The 17th World Conference on Earthquake Engineering

17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

PROBABILISTIC SEISMIC RISK ASSSSMENT FOR REINFORCED CONCRETE BUIDINGS IN ROMANA

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Abstract

The total seismic losses incurred by March 4 1977 Vrancea earthquake amounted at two billion US dollars. The bulk of the direct seismic losses stemmed from the 32 buildings that completely collapsed in Bucharest. Thus, assessing and reducing seismic risk of buildings represent outstanding tasks and responsibilities for civil engineers and building officials.

A recent study performed at the Seismic Risk Assessment Research Centre of Technical University of Civil Engineering of Bucharest assessed the annual probabilities of failure of reinforced concrete buildings for the main cities in Romania. Taking into account the dominant characteristics of the existing reinforced concrete building stock in Romania, only high-rise (more than 8 stories) structures were considered in the study. Both height categories were further divided, based on the seismic design building codes enforced in Romania since 1963, namely: low-code, medium-code and high-code

The methodology employed for the seismic risk assessment is based on a full probabilistic approach, taking into account either (i) the results of recent seismic hazard studies employing as engineering demand parameter the peak ground acceleration and the fragility functions obtained during RO-RISK project for reinforced concrete structures, and (ii) the results of seismic hazard studies employing as seismic demand parameter the MSK macroseismic intensity and the fragility functions obtained based on the results of post-earthquake investigation performed in Bucharest after March 4, 1977 Vrancea earthquake.

The results of the study highlight the influence of the seismic design code evolution on the exceedance probabilities associated with the extensive and complete damage states. Based on the results obtained in this study, it is noted that the evolution of the seismic design codes had a significant influence on lowering the annual probabilities of failure for the reinforced concrete building stock in Romania.

Keywords: seismic; risk; assessment; Vrancea; concrete

1. Introduction

The effects of the 1977 earthquake highlighted major deficiencies of old RC structures, such as irregular architectural layouts, no seismic design and also existing damages that followed the earthquake from the 10th of November 1940. Therefore, around 10% of the existing building stock of RC structures with more than 8 stories built before 1950 from Bucharest were partially or completely collapsed, while more than 30% suffered extensive damages. However, significant improvements were observed in case of RC frames built before 1950, but considering the high intensities and the flexibility of this type of structures, damages ranging from minor to heavy were recorded [1].

Damage surveys performed after the Vrancea earthquake from 1977 in Iași and București were presented in the 8th ECEE Report [2], as part of vulnerability studies performed in European countries. The methodology used in the process of post-earthquake inspections had as main goal to establish whether the analyzed buildings could be used or not after the seismic event. The procedure was based on a questionnaire, focused on individual assessment of structures. The ground motion intensity was expressed as macroseismic intensity, ranking damage grades from 0 (no damage) to 5 (collapse).

The present paper aims to capture the influence of the seismic design code evolution thorough a probabilistic seismic risk assessment of reinforced concrete structures, using the fragility assessment completed within RO-RISK project [3], as well as post-event damage surveys conducted in Bucharest and Iasi after the 1977 earthquake.

2. Building typologies

For the seismic risk assessment that uses fragility functions obtained in RO-RISK project, 41 capital cities were considered and two main types of RC structural systems were examined high-rise (more than 8 stories) frames and shear walls. Taking into account that most of the existing RC building stock consists in residential buildings with more than 8 stories, mid-rise RC structures were not analyzed in the present study.

To evaluate the influence of the seismic design code provisions on the risk of the reinforced buildings, three generations of seismic design code where considered, namely low-code, moderate-code and high-code. The low-code generation was inspired by the Russian practices regarding seismic design, while the moderate-code adopted ductility measures for reinforced concrete structures following the rules of the American Concrete Institute. The seismic design code P100-78 was developed after the earthquake from the 4th of March 1977, taking into consideration the seismic demand from the only ground motion recorded in Bucharest, in soft soil conditions. The predominant period of ground vibration was equal to 1.6 seconds, which led to a significant increase in the control period of the response spectra, from 0.4 seconds (low-code) to 1.5 seconds (moderate-code).

The evolution of the seismic design codes in Romania is summarized in Table 1. Additional information related to the soil types and the seismic zonation was also considered for the fragility assessment. The taxonomy that considers the characteristics mentioned previously follows the RC structural typologies analyzed within the RO-RISK project [4] and is listed in Table 2.

Table 1 – Seismic design code evolution in Romania

Code generation	**Period**	**Design codes**
Low-Code	1963-1977	P13-63, P13-70
Moderate-Code	1978-1992	P100-78, P100-81
High-Code	After 1992	P100-92, P100-1/2006, P100-1/2013

Table 2 – Taxonomy

Abbreviation	Structural system	Seismic design code	Height	Seismic zonation (x)	Corner period Tc (y)
F_LC_H_x	RC frames	low-code	high-rise	7/8/9	-
F_MC_H_x		moderate-code		6/7/7.5/8/9	-
F_HC_H_x_y		high-code		A/B/C/D/E/F	0.7/1/1.5
W_LC_H_x	RC shear walls	low-code		7/8/9	-
W_MC_H_x		moderate-code		6/7/7.5/8/9	-
W_HC_H_x_y		high-code		A/B/C/D/E/F	0.7/1/1.6

Damage surveys were carried out after the 1977 Vrancea seismic in Bucharest and Iasi in order to evaluate the damage state for more than 20000 buildings. The typological classifications done in these two cities was different, shear wall reinforced concrete structures being separated intro closely spaced (A7) and widely spaced (A8) in Bucharest, while in Iasi there were treated all together (B6). Based on the mean values of damage degrees expressed in terms of macro-seismic intensities, vulnerability indexes (V) and ductility factors (Q) were obtained through regression analysis, the final values obtained being listed in Table 3. These parameters determined using the post-event damage date were then applied to estimate vulnerability indexes for the entire range of intensities, by using the relation proposed by Lagomarsino and Giovinazzi [5]:

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \tag{1}$$

Table 3 – Damage degree data for RC structures with shear walls

	Bucharest		Iasi
RC bearing walls	A7: walls closely spaced	A8: walls widely spaced	B6: shear wall buildings
V	0.867	0.862	0.873
Q	2.42	2.42	2.22

2. Seismic hazard

The hazard curves obtained from the probabilistic seismic hazard assessment, indicate the annual probability of exceedance for various values of the ground motion intensity parameter [6]. The ground motion levels are obtained considering the earthquakes' recurrence, size, location and effects along with their corresponding uncertainties. Within BIGSEES national research project [7], all seismic sources illustrated in Fig. 1 were taken into account, and aggregated hazard levels were obtained for 200 sites in the country [8]. This recent probabilistic seismic hazard assessment was considered for the risk evaluations of the reinforced concrete structures, for each capital city from Romania. The risk assessment performed based on these results, used the mean annual probabilities of exceedance, derived from the data which considered probabilities of exceedance in 50 years.

In order to perform the seismic risk assessment using the data collected from post-earthquake investigations, results obtained from RO-RISK were selected, thus using annual probabilities of exceedance expressed in terms of macroseismic intensities.

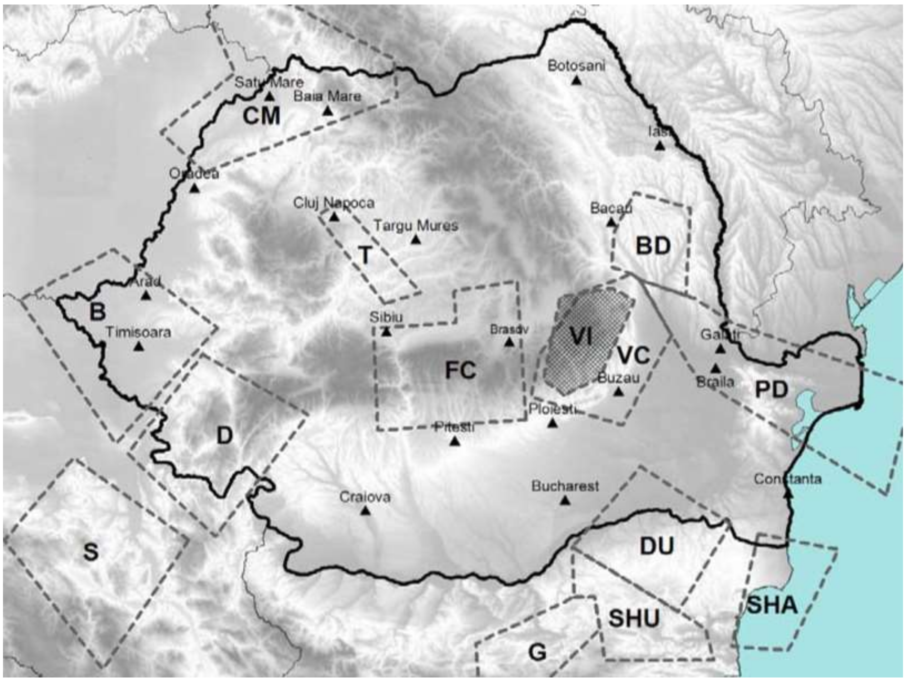
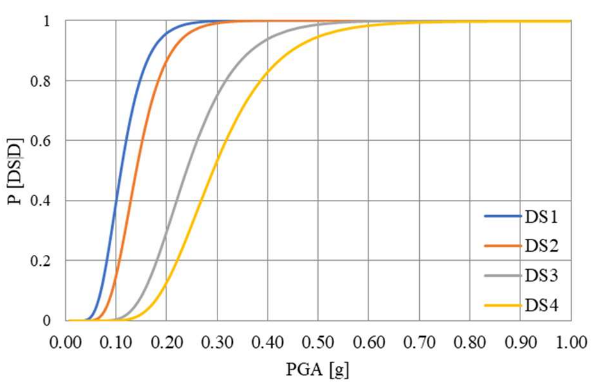


Fig. 1 – Seismic sources considered for the PSHA of Romania [8]

3. Fragility functions

The structural fragility expresses in a probabilistic manner, the relationship between the probability of exceeding a certain damage state and the seismic action [9]. The classification of damage adopted for obtaining the fragility curves within the RO-RISK project [4] considered four damage states: slight (D1), moderate (D2), extensive (D3) and complete (D4), similar with the one proposed in HAZUS. The parameters defining the fragility curves were obtained from nonlinear dynamic analyses performed on single degree of freedom systems, subjected to a set of accelerograms. Assuming a lognormal distribution of the data, the median and the logarithmic standard deviation are the only parameters needed for defining the fragility curves, in terms of peak ground acceleration values. Fig. 2 presents the fragility functions obtained for high-rise low-code RC shear wall structures, located in seismic zones with intensity equal to 7 and a corner period of 1.6 seconds (such as Bucharest), using PGA as intensity measure and for closely spaced shear wall systems (A7) expressed in macroseismic intensities.



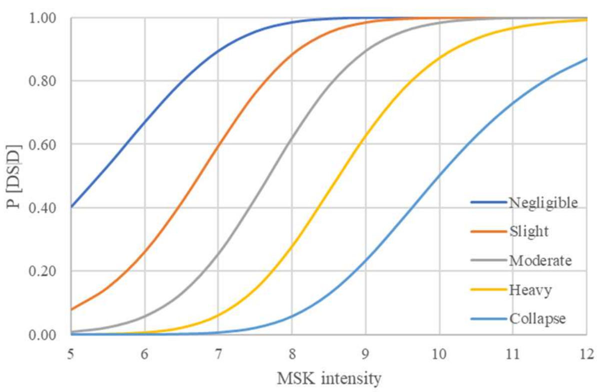


Fig. 2 – Fragility functions for W_LC_H_7 (T_c = 1.6s) on the left and for A7 on the right

For the second approach of the seismic risk assessment, fragility functions expressed in terms of macroseismic intensities were determined based on the mean damage values μ_D and assuming a binomial distribution. Even though by using this type of distribution it is not possible to consider a different scatter around the mean value, previous studies proved that using the binomial distribution for the analysis of post-earthquake damage data is successful [5]. Taking into account that buildings located both in Bucharest and Iasi had the same level of intensity considered in the seismic design, according to the seismic zonation map from the national design code P13-1963, there are no major differences regarding the fragility of structures assessed in groups A7, A8 and B6. Thus, the fragility of shear wall structures (A7) from Fig. 2 is representative for the entire range of RC shear walls structures constructed during the low-code period in seismic zones with intensity equal to seven.

4. Probabilistic seismic risk assessment

The convolution integral used to calculate the failure probability P_F, meaning the annual frequency of exceeding a certain damage state, is the one given by [10]:

$$P_F = \int_0^{+\infty} H_A(a) \cdot \frac{d\,P_{F|a}}{da} da \tag{2}$$

$H_A(a)$ is the hazard curve, expressed as the annual rate of occurrence, corresponding to a ground motion level a and $P_{F|a}$ is the conditional cumulative distribution function of the probability of failure for a specific ground motion value a. The probability of failure, obtained based on the fragility parameters, is seen as unacceptable performance. The results in terms of annual failure probabilities were obtained by combining the seismic hazard with the fragility of the reinforced concrete structures, while considering a permanent exposure of the building stock.

In the case of the approach that uses PGA as intensity measure, the fragility curves considered for each capital city, were chosen according to the zonation maps, which vary function of the code generation analyzed. The final results in terms of annual probabilities of exceeding a certain damage state were determined for extensive (DS3) and complete (DS4) damage, for each municipality. For the annual failure probabilities estimates based on post-earthquake damage survey, the corresponding typology would be W_LC_H_7 from Bucharest and Iasi. Fig. 3 highlights the comparison between the results obtained with the two approaches used, expressing annual probabilities of exceeding damages states based on two different intensity measures. The results presented in the figure are rounded in order to compare the order of magnitude for the estimated probabilities.

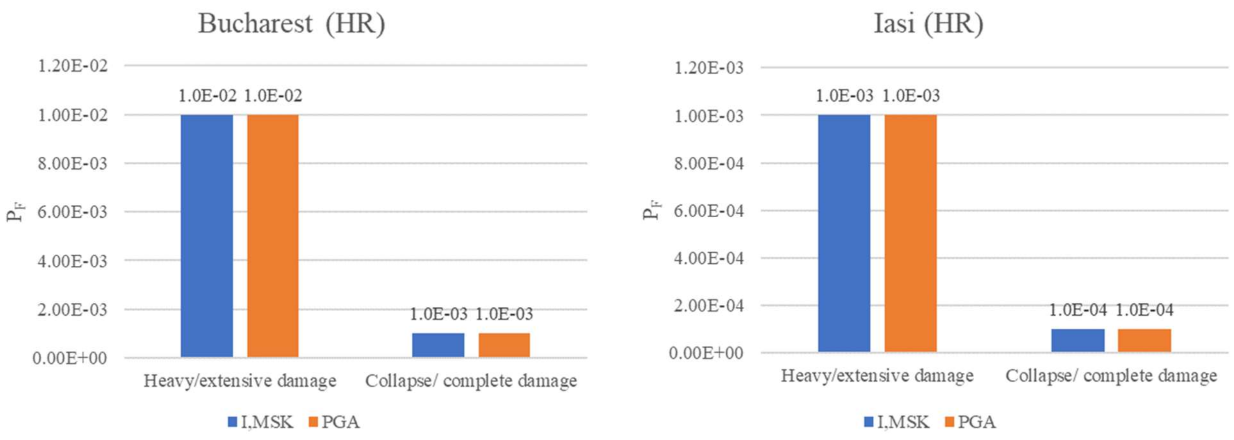


Fig. 3 – Comparison between annual failure probabilities for high-rise, low-code RC shear wall structures

4.1 Absolute probabilities of failure: design code evolution

For each of the 41 capital cities considered in the paper, the design code evolution was analyzed in terms of annual probabilities of failure. Two sets of data were obtained, one considering the probability of exceeding the extensive damage state (DS3) and other for the complete damage state (DS4).

An example for the evolution of the annual probabilities of failure for Iasi and Bucharest are shown in Fig. 4. The changes in the seismic design codes (1963, 1978 and 1992) mark significant decreases in the probabilities of exceedance for both extensive and complete damage states, which generate consequently a reduction in terms of seismic risk. For the entire set of the capital cities analyzed, it was observed a decreasing trend of the annual exceedance rates P_F along with the evolution of seismic design codes.

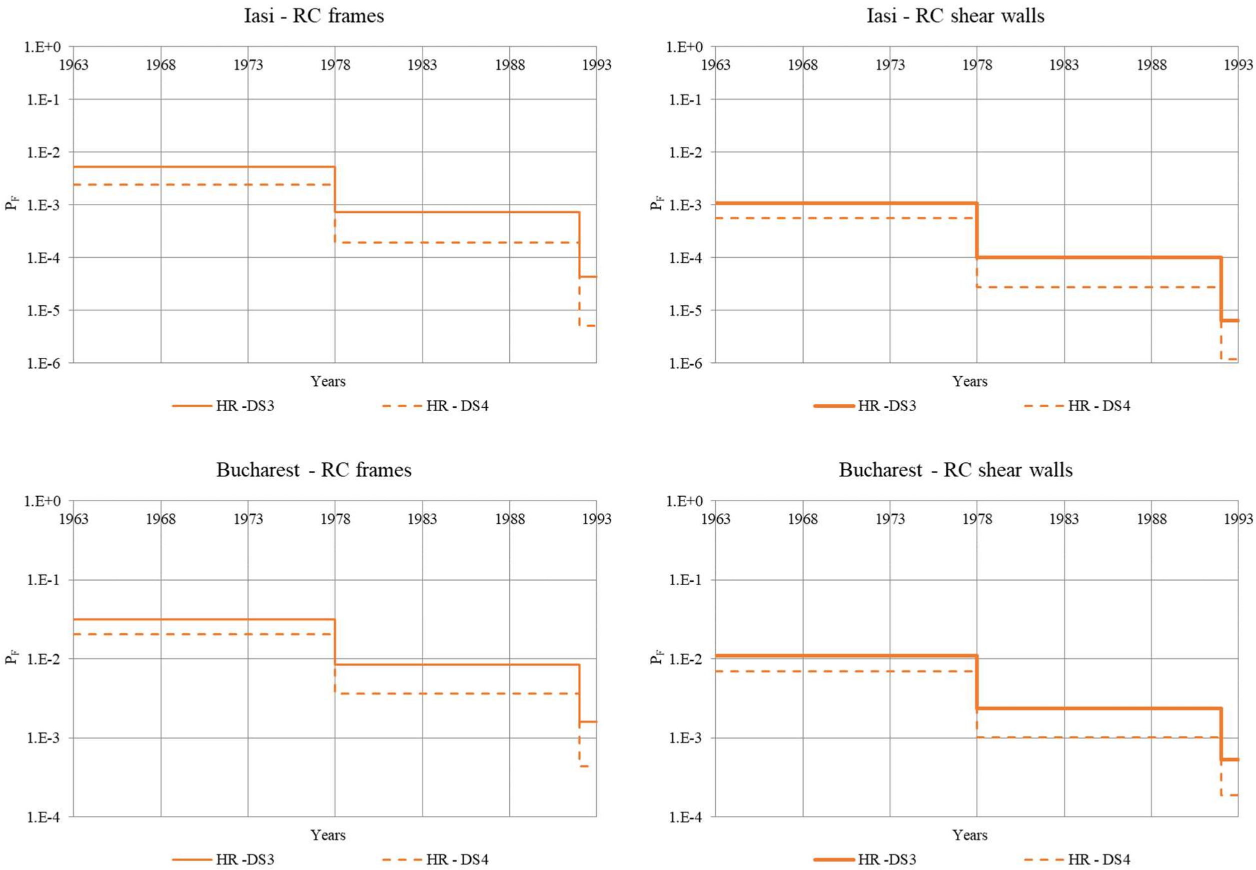


Fig. 4 – Annual probabilities of failure for Iasi (T_C=0.7 seconds) and Bucharest (T_C=1.6 seconds)

4.2 Absolute probabilities of failure: comparison between municipalities

To allow a comparison of the seismic risk at national level, map representations with the absolute values of the annual probabilities of failure associated to extensive and complete damage, were obtained for each code generation and each typology (reinforced concrete frames and shear walls, with different height regimes).

The annual rates of exceeding the extensive damage state (DS3) are represented in Fig. 5, for the reinforced concrete frame structures, designed according to low-code provisions (P13-1963). For the capital cities located in the western part of the country, with a reduced influence of Vrancea intermediate-depth seismic source, lower values of P_F are obtained, compared to the municipalities placed in the fore-arc region.

When comparing the probabilities of exceeding the extensive damage state obtained for low-code (Fig. 5) with the ones for high-code (Fig. 6) for the same capital city, changes in the order of magnitude are observed, such as the case of Targu-Jiu (10^{-3} and <= 10^{-5}) or Piatra Neamt (10^{-2} and <= 10^{-5}). The minimum level of P_F resulting from the representation of low-code design, namely 10^{-4} lowers to 10^{-5} or less, for the case of high-code, highlighting once again a decrease of the seismic risk for the reinforced concrete building stock.

4.3 Relative probabilities of failure: design code evolution

For having a better picture regarding the magnitude of the changes from one code to another, in terms of annual probabilities of exceeding a certain damage state, map representations of relative values were realized. Therefore, the absolute values of P_F corresponding to low-code and moderate-code, were normalized to the high-code values, considered as reference.

An example of relative values of exceeding the extensive damage state (for high-rise reinforced concrete shear wall structures) is shown in Fig. 7 for low-code design and in Fig. 8 for medium-code design. As it can be observed, differences range from 7 up to more than 100 times larger values of P_F for buildings following low-code provisions. For instance, Craiova was located in an area considered to have no macro-seismic intensity, according to P13-1963 (low-code) and changed to 7 and ½ macro seismic intensity, as stated in the seismic zonation map from P100-1978 (medium-code). Consequently, this was recoded as an influence on the seismic risk associated to Craiova, so that P_F, low-code is 138 times larger than P_F, high-code, and P_F, medium-code is 16 times larger than P_F, high-code.

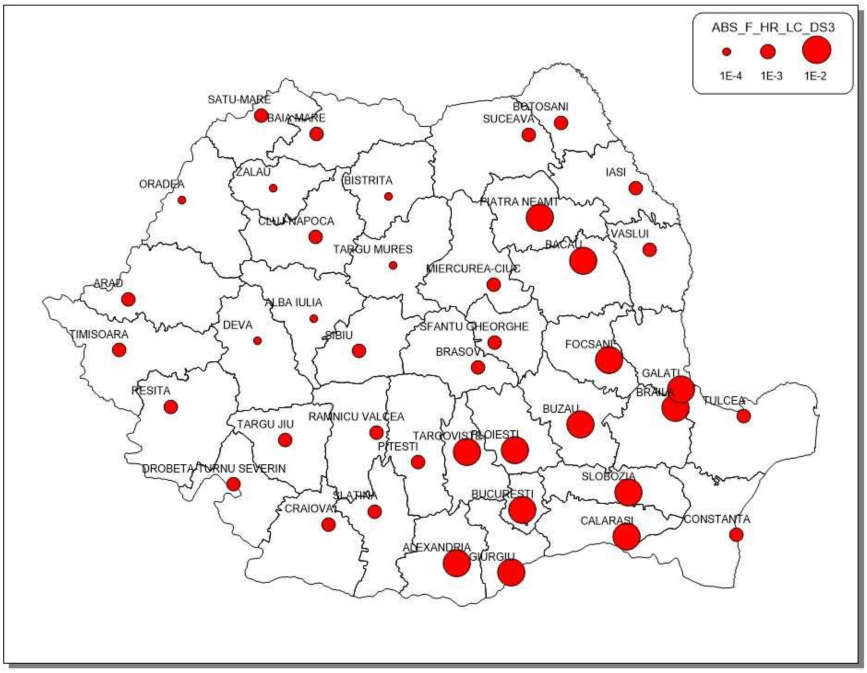


Fig. 5 – Map representation of P_F for F_HR_LC (absolute values)

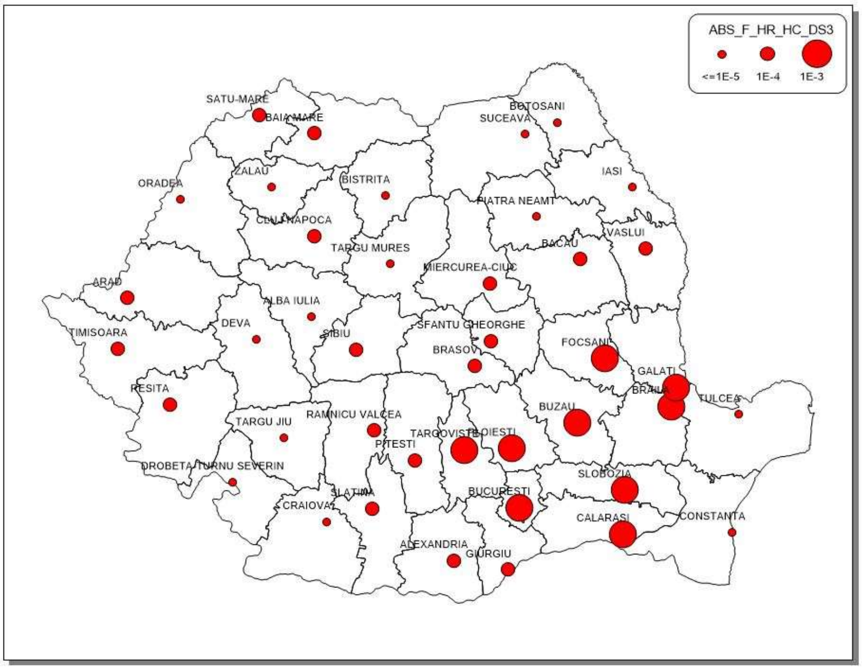


Fig. 6 – Map representation of P_F for F_HR_HC (absolute values)

According to the values obtained, capital cities located in north-eastern part of the country (Iasi, Piatra-Neamt, Suceava, Botosani), but also Craiova and Tulcea have the most significant changes while the ones near Vrancea seismic source tend to have closer values when passing from one code generation to another. For example, Focsani annual failure probabilities are 12 times larger in case of low-code and 4 times larger for the medium-code, when compared to the high-code reference P_F values.

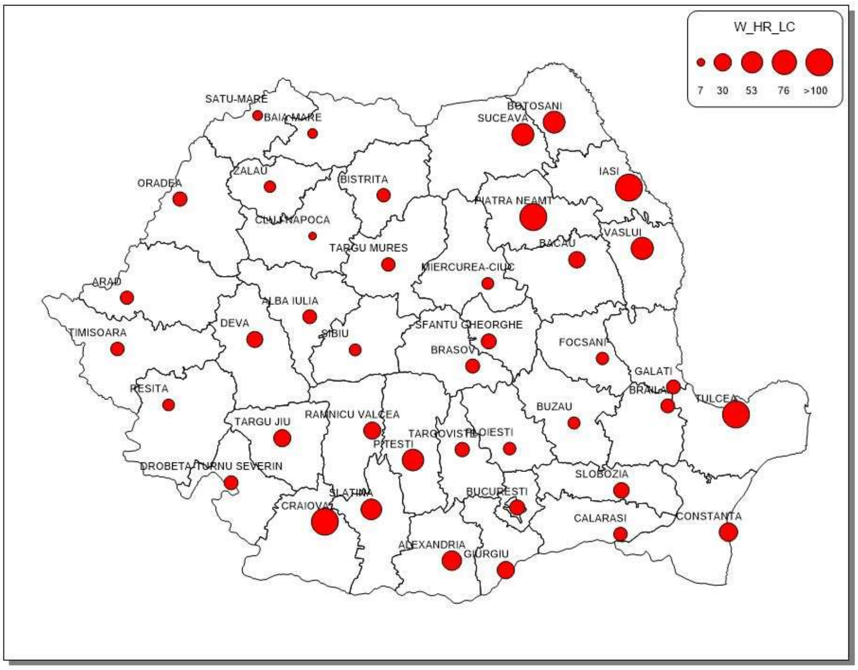


Fig. 7 – Map representation of P_F for W_HR_LC_DS3 (values relative to HC)

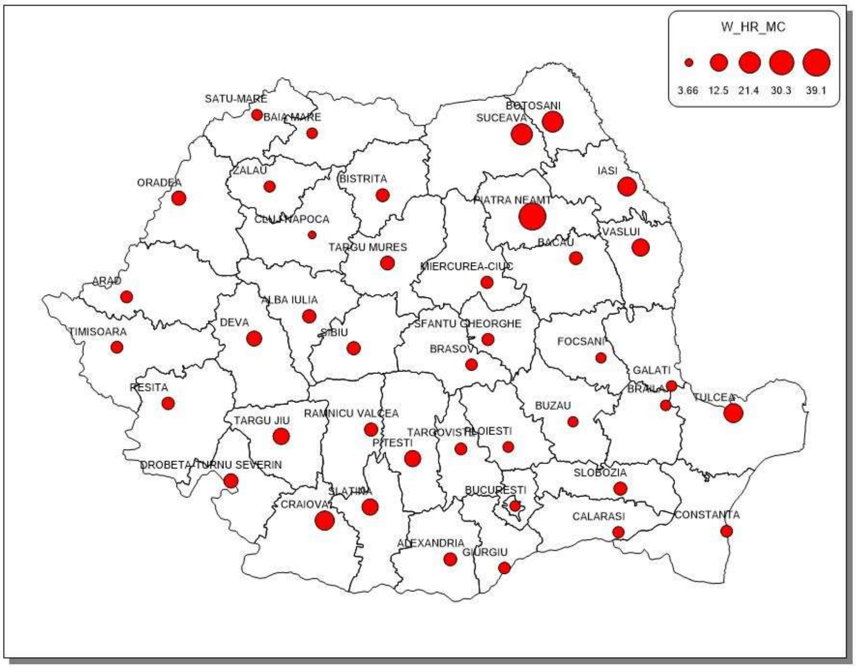


Fig. 8 – Map representation of P_F for W_HR_MC_DS3 (values relative to HC)

4.4 Relative probabilities of failure: comparison between typologies

If the previous maps highlighted the effects of codes' evolution, a different set of maps was realized to point out the seismic hazard's contribution to the risk calculations. Relative values of P_F for each city were obtained function of the maximum failure probability determined for each structural typology. The location of capital cities near Vrancea intermediate-depth seismic source strongly influences the seismic hazard associated to them, and consequently the seismic risk. Taking into consideration both the complete (DS3) and the extensive damage state (DS4), it was observed that the maximum annual probabilities of failure associated to the exceedance of these damage states, was obtained in the capital city Buzau. Therefore, Buzau's probability of failure was considered as reference value and the relative P_F values of other cities were calculated function of it.

An example is displayed in Fig. 9, for the high-rise reinforced concrete frames, designed according to low-code provisions (F_HR_LC), where the probabilities of exceeding DS4 are normalized to the value of Buzau city, namely $P_{F,max} = P_{F,Buzau} = 0.044$. It can be observed that cities like Ploiesti, Focsani and Bucharest have the closest values to $P_{F,max}$, the relative values for other cities continuing to decrease along with increasing the distance from Vrancea seismic source. Comparing the relative values obtained for low-code design with the ones for high-code design presented in Fig. 10, it can be noticed that annual failure probabilities are significantly reduced in absolute terms, but also relatively to the considered reference value from Buzau. More than 75% of the capital cities had annual failure probabilities about 70% lower than the considered reference in LC provisions.

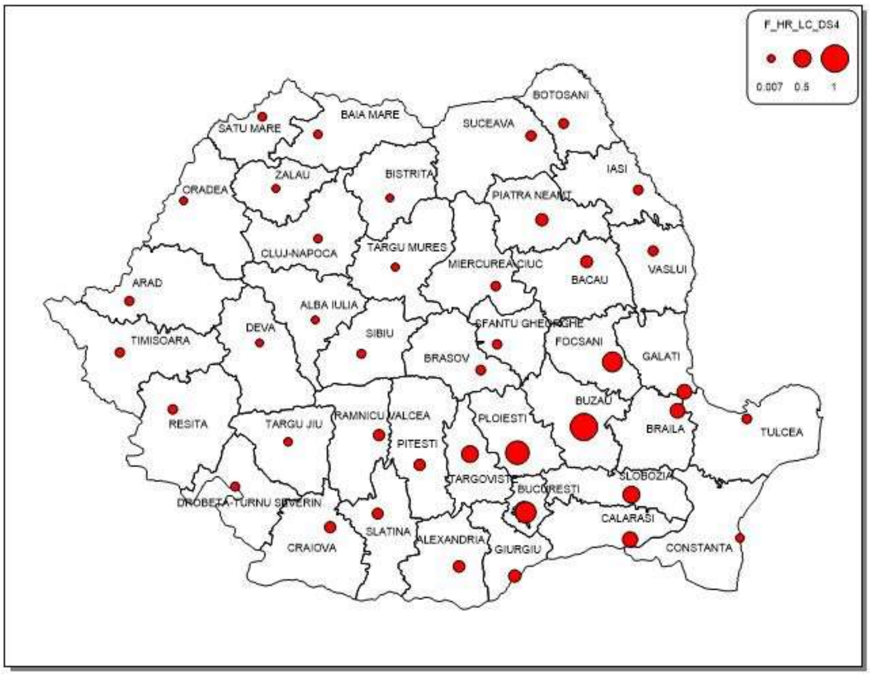


Fig. 9 – Map representation of P_F for F_HR_LC (values relative to $P_{F,max}$)

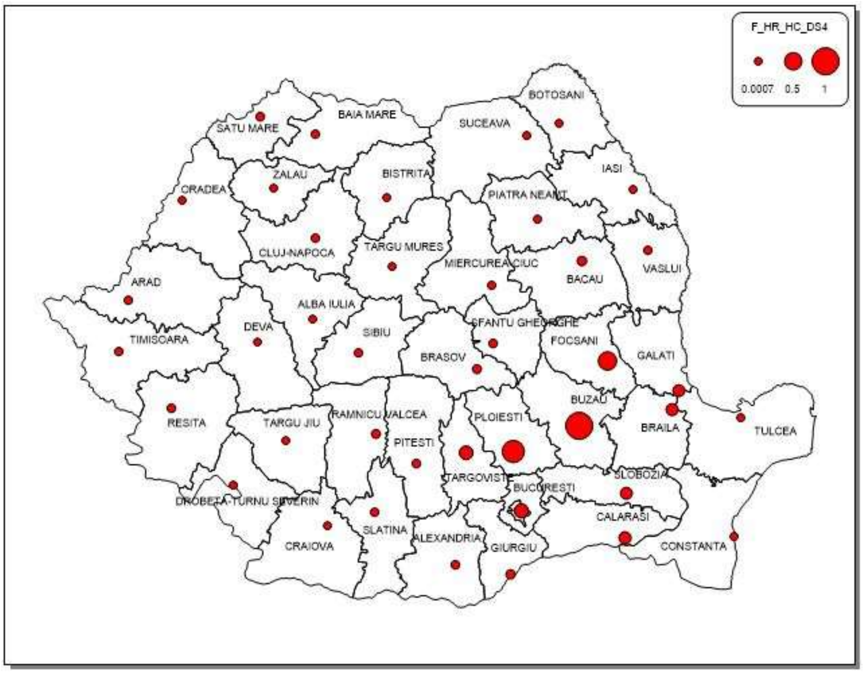


Fig. 10 – Map representation of P_F for F_HR_HC (values relative to $P_{F,max}$)

5. Conclusions

Seismic risk curves were obtained based on the procedure previously described, in order to quantify the seismic risk evolution in terms of annual occurrence probabilities. Comparing the fragility curves determined using the post-event damage surveys in Bucharest and Iasi with the fragility assessment done for low-code RC structures within RO-RISK project, it can be observed that there is a good agreement for RC shear wall structures. However, the other typologies assessed after the 1977 earthquake had less samples for which damage indexes were evaluated, therefore it is difficult to consider those results as representative for the entire structural typology.

Considering that the seismic hazard, namely the occurrence rate of the ground motion parameters cannot be reduced, reducing the seismic risk implies the decrease in terms of seismic fragility. For newly built structures, high-codes provide measures intended to minimize the effects of earthquakes' action, while for the case of existing buildings, retrofitting actions should be considered in this respect. As it can be observed, from the results presented in this paper, the evolution of the seismic design codes had a significant influence on lowering the annual probabilities of failure for the reinforced concrete building stock in Romania.

7. References

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