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Region-sensitive comprehensive procedure for determination of seismic fragility curves

Kristina Milkova[1], Christoph Butenweg[2], Elena Dumova-Jovanoska[3]

[1] *Assistant Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, milkova@gf.ukim.edu.mk
[2] *Professor*, FH Aachen, Jülich, Germany, christoph.butenweg@fh-aachen.de
[3] *Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, dumova@gf.ukim.edu.mk

Abstract

Seismic vulnerability estimation of existing structures is unquestionably interesting topic of high priority, particularly after earthquake events. Having in mind the vast number of old masonry buildings in North Macedonia serving as public institutions, it is evident that the structural assessment of these buildings is an issue of great importance. In this paper, a comprehensive methodology for the development of seismic fragility curves of existing masonry buildings is presented. A scenario – based method that incorporates the knowledge of the tectonic style of the considered region, the active fault characterization, the earth crust model and the historical seismicity (determined via the Neo Deterministic approach) is used for calculation of the necessary response spectra. The capacity of the investigated masonry buildings has been determined by using nonlinear static analysis. MINEA software (SDA Engineering) is used for verification of the structural safety of the structures Performance point, obtained from the intersection of the capacity of the building and the spectra used, is selected as a response parameter. The thresholds of the spectral displacement are obtained by splitting the capacity curve into five parts, utilizing empirical formulas which are represented as a function of yield displacement and ultimate displacement. As a result, four levels of damage limit states are determined. A maximum likelihood estimation procedure for the process of fragility curves determination is noted as a final step in the proposed procedure. As a result, region specific series of vulnerability curves for structures are defined.

Key words: Seismic risk, seismic vulnerability, fragility curves, masonry structures

1 Introduction

The new Regulations for seismic design present worldwide deal not only with the design of new structures, but high importance is assigned to the methodologies for structural assessment of existing structures as well. Moreover, many documents and programs are also developed for post-earthquake recovery and retrofitting of structures. All of these documents are pre-requisite for creating a national strategy for seismic risk mitigation and successful management of resources in any future ground shaking. The unpreparedness of the national authorities for this issue is usually visible after an earthquake, especially if the ground shaking is in expected limits as prescribed in Regulations for design, and yet, there are some damages and huge panic.
In the direction of creation of national strategy for seismic risk mitigation, the existence of fragility functions for local defined prototypes of structures is a very important component. Defined as a plot of the probability of exceedance of prescribed level of damage for a certain ground motion intensity, they can be used as a basis for seismic losses estimation. A multidisciplinary approach with a knowledge in the field of hazard and risk estimation is needed for an application of a comprehensive procedure for seismic vulnerability evaluation of buildings. The wide spectra of application of any existing methodologies (buildings of various types, lifelines, essential facilities, etc.) allows for a large number of proposed approaches and their categorizations.

2 Motivation and organization

The available resources and knowledge in the field of construction, as well as the local tradition and experience in various parts of the world have defined the diversities among the existing typologies of buildings. Each region can be characterized with its own characteristic buildings, build with certain type of materials and construction specifics. Unreinforced masonry structures, as one of the oldest and still-in-use buildings, are among the most present type of structures within the building stock of Republic of North Macedonia, as well as in the neighboring countries. The number and location, the structural topology and assessment, or any kind of classification of the existing buildings in R.N. Macedonia has never been performed. The existence of such a base would be a first step in the process of seismic risk mitigation planning and the results of the structural assessment would potentially provoke local authorities to make a future strategy for any required strengthening of the buildings.
In this research, in the frame of the project SEIZMOWALL [1] sixteen building topologies of existing masonry structures located in various parts of N. Macedonia are selected, each of them chosen to represent a class of similar buildings. In favor of creating a larger pool of results, all of the buildings are analyzed with a seismic input consisting of all of the calculated spectra.

The typological classification is made according to the classification system adopted in Risc-UE project [2], where structures are divided in function of the structural material: masonry, reinforced concrete, steel, timber and sub-divisions are made for each category. There are seven categories of masonry structures. In our building inventory, two of these categories are identified:

- M5: unreinforced masonry structures with flexible floors (old bricks)
- M6: unreinforced masonry structures with rigid floors

Further classification is related to the regularity of the structures, hence sets of fragility curves are also developed for Regular and Irregular buildings. The aim is to develop a base of region – specific fragility curves by a comprehensive analysis of using local building topologies on one hand, and region-defined response spectra as seismic input in the analysis on the other hand. Finally, set of fragility curves will be developed for each site for M5 and M6 structures. Additionally, a set of fragility curves for the whole territory for classes M5 and M6 buildings, subdivided as Regular and Irregular will be developed, as shown in Figure 1.

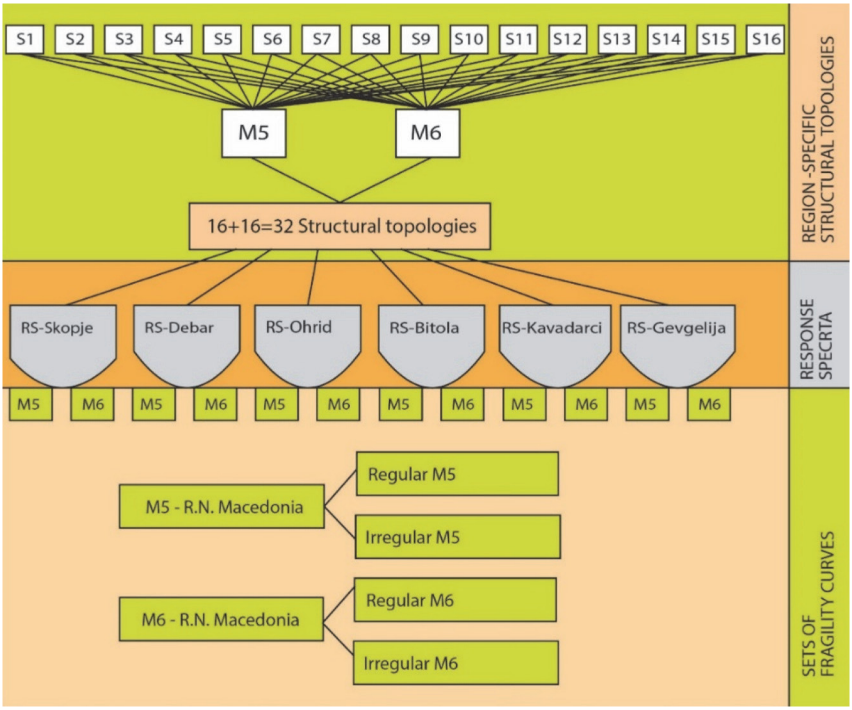

Figure 1. Organization

3 Methodology

Having in mind the computationally expensive and time-consuming nature of the probabilistic simulations, as an inseparable part of risk analysis, various methods that reduce the number of samples are proposed in the field. In general, these are procedures that define the efficient number of sampling data in order to optimize computer responses. In this study the Latin Hypercube sampling is applied. The main steps of the proposed procedure for derivation of the curves are presented in Figure 2.

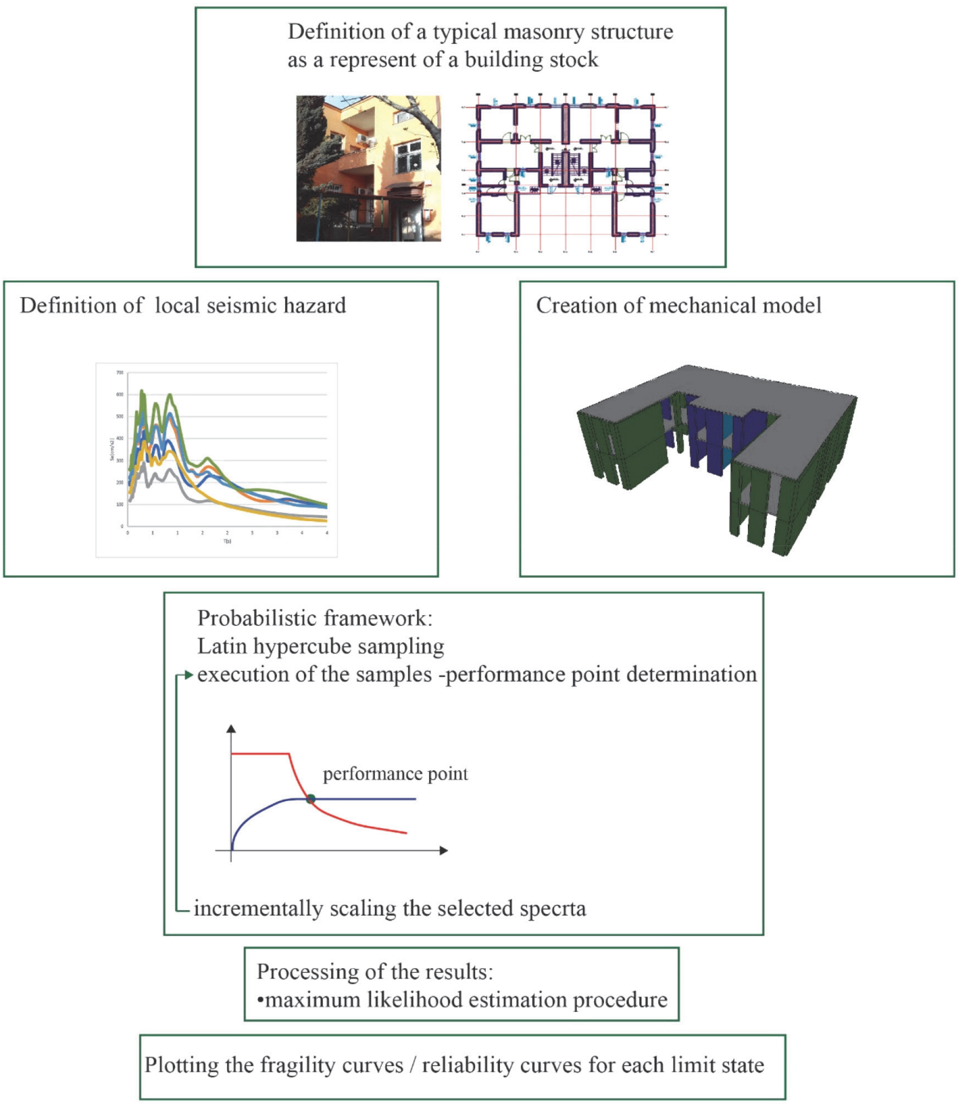

Figure 2. Methodology

3.1 Local hazard definition

The reliable seismic hazard assessment (SHA) for any selected region is a crucial requirement for performing the seismic risk analysis of a given characteristic building class. The accuracy of the estimated risk is in direct relationship with the reliability of the seismic input utilized in the analysis. Namely, for increased accuracy in obtained results the nonlinear calculations should be performed using regionally defined spectra or time-histories.

NDSHA at regional scale [3, 4] incorporates together the knowledge of tectonic style of the considered region, the active fault characterization, the earth crust model and the historical seismicity. Some serious neglections inherited in Probabilistic Seismic Hazard Assessment (PSHA) connected with the effect of crustal properties of the propagation and attenuation of waves are addressed in NDSHA. Here, instead of using attenuation relationships, synthetic seismograms are computed at all of the points at the region of interest by using the modal summation technique. The standard NDSHA takes into account two types of polygons: 1) which describe the seismic sources and 2) which associate structural models to certain territory. The calculated maximum values of ground horizontal velocity, horizontal displacement and design ground acceleration are used as seismic hazard parameters, however any other relevant quantity can be readily extracted from the database of the synthetic signals.

The map of geotectonic zoning from [5] 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 year 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.

The seismic input at a given site for the design process of the structures is determined as a response spectrum by using Maximum credible seismic input procedure (MCSI) within the NDSHA, proposed by Fasan [6, 7]. With this procedure the upper bound ground motion, which should be adopted in the design or retrofit of structures, is determined. This procedure has been applied to all six sites of interest in R.N. Macedonia.

3.2 Mechanical model

The structures are analyzed using the research version of the software package MINEA (SDA Engineering) [8], as a special software for verification of the structural safety of masonry structures and mixed structures made of masonry and reinforced concrete.

The verification of the structure is based on the capacity spectrum method, by creating a non-linear pushover curve, which is determined using a static non-linear calculation by successively increasing a horizontal load distribution. In general, the procedure for verification of the structural safety in MINEA can be described by the following steps:

Step 1: Deformation curves of each wall
Based on the recommendations in Eurocode 6 and Eurocode 8, the force – deformation curves of each single wall – at element level are calculated. The calculations are dependent of the superimposed vertical load, the wall geometry, the material properties of bricks and mortar, the drift limits and the level of restrains. The bending and longitudinal failure mode, the shear failure mode, and the brick structural failure mode has been considered during calculation.

Step2: 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. Because of the assumption that the failure will occur on the ground floor where the location of the control point is defined, the curve of the building is actually the capacity curve of the ground floor.

Step3: Transformation of the curve into Acceleration Displacement Response Spectrum - Sa-Sd diagram using an equivalent single mass oscillator.

Step4: Performance point
By superimposing the capacity spectrum curve with the earthquake demand curve, the performance point is calculated. It is obtained at the intersection between the spectrum 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.

3.3 Calculation of the fragility curves

The damage limit states are identified by the calculated bi-linearized push-over curves of the structures. Deformation thresholds are proved to be the best indicators of the damage of the masonry structures and consequently, the spectral displacement is utilized as damage indicator in this research. Yield and ultimate displacement points are identified and the curve is divided into four parts [9].
The representation of probability of exceeding different damage states for considered intensity level of earthquake loading, is generally described by vulnerability curves. The most commonly accepted form of a seismic vulnerability function is the lognormal cumulative distribution function (CDF) shown in Eq.1.

$$P\left(LS|Sa = x\right) = \phi\left(\frac{lnx - \mu}{\beta}\right) \quad (1)$$

Where is the probability of exceeding a particular limit state, given a ground motion with Φ( ) is the standard normal cumulative distribution function, and are the mean and standard deviation of lnSa. The maximum likelihood estimation is used to best fit the data obtained with numerical simulations [10].
Reliability curves are also calculated in the frame of this research. The reliability index is directly related to the probability of failure and as this index increases, the failure probability decreases. Corresponding with the accepted maximum failure probability, the reliability index is calculated, defined as a negative value of the standardized normal variable corresponding to probability of failure, according to Eq. 2.

$$P_f = \phi(-\beta) \quad (2)$$

Herein, a plot of one set of fragility / reliability curves for a selected structure topology of the school building in Ohrid, North Macedonia is shown. This building has been analyzed by the presented methodology and the vulnerability /reliability curves have been obtained. The four presented curves shown in Figure 3 represent the probability of exceedance of the specified limit states: slight, moderate, extensive and collapse.

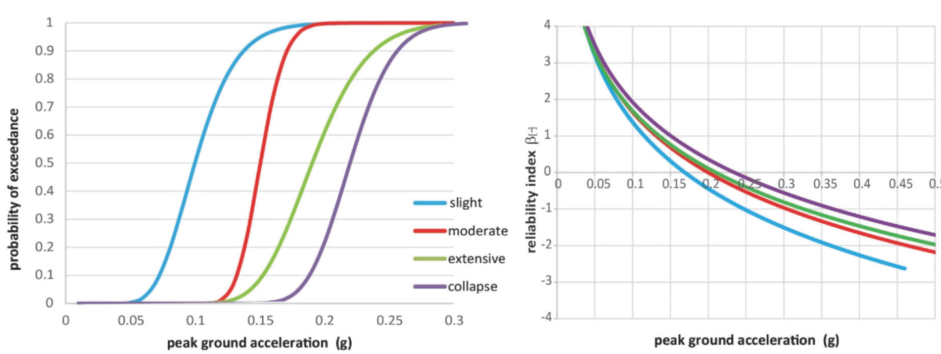

Figure 3. Fragility/reliability curves

4. Conclusion

This proposed methodology for fragility curves determination represents an approach that connect the region – specific topologies of masonry buildings on one hand, and region – specific response spectra on the other. In that manner, the legacy of creating this sets of curves for the selected classes of masonry structures lies in the following benefits:

- A data-base of the existing masonry structures in R.N. Macedonia can be obtained and the structures can be categorized in groups, depending on their structural system, according to the groups shown in Figure 1.
- The sets of fragility / reliability curves can serve as a confidential "scanner" for the instantaneous structural condition of a certain building and consequently, in the process of risk mitigation.
- A national strategy for any necessary strengthening can be further developed, depending on the results.
- The fragility / reliability curves would provide clear illustration for expected damages after a potential earthquake.

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