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Harmonization of seismic vulnerability assessment of urban historic centers

Aleksandar Zlateski[1], Veronika Shendova[2]

[1] *Research Assistant*, Institute of Earthquake Engineering and Engineering Seismology – Skopje, N. Macedonia, *azlate@iziis.ukim.edu.mk*

[2] *Professor,* Institute of Earthquake Engineering and Engineering Seismology – Skopje, N. Macedonia, *veronika@iziis.ukim.edu.mk*

Abstract

Urban historic centers, represented by unreinforced stone and brick masonry structures constructed before the introduction of a more demanding seismic design code, are important part of the cultural heritage. Beside their cultural-historic value, they usually represent important economic and touristic centers. Encouraged by a substantial increase in tourism, the authorities have often carried out a series of renovation works, usually being pursued either on a too superficial or on a too intrusive way, in which little respect is shown by existent materials and construction techniques. Consequently, the vulnerability assessment of historic masonry buildings in a given urban area, is a key prerequisite for evaluating global risk. The considered vulnerability index method, obtained by the calculation of a score for a building as weighted sum of characteristic parameters related to the building's seismic response and distributed into vulnerability classes, represents an innovative hybrid methodology for bridging the gap between empirical and analytical methods providing initial seismic vulnerability assessment by using simplified scoring method. The knowledge gained through reviewing the available literature on seismic vulnerability assessment of historical centers, has been used to set-up of vulnerability index method, harmonized with the specific characteristics of urban historic centers in N. Macedonia. The paper will present selecting the specific independent parameters, characteristic for the urban historic center in the old part of the city of Skopje, capital of N. Macedonia, and establishing the relation between the chosen specific parameters and the vulnerability class levels for each of them, as well as calibration od the weight parameter by ranging the importance of each of the parameters using data from the screening of 15 historic buildings after the 2016 Skopje earthquake.

Key words: vulnerability assessment, historic centers, masonry structures

1 Introduction

Urban historic centers are important part of the cultural heritage. Beside their cultural-historic value, they usually represent important economic and touristic centers. Within the broad range of construction techniques and building materials that might be included in the urban historical centers, seismically very vulnerable unreinforced stone and brick masonry structures, constructed before the introduction of a more demanding seismic design code, are one of the most common not only in Europe, but worldwide.

On the territory of the historic city of Skopje, various cultures and spheres of influence intertwined, whose material remains have always attracted the interest of scholarly circles. Each of these cultures left its own mark both in the material and spiritual culture of the people. However, it seems that the Ottoman presence of five hundred years (XIV to early XX century) left a special mark and permanent traces in the physiognomy of the city which in this period achieved their cultural and economic rise.

In addition, for urban historic center located in one of the seismically most active regions in Europe, the vulnerability assessment of historic masonry buildings in this urban area, is a key prerequisite for evaluating global risk. Within the framework of this work, the available literature on seismic vulnerability assessment of historical centers, that has been accumulated over the past decades and calibrated based on broad damage data obtained from post-earthquake damage surveys, has been chosen. The gained knowledge has been used to set-up of vulnerability index method, harmonized with the specific characteristics of urban historic center in Skopje, the capitol of N. Macedonia.

2 Description and seismic effects of the historic center of Skopje (Old Bazaar)

2.1 Description of the historic center of Skopje (Old Bazaar)

The capital city of Skopje is situated in the Skopje valley on the banks of the biggest Macedonian river Vardar. Next to the river is located heart of the city, the old part of Skopje, known as Skopje Old Bazaar, (Figure 1). It is one of the oldest and largest marketplaces in the Balkans and its trade and commerce center since at least XII century. Besides, it is known for its cultural and historical values. Although Ottoman architecture is predominant, remains of Byzantine architecture are evident as well, while recent reconstructions have led to the application of elements specific to modern architecture.

The Ottoman influence left a special mark and permanent traces in the physiognomy of the historic city of Skopje. The building of Ottoman structures reached its peak in the XV and XVI century, when a large number of mosques, baths, covered bazaars, inns and other facilities, mostly visible in the old part of today's Skopje, were built as a reflection of the economical and politic circumstances, and represent an expression of the cultural and artistic tendencies and potentials of respective periods. Among them, Mustafa Pasha, Sultan Murat and Ishak Bay Mosques are among the oldest and best-preserved mosques in the Balkan region, while Kurshumli Inn, Suli Inn and Kapan Inn, all of them from XV century, together with Chifte Hammam and Daut Pasha Hammam represent the commercial and public bath areas. In addition, the presence of individual commercial buildings should be emphasized. They form almost 70 % of the structure of the entire historic center.

Figure 1. Skopje Old Bazaar

Figure 2. Typical street in the Skopje Old Bazaar

The urban configuration of the historic center of Skopje is characterized with huge authenticity. The buildings are placed in the irregular urban mesh, with a couple of main quite wide streets and the narrowness of the other streets and passes between them. A great percentage of the built urban stock is constituted without any earthquake resistant criteria. The masonry walls constitute the main structural elements with the timber floor slabs resulting in a very simple box-type structure. Brick and stone masonry are the most common building materials but adobe masonry with timber bracing can be found too. Regarding the geometry in height, the buildings usually are constituted by ground floor, one or two elevated floors (Figure 2).

2.2 History and 11th September 2016 earthquake effects

Before 1900, the seismic history of Skopje as part of the Vardar zone is reduced to a rather brief description of the earthquake catastrophes of Scupi in 518 A.D. and that of Skopje in 1555. The 518 A.D. earthquake seems to be the strongest shock that has ever occurred on this territory. The earthquake of 1555 is said to have demolished a part of Skopje. Both earthquakes are estimated to be of an intensity of XII MCS, [1].
During XX century, the region of Skopje was affected by series of damaging earthquakes, which lasted from August to September 1921 with a magnitude of 4.6 to 5.1. Besides the local earthquakes, region of Skopje has suffered several times from earthquakes occurring at a distance.
In the early hours of July 26, 1963, Skopje was struck by an earthquake with magnitude 6.1, one of the most severe catastrophes in its history. The entire territory of SR Macedonia was shaken with intensities varying between V and IX, MCS. Major earthquake effects were manifested by loss of 1070 human lives and 3300 injuries, destruction and severe damage to a large number of buildings and other public and social facilities, damage to the infrastructure, lifelines, urban furniture, etc. Damage to existing buildings was tremendous. Out of the total building area 80.7 % was destroyed or heavily damaged and about 75.5 % of the inhabitants were left homeless. Only 19.7 % remained non - or slightly damaged, which, in accordance with the damage and usability criteria were usable immediately after the earthquake, [2].
In addition to the damage to residential and public buildings the catastrophic 1963 Skopje earthquake inflicted inestimable damage to cultural monuments and historic buildings. The entire monument fund of historical center of Skopje was damaged, while part of it was destroyed. Damages were manifested by failure of individual parts of the structures, large cracks, inclination and deformations of the walls, the vaults, the columns and other structural elements (Figure 3).

Figure 3. Ruins of Suli Inn and damages on Mustafa Pasha Mosque

During the years following the catastrophic earthquake, there were works on protection of cultural historic structures considering their value and importance. Structural consolidation has been performed in the first phase, while during the renovation of the buildings, particularly those adapted to modern needs whose structural systems did not provide the necessary seismic safety, the principle of repair and seismic strengthening has been applied, involving reinforced concrete bearing structure, columns and belt courses interconnected and incorporated into the existing masonry. Cement as a material was also applied in repair of the medieval churches and monasteries through injection of the occurred cracks or rebuilding of the ruined parts and seismic strengthening.

On September 11, 2016, the city of Skopje and its surroundings was hit by a series of earthquakes with main shock of moderate size moment magnitude of 5.1. The main shock was felt in the urban city area with intensity of about VI to VII degrees according to EMS. Immediately after the occurring of the main shock, an activity of rapid visual screening was performed by IZIIS, within a framework of which 15 cultural heritage buildings and monuments were inspected, located in the old historic part of the city, [3].

As known from history, interventions to a different extent have been taken in the past for all monuments in Skopje region, [4]. Table 1 presents the list of the inspected monuments along with the information on their previous interventions and damage level during the last earthquake. After the fast visual screening vast majority of inspected monumental buildings were assessed as safe and usable, since their damage varies from slight non-structural one, (failing of pieces of mortar or bricks from the cornices or facade walls, hair cracks in mortar joints on facade walls and ceiling, breaking of glass from large windows), to very localized or negligible structural damage, (initial cracks to the walls and ceiling elements, falling of large patches of mortar from wall and ceiling surface, considerable cracks or partial failure of chimneys). However, there are isolated cases of considerable structural damage manifested as widening and elongating of older cracks or occurring of newly developed cracks, usually in the walls or along with the connection between the walls and vaults or domes.

Table 1. List of inspected cultural heritage buildings and monuments

Monument/ Historic building	Period of construction	Previous Intervention	Damage description
Church of Holy Salvation	1817-1824 (on XIV century foundation)	Repair, partial reconstruction, conservation, adaptation	Extension of old minor cracks, Occurrence of new minor cracks between walls and ceiling surface
Suli Inn	First half of XV Century	Reconstruction, strengthening with RC vertical and horizontal belt courses	No new structural damage, Failing down of large windows
Aladza Mosque	Beginning of XV century	Reconstruction of porch with RC elements, conservation, adaptation	Cracks on north and south main vault, continuing into adjacent domes, failing of mortar from central dome
Hadzi Balaban Mosque	XV Century	Replacement of original dome destroyed in XVIII century with wooden roof structure	Separation of bearing walls from pendentives
Bezisten, the central part of Old Bazar	XIX century (XV century foundation)	Repair, consolidation, adaptation	Extension of old cracks in the walls, visible separation of bearing walls from ceiling structure
Daut Pasha Hammam	XV century	Repair, consolidation, partly reconstruction with RC vertical and horizontal belt courses	Major cracks in entrance dome, failing of mortar and cornices from facades, extension of old cracks
Cifte Hammam	First half of XV century	Repair, consolidation, partly reconstruction with RC vertical and horizontal belt courses	Initial minor cracks in bearing walls and over the openings
Kurshumli Inn	First half of XVI century	Repair, reconstruction, strengthening with RC vertical and horizontal elements	Structural damages along the walls and vaults, disturbed local stability, failing of partition wall, roof stones and chimneys
Kale fortress	XIV Century	Repair, consolidation, adaptation, reconstruction with RC elements	Minor cracks as extension of old one
Sultan Murat Mosque	XV Century	Repair, strengthening with RC vertical and horizontal elements	Initial cracks between walls and vaults, failing of mortar, extension of old cracks
Mustafa Pasha Mosque	XV Century	Repair, dome strengthening with RC ring, upgrading with CFRP in 2006	No visible cracks
St. Panteleymon Church	XII Century	Repair, strengthening with RC vertical and horizontal elements	Minor cracks in bearing walls. Failing of mortar from facades
Hussein Shah Pasha Mosque	XVI Century	Repair, consolidation, strengthening with RC horizontal elements	Minor cracks in bearing walls. Failing of mortar from facades
Historic building in the Old Bazar	XIX Century	Repair, consolidation, adaptation	Structural damage, disturbed local stability
Historic building in the Old Bazar	XIX Century	Repair, consolidation, adaptation	Disturbed global stability (old substandard adobe structure)

3 Harmonized vulnerability index for urban historic center of Skopje

The vulnerability assessment of historic masonry buildings in a given urban area is a key prerequisite for evaluating global risk. This is not only important because of the obvious physical consequences in the possible occurrence of an event but also because of its relationship with human presence and evacuation support systems, which are essential aspects in the definition of effective risk reduction strategies. In fact, the combination between vulnerability assessment of existing buildings and the implementation of appropriate seismic retrofitting and emergency planning solutions can help to reduce physical damages, human losses and critical emergency conditions for the population, as well as the economic impact of future events.

The available literature on seismic vulnerability assessment of historical centers, related to the collected data that has been accumulated over the past decades about post-earthquake damage surveys and interventions in the historical center of Skopje, opens a unique opportunity to set-up of vulnerability index method, harmonized with the specific characteristics of the specified urban historic center. This was the starting point of the internal IZIIS' project as a contribution to the governmental long-term project on Skopje Old Bazaar revitalization.

The considered vulnerability index method represents an innovative hybrid methodology for bridging the gap between empirical and analytical methods and provides seismic vulnerability assessment by using simplified scoring method. This method has been originally developed by Benedetti and Petrini, [5], adapted and applied to several historic centres in Portugal [6, 7, 8] and calibrated using post-earthquake damage data [9]. This methodology also has been successfully calibrated and implemented for vulnerability assessment in order to evaluate, manage and mitigate the earthquake risk in the historical center of Coimbra, Portugal, with the urban configuration very similar to Skopje old Bazar, [10]. The vulnerability index is obtained by the calculation of a score as the weighted sum of 14 parameters:

$$I_{vf}^{*} = \Sigma_{i=1}^{14} c_{vi} p_{vi} \tag{1}$$

Each parameter shown in Table 2 covers one aspect related to the building's seismic response and is distributed into four vulnerability classes (c_{vi}) of growing vulnerability: A, B, C and D, while two sets of weights show those originally proposed and recently calibrated by post - eq data, [9].

Beside the weight parameter, essentially the most important issue in this method is to prescribe the vulnerability class for each of the parameter, which should be in relation with the specificity of historic buildings in the urban historic center in consideration. The most important part of this harmonization is setting up the specific independent parameters, characteristic for the urban historic centre in the old part of the city of Skopje, capital of North Macedonia, and establishing the relation between the chosen specific structural parameters and the vulnerability class levels A, B, C, D for each of them.

Table 2. Vulnerability index associated parameters classes and weights (p_i according [6] and [9])

Parameters	Class, C_{vi}				Weight, p_i	
	A	B	C	D	Original	Calibrated
1. Structural building system						
P1. Type of resisting system	0	5	20	50	0.75	2.50
P2. Quality of resisting system	0	5	20	50	1.00	2.50
P3. Conventional strength	0	5	20	50	1.50	1.00
P4. Maximum distance between walls	0	5	20	50	0.50	0.50
P5. Number of floors					1.50	0.50
P6. Location and soil condition	0	5	20	50	0.75	0.50
2. Irregularities and interactions						
P7. Aggregate position and interaction	0	5	20	50	1.50	1.50
P8. Irregularity in plan	0	5	20	50	0.75	0.50
P9. Irregularity in height	0	5	20	50	0.75	0.50
3. Floor slabs and roofs						
P10. Alignment of openings	0	5	20	50	0.50	0.50
P11. Horizontal diaphragms	0	5	20	50	1.00	0.75
P12. Roof systems	0	5	20	50	1.00	0.50
4. Conservation status and other elements						
P13. Fragilities and conservation status	0	5	20	50	1.00	1.00
P14. Non-structural elements	0	5	20	50	0.50	0.75

Based on the acquired knowledge for Old Bazaar' structures, what follows are established relation between the chosen specific independent structural parameters, (P1, P2, P4, P5, P6, P7, P8, P9, P10 and P11) and the vulnerability class levels, (Table 3, 4, 5, 6). The content of the Tables 3, 4, 5 and 6, along with the corresponding schemes and necessary explanations, like those presented on Figures 4, 5 and Figure 6, represent the part of harmonized vulnerability index regarding the independent parameters and associated vulnerability class levels, specific for the historic buildings in Skopje Old Bazaar.

Table 3. Harmonized independent parameters associated to vulnerability class, Type of resisting system P1, Quality of resisting system P2 (P3, P13)

Class C_{vi}	P1 Resisting system	P2, Quality of resisting system						P3, P13 Cracked stiffness
		Mortar	w [kN/m³]	f_c [kPa]	f_t [kPa]	E [MPa]	G [MPa]	
A	Confined masonry	Cement	22	800	40	4200	1400	1.00
B	Brick/stone masonry	Lime/cement	20	600	30	3300	1100	0.83
C	Brick/stone masonry	Lime	19	400	20	2100	700	0.67
D	Adobe masonry	Adobe mud	18	100	5	450	150	0.50

Table 4. Harmonized independent parameters associated to vulnerability class, Distance between walls P4, Number of floors, P5, Location and soil type P6

Class C_{vi}	P4 Maximum distance between walls (l/d, h_0/d) wall thickness:	P5 Number of floors	P6 Location and soil condition (according EN 1998-1)
A	0.60 m	1	A
B	0.50 m	2	B
C	0.40 m	3	C
D	0.30 m	enlarging/ upgrading	D, E

Table 5. Harmonized independent parameters associated to vulnerability class, Position - interaction P7, Irregularity in plan P8, Irregularity in height P9

Class C_{vi}	P7	P8	P9 change in vertical elements' geometry
A	Figure 4, a	Figure 5, a	0%
B	Figure 4, b	Figure 5, b	up to 10%
C	Figure 4, c, d	Figure 5, c	(10 -20) %
D	Figure 4, e, f	Figure 5, d	(20 – 30) %

Table 6. Harmonized independent parameters associated to vulnerability class, Alignment of openings P10, Horizontal diaphragms P11, (Roof structure P12)

Class C_{vi}	P10 Alignment of openings	P11, P12 Horizontal diaphragms (Roof structures)
A	Figure 6, a, regular and aligned	Rigid and well connected
B	Figure 6, b, horizontal misalignment	Flexible and well connected
C	Figure 6, c, horizontal and vertical misalignment	Rigid and poorly connected
D	Figure 6, d, large openings in ground floor	Flexible and poorly connected

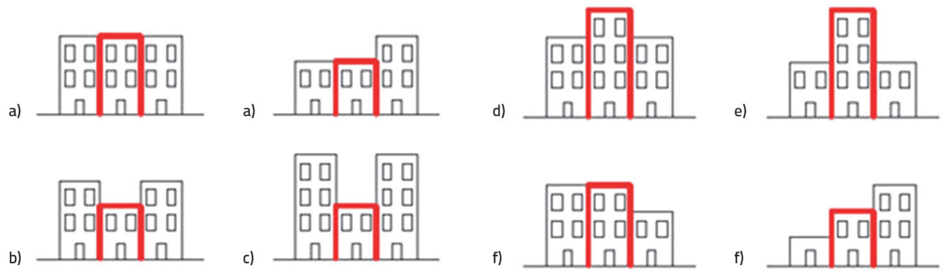

Figure 4. Building position

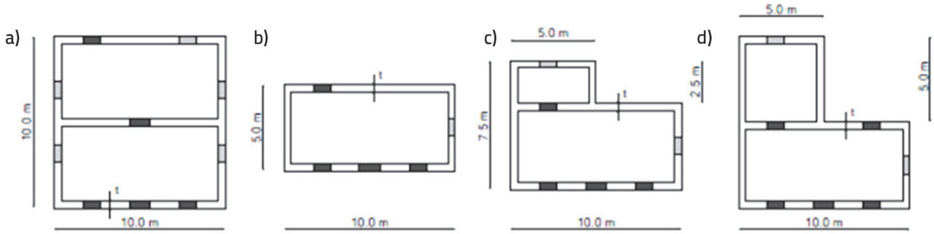

Figure 5. Plan regularity

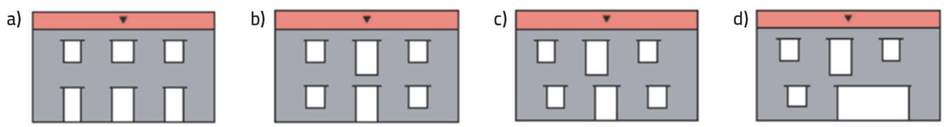

Figure 6. Alignments in openings

With this part is prepared an understandable guideline for pre-earthquake vulnerability assessment of specific historic urban centre, which can be easily applied by the key target groups such as architects and civil engineers involved in the earthquake protection of structures pertaining to cultural heritage. The final aim is to be reached the vulnerability index method related to the specific independent parameters and associated vulnerability class levels, specific for the historic buildings in Skopje Old Bazaar. However, for making the vulnerability index method usable and applicable, it remains to calibrate the weight parameter, *p*i, by ranging the importance of each of the parameters (in terms of structural vulnerability). This should be done in near future with the application of the methodology of the entire historical center of Skopje, using and comparison of the knowledge from the past real events, and finally comparison with the results which uses the originally established methods.

4 Conclusions

The vulnerability assessment of masonry buildings in a given historical urban area is a key prerequisite for evaluating global risk which is defined as the probability of the occurrence of a seismic event of a certain intensity, at a specific site, during a determined period of time. The vulnerability analysis is not only important because of the obvious physical consequences in the possible occurrence of an event but also because of its relationship with human presence and evacuation support systems, which are essential aspects in the definition of effective risk reduction strategies.
In fact, the combination between vulnerability assessment of existing buildings and the implementation of appropriate seismic retrofitting and emergency planning solutions can help to reduce physical damages, human losses and critical emergency conditions for the population, as well as the economic impact of future events. Particularly re-

garding the seismic vulnerability assessment of masonry buildings in historical centers, the amount of knowledge that has been accumulated over the past decades, together with the broad damage data obtained from post-earthquake damage surveys, opens a singular opportunity to harmonized and calibrate effective seismic vulnerability assessment approaches.

Given that the achievements were obtained as a result of recent knowledge in the field, calibrated methods using databases from previous earthquakes, as well as specific knowledge on the characteristics of the Old Bazaar' historic buildings over time, the result are undoubtedly sustainable and could be successfully applied and easily modified in the case of a new event in the future.

The proposed harmonized vulnerability index method, obtained by the calculation of a score for a building as a weighted sum of characteristic parameters related to the building's seismic response and distributed into vulnerability classes, represents an innovative and effective tool for bridging the gap between empirical and analytical methods providing initial seismic vulnerability assessment. The knowledge gained through reviewing the available literature on seismic vulnerability assessment of historical centers, has been used to set-up of vulnerability index method, harmonized with the specific characteristics of urban historic centers in N. Macedonia.

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