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SEISMIC VULNERABILITY ASSESSMENT OF PART OF HISTORIC CENTER OF SKOPJE

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Abstract

Urban historic centers, consisting mostly of vulnerable unreinforced stone and brick masonry structures constructed without seismic design considerations, experience significant earthquake damage. This paper uses a vulnerability index method to obtain and discuss a pre-earthquake vulnerability assessment of a representative part of Skopje's Old Bazaar. This method calculates a score for each building based on a weighted sum of key parameters related to its seismic response, categorizing them into different vulnerability classes. The vulnerability index has been previously adapted and calibrated to reflect the unique features of Skopje's urban historic center.

The research aims to create a seismic vulnerability map for the Bazaar, ultimately safeguarding the urban historic center of Skopje and protecting lives through timely structural assessments and the identification of the most at-risk buildings.

The research draws on recent advancements in the field, utilizing calibrated methodologies based on data from past earthquakes and extensive knowledge of the historic buildings in the Old Bazaar. Consequently, the results are sustainable and can be effectively applied to the entire historic center of Skopje, as well as modified for other hazard events in the future.

Keywords: Masonry structures, Historical centers, Vulnerability Assessment, Damage Grade.

1. Introduction

Masonry has been used as a structural material in a wide range of forms for thousands of years. Urban historic centers, almost without exception, consist of complexes of masonry buildings, and stone and brick structures are among the most common, not only in Europe but worldwide. In areas with high seismic activity, masonry structures suffer the most damage during earthquakes. Considering this, it is easy to conclude that the assessment of the vulnerability of masonry buildings in a given urban area directly depends on defining seismic resistance, which is a key condition for assessing overall risk.

The negligible tensile strength, heterogeneity, and anisotropy of the material in masonry are among the main reasons for the weak resistance of masonry structures under seismic actions. Additionally, masonry structures typically have flexible inter-floor diaphragms, often with inadequate connections to the load-bearing walls of the structure. Among the various failure mechanisms in masonry buildings, the most observed is the separation of facade load-bearing walls from other parts of the structure. This type of structural failure is particularly dangerous in densely populated urban areas (historical city centers generally built with masonry structures). First, due to the direct consequences that can result in system collapse, in terms of casualties and economic losses, and second, due to its indirect impact, such as obstructing overall infrastructure due to debris and rubble accumulation.

Given this, it can easily be concluded that assessing the seismic vulnerability of masonry structures is a fundamental step toward defining more effective strategies for their repair and strengthening. To this end, when assessing larger urban areas, it is first necessary to present expected scenarios to identify

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potentially vulnerable buildings or urban areas that require special attention and to determine the most suitable reinforcement methods for them.).

2. Vulnerability Index Method for Urban Historic Centers

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 [2], adapted and applied to several historic centres in Portugal [3, 4, 7], and calibrated using post-earthquake damage data, [8]. 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, [11].

The vulnerability index is obtained by the calculation of a score as the weighted sum of 14 parameters,

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

Table 1 – Vulnerability index associated parameters classes and weights (according [3] and [8])

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

Each parameter shown in Table 1 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.

The first group includes parameters (P1, P2) that characterize the structural system of the building and define its structural behaviour, including the quality of the masonry through the material (size, shape, and type of masonry), layout, and level of connection between walls. Parameter P3 is one of the most important because it quantitatively assesses shear strength.

The assessment of the vulnerability class for parameter P4 (maximum distance between walls) essentially depends on the ratio L/s and H/s. L/s represents the ratio between the maximum span between load-bearing walls, L, and the average wall thickness, s; H/s represents the ratio between the average inter-story height, H, and the average wall thickness, s. Parameter P4 evaluates the contribution level of walls and implicitly the risk of out-of-plane collapse.

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Parameter P5 assesses the height of the buildings and is directly defined as a function of the number of floors. The vulnerability classes for the parameter related to location and soil condition (P6) are mainly assigned as a function of the specific soil type, based on the definition provided in EN 1998-1.

The second group of parameters mainly focuses on the location and interaction between buildings. Parameter P7 is extremely important for vulnerability because, in dense urban areas, adjacent masonry structures are connected or placed next to each other without space between them. This configuration significantly affects the vulnerability of the building of interest in terms of stiffness, strength, and deformability. This characteristic is not considered in other methodologies but is particularly important because the seismic response of the entire area as a whole differs greatly from the response of a single building.

A drawback of this method is that it does not address so-called "corner buildings," located at the edges or corners of a specific block. According to evidence from past earthquakes, "corner buildings" suffer the most damage compared to other buildings in a given urban block. Therefore, to overcome this limitation of the method, corner buildings are proposed to be classified in the lowest vulnerability class, i.e., for such buildings, the parameter P7 should be assigned the class "D."

Parameters P8 and P9 evaluate irregularities in the building's base and height. Four different configurations are identified as generally representative of many urban areas: square shape, rectangular shape, L-shape, and L-square shape.

The parameter for the layout of openings (P10) identifies the irregularity of openings along the height of the walls. The highest class corresponds to a configuration where the openings are regular and aligned; vulnerability class B is assigned to horizontal misalignment, and vulnerability class C is assigned to both horizontal and vertical irregularities. Finally, vulnerability class D corresponds to situations where openings are misaligned both horizontally and vertically (class C), the presence of a large opening at the ground floor level, a common but erroneous practice observed in many buildings in historical centers.

The remaining two parameters from the third group (P11 and P12) evaluate the horizontal load-bearing substructures and essentially assess the level of connection between the inter-floor structures and the main load-bearing system. Horizontal diaphragms can thus be rigid or flexible and well or poorly connected to the rest of the load-bearing system.

Parameter P13 assesses the level of damage to a specific building, i.e., the current condition of the structure. This includes all observed damages as well as any structural interventions.

The final parameter, P14, considers the presence of external non-structural elements such as balconies, ornaments, chimneys, and so on. Despite their non-structural nature, the presence of such elements must be considered due to the risk associated with their fall or the potential development of localized damage, which could potentially trigger partial collapse mechanisms.

2.1. Harmonized Vulnerability Index for Urban Historic Center of Skopje

The key aspect of this method is determining the vulnerability class for each parameter, ensuring it aligns with the unique features of historic buildings within the urban historic center. A critical component of this process involves identifying the specific independent parameters characteristic of the historic urban area in the old part of Skopje and defining the correlation between these selected structural parameters and their assigned vulnerability classes - levels A, B, C, or D for each parameter.

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 [1, 5, 6 ,9], 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.

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Based on the gathered knowledge about the structures in the Old Bazaar, the relationship between the selected specific independent structural parameters (P - P14) and the vulnerability class levels has been established (as shown in Tables 2, 3, 4, and 5). The content of these tables, along with the corresponding diagrams and detailed explanations provided in Figures 1, 2, and 3, forms part of the harmonized vulnerability index. This index links the independent structural parameters to their associated vulnerability class levels, specifically tailored to the historic buildings of Skopje's Old Bazaar [12].

Table 2 – 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/m^3**	**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 3 – 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 4 – 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 1, a	Figure 2, a	0%
B	Figure 1, b	Figure 2, b	up to 10%
C	Figure 1, c, d	Figure 2, c	(10 -20) %
D	Figure 1, e, f	Figure 2, d	(20 – 30) %

Table 5 – 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 3, a, regular and aligned	Rigid and well connected
B	Figure 3, b, horizontal misalignment	Flexible and well connected
C	Figure 3, c, horizontal and vertical misalignment	Rigid and poorly connected
D	Figure 3, d, large openings on ground floor	Flexible and poorly connected

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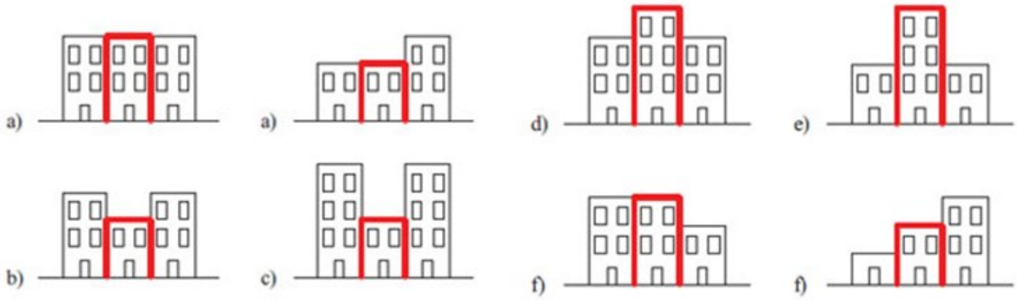

Figure 1. Building position (figure according [10)]

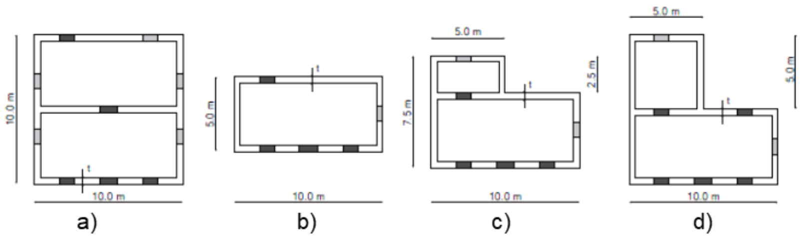

Figure 2. Plan regularity (figure according [10)]

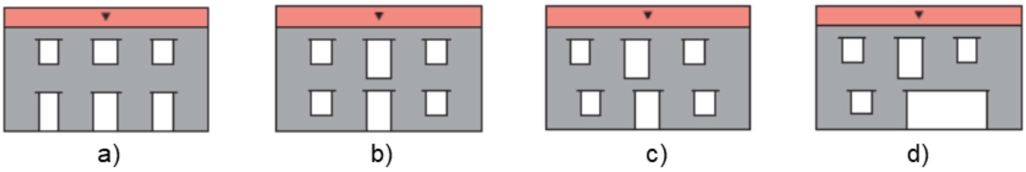

Figure 3. Alignments in openings (figure according [10)]

This section provides a clear and practical guideline for pre-earthquake vulnerability assessment of a specific historic urban center, designed for use by key target groups such as architects and civil engineers involved in the seismic protection of structures with cultural heritage significance. The goal is to develop a vulnerability index method tailored to the specific independent parameters and associated vulnerability class levels unique to the historic buildings in Skopje's Old Bazaar.

3. Application Of the Harmonized Method to Part Historical City Centre of Skopje

The seismic vulnerability assessment of one representative street of the historical city center of Skopje was carried out by applying the harmonized vulnerability index methodology, shortly presented in section 3. Because the methodology requires accurate knowledge of the building characteristics, which can only be obtained via thorough and detailed inspection, 33 buildings were analysed, in function of the detail of the information available and used on its seismic vulnerability assessment.

It is important to note that during the field assessment and analysis of the buildings, 6 buildings were observed that were reconstructed using reinforced concrete. These buildings were not exempted from the seismic assessment.

To efficiently and quickly collect the large amount of field data, a form for field inspections was created, properly adapted to the characteristics of the historical center of Skopje, which enables the systematic collection of a set of structural parameters needed for the assessment of seismic vulnerability according to the selected and harmonized method. This form consists of four main parts that select the most representative characteristics of the objects: general information, material and structure characteristics and their current condition, structure regularity, non-structural elements, and roof structure. A completed form for a building is shown in Figure 4, as an example.

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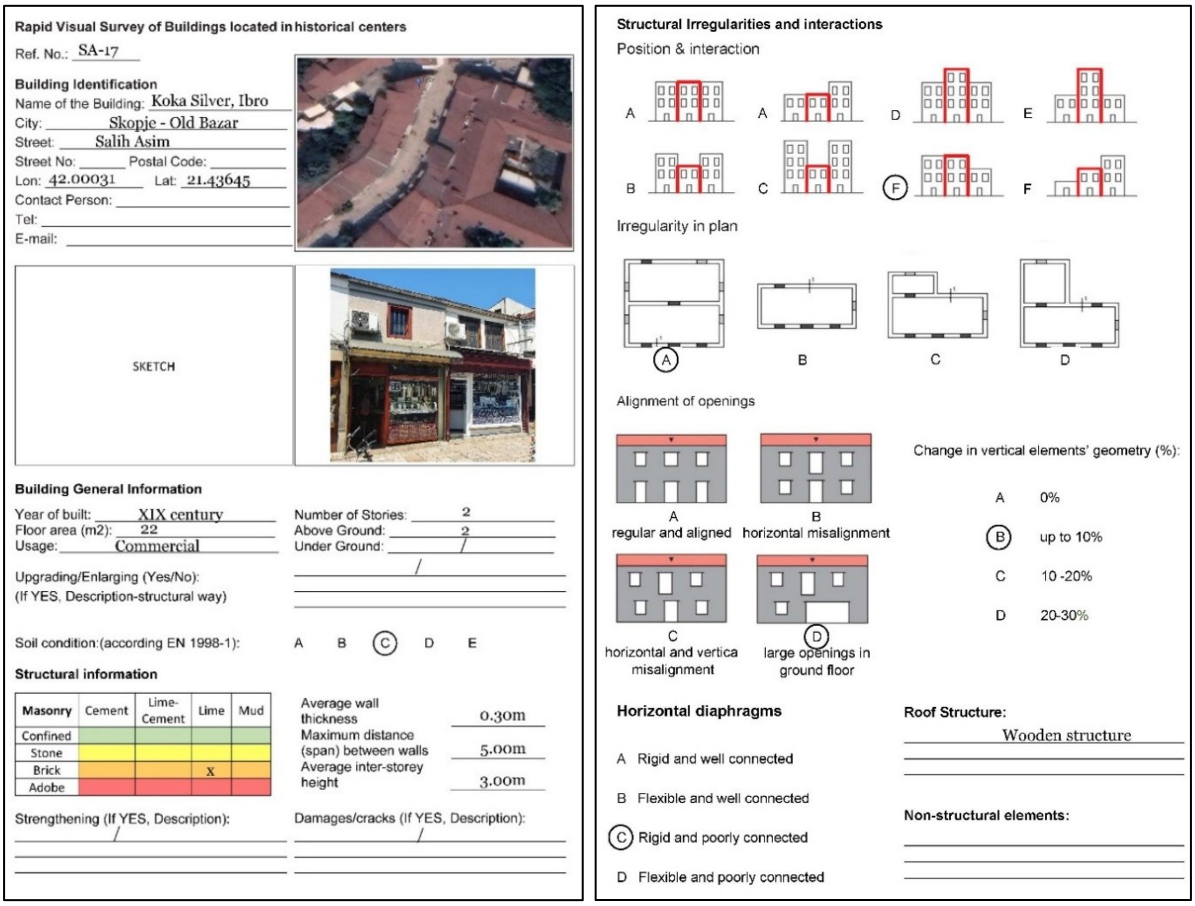

Rapid Visual Survey of Buildings located in historical centers

Ref. No.: SA-17

Building Identification
Name of the Building: Koka Silver, Ibro
City: Skopje - Old Bazar
Street: Salih Asim
Street No: ______ Postal Code: ______
Lon: 42.00031 Lat: 21.43645
Contact Person:
Tel:
E-mail:

SKETCH

Building General Information
Year of built: XIX century
Floor area (m2): 22
Usage: Commercial
Number of Stories: 2
Above Ground: 2
Under Ground: /
Upgrading/Enlarging (Yes/No): /
(If YES, Description-structural way)

Soil condition:(according EN 1998-1): A B (C) D E

Structural information

Masonry	Cement	Lime-Cement	Lime	Mud
Confined				
Stone				
Brick			X	
Adobe				

Average wall thickness: 0.30m
Maximum distance (span) between walls: 5.00m
Average inter-storey height: 3.00m

Strengthening (If YES, Description): /
Damages/cracks (If YES, Description): /

Structural Irregularities and interactions
Position & interaction
A A D E
B C (F) F

Irregularity in plan
(A) B C D

Alignment of openings
A regular and aligned
B horizontal misalignment
C horizontal and vertica misalignment
(D) large openings in ground floor

Change in vertical elements' geometry (%):
A 0%
(B) up to 10%
C 10 -20%
D 20-30%

Horizontal diaphragms
A Rigid and well connected
B Flexible and well connected
(C) Rigid and poorly connected
D Flexible and poorly connected

Roof Structure:
Wooden structure

Non-structural elements:

Fig. 4 A completed form for quick collection of field data

Fig. 5 The assessed urban area with marked buildings – Salih Asim street (Skopje old Bazaar)

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The proposed data collection method allows for a straightforward process to obtain the required data. It also streamlines and shortens the time needed to process the information and assess the seismic vulnerability of each structure. An additional benefit is that the information collected can be used to create databases for future projects and research.

The methodology applied herein, and results obtained are presented resourcing to a Google Earth application. Figure 5 shows the assessed urban area with marked buildings.

The seismic vulnerability index I_{vf} was calculated according to Equation (1). The values of the I_{vf} are presented in Table 6.

As already mentioned, seismic vulnerability results were mapped using the Google Earth tool, developed to provide a global overview of the vulnerability assessment results and the consequent risk scenarios.

Based on the previous seismic vulnerability values of the buildings within the study area, descriptive damage grades were estimated for seismic scenarios with macroseismic intensity IX.

Tab. 1 vulnerability index values for the whole study area

No.	Ivf	No.	Ivf
SA-1	0	SA-17	320
SA-2	295	SA-18	0
SA-3	325	SA-19	245
SA-4	290	SA-20	275
SA-5	255	SA-21	275
SA-6	255	SA-22	285
SA-7	255	SA-23	275
SA-8	0	SA-24	245
SA-9	275	SA-25	275
SA-10	270	SA-26-A	247.5
SA-11	245	SA-26-B-C	197.5
SA-12	217.5	SA-27	227.5
SA-13	107.5	SA-28	345
SA-14	195	SA-29	0
SA-15	245	SA-30	0
SA-16	275	SA-31	0

Tab. 2 Damage grade, according to vulnerability

	Damage - Intensity IX - MSC
	Ivf=0-100 - No damage
	Ivf =101-200 - Slight / moderate damage
	Ivf =201-300 - Severe damage
	Ivf >300 - Very severe damage / destruction

The proposed damage for this work, according to the vulnerability, is presented to table 7. Figure 6 presents the spatial distribution of the vulnerability index values for the whole study area and, also presents the damage scenario for seismic intensity IMS-98= IX.

From the results, it is observed that for earthquake intensities IX, 10% of the buildings would collapse, 64% of them would have severe damage, 10% would have minor damage, and 16% would remain undamaged. In this 16 percent, reinforced concrete constructions are placed (Figure 7).

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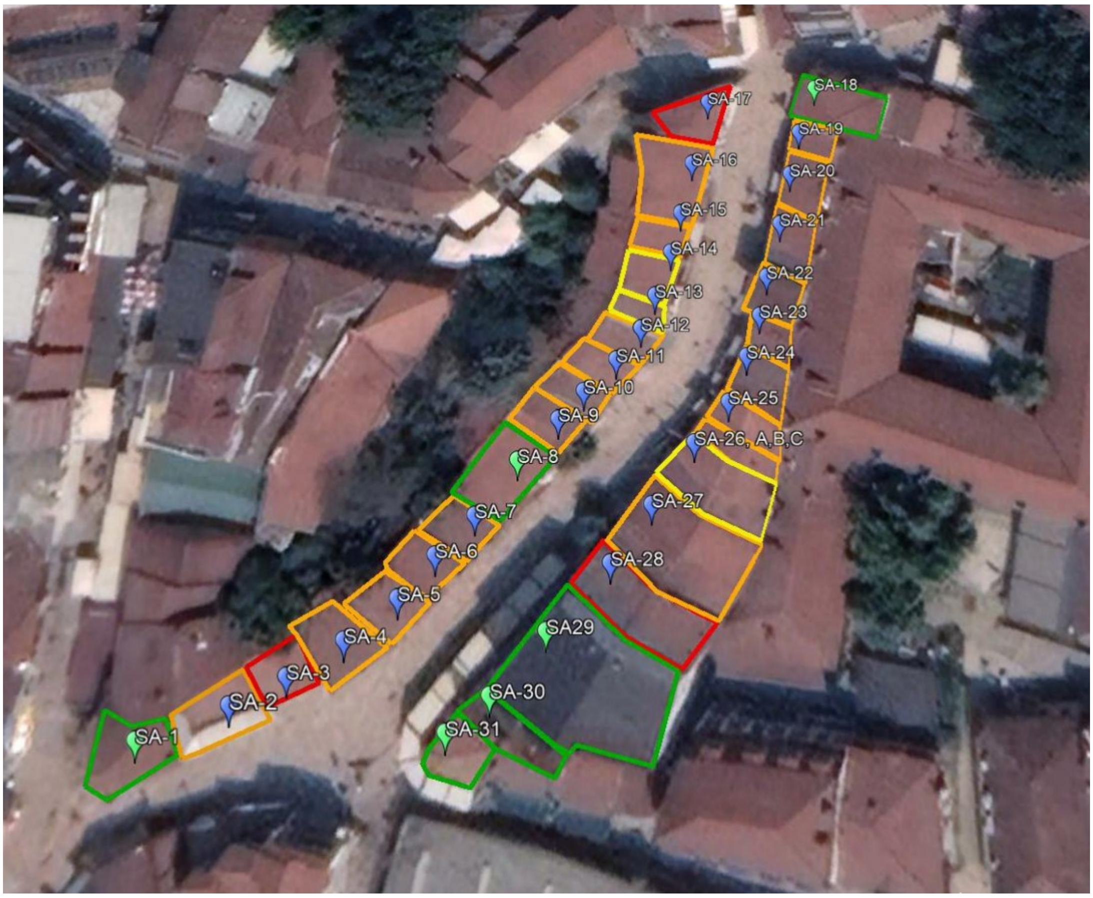

Fig. 6 The assessed urban area with marked buildings – Salih Asim street (Skopje old Bazaar)

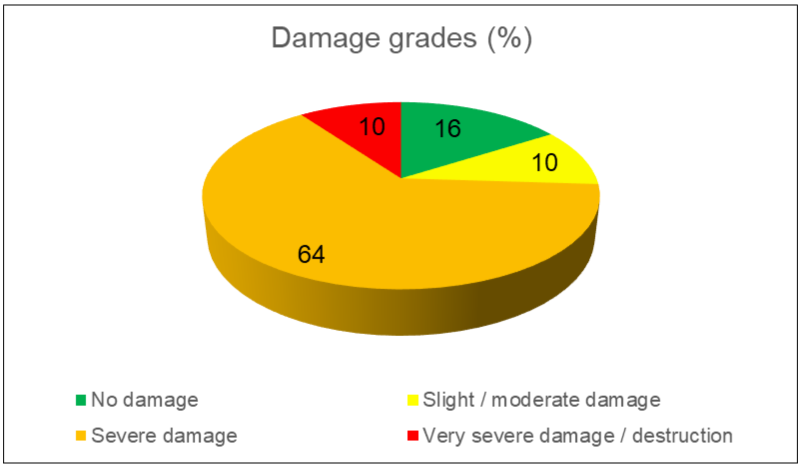

Fig. 1 Percentage representation of different damage grades

4. Conclusions

The vulnerability assessment of masonry buildings in a historical urban area is a fundamental step in evaluating global seismic risk, defined as the likelihood of a seismic event of a certain intensity occurring at a specific location within a given timeframe. This analysis is critical not only due to the physical consequences of potential seismic events but also because of its connection to human safety and evacuation planning—key elements in devising effective risk reduction strategies.

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By integrating vulnerability assessment with the implementation of suitable seismic retrofitting measures and emergency response plans, it becomes possible to mitigate physical damage, reduce human casualties, alleviate critical emergencies, and minimize the economic impact of future seismic events. Specifically, in the context of masonry buildings in historical centers, decades of accumulated knowledge and extensive damage data from post-earthquake surveys provide a unique opportunity to harmonize and refine seismic vulnerability assessment methodologies.

The results achieved through recent advancements in the field, leveraging calibrated methods based on earthquake databases and specific insights into the characteristics of historic buildings in the Old Bazaar, are robust and adaptable. These results can be effectively applied and modified to address the challenges of future seismic events.

The proposed harmonized vulnerability index method, derived by calculating a building's score as a weighted sum of its characteristic parameters, linked to its seismic response and categorized into vulnerability classes, offers an innovative and practical tool. It bridges the gap between empirical and analytical methods, providing a reliable foundation for initial seismic vulnerability assessments.

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