Vulnerability assessment of building aggregates: A macroseimic approach

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SUMMARY:
The evolution of the urban layout is of great importance in the seismic behaviour of buildings in urban areas. The chronological construction process frequently results in characteristic heterogeneity of masonry wall fabric and connection quality. In addition, buildings do not constitute independent units given that they share the mid-walls with adjacent buildings and the façade walls are aligned. Thus, as post-seismic observations proved, buildings do not have an independent structural behaviour, but they interact amongst themselves, mainly for horizontal actions and so the structural performance should be evaluated at the level of the aggregate and not only for each isolated building. In most cases, for masonry structures there is no need for sophisticated dynamic analyses to assess seismic vulnerability taking to account all the inherent uncertainty of such analysis. This is even more relevant when an assessment at the level of a city centre is pursued. In this paper, attention will be focused on the exposure of the simplified method based on the concept of the evaluation of building parameters that compose an aggregate, such as geometrical irregularities, building typology differences and interaction issues. This method was applied to an old city centre and results are treated and shown resourcing to a GIS application.

Keywords: building aggregates, interaction, vulnerability assessment, GIS scenarios

1. INTRODUCTION

To undertake vulnerability assessment, evaluate seismic risk and estimate loss at the urban scale for old city centres in which building stock is aggregated consequence of a diachronically construction process (see Figure 1). A building aggregate can be considered as a unit, for which it is fundamental, the knowledge on building typology, conservation state and connection scheme between buildings consequence of the evolution of the urban layout in which the diachronic construction of buildings creating a urban mesh very characteristic of old city centres.

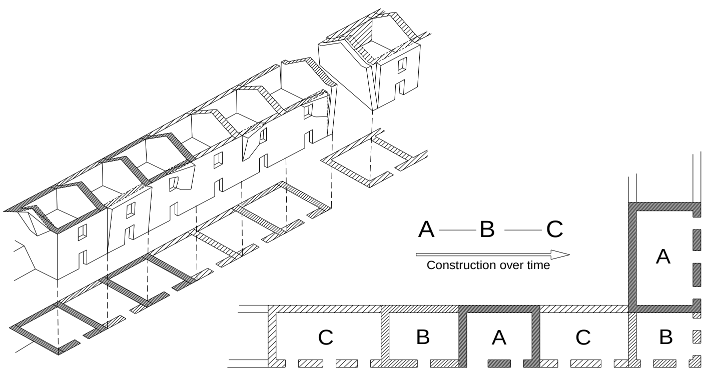

Figure 1. Diachronic construction process and building interaction (adapted from Giuffre, 1990)

This growth implies the connection between buildings, through sharing and using existent load-bearing walls for floor and roof structures, lateral and façade wall connections, etc. These changes cause differences in the structural behaviour of single buildings within the building aggregate (Giuffre, 1990).

2. VULNERABILITY INDEX OF BUILDING AGGREGATES

When carrying out building appraisal and assessment in an urban zone, there are structural aggregates that are composed of several buildings which are in contact or present some kind of connection. The aggregate can be constituted only by three or four buildings to as large as the city block scale. These aggregates are composed by homogeneous buildings in terms of materials and/or constructive solutions. Their interaction is determinant on the structural response in case of a seismic action (see Figure 2).

In each structural aggregate, adjacent buildings are distinguished at least by one of the following features:

- Structural typology and quality of masonry;
- Different building heights;
- Irregularities in plan and height;
- Efficiency of the connections between structural elements;
- Misalignment between floors and openings (staggering floors and pounding).

The seismic vulnerability of building aggregates has been widely observed in post-earthquake damage surveys. Based on these observations, from the point of view of the damage interpretation, it is recognised that is much more relevant to assess the seismic vulnerability of a group of buildings instead of performing an individual assessment of each singular building.

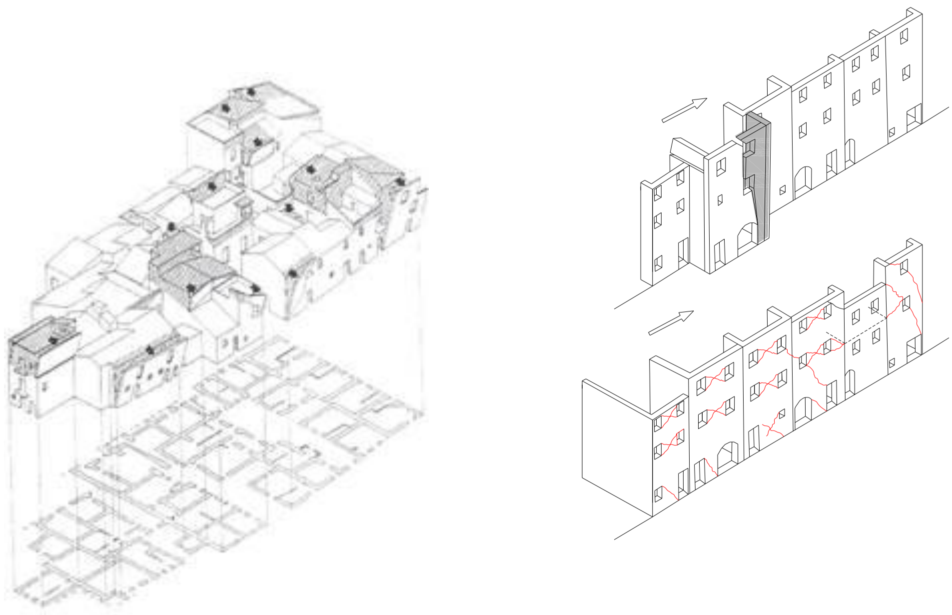

Figure 2. Interaction phenomena (Ortigia, 2000; MRRP, 2001)

This index, developed specifically to assess building aggregates, is composed by five parameters, some of which resultant from the analysis of other vulnerability index methods developed by the same authors for the case of buildings and façade walls (Vicente, 2008; Ferreira, 2010).

The vulnerability index is calculated as the weight sum of 5 parameters (see Table 1), 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 aggregate, calculating or defining the vulnerability class through the analysis of different properties associated with mechanical, geometrical and implementation characteristics. Subsequently, for each one of the 5 parameters, a weight, p_i, is assigned. As shown in Table 1, this weight can assume the value of 0.5, for the less important parameter in the calculation of the seismic vulnerability, I^*_{va}, or 1.75 for the more important one. The value of Iva ranges between 0 and 225. 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 aggregate seismic vulnerability, I_{va}.

Table 1. Vulnerability index assessment parameters and weights

PARAMETERS		Class C_{vi} A	B	C	D	Weight (p_i)	VULNERABILITY INDEX
P1	Quality of the masonry fabric	0	5	20	50	1.50	
P2	Misalignment of openings	0	5	20	50	0.5	
P3	Irregularities in height	0	5	20	50	0.75	Normalized index $0 \leq I_{va} \leq 100$
P4	Plan geometry	0	5	20	50	0.75	
P5	Location and soil quality	0	5	20	50	0.75	

As exposed in Table 1, parameter P1 assumes the highest influence in the formulation of the vulnerability index, I_{va}. As will be presented next, this parameter evaluates the masonry quality and homogeneity of the masonry fabric that constitutes the buildings that compose the aggregate. Following, the 5 parameters which evaluate the seismic vulnerability of the aggregate, I_{va}, are presented:

Parameter P1: Quality of the masonry fabric

This parameter assesses, in an isolated manner, each one of the buildings regarding the quality of its masonry. This parameter benefits the more homogeneous aggregates in terms of the masonry quality of the buildings which compose it. Table 2 presents the vulnerability class definition for Parameter P1 and complementary subclass definition.

Table 2. Vulnerability class definition for Parameter P1

A	More than 75% of buildings belong to subclass Sc1.
B	Less than 25% of buildings belong to subclass Sc3 and Sc4 and more than 25% of buildings belong to subclass Sc2, Sc3 and Sc4.
C	Less than 25% of buildings belong to subclass Sc4 and more than 25% of buildings belong to subclass Sc3 and Sc4.
D	More than 25% of buildings belong to subclass Sc4.

Parameter P1: Subclass definition

Sc1	Brick masonry of good quality and fabric (solid bricks or hollow bricks with less than 45% of voids). Well-tailored stone masonry with homogeneous size units. Well mortared irregular stone masonry, well interlocked, presenting transversal elements in the connection between leafs.
Sc2	Brick masonry (less than 45% of voids). Well-tailored stone masonry with little homogeneous units. Irregular stone masonry with transversal connection between leafs.
Sc3	Brick masonry of poor quality with connection and bricklaying irregularities. Stone masonry with no tailored and heterogeneous units. Irregular stone masonry well mortared and well interlocked but with no transversal connection elements.
Sc4	Poor quality brick masonry incorporating stone and brick fragments. Loose stone masonry. Rubble stone masonry, with no transversal connection and poorly mortared.

Parameter P2: Misalignment of openings

This parameter assesses the horizontal misalignment of openings and floors particularly relevant when a concrete floor solution is detected. The vulnerability class attribution is made in function of the worst conditions assessed in terms of the criteria defined in Table 3.

Table 3. Vulnerability class definition for Parameter P2

A	Less than 25% of cases of horizontal misalignment of openings between adjacent buildings.	(or)	Less than 25% of cases of floor misalignment between adjacent buildings wherein one of the buildings presents concrete floors and/or structure.
B	More than 25% and less than 50% of cases of horizontal misalignment of openings between adjacent buildings.	(or)	More than 25% and less than 40% of cases of floor misalignment between adjacent buildings wherein one of the buildings presents concrete floors and/or structure.
C	More than 50% and less than 75% of cases of horizontal misalignment of openings between adjacent buildings.	(or)	More than 40% and less than 60% of cases of floor misalignment between adjacent buildings wherein one of the buildings presents concrete floors and/or structure.
D	More than 75% of cases of horizontal misalignment of openings between adjacent buildings.	(or)	More than 60% of cases of floor misalignment between adjacent buildings wherein one of the buildings presents concrete floors and/or structure.

Parameter P3: Irregularities in height

This parameter assesses, in a very simple way, the deviation of the building heights in relation to an average height of the aggregate. The heterogeneity of the heights is quantified, i.e., the accumulated difference between the number of floors of the adjacent buildings and the total number of buildings that compose the aggregate, through a height differences ratio as shown in Figure 3. Table 4 presents the vulnerability class definition for Parameter P3.

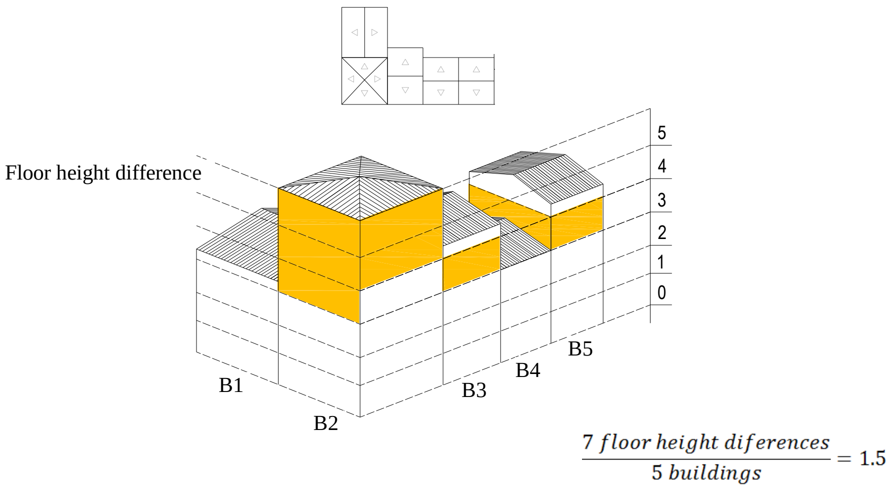

Figure 3. Evaluation of the irregularity in height

Table 4. Vulnerability class definition for Parameter P2

A	$\frac{nº\ of\ floor\ height\ diferences}{nº\ of\ buildings} < 0.2$
B	$\frac{nº\ of\ floor\ height\ diferences}{nº\ of\ buildings} < 0.5$
C	$\frac{nº\ of\ floor\ height\ diferences}{nº\ of\ buildings} < 0.8$
D	$\frac{nº\ of\ floor\ height\ diferences}{nº\ of\ buildings} \geq 0.8$

Parameter P4: Plan geometry

This parameter assesses the irregularity in plan of the structural aggregate, using a known relationship between the area, A, and the perimeter, P, (see Figure 4). Table 5 presents the classification of vulnerability classes proposed for this parameter.

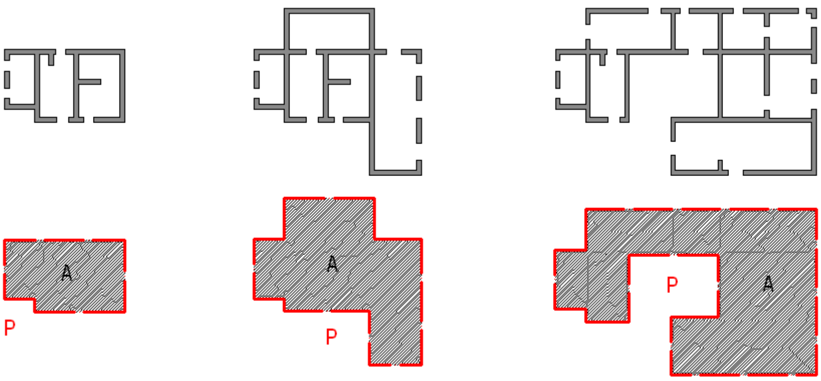

Figure 4. Evaluation of the aggregate geometry in plan

Table 5. Vulnerability class definition for Parameter P4

A	$\frac{16A}{P^2} < 1$
B	$0.75 \leq \frac{16A}{P^2} < 1$
C	$0.5 \leq \frac{16A}{P^2} < 0.75$
D	$\frac{16A}{P^2} < 0.5$

Parameter P5: Location and soil quality

This parameter assess, in a very expedite way, the location of the aggregate in terms of the quality of the foundation soil and slope. Table 6 shows the classification proposed for this parameter.

Table 6. Vulnerability class definition for Parameter P5

A	Aggregate founded on rock or on a coherent soil with less than 10% slope. Located in areas with no special constraints and no gaps.
B	Aggregate founded on rock or on a coherent soil with a slope between 10 and 30%. Landfill soils with gaps.

C	Aggregate founded on rock or on a coherent soil with a slope between 30 and 50%. Landfill soils with probable impulses.
D	Aggregate founded on rock or on a coherent soil with more than 50% slope or on heterogeneous soil with more than 50% slope. Located in ravine or cliff. Possible soil liquefaction, soil slip (landfill and alluvial layers), layered soil heterogeneity, soft and loose clay soil, landfills

3. APPLICATION OF THE VULNERABILITY INDEX METHOD

3.1 Case study

The proposed methodology was used to evaluate the seismic vulnerability of an existent aggregate located in the old city centre of Coimbra. The aggregate is composed by 13 limestone masonry buildings. Figure 5 presents the shape and the location of the evaluated building aggregate in the old city centre of Coimbra.

Figure 5. Building aggregate assessed

The vulnerability assessment of the aggregate was undertaken in two phases. In the first phase, the 13 buildings were assessed individually through the application of a seismic vulnerability assessment proposed by one of the authors (Vicente, 2011). In the second phase, the aggregate was assessed through the methodology presented in this work

3.2 Vulnerability assessment and damage scenario

Although the methodology proposed here is expedite, it requires accurate knowledge of building characteristics, which can only be obtained via thorough and detailed inspection. In accordance with this, evaluation of vulnerability was undertaken at two levels. In the first phase, an evaluation of vulnerability index, was carried out for all buildings individually using detailed information available in the SIG database developed (Vicente, 2008).

At a second level a more expeditious approach to the assessment of the building aggregates was carried out also resourcing to the detailed information and analysis of group of buildings that constitute the aggregate.

Figure 6. Individual building vulnerability assessment and aggregate assessment

From figure 6 it is evident that the individual assessment overestimates the vulnerability. The structural aggregate makes row buildings in general less vulnerable when compared to isolated. For the case of a row of buildings, many situations can arise from the interaction between buildings. Normally flexural failure is expected for buildings with slender masonry piers at ground floor due to big openings and shear failure for buildings with thick masonry piers between openings, but this kind of failure mechanisms are altered because of the group response. The misalignments of building front, misalignments of window openings of adjacent buildings, big differences in wall area and stiffness from aligned buildings change completely the failure mechanisms and stress and load paths for the horizontal forces.

Another feature is the end buildings are very vulnerable due to their position and normally suffer most damage by rotation and sliding phenomenon's induced by inertial forces of the whole aggregate in one direction, and for this case the aggregate vulnerability underestimates.

Once the vulnerability index is estimated, physical damage scenarios can be constructed. For the operational implementation of the methodology, an analytical expression was proposed (Bernardini *et al.* 2007) which correlates hazard with the mean damage grade ($0 < \mu_D < 5$) of the damage distribution (discrete beta distribution) in terms of the vulnerability value, as shown in Eq. 1.

$$\mu_D = 2.5 + 3 \times \tanh\left(\frac{I + 6.25 \times V - 12.7}{Q}\right) \times f(V, I) \quad 0 \leq \mu_D \leq 5 \tag{1}$$

where I is the seismic hazard described in terms of macroseismic intensity, V the vulnerability index, given as $V = 0.56 + 0.0064 \times I_v$, Q, a ductility factor, and $f(V, I)$ is a function of the vulnerability index and intensity. The latter is introduced in order to understand the trend of numerical vulnerability curves derived from EMS-98 DPMs for lower values of the intensity grades (I =V and VI) where:

$$f(V, I) = \begin{cases} e^{V/2\times(I-7)} & I \leq 7 \\ 1 & I > 7 \end{cases} \quad 0 \leq \mu_D \leq 5 \tag{2}$$

This analytical expression derives from the interpolation of vulnerability curves calculated from the completed DPMs, as suggested in the EMS-98 scale. Used to estimate physical damage, this mathematical formulation is based on work previously proposed by Sandi and Floricel (1995).

Figures 7 a), b), c) and d) present the damage scenarios mean damage grade assessment, combining building vulnerability and seismic hazard data for earthquake intensities of VI to IX. The higher two seismic scenarios correspond to the strongest historically-felt earthquake ever experienced in the district of Coimbra (in 1755). Damage estimation ranges from 1.1 for the earthquake scenario using *I* (EMS-98)=VI, 1.6 for *I* (EMS-98)=VII, 3.0 for *I* (EMS-98)=VIII and 4.3 for *I* (EMS-98)=IX. Maps in this GIS format enable the identification of urban areas with higher exposure and at greater risk of damage. However damage assessment is just the first step in the estimation of seismic loss, with the potential number of victims (deaths and severely injured), number of unusable buildings, homelessness and the economic impact of an earthquake also considered.

Figure 7. Physical damage scenario for intensities VI, VII, VIII and IX

4. CONCLUSIONS

The simplified vulnerability assessment procedure developed is useful on a large scale assessment, typically for old city centres. This procedure accounting for only five parameters is clearly a first level screening to identify more vulnerable areas of a dense urban mesh that do not only compromise the structural integrity of the aggregate, as well as the accessibility into the mesh, in terms of emergency and post-seismic intervention.

The results obtained through the methodology are satisfactory and reasonably comply with the more detailed singular building assessment in terms of overall value. However, further validation is needed by means of masonry building damage post-seismic observation.

Future steps are to compare with simplified mechanical methods that assess the building from the two principal directions, leading to improvement or incorporation of new parameters.

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