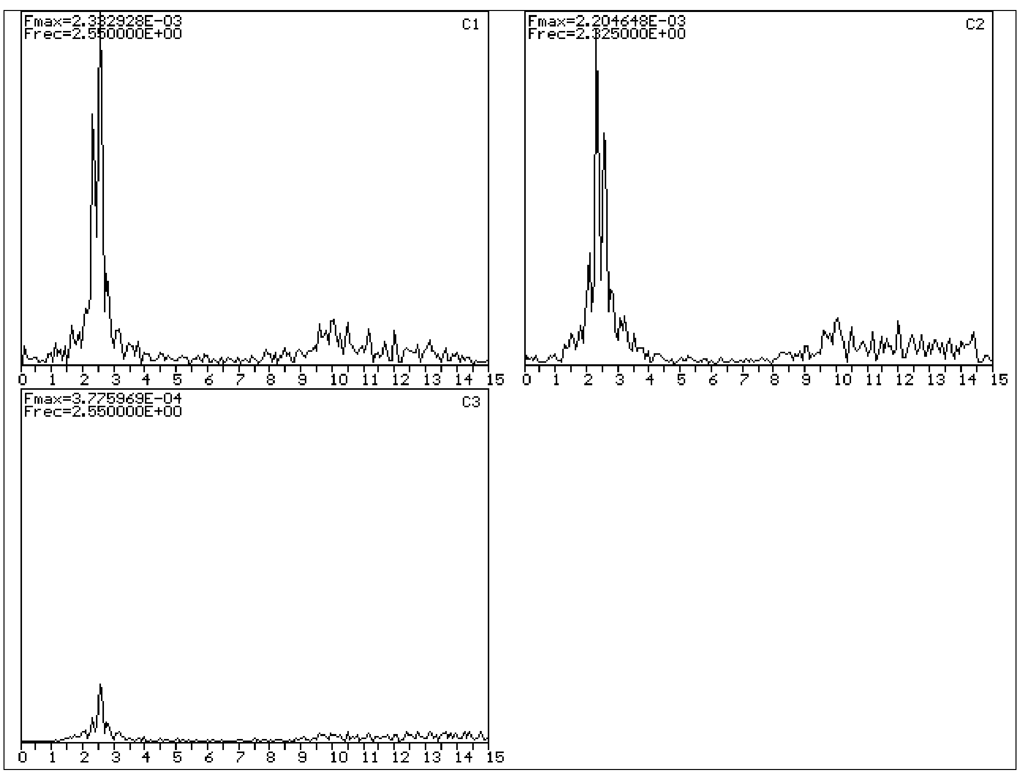

Figure 3. Structural core “A_1”. Microtremors. Amplitude Fourier spectra.

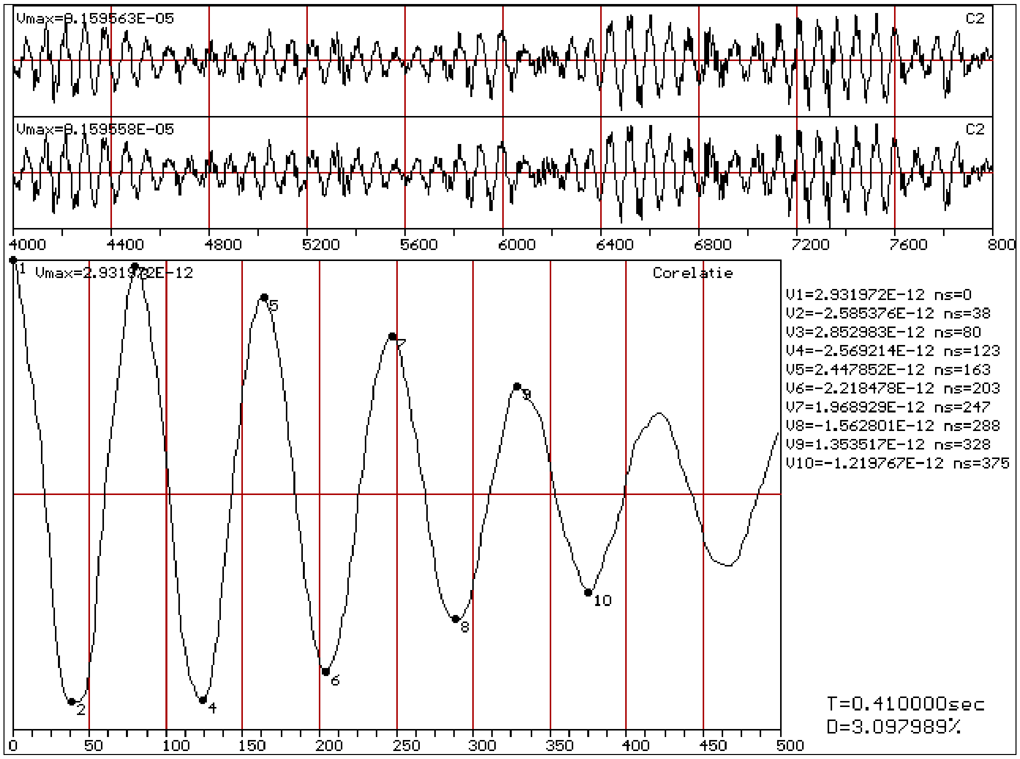

Figure 4. Structural core "A$_1$". Microtremors. Auto-correlation function.

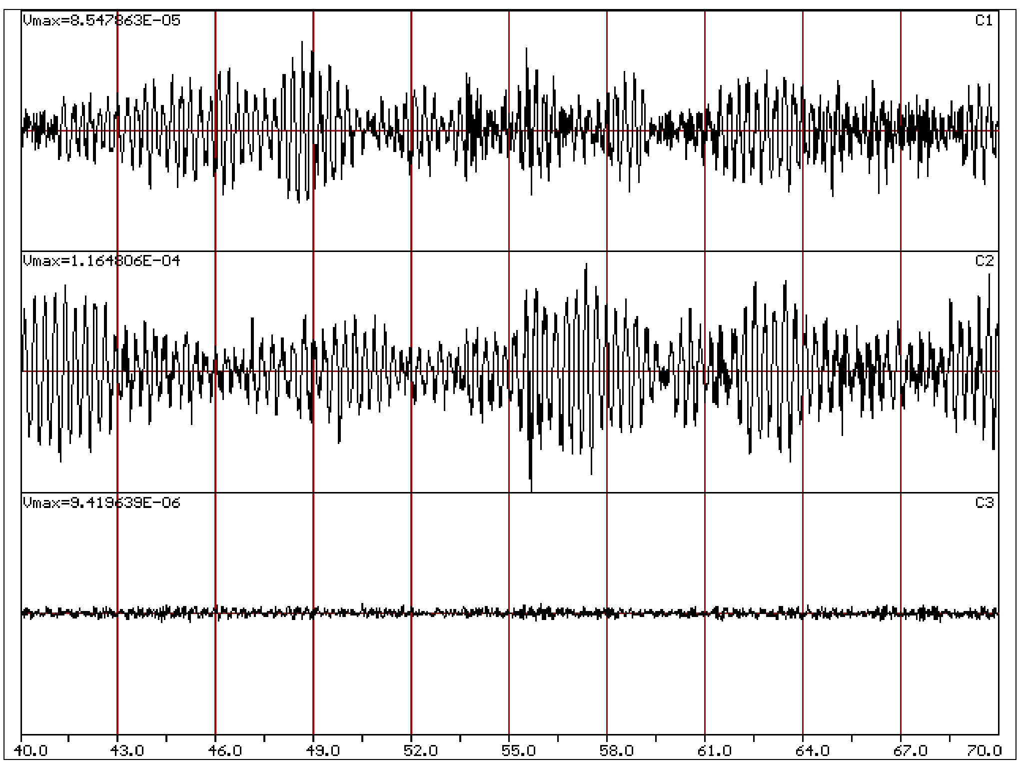

Figure 5. Structural core "A$_3$". Microtremors. Time domain - velocities.

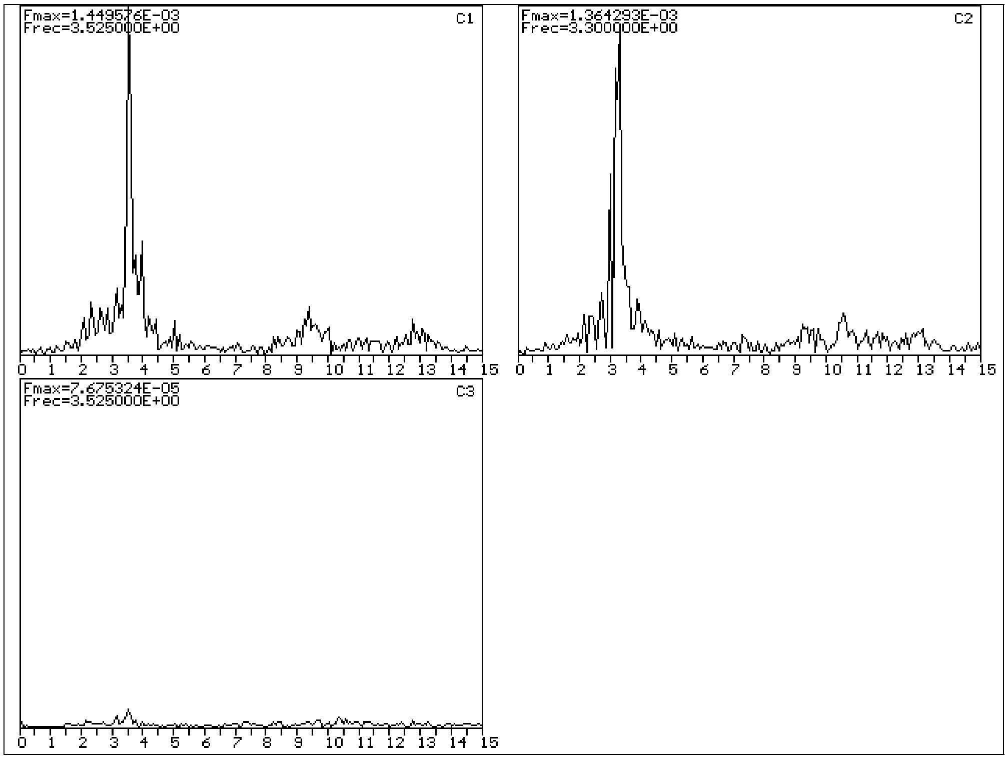

Figure 6. Structural core "A_3". Microtremors. Amplitude Fourier spectra.

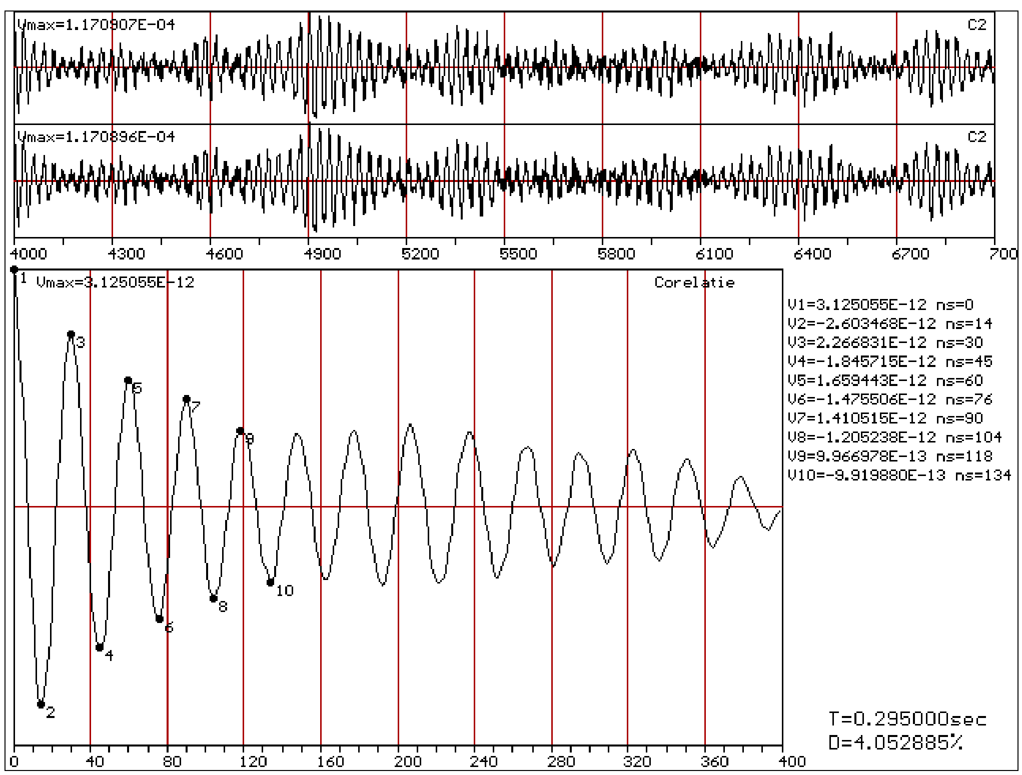

Figure 7. Structural core "A_3". Auto-correlation function.

(b) Field procedures. Selection of measuring points (second stage).

In the second stage of experimental investigations, after the achievement of the steel structural subsystem, the identification of the dynamic characteristics (eigenfrequencies, damping) of the whole structural system of the building was carried out. Alternative settings of the pick-ups were performed, placing the 6 sensors in simultaneous configurations. Two of the settings are presented in Figures 8 and 9. In Figures 10 and 11 the time domain velocities (μm/s) and the corresponding amplitude Fourier spectra for one of the several configurations made at the top level of the new building are presented. In Figures 12 and 13 are shown the same results for a vertical orientation of the pick-ups.

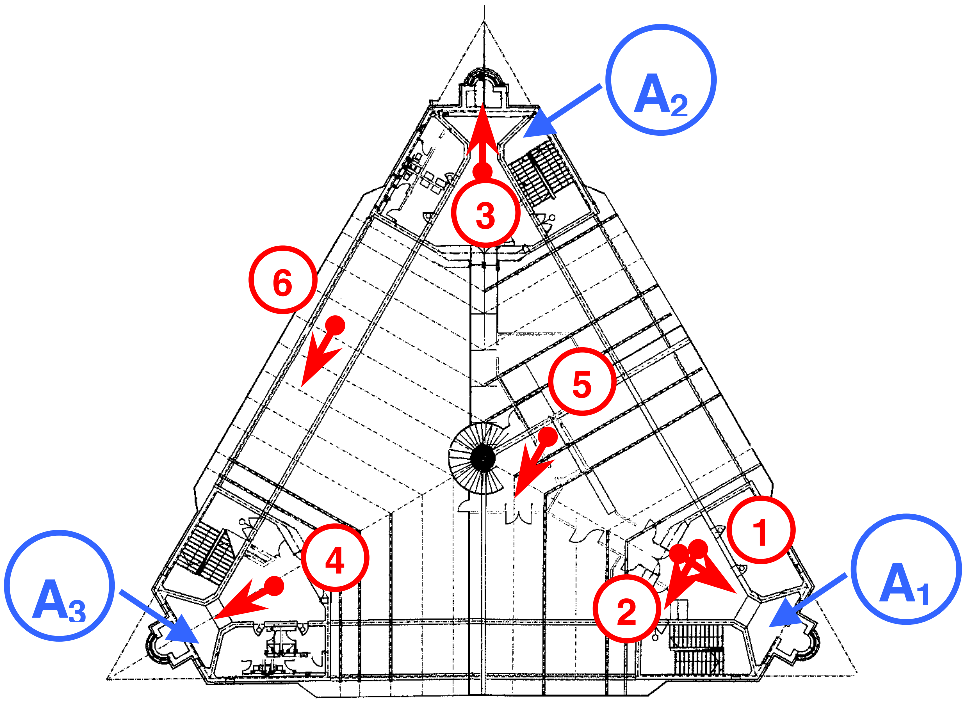

Figure 8. In plane configuration of the sensors (second stage)

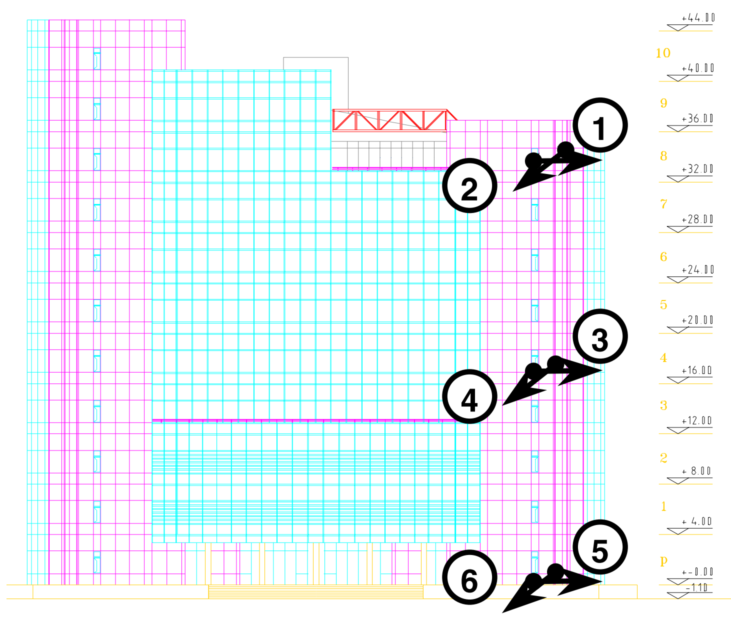

Figure 9. Vertical orientation of the sensors (second stage)

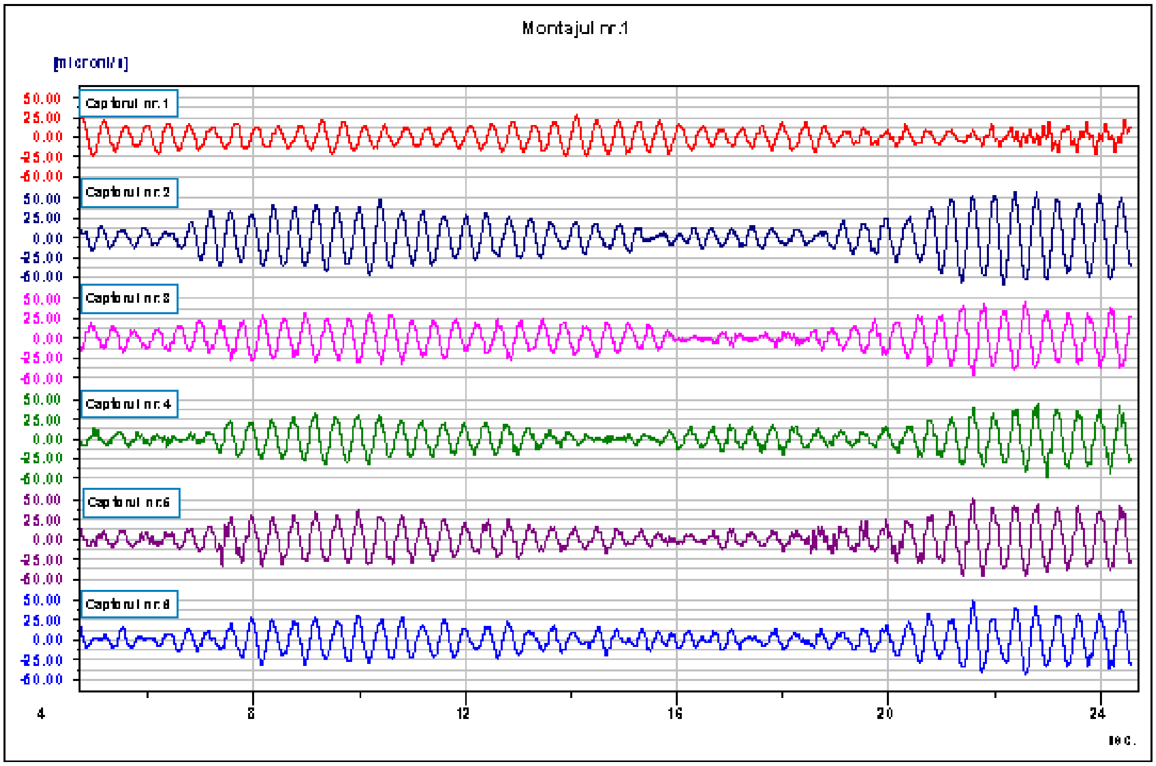

Figure 10. Microtremors. Time domain – velocities (second stage).

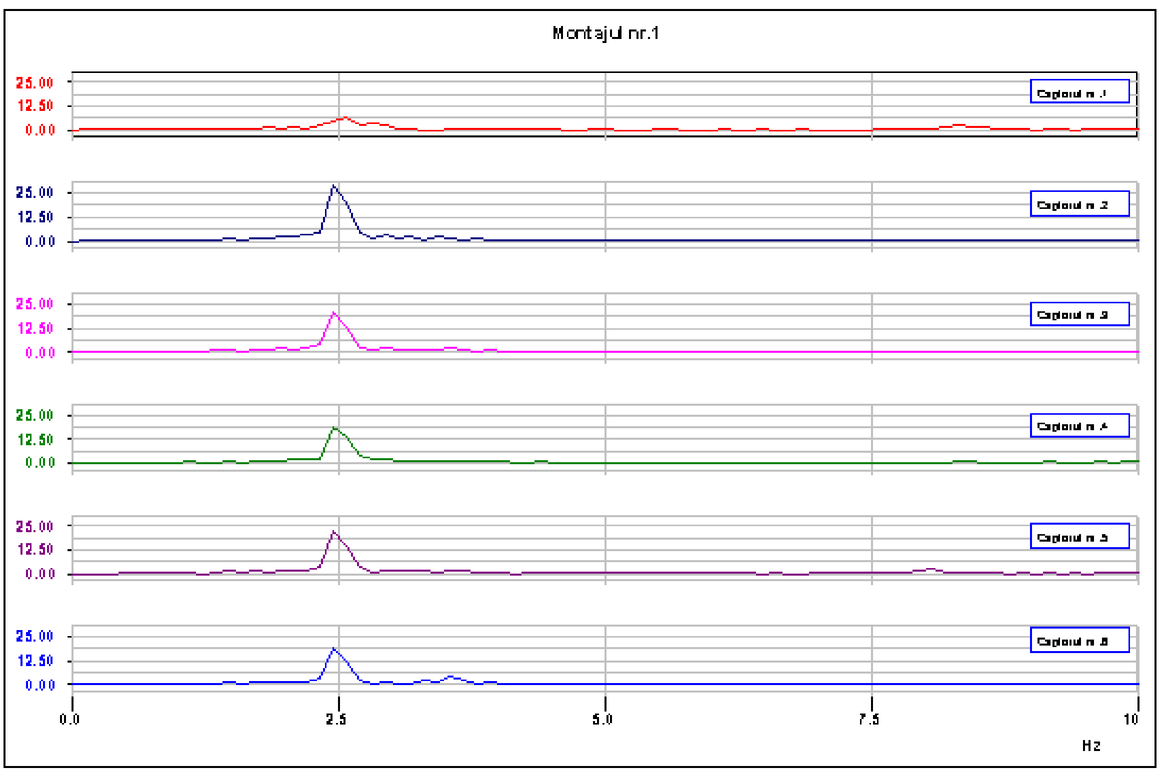

Figure 11. Microtremors. Amplitude Fourier spectra (second stage).

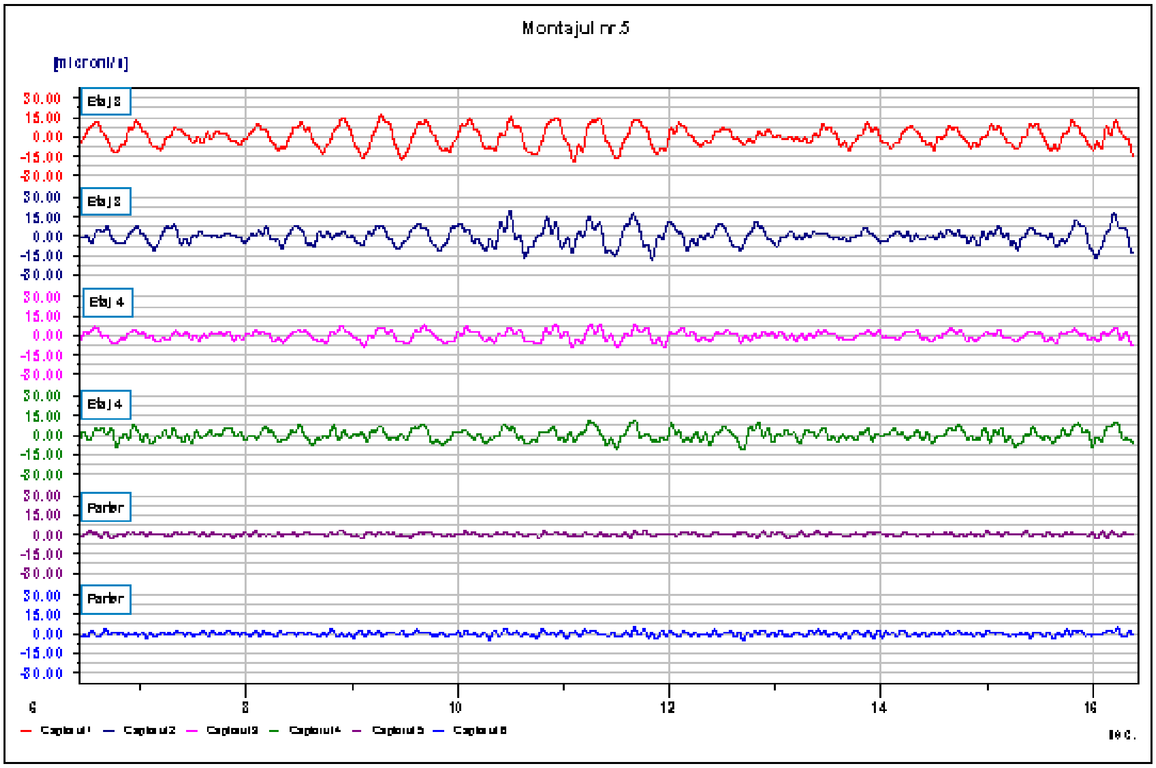

Figure 12 Microtremors. Time domain – velocities (second stage).

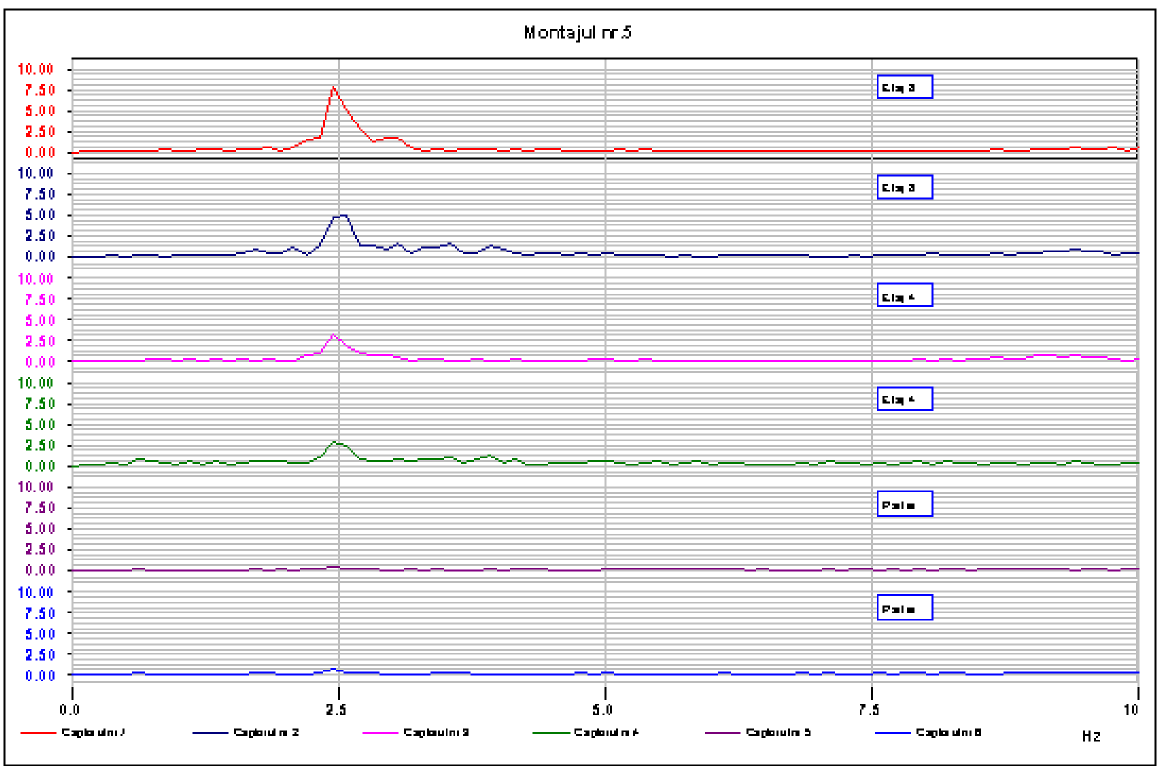

Figure 13. Microtremors. Amplitude Fourier spectra (second stage).

5. SOME RESULTS AND FINAL REMARKS

Some remarks on the design of the building were made in the companion paper no.1903, Vlad [5]. The main objective of the structural control in the design of the structural system of the building is that of obtaining a favorable response to future seismic actions. Taking into account that the building is placed in a high seismic hazard region and is provided with a curtain wall system, it was necessary to assure a favorable spectral position by design. Concerning the structural models of analysis with finite elements, ETABS program offers a natural period for the fundamental mode of vibration equal to 0.4024 sec, and ANELISE – 2D program offers a value equal to 0.4270 sec. The examination of the natural period for the fundamental mode of vibration for the structural core (A_1), based on recording of its vibrations (0.43 sec, E-W direction), shows that the structural models of analysis for the two programs were correctly calibrated. Similar results for the other two structural cores (A_2) and (A_3) were instrumentally obtained. On the basis of the auto-correlation functions of the recorded signals it turned out that the values of the fraction of critical damping pertain to the expected range for reinforced concrete values (4%).

In the second stage of the instrumental investigations (after the construction of the steel structural subsystem), small decreases of the natural period for the fundamental mode of vibration were observed (0.41 sec).

This building has larger span lightweight composite floor system (large uninterrupted floor areas). It was therefore important that the levels of acceptable vibration be established in the conceptual stage, having in mind the anticipated usage of the floors. The instrumental investigations pointed out that the frequency domain established in the design stage was confirmed, Wyatt [6].

Based on the available data, one can state that the results of the structural control in the designing stage were confirmed by experimental dynamic investigations.

Up to the present moment, this building is the first one in Romania to which instrumental dynamic investigations were carried out, in different stages of its construction. This aspect is very important for the detection and assessment of structural damage in case of accidental events or earthquakes, in connection with:

- establishing the existence of damage in the structural system, as a whole;
- location of damage in the overall geometry of the structural system;
- quantification of the degree of damage;
- prediction of the future service duration of the building.

A seismic instrumentation system for the building was conceived for its structural health monitoring.

REFERENCES

1. Olariu I. "Passive control of structural response, an alternative to the seismic structural control in the specific conditions of Romania". Symposium on Structural Control, Technical University of Civil Engineering Bucharest, 2001.
2. Connor J.J. "Introduction to structural motion control". MIT – Prentice Hall series on Civil, Environmental and System Engineering, Pearson Education Inc., 2003.
3. Housner G.W., Bergman L.A., Caughey T.K., Chassiakos A.G., Claus R.O., Masri S.F., Yao J.T.P. "Structural control: Past, Present, and Future", Journal of Engineering Mechanics, ASCE, Vol.123, No.9, 1997.
4. Hanson R.D., Soong T.T. "Seismic design with supplemental energy dissipation devices", Earthquake Engineering Research Institute, MNo-8, 2001.
5. Vlad I. "Seismic structural design of an office building in Romania", Proceedings of the 13^{th} World Conference on Earthquake Engineering, Vancouver, B.C., Canada, 2004.
6. Wyatt T.A. "Design guide on the vibration on floors", The Steel Construction Institute Publication 076, 1986.