1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.159

Seismic vulnerability of existing masonry buildings in the Balcan area – case North Macedonia

E. Dumova-Jovanoska[1], G. Aleksovski[2], L. Denkovska[3], S. Churilov[4], K. Milkova[5], S. Bogoevska[6], S. Micevski[7]

[1] *Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *dumova@gf.ukim.edu.mk*
[2] *Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *aleksovski@gf.ukim.edu.mk*
[3] *Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *denkovska@gf.ukim.edu.mk*
[4] *Associate Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *curilov@gf.ukim.edu.mk*
[5] *Assistant Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *milkova@gf.ukim.edu.mk*
[6] *Assistant Professor*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *simona.bogoevska@gf.ukim.edu.mk*
[7] *PhD student*, Ss. Cyril and Methodius University, FCE, Skopje, R.N. Macedonia, *micevski@gf.ukim.edu.mk*

Abstract

A significant number of masonry buildings, built prior to existing seismic codes, nowadays are used and serve a function as public institutions, namely schools, administration offices, courts, museums, theatres, etc. The necessity for evaluation of the seismic risk of these existing buildings is of high priority. In the framework of the research project SeismoWall, sixteen representative masonry buildings were selected and studied. The investigated buildings with their architectural layout, structural system and materials are typical for the buildings built between the end of the nineteenth and the beginning of twentieth century, not only in the country, but in the wider region of the Balkan Peninsula. The research activities in the project are divided in four main work packages: WP1-Selection of representative buildings and their static and seismic analysis, WP2-Experimental analysis of the mechanical properties of constituent components of the buildings and ambient vibration testing (AVT), WP3-correlation of numerical and experimental data and calibration of the dynamic characteristics of the buildings with the results from AVT and WP4-Determination of vulnerability curves for the selected masonry buildings. The main aim of the project SesimoWall is to define a series of seismic vulnerability curves for four classes of masonry buildings (unreinforced masonry with rigid/flexible floors, regular/irregular plan layout) for five geographical regions in Republic of North Macedonia with distinctive severe seismic hazard.

Key words: Masonry structures, ambient vibration tests, seismic hazard, seismic vulnerability

1 Introduction

The series of earthquakes that affected the city of Skopje and its surrounding in the autumn of year 2016 and the Ohrid region in the summer of year 2017 have strongly disturbed the community in our country. Having in mind the low to medium intensity of these events, the effects they produced have seriously imposed the question about the level of implemented risk management in the country.

In historical point of view, the devastating 1963 Skopje earthquake initiated a lot to be invested, with support of the world elite in the field of earthquake engineering, not only in the renewal of the city of Skopje but also in establishing a system for managing this type of natural hazards. The triggered public awareness for earthquake hazards in the proceeding days of the tragic event led to various experts' findings and discussions, which can be summarized in two general conclusions: i) the seismic risk management is dominated by prevention, or only limited to design and construction of new buildings and ii) the mitigation of seismic risk of existing structures is seriously neglected. The prevention aspect is provided by the regulations for design of seismic resistant structures which are dating from the 1980s. However, the number of existing buildings in the country, especially the ones built prior to any seismic regulation, is significant. Therefore, it is not a surprise that even during minor earthquakes, like the recent ones, exactly such type of buildings has suffered a certain amount of nonstructural and structural damage. These considerations have directed the scientific society in the country towards analysis of seismic vulnerability of existing structures. The first experiences in the field of seismic vulnerability assessment in Republic of North Macedonia date from the early 1990-ies in Petrovski J. et al. [1]. Following this, Nocevski [2] in his Doctoral thesis presented methodologies for the definition of empirical and analytical vulnerability functions. Dumova-Jovanoska [3] proposed an analytical method for the development of *earthquake intensity - damage* relations, specified as fragility curves and damage probability matrices. The proposed method was applied on reinforced concrete frame-wall structures. Milutinovic and Trendafiloski [4] in the frame of a Risk-UE European project have developed an integral approach for estimation of seismic behavior and vulnerability of RC structures.

In this context, within this study the authoring team has focused to existing buildings built at the end of the 19th until the mid-20th century (before the devastating 1963 Skopje earthquake), which nowadays represent public institutions in the field of education, culture and administration. The main goal of the research project Seismic Vulnerability of Existing Masonry Buildings (SEISMOWALL 2017-2020) is to provide geographically sensitive vulnerability curves for this type of buildings. As a first step, and with the support of local authorities from several cities characterized with medium to serious seismic risk, namely Skopje, Bitola, Ohrid, Debar, Kavadarci and Gevgelija, representative buildings were selected. The selected buildings include a kindergarten, four primary schools, a high school, three museums, a film agency, a local court, a post office, a sport hall, a railway station, a town hall and a health care facility [5]. Regarding their structural systems these buildings are categorized as M5 - U masonry (old bricks) and M6 - U masonry RC floors types according to the classification system adopted in Risc-UE project [6]. The selected structures are divided as regular and irregular; Table 1 present this classification.

Table 1. Selected buildings type M6- U masonry RC floors (left) and Selected building type M5 -U masonry -old bricks (right)

Building	City	Year of build
Film agency of RM	Skopje	1950
Museum	Bitola	1928
Sch. "Strasho Pindzur"	Kavadartsi	1941
Sch."Vojdan Cernodrinski"	Skopje	1955
Municipality building	Kavadartsi	1955
Kindergarten "Pepelashka"	Skopje	1920
Basic court	Kavadartsi	1945
Sch. "Dimkata A. G."	Kavadartsi	1928
Post office/Telekom	Debar	1935

Building	City	Year of build
Sch. "St. Kliment Ohridski"	Ohrid	1910
Mental health center	Gevgelija	1910
Museum of Alban. alph.	Bitola	1921
Sports center "Partizani"	Debar	1930
Train station	Gevgelija	1880
Sch. "St. Sava"	Ohrid	1900
Museum	Ohrid	1929

2 Organization of the SEISMOWALL project

The research program is organized as 4 Working Packages (WP). For most of the selected buildings there are no relevant design documents, often they were scarce and far from easily applicable. Therefore, the goal was to produce drawings of structural and non-structural elements of the buildings as detailed as possible. To accomplish this, in-situ geometry measurements, comparison with available documents, and communication with occupants to get information of possible interventions either for repair/strengthening or adaptation of the buildings were conducted.

The key point of WP1 is the definition of three-dimensional FE models of the selected structures for further utilization for linear static and modal analysis, Figure . 3. SAP2000 [8] is used as a calculation tool. The mechanical properties of the masonry are assumed in line with previous experiences (Churilov and Dumova-Jovanoska, [9]) as well as recommendations proposed in Eurocode 6 [10] and Tomazevič [11].

The experimental analysis is performed as part of the WP2 of the project framework. It encompasses two main activities: (1) laboratory testing of properties of inbuilt materials and (2) in-situ dynamic testing. The investigated buildings are constructed from solid clay bricks and lime mortar, hence the aim of the laboratory testing was to obtain the physical and mechanical properties of the masonry components and the masonry itself, as a structural material. As a second step, 6 wallets with dimensions 500 x 440 x 125 mm made from the original brick samples from the buildings and laboratory prepared lime mortar with similar characteristics as the original mortar samples, were tested. The results are shown in Table 2.

Table 2. Results from laboratory testing of material properties.

Material properties	Value
mean density of the bricks	1744.66 kg/m^3
mean compressive strength of the bricks	9.02 MPa
specific density of the mortar	1700 kg/m^3
compressive strength of the mortar	2.18 MPa
flexural tensile strength of the mortar	0.47 MPa
specific density of the wallet	1910 kg/m^3
compressive strength of the wallet	2.28 MPa
flexural tensile strength of the wallet	0.48 MPa
mean compressive strength (6 wallets)	2.45 N/mm^2

The in city dynamic tests were conducted by measuring the accelerations on certain locations in each building from ambient vibration sources. Different number of measurement points was used for each structure, generally in the range of 3 to 12 per floor. The results of the fundamental frequencies are shown on Table 3 [12].

Table 3. Fundamental frequencies of the surveyed buildings.

Building		Frequency (Hz)		
		Translation X	Translation Y	Rotation XY
1	Sch. "St. Kliment Ohridski"	3.906	2.539	2.832
2	Mental Health Centre	6.151	3.711	4.883
3	Museum of Alban. alph.	4.297	5.273	7.813
4	Sports center "Partizani"	12.402	7.324	NI
5	Train station	NI	NI	7.129
6	Sch. "St. Sava"	5.469	3.711	7.227
7	Museum in Ohrid	4.785	2.051	6.25
8	Film agency of RM	8.301	6.348	NI
9	Museum in Bitola	NI	NI	NI
10	Sch. "Strasho Pindzur"	NI	4.813	NI
11	Sch. "Vojdan Cernodrinski"	5.080	4.490	NI
12	Municipality building	NI	NI	NI
13	Kindergarten "Pepelashka"	6.455	7.422	8.203
14	Basic Court	4.102	4.199	4.213
15	Sch. "Dimkata Angelov G."	5.957	NI	5.762
16	Post office/Telekom	6.055	6.934	11.523

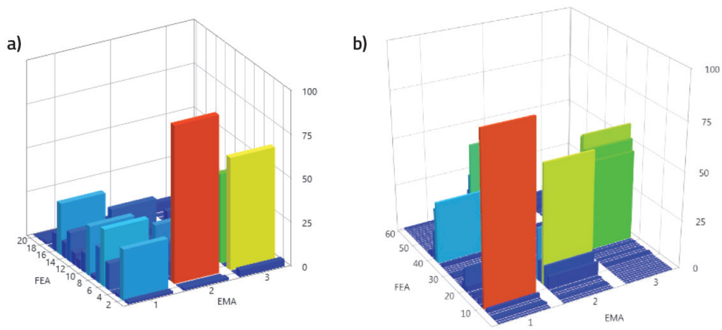


Figure 1. Obtained MAC values after calibration: a) St. Sava school ; b) St. Kliment Ohridski school

The WP3 aims at providing efficient methodology for calibration of developed 3D finite element models with the experimentally obtained information, more precisely the estimated frequencies and mode shapes of the structures. For this purpose, the software tool FEMtools [13] offers automatized algorithms which will significantly reduce computational load in calibration of detailed mathematical models. The WP4 in the SEISMOWALL project is obtaining series of vulnerability curves for 4 structural types of masonry structures (unreinforced masonry with stiff/flexible floor, regular/irregular) typical for five geographical regions in the country which are characterized with severe seismic hazard. This objective revolves around two main points: a) the selection of suitable approach in representation of the local/ regional seismic hazard; b) the selection of the type of methodology for obtaining the vulnerability curves.

Within the SEISMOWALL project the seismic hazard is defined with a neo-deterministic approach proposed by the partner institution [14], and it is represented via acceleration spectra for five regions of the territory of Republic of North Macedonia. It is worth mentioning herein that the region seismicity estimation is based on available seismic data, gathered from a network of six active permanent seismological stations located in various parts of the country, provided by the Seismological observatory of R.N. Macedonia. The main points of the methodology for vulnerability/reliability curves determination is summarized in the following steps:

- Functions for damage distribution are based on calculated structural responses, ground type and seismic intensity variations.
- All of the single results are assigned to a corresponding damage grade and the ratio of the number of realizations in the selected damage grade and the total number of realizations is calculated for every PGA.
- Maximum likelihood estimation procedure is applied for the determination of the discrete points that describe the relationship between the earthquake intensity and the probability of damage.
- Vulnerability and reliability curves are generated for the selected structure.

3 Seismic analysis of the buildings

One of the goals in frame of the SEIZMOWALL project was to verify the seismic resistance of the structures, built before the Skopje earthquake, according to relevant actual codes. Consequently, in frame of WP1 the seismic capacity of the buildings was performed with linear analysis, as specified in current Regulation PIOVSP'81 [15].

The latest earthquakes in Croatia just confirmed the importance of the seismic resistance assessment of the structures built before the existence of the codes. Additionally, it should be outlined that in R.N. Macedonia and in most of the former Yugoslav Republics the seismic codes dating from 1987 are still in use. In the period of time when this Regulations were created, the static analysis was conducted with using 2D models, instead of today's wade use of available contemporary software tools that enable a relatively simple generation of more complex 3D FE models. The analysis and distribution of seismic forces in PIOVSP'81 [15] is provided for an assumed 2D model of a structure, a frame console where structural bearing walls are assumed as continuous in height, without openings. As a result, the equations for calculating principal tensile stresses in structural walls are adjusted to this simple model. On the other hand, by using the today's software tools the modelling of bearing walls as shell structures with using shell finite elements is enabled. Therefore, an adjustment of the proposed methods for a more detailed and up-to-date 3D FE analysis of masonry structures is necessary.

A comparison between the application of the two methods is presented on a chosen masonry structure, used as a case example. Furthermore, suggestions for seismic resistance assessment of existing masonry structures with a utilization of linear analysis are presented.

The calculation and distribution of the seismic force is done as defined in the actual Regulations. According to the Regulations, the defined maximum expected earthquake can cause damage, but not collapse on the structural elements. The intensity of the seismic force is calculated in dependence of the category of the building, seismic parameters of the location, the type of the structural system, the ductility and the damping. According to this Regulation, the seismic analysis for the selected types of buildings can be conducted as linear analysis with equivalent design force calculates as:

$$S = K \cdot G = K_o \cdot K_s \cdot K_d \cdot K_p \cdot G \qquad (1)$$

The distribution of the seismic forces to floors is calculated according to PIOVSP'81:

$$S_i = S \cdot \frac{G_i \cdot H_i}{\sum_{i=1}^{n} G_i \cdot H_i} \qquad (2)$$

The mass distribution to the walls is done according to the following several steps (for both X and Y direction separately):

- Self – weight of all of each of the bearing walls is calculated. The floor is divided into several parts according to the defined corresponding areas of the walls. Each area of the floor is assigned to the bearing supportive walls, as shown on Figure 2.
- The weight of floors, dead and live loads is calculated and assigned to each wall, proportionally to the defined corresponding area. The self-weight of the walls in the opposite direction is also calculated and assigned to the corresponding bearing walls.
- The total weight of each wall is calculated and the seismic force of each wall is calculated according to Equation 3:

$$S_{w,i} = S_i \cdot \frac{m_{w,i}}{\sum_{i=1}^{n} m_{w,i}} \tag{3}$$

where: seismic force of the wall of the -th floor, seismic force of the -th floor , is total weight of the floor of the -th floor.

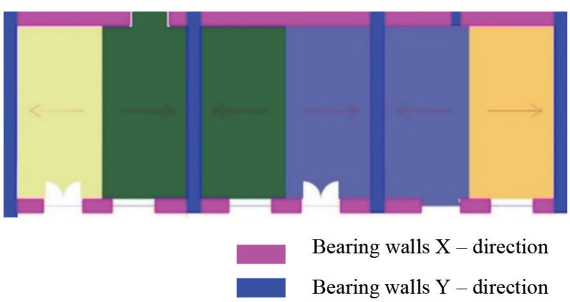


Figure 2. Mass distribution

The analyzed representative structure (shown on Figure 3) is a museum building located in Ohrid, North Macedonia, dating from the beginning of the XX century (1929). Bearing walls with clay bricks in both directions are constituting the structural system of the object. The shape in plane is rectangular with total dimensions 16.3x21.7m and the structure height is 10 m.

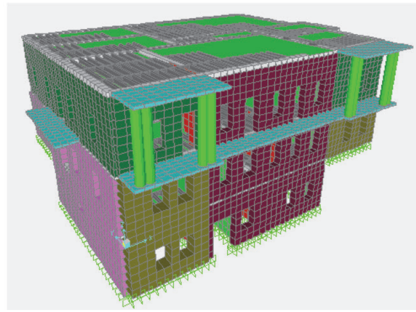
 

Figure 3. The maximum (left) and minimum (right) principal stresses from vertical loads and seismic forces of one selected building [KPa]

The seismic forces are calculated and applied in both directions on the FE model made in SAP2000.. Then, the seismic capacity is conducted by respecting the Equations given in the Regulations, as shown in point 3.1 and by direct use of the results from the 3d model (point 3.2).

3.1 Calculation of stresses according to equations in the current regulations

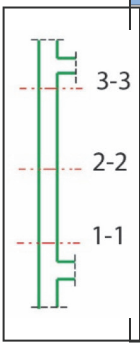
The current standards provide Equations 1 and 2 for calculating principal tensile stresses in structural walls, as well as control of the walls' seismic capacity:

$$\sigma_n = \sqrt{\sigma_0^2 / 4 + \left(1{,}5 \cdot \tau_0\right)^2} - \sigma_0 / 2 \geq \sigma_{n,doz} \quad (4)$$

$$\tau_{ult} = \sigma_{n,ult} / 1{,}5 \cdot \sqrt{1 + \sigma_0 / \sigma_{n,ult}} \quad (5)$$

where: σ_n - principal tensile stresses, $\sigma_{n,doz}$ - allowed principal tensile stresses (predefined in the code), σ_0 - normal stresses due to gravity loads and τ_0 - shear stresses due to seismic forces, τ_{ult} - ultimate shear stresses, $\sigma_{n,ult}$ - ultimate principal tensile stresses (predefined in the code) and σ_0 - normal stresses due to gravity loads. The normal stresses due to gravity loads and the shear stresses due to seismic forces are obtained from the analysis of the building in SAP2000 and the calculation is conducted in the three sections of each wall, as shown on Table 4 (herein, presented only for 3 walls).

Table 4. Calculation of the stresses according to the formulas in the Actual Regulations



Wall	Cross section	Normal stresses s_0 [MPa]	Shear stresses t_0 [MPa]	Principal tensile stresses s_n	Criteria
W1	1-1	0.165	0.000	**0.0000**	yes
	2-2	0.260	0.069	**0.0366**	yes
	3-3	0.152	0.021	**0.0061**	yes
W2	1-1	0.240	0.088	**0.0583**	yes
	2-2	0.229	0.174	**0.1700**	no
	3-3	0.157	0.056	**0.0368**	yes
W3	1-1	0.248	0.207	**0.2110**	no
	2-2	0.239	0.221	**0.2330**	no
	3-3	0.199	0.205	**0.2237**	no

According to PIOVSP'81, the allowed values of the principal stresses (tensile) are $\sigma_{z,allowed}$ = 90 kPa (in the Regulations the 50 % increasing of this value is allowed, $\sigma_{z,allowed}$ = 1.5 · 90 = 135 kPa). Regarding the results from the conducted laboratory testing of material properties in frame of the project SEIZMOWALL, the allowed values of the principal stresses (compressive) are $\sigma_{p,allowed}$ = 2450 kPa. The results of the conducted analysis of the whole building are shown on Figure 4, where all of the walls not satisfying the criteria are red colored.

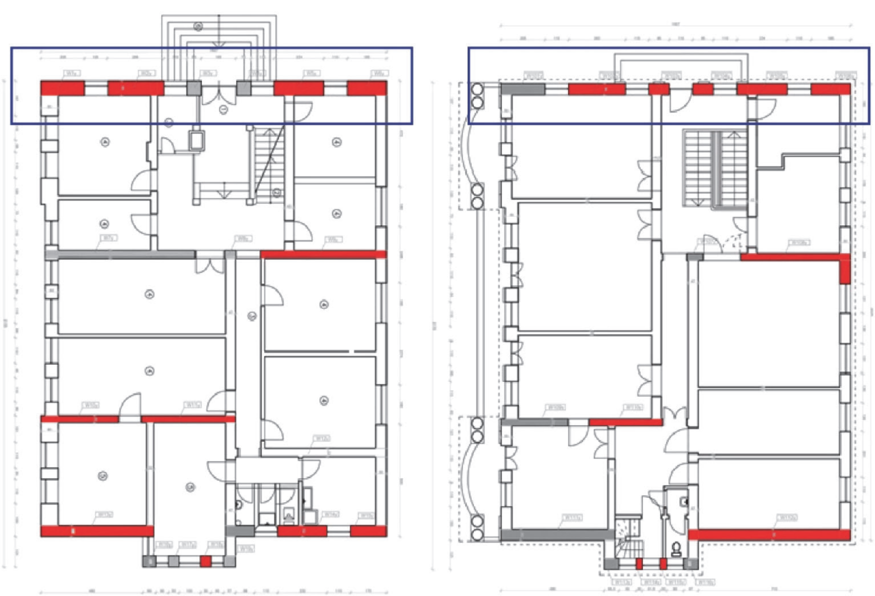


Figure 4. The base floor (left) and the first floor (left) of the Museum in Ohrid

3.2 Calculation of stresses - direct use of results

The available contemporary software tools enable a relatively simple generation of more complex 3D FE models. These spatial and more detailed modeling approaches introduce the effects from adjacent in-plane walls (between openings) and from the walls distributed in the orthogonal direction, which in turn imposes a different verification approach of the seismic resistance (not as proposed in Eq. (4) and Eq. (5)).

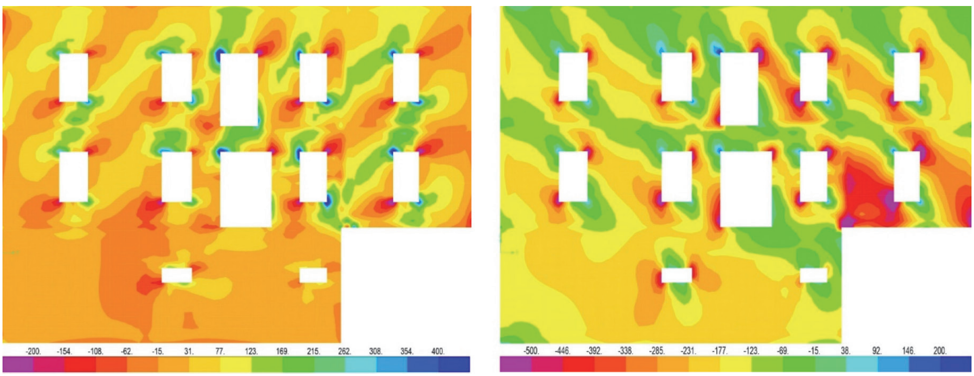


Figure 5. The maximum (left) and minimum (right) principal stresses from vertical loads and seismic forces of one selected building [kPa]

Namely, the maximum FEM calculated principal stresses to be compared with allowed principal tensile stresses, and FEM-based minimum principal stresses to be compared with allowed principal pressure stresses. In Figure 5, the maximum and minimum principal stresses for the marked with blue walls on Figure 4 are presented.
I can be seen that the compressive stresses are smaller than the allowed ones and tensile stresses are larger than the allowed in the Regulations only in the areas located around the angles of the openings. Knowing the locations of damages during earthquake, this result can certainly be expected. This "direct" reading of the stresses allows us to detect the exact locations of the accumulated stress and the strengthening of the existing buildings can be concentrated only on the selected areas of the wall. This is the biggest advantage in the approach compared to the "classic" approach presented in point 3.1.

Acknowledgments

The authors would like to acknowledge the public institutions authorities for the provided access and the available documentation of the buildings. The ambient vibration tests were supported by Digitexx Data Systems Inc. and the laboratory tests by the Institute for Testing Materials and Development of New Technologies "Skopje", AD Skopje. Also the authors would like to acknowledge the support of the Faculty of Civil Engineering in Skopje and the valuable contribution from our master students.

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