State of the art of structural health monitoring in seismic zones of Romania

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Abstract

Structural health monitoring using measurements of dynamic parameters under microtremor of forced excitation has a rather long history in Romania, starting with the 1960's, and INCERC was a promoter of this approach. A data base of measured natural periods for some 50 high-rise buildings existed prior to Vrancea, March 4, 1977 earthquake and it was possible to compare the pre- and post-earthquake periods, i. e. to correlate them with the damage and further on with the effect of strengthening. Other measurements were performed after the 1977 earthquake for a large number of standard design condominia. The INCERC Bucharest Branch Seismic Strong-Motion National Network is the larger in Romania ant it has over 100 accelerometers, out of which 50 % are digital, in Bucharest and in all Romania. The increasing number of instrumented buildings made it possible subsequent records when Vrancea earthquakes of 1986, 1990 and 2005 struck, and the response of structures was analysed by INCERC researchers. One of these analyses is presented in the paper. A system of permanent monitoring was designed and made available for multipurpose applications in INCERC in 2002. Thus, the instrumental health monitoring has proved its advantages and it is now a requirement of the new Romanian Earthquake Design Code (2006), for buildings over 50 m height or more than 16 stories or with an area over 7,500 sq. m.

Keywords: Vrancea earthquakes, Romania, structural dynamic parameters

1. Seismic setting, earthquake damage and structures at risk in Romania

The seismic hazard of Romania is dominated by the Vrancea intermediate depth source, producing earthquakes in south-east of the country, that affect with high intensities ca. 50% of the territory at each strong event [1]. Sources of crustal (shallow) earthquakes can generate locally high intensities in west and north. The seismic areas cover 65% of the territory, including almost 75% of population (over 60% in strong seismic zones). At country scale, urban localities expose ca. 35% of the total population or 66% of the whole urban population to the seismic hazard of the Vrancea zone.

In Romania, the earthquake design began in 1942, following the November 10, 1940 Vrancea earthquake (M_{G-R}=7.4; Mw=7.6…7.7). After this earthquake, reports of damages were available in newspapers and a safety and usability survey was performed in Bucharest by teams of engineers and architects.

Owners were warned that they were responsible and liable under the law for the quality of strengthening and repair works, as well as for any serious subsequent accidents and damages.

In fact, the repairs were superficial and in fact the structural strengthening was neglected by owners, the 2-nd World War broke out, thus some of the buildings were declared at that time as safe after an additional inspection. Many buildings reported with serious damages in 1940 collapsed in 1977 earthquake.

After the earthquake of 4th of March 1977 (M_{G-R}=7.2, Mw=7.5), the emergency investigation of buildings in Bucharest was performed with civil engineers from all over the country.

A vulnerability survey based on MSK Scale, with some special adjustments and an algorithm to account for the spectral content was made in 1977 on some 18.000 buildings, on other 800 standard design buildings in Bucharest and then on some hundreds of buildings in Iasi. [1, 4].

The Vrancea earthquakes of August 30, 1986 (M_w=7.2) and May 30, 1990 (M_w=7.0) caused only some non-structural damage. As a consequence of those earthquakes, a study of damages was initiated by INCERC, but later on the information was not completely shared because of the general official policy of neglecting the effects of that earthquake.

After the earthquakes of 30th and 31st of May 1990, the non-structural members were mostly affected. In the new social and political context a revision of the earthquake code was undertaken, with an emphasis on the assessment of and intervention on the existing buildings.

Following the 1942 and 1945 regulations, some provisional rules were enforced since 1950, and a first compulsory Earthquake Code was enacted in 1963. Earthquake resistant design codes that were enacted after the 1977 disaster in 1978 and 1981, 1991/1992, with important contribtions of INCERC, were based on original studies and strong motion data processing. The new earthquake resistant design codes P100/ 1991, 1992 introduced in chapters 11 and 12, revised 1997, the obligation to evaluate and, if required, to rehabilitate the existing buildings. The Government Ordinance on Strengthening of Existing Buildings (Ordinance no. 20/ 1994), lead to the labelling of some hundreds of buildings as being in the first class of risk

It is well known that tall buildings erected before 1940 and some structural types built between 1950 and 1977 proved to be highly vulnerable, and the Vrancea earthquake of March 4, 1977 was a national disaster, with over USD 2 Bln. in losses, numerous collapses and heavy casualties.

The 1940, 1977, 1986 and 1990 earthquakes pointed-out the ne for the pre-code high-rise buildings (before 1940) to be strengthened,as a critical point in advance of risk reduction programmes, first of all in down-town of Bucharest. [2, 3].

2. Damage survey vs. instrumental structural health monitoring

Instrumental monitoring of structures under microtremors, industrial and urban vibrations was promoted in Romania by INCERC. Structural health monitoring using measurements of dynamic parameters under microtremors or forced excitation has a rather long history in Romania, starting with the 1960's INCERC records.

The INCERC Strong-Motion Seismic Network obtained the unique record of great engineering use at March 4, 1977, in the basement of INCERC building of Pantelimon Street, where a long-period content of motion was recorded. Other INCERC instruments installed in buildings allowed a partial record in a high-rise structure in Balta Alba District of Bucharest [1].

A data base of measured natural periods for some 50 high-rise buildings existed prior to Vrancea, March 4, 1977 earthquake and it was possible to compare the pre- and post-earthquake natural periods, i. e. to correlate them with the damage and further on with the effect of strengthening. Other measurements were performed after the 1977 earthquake for over 100 standard design condominia. [4, 5, 6]. Several valuable records were possible in buildings during Vrancea earthquakes of 1986 and 1990. [10, 11, 13, 15, 16].

The Romanian experience of INCERC after 1977 [1] proved that low damage was associated to increases of natural periods under 20...25%. Multiple, but relatively light damage may rise periods up to 25...50%, while systematic damages or local and significant ones raised periods by more than 50%. Spectral content was a major issue, since buildings having natural periods closer to high spectral values have been heavily damaged.

Some urban-mark buildings, like the trussed large-span Dome of the National Exhibition have been investigated using these techniques [5].

After a first edition in 1999, a new methodology for emergency investigation of post-seismic safety of buildings and framework solutions for intervention, was enforced in 2007 by the Ministry of Development, Public Works and Housing – MDPWH, Romania.

The quick inspection is followed by a rapid evaluation, based on specific criteria and record forms, with application of four types of coloured placards, in view of building usability. The emergency intervention measures for safety of living inside buildings include techniques and drawings for provisional shoring and/or local repair.

The methodology is limited to residential, socio-cultural and administrative buildings, as well as to buildings with other functions, as applicable. For buildings and facilities with other functions, one should apply specific regulations and if they do not exist one can tentatively take over provisions from this regulation. [18].

Since the number of high-rise structures is increasing, field surveys, laboratory testing and instrumental data are a background in this respect and the recent Earthquake Design Code (2006) and its companion for existing buildings evaluation (Code P100-3/2008) provides a framework for advanced instrumental monitoring. [8, 9].

3. Strong-motion Seismic Networks in Romania

For engineering purposes and structural health monitoring, the INCERC Bucharest Branch Seismic Strong-Motion National Network is the larger in Romania ant it has over 100 accelerometers, out of which 50 % are digital, in Bucharest and in all Romania. NIEP network is devoted to seismological purposes, while other seismic monitoring networks are devoted to public works, as ISPH/GEOTEC (for dams) and METROU (Bucharest Subway).

At present, I.N.C.D.URBAN – INCERC, within the INCERC Branch, includes the Laboratory Seismic Strong-Motion National Network for Constructions (RNSC). The Network has an agreement with the State Inspectorate for Constructions to operate its instruments; recently INCD URBAN-INCERC incorporated the seismographic network donated by JICA Project to NCSRR (The National Center for Seismic Risk Reduction).

Thus, a total of 117 equipments exist under INCERC maintenance, out of which 4 in buildings, and 39 instruments in Bucharest, out of which 7 in buildings. [14]. As much as new high-rise buildings are erected, the number of instrumented buildings is increasing.

4. An example of advanced use of structural monitoring instrumental information

Romanian Vrancea seismic area has been relatively active during last period. One significant seismic event occured on May 14th, 2005, at 4:53 AM local time (M_w = 5.2, h = 147 km), epicenter coordinates (45.64N, 26.53E), coded 051) (http://www . infp.ro).

The block of flats in Bucharest instrumented for recording earthquake response, at No. 44 Stefan cel Mare Avenue, is part of the JICA-NCSRR seismic network endowed with a system of numerical recording K2 (Kinemetrics).

The sensors are installed at four levels (basement (coded 11), intermediary floor (coded e4), tenth floor the floor below (coded k2) and the upper floor (coded E11) and are depicted in the figure 1 [13] together with the time histories of absolute acceleration in the horizontal plane recorded during the earthquake on May 14th, 2005.

This block is the first to offer records at four stories during moderate Vrancea earthquakes. In addition to time histories of absolute accelerations, the paper includes data processing which contributes to the understanding of structural response.

These are absolute acceleration response spectra (floor spectra), Fourier amplitude spectra and amplification functions obtained based on the records gathered in the building unit instrumented for recording earthquake response during the Vrancea earthquake of May 14th, 2005. [15].

In this context we mention that for the records obtained in instrumented buildings, seismic response spectra represent the action spectra (floor spectra) for equipment, facilities, etc. located at that a given level / story of the structure. It should be noted that these spectra ARE NOT structural design spectra.

Absolute acceleration response spectra (floor spectra) provide the values of maximum base acceleration of a pendulum having the vibration period T, for example located at the ground level (11) or the last level (e11). Thus (the left column in the Figure 2), a pendulum having the vibration period T = 0.18 seconds would have been subjected to a base acceleration of 0.697 m/s^2 if it were located at e11 story and a base acceleration of 0.207 m/s^2 if it were located at ground level.

Also a pendulum having the vibration period of 0.57 seconds would have been subjected to a base acceleration of 0.469 m/s^2 if it were located at e11 story and to a base acceleration of 0.068 m/s^2 if it were located at ground level.

For comparison with the provisions of the new code "Seismic Design code – Part I: Design provisions for buildings" – P100-1/2006:

- $K_z = 1 + 2\dfrac{z}{H}$ is a coefficient representing the amplification of ground acceleration with the height of the building, where z is the height of attachment point of non-structural components to the structure;
- H is average height of the roof related to the base of the building"

The table 1 presents synthetic data of ground acceleration recorded and the values of K_z .

5. Conclusions on using advanced territorial instrumentation for structural health monitoring

After a research activity of almost four decades, the experience within INCERC and the World [4, 5, 6, 7, 8, 9] allowed to use the data obtained from instrumental seismic monitoring of territory and buildings for:

- Drafting seismic zoning maps and microzonation criteria;
- Improving earthquake design codes and checking new provisions after significant events;
- Studying the influence of local geological conditions upon eartahquake effects; evaluating soil-structure interaction and damping, under specific site conditions;
- Rapid evaluation of seismic effects in multistoried structures, identification of modes and periods, influence of superior modes, in order to check the validity of dynamic or mathematical models in comparison with damages, checking of story drifts and torsions;
- Identification of repair and strengthening needs, as well as of efficacy of previous interventions;

A system of permanent monitoring was designed and made available for multipurpose applications in INCERC in 2002 [12], using Kinemetrics Software [7], a system that was prized at the 31-st Invention Fair, Geneva, April 2003. The system includes:

- data collection for external transducers, for displacements, velocities or acceleration (DSP convertor, 24 bits); storage or processing of copied data for saving as specific records, response spectra, Fourier spectra;
- on-line visualization of data and data storage for one hour record on hard disk, and retransmision of data to larger storage, 8 channels a day;
- conectics TCP/IP 10/100Mbps; Linux operating system.

INCERC tested a wireless connection but it was proved unreliable under urban conditions, as compared with underground optical glass-fiber.

Seismic instrumentation of buildings is a modern, complex and versatile system of obtaining on-site seismic data about dynamic structural characteristics of buildings.

It is considered normal and legitimate when designing important objectives or when building have a large scale utility, a socially important role, as investments of public or private funds, to make post-earthquake comparative analysis using specific certain and realistic data, adequate instrumentation data. Without such data it can never be made a progress in providing a higher level of structural safety.

Each earthquake provides new information that must be evaluated in agreement with data concerning seismic motion in the source area, in the reference points in the direction towards the epicentre, with observations and analysis from the engineers about on site buildings behaviour.

In fact the new "Seismic Design code – Part I: Design provisions for buildings" – P100-1/2006 states in the Appendix A regarding future seismic instrumentation of buildings in Romania ("A.4. Seismic instrumentation of buildings") the following:

"In seismic areas where the value of design ground acceleration for a MRI≥100 years is a_g≥0.24g, buildings having over 50 m in height or more than 16 stories or having a total floor area of more than 7500 sqm, will be instrumented with a digital system of data acquisition and at least 4 triaxial acceleration sensors. This minimal instrumentation will be positioned: 1 sensor in free field in the proximity of the building, 1 sensor at the basement and 2 sensors on the last story floor. The instruments will be placed to make the access possible anytime. The instrumentation, the maintainance and the operation will be financed by the building's owner and will be provided by authorized organizations. The records obtained during the strong earthquakes must be made available to the competent authorities and to specialized institutions in 24 hours after the earthquake."

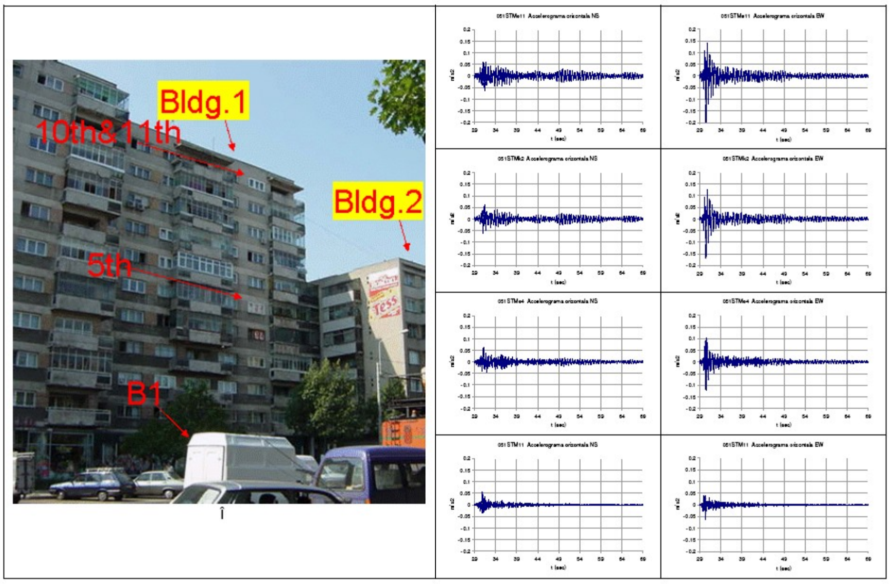

Figure 1. Records obtained during Vrancea earthquake of May 14th, 2005 (the main part: 40 seconds) in the instrumented block of flats in Bucharest, at No. 44, Stefan cel Mare Avenue (Bldg 1) (main part: 40 seconds)

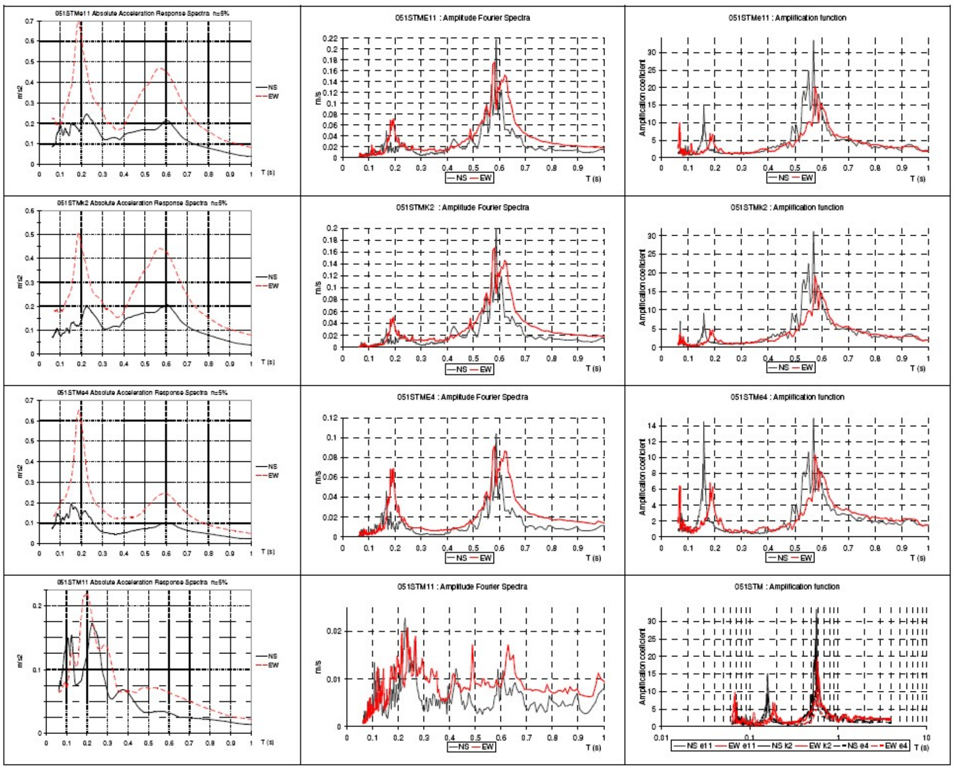

Figure 2. Absolute acceleration response spectra (floor spectra), Fourier amplitude spectra and amplification functions for records of May 14th, 2005 Vrancea earthquake in the instrumented block of flats in Bucharest, No.44, Stefan cel Mare Avenue.

Table 1
Synthetic data on ground acceleration recorded at three levels of the building

Seismic code - 051	Acceleration [m/s^2]	Acceleration [m/s^2]	Amplification of ground acceleration	Amplification of ground acceleration	As provided by P100-1/2006
story	NS	EW	NS	EW	K_z
e11	0.0652	0.1975	1.17	3.13	3
e4	0.0612	0.1232	1.10	1.95	2
11	0.0558	0.0631	1	1	1

Equipments and installation cost is low compared to the total value of the finishing, facilities and modern equipment of modern high-rise buildings, or from that of an industrial investment park which otherwise would be removed from service while pending an usual expertise. Proper understanding by the designer of the importance and influence of various factors on the dynamic response of the structure, and their correlation with the objectives of interest to the owner, leads to a choice and an adequate distribution of the components of seismic monitoring systems in the building.

Upon request, the experts from I.N.C.D. URBAN-INCERC can provide the consultance needed for instrumenting buildings, in order to know the real strength capacity of the damaged / undamaged building and to establish reabilitation solutions.

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References

[1] Balan St., Cristescu V. and Cornea I., (coordinators): "The Romania Earthquake of 4 March 1977 " (in Romanian). Editura Academiei, Bucharest, Romania (1982).

[2] Georgescu, E.S., et al: Towards a national earthquake protection program under the conditions of Romania, in F. Wenzel et al. (eds), Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, Kluwer Academic Publishers, Netherlands, pp. 241-250. (1999).

[3] Georgescu, E.S.: Patterns and trends of earthquake disasters and preventing policies in Romania Proc. JICA International Seminar "Earthquake Hazard and Countermeasures for Existing Fragile Buildings'. UTCB, Bucharest, D. Lungu & T. Saito, Editors.(2000).

[4] Sandi, H, Cazacu, D., Constantinescu, C., Stancu, M.: A Summary of Studies on the Seismic Vulnerability of Buildings, Carried out in Bucharest Subsequent to the March 4, 1977, Earthquake. Proc. Joint US-Romania Seminar on Earthquakes and Energy, Bucuresti, Vol. 2. Earthquakes. Editors: S. Aroni and R. Constantinescu. (1985).

[5] Sandi, H., Stancu, M., Stancu, O., and Constantinescu, C.: A Biography of a Large – Span Structure, Pre- and Post-Earthquake, After the Provisional and Final Strengthening. Proc. Joint US-Romania Seminar on Earthquakes and Energy, Bucuresti, Vol. 2 . Earthquakes. Editors: S. Aroni and R. Constantinescu. (1985).

[6] Constantinescu, C., Stancu, M.,: Statistical Studies for the Prediction of Seismic Damage of Reinforced Concrete Structures. Proc. Joint US-Romania Seminar on Earthquakes and Energy, Bucuresti, 1985. Vol. 2 . Earthquakes. Editors: S. Aroni and R. Constantinescu.

[7] Kinemetrics, Inc., USA,: Seismic Workstation Software, User's Manual.(1989).

[8] Celebi, M.: Seismic Instrumentation of Buildings, Open-File Report 00-157 USGS, Menlo Park, California. (2000).

[9] Celebi, M.: Current Practice and Guidelines for USGS Instrumentation of Buildings Including Federal Buildings, in Proc. COSMOS Workshop on Structural Instrumentation, USA (2001).

[10] Demetriu, S., Borcia, I. S.: "Seismic Response of Instrumented Buildings during Vrancea Earthquakes", Bulletin of Technical University of Civil Engineering, Structural Mechanics and Structural Engineering,2,1-11, (2001).

[11] Borcia, I. S. "Prelucrarea înregistrărilor obţinute în timpul cutremurelor vrâncene puternice în două clădiri instrumentate seismic din municipiul Galaţi", în Conferinţa naţionala, cu participare internaţională-Comportarea IN SITU a Construcţiilor, Galaţi, (2002).

[12] *** : „Diagnosticarea sigurantei in exploatare si a starii de degradare seismica pentru constructii civile si constructii in transporturi, pe baza masuratorilor dinamice la scara naturala", referate INCERC, UTCB si ICI la Programul AMTRANS nr.1B02/2001, 2001 – 2004.

[13] Lungu, D., "Earthquake Mitigation in Romania: Synergy from International Projects", in Review of the Collaborative Research Center 461 "Strong Earthquakes: A Challenge for Geosciences and Civil Engineering", Karlsruhe, September, 28 - 29, 2004. (2004).

[14] Aldea, A., Kashima, T., Lungu, D., Vacareanu, R., Koyama, S., Arion, C. : "Modern Urban Seismic Network in Bucharest, Romania", First International Conference on Urban Earthquake Engineering, Tokyo Institute of Technology, Japan, March 8-9 2004.(2004).

[15] Borcia., I. S.: " Prelucrarea înregistrărilor obţinute în timpul cutremurelor vrâncene recente într-un bloc de locuinţe instrumentat seismic din Bucureşti " (Processing of records obtained during recent Vrancea earthquakes in a block of flats with seismic instrumentation in Bucharest), in: CONSTRUCTII civile si industriale, anul VI, nr. 66- 68, (2005).

[16] Borcia, I. S. "Procesarea înregistrărilor mişcărilor seismice puternice specifice teritoriului României", Teza de doctorat, UTCB, 2006. (Processing of strong motion records specific for the territory of Romania, Ph D Thesis). (2006).

[17] MDRL: Romanian Earthquake Design Code – Part I – Design Provisions for Buildings, P10-1/2006). (2006).

[18] *** Methodology for emergency investigation of post-seismic safety of buildings and establishing of framework solutions for intervention. ME-003-2007. Official Gazette No. 562 / 2007; Buletinul Constructiilor, Vol. 8 / 2007. MTCT-INCERC.