Seismic vulnerability assessment of masonry facade walls

T. Ferreira, R. Vicente & H. Varum
University of Aveiro, Portugal

ABSTRACT:
This paper approaches the issue of seismic vulnerability assessment strategies for facade walls of traditional masonry buildings through the development of a methodology and its subsequent application to the old building stock of the historical city centre of Coimbra. Over 600 building facades were evaluated in accordance to the methodology developed. From the post-earthquake damage assessment of masonry buildings in Aquila, Italy, it was developed and calibrated an analytical function to estimate the mean damage grade for masonry facade walls. Once defined the vulnerability function for facade walls, the calculation of damage scenarios was carried out and was subsequently used in the development of an emergency planning tool and in the elaboration of an accessibility routing proposal for the case study – Old city centre of Coimbra.

Keywords: Masonry facade, vulnerability index method, seismic vulnerability, damage scenarios, GIS mapping.

1. INTRODUCTION

1.1 Scope

The proposed vulnerability index formulation is based essentially on a vast set of post-seismic damage survey data and on the identification of constructive aspects that most influence the damage on masonry building facades. The seismic risk evaluation of built-up areas is associated to the level of earthquake hazard of the region, to the building vulnerability and to the exposure. Within this holistic approach that defines seismic risk, building vulnerability assessment assumes great importance, not only because of its obvious physical consequences in the eventual occurrence of a seismic event, but because it is the potential aspect for which the engineering research can intervene.

Development of vulnerability studies in urban centres should be conducted aiming to identify building fragilities and reduce the seismic risk. Therefore, in the scope of the rehabilitation process of the old city centre of Coimbra, a complete identification and inspection survey of the old masonry buildings has been carried out. The main purpose of this research is to present and discuss the strategy and proposed methodology adopted for the vulnerability assessment of masonry facade walls and damage scenarios, using GIS mapping application.

1.2 vulnerability index methodology

The vulnerability index is calculated as the weight sum of 13 parameters (see Table 1.1). These parameters are related to 4 classes (C_{vi}) of growing vulnerability: A, B, C and D. Each parameter evaluates one aspect related to the seismic response of the masonry building facade wall, calculating or defining the vulnerability class through the analysis of different properties associated with geometrical, mechanical and conservation state characteristics [Ferreira, 2009].

Subsequently, for each one of the 13 parameters, a weight, p_i, is assigned. As shown in Table 1.1, this weight can assume the value of 0.5, for the less important parameters in the calculation of the seismic vulnerability, I^*_{vf}, or 0.75 for the more important ones.

Therefore, the facade wall vulnerability index, I^*_{vf} , is given by:

$$I^*_{vf} = \sum_{i=1}^{13} C_i \times p_i \qquad (1.1)$$

The value of I^*_{vf} ranges between 0 and 350. For ease of use, this was normalized through a weighted sum, varying between 0 and 100, whereby the lower the value, the lower will be the facade wall seismic vulnerability, I_{vf}. The vulnerability index calculated can be used to estimate the building facade damage under a specified seismic intensity, as will be discussed and presented in Section 3.

Table 1.1. Vulnerability index assessment parameters and weights

PARAMETERS		Class C_{vi}				Weight	VULNERABILITY INDEX
		A	B	C	D	p_i	
Group 1. Facade geometry and openings							
P1	Facade wall geometry	0	5	20	50	0.50	
P2	Wall slenderness	0	5	20	50	0.50	
P3	Area of wall openings	0	5	20	50	0.50	
P4	Misalignment of wall openings	0	5	20	50	0.50	
Group 2. Masonry materials and conservation							
P5	Masonry quality	0	5	20	50	0.75	$I^*_{vf} = \sum_{i=1}^{13} C_{vi} \times p_i$
P6	Conservation state	0	5	20	50	0.75	
Group 3. Connection efficiency to other structural elements							
P7	Connection to orthogonal walls	0	5	20	50	0.50	
P8	Connection to horizontal diaphragms	0	5	20	50	0.50	
P9	Connection to roofing system	0	5	20	50	0.50	
Group 4. Elements connected with the facade							
P10	Nonstructural elements	0	5	20	50	0.50	
P11	Beneficial elements to behaviour	0	5	20	50	0.50	Normalized index $0 \leq I_{vf} \leq 100$
P12	Interaction between adjacent facades	0	5	20	50	0.50	
P13	Type and mass of flooring structures	0	5	20	50	0.50	

As exposed in Table 1.1, parameters P5 and P6 assume higher influence in the formulation of the vulnerability index, I_{vf}. These parameters evaluate the type and nature of the materials that constitutes the masonry facade walls and its conservation state.

2. APPLICATION OF THE VULNERABILITY INDEX METHOD TO THE MASONRY BUILDING FACADES

2.1. Case study

In this section will be presented and discussed the results obtained with the developed vulnerability index method for facades. The methodology was used to estimate the value of 672 (out of 803) buildings, distributed throughout the area of the historical city centre of Coimbra. Buildings were grouped into eight distinct subzones (Z1 to Z8) and were organized in two groups, function of the level of detailed information available for the vulnerability assessment. Therefore, the evaluation of the vulnerability facades was undertaken in two phases.

In a first phase, the evaluation of the vulnerability index, I_{vf}, was carried out for the buildings with detailed information: drawings with accurate dimensions for the determination of the parameters depending on geometry (P1, P2, P3 and P4) and photographic information to evaluate the remaining parameters. In this phase, 330 building facades out of 803 were evaluated. In a second phase, an expedite approach has been adopted for the assessment of buildings for which it was not possible to obtain or consult drawings. The evaluation of the vulnerability parameters in this second phase was estimated by resorting to photographic documentation (342 building facades, out of 803). The remaining 131 buildings were not evaluated in this study, because they are reinforced concrete structures, or were demolish or are in ruin, all for which the assessment method is not applicable.

2.2. Seismic vulnerability assessment results

The masonry building stock of the city centre of Coimbra was assessed, quantifying for each building the vulnerability index, I_{vf}. For the first group of buildings (330) detailed assessment resulted in a mean value of the seismic vulnerability index of 36.52. For the second group of buildings a non-detailed assessment was carried out, resulting in a slight increase of the mean vulnerability index to 37.08. The standard deviation, σ_{Ivf}, associated with the vulnerability index distribution of the detailed assessed buildings is 10.21. Considering the results for the non-detailed assessed buildings, as expected, the standard deviation value reduces to 8.68, corresponding to a 17% reduction.

Fig. 2.1 shows the distribution of the vulnerability index calculated for the 672 buildings assessed (detailed and non-detailed approaches), as well as the best-fit normal distribution.

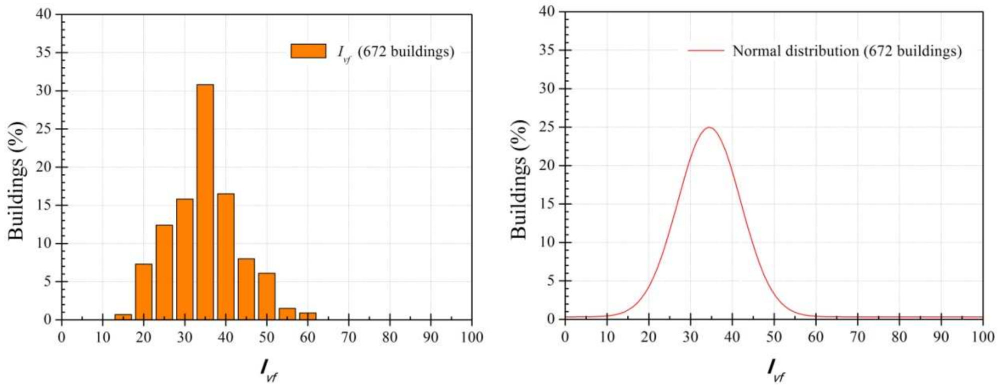

Figure 2.1. Vulnerability index distributions: histogram and best-fit normal distribution

The mean value of the seismic vulnerability index ($I_{vf,\ mean}$=37.08) obtained for the facade walls, indicates that these structural systems of the traditional limestone load bearing masonry buildings of the historical city centre of Coimbra is relatively high. About 33% of the evaluated facade walls presented a seismic vulnerability index above 40, while about 16.5% presented a value higher than 45. The maximum and minimum values obtained for I_{vf}, for all the buildings assessed was 64.09 and 11.36 respectively.

2.3 Integration into a GIS tool

A relationable database with all facade information gathered and the results of the vulnerability index assessment was created. The GIS tool (Geographical Information System) developed allows to intercross different results and building features, namely, the seismic vulnerability index with building facade characteristics. Two types of spatial view are possible: a global view of the whole area studied and, alternatively, a local view of a subzone.

In the GIS platform, specific commands were programmed to allow an easy access to all the information, as well as for the implementation of the damage and loss estimation algorithms (mathematical and probability functions). Fig. 2.2 presents the seismic vulnerability index distribution for all the facade walls evaluated. Through the overall analysis of Fig. 2.2, it is possible to identify the critical buildings, as well as the urban areas where an expressive concentration of building facades with high seismic vulnerability index.

Figure 2.2. Vulnerability mapping of the facade buildings: a) Global vulnerability index distribution; b) Identification of the buildings with $I_{vf} > 45$

3. DAMAGE ESTIMATION DAMAGE SCENARIOS

Once applied the vulnerability index methodology to the whole building stock of the historical city centre of Coimbra, it is possible to estimate the expected damage for different levels of seismic intensity. However, unlike in the case of buildings, vulnerability curves have not been developed and calibrated for masonry facade walls, allowing to correlate the severity of a seismic action (European Macroseismic Intensity Scale, $I_{EMS\text{-}98}$ [Grünthal, 1998]) with a mean damage grade, μ_D [Lagomarsino and Giovinazzi, 2006; Vicente, 2008].

Based on the building information and damage reported in the post-earthquake assessment of the 2009 Earthquake that hit the city of Áquila, in the Abruzzo region in Italy, the methodology proposed and developed was tested and calibrated by the application of the methodology to a group of representative old masonry buildings. With this analysis it was possible to derive correlations between the vulnerability index calculated, I_{vf}; the macroseismic intensity registered (according to [EEFIT, 2009] and based on the EMS-98 scale [Grünthal, 1998]); and the observed damage. This analysis was applied to the representative buildings stoked by the earthquake, that were distributed in three different macroseismic intensity zones: four buildings in Onna, with an associated intensity of IX; seven buildings distributed between the cities of Áquila and Paganica, with an intensity of VIII; and, the remaining six buildings, located in Poggio di Roio and Monticchio, where the registered intensity was approximately VII.

Following the vulnerability index assessment of the selected buildings, a mean damage grade, μ_D, ranging between 1 and 5, was estimated for each building facade wall (according to EMS-98 [Grünthal, 1998]). The average value attained for the seismic vulnerability index of the facade walls of these buildings, $I_{vf,\ mean}$, is 28.6. Nevertheless, taking into account that the damage description of the EMS-98 scale was developed initially for buildings, before its application, it was necessary to readjust the description of each damage level, adapting it to the facade walls. Table 3.1 presents the mean damage grade classification and the damage description adopted and used in the analysis of the masonry facade walls.

Table 3.1. Damage grades adopted for masonry facade walls (adopted from [Grünthal, 1998])

Damage grade		Description
	Grade 1: No damage	No damage or with a presence of very localized and hairline cracking
	Grade 2: Moderate damage	Cracking around door and window openings; localized detachments of the wall coverings (plasters, tiles, etc.)
	Grade 3: Substantial and extensive damage	Opening of large diagonal cracks; significant cracking of parapets; masonry walls may exhibit visible separation from diaphragms; generalized plaster detachments
	Grade 4: Severe and heavy damage	Facade walls with large areas of openings have suffered extensive cracking. Partial collapse of the facade (shear cracking, disaggregation, etc.)
	Grade 5: Collapse	Total in-plane or out-of-plane failure of the facade wall

Associating the mean damage vulnerability index obtained for each group of facades (I_{vf}=28.6) with the different damage grades for each of the three seismic intensities and with the buildings assessed (VII, VIII and IX), it was possible to obtain a first approximation of the vulnerability curve which correlates the macroseismic intensity, I_{EMS-98}, with the mean damage grade, μ_D. Fig. 3.1 presents the approximation obtained for the mean vulnerability index value, I_{vf}=28.6, through an adjusted third degree polynomial curve.

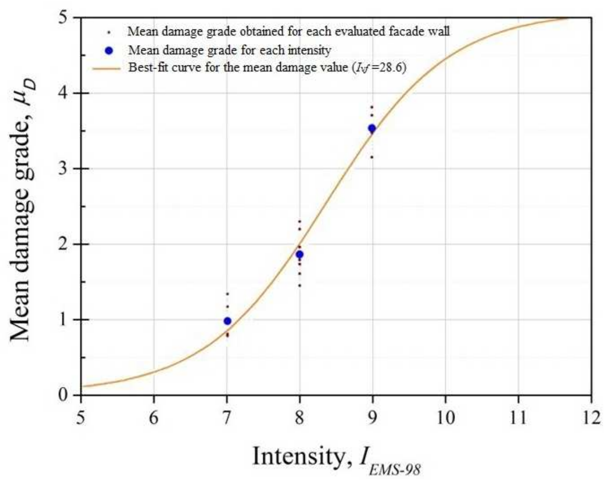

Figure 3.1. Best-fit curve for the mean damage grade

The three values for mean damage grade were obtained through the average of the values resulting from the vulnerability index method application for all the facade walls, for intensities VI, VII and VIII, while the remaining two values were defined in correspondence to mean damage grade 0 (no damage) and 5 (total collapse), to give a start and an end point to the function.

It is evident the resemblance between the obtained curve and the proposed vulnerability curves for masonry buildings, based on the development of analytical expressions proposed in the macroseismic methodology [Giovinazzi, 2005] and used by Vicente [Vicente, 2008]. As shown in Eqn. 3.1, these vulnerability curves are based on the development of correlating the seismic intensity and mean damage grade value (0<μ_D<5) of a damage distribution (discrete beta distribution) conditioned to the vulnerability index value.

$$\mu_D = 2.5 \times \left[1 + tanh\left(\frac{I + 6{,}25 \times V - 13.1}{Q}\right)\right]; \;\; 0 \leq \mu_D \leq 5 \tag{3.1}$$

where: I is the seismic intensity described in terms of macroseismic intensity, V the vulnerability index (ranging from 0 to 1), Q, a ductility factor, which expresses the ductility of a determined constructive typology (ranging from 1 to 4). The V value defines the position of the vulnerability function, and the ductility coefficient (Q) defines the slope of the vulnerability function, that is, the growth of the damage with the seismic intensity. The relation established between the vulnerability index, I_{vf}, can be transformed into a vulnerability index, V, referent to the macroseismic method based on the confrontation made by Vicente [Vicente *et al.*, 2008]. The following analytical correlation was derived between the vulnerability indexes of the two methods, is given by:

$$V = 0.592 + 0.0057 \times I_{vf} \tag{3.2}$$

Adjusting the curve presented in Fig. 3.1 for facade walls, to the analytical function given by Eqn. 3.1, it was possible to obtain a new semi-empirical expression for the mean damage grade estimation for facade walls. Eqn. 3.3 arises from several adjustments and calibrations, based on intensity/damage observation of facade walls affected by Abruzzo earthquake.

$$\mu_D = 1.51 + 2.5 \times tanh\left(\frac{I + 5{,}25 \times V - 11.6}{Q}\right); \;\; 0 \leq \mu_D \leq 5 \tag{3.3}$$

The ductility factor, Q, assumed for this study is equal to 2.0. This value lead to the best approximation between the mean damage grade, μ_D, values obtained through the vulnerability function and the post-seismic damage evaluation. Eqn. 3.2, which relates I_{vf} and V, continues valid.

Fig. 3.2 presents the confrontation between both vulnerability curves, developed for buildings, and facade walls, given for the mean vulnerability index value of 28.6. Based on recent seismic events, it is possible to state that masonry facade walls, when compared to buildings themselves, and for the same seismic intensity, tend to present more extensive damage. Thus, this typical difference in damage justifies the gap between both vulnerability curves plotted in Fig. 3.2.

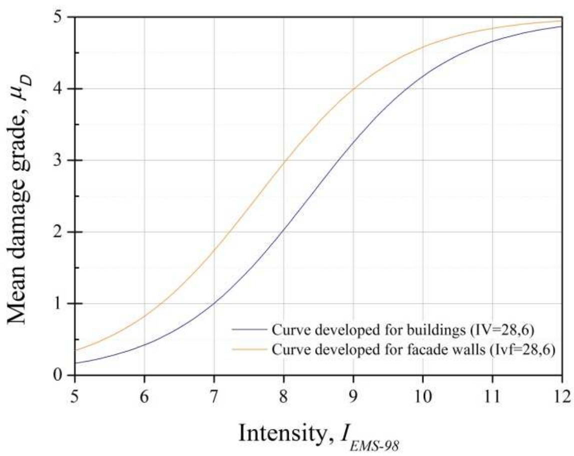

Figure 3.2. Confrontation between vulnerability curves for buildings and facade walls (I_{vf}=28.6)

In Fig. 3.3 are shown the seismic vulnerability curves (in the $I_{EMS\text{-}98}$ versus μ_D format), obtained with Eqn. 3.3, for the average value of the vulnerability index estimated for all the masonry facades of the traditional buildings of the old city centre of Coimbra ($I_{vf,mean}$=37.08). Also, in the same figure are plotted upper and lower bound ranges ($I_{vf,mean} - 2\ \sigma_{Ivf}$; $I_{vf,mean} - \sigma_{Ivf}$; $I_{vf,mean}$; $I_{vf,mean} + \sigma_{Ivf}$; $I_{vf,mean} + 2\ \sigma_{Ivf}$) obtained for the 672 assessed masonry facade walls (standard deviation, σ_{Ivf}=8.68).

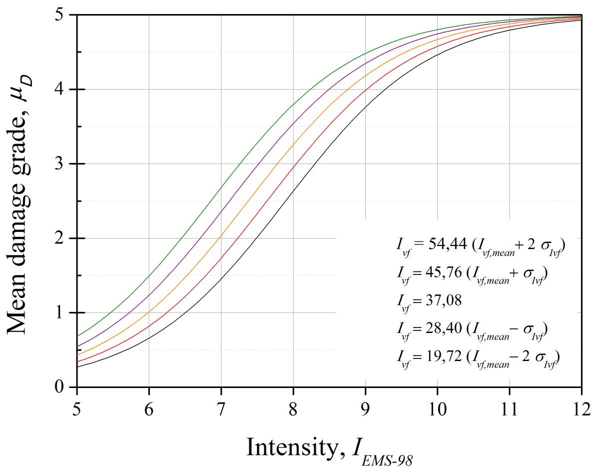

Figure 3.3. Vulnerability curves for the facade walls of the historical city centre of Coimbra

Using GIS, loss scenarios for the whole area under study can be developed and evaluated, for each building facade. Fig. 3.4 presents the damage scenarios obtained for seismic intensities of VII and VIII. These two seismic scenarios correspond to the maximum felt earthquake event in the district of Coimbra (1755 historical event). The building facades damage estimation ranges from 1.21 to 3.03 for an earthquake scenario with $I_{EMS\text{-}98}$=VII, and from 2.32 to 4.04 for $I_{EMS\text{-}98}$=VIII. The mapping of mean damage grade, μ_D, resorting to the GIS tool, facilitates the risk analysis, identifying areas of higher vulnerability and consequently with higher potential risk of damage. Moreover, it allows to prepare and plan post-event strategies, such as rescue and safety planning [see Ferreira, 2009]

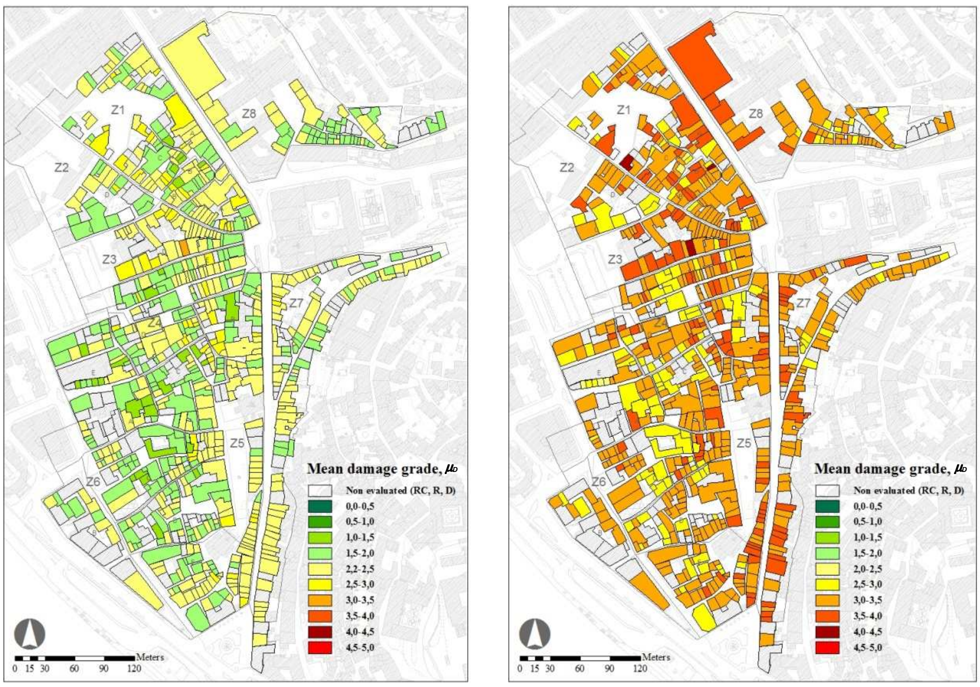

Figure 3.4. Building facade damage distribution for $I_{EMS\text{-}98}$=VII and $I_{EMS\text{-}98}$=VIII

From the analysis of Fig. 3.4, for a scenario of seismic intensity of VIII, it is estimated that the majority of the assessed masonry facade walls present a mean damage grade, μ_D, of about 3. This indicates, for the earthquake intensity VIII scenario, that the majority of building facades would suffer severe damages ($3 \leq \mu_D < 4$) and a relevant number would be in a situation of imminent collapse.

3. FINAL CONCLUSIONS

The vulnerability assessment method development for masonry facade walls has revealed to be very assertive in analysis of the building constructive characteristics and therefore is of good reliability and consequently the results attained. The use and implementation of the vulnerability assessment method integrated into a macroseismic method has enabled to put forward vulnerability and damage scenarios for risk mitigation and management. The proposed vulnerability assessment method and risk scenario mapping can be easily adapted for specific building features and adopted for other regions and old city centres.

The data analysis that resulted from the application of the vulnerability index method for masonry facade walls developed in this study has allowed to identify the parameters that rule the seismic response of building facades and its importance by quantifying each parameter within the assessment methodology, I_{vf}. In fact, a rigorous vulnerability assessment of existing buildings, and the implementation of appropriate retrofitting solutions can help to reduce the levels of physical damage and economical loss in future seismic events.

The integration of the results in a GIS tool is fundamental in a vulnerability assessment at this urban scale, thus being useful for its management and analysis. The possibility of spatial presentation of results, associating the whole probabilistic algorithm, makes SIG an effective tool in the support of the mitigation strategies and management of seismic risk.

The information obtained through the post-seismic damage observation, in the recent case of the Abruzzo earthquake, allowed the development and calibration of a vulnerability function for masonry facade walls. The results obtained through the application of this vulnerability function has allowed the creation of damage scenarios for different earthquake intensities and subsequently the proposal of possible evacuation routes and emergency planning, as well as the identification of the most vulnerable buildings.

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