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METHODOLOGY FOR ASSESSING THE VULNERABILITY OF EXISTING MASONRY BUILDINGS: CASE STUDY OF GOSTIVAR CITY

Seismic vulnerability assessment of masonry structures is a very important issue even for regions with moderate to low seismic hazard. This is even more important when dealing with old buildings, such as the buildings located in the geographical area of interest, where all masonry structures were built in nineteenth century and in the first half of the twentieth century, that is, before the adoption of the aseismic design regulation. Although most of the masonry building stock in the researched region consists of residential buildings, there are also public and religious buildings. As a result of the field studies, it was determined that many people lived in these buildings. The uncertain behavior of masonry structures during earthquakes shows that people living in these residences are at risk. In this context, the aim of the research is to examine the building stock of masonry structures to evaluate the seismic risk in the region. There are different methods for assessing the vulnerability of structures. The purpose of the research, scope of the study, available resources, etc. should be considered when choosing the appropriate methodology. This paper presents a methodology for assessing the seismic vulnerability of existing masonry structures and the results obtained from the application of the methodology for the city of Gostivar.

Keywords: masonry structures, seismic risk, vulnerability assessment, vulnerability index, urban areas

1. INTRODUCTION

The high sensitivity of today's technologies, large cities built in seismic hazard zones are some of the reasons for the increase in losses from natural disasters in recent years [1]. All this has increased interest in the development of seismic assessment methodologies as well as solutions for reinforcing existing building stocks [2].

It is necessary to construct buildings in accordance with the seismic design rules to ensure seismic safety. However, existing buildings do not meet these rules, which has led to the need to estimate the vulnerability of existing buildings [3].

The assessment of the vulnerability of buildings can be defined as their susceptibility to damage at a certain earthquake intensity. In the past, many methods have been proposed to assess seismic vulnerability [4].

These methods are used from single buildings to large urban areas. To select the right method, the purpose of the research, the available resources, the approach to obtaining information, the economic situation and the computational effort should be taken into consideration [5].

1.1 METHODS FOR VULNERABILITY ASSESSMENT

To determine the seismic vulnerability of a building, there is a need to establish a correlation that can provide the expected damage level for each seismic intensity level and define appropriate parameters to measure damage and severity [6].

Different vulnerability assessment methods have been proposed and applied in the past. They can be classified generally into two groups: empirical and analytical, both groups can be used in hybrid methods [7].

2. METHODOLOGY FOR SEISMIC VULNERABILITY ASSESSMENT OF MASONRY BUILDINGS

The seismic vulnerability assessment of many buildings in an urban environment is a difficult and complicated task because it is not rational to perform nonlinear analysis of all buildings. To solve this, vulnerability curves obtained by numerical analysis and statistical processing of the results for a class of buildings can be defined. Vulnerability curves relate to the probability of exceeding a certain damage level for a given earthquake intensity [8] [9] [10].

Various studies have been conducted using vulnerability curves to assess seismic vulnerability and damage scenarios of buildings in urban centers and to determine basic critical situations. Empirical methods such as the vulnerability class method and the vulnerability index method are widely used methods to define the vulnerability of buildings in urban areas. In this research, the Vulnerability Index (VIM) method was used to assess the vulnerability of the selected buildings in Gostivar. The vulnerability index method (VIM) is based on the statistical relationship between macroseismic intensity and apparent or observed damage observed in previous earthquakes, as well as the fact that different structural classes tend to experience the same or similar types of damage. The vulnerability index method was originally developed by Benedetti and Petrini [11] [12].

This method, called an indirect method since the relationship between seismic action and response is established through the sensitivity index, is based on a large amount of data obtained from the detected damages. According to this classification, the vulnerability index of each building is evaluated using the following formula:

$$I_{vf}^{*} = \sum_{i=1}^{11} C_{vi} \cdot P_{vi} \tag{1}$$

The vulnerability index (I_{vf}^{*}) is calculated as a scaled sum of 14 parameters where each parameter is defined by a weighting factor P_{vi}, and each parameter is associated with four classes (C_{vi} – A, B, C, D) from (A – optimal) to (D – unfavorable). Later, Vicente made additions and added 3 more parameters to the existing 11 parameters [5]. Ferreira also made additions and calibrated according to the data from the 1998 Azores earthquake [13]. After these calibrations, the method was used to assess the seismic vulnerability of different historical city centers. With the changes made, the final formula is as follows:

$$I_{vf}^{*} = \sum_{i=1}^{14} C_{vi} \cdot P_{vi} \tag{2}$$

The methodology used in this study is based on the calculation of a vulnerability index for each building. The vulnerability index is calculated as the sum of the determined values of the seismic responses of 14 parameters for each building (Table1).

Table 1. Parameters for calculating vulnerability index [5] [13]

Parameters	Class (C_{vi}) A B C D	Weight Factor P_{vi}	
		Vicente, 2008	Ferreira, 2017
Group 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	0 5 20 50	1.50	0.50
P6.Location and soil conditions	0 5 20 50	0.75	0.50
Group 2. Irregularities and interaction			
P7. Aggregate position and interaction	0 5 20 50	1.50	1.50
P8. Plan configuration	0 5 20 50	0.75	0.50
P9. Irregularity in elevation	0 5 20 50	0.75	0.50
P10. Wall façade openings and alignments	0 5 20 50	0.50	0.50
Group 3. Floor slabs and roofs			
P11.Horizontal diaphragms	0 5 20 50	0.75	0.75
P12. Roofing system	0 5 20 50	2.00	0.50
Group 4. Conservation state and other elements			
P13. Conservation state	0 5 20 50	1.00	1.00
P14. Non-structural elements	0 5 20 50	0.75	0.75

For each parameter, a weighting factor P_{vi}, with a value between 0.5 and 2.5, is determined according to its contribution to the examined building. The weighting factors P_{vi}, are evaluated in four vulnerability classes C_{vi} (A, B, C, D) where (A – optimal) to (D – unfavorable).

2.1 VERIFICATION FOR THE PROPOSED METHODOLOGY

The vulnerability index method is like the GNDT II (National Group for Earthquake Defense) proposal. GNDT II is developed with this method, but it allows correlation between data because important parameters are similar [14]. This equivalence allows the validation of the proposed methodology and its correlation with the macroseismic methodology of Giovinazzi and Lagomarsino [15] and allows the construction of damage and loss scenarios.

The methodology developed by Benedetti and Petrini (1984) uses the vulnerability index as an intermediate step in the damage assessment process for buildings subjected to a certain level of seismic action. This deterministic correlation between seismic action (expressed in terms of PGA) and damage (expressed as a vulnerability index ranging from 0 to 1) represents the quotient between the costs of repairing and replacing the original undamaged condition, referring to the present value of the structure. When using the vulnerability curves of the macroseismic methodology proposed by Giovinazzi and Lagomarsino [15], it is essential that they correspond to the GNDT II methodology [14], due to its similarity with the proposed methodology. The macroseismic methodology is based on the definition of building typologies belonging to vulnerability classes, damage classifications and intensity levels according to the European Macroseismic Scale EMS-98 defined by Grünthal [16].

In the macroseismic methodology, vulnerability is also expressed by a numerical value, the vulnerability index (V), which varies from 0 to 1, initially defined according to typological information (type of construction), which is then adjusted with scores attributed to the modified parameters. These parameters depend on the unique characteristics of buildings [17], such as: building condition, quality of materials and construction, number of floors, irregularities, etc. From this value of the vulnerability index (V), a vulnerability function is constructed, translated into an analytical expression of the building or typology of buildings for different EMS-98 macroseismic intensities [16]. In this way, expression (3) is obtained, which allows the calculation of the average damage level (μ_D), defined in the range from 0 to 5.

$$\mu_D = 2.5 \left[1 + \tanh\left(\frac{I + 6.25 - 13.1}{Q}\right)\right], \quad 0 \leq \mu_D \leq 5 \tag{3}$$

The value of the intermediate damage level $\mu_D =$ depends on the fragility index (V), macroseismic intensity (I) and ductility factor (Q), which can vary from 1 to 4. According to the latest calibrations, it has been determined that the most suitable value for masonry buildings is the ductility factor Q = 2.0 [18].

The damage assessment according to the Petrini and Benedetti methodology [11] is expressed as an index of the mean damage value, table 2. This damage index is correlated with the mean damage level (μ_D), given by the macroseismic methodology, which represents the average value of the damage degree (p_k) and is used for the discretized damage degree (D_k), (Table 2), expressed as:

$$\mu_D = \sum_{k=0}^{5} p_k \cdot D_k \tag{4}$$

Table 2. Division of damage by factor and average level of damage

Discretized degree of damage	Damage factor DF	Medium level of damage μ_D
D0- No damage	0.00	[0.00 – 0.50]
D1- Slight damage	0.01	[0.50 – 1.42]
D2- Moderate damage	0.10	[1.42 – 2.50]
D3 – Major damage	0.35	[2.50 – 3.50]
D4 – Very major damage	0.75	[3.50 – 4.00]
D5 - Destroyed	1.00	[4.00 – 5.00]

For ease of application, the relationship between the average damage index value (DF) and the average damage value (μ_D) is converted into an analytical expression given by equation (5), and the correlation of the two procedures is shown in table 3.

$$\mu_D = 4 \cdot DF^{0.45} \tag{5}$$

Table 3. Correlation between vulnerability index of two procedures [19]

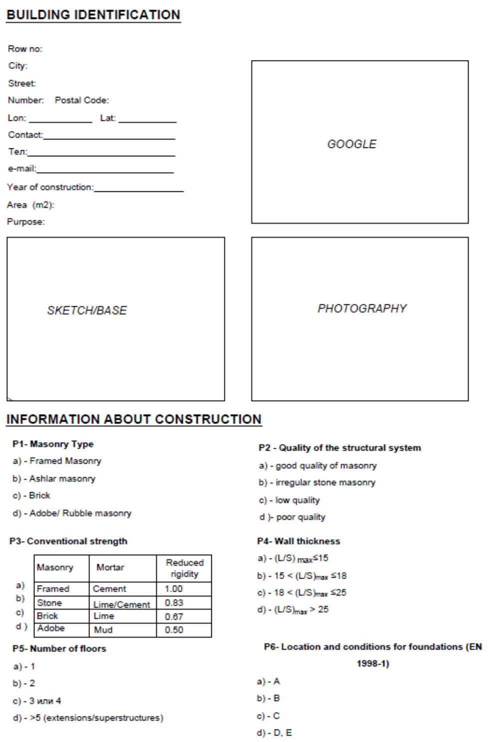
GNDT II Methodology	I_v = 45	I_v = 20	I_v = -5
Macroseismic methodology	Class A (V = 0.88)	Class B (V= 0.72)	Class C (V= 0.56)

Based on this comparison, it is possible to define an analytical linear correlation between the vulnerability indexes of the two methodologies (V and I_v):

$$V = 0.592 + 0.0057 \cdot I_v \tag{6}$$

3. APPLICATION OF SEISMIC VULNERABILITY ASSESSMENT METHODOLOGY IN GOSTIVAR

According to the proposed methodology of Vicente, a data collection form for field research is proposed. The parameters of the vulnerability index methodology are adapted to the research area. The aim is to collect more accurate information needed for the assessment of the seismic vulnerability of buildings more quickly. Figures 1 and 2 show the proposed data collection form, while Figure 3 shows an example of completed forms from field research.



BUILDING IDENTIFICATION

Row no:
City:
Street:
Number: Postal Code:
Lon: __________ Lat: __________
Contact:____________________
Теn:____________________
e-mail:____________________
Year of construction:____________
Area (m2):
Purpose:

GOOGLE

SKETCH/BASE

PHOTOGRAPHY

INFORMATION ABOUT CONSTRUCTION

P1- Masonry Type
a) - Framed Masonry
b) - Ashlar masonry
c) - Brick
d) - Adobe/ Rubble masonry

P2 - Quality of the structural system
a) - good quality of masonry
b) - irregular stone masonry
c) - low quality
d)- poor quality

P3- Conventional strength

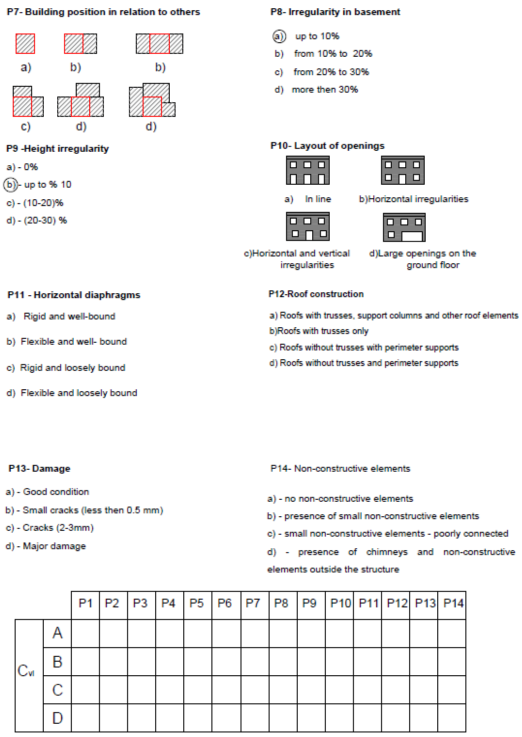
	Masonry	Mortar	Reduced rigidity
a)	Framed	Cement	1.00
b)	Stone	Lime/Cement	0.83
c)	Brick	Lime	0.67
d)	Adobe	Mud	0.50

P4- Wall thickness
a) - $(L/S)_{max} \leq 15$
b) - $15 < (L/S)_{max} \leq 18$
c) - $18 < (L/S)_{max} \leq 25$
d) - $(L/S)_{max} > 25$

P5- Number of floors
a) - 1
b) - 2
c) - 3 или 4
d) - >5 (extensions/superstructures)

P6- Location and conditions for foundations (EN 1998-1)
a) - A
b) - B
c) - C
d) - D, E

Figure 1. Form - Page 1 (by author)


P7- Building position in relation to others

a) b) b)

c) d) d)

P8- Irregularity in basement

a) up to 10%
b) from 10% to 20%
c) from 20% to 30%
d) more then 30%

P9 -Height irregularity

a) - 0%
b)- up to % 10
c) - (10-20)%
d) - (20-30) %

P10- Layout of openings

a) In line
b)Horizontal irregularities
c)Horizontal and vertical irregularities
d)Large openings on the ground floor

P11 - Horizontal diaphragms

a) Rigid and well-bound
b) Flexible and well- bound
c) Rigid and loosely bound
d) Flexible and loosely bound

P12-Roof construction

a) Roofs with trusses, support columns and other roof elements
b)Roofs with trusses only
c) Roofs without trusses with perimeter supports
d) Roofs without trusses and perimeter supports

P13- Damage

a) - Good condition
b) - Small cracks (less then 0.5 mm)
c) - Cracks (2-3mm)
d) - Major damage

P14- Non-constructive elements

a) - no non-constructive elements
b) - presence of small non-constructive elements
c) - small non-constructive elements - poorly connected
d) - presence of chimneys and non-constructive elements outside the structure

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
C_{vi}	A														
	B														
	C														
	D														

Figure 2. Form - Page 2 (by author)

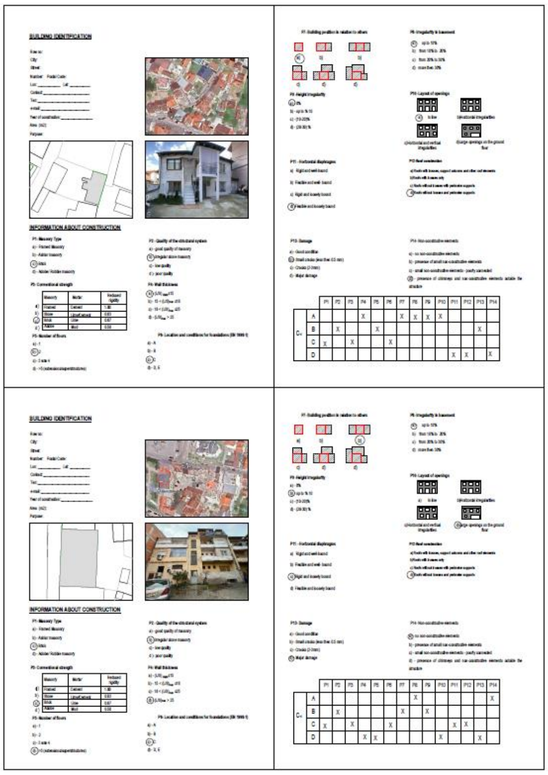


Figure 3. Examples of completed forms in field research (by author)

The seismic vulnerability assessment is made by calculating the vulnerability index I_{vf}^*, which is calculated with equation (2). The vulnerability index I_{vf}^* is normalized from 0 to 100. The weighting factors (p_{vi}) provided by Ferreira were used in the calculation of the vulnerability index. 143 buildings were evaluated in the central urban area of the city of Gostivar. Figure 4 presents the percentage repesresentation of buildings according to I_{vf}.

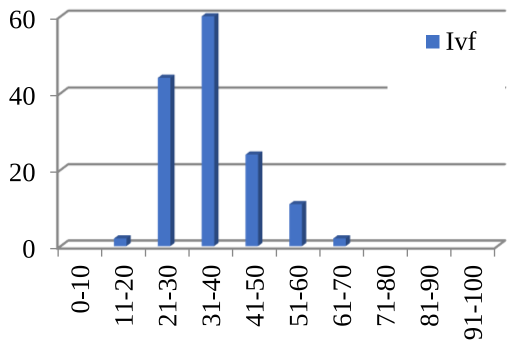


Figure 4. Percentage representation of buildings in Gostivar according I_{vf} - (by author)

From the obtained values, it can be noted that most masonry buildings in Gostivar have a vulnerability index between 21 and 40. According to Ferreira's weighting factors, 1.3% of the buildings belong to the interval between 11 and 20, 30.7% to the interval 21-30, 41.9% to the interval 31-40, 16.7% to the interval 41-50, 7.6% to the interval 51-60 and 1.3% of the buildings to the interval 61-70. Figure 5 shows the spatial distribution of I_{vf} for the current state of the buildings in Gostivar.

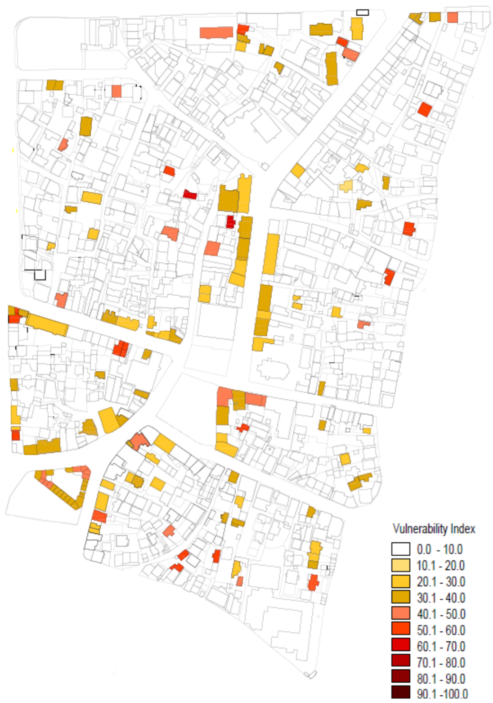


Figure 5. Spatial distribution of I_{vf} for the current state of the buildings in Gostivar - (by author)

Based on the calculated values of the vulnerability index, using equation (3), the average damage level (μ_D) was calculated for different scenarios of macroseismic intensities. The study calculated 4 different scenarios of macroseismic intensities between VI and IX degrees according to the MCS scale. Figure 6 shows the statistical data for the percentage representation of the obtained average damage level for each of the four individual scenarios.

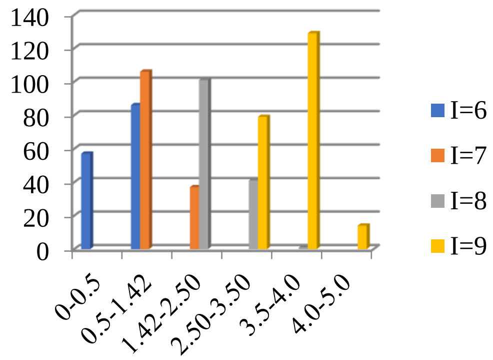


Figure 6. Percentage of buildings according to the average level of damage (μ_D)

According to the analysis of the results, it is noted that for lower earthquake intensities (VI and VII degrees), the buildings in Gostivar are evaluated with scores from 0 to 2.5. For higher earthquake intensities (VII and IX degrees), the buildings receive scores from 2.5 to 5.

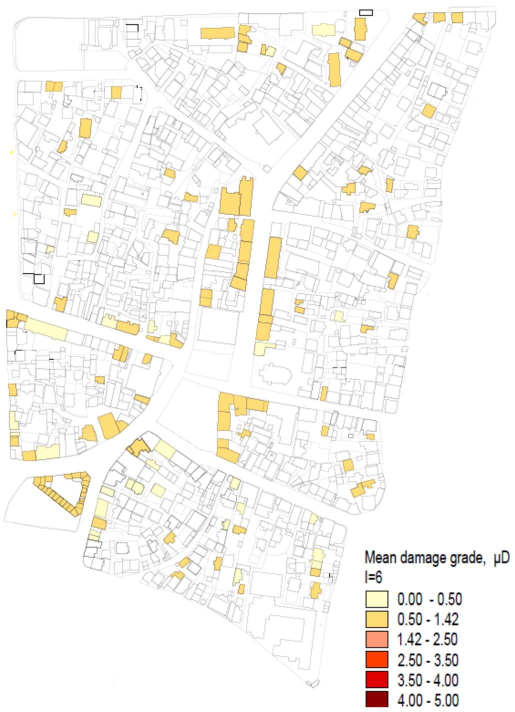


Figure 7. The spatial distribution of the average level of damage for I=6, for buildings in Gostivar

Figure 8. The spatial distribution of the average level of damage for I=7, for buildings in Gostivar

A graphical representation of the spatial distribution of the mean level of damage for earthquake intensities from I=6 to I=9 for Gostivar is shown in Figure 7,8,9 and 10.

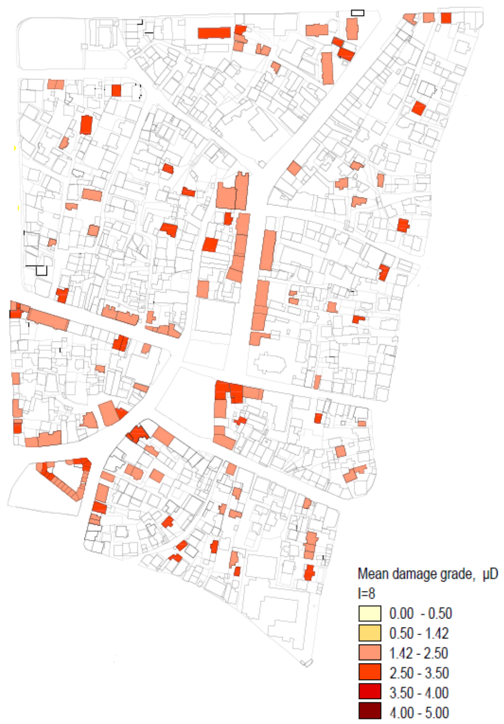


Figure 9. The spatial distribution of the average level of damage for I=8, for buildings in Gostivar

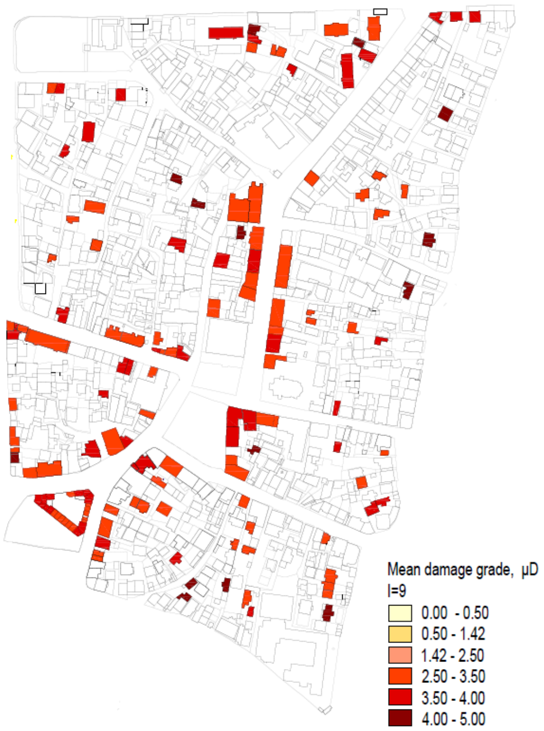


Figure 10. The spatial distribution of the average level of damage for I=9, for buildings in Gostivar

According to the seismic vulnerability obtained of the buildings, vulnerability curves of the masonry buildings in Gostivar were constructed depending on different macroseismic intensities (Figure 11).

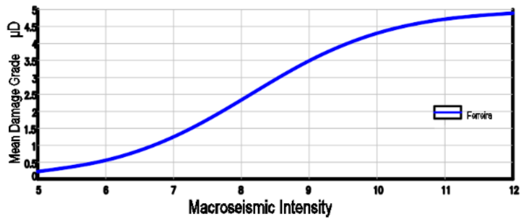


Figure 11. Vulnerability curves for the existing condition of the buildings in Gostivar

4. CONCLUSION

The aim of the study is to analyze a larger number of buildings to examine the vulnerability of existing masonry structures in urban areas. From the obtained results, a typological classification of existing masonry structures can be used to assess seismic risk at a regional level. For this purpose, the vulnerability index methodology was chosen as a methodology for assessing existing masonry structures. From the results obtained presented in the paper, most of the buildings analyzed in Gostivar would experience very large damage or even collapse at the highest earthquake intensity. From the results obtained, buildings or areas that are at the highest risk can be identified and measures can be taken to strengthen them. A precise assessment of the vulnerability of existing buildings and the implementation of appropriate strengthening solutions can significantly reduce physical damage and economic losses from future seismic events.

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