VULNERABILITY AND RISK EVALUATION FOR A REINFORCED CONCRETE FRAME

BY

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Abstract. Vulnerability and risk assessment can be evaluated in a deterministic or a probabilistic way and this paper makes a comparison between the two approaches. A 2-D reinforced concrete frame, design according to the Romanian norm, was studied. Starting from the capacity curve obtained with a static non-linear analysis, fragility curves were ploted and an average damage index for the performance point of the structure was calculated. In the probabilistic approach the influence of uncertainties in the damage states thresholds is investigated on fragility and vulnerability curves. The obtained results for two coefficients of variation of the damage states thresholds simulated as random variables, meaning 10% and 20%, are also compared. The used procedures are based on the capacity spectrum method and on Monte Carlo simulations.

Key words: deterministic analysis; probabilistic analysis; vulnerability assessment, reinforced concrete frame.

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1. Introduction

Vulnerability and risk assessment represent an important research topic in the last years, emphasizing the necessity to evaluate the built environment in order to diminish earthquake effects. The physical seismic vulnerability, which is of interest for this paper purpose, can be evaluated: by qualitative descriptors or variables (Grünthal, 1988); by means of physical vulnerability indices (Benedetti & Petrini, 1984) and by means of capacity curves. To complete the earthquake damage information in areas with lack of data, Monte Carlo simulation procedures are used (Kappos *et al.*, 1984; Barbat *et al.*, 1996).

The seismic damage evaluation in urban area is highly influenced by uncertainties in each step of the evaluation process. The most recent trends in vulnerability assessment operate with simplified mechanical models essentially based on the Capacity Spectrum Method (Freeman, 1978; Fajfar, 2000). Different approaches to evaluate the seismic vulnerability have been developed and applied in research projects dealing with risk assessment, like HAZUS, Risk-UE and CAPRA (HAZUS 99-SR2; RISK-UE; ERN-AL. CAPRA).

The paper evaluates the seismic vulnerability using the deterministic methodology proposed in Risk-UE project. This method defines building vulnerability from the capacity spectrum and evaluates the expected seismic performance of the structure by comparing the capacity spectrum with the demand spectrum of the seismic hazard (Calvi *et al.*, 2006).

Four damage states are considered in this paper for a building, defined according to Risk-UE handbook specifications, obtaining the damage expressed as probability matrices (Milutinovic & Trendafiloski, 2003). Even though the used approaches have been improved significantly, the uncertainties in the structural characteristics and in the damage state thresholds have a great influence on the results.

The main objective of this paper is to study the influence of uncertainties in the damage states thresholds of a reinforced concrete structure. The used methodology is based on developing probabilistic vulnerability curves which consider the damage states threshold as random. The problem is solved by performing Monte Carlo simulations in order to obtain probabilistic capacity curves, probabilistic fragility curves and probabilistic vulnerability curves.

For the random values simulation a normal distribution was considered with two values for the coefficient of variation – 10% and 20%, respectively. The differences between the ductility factors computed with deterministic and probabilistic approaches, respectively, are discussed.

For the case study a 3 storey reinforced concrete frame structure situated in Romania, in the second seismic area of the country, with a peak ground acceleration of 0.2 g, was considered.

2. Theoretical Background

In order to evaluate the building behaviour, capacity curves can be obtained through nonlinear analysis. The pushover analysis is a nonlinear static incremental procedure able to describe, in a simplified way, the structural behaviour when subjected to earthquake load (Riddell & Liera, 2010; FEMA-273, 1997). It allows the identification of weak structural members and the failure mechanisms. The capacity curve is in fact the graphical representation of the relation between the base shear and the displacement at the roof of the structure (ATC-40, 1996; Zou & Chan, 2005).

The capacity spectrum method requires the following steps: (1) perform the pushover analysis of the building; (2) plot the capacity curve of the building; (3) represent it in a ADRS format, that is, spectral displacement – spectral acceleration coordinates; (4) calculate and plot the bilinear representation of the capacity spectrum; (5) plot the demand spectrum of the considered earthquake; and finally (6) intersect capacity and demand spectra to obtain the performance point, and thus the expected spectral displacement. Even though there is a variety of methods to evaluate the behaviour of the structure, it is considered that the pushover analysis is an accurate approximation in comparison with the nonlinear dynamic analysis. The performance point is calculated using the equal displacement approximation described in ATC-40 (Nour, 2007; Fajfar, 2000).

In order to evaluate the seismic risk of a building, damage fragility curves are used. Fragility curves define the probability that the expected global damage, d, of a structure exceeds a given damage state, dsi, as a function of a parameter quantifying the severity of the seismic action. Thus, for each damage state, the corresponding fragility curve is completely defined by plotting $P[d \geq dsi]$ in the ordinate and the spectral displacement, Sd, in the abscissa. For a given damage state, dsi, a fragility curve is well described by the following lognormal probability density function (Barbat et al., 2008):

$$P\big[dsi\big|Sd\big] = \Phi\left[\frac{1}{\beta_{dsi}}\ln\left(\frac{Sd}{Sd_{dsi}}\right)\right], \qquad (1)$$

where Sd is the spectral displacement (seismic hazard parameter), representing the median value of spectral displacement at which the building reaches a certain threshold of the damage state, dsi, β_{dsi} – the standard deviation of the natural logarithm of the spectral displacement of the damage state ds and Φ – the standard normal cumulative distribution function.

The considered approach proposes four damage states: slight – the damage is considered negligible, moderate – slight structural damage and moderate non-structural damage, severe – moderate structural damage and

heavy non-structural damage and collapse when structure is in imminent danger of collapse. Table 1 shows a summary of the used parameters for the damage state thresholds as functions of the yielding displacement, *dy*, and the ultimate displacement, *du*, of the structure (Milutinovic & Trendafiloski, 2003).

A further step is given by describing the seismic structural damage by means of vulnerability curves. These curves are useful in risk analyses of urban areas, in which case a library of curves covering all the existing building typologies can be realized. They quantify the damage as a function of a parameter characterizing the seismic action, for example the spectral displacement, *Sd*. From a theoretical point of view, they represent the normalized mathematical expectation of the damage states in each spectral displacement (Sobol, 1983):

$$DI = \frac{1}{n} \sum_{i=1}^{n} x_i p_i \ , \qquad (2)$$

where *DI* is the mean damage index, x_i – the damage state number which varies from 1 to 4, and p_i – the probability of corresponding damage state. The probability of damage is computed from the fragility curves.

Table 1
Damage State Thresholds

Damage state	$\overline{Sd}_{dsi}$ values	Graphical representation of the damage thresholds in the bilinear capacity spectrum
Slight	$0.7dy$	
Moderate	dy	
Severe	$dy + 0.25(du - dy)$	
Collapse	du	

In the deterministic approach various combinations of each input variable can be chosen (such as best case, worst case, and most likely case), and the obtained results for each are called "what if" scenarios (Mohamed). By contrast, the probabilistic approach considers random input data adequate probability distribution functions to compute hundreds or thousands of outcomes instead of a few discrete values or scenarios (Möller & Reuter 2007). At the end of a probabilistic analysis, statistics are computed using the output results in order to be able to make observations on the generated results.

Uncertainties in the loading process and their influence on the assessment of the damage were analysed by Möller & Reuter (2001). On the

contrary, in this paper the purpose is to study the uncertainties in the damage state thresholds definition and their influence on the vulnerability of the structure. To do that, a Monte Carlo simulation is performed with the following steps: (1) generation of dependent variables for the damage state thresholds, (2) seismic vulnerability and risk evaluation and (3) statistical result interpretation.

3. Case Study

3.1. Frame Description

A two dimensional, 3 storey reinforced concrete frame was analysed. The frame has 2 openings of 4.85 m and 3.25 m, respectively, and a ground floor of 5 m high and two others of 2.55 m. The properties of the used materials are presented in Table 2.

Table 2
Materials Properties

Materials	E, [GPa]	v	$f'c$	fy	fu
			MPa		
Concrete, C20/25	30	0.2	20.5	–	–
Longitudinal reinforcement, PC 52	210	0.3	–	355	570
Shear reinforcement, OB 38	210	0.3	–	235	360

The frame was designed according to P-100/2006 prescriptions. The columns cross-section dimensions are 60×60 cm for the ground floor, 55×55 cm for the first floor and 50x50 cm for the second one. The longitudinal steel rebars have diameters of 22 mm and 20 mm, and the transversal reinforcement is made of stirrups of 10 mm and 8 mm, spaced at 12 cm in the potentially plastic areas and in the beam–column connections, and at 14 cm in the rest of the column. The beam cross-section dimensions are 30×60 cm for level +4.95 m and $30 \times \times 45$ cm for levels +7.50 m and +10.05 m, respectively. The reinforcement consists of bars with diameters of, respectively, 16 mm, 18 mm and 20 mm in the longitudinal direction, and stirrups of 8 mm spaced at 10 cm in the support areas and at 15 cm in the field.

3.2. Vulnerability Assessment Considering Deterministic Approach

The nonlinear static incremental analysis (pushover analysis) is performed with SAP2000 program considering nonlinear properties for the materials and a monolithically increased load at the top roof of the structures. A capacity curve in terms of base shear force – displacement at the top of the structure is obtained. The intersection of the capacity spectrum with the demand spectrum gives the performance point, as it can be seen in Fig. 1. For the demand spectrum the record for the 1977 Vrancea earthquake was considered.
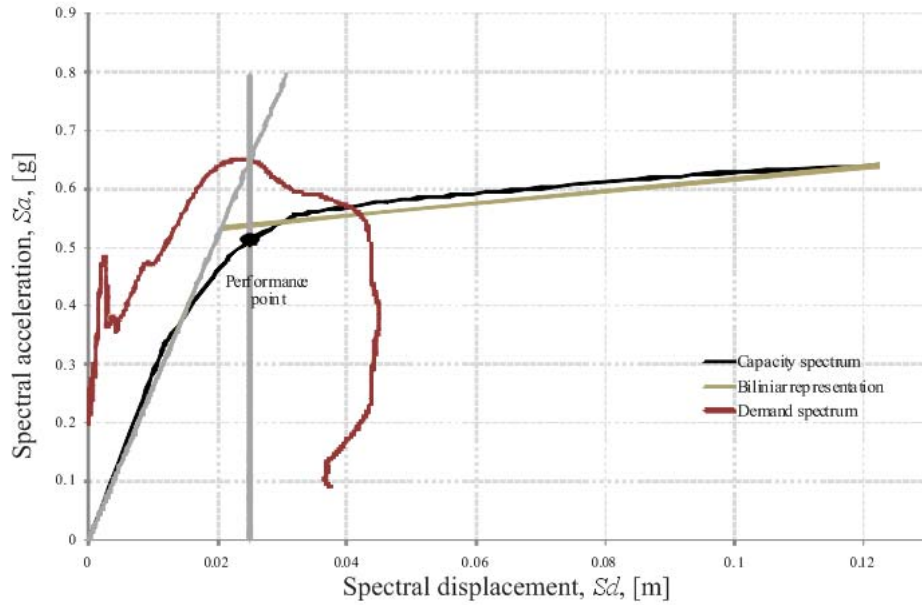
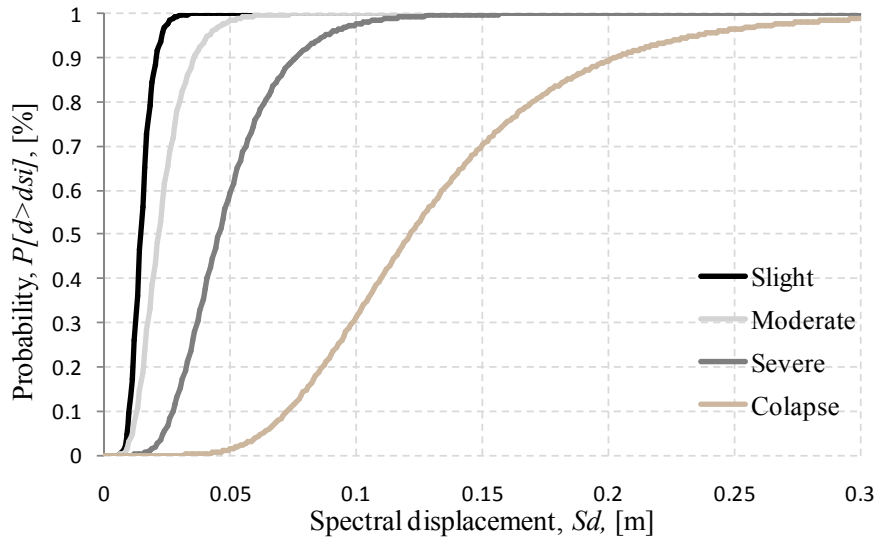Fig. 1 – Evaluation of the performance point.

Fig. 2 – Fragility curves representation.

In order to perform the risk evaluation of the studied frame, fragility curves have been developed with eq. (1) (Fig. 2). For the performance based design, the spectral displacement of the performance point is considered in

order to determine the probabilities for each damage state The damage probability for each damage state corresponding to the performance point is given in Fig. 3. Considering these values the mean damage index, evaluated for the studied model with eq. (2), is 0.6.
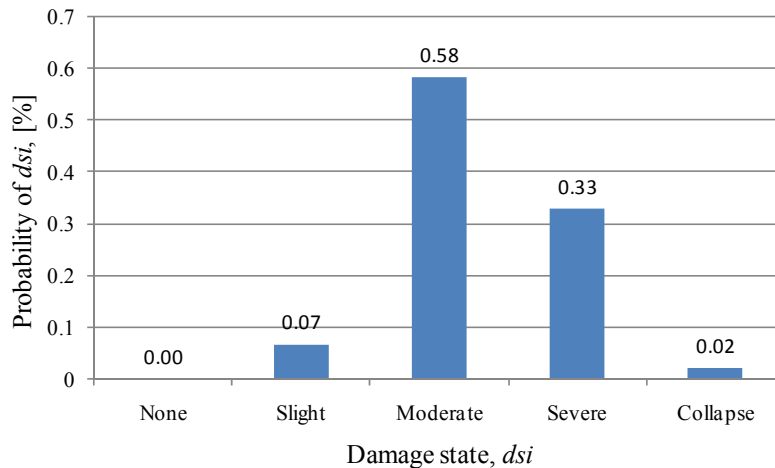

Fig. 3 – Damage states thresholds probabilities.

3.3. Vulnerability Assessment Considering Probabilistic Approach

Proceeding to the probabilistic approach, 1,000 random Gaussian samples were generated for the ultimate displacement of the capacity curve. In order to establish the influence of the variation coefficient, two values were considered, 10% and 20%, respectively. The standard deviation is computed by multiplying the mean values with the variation coefficient.

For each of the obtained random capacity curve, the corresponding fragility curves were computed and plotted in Fig. 4. This figure clearly shows a difference between the results of the two Monte Carlo simulations. It is clear that in the case of a coefficient of variation equal to 20%, the uncertainties in the results covered a wider range.

Based on the fragility curves from Fig. 4, the vulnerability curves showed in Fig. 5 are plotted. The figure represents the mean damage index at each spectral displacement coordinate, for all the 1,000 random variables.

For each spectral displacement coordinate, Sd, the 1,000 values of the average damage index, Dim, of Fig. 5, are characterized by mean and standard deviation. The standard deviation increases with the coefficient of variation, but not in the same proportion.

Plotting histograms for the distribution of the average damage index, Dim, represented in Fig. 5, from 10 to 10 cm of the spectral displacement, different distribution curves were fitted for each considered abscissa using

EasyFit software. The name of each curve and the corresponding parameters are given in Table 3.
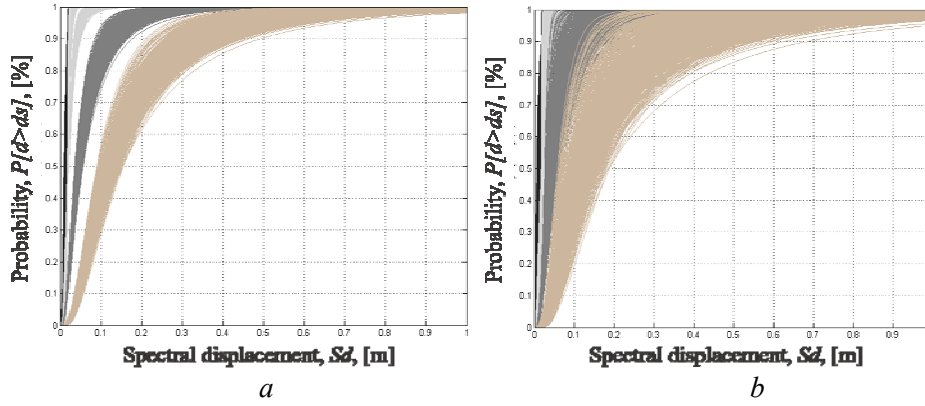

a   *b*

Fig. 4 – Probabilistic fragility curves, considering a coefficient
of variation of: *a* – 10% and *b* – 20%. The legend from Fig. 2 is used.
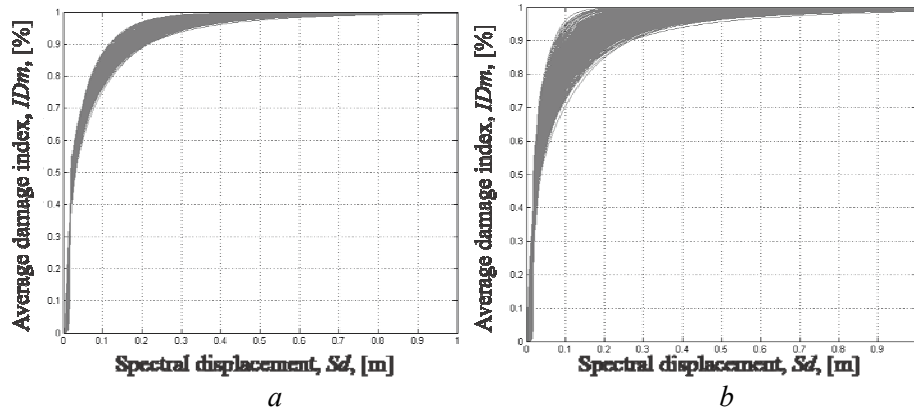

a   *b*

Fig. 5 – Probabilistic vulnerability curves considering a coefficient
of variation of: *a* – 10% and *b* – 20%.

If an average error of 7% is assumed, all the distributions listed in Table 3 can be approximated by the Johnson SB distribution, which has the following equation [37]:

$$f(x) = \frac{\delta}{\lambda\sqrt{2\pi}z(1-z)}\exp\left\{-\frac{1}{2}\left[\gamma + \delta\ln\left(\frac{x-\xi}{\lambda-x+\xi}\right)\right]^2\right\}, \qquad (3)$$

where γ is the continuous shape parameter (< 0), δ – the continuous shape parameter (> 0), λ – the continuous scale parameter (> 0) and ξ – the continuous location parameter.

The behaviour factors have been calculated for all the capacity curves obtained by performing the Monte Carlo simulation. The behaviour factor initially assumed in the design, in reality is not reached. Considering the capacity curve, a behaviour factor of 5.9 is obtained. On the other hand, through the probabilistic study, the behaviour factors vary between 4.87 and 8.3, with a mean value of 6.75, in the case of a variation coefficient of 10% of the damage state thresholds. In the case of a variation coefficient of 20%, the behaviour factor varies between 3.42 and 9.85, with a mean value of 6.68. These values attest the fact that the assumed value for the behaviour factor is a safety one.

Table 3

Distribution Curves for the Average Damage Index

Sd, [cm]	Recommended distribution	Parameters	Approximating with Johnson SB distribution
10	Pearson 5	α=171.46, β=43.985, γ=0.555	γ=1.073, δ=2.396, λ=0.206, ξ=0.732
20	Gamma	α=166.5, β=0.001, γ=0.75	γ=1.7431, δ=4.183, λ=0.242, ξ=0.83
30	Gamma	α=11,909, β=0.11E–5, γ=0	γ=–0.199, δ=3.013, λ=0.11, ξ=0.909
40	Log-Pearson 3	α=82.863, β=–6.5E-4, γ=0.036	γ=–0.955, δ=2.404, λ=0.06, ξ=0.947
50	Weibull	α=6.251, β=0.022, γ=0.97	γ=–1.469, δ=2.144, λ=0.038, ξ=0.965
60	Johnson SB	γ=–1.831, δ=1.975, λ=0.026, ξ=0.976	γ=–1.831, δ=1.975, λ=0.026, ξ=0.976
70	Johnson SB	γ=–2.086, δ=1.85, λ=0.018, ξ=0.982	γ=–2.086, δ=1.85, λ=0.018, ξ=0.982
80	Johnson SB	γ=–2.4, δ=1.78, λ=0.014, ξ=0.987	γ=–2.4, δ=1.78, λ=0.014, ξ=0.987
90	Johnson SB	γ=–2.61, δ=1.71, λ=0.011, ξ=0.99	γ=–2.61, δ=1.71, λ=0.011, ξ=0.99

4. Conclusions

In order to evaluate the seismic vulnerability of buildings, two approaches can be considered: a deterministic and a probabilistic one. Even though the deterministic procedure is simpler and faster, the results are limited. The amount of results obtained by applying a probabilistic procedure covers a wider range of possible behaviours.

The differences between vulnerability curves obtained in a deterministic or probabilistic way consist in taking into consideration, in the second case, the uncertainties that can influence the behaviour of the structure. These parameters can refer to the design stage, to the erection of the building, and also to different

factors that can appear during the building life and can influence its behaviour: previous earthquakes, degradations in some elements, unexpected loads, etc.

The main advantage of the probabilistic approach consists in the fact that the obtained results are closer to the real behaviour of the building, that is, to the uncertainties the building can suffer during its life time.

The paper performs deterministic and probabilistic analyses on a low-rise reinforced concrete framed structure. For the deterministic approach the computed average damage index is represented as a line, in contrast to the probabilistic approach results that consist of a fascicule of lines.

The probabilistic approach was performed for two range of uncertainties in the damage state thresholds, characterized by variation coefficients of, respectively, 10% and 20%.The results for the first variation coefficient are closer to those of the deterministic approach, but the results for the second one are considered to be safer if the analysis focuses on the uncertainties in the risk and vulnerability assessment.

Another important observation consists in the fact that the distribution of the calculated average damage index can be approximated by one function, in this case by the Johnson SB distribution. This distribution is different from the initial Gaussian distribution considered for the random samples.

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EVALUAREA RISCULUI ȘI A VULNERABILITĂȚII PENTRU UN CADRU DIN BETON ARMAT

(Rezumat)

Evaluarea vulnerabilității și riscului seismic poate fi realizată pe cale deterministă sau probabilistă, iar această lucrarea realizează o comparație între ele. S-a considerat un cadru plan din beton armat, proiectat după normativul românesc. Pornind de la curba de capacitate obținută prin analiză static neliniară, s-au trasat curbele de fragilitate și s-a calculat indicele de degradare mediu pentru abscisa punctului de performanță. In analiza probabilistă s-a studiat influența incertitudinilor asupra curbelor

de fragilitate şi vulberabilitate. S-au comparat rezultatele pentru două valori ale coeficientului de variaţie: 10% şi 20%. Metodele utilizate se bazează pe metoda spectrului de capacitate şi pe principiile metodei Monte Carlo.