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DEVELOPMENT OF SEISMIC VULNERABILITY CURVES FOR REGION SPECIFIC MASONRY BUILDINGS

Kristina MILKOVA[1], Julia ROSIN[2], Christoph BUTENWEG[3], Elena DUMOVA - JOVANOSKA[4]

ABSTRACT

Recent earthquake events have immediately placed topics related to seismic behaviour and risk assessment of existing structures under the research community radar.
A methodology for the development of seismic vulnerability curves of existing masonry buildings in former Yugoslav Republic of Macedonia, a country with moderate to high seismic hazard is shown in this paper. The first step in the proposed methodology consists of proper buildings selection and classification. In order to alleviate the shortage of available design documentation and uncertainties in the mechanical characteristics, a FEM updating based on ambient vibration measurements is employed as a second step. The estimated averages of the proposed input parameters are then utilized within a Response Surface method in conjunction with Monte Carlo simulation in order to get the close form of the complex relationship between the structure and the response. Response Spectrum calculated from time histories of the historic earthquakes is used in a huge number of nonlinear finite element analyses performed. Since the drift is well correlated to the earthquake damage, maximum inter-story drift ratio is used as a response parameter. With the gained experience of the damage on masonry structures after the catastrophic 1963 Skopje earthquake, damage states are suggested. Maximum likelihood estimation procedure implementation for the process of vulnerability curves determination is noted as a final step in the procedure. The proposed methodology has been applied to a selected number of buildings in the selected region.

Keywords: Masonry structures; Updating, Response Surface; Vulnerability Curves

1. INTRODUCTION

A huge number of procedures for seismic vulnerability estimation of buildings have been suggested in the last 40 years. This complex task includes seismic hazard estimation on one hand, as well as definition of the characteristics of the imposed structures on the other. In general, the methodologies for seismic vulnerability estimation can be divided into three categories: empirical, analytical and hybrid.
Seismic vulnerability assessment of the buildings for the first time was calculated in the early 70ties, using empirical approach. Whitman et al (1973) proposed Earthquake damage probability matrices, as an option for the relationship earthquake intensity – damage level for the first time. In his research, nine categories of damage have been proposed, identified by subjective word description and by the ratio of damage cost to building replacement cost. Damages of several types of buildings as a result from earthquakes with different intensities have been summarized in Tables. Damage probability matrices for several types of structures are calculated by statistically analyzing the data collected from more than 1600 buildings after the San Fernando earthquake in 1971.

[1]Assistant, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering, "Ss. Cyril and Methodius" University, Skopje, former Yugoslav Republic of Macedonia, milkova@gf.ukim.edu.mk
[2]SDA-Engineering GmbH, Kaiserstraße 100, TPH III/B, 52134 Herzogenrath, Germany, rosin@sda-engineering.de
[3]Professor, FH Aachen, Jülich, Germany, christoph.butenweg@fh-aachen.de
[4]Professor, Head of the Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering, "Ss. Cyril and Methodius" University, Skopje, former Yugoslav Republic of Macedonia, dumova@gf.ukim.edu.mk

HAZUS (Porter, 2009) is the outcome of a project conducted for the National Institute of Building Science (NIBS), supported by the Federal Emergency Management Agency (FEMA), in order to develop a nationally applicable methodology for estimating the potential losses on a regional basis (FEMA, 2003). Seismic vulnerability assessment is based on a Spectral Capacity Method, and the intersection point between the capacity curve – pushover curve and the response spectra is calculated. The capacity spectrum has been developed for each building class using model buildings designed for different levels of design practice in the US. At the end, an expected overall rebuilding cost, based on a percentile of the different types of expected damages is calculated.

The researchers in former Yugoslav Republic of Macedonia in this field have followed the research on a global level since the origins. Namely, Nochevski in his PhD, under the supervision of Petrovski, has proposed an original methodology for empirical and analytical vulnerability calculation of the curves (Nochevski, 1993). An innovative approach including a criterion for calculation of the damage on a local level has been suggested. Namely, five levels of damages are selected and the criteria depend of the characteristic points of the calculated force-deformation relationship in a structural element. Dumova – Jovanoska in her Phd research proposes a methodology for expressing the relationship damage – earthquake intensity in the forms of vulnerability curves and damage probability matrices (Dumova, 2004). This methodology has been applied on a reinforced concrete structures. Special attention has been dedicated to local seismic hazard determination. By using geological profiles from the Skopje Region, a set of 240 artificial earthquakes has been generated and nonlinear analysis for the buildings have been performed.

In the framework of the RISK-UE (RISK-UE, 2001-2004) project, an approach for development of seismic vulnerability of structures for reinforced concrete structures, as dominant residential building topology in former Yugoslav Republic of Macedonia for new structures (RC1 and RC4) has been proposed. Databases from 1979 Montenegro earthquake, as well as data from 1994 Bitola Earthquake were chosen as a seismic input in the dynamic analysis of a 1D shear type lumped mass model that was used to model the RC structures (Milutinovic, Trendafiloski, 2003).

One of the biggest shortages of the procedure for the analytically calculation of the seismic curves is the duration of the analysis, because of the huge number of nonlinear analysis that have to be performed. That is one of the reasons why in the future research hybrid methods are more popular, as combination of statistical data from damages after earthquakes and the analytical models.

2. MOTIVATION AND WORKING PLAN

Knowing the fact that there is a the huge number of old masonry buildings in the building stock of former Yugoslav Republic of Macedonia currently serving as public institutions and that they have never been assessed or verified from one side, and the severe ground motions that happened lately on the other, it can be concluded that the need of seismic risk evaluation of these existing structures is of a high priority. Despite the big amount of proposed methodologies for seismic risk methodologies on a world level, uncertainties and inconsistencies still exist.

This research is conducted under the frame of the ongoing project SeismoWall (SeismoWall, 2017-2019), which main purpose is definition of four sets of vulnerability curves for regular and irregular unreinforced masonry (flexible/stiff floors) structures in former Yugoslav Republic of Macedonia. The main goal of the research is seismic vulnerability assessment of the structures with using an innovative methodology for seismic vulnerability curves calculation of excising masonry buildings. The methodology includes data collection for the excising structures and their classification, experimentally determination of the geometric and material characteristics of the chosen buildings, seismic hazard assessment, nonlinear analysis and statistical analysis for vulnerability curves calculation. The main purpose is to propose a methodology for assessment of the masonry buildings, which will result with seismic risk determination and increasing the security level by taking measures which will be considered essential. The frame of the research is presented in Figure 1.

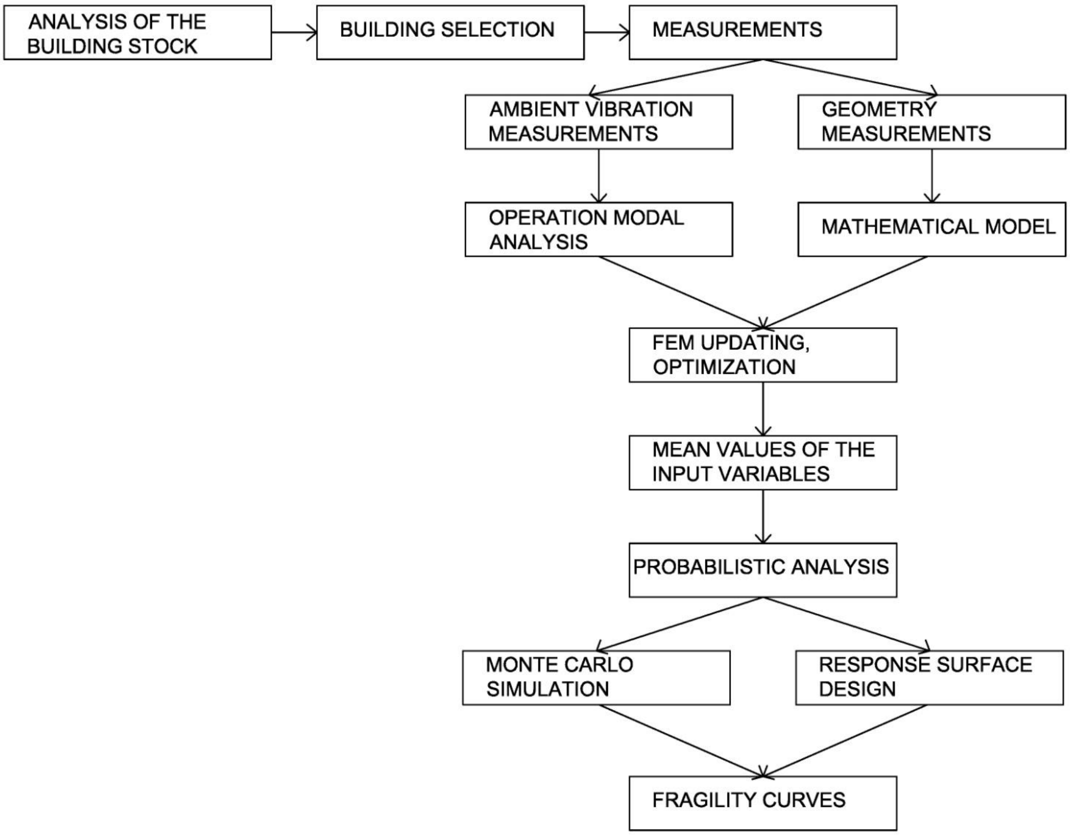


Figure 1. The general framework of the research

3. THE METHODOLOGY

The first step of the methodology is to completely analyze the building stock and do a careful selection of the buildings. A selection of sixteen masonry structures have been done by meeting two main criteria: structures are built before the Skopje earthquake in 1963 and serve as public institutions. The chosen buildings represent the classes of buildings with similar architecture, structural system and structural materials. Buildings serving as public institutions (schools, administration offices, courts, museums, theaters, etc.) located in a six cities in former Yugoslav Republic of Macedonia (Skopje, Bitola, Ohrid, Debar, Kavadarci and Gevgelija) were selected. They are classified according to classification system adopted in Risk-UE project (2003) in the following groups:

- *M5 - U masonry (old bricks) – regular structures (3 buildings)*
- *M5 - U masonry (old bricks) – irregular structures (4 buildings)*
- *M6 - U masonry RC floors* types– *regular structures (2 buildings)*
- *M6 - U masonry RC floors* types– *irregular structures (7 buildings)*

Knowing the fact that almost all of the buildings have been built without any design documentation, in the period of time when there were no regulations for seismic design of structures, a detail on site measurements of the geometry has been done for all of them. The dimensions of all of the structural members have been measured and the layouts have been provided.

Laboratory testing of masonry properties and also in-situ dynamic testing of the dynamic characteristics is listed as a second part of the research. Laboratory testing of the solid clay bricks and lime mortar have been performed. Also, six wallets with dimensions 500x440x125 mm made from the original bricks from the buildings were tested for compressive strength determination. The results showed a vast variety of the measured parameters, as expected for the masonry as a material. The mean value of the compressive strength is 2.45 N/mm^2.

In the process of identifying the dynamic characteristics, in city dynamic tests were performed for all

of the selected buildings. Using the frequency domain decomposition algorithm, frequencies and mode shapes of all of the buildings were estimated.
The finite element method allows the analysis of complex structural dynamics problems. However, the extent to which the model is in error due to several reasons is very hard to estimate and it is always justified to find a procedure for confirmation of the validity of the FE model. In this methodology, in order to alleviate the uncertainties of the material parameters, an algorithm for calibration of the finite element model was used, using as a target values the experimentally obtained values of the dynamic characteristics and MAC values. This algorithm uses a sensitivity coefficients and weight factors. The process begins with a dynamic analysis of the defined finite element mathematical model, using the experimentally obtained information of the mechanical characteristics: the mean values and the standard deviations. The results of the finite element model analysis are used for correlation check with the experimentally obtained results. Sensitivity coefficients are used in order to mitigate the difference between the experimental and analytically derived values, then again with newly generated parameters dynamic analysis is performed, looping until the defined convergence criterion is achieved. Generally, the updating method is based on the use of sensitivity coefficients that iteratively update selected physical element properties (parameters that we consider uncertain) so that correlation between simulated responses and target values improves, shown on Equation 1.

$$\{R_e\} = \{R_a\} + [S](\{P_u\} - \{P_0\}) \quad (1)$$

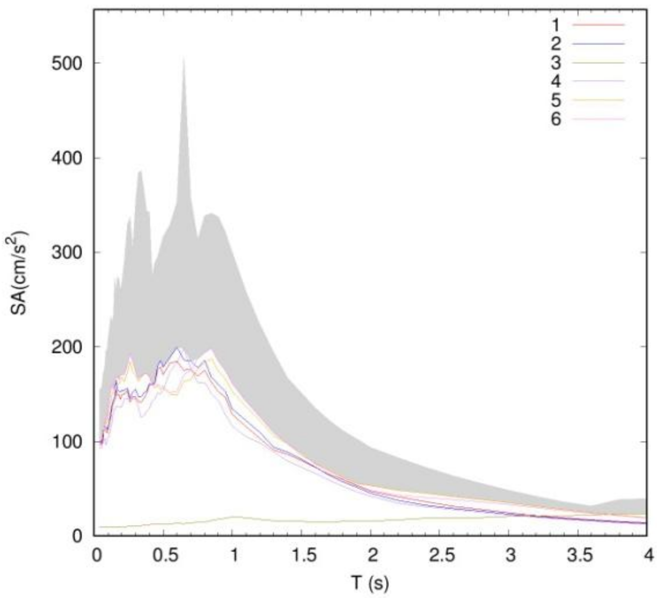
where

$\mathrm{R_e}$ and $\mathrm{R_a}$ − simulated responces
$\mathrm{P_u}$ and $\mathrm{P_o}$ − parameters (material propreties, geometry, damping propreties …)

The estimated mean values and standard deviations, or the ranges of the material parameters will be utilized as input parameters in the probabilistic analysis.

3.1 Local Hazard definition

Using site-specific calculated response spectra in the analysis instead of the code defined ones can influence the final results in a great manner. An innovative method, named Neo Deterministic approach (Panza et al, 2001) is used for calculation of the spectra for the location of all of the buildings, selected as archetypes within the project. This scenario – based method incorporates together the knowledge of tectonic style of the considered region, the active fault characterization, the earth crust model and the historical seismicity. The map of geotectonic zoning from Arsovski (1997) was used for the definition of the structural polygons characterized by the thickness of each layer, the density, P and S wave velocity and their attenuation factors. The earthquake catalogue that is used consists of all of the significant registered events from 518 until 2015. The fault plane mechanism for all of the events is calculated at the Seismological Observatory of the Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Skopje. Since the structural model and the seismicity is defined, modal summation technique (up to 10Hz) is used for wave propagation modeling and the synthetic seismograms are generated in all of the predefined grid points distributed over the region of interest. Maps of acceleration, velocity and displacement are obtained as a result of this procedure.
Variations of the rupturing process are taken into account in the nucleation point of the rupture, in the rupture velocity pattern and in the distribution of the slip on the fault. Six families of scenarios (50 realizations for each scenario) are considered: bilateral rupturing style with 0°, 90° and 180° directivity, unilateral rupturing style with 0°, 90° and 180° directivity. The results obtained from the multiple scenarios are obtained as an envelope of the response spectra computed at each site using the procedure Maximum Credible Seismic Input (MCSI) proposed by Fasan et al (2016) and Fasan et al (2017). This procedure has been applied to all six cities of interest in frame of the aforementioned project in former Yugoslav Republic of Macedonia. Here, the result for the city of Skopje is shown (Figure 2). MCSI is calculated for 5% damping of the response spectra.



	source	profile	M_w	edi (km)	depth (km)	strike (°)	dip (°)	rake (°)	sre (°)	slon (°N)	slat (°E)
1	sz 0001 bf	-	6.1	13.9	10.0	303	74	339	266	21.5	41.9
2	sz 0001 bf	-	6.1	13.9	10.0	303	74	339	159	21.5	42.1
3	sz 0010 bf	-	7.5	145.1	15.0	22	56	40	98	23.3	41.7
4	sz 0001 bb	-	6.1	13.9	10.0	303	74	339	159	21.5	42.1
5	sz 0001 uf	-	6.1	13.9	10.0	303	74	339	266	21.5	41.9
6	sz 0001 uf	-	6.1	13.9	10.0	303	74	339	159	21.5	42.1

Figure 2. MCSI obtained at one selected site of interest. Maximum horizontal components are considered. In the source label, *bf* indicates bilateral rupture with forward directivity, *bb* bilateral rupture with backward directivity, *uf* unilateral rupture with forward directivity. At this site, no part of the MCSI spectrum is associated with the scenarios generated with neutral directivity (*bn* or *un*), or unilateral rupture with backward directivity (*ub*).

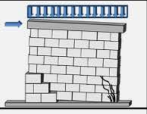
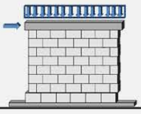
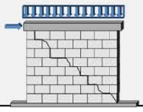
3.2 Mechanical model

MINEA software (SDA Engineering) is used for verification of the structural safety of masonry structures and mixed structures made of masonry and reinforced concrete. Additional module in the frame of the software is programmed for the special needs of the analysis performed for obtaining the vulnerability curves. All of the buildings are modelled and analysed separately (one of the building is shown on Figure 3) and the verification of the structure is based on the non-linear pushover curve, which is determined using a static non-linear calculation by successively increasing a horizontal load distribution. Also, the nonlinearity is included by the newly implemented iterative procedure of calculating the compressed length of the wall. Namely, the length of the wall decreases when the deformation of the wall increases. Generally, the procedure in MINEA consists of four steps:

- Calculation of load- displacement curves of each single wall. Based on the superimposed vertical load, the wall geometry, and the material properties of bricks and mortar, the capacities of the each walls are calculated. The bending and longitudinal failure mode, the shear failure mode, and the brick structural failure mode has been considered during calculation.
- Calculation of building capacity – Push Over curve of the structure. The capacity curves of the individual walls are superimposed to give one resulting capacity curve for the building.
- Transformation of the curve into Sa-Sd diagram using an equivalent single mass oscillator.
- Performance point – the intersection between the spectra and the Push Over curve. If an intersection point (a "performance point") of the two curves can be found in the stable area of

the capacity curve, then it is concluded that sufficient earthquake resistance is guaranteed. The determination of the intersection point of the curves is done iteratively taking into account deformation- dependent effective structural damping. (Gellert, Butenweg, 2014).

Table 1. Maximum deformation capacities (Acording to German Codes, EC6, EC8)

Failure mode	Maximum horizontal capacity		Max. deformation [m]
Bending and normal force 	$\frac{L^2 \cdot q_0}{p_V \cdot \alpha \cdot 2 \cdot H_W}\left(1-1{,}15\frac{q_0/t}{f_k}\right)$		$0{,}006 \cdot \frac{H_W^2}{L} \cdot \alpha$
Friction failure 	Head joints without mortar: $(0{,}5 \cdot f_{vk0} \cdot t + 0{,}4 \cdot q_0) \cdot L$	Head joints with mortar: $(1{,}0 \cdot f_{vk0} \cdot t + 0{,}4 \cdot q_0) \cdot L$	$0{,}004 \cdot H_W;\ \sigma_0 \leq 0{,}15 \cdot f_k$ $0{,}003 \cdot H_W;\ \sigma_0 \geq 0{,}15 \cdot f_k$
Brick tension failure 	Head joints without mortar: $0{,}045 \cdot f_k \cdot L \cdot t$	Head joints with mortar: $0{,}065 \cdot f_k \cdot L \cdot t$	$0{,}004 \cdot H_W;\ \sigma_0 \leq 0{,}15 \cdot f_k$ $0{,}003 \cdot H_W;\ \sigma_0 \geq 0{,}15 \cdot f_k$

In the process of definition of the load-displacement curves, the maximum deformation capacities for bending failure and shear failure used are shown in Table 1.

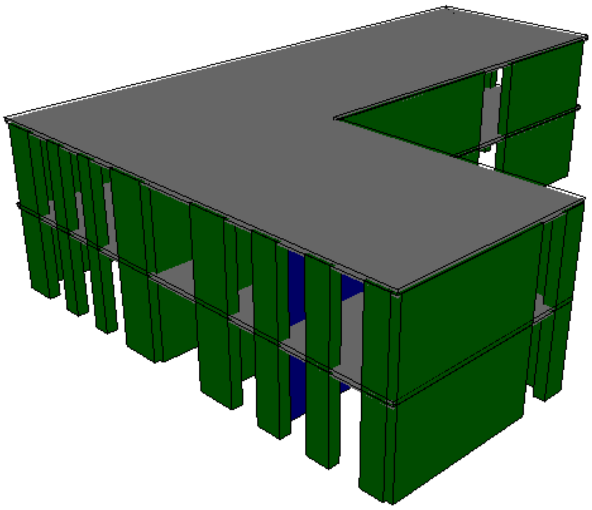


Figure 3. Mathematical model in MINEA

3.3 Probabilistic analysis

Knowing the fact that a huge number of results from the nonlinear analysis are required for vulnerability curves generation, the use of the direct Monte Carlo sampling would be an expensive option, since it produces an enormous number samples that should be performed. The Response Surface Methodology is a statistical tool used for the design of experiments and the process of optimization of the number of samples and simulations is significant (Towashiraporn et al, 2008). In dependence of the chosen method (Box-Behnken design, Central Composite design), the analyses only for the chosen points are performed and a polynomial relationship between the output and the input parameters should be done (regression analysis). In this fashion, more efficiently and with less computational demand, the same number of output results as the number obtained by Direct Monte Carlo Analysis can be obtained. The comparison of the both procedures is shown on Figure 4.

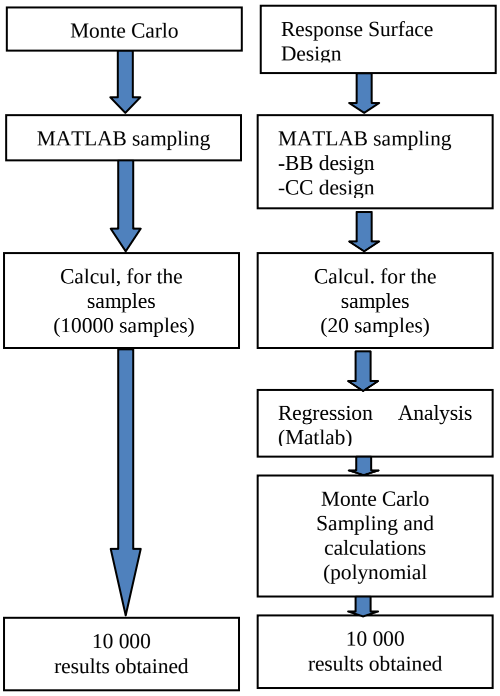


Figure 4. The difference between the Monte Carlo and Response Surface Methodology

The first step in the analysis is to define the input and the output parameters. Their mean values and statistical variations are carefully chosen, based on a huge data of experimental research. In the current

Table 2. Input variables

		input variables		**low**	**high**
load	1	additional load – slab	[kN/m²]	1	3
	2	additional load – roof	[kN/m²]	1	3
mat 1 E=2880 MPa	3	Compressive strength	fk [N/mm²]	0.3	2
	4	Shear strength	fvk [N/mm²]	0.07	0.4
	5	additional damping	[%]	5	10
	6	Degree of resraint	[-]	0.5	0.75
mat 2 E=5440 MPa	7	Compressive strength	fk [N/mm²]	4	10
	8	Shear strength	fvk [N/mm²]	0.07	0.4
	9	additional damping	[%]	5	10
	10	Degree of resraint	[-]	0.5	0.75

research, the chosen input variables are the following:

- compressive strength of masonry
- shear strength of masonry
- dead load
- additional damping
- degree of restrained

With investigations and many trials, it is concluded that these parameters influence the result in a great manner. Estimation of the damage indicator and performance levels is a critical point in vulnerability curves definition. The interstory drift is defined as damage indicator, as parameter that can describe the damage the most correctly. Four damage levels are employed in this study. The corresponding drifts are 0.1%, 0.3% , 0.5% и 0.8%, according to Calvi (Calvi et all, 2006, Mouyiannou et al, 2003).

With variation of these characteristics, despite the uncertainties in the structures, the differences among the objects that are representing a group of objects are taken into account. In Table 2, the input variables and their boundaries are shown.

The most widely used function in the Response Surface Method is the polynomial function with as less as possible terms because the further calculations would be simplified. Equation 2 shows the shape of the polynomial function used in the analysis:

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j>i}^{k} b_{ij} x_i x_j \tag{2}$$

y - responce
x_i,x_j - input parameters
b_0,b_i, b_{ii}, b_{ij} - unknown coefficients
k - number of input parameters

With this function the connection between the input and the output parameters is defined, or the interstory drift is calculated in dependence of the compressive strength, shear strength of masonry, dead load, additional damping and degree of restraining of the wall. However, this function has to fulfill some criteria:

- The mean of the residuals should be approximately zero for all the values of X.
- The variance of the residuals should be approximately constant for all the values of X.
- The distribution of the residuals should be approximately Normal

To address the first two we can examine a scatter-plot of the residuals against the fits with the horizontal zero line drawn in. In order to check the normality of the distribution of the residuals the Normal Probability plot with Matlab program is calculated.

Since it is confirmed that the polynomial calculated is a good approximation of the response, for 10 000 samples generated with Monte Carlo Analysis, interiority drift was calculated.

Vulnerability curves are mathematically defined as damage state exceedance probability, corresponding to specific seismic level. The analyses are performed in MATLAB program, where for every earthquake level employed four results (four points in the diagram) are obtained. These points represent the percentage of exceeding the corresponding damage level. Using Maximum likelihood estimation vulnerability curves are obtained. The results of the analysis are four curves for the M5 and M6 types, for both regular and irregular structures.

The calculated preliminary vulnerability curves for one building are represented on Figure 5a and Figure 5b, for both Direct Monte Carlo Analysis and Response Surface Method.

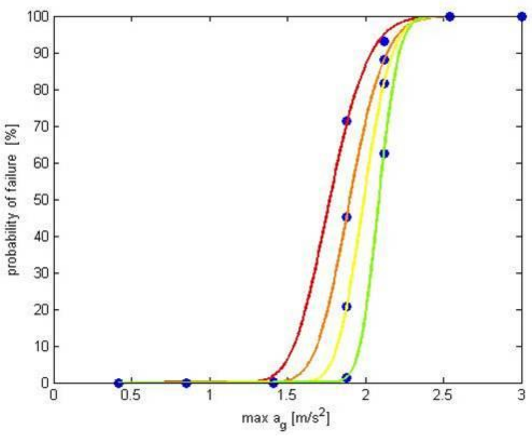


Figure 5a. Vulnerability Curve (MCS)

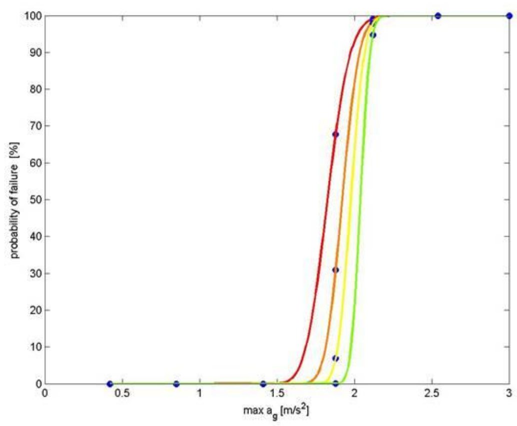


Figure 5b. Vulnerability Curve (RSM)

Legend: Red line: Limit State 1 – 0.1% drift; Orange line: Limit State 2 – 0.3% drift; Yellow line: Limit State 3– 0.5% drift; Green line: Limit State 4 – Collapse

4. CONCLUSIONS

A complex methodology for seismic vulnerability assessment of a masonry structures located in former Yugoslav Republic of Macedonia has been proposed. The framework includes selection of a prototypes, experimental work (laboratory and in city dynamic testing), nonlinear analysis of the structures, finite element model updating and statistical analysis for vulnerability curves determination. A set of four curves for the previously defined classes of structures (M5- regular, M5-irregular, M6- regular, M6- irregular) would be of a great value for the future structural assessment of the buildings in the selected region.

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