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Vulnerability Evaluation of the Old Building Stock in Historical Areas: The Case of the Old City Centre in Coimbra in Portugal

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ABSTRACT: The increasing concern and consequent appraisal on durability, conservation state and changeable use of old buildings in urban centres relies a great deal on the structural safety evaluation for vertical load bearing capacity, but principally for seismic actions. The need to catalogue buildings according to their seismic vulnerability, particularly old buildings is a key issue in any renewal of rehabilitation process. However, in most countries, little has been done to reduce the seismic vulnerability of buildings in the historical city centres. The occurrence of an earthquake of moderate/high intensity can result in the collapse and severe damages in buildings, and can have catastrophic social and economical implications. Simplified seismic capacity evaluation methods for old masonry buildings, constructed without earthquake-resistant concerns, can be a valuable tool in the seismic risk assessment. The criteria adopted in a seismic risk assessment of a group of buildings must give results that can guide strengthening intervention priorities.

1 INTRODUCTION AND SCOPE

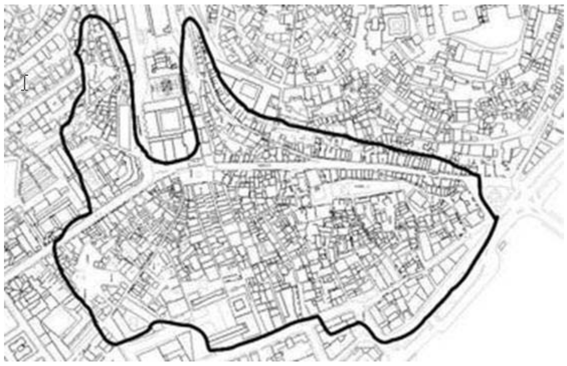
1.1 Vulnerability of old masonry buildings

Earthquake's impacts are always associated with the socio-economical costs, the human losses and the effects on the constructions that it causes. The losses in terms of cultural and architectural heritage are particularly unrecoverable. The seismic safety evaluation of historic buildings (such churches, monuments, towers, etc) has motivated the development of vulnerability assessment methods adapted to these types of constructions, and quickly extended to other constructions, such as common residential buildings (Giuffrè 1993).

Structural vulnerability analysis in old city centres urges to be taken to a higher stake in Portugal. Seismic risk evaluations based on building's vulnerability estimation (from the vulnerability index, per example) and local hazard can support planning measures, at an urban scale, helping in the earthquake risk mitigation. The results of s seismic vulnerability assessment can guide in the decision of the rehabilitation, strengthening or at the worst demolition of buildings. Simplified seismic capacity evaluation methods for old masonry buildings, constructed without earthquake-resistant concerns, can be a valuable tool in the seismic risk assessment. The criteria adopted in a seismic risk assessment of a group of buildings must give results that can guide strengthening intervention priorities. There are different methods of seismic vulnerability evaluation, with different levels of detail, which have been adopted in several vulnerability studies throughout the world.

In this paper, it is presented a proposed methodology for seismic vulnerability evaluation, based on observed and calculated vulnerability parameters (analysis of qualitative and quantitative indicators). The proposed method is an improvement of a methodology proposed and largely used by several Italian research groups. The method is especially adapted for typical masonry buildings (vertical masonry load-bearing walls), representing the majority of the basic structural typologies of buildings in the historical centres. With this method, a vulnerability index is estimated from the degree of quality of the appraised indicators. The vulnerability index obtained can be correlated with the local hazardousness and therefore allow to estimate damage, human losses and costs, in risk analysis scenarios. The method proposed was applied to over than 230 buildings in the old city centre of Coimbra (see Fig. 1) and the main results obtained are presented.

Aerial view



Project perimeter

Figure 1 : Old city centre of Coimbra

2 TRADITIONAL BU ILDING CHARACTERIZATION: MATERIALS AND ELEMENTS

2.1 Traditional masonry structures

The most vulgar stone is the so-called yellow-stone of Coimbra, designated by *dolomia*. A calcareous limestone with a strong percentage of clay in its composition, making it that is very heterogeneous in constitution, aspect and of difficult workability. The *dolomia* stone of local origin is extracted from quarries in the peripheral outskirts of the city, namely in Santa Clara region and also from the inside of the city in deactivated quarries. This stone was used essentially in the constitution of external load-bearing masonry walls and the smaller undressed rubble stone for interior wall filling of timber triangulated structures designated as *"taipa de rodízio"* or *"frontal"* walls (Vicente et al. 2005).

Other types of limestones, with higher rates of calcareous purity are also present in the old buildings but are more commonly used and observed framing elements of doors and window openings (side posts and lintels) an more presently in ornamental pieces and monuments (Santa Clara Monastery, Old Cathedral of Coimbra, etc.). This stone is of excellent workability but is also very vulnerable to dampness and water, revealing throughout the city disaggregation and superficial scaling problems.

From the structural point of view this material has revealed to be very fragile to the degradation due to the climatic agents (e.g rain water), and to the long-term moisture problems. The disaggregating is not only due to the masonry stone vulnerable to water, but also to the poor quality mortars.

The stone masonry is basically classified into two types according to the shape, size and stone laying technique:

- Masonry with irregular fabric, made of field and rubble stone of different formats and sizes, these hewn stones are arranged together in a irregular fashion and with lime and clay as main mortar binders mixed with river sand in mixture proportions of 1:2 and 2:3 respectively (see Fig. 2);
- Masonry with more regular faced stones with horizontal courses and a incohesive interior core. Smaller stones and clay waste material from the local ceramic industry fill in openings between the bigger stones. Poor lime mortars are used and in some cases red clay mortars, being relative to older buildings (see Fig. 2).

Figure 2 : Masonry with irregular fabric.

The inner and outer facings are not effectively connected and the interconnection between perpendicular walls and corner angles is in many cases is inexistent or inefficient.

Another type of common type of masonry used mainly for mid-walls between buildings is composed of a wooden triangulated structure referred earlier. This type of solution assumes a tridimensionality with the use of wood stud elements filled with irregular stone (see Fig. 3). However, this wood structure does not obey geometric regularity. These "*frontal"* walls with vertical, horizontal, diagonal crossbars have notoriously improved lateral loading resistance.

Figure 3 : Timber triangulated structure

2.2 Timber floor structures

In the area of Coimbra it is more frequent to observe the use of the pitch-pine, portuguese oak and chestnut. Also, in smaller expression the white poplar, eucalyptus and other types of pine (these first two are not adequate for construction being rarely seen). The use of imported wood was not common, except in cases of very large and noble buildings. However in other European countries the import of wood of North America and of the north of Europe it was common, as in the case of England.

These several types of wood are use in a widespread manner: pine, oak and chestnut used for structural elements of pavements and floor coverings. (The pine is the most common of the three, but has lower durability and performance); poplar and cone with several applications: built-in frames of the "*frontal*" walls, partitions, etc.

The wood structure floors are constituted of timber beams distanced on average, among 30 to 60 cm in which is placed a wood covering in the transverse direction. The distance of the timber framework reflects the better or worse quality of the building. The transverse section of the beams vary in function of the room span, but for average spaces (ranging about 3 to 3 to 3.5m) the dimensions are very dispersed, they range among 10 to 20cm for the width and from 12 to 25cm for the height (see Fig. 4). Besides this variability in the measured dimensions, they are not always squared, in some cases are circular or irregular, evidencing no such treatment.

The connection of floor beams, in the majority of the buildings, simply consists of the fitting of the wood framework into masonry openings with the dimensions of the timber beams. In other cases was seen the existence of an element of load distribution, horizontal beams and vertical wood studs embedded in the wall, avoid the stress concentration of the masonry. Most rare are cases in which the effectiveness of the floor diaphragm and wall connection is guaranteed, with resource to metallic elements and steel tendons crossing walls.

The decay of these hidden timber beams and elements have lead to bulging and fracture of the walls. The Later alterations have disrespected the original structural, cutting and removing of structural members of wall timber framed elements and floor beams.

2.3 Timber roof structure

The configuration of the narrow buildings in the building aggregate is constituted by two sloped pitched roofs. The most observed structural solution (without going into the complex trusses) are constituted by simple ridge beam, rafters and angled purlins without constituting a triangulated structure and the simple timber trusses (with different geometry ands bracing) as shown in Fig. 4. The connections are normally nailed and scarf jointed together, but iron tie elements were observed in larger spanned roof trusses.

The major problem that has lead to a great number of roof failures is through the decay of the timbers resulting from failure and floor covering. Other problems such as poor-quality timber, buckled and bent struts contribute to the continuous degradation. Outward thrusts on walls from movement of deteriorated and sagged trusses or rafters are particularly wall weakening.

Figure 4 : Timber floor and roof structures

3 VULNERABILITY ASSESSMENT

3.1 New methodology and approach

The methodology used to evaluate the vulnerability of the historical city centre of Coimbra, is considered an indirect method, chosen normally for urban scale analysis, due to the number of buildings to classify. The formulation proposed by GNDT (GNDT, 1994) and Petrini (Petrini et al., 1984) group in Italy for the vulnerability assessment of residential masonry buildings, used over 20 years was adapted and improved particularly for the Portuguese masonry buildings and extensively applied in the case study of Coimbra (Vicente et al., 2005a). All information used in the vulnerability assessment was preceded by the appraisal, diagnosis and inspection actions, gathering information on the buildings by fieldwork using a detailed check-list, through an extensive survey of all building stock of the old city centre (CNR, 1999), (Yépez, 1993).

The method is based on the calculation of a vulnerability index as the weighed sum of 13 parameters. These parameters are related to 4 classes of growing vulnerability: A, B, C and D. Each parameter evaluates an aspect influencing the building response and is chosen the vulnerability class associated to it. A weight 'p' is assigned to each vulnerability parameter, ranging from 0.25 for the less important parameters in terms of vulnerability up to 1.5 for the most important ones (e.g. conventional strength) as shown in figure 4. This weight that is attributed to each one of the 13 parameters is function of its influences on the global seismic vulnerability of the structure. The vulnerability index ranges between 0 and 575, but the values obtained by the weighted sum can be divided by 5.75 to obtain a normalized value with the range of variation $0 < I_v < 100$ and it is defined as the vulnerability index or score. The vulnerability index calculated can be used to estimate the building damage under a specified seismic action, as will be shown further on. In table 1 are shown the 13 parameters used in the formulation of the seismic vulnerability index.

Table 1 : Parameters of the vulnerability index (Iv)

	PARAMETERS	Class C_{vi}				Weight	VULNERABILITY INDEX
		A	B	C	D	Pi	
1	Type of resisting system	0	5	20	50	1.00	
2	Quality of the resisting system	0	5	20	50	1.00	
3	Conventional strength	0	5	20	50	1.50	
4	Maximum distance between walls	0	5	20	50	0.75	
5	Location and soil conditions	0	5	20	50	0.75	
6	Position and interaction	0	5	20	50	1.50	$I_v = \sum_{i=1}^{11} C_{vi} p_i$
7	Plan configuration	0	5	20	50	0.75	
8	Regularity in height	0	5	20	50	0.75	
9	Wall openings and alignments	0	5	20	50	0.50	
10	Horizontal diaphragms	0	5	20	50	1.00	$0 \leq I_v \leq 575$
11	Roof system	0	5	20	50	1.00	
12	Fragility and conservation state	0	5	20	50	0.75	Normalized index
13	Non-structural elements	0	5	20	50	0.25	$0 \leq I_v \leq 100$

From the vulnerability analysis the carried evidence a average vulnerability index of 48.09 (see Fig. 5). Around 83% of the building stock has a vulnerability index over 40 and 44% over 50 (see figure 4b). This first level evaluation, even though limited is fundamental not only for the 13 parameter evaluation (masonry quality, state of conservation, structural irregularities, building interaction, etc.) but also for the identification of more critical and vulnerable buildings and that are picked out for a more detailed analysis in terms of seismic behaviour. Only 15% of the buildings have an I_v below 40, which figures as the lower limit for vulnerability allowed.

The vulnerability was mapped using GIS software (ArcGis, 2005) connected with a relational data base on structural building characteristics that governs the structural behaviour of historic buildings, with particular focus on their seismic vulnerability. Several aspects characterizing any urban area, which are at present stored and managed, require the use of GIS in order to achieve an organic view of the inter-connected problems concerning the given area. GIS tools are used to provide good global overview of building quality, current conservation status, risk scenarios and potential damage mapping for different seismic intensities.

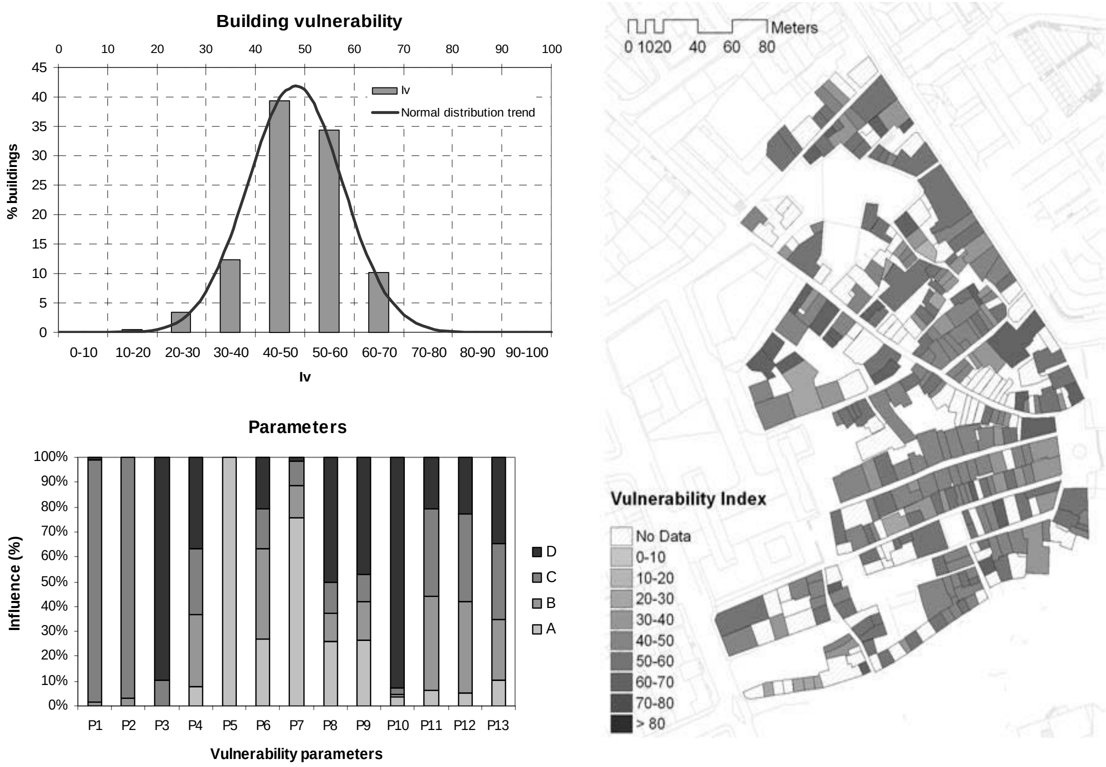
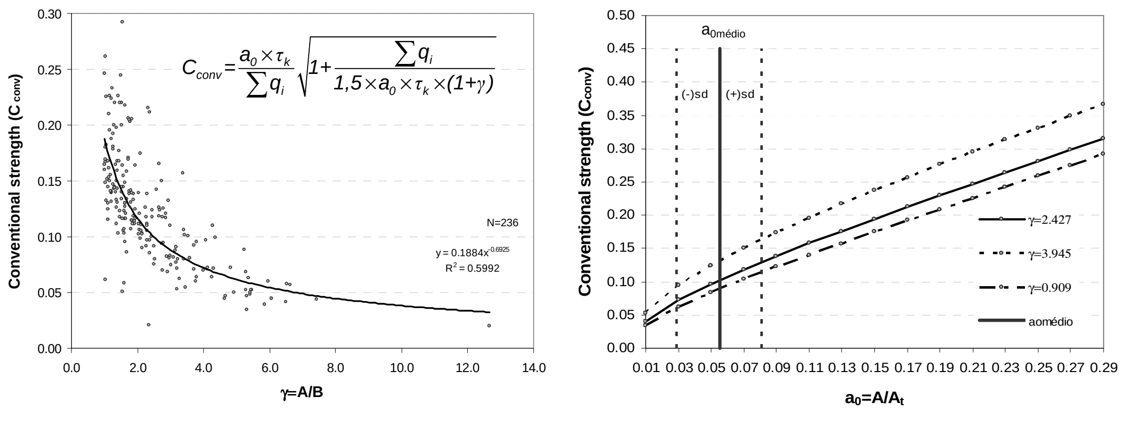


Figure 5 : Vulnerability results

3.2 Case study results

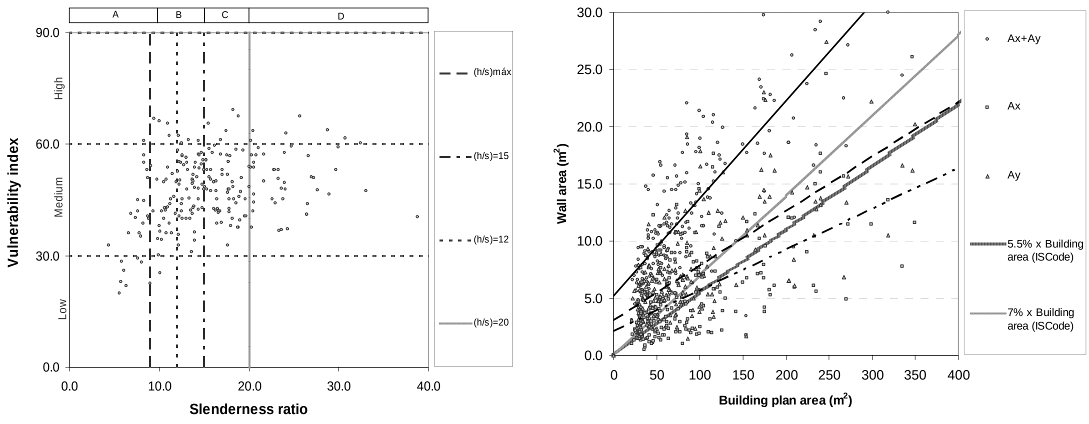
Fig. 6a, shows the relationship between the conventional strength of the vertical load bearing structure, which is a measure of the masonry shear strength and the ratio of maximum/minimum walls area. It is verified that the conventional strength grows when the ratio A_{max}/A_{min} revealing better behaviour and consequently lower vulnerability index for buildings with similar resistance in both directions. In Fig. 6b, can be seen the conventional strength growth with the mean values of parameters γ and a_0 for the masonry buildings of the old city centre analysed. For the masonry shear strength, τ_k, and vertical loading, q_i, characteristic values of 40 kPa and 50 kN/m^2



(a) (b)

Figure 6 : Conventional strength relationships

The analyses of the wall façade slenderness of the building stock shows that the overturning mechanism (total or partial) of the majority of unrestrained walls is associated to high vulnerability levels (see Fig 7a). It is also observed that the EC8 (EC8, 2003) recommended slenderness ratio for shear walls of 9 and 15, respectively for unreinforced stone masonry units and other masonries in low seismicity zones is clearly exceeded. Fig. 7b, has revealed that the wall area in both directions is under the values indicated, for example, in the Italian seismic code (Italian Seismic Code, 1996) (5.5% of building area) for a project seismic action, by means of a peak ground acceleration of about 0.20g.



(a) (b)

Figure 7 : Slenderness and resisting wall area results

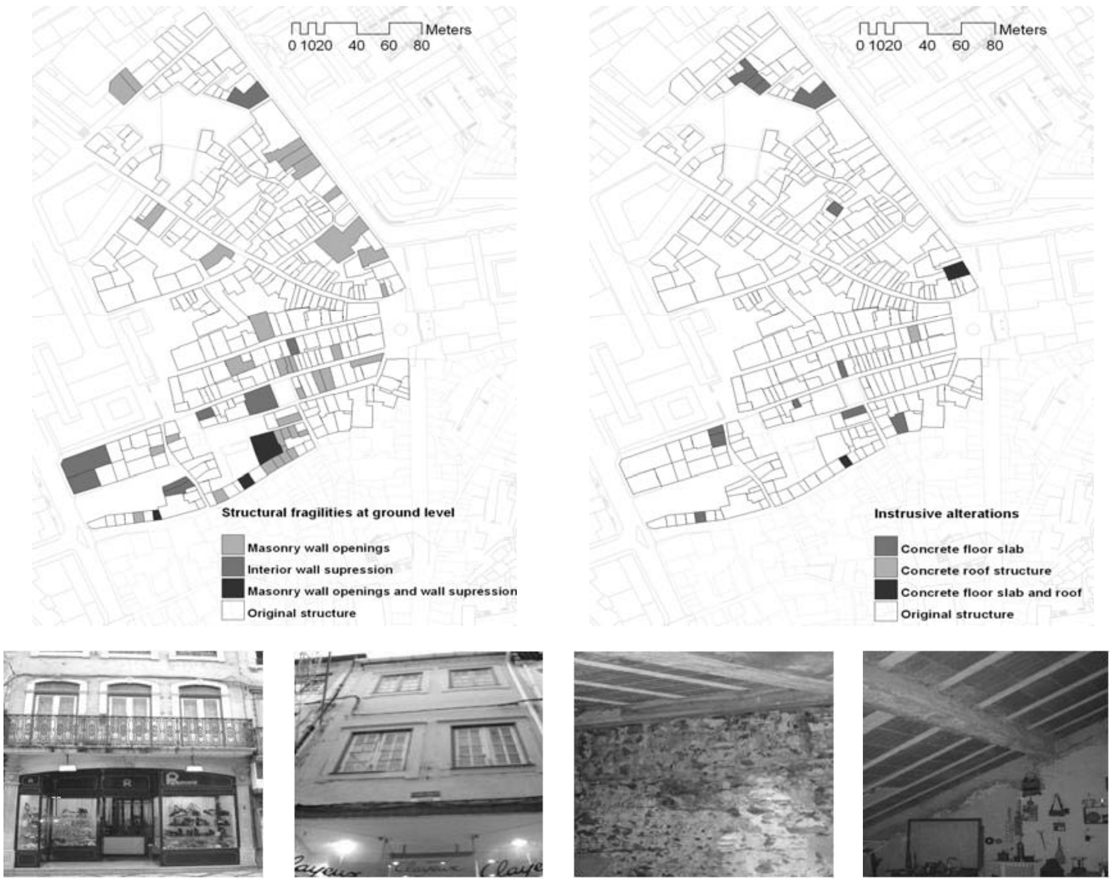


Figure 8 : Structural fragilities and intrusive techniques

The old building stock, over the years, has suffered many structural alterations required by functional adaptability of these building to new functions (see Fig. 8). The use of concrete increases its global mass, without contributing to the increase the global stiffness. Other actions, such as the cutting of masonry walls and demolition of interior partition walls also reduce global stiffness and weaken the seismic response of these building typologies.

4 CONCLUSIONS

Risk management of historical towns in many cases is undertaken without a general planning tool. A first consequence of this is that technicians and decision makers do not have a global view of the site area where they must operate and this can lead to inadequate decisions as far as what concerns rehabilitation and refurbishment policies. Therefore, it is highly recognized the advantages of an integrated multi-purpose tool, connected with a GIS, as well as with a relational database, in order to have a deeper and interdisciplinary knowledge of the site and hence to be able to manage the historical building stock, conservation works, risk assessment, building vulnerability, damage and cost estimation (Risk-UE, 2001).

The inoperativeness of the responsible agents and the lack of strategies and policies in the last half of the XX century in this domain drove the built urban stock to a situation of deep degradation in a great number of historical centres. Worsening this context, it is witnessed the adoption of intrusive and inadequate rehabilitation and conservation practices, using new materials and construction techniques (concrete) on structural and non-structural elements, moving away the knowledge of traditional practices, the capability and connection of the solutions with the existent, leading to the discharacterization of the urban and patrimonial image.

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