**Structural Engineering and Mechanics**, *Vol. 50, No. 4 (2014) 541-561*
DOI: http://dx.doi.org/10.12989/sem.2014.50.4.541 

# Seismic vulnerability assessment of masonry facade walls: development, application and validation of a new scoring method

Tiago M. Ferreira*, Romeu Vicente[a] and Humberto Varum[b]

*Department of Civil Engineering, University of Aveiro, 3810-193 Aveiro, Portugal*

*(Received May 10, 2013, Revised March 6, 2014, Accepted March 24, 2014)*

**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 over 600 building facades from the old building stock of the historic city centre of Coimbra. Using the post-earthquake damage assessment of masonry buildings in L'Aquila, Italy, an analytical function was developed and calibrated to estimate the mean damage grade for masonry facade walls. Having defined the vulnerability function for facade walls, damage scenarios were calculated and subsequently used in the development of an emergency planning tool and in the elaboration of an access route proposal for the case study of the historic city centre of Coimbra. Finally, the methodology was pre-validated through the comparison of a set of results obtained from its application and also resourcing to a widely accepted mechanical method on the description of the out-of-plane behaviour of facade walls.

**Keywords:** masonry facade walls; 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 construction parameters that most influence damage suffered by masonry building facades. The seismic risk evaluation of built-up areas is associated with the level of earthquake hazard in the region, building vulnerability and exposure (Barbat *et al*. 2006). Within this holistic approach defining seismic risk, the assessment of building vulnerability assumes great importance, not only because of its obvious physical consequences in the eventual occurrence of a seismic event, but also because it is a factor which engineering research may influence (Carreño *et al*. 2007, Ramos and Lourenço 2004).

Development of vulnerability studies in urban centres should be conducted with the aim of

∗Corresponding author, Ph.D. Student, E-mail: tmferreira@ua.pt
[a]Ph.D., E-mail: romvic@ua.pt
[b]Ph.D., E-mail: hvarum@ua.pt


http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

(a)

(b)

Fig. 1 Out-of-plane collapse of unreinforced masonry facade walls after the 2009 L'Áquila earthquake: (a) global overturning and (b) partial collapse

identifying building weaknesses and reducing seismic risk (see Mallardo *et al*. 2008, Dolce *et al*. 2006, Neves *et al*. 2012, Ferreira *et al*. 2013). Within the Rehabilitation Process of the historical city centre of Coimbra, still undergoing, a detailed identification and inspection survey of the old masonry building stock was carried out. It was possible to collect and organize information on various levels for different purposes, specifically for the building vulnerability assessment. The main purpose of this research is to present and discuss the strategy and proposed methodology to be adopted in the vulnerability assessment of masonry facade walls and damage scenarios, using a GIS mapping application (ArcGis 2008).

As a result of the set of damage mechanisms that can develop during an earthquake, the out-of-plane movement of masonry facade walls is very common, but depends particularly on the efficiency of the connection between the facade itself and orthogonal walls, and can be evaluated resourcing to mechanical methods (Shi *et al*. 2008, D'Ayala and Speranza 2003, Pagnini *et al*. 2011). Out-of-plane mechanisms are characterized by brittle behaviour and, therefore, may represent a threat to human safety, as was the case of many killed by the collapse of wall panels in the Messina Earthquake in 1908 and in Carlentini in 1990, in Italy (Guiffrè 2003) (see Fig. 1). Therefore, in the case of assessing masonry facade walls of the old building stock in city centres, the need of a more expedite but reliable approach in terms of qualitative and quantitative evaluation is necessary.

Vulnerability index and scoring methods were originally developed for buildings. The approach herein developed, applied and pre-validated for masonry wall facades is an original contribution due to various aspects: i) introduction of a detailed analysis of all methodology parameters, resulting from the good level of building stock information; ii) the discussion and redefinition of the qualitative and quantitative criteria of some of the most important aspects that govern masonry wall facades behaviour and seismic response; and, iii) a simplified methodology that can be, in certain cases, an alternative to mechanical methods.

### *1.2 Vulnerability index methodology*

The vulnerability index is calculated as the weighted sum of 10 parameters (see Table 1), each of which are related to 4 classes ($C_{vi}$) of increasing vulnerability: A, B, C and D. These four vulnerability classes were defined based on previous broad experience and application of other

Table 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 | |
| P6 | Conservation state | 0 | 5 | 20 | 50 | 0.75 | $I_{vf}^{*}=\sum_{i=1}^{10} C_{vi}\times p_i$ |
| 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 wall | | | | | | | Normalised index |
| P10 | Non-structural elements | 0 | 5 | 20 | 50 | 0.50 | $0 \leq I_{vf} \leq 100$ |

scoring methods developed for buildings, such as the GNDT II level approach (GNDT-SSN 1994). The vulnerability class values assigned, $C_{vi}$ (0, 5, 20 and 50) are coherent with the exponential formulation of a typical vulnerability function.

Each parameter evaluates one aspect related to the seismic response of a masonry building facade wall, calculating or defining the vulnerability class through the analysis of different properties associated with geometric, mechanical and conservation state characteristics (Ferreira 2009).

Subsequently, for each of the 10 parameters, a weight, $p_i$, is assigned. As shown in Table 1, the value of this weighting is either 0.5, for the less important parameters in the calculation of seismic vulnerability, $I^{*}_{vf}$, or 0.75 for the more important ones. Therefore, the facade wall vulnerability index, $I^{*}_{vf}$, is given by

$$I_{vf}^{*}=\sum_{i=1}^{10} C_i \times p_i \tag{1}$$

The value of $I^{*}_{vf}$ ranges between 0 and 275. For ease of use, this was normalised through a weighted sum to a value between 0 and 100, whereby the lower the value, the lower the seismic vulnerability of the facade wall. The calculated vulnerability index can then be used to estimate potential building facade damage under a range of seismic conditions, as will be discussed in Section 3.

To each parameter a weight based on its importance on the overall vulnerability assessment is assigned. Uncertainty is inherent to the definition of each parameter weight, despite being based on expert opinion for starting values. Parameters were grouped to emphasize the differences and relative importance amongst them (see Vicente 2008). Consequently in order for the results to be accurately interpreted statistically, upper and lower bounds of the vulnerability index, $I_{vf}$ were defined.

The method proposed here is considered robust, taking into account that the inspection of the majority of buildings was carried out in detail and accurate geometrical information was available. Therefore, uncertainty in the assignment of vulnerability classes to each parameter is considered low.

The first group includes parameters that evaluate the facade wall geometry (P1), the slenderness ratio (P2) and openings relative location, due to its importance in the horizontal forces load path (P3, P4). The second group of parameters assume a high influence in the formulation of the vulnerability index, since they are focused on the masonry quality and its conservation state. Parameter P5 evaluates the masonry quality, through the material (size, shape and stone type), masonry fabric and arrangement. Parameter P6 evaluates the conservation state of the masonry. The third group of parameters, which include parameters P7, P8 and P9, evaluates the efficiency of the connection between the facade wall and other structural elements, namely, orthogonal walls (P7), timber floors (P8) and pitched roofing systems (P9). The assessment of these parameters depends, among other features, on the masonry fabric and arrangement at the connection area between walls, and on the presence of connection elements, such as tie-rods. It is worth underlining the great importance of these parameters on the assessment of the vulnerability of the facade walls on the development of out-of-plane mechanisms (see Fig. 1).

Finally, the fourth group evaluates the negative influence of the presence of external elements and their interaction with the masonry facade wall. This group is only composed by Parameter 10, which assesses the connection between the masonry facade and non-structural elements (i.e., balconies, ornaments, lamps, awnings, shading overhangs and fins). Despite its non-structural nature, the presence of such elements must be evaluated either because of the risk of falling or lead to the development of located damage, potentially triggering of partial collapse mechanisms.

## 2. Application of the vulnerability index method to masonry building facades

### *2.1 Case study*

This section will present and discuss results obtained using the proposed facade vulnerability index. The methodology was used to estimate the vulnerability of 672 (out of 803) main street faced building facades, distributed throughout the historic city centre of Coimbra (see Fig. 2). Building facades were grouped into eight distinct zonal areas (Z1 to Z8) and assigned to one of two sub-groups, depending on the level of detailed information available for the vulnerability assessment. The evaluation of facade vulnerability was therefore undertaken in two phases.

In the first phase, evaluation of the vulnerability index, $I_{vf}$, was carried out for buildings for which detailed information was available: building plans with accurate dimensions enabling the determination of geometric parameters (P1, P2, P3 and P4) and photographic information for evaluation of the remaining parameters. In this phase, 330 building facades, out of 803, were evaluated. In the second phase, a more expeditious approach to assess the building facades for which it was not possible to obtain or consult detailed plans was adopted.

In the second phase, the vulnerability index values were determined in function of the mean values obtained for each one of the parameters from the detailed analysis of the first group of building facades, taking into account that the masonry building characteristics are quite homogeneous in this region. In this sense, it is worth stressing that the reliability of this assumption depends, directly and proportionally, on the homogeneity of the main building

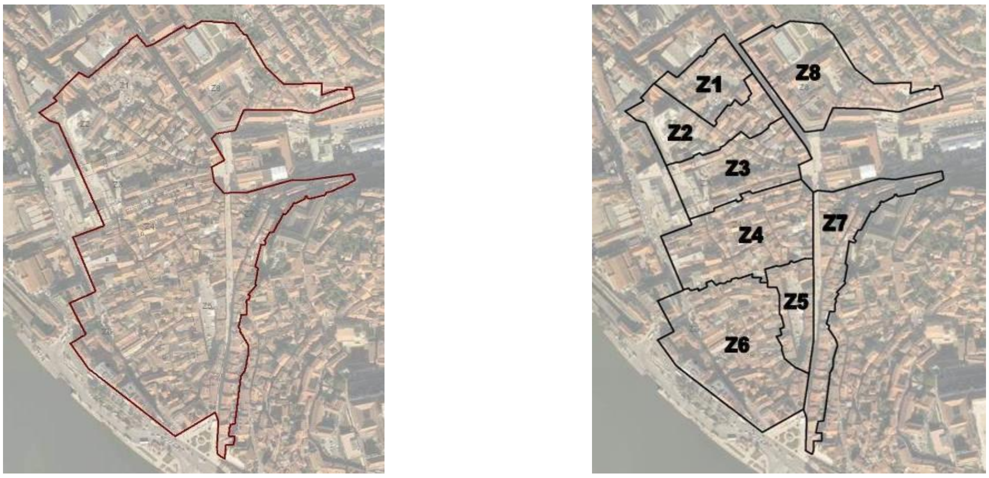



Fig. 2 Project area and zonal divisions

features. The evaluation of vulnerability parameters in this second phase was estimated by resorting to only photographic documentation (342 facades out of 803). Finally, the remaining 131 building facades were not evaluated in this study, because they were either reinforced concrete structures, or correspond to buildings demolished or in ruin.

### *2.2 Seismic vulnerability assessment results*

The masonry wall facades of the old building stock were assessed, quantifying the vulnerability index, $I_{vf}$, building by building. For the first group of buildings (330), detailed assessment resulted in a mean seismic vulnerability index value of 36.52, while for the second group, subject to non-detailed assessment, a slight increase in mean vulnerability index to 37.08 was observed. The standard deviation, $\sigma_{Ivf}$, associated with the vulnerability index distribution of the buildings that underwent detailed assessment is 10.21. The corresponding value for the buildings subject to non-detailed assessment was, as expected, lower at 8.68, corresponding to a 17% reduction.

Fig. 3 shows the distribution of vulnerability index values calculated for the 672 buildings assessed (detailed and non-detailed approaches), as well as the best-fit normal distribution.

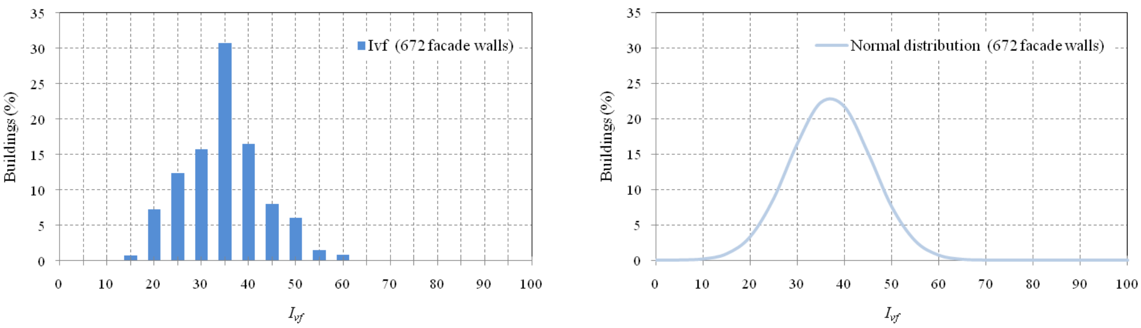



Fig. 3 Vulnerability index distributions: histogram and best-fit normal distribution

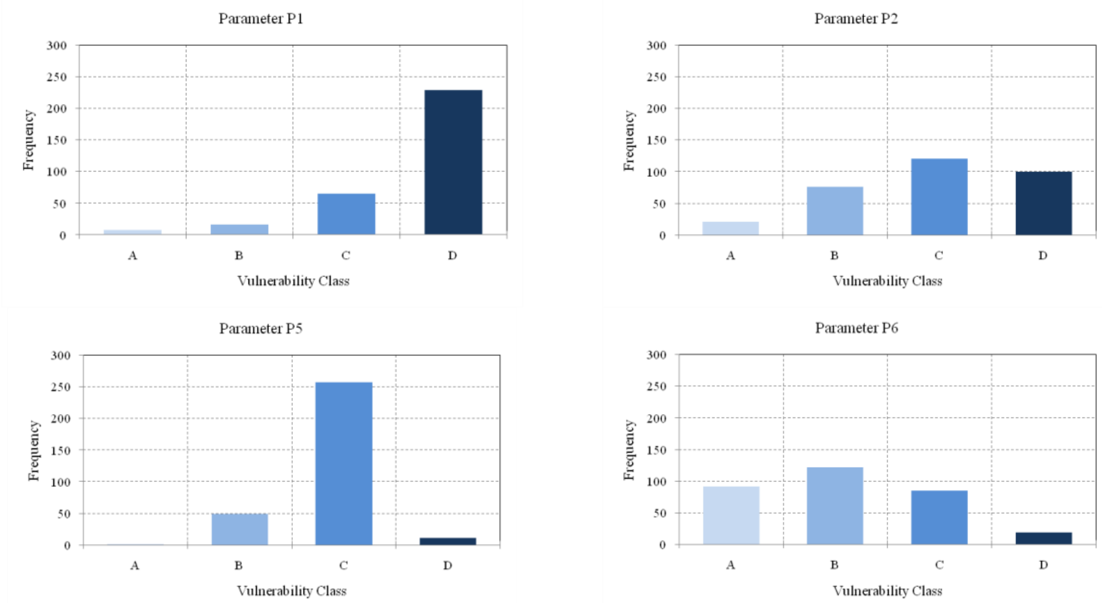



Fig. 4 Vulnerability class distribution for parameters P1, P2, P5 and P6

The mean seismic vulnerability index value ($I_{vf,\ mean}$=37.08) obtained for the facade walls indicates that the physical risk posed to these traditional limestone load-bearing masonry buildings within the historic city centre of Coimbra is significant in the case when associated to prone moderate and high seismic zones (Intensity VII, VII and IX given by the EMS-98 (Grünthal 1998)), that could lead to significant damage levels ($D_3$ and $D_4$). About 33% of the evaluated facade walls had a seismic vulnerability index above 40, while about 16.5% had values higher than 45. The maximum and minimum $I_{vf}$ values for all buildings assessed were 64.09 and 11.36, respectively.

Fig. 4 shows the vulnerability class distribution for parameters P1, P2, P5 and P6, referring only to the group of 330 building facades subject to detailed assessment. These parameters are the most important, with P1 and P2 referring to fundamental geometric properties (height to length ratio; slenderness ratio) and P5 and P6 to masonry quality (stone type; masonry fabric; conservation state).

The analysis of these four parameters provides a clear picture of the geometric and mechanical properties of typical masonry buildings in the historic city centre of Coimbra. The majority of these buildings are characterised by very high *H*/*B* ratios (*H* – wall height; *B* – wall length), as presented in Table 2. This feature is a consequence of the high medieval urban building density and diachronic construction process.

Table 2 also presents the mean values of *H* and *B* for the facade walls studied, as well as the mean ratio (*H/B*) value and so-called "optimal ratio", which corresponds to vulnerability class A for parameter P1.

Table 3 presents the mean values of wall thickness, *s*, and *H/s* ratio. As is apparent, the latter is much higher than the "optimal ratio", which corresponds to a vulnerability class A for parameter P1.

Table 2 Vulnerability index assessment parameters and weights

| Mean height, *H* (m) | Mean width, *B* (m) | Mean *H/B* ratio | Optimal *H/B* ratio |
|---|---|---|---|
| 10.88 | 7.41 | 1.47 | < 0.40 |

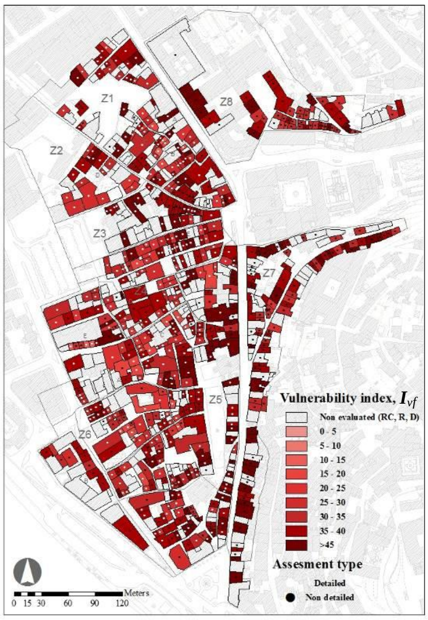
Table 3 Facade walls: thickness

| Mean wall thickness, *s* (m) | Mean *H/s* ratio | Optimal *H/s* ratio |
|---|---|---|
| 0.61 | 17.85 | ≤ 9.00 |

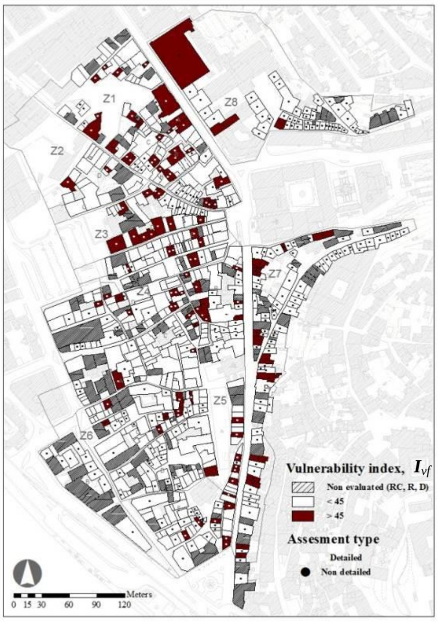
### 2.3 Integration into a GIS tool

A database gathering all facade information together with the results of the vulnerability index assessment was created. The GIS tool (Geographical Information System) developed allows the comparison of different assessment results with building feature data, i.e., the seismic vulnerability index with building facade characteristics. Two types of spatial view are possible: a global view of the whole study area and a local view of each subzone.

Within the GIS platform, specific commands were programmed to allow easy access to all information, as well as the implementation of damage and loss estimation algorithms (mathematical and probability functions). Fig. 5(a) presents the seismic vulnerability index distribution for all the facade walls evaluated. Through the overall analysis of Fig. 5(b), 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.




(a)




(b)

Fig. 5 Vulnerability map of building facades: (a) Global vulnerability index distribution; (b) Identification of buildings with $I_{vf}$ > 45


Fig. 6 Vulnerability class distribution for parameters P1, P2, P5 and P6

As stated in Section 2.2, the vulnerability index of individual wall facades is highly influenced by parameters P1, P2, P5 and P6. Fig. 6 shows the vulnerability class distribution for each of these four parameters.

From Fig. 6, it can be observed that the majority of buildings are within vulnerability classes B to D in terms of masonry quality (parameter P5). Regarding conservation state (parameter P6), zones Z1, Z2 and Z3 demonstrate slightly higher vulnerability class levels.

## 3. Damage estimation and seismic scenarios

### 3.1 Development of the vulnerability function

Having applied the vulnerability index method to the entire building stock of the historic city centre of Coimbra, it was then possible to estimate expected damage for different levels of seismic intensity. However, while vulnerability curves, which enable a correlation to be made between the severity of a seismic event (European Macroseismic Intensity Scale, $I_{EMS\text{-}98}$) and a mean damage grade, $\mu_D$ have been applied to buildings (Vicente 2008, Giovinazzi and Lagomarsino 2006, Vicente *et al*. 2011), they have not yet been developed and calibrated for masonry facade walls.

Based on building information and damage reported in the post-event assessment of the 2009 Earthquake that hit the city of L'Aquila in the Abruzzo region of Italy, the methodology proposed and developed in this paper was tested and calibrated through application to a group of representative old masonry buildings. The cases were selected on the bases of two criteria: i) access to detailed information to apply mechanical methods; ii) representativeness of the buildings in terms of typical masonry construction technology of the Abruzzo's region. Via this analysis it was possible to derive correlations between vulnerability index, $I_{vf}$; macroseismic intensity maps (according to EEFIT 2009, Tertulliani *et al*. 2011, D'Ayala and Dolce 2011) and observed damage. Representative buildings affected by the earthquake 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 L'Aquila and Paganica, with an intensity of VIII and a final six buildings, located in Poggio di Roio and Monticchio, where the registered intensity was approximately VII.

The mean seismic vulnerability index value of the facade walls of these buildings, $I_{vf,\,mean}$, was 28.6. Following the vulnerability index assessment, a mean damage grade, $\mu_D$, ranging between 1 and 5 was estimated for each facade wall (according to EMS-98). However before this application, taking into account that the EMS-98 scale of damage description was developed initially for buildings, it was necessary to readjust these descriptions and adapt them for use with facade walls. Table 4 presents the damage grade classification and equivalent damage descriptions adopted in the analysis of masonry facade walls.

Through associating the mean damage vulnerability index of each group of facades in Coimbra ($I_{vf}$=28.6) with the different damage grades for each of the three seismic intensities (VII, VIII and IX), it was possible to obtain a first approximation of the vulnerability curve which correlates macroseismic intensity, $I_{EMS\text{-}98}$, with mean damage grade, $\mu_D$. Fig. 7 presents this approximation, obtained through an adjusted third degree polynomial curve.

The three values of mean damage grade were calculated as the mean facade wall vulnerability index values at seismic event intensities VII, VIII and IX, while the remaining two values correspondence to mean damage grades 0 (no damage) and 5 (total collapse) and provide a start and end point for the function.

The obtained facade wall curve visibly resembles previous vulnerability curves developed for masonry buildings based on earlier macroseismic methods (Lantada *et al*. 2008, Giovinazzi 2005)

Table 4 Damage grades adopted for masonry facade walls (adapted from Grünthal 1998)

| | Damage grade | Description |
|---|---|---|
|  | Grade 1: No damage | No damage or presence of very localised and hairline cracking |
|  | Grade 2: Moderate damage | Cracking around door and window openings; localised detachment of wall coverings (plaster, 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; generalised plaster detachment |
|  | 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 |

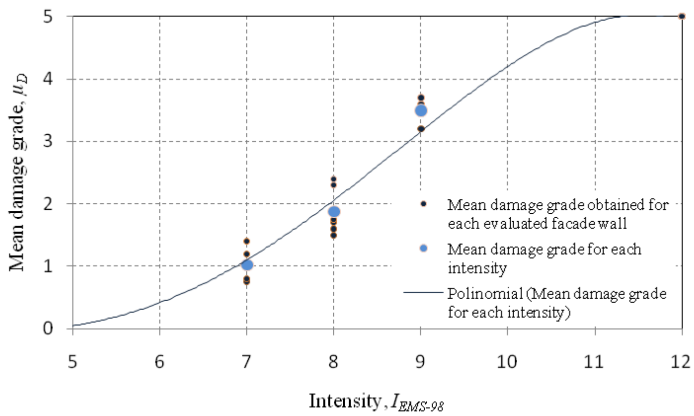



Fig. 7 Best-fit curve for mean damage grade

and used by Vicente (2008) and Ferreira *et al*. (2013). As shown in Eq. (2), these vulnerability curves are based on the correlation between seismic intensity and mean damage grade value ($0 \leq \mu_D \leq 5$) of a damage distribution (discrete beta distribution) conditioned to the vulnerability index value

$$\mu_D = 2.5 \times \left[1 + tanh\left(\frac{I + 6.25 \times V - 13.1}{Q}\right)\right]; \;\; 0 \leq \mu_D \leq 5 \qquad (2)$$

where $I$ is the seismic intensity described in terms of macroseismic intensity, $V$ is the vulnerability index (ranging from 0 to 1) and $Q$ is a ductility factor which expresses the ductility of a determined construction typology (ranging from 1 to 4). The value of $V$ defines the position of the vulnerability function, while the ductility coefficient ($Q$) defines its slope, that is, the increase in damage with seismic intensity. The relationship between the original vulnerability index defined in this study, $I_{vf}$, and this vulnerability index, $V$, can be established using the method of Vicente (2008), which is given by

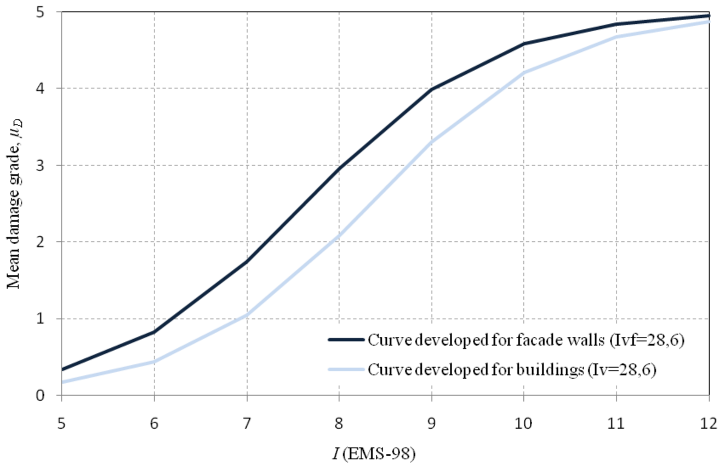



Fig. 8 Confrontation of vulnerability curves for buildings and facade walls ($I_{vf}$=28.6)

$$V = 0.592 + 0.0057 \times I_{vf} \tag{3}$$

Adjusting the curve presented in Fig. 7 with the analytical function given by Eq. (2), it is then possible to obtain a new semi-empirical expression estimating the mean damage grade for facade walls. Eq. (4) was produced after several adjustments and calibrations, based on observed intensity/damage to facade walls affected by the Abruzzo earthquake

$$\mu_D = 2.51 + 2.5 \times tanh\left(\frac{I + 5.25 \times V - 11.6}{Q}\right); \;\; 0 \le \mu_D \le 5 \tag{4}$$

The ductility factor, $Q$, assumed for this study is equal to 2.0. This value was considered to lead to the best approximation between mean damage grade values, $\mu_D$, obtained through the vulnerability function, and the post-seismic damage evaluation. Eq. (3), which relates $I_{vf}$ and $V$, continues to be valid.

Fig. 8 presents a confrontation between the two vulnerability curves, developed for buildings and facade walls respectively, given a mean vulnerability index value of 28.6. From the analysis of the two vulnerability curves presented in Fig. 8 it is possible to observe that for the same seismic intensity level, the facade walls present higher mean damage grades than buildings, a result that has been corroborated by recent seismic events wherein, for similar seismic intensities, the level of damage associated to the seismic response of facade walls is typically more severe than that associated to the buildings as a whole. This fact was already reported in the literature by several authors (see for example De Felice and Giannini 2001, Menon and Magenes 2008).

Fig. 9 shows the seismic vulnerability curve (in the $I_{EMS\text{-}98}$ versus $\mu_D$ format), obtained via Eq. (4), of the estimated mean vulnerability index for all 672 assessed masonry facades of the traditional buildings of the historic city centre of Coimbra ($I_{vf,mean}$=37.08). The figure also shows upper and lower bound ranges ($I_{vf,mean} - 2\,\sigma_{Ivf}$; $I_{vf,mean} - \sigma_{Ivf}$; $I_{vf,mean}$; $I_{vf,mean} + \sigma_{Ivf}$; $I_{vf,mean} + 2\,\sigma_{Ivf}$) curves for the $I_{vf,mean}$ +/- one and two standard deviations obtained for the 672 assessed masonry facade walls (standard deviation, $\sigma_{Ivf}$=8.68).

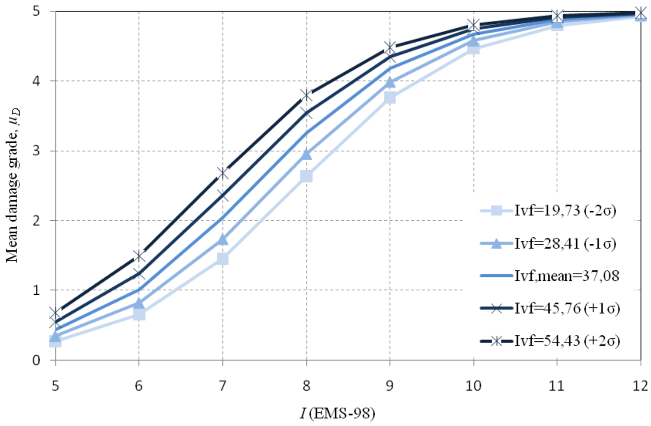



Fig. 9 Vulnerability curves for the facade walls of the historic city centre of Coimbra

### *3.2 Damage scenarios*

Using GIS, loss scenarios can be developed and evaluated for each building facade in the study area. Fig. 10 presents damage scenarios calculated for events of seismic intensity VII and VIII, which correspond to the strongest earthquake recorded in the district of Coimbra (in 1755). Building facade damage estimates range from 1.21 to 3.03 for an earthquake scenario where $I_{EMS\text{-}98}$=VII, and from 2.32 to 4.04 for $I_{EMS\text{-}98}$=VIII. The mapping of mean damage grade, $\mu_D$, with a GIS tool facilitates risk analysis by identifying areas of higher seismic vulnerability and

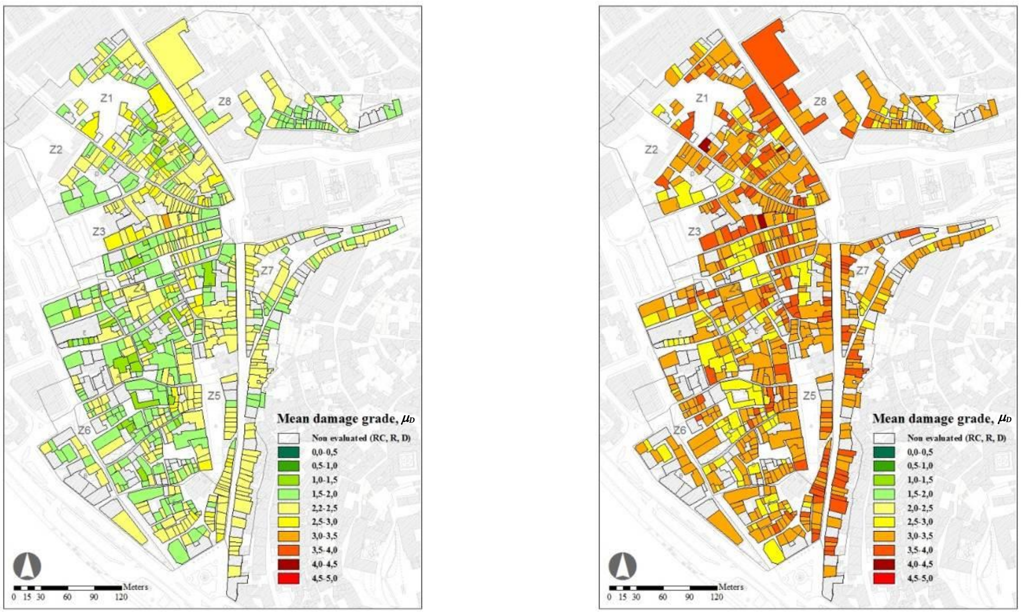



Fig. 10 Building facade damage distribution for $I_{EMS\text{-}98}$=VII and $I_{EMS\text{-}98}$=VIII

consequently those where risk of damage is greater. In addition, also enables the planning of post-event strategies, such as emergency rescue and other safety issues (see Ferreira 2010).

Analysing Fig. 10, it is apparent that for a seismic event scenario of intensity VIII, the majority of assessed masonry facade walls have a mean damage grade, $\mu_D$, of about 3. This indicates that in this scenario the majority of building facades would suffer severe damage ($3 \leq \mu_D < 4$), with a significant number in danger of imminent collapse (Blong 2003).

## 4. Civil protection and emergency management

In many countries, civil protection bodies are the agencies responsible for acting after a seismic event. As part of their commitment to protect and serve the affected population, the planning of rescue operations is critical, including transportation of the injured, dealing with the homeless, the provision of basic services and post-event management. The agents involved in planning should be able to define zones most prone to different hazards and prepare logistic and field exercises to simulate situations that may arise in a real earthquake situation (Goula *et al*. 2006).

Using the damage scenarios developed from the estimation of mean damage grades, $\mu_D$, for the street faced masonry wall facades, it is possible to identify the zones most vulnerable to events of different seismic intensity, according to $I_{EMS\text{-}98}$, in particular identifying which buildings may become inaccessible and which streets may or may not constitute suitable evacuation routes. This tool can play an important role in the development of initial intervention and rescue plans, promoting better articulation between corporations (civil protection, medical, etc.), a crucial ability given that recent seismic events have proved that out-of-plane collapse of facades can compromise access routes for civil protection forces and for the rescue and evacuation of the injured.

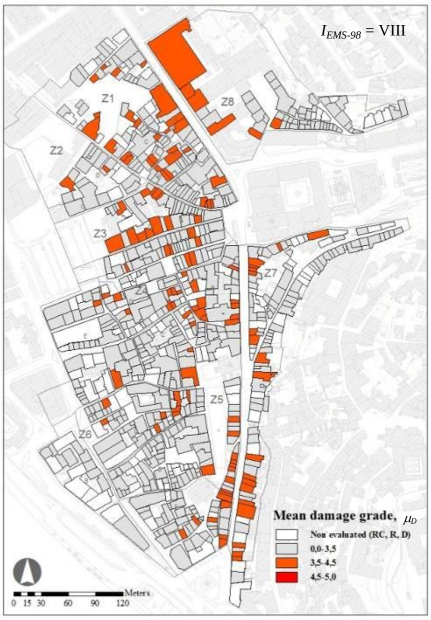



Fig. 11 Facade walls with a mean damage grade equal to or greater than 3.5, for $I_{EMS\text{-}98}$=VIII

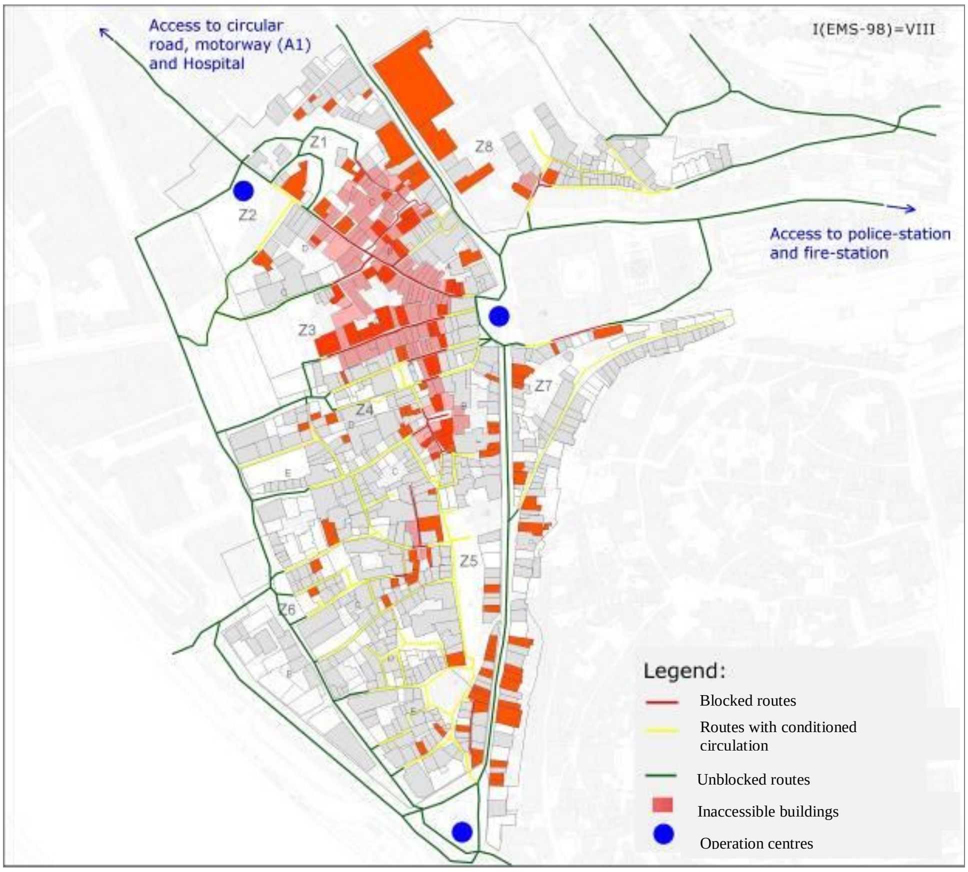



Fig. 12 Proposed evacuation routes for the historic city centre of Coimbra

Fig. 11 identifies facades that, in response to an intensity VIII event, have a mean damage grade equal to or greater than 3.5. Although this level of damage does not normally lead to total collapse, in some situations partial collapse may occur. In these cases, the fall of wall panels between openings, the disaggregation of the outer surfaces of walls and other non-structural elements (balconies, parapets, chimneys, cornices, ornaments, etc.) may obstruct, totally or partially, routes adjacent to the building facade and prevent the free circulation of rescue teams.

By establishing a set of criteria to determine if a street, alley or avenue can be considered as a possible access and evacuation route to a strategically located operation centre, it is possible to create maps containing information essential for planning and management after an earthquake.

In this case study, routes passing at least one facade with damage equal to or greater than 3.5 and that do not posses alternative access, are considered to be obstructed, both upstream and downstream (obstructed routes are indicated in Fig. 12). Fig. 12 also illustrates the location of inaccessible buildings, which are those that may become isolated due to their being exclusively served by routes considered obstructed. Although the remaining routes were considered as being not obstructed in this first iteration, there remains the need to differentiate and separate them into two categories. The first category contains the unblocked routes that, complying with a minimum pre-established width, were able to guarantee the passage of rescue vehicles (ambulances and fire

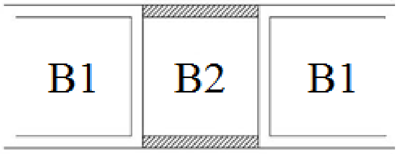



Fig. 13 Diachronic construction process of buildings located in historic city centres (Guiffrè 2003)

trucks). The minimum width recommended and used in this study is 4 m. The second category includes all the remaining routes, for which only pedestrian access is guaranteed and thus circulation is conditional.

Fig. 12 includes a possible layout of all alternative evacuation routes and operation centres for the historic city centre of Coimbra, based on the damage scenario presented in Fig. 11, for an $I_{EMS\text{-}98}$=VIII.

Finally, it is important to mention that the operation centres were strategically located according to accessibility, since they are the principal penetration points into potentially affected areas. Open areas were sought that were served by unblocked roads and with privileged access to the main network of vital buildings (hospitals, fire department, police stations, etc.).

## 5. Implementation and application of a mechanical model

### *5.1 Identification of the conditioning collapse mechanism*

As a result of the set of damage mechanisms that can develop during an earthquake, the out-of-plane movement of masonry facade walls is very common, but depends particularly on the efficiency of the connection between the facade itself and orthogonal walls (Shi *et al*. 2008, Speranza 2003).

A lack of connection between these walls is a typical problem in old masonry buildings in historic city centres, with their diachronic process of construction resulting in characteristic heterogeneity of masonry and wall connection quality. For this reason, simultaneously-built adjacent buildings normally present well-constructed wall connections at their corners, whereas the connection between the facade walls of a newer building and those of the existing adjacent buildings may not possess effective interlocking (see example in Fig. 13, Building B2).

Observations of post-seismic damage suffered by masonry facade walls have proven that the degree of connection between the facade walls and mid- or end walls considerably influences cracking patterns and associated collapse mechanisms (EEFIT 2009). In those cases where that connection is weak or nonexistent, facades tend to suffer a global rotation about a horizontal axis at their bases, without any contribution from the shear resistance of the orthogonal lateral walls (see Type A mechanism, Fig. 14). When there is an effective connection between the facade wall and the lateral walls, the impact of shear resistance may influence the subsequent collapse process (see Type B mechanism, Fig. 14). Both collapse mechanisms result in a different damage pattern. The first is characterised by the opening of a bottom-to-top vertical crack in the connection between the facade and the lateral walls, with a larger opening at upper floor levels. The second is characterised by diagonal cracks running through the lateral walls due to the contribution of shear resistance.

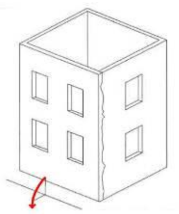


Fig. 14 Type A mechanism: facade overturning

The Type A mechanism is most relevant attending to the diachronic construction process, building degradation level and masonry heterogeneity, and as a result was assumed during the formulation of the mechanical model in this study.

### *5.2 Formulation of Type A mechanism*

As previously discussed, this mechanism refers to the global rotation of the facade wall, relative to a hinge located at its base. This mechanism develops when a weak or non-existent connection between orthogonal walls exists, which is highly influenced by the dimension of the stone elements at wall intersections and corners.

Although less common, this type of mechanism can also affect only part of the facade, i.e. when the rotation axis is not located at the wall base but, for example, at an upper floor level. In its general form, its analytic formulation can be applied to any of the *N* floors of a masonry building, with the horizontal rotation axis located at the base of each floor.

According to Speranza (2003), for Type *A* mechanism, used in this work to pre-calibrate the developed methodology, the sum of the moments regarding all storeys above level *j*, in relation to a given hinge *j*, is given by

$$\sum_{i=1}^{j} M_{i,j} = \sum_{i=1}^{j} (W_j \times \Delta x_{i,j}) - \sum_{i=1}^{j} \left(\lambda \times W_i \times \Delta y_{i,j}\right) \tag{5}$$

The seismic factor, $\lambda$, for a mechanism of Type A relative to a generic hinge *j* (where $1 \leq j \leq N$) placed along the height *H* of the building, considering effective the corner edge connections, is given by

$$\lambda_{(0),j} = \frac{\sum_{i=1}^{j} (W_i \times \Delta x_{i,j}) + (\varepsilon + \beta) \times \left(C_{tot-j} \times \frac{h_j}{3}\right)}{\sum_{i=1}^{j} \left(W_i \times \Delta y_{i,j}\right)} \tag{6}$$

where:

- $\varepsilon$ is the number of edge party walls considered orthogonal to the facade in analysis;
- $\beta$ is the number of orthogonal internal load-bearing walls effectively connected to the facade;
- $C_{tot}$ is the total shear strength along a vertical crack of height $H_j$ applied at 1/3 of the height $H_j$. This formulation is applied to all ($\varepsilon$+$\beta$) orthogonal walls considered, characterised by sufficient connections with the front wall.

Table 5 Mean values of parameters P4, P5, P6, P8, P9 and P10

| Parameter | P4 | P5 | P6 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|
| Mean value | 18.10 | 17.59 | 10.81 | 18.29 | 16.24 | 19.77 |

For further information about the mechanical framework above, please see Speranza (2003) and D'Ayala and Speranza (2003).

## 6. Application of the mechanical model to the analysis of facade walls

In this Section, some of the facades previously assessed via the vulnerability index method presented in Section 1, are here analysed with the mechanical model. The results obtained using the two methodologies are then compared.

Eleven facades were selected for this analysis in accordance with their mean geometric properties. Although Type A is the most representative collapse mechanism for facades evaluated using the mechanical method, it does not incorporate some of the parameters evaluated directly by the vulnerability index methodology, such as the misalignment of wall openings (P4) and the presence of non-structural elements connected to the facade (P10). Therefore, the selection criteria for facades to be analysed using the mechanical model were conditioned by the proximity between the obtained value for each of these parameters and the mean value of each parameter from the entire set of assessed facades. Table 5 presents the mean value obtained for each of the aforementioned parameters, of the 330 facades evaluated in detail using the vulnerability index method.

The formulation of collapse mechanism Type *A* is only sensitive to those facade characteristics that directly influence weight and the degree of connection to orthogonal walls. Therefore, the calculated values of $I_{vf}$ for parameters P1, P2 and P3 were disregarded. The key to this evaluation and for the comparison of results using the two methods relies on the fact that the degree of connection between the facade and orthogonal walls was considered. Although this connection is characteristically very weak in terms of the evaluated facades, it was still considered in the determination of collapse factors, since if ignored or underestimated can lead to errors in vulnerability evaluation.

From analysis of Eq. (6), it is clear that load factor, $\lambda_{(0),j}$, is directly influenced by the total shear force, $C_{tot}$. The facades of the old masonry buildings of Coimbra are typically composed of very irregular limestone units of different dimensions and were constructed with poor workmanship. Thus for this type of masonry, it is not always possible to precisely determine either the dimensions of the units, or the number of layers in a wall. Therefore for this analysis, reasonable values were assumed for parameters $h_i$, $s$ and $b$, concentrating all the uncertainties associated with the total shear force ($C_{tot}$) calculations in the friction coefficient, $f$.

Several authors have presented different proposals regarding this friction coefficient in masonry walls. In the analysis based on a mechanical model carried out by Speranza (2003) of the historic centre of Nocera Umbra in Italy, values of 0.45 for good masonry fabric and arrangement and 0.3 for medium quality masonry were adopted. This range of values was estimated as part of a function dealing with the roughness and regularity of the masonry blocks, using the values obtained experimentally by Ceradini (1992) as a reference. The typical limestone masonry of the old buildings in Coimbra city centre has a more irregular morphology, as well as being more

Table 6 Limits for the comparative analysis of results obtained with both methodologies

| Wall thickness, *s* (m) | $I_{vf}$ | $\lambda$ |
|---|---|---|
| 0.30 | 62 | 0.05 |
| 0.75 | 43 | 0.14 |

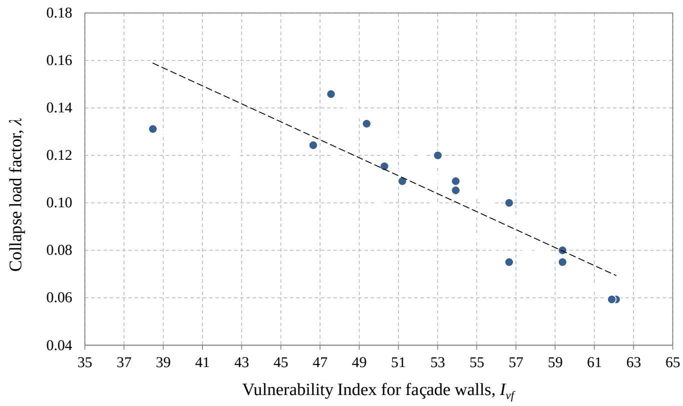



Fig. 15 Confrontation of the results of the vulnerability index and mechanical model methods

variable in terms of quality, in comparison with that in Speranza's study (thick mortar layers between the stone units). Therefore for this work, all these uncertainties led to the adoption of a more conservative value for the friction coefficient, *f*, i.e., 0.2.

## 7. Confrontation of methodologies: vulnerability index versus mechanical model

The plausibility limits for the comparison of the methods were defined as a function of wall slenderness (parameter P2), which in turn depends on the wall dimensions: *H* (height), *B* (width) and thickness, *s*, and its connection to orthogonal walls (parameter P7). For the vulnerability index method limit values, $I_{vf}$, two limit values of the slenderness ratio were considered, associated with vulnerability classes *A* and *D* of parameter P2 and P7 and for the remaining parameters, mean values were used.

Applying the mechanical model in the analysis of the same facades, a maximum and minimum value of the collapse load factor, $\lambda$, were used as the upper and lower limits. Table 6 presents the values of the two limits in terms of $\lambda$ and $I_{vf}$.

The confrontation between methodologies shown in Fig. 15 reveals that both produce reasonable correlated results, obtaining a correlation value of 0.79, which suggests that some of the attributed weights to the parameters of the vulnerability index method could be slightly readjusted.

## 8. Conclusions

### *8.1 Evaluation of the vulnerability index method of facade assessment*

The vulnerability assessment method developed for masonry facade walls has proven to be adequate in the analysis of old buildings. The implementation of this index on a macroseismic basis has enabled the calculation of vulnerability and damage scenarios that contribute to risk mitigation and management. The proposed vulnerability assessment method and risk scenario mapping can be easily adapted to other specific building features and adopted in other regions or historic city centres.

The data analysis from the vulnerability index method for masonry facade walls allowed the identification of the parameters that control the seismic vulnerability of the building facades, by quantifying each parameter within the assessment methodology, $I_{vf}$.

The integration of results within a GIS tool is a fundamental part of vulnerability assessment at an urban scale and is crucial in terms of both initial analysis and management. The possibility for spatial presentation of results makes GIS an effective tool in support of mitigation strategies and management of seismic risk.

The information obtained through post-seismic event damage observation after the recent Abruzzo earthquake, allowed a vulnerability function to be developed and calibrated for application to the facade walls of masonry buildings. The results obtained through this vulnerability function have allowed the construction of damage scenarios for different earthquake intensities, as well as the subsequent development of proposed evacuation routes to support emergency planning and the identification of the most vulnerable building facades. Emergency planning for historic city centres has revealed itself to be extremely dependent on results obtained through the application of the vulnerability index, since the defined evacuation routes are limited by facade collapse.

### 8.2 Confrontation of methodologies

The mechanical model constitutes an alternative to the vulnerability index method, which is more appropriate for large-scale analyses, such as city centres. Although the mechanical model involves some simplifications, its ability to interpret structural performance in response to specific seismic action can be a valuable tool in studies undertaken at different analytical scales.

Confrontation of the two methodologies has shown good correlation for the majority of facades assessed. However, this preliminary result should be analysed carefully, since both methodologies are affected by several uncertainties, such as the evaluation of parameter vulnerability classes, or the definition of the friction coefficient, $f$.

### 8.3 Final comments

A rigorous vulnerability assessment of existing buildings, particularly of their facades, and the subsequent implementation of appropriate retrofitting solutions may reduce both physical damage and economic losses in future seismic events. The tool presented here can be used for the analysis of the efficiency of retrofitting solutions for individual facade walls and as a result can assist in the selection of the most appropriate retrofitting strategy for a specific city or region, considering all economic and technical restrictions (Vicente *et al*. 2011).

As a final comment, it is emphasised that these macroseismicity-based studies may play an important role in the vulnerability assessment of the built environment in seismically-active regions, helping to prevent the loss of architectural and cultural heritage. It is important to develop these tools in collaboration with decision makers, to create specific legislation/recommendations for the safeguarding of architectural and cultural heritage, to develop orientation guidelines for interventions and to define rules, criteria and basic safety levels for their application in old masonry buildings.

## References


ArcGis 9.3 (2008), Geographic Information Systems, 310 New York Street, Redlands, 92373-8100, USA, ESRI® .

Barbat, A., Lagomarsino, S. and Pujades, L. (2006), *Assessing and Managing Earthquake Risk*, Chapter Title - Vulnerability Assessment of Dwelling Buildings.

Blong, R. (2003), “A review of damage intensity scales”, *Natural Hazards*, **29**(1) 57-76.

Carreño, M., Cardona, O. and Barbat, A. (2007), “Urban seismic risk evaluation: a holistic approach”, In: *Natural Hazards*, **30**(1), 137-172.

D’Ayala, D. and Dolce, M. (2011), “L’Aquila earthquake: seismic sequence of 6th April 2009, Abruzzo, Italy”, *Bull. Earthq. Eng*., **9**(1), 1-10.

D'Ayala, D. and Speranza, E. (2003), “Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings”, *Earthq. Spectra*, **19**, 479-509.

De Felice, G. and Giannini, R. (2001), “Out-of-plane seismic resistance of masonry walls”, *J. Earthq. Eng*., **5**(2), 253-271.

Dolce, M., Kappos, A., Masi, A., Penelis, G. and Vona, M. (2006), “Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies”, *Eng. Struct*., **28**(3), 357-371.

EEFIT (2009), The L’Aquila, Italy earthquake of 6 April 2009 - A preliminary field report by EEFIT.

Ferreira, T. (2010), “Seismic vulnerability assessment of old urban centres - Case study of the old city centre of Seixal, Portugal”, Thesis of the post-graduate course in Rehabilitation of the Built Heritage, Faculty of Engineering of the University of Porto, Portugal. (in Portuguese)

Ferreira, T. (2009), “Vulnerability assessment of masonry facade walls”, MSc. Thesis, University of Aveiro, Portugal. (in Portuguese)

Ferreira, T.M., Vicente, R., Mendes da Silva, J.A.R., Varum, H. and Costa, A. (2013), “Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal”, *Bull. Earthq. Eng*., **1**(5), 1753-1773.

Giovinazzi, S. (2005), “The vulnerability assessment and the damage scenario in seismic risk analysis”, PhD Thesis of the doctoral course “Risk Management on the built environment” jointly organized by University of Florence and TU-Braunschweig.

Giovinazzi, S. and Lagomarsino, S. (2006), “Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings”, *Bull. Earthq. Eng*., **4**(4), 415-443.

Giuffrè, A. (2003), “Sicurezza e conservazione dei centri storici. Il caso di Ortigia”, Editori Laterza, Bari, Italy.

GNDT-SSN (1994), “Scheda di esposizione e vulnerabilità e di rilevamento danni di primo e secondo livello (murata e cemento armato)”, Gruppo Nazionale per la Difesa dai Terremoti, Roma.

Goula, X., Roca. A. and Oliveira, C.S. (2006), *Assessing and managing earthquake risk - Geo-Scientific and Engineering Knowledge for Earthquake Risk Mitigation: developments, tools, techniques*, Springer.

Grünthal, G. (1998), *European Macroseismic Scale 1998 (EMS-98)*, Cahiers du Centre Europèèn de Géodynamique et de Séismologie, Luxembourg.

Lantada, N., Irizarry, J., Barbat, A., Goula, X., Roca, A., Susagna, T. and Pujades, L. (2008) “Seismic hazard and risk scenarios for Barcelona, Spain, using the Risk-UE vulnerability index method”, *Bull. Earthq. Eng*., **8**(2), 201-229.

Mallardo, V., Malvezzi, R., Milani, E. and Milani, G. (2008), “Seismic vulnerability of historical masonry buildings: A case study in Ferrara”, *Eng. Struct*., **30**(8), 2223-2241.

Menon, A. and Magenes, G. (2008), "Out-of-Plane Seismic Response of Unreinforced Masonry: Definition of Seismic Input", IUSS Press, Research report / European School for Advanced Studies in Reduction of Seismic Risk.

Modellazione, C.V. (1992), "Sperimentazione per lo studio della strutura murari storica", PhD Thesis, University of Rome, Faculty of Architecture, Italy. (in Italian)

Neves, F., Costa, A., Vicente, R., Oliveira, C.S. and Varum, H. (2012) "Seismic vulnerability assessment and characterisation of the buildings on Faial Island, Azores", *Bull. Earthq. Eng*., **10**(1), 27-44.

Pagnini, L.C., Vicente, R., Lagomarsino, S. and Varum, H. (2011), "A mechanical model for the seismic vulnerability assessment of old masonry buildings", *Earthq. Struct*., **2**(1), 25-42.

Ramos, L.F. and Lourenço, P.B. (2004), "Modeling and vulnerability of historical city centers in seismic areas: a case study in Lisbon", *Eng. Struct*., **26**(9), 1295-1310.

Shi, Y., D'Ayala, D. and Prateek, J. (2008), "Analysis of out-of-plane damage behaviour of unreinforced masonry walls", *Proceedings of the 14th International Brick & Block Masonry Conference*, Sydney, February.

Speranza, E. (2003), "An integrated method for the assessment of the seismic vulnerability of historic buildings", PhD Thesis, University of Bath, UK.

Tertulliani, A., Arcoraci, L., Berardi, M., Bernardini, F., Camassi, R., Castellano, C., Del Mese, S., Ercolani, E., Graziani, L., Leschiutta, I., Rossi, A. and Vecchi, M. (2011), "An application of EMS98 in a medium-sized city: The case of L'Aquila (Central Italy) after the April 6, 2009 Mw 6.3 earthquake", *Bull. Earthq. Eng*., **9**(1), 67-80.

Vicente, R. (2008), "Strategies and methodologies for urban interventions", PhD. Thesis, University of Aveiro, Portugal. (in Portuguese)

Vicente, R., Parodi, S., Lagomarsino, S., Varum, H. and Mendes da Silva, J.A.R. (2011), "Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal", *Bull. Earthq. Eng*., **9**(4), 1067-1096.

Vicente, R., Rodrigues, H., Varum, H. and Mendes da Silva, J.A.R. (2011), "Evaluation of strengthening techniques of traditional masonry buildings: case study of a four-building aggregate", *J. Perform. Constr. Facil*., **25**(3), 202.