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Comparative Study on Seismic Vulnerability of the Bucharest Buildings

Andrei-Gabriel Bica
PhD Student
Technical University of Civil Engineering Bucharest
Romania

Gabriel Danila
PhD Student
Technical University of Civil Engineering Bucharest
Romania

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209
Email: info@atiner.gr URL: www.atiner.gr
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Comparative Study on Seismic Vulnerability of the Bucharest Buildings

Andrei-Gabriel Bica
PhD Student
Technical University of Civil Engineering Bucharest
Romania

Gabriel Danila
PhD Student
Technical University of Civil Engineering Bucharest
Romania

Abstract

Having a population of over 2 million inhabitants and an existing building stock of more than 110.000 buildings, Bucharest is considered, by many specialists, one of the capitals with the highest seismic risk in the world, being particularly vulnerable to seismic hazard due to:
(i) high fragility of tall reinforced concrete buildings, built before World War II and even before the 1977 devastating earthquake;
(ii) subcrustal seismic hazard from Vrancea source;
(iii) soft soil condition characterized by long predominant periods (1.4 ÷ 1.6 s) of ground vibration during strong events.
The paper presents a seismic vulnerability analysis of two different residential building types: reinforced concrete resisting moment frames and shear walls, designed according to the provisions of different codes in force at the moment of construction: low-code, moderate-code and high-code. The selected buildings are subjected to a nonlinear modelling through a representative set of 1977 Vrancea earthquake records, considered to be similar with an expected earthquake. The paper identifies the fragility curves for these typical existing Bucharest buildings and the results will consist in comparing the possible damage level of the studied structures. It shall also be observed the continuous time improving of the seismic provisions from the Romanian design codes over the last 50 years.

Keywords: seismic vulnerability, earthquake, damage, seismic risk, fragility curves.

Corresponding Author:

Introduction

The seismic risk assessment of buildings is especially influenced by the proceeding type used to highlight the earthquake vulnerability of the buildings. Over the last decades, many empirical, hybrid and analytical methodologies have been developed for earthquake vulnerability assessment. The seismic vulnerability assessment can be related to a specific building, structural design system, building types, vulnerability classes and may be scaled for a city, region or country.

Bucharest - A Vulnerable Seismic City

The seismic risk that threatens the city of Bucharest is due to the presence of subcrustal Vrancea source at 110 km, capable of many damages. In the last century, Bucharest was hit by 2 major earthquakes (1940 - M_w = 7.7 and 1977 - M_w = 7.5) that caused collapses, losses and serious failures to the building stock.

Bucharest's buildings, vulnerable to ground motions, can be classified according to the seismic knowledge level incorporated into the design codes as following:

- buildings built before World War II, based on regulations without any seismic references;
- buildings built after World War II, designed with low seismic knowledge;
- buildings built after the 1977 earthquake, with medium level of earthquake resistance.

The most vulnerable structures are those built before the 1977 earthquake and even after: low-rise (1÷4 storeys) masonry buildings and tall (> 7 storeys) reinforced concrete buildings with frame structures and masonry infill [2].

Table 1. *Catalogue of Vrancea earthquakes (M_w>6.5) produced during the 20th century [6]*

Date yyyy. mm.dd	Lat. N°	Long. E°	Depth (km)	M_w
1903.09.13	45.7	26.6	70	6.6
1908.10.06	45.7	26.5	125	7.1
1934.03.29	45.8	26.5	90	6.6
1940.10.22	45.8	26.7	125	6.8
1940.11.10	45.8	26.4	150	7.7
1945.07.07	45.9	26.7	80	6.8
1945.12.09	45.7	26.5	80	6.5
1977.03.04	45.34	26.3	94	7.4
1986.08.30	45.53	26.47	131	7.1
1990.05.30	45.82	26.9	91	6.9

Also, an important issue of the local vulnerability is represented by the terrain conditions, characterized by the presence of soft clay layers, which decisively contribute to the long predominant periods (1.4 ÷ 1.6 s) of ground vibration during strong Vrancea events.

Existing Buildings Seismic Evaluation Method

The paper analyses the seismic vulnerability of six existing high-rise residential buildings by adapting the capacity spectrum method from ATC- 40 and HAZUS MH-MR5 to the Romanian seismic conditions. The selected buildings: reinforced concrete resisting moment frames and reinforced concrete shear walls were built based on standards projects according to the provisions of different codes in force at the moment of construction: low-code, moderate-code and high-code.

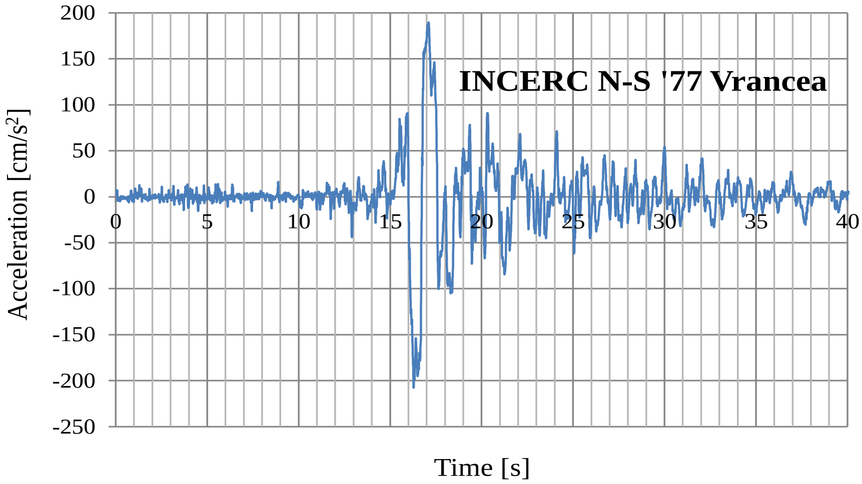
Step-by-step Procedure used to obtain the Fragility Curves

- Perform a pushover analysis of the 3D building model through SeismoStruct computer software and plot the capacity curve: roof displacement - base shear (Δ_{roof} - V_i) curve on the long (weak) direction;
- Develop the capacity spectrum by converting point-by-point the capacity curve: any point V_i and Δ_{roof} on the pushover curve is converted to the corresponding point S_{ai} and S_{di} on the capacity spectrum using the following equations:

$$S_{ai} = \frac{V_i/W}{\alpha_1} \quad (1)$$

$$S_{di} = \frac{\Delta_{roof}}{PF_1 * \emptyset_{1,roof}} \quad (2)$$

Figure 1. *Acceleration of 1977 Earthquake Record*

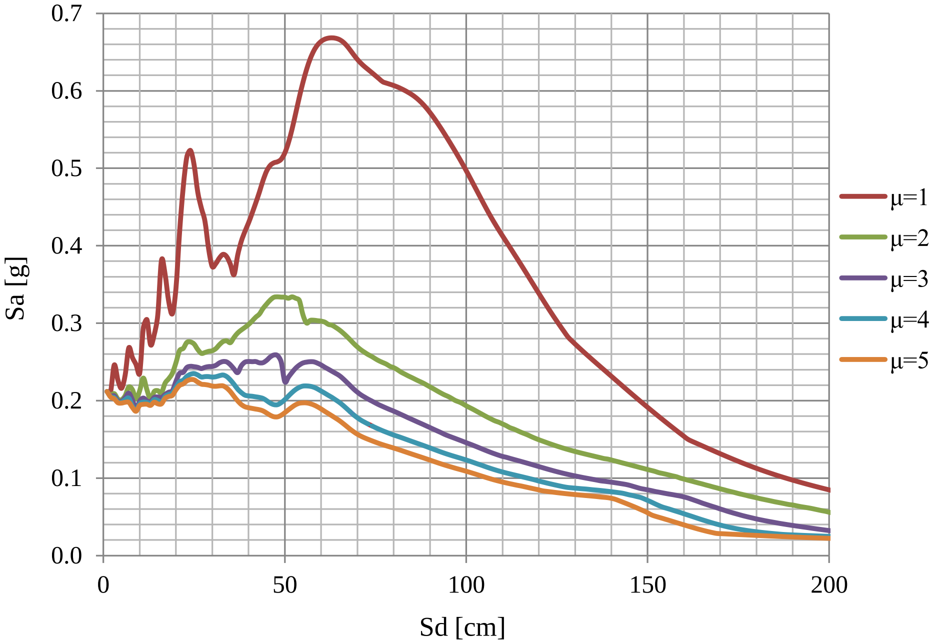


where:

V_i represents the base shear at level i;
S_{ai} is the spectral acceleration;
S_{di} represents the spectral displacement;
PF_1 is the modal participation factor for the first natural mode;
$\varnothing_{1,roof}$ represents the amplitude of the mode 1at the roof level;
W is the building weight;
α_1 represents the modal mass coefficient for the first natural mode.

- Obtain the demand response spectrum in acceleration-displacement response format. From the NS component of INCERC 1977 earthquake record, it was computed the inelastic constant-ductility displacement spectrum with the SeismoSignal software. This approach was selected instead of using the elastic spectrum recommended by ATC-40 and HAZUS procedures, that is not appropriate for narrow frequency band motions characterized by long predominant period ($T_C = 1.4 \div 1.6$s) - as in the Bucharest case. *Figure 1* presents the acceleration of the record and in *Figure 2* are represented the inelastic acceleration-displacement spectra for different μ (ductility factor) values.
- Represent on the same graph both the demand and the capacity spectrum. The yielding branch of the capacity curve intersects the demand spectra for different μ values. One of these intersection points will provide the performance point where the ductility factor computed from the capacity curve matches the ductility value associated with the intersecting demand spectrum.

Figure 2. *Inelastic acceleration - displacement response spectra*



- Determine and plot the building fragility functions. For structural damage, the probability of being in or exceeding a specific damage state, *ds*, given the spectral displacement S_d, is defined by:

$$P[ds \mid S_d] = \Phi \left[\frac{1}{\beta_{ds}} \ln \left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \tag{3}$$

where:

$\bar{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of the damage state, ds*;*

ds is the standard deviation of the natural logarithm of spectral displacement of damage state, ds;

Φ is the standard normal cumulative distribution function.

Case Study

A short description of the 6 buildings considered for the case study is presented below.

Example A was erected in 1969, designed using the P13-63, the first Romanian design code with earthquake provisions. It has 12 storeys (B+GF+10S) with a shopping centre at the ground-floor and apartments in the upper floors. The structural system consists of reinforced concrete frames in the ground-floor and structural walls in the higher storeys. The ground-floor is a soft and weak story with no structural walls. The building has 6 spans: 4.20m, 4.50m and 5.00m, two for each type. There are 4 types of bays with a total length of 14.75m. The walls thickness is 17.5cm on the both directions, the columns sections are 40x40cm and the beams 30x30cm. The slabs are 10cm thickness. The concrete used for the structure was C12/15, while the reinforcing steel type was S235.

Example B has a structural system made of C16/20 reinforced concrete frames with 5 spans and 2 bays each having 6.00m. The columns have different sections 50x60cm and 40x50cm, the long direction beams section are 30x70cm and 30x55cm for the transversal direction. The slabs have 13cm thickness. The typical story height is 2.55m.

Example C is a 1982 reinforced concrete walls structure. It has 1 basement of 3.00m, 4.00m ground-floor and 8 storeys of 2.75m each. The building consists of 7 spans: 6 of 3.60 m and one of 4.45m in the middle, while the 3 bays have dimensions of 2*4.40m + 3.90m. The columns sections are 50x70cm and 50x50cm. There are 2 types of beams: 30x50cm and 25x55cm. The concrete walls thickness is 25cm and the slabs only 10cm. The materials types were C16/20 for the cast-in-place concrete and S275 for the reinforcing steel.

Example D is a regular building from 1998, with 3 spans and 3 bays each of 6.00m. Its destination is residential in the upper 7 floors and commercial in the ground-floor. The typical story height is 2.75m, but in the ground-floor the height is 4.50m. The columns have constant section of 65x65cm for the first 2 storeys and reduced sections at the other floors. The beams section is 25x55cm and the slabs' thickness is 13cm. The reinforcing steel type is S355 while the concrete is C20/25.

Example E is a residential office building, designed in 2008 using P100/2006 seismic design code that corresponds to European structural design codes. The structural system is made of C30/37 reinforced concrete frames with 5 spans each having 6.00m and 3 bays: 2*4.50m and one of 4.80m in the middle. The columns have 60x60cm and 50x50cm sections, the long direction beams section is 25x55cm and 25x45 for the transversal direction. The slabs have 15 cm thickness. The story height is 3.60m for basement and ground-floor and 3.20m for the rest of 8 storeys.

Example F is an office building, erected in 2010 with a reinforced concrete walls structure. It has 2 basements and 10 storeys with a floor height of 3.40m. The structure consists of 5 spans each having 8.00m and 5 bays: 4 of 7m and a central one of 4.00m. The columns are rectangular with sections of 70x70cm at the first floors and with reduced sections at the other floors. There are 3 types of beams: 30x70cm, 30x60cm and 30x40cm with constant sections for the entire building. The concrete walls have 70cm width and thickness of section edges and 45cm core thickness. The slabs have 18cm thickness. The materials types were C25/30 for the reinforced concrete and S355 for reinforcing steel.

Table 2. *Selected Buildings for Case Study*

Building	Number of storeys	Construction year	HAZUS		Expected displacement Sd [cm]
			Structural type	Design code level	
Example A	B+GF+10S	1969	C2H	Low	18.5
Example B	B+GF+8S	1975	C1H	Low	24.3
Example C	B+GF+8S	1982	C2H	Moderate	13.4
Example D	B+GF+7S	1998	C1H	Moderate	12.2
Example E	B+GF+8S	2008	C1H	High	7.8
Example F	2B+GF+10S	2010	C2H	High	2.3

Results

The fragility curves describe the probability of reaching or exceeding different states of damage. Structural damage fragility curves for buildings are described by median values of drift that define the thresholds of *Slight*, *Moderate*, *Extensive* and *Complete* damage states. The fragility curves obtained for the 6 high-rise buildings are presented below.

Figure 3. *Fragility curves for low code buildings*

a) C1H – Example B **b) C2H – Example A**

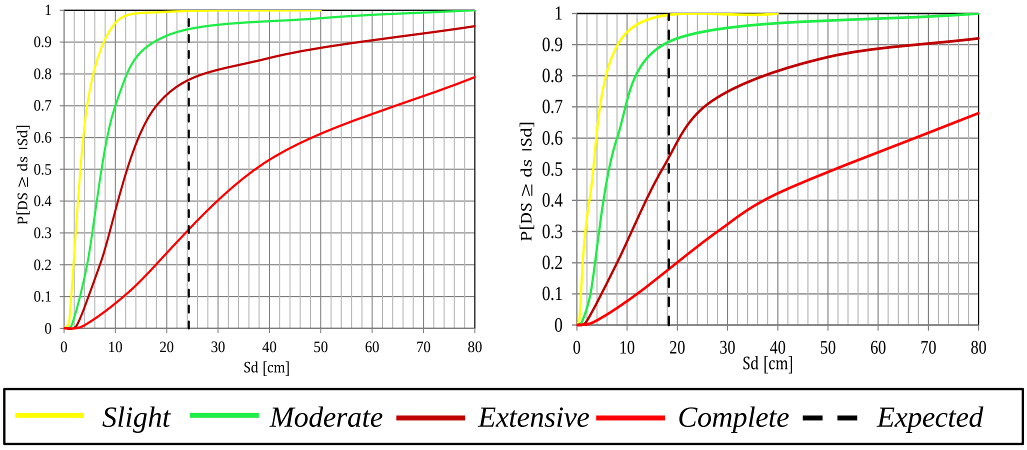


Figure 4. *Fragility curves for moderate code buildings*

a) C1H – Example C **b) C2H – Example D**

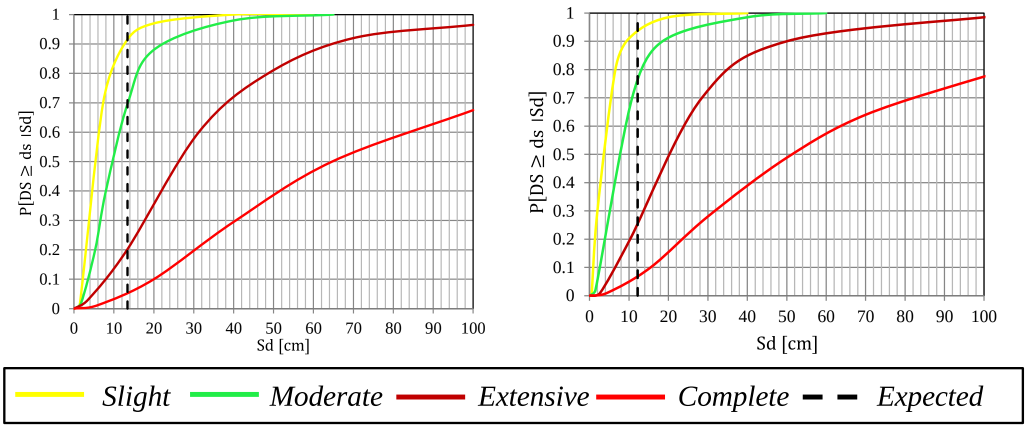
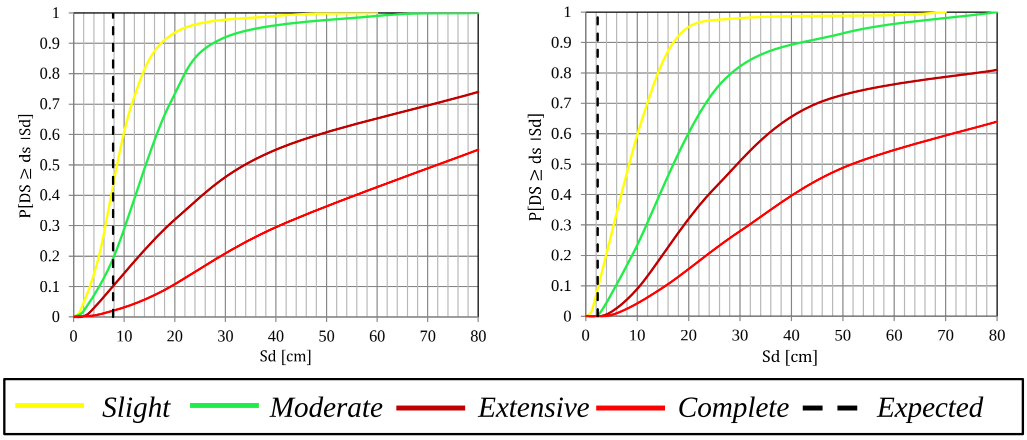


Figure 5. *Fragility curves for high code buildings*

a) C1H – Example E **b) C2H – Example F**



Conclusions

The above case study is subjected to additional uncertainties with respect to the damage state in which the building will be found after the expected seismic event. The pushover analysis did not take into consideration the structural damage of buildings from previous earthquakes.

Analysing the structural damage fragility curves, it can be observed the continuous time improving of the seismic provisions from the Romanian design codes over the last 50 years.

The HAZUS and ATC-40 methodologies are calibrated for buildings in the USA, but they can be used with some limitations in Romania, being efficient for the evaluation of building seismic behaviour.

The vulnerability assessment is useful for disaster preparedness, loss assessment, planning for buildings rehabilitation and represents a significant aspect of the seismic risk mitigation in a city like Bucharest.

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