SEISMIC VULNERABILITY ASSESSMENT, DAMAGE SCENARIOS AND LOSS ESTIMATION
Case study of the old city centre of Coimbra, Portugal

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ABSTRACT :

The evaluation of the seismic risk of built-up areas is associated to the level of earthquake hazard, building vulnerability and level of exposure. Within this holistic approach that defines seismic risk, building vulnerability is from all three variables, the one that assumes great importance not only because of its obvious physical consequences in the occurrence of a seismic event, but because it is the potential aspect, for which the engineering research can intervene, improve and even control seismic behaviour of existing buildings, reducing the level of vulnerability and consequently the level of physical damage, life loss and economical loss. Development of vulnerability studies in urban centres can 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 paper is to discuss the vulnerability assessment methodologies, particularly the first level approaches, by presenting a proposed method which determines previously the level of vulnerability, only then assessing physical damage and its relationship to seismic intensity. It is presented and discussed the strategy and proposed methodology adopted for the vulnerability assessment, damage and loss scenarios for the city centre of Coimbra, in Portugal, through the GIS mapping of the building stock of the project perimeter.

KEYWORDS: Masonry, GIS mapping, seismic vulnerability, damage scenarios, loss estimation

1. HISTORICAL CITY CENTRE OF COIMBRA

The rehabilitation process of the old city centre of Coimbra is a national singular experience on urban renewal and rehabilitation. Other portuguese historical centres have started and are still ongoing renewal actions, but have not undertaken the renewal process in such an organized, integrated and methodological manner. In order to survey and study the old city centre area, the project perimeter (see Figure 1) was divided into eight zones (big city blocks).

1.1. Inspection and appraisal - Database

In the scope of the renovation and rehabilitation process, the city council invited the University to carry out a complete identification and inspection survey of the old masonry buildings. All the information gathered was processed and a database management system was developed to manage, inter-cross and analyze the information gathered. To take advantage of this information for other studies such as the vulnerability assessment a methodology was developed as further on explained in section 2.2. The building stock of the old city centre was built over the XVII to the XX Century. The necessary information used in the vulnerability assessment allowed presently 679 buildings to classified and evaluated in respect to their seismic vulnerability. The building inventory process is without doubt a key factor in assessing a urban area.

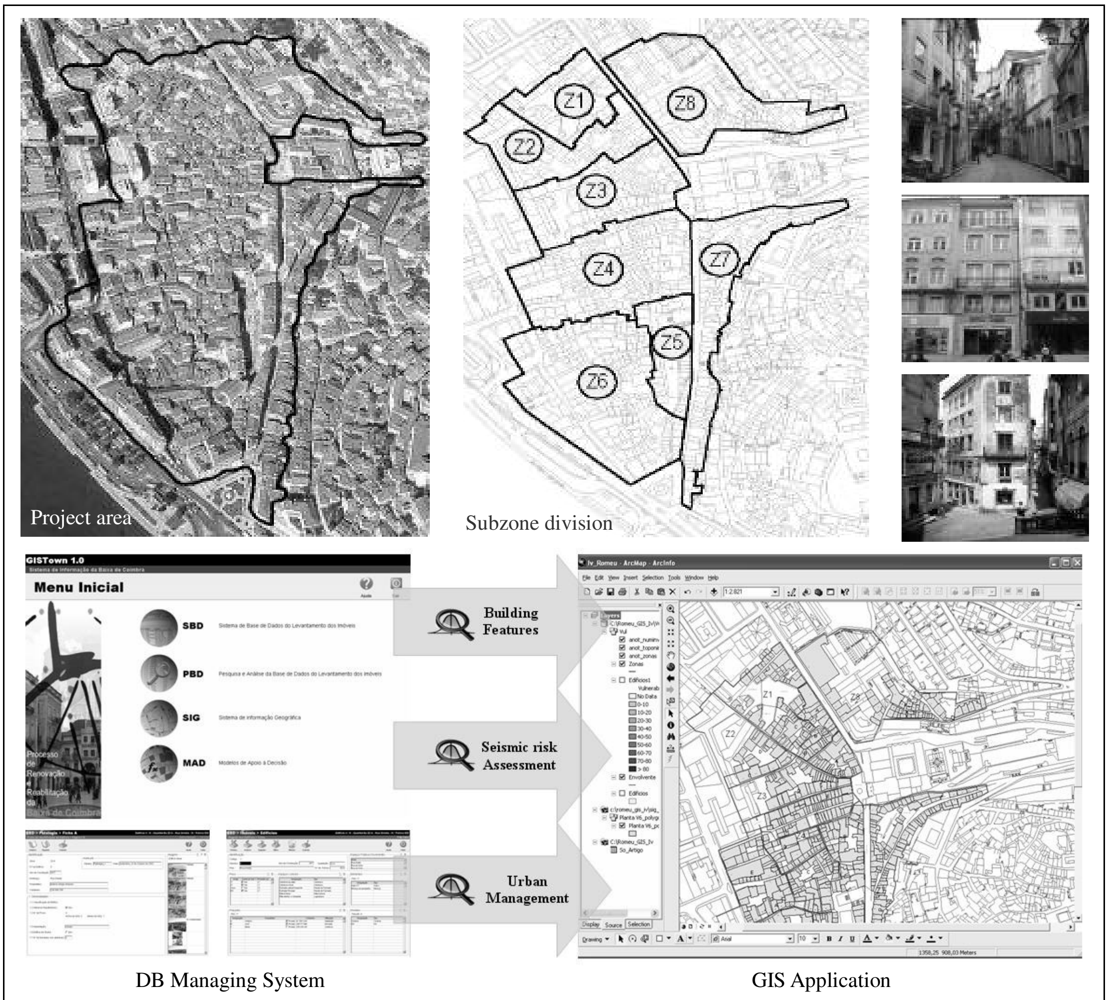


Figure 1 Project perimeter of the old city centre of Coimbra, database and GIS framework

1.2. Urban data collection and organization into a GIS tool

Risk management of historic and urban areas is normally undertaken without a general planning tool. A first consequence of this is that technicians and decision makers (city councils or regional authorities) 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 building retrofitting. By these considerations arises the strong necessity 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 project perimeter and hence to be able to manage the historical building stock, conservation needs, building vulnerability, assessing and managing earthquake risk.

The chosen software used for the GIS application is ArcGis 9.2 [ESRI, 2005] has been connected with a relational data base (see Figure 1), specifically on structural building parameters that rule the structural behaviour of old masonry buildings, with particular focus on their seismic vulnerability. In the GIS environment, all routines where programmed and compiled using Visual Basic® and are compatible with ArcGis 9.2 [ESRI, 2005] programming language on a Windows® platform. Various modules were developed for different tasks: spatial visualization of results by zones, algorithms for the vulnerability assessment (using information on building parameters and features used to define the vulnerability), damage and loss estimation for different earthquake intensities. All the database information associated to the GIS application can be periodically updated, allowing the mapping of different damage scenarios, for example testing risk reduction actions associated to reduction of vulnerability through strengthening strategies.

2. VULNERABILITY ANALYSIS

When assessing seismic vulnerability of buildings it is fundamental to establish the objectives pursued, and in function of those chose the most adequate strategy and tools for the assessment. First of all it is very important to understand the difference of detailed approaches used on single buildings and others most efficient in larger scale analysis for groups of buildings. In the first case, the use of a detailed methodology implies a very reliable evaluation with necessarily a very good level of information on the analyzed structure. However enlarging the number of buildings and area do be assessed, increasing consequently the resources and quantity of information needed, the use of less sophisticated and onerous inspection and recording tools are preferable. The methodologies to assess vulnerability at a territorial scale should be based on few parameters, some of empirical nature, on the knowledge of the effects of the past earthquakes on masonry buildings and on the resource of statistical approaches. Acquainted with the definition of risk provided in a more broad and general sense, the vulnerability is a variable in the mathematical formulation of risk evaluation. It is convened by most authors [Coburn and Spence, 2002]) that the absolute risk can be expressed as the results of the mathematical convolution between hazard, vulnerability and exposure.

$$R_{ie}|_T = |(H_i \otimes V_e) \otimes E|_T \tag{2.1}$$

R, is defined as the probability of exceedance of a certain level of absolute loss of a exposed element *e*, as consequence of a occurrence of a seismic event of certain intensity *i*.
H, is defined as the probability of exceedance of a certain level of seismic intensity *i*, during an specified recurrence period, *T* and area.
V, is the vulnerability, that is a intrinsic predisposition of a certain element *e*, to suffer damage result of a seismic event with intensity *i*.
E, is the exposure of the elements in risk, reflecting the value of the elements exposed.

Vulnerability in this case is defined as a intrinsic property of buildings that limits the certain level of damage to be suffered when subjected to a determined seismic event of defined intensity. The seismic vulnerability of buildings can be evaluated in ways more or less complex in function of the scale and specificity of the study case. The definition and nature of the criteria (qualitative and quantitative) naturally condition the formulation of the methodologies and evaluation level, that can go from the expedite evaluation procedures based on visual observation until the most complex, non-linear modelling strategies of single buildings.

2.1 Vulnerability index methodology

The methodology applied to evaluate the vulnerability over all the historical city centre of Coimbra can be considered an hybrid method. The vulnerability index method formulation proposed is based essentially on the GNDT II level approach [GNDT, 1994] for the vulnerability assessment of residential masonry buildings, that is based on a vast post-seismic damage observation and survey data that has brought to attention the most important parameters that control building damage and must be surveyed individually. This method used in Italy over the last 25 years, has been adapted to the Portuguese masonry buildings and improved by introducing more detailed analysis, resulting from the good level of building stock information, discussion and redefinition of the criteria of some of the most important parameters and the introduction of new parameters that take into account the interaction amongst buildings (structural aggregates) and other overlooked building features.

The overall vulnerability is calculated as the weighed sum of 14 parameters used in the formulation of the seismic vulnerability index. These parameters are related to 4 classes of growing vulnerability classes: A, B, C and D. Each parameter evaluates a building feature influencing the building response, choosing the vulnerability class associated to it. A weight p_i is assigned to each parameter evaluated from 0.50 for the less important parameters in terms of vulnerability, up to 1.5 for the most important ones (for example parameter P3, conventional strength) as shown in Table 1. These weights were attributed to each one of the 14 parameters is function of their importance on the global seismic vulnerability of the structure. The vulnerability index ranges between 0 and 650, but the value obtained by the weighted sum can be normalized within the range, $0 < I_v < 100$, and it is defined as the vulnerability index. The vulnerability index calculated can be used to estimate the building damage under a specified seismic intensity, as will be shown in section 3.1.

Table 1 Parameters and vulnerability index proposed (I_v)

PARAMETERS		Vulnerability Class C_{vi} A	B	C	D	Weight p_i	VULNERABILITY INDEX
P1	Type of resisting system	0	5	20	50	0.75	
P2	Quality of the resisting system	0	5	20	50	1.00	
P3	Conventional strength	0	5	20	50	1.50	
P4	Maximum distance between walls	0	5	20	50	0.50	
P5	Number of floors	0	5	20	50	1.50	$I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i$
P6	Location and soil conditions	0	5	20	50	0.75	
P7	Aggregate position and interaction	0	5	20	50	1.50	
P8	Plan configuration	0	5	20	50	0.75	
P9	Regularity in height	0	5	20	50	0.75	
P10	Wall openings and alignment	0	5	20	50	0.50	$0 \le I_v^* \le 650$
P11	Horizontal diaphragms	0	5	20	50	1.00	
P12	Roof system	0	5	20	50	1.00	
P13	Fragilities and conservation state	0	5	20	50	1.00	Normalized index
P14	Non-structural elements	0	5	20	50	0.50	$0 \le I_v \le 100$

Without going into great detail for all the 14 parameters evaluation criteria, in a broad sense parameters are regrouped. The first group includes parameters (P1, P2) that characterize the building resisting system that rule structural behaviour, recording the type and quality of masonry, through the material (size, shape and stone type), masonry fabric and arrangement and level of connections amongst walls. Parameter P3, is one of the most important since it is of quantative, roughly estimating the shear strength capacity of the building. Parameter P4 evaluates the level of wall bracing and implicitly the out-of-plane collapse risk. Parameters P5 and P6 evaluate the height and the soil foundation conditions of the buildings. Seismic behaviour does not only depend on the structural behaviour of the building but is also affected by other factors. The second group is mainly focused on the building location and interaction (parameter P7), since typically in historical areas neighbouring masonry buildings are structurally attached or side-by-side (without gap). This feature is not contemplated in other methodologies and is considerably important, because the building aggregate seismic response is very different from single building response. Parameters P8 and P9 evaluate the irregularity in plan and height. Parameter P10 identifies window opening irregularity important in load path transfer. The third group with resource to parameters P11 and P12 evaluates horizontal structures, essentially it evaluates the level of connection of the timber floors and the impulsive nature of the pitched roofing systems are classified. Finally parameter P13 evaluates structural building fragilities and level of conservation and parameter P14 the presence of non-structural elements with poor connections that can aggravate damage.

The proposed methodology in essence is similar to the GNDT II level approach [GNDT, 1994] with some modifications, however the "backbone" parameters assessed are essentially the same. Taking this into account, the equivalence in the vulnerability definition between the GNDT II level approach (I_v) and the Macroseismic method (V) [Lagomarsino and Giovinazzi, 2006], allows to make reference to the vulnerability functions that relate the mean damage grade, μ_D with macroseismic intensity [Lagomarsino and Giovinazzi, 2006]. It has been demonstrated that GNDT II level approach [Benedetti and Petrini, 1984] is equivalent to the Macroseismic method [Lagomarsino and Giovinazzi, 2006], derives from the EMS-98 scale [Grunthal, 1998] which expresses the mean damage grade, μ_D, in function of the intensity and vulnerability index V. The mean vulnerability values relate to the vulnerability classes as shown in Table 2.

Table 2 Correlation between the vulnerability indexes and EMS defined vulnerability classes

Macroseismic method	Classe A (V = 0.88)	Classe B (V = 0.72)	Classe C (V = 0.56)
GNDT II level	Iv = 45	Iv = 20	Iv = -5

On the basis of this confrontation the following analytical correlation is derived between the two method vulnerability index's:

$$V = 0.592 + 0.0057 \times I_V \tag{2.2}$$

2.2 Vulnerability assessment completion

The detailed methodology is applied to a majority of buildings of the old city centre of Coimbra, but for the all the other buildings in the project perimeter for which the lack of information does not allow to carry out a more detailed study. Thus a more simpler approach has been used in function of the mean values attained from the detailed analysis, taking into account that the masonry building characteristics are homogeneous in this area. The mean value of the vulnerability index obtained for all masonry buildings from the first detailed evaluation was used as a typological vulnerability index (average value) that can be affected by modifiers of the mean vulnerability index for each building. The classification of the modifier factors can reduce or aggravate the final vulnerability index as the sum of the scores for all the modifiers. The modifiers are exactly some of the parameters of the vulnerability index definition as shown in Figure 2.

	Vulnerability classes, C_{vi}			
	0	5	20	50
Vulnerability modifier factors	A	B	C	D
P5 - Number of floors	-4.1	-3.1	0.0	6.2
P6 - Location and soil conditions	-0.5	0.0	1.6	4.7
P7 - Aggregate position and interaction	-1.0	0.0	3.1	9.3
P8 - Plan configuration	-2.1	-1.6	0.0	3.1
P9 - Regularity in height	-2.1	-1.7	0.0	3.1
P12 - Roof system	-2.8	-2.1	0.0	4.1
P13 - Fragilities and conservation state	-2.8	-2.1	0.0	4.1
Maximum modifier range, ΣI_v	-15.3	-10.5	4.7	34.7

Modifier score: $\frac{p_i}{\sum_{i=1}^{7} p_i} \times (C_{vi} - \bar{C}_{vi})$

p_i: Parameter, i, weight assigned

$\sum_{i=1}^{7} p_i$: Sum of parameter weights

C_{vi} : Modifier factor vulnerability class

$\bar{C}_{vi}$: Average vulnerability class of parameter, i. *

* - defined by the detailed analysis (410 buildings)

Figure 2 Vulnerability modifier factors and scores

3. DAMAGE ASSESSMENT AND LOSS SCENARIOS FOR COIMBRA

The typical traditional limestone masonry buildings of the city centre of Coimbra are best represented if evaluated through the average of the assessed buildings, taking into account that the masonry building characteristics are homogenous in this area. In this case the mean vulnerability index, I_v, ranges between 38 to 39 corresponds to the EMS building typologies and vulnerability classes, A to B by adjusting the construction description. The use of the proposed detailed approach for over 410 buildings, results in a mean vulnerability index of I_v=38.13, but with the complementary approach for the remaining 269 buildings the final results do not differ much in terms of average vulnerability, shifting to I_v=38.38 (see Figure 3). For about 39% of the building stock it was calculated a vulnerability index over 40, and a concerning value of 20% over 45 (equivalence to a vulnerability class A). Only 1% of the buildings have a I_v below 20 (equivalence to a vulnerability class A).

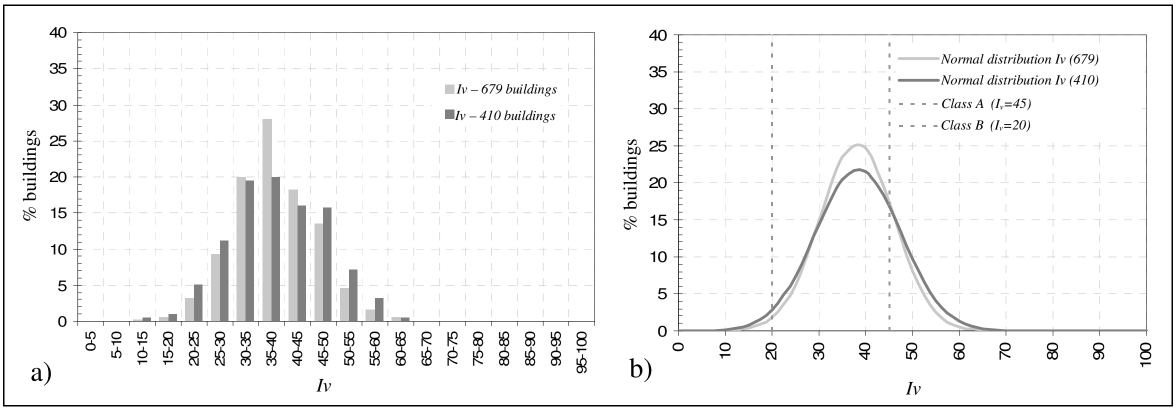


Figure 3 Vulnerability index: a) histogram distribution; b) adjusted normal distribution

The standard deviation (σ_{Iv}) associated with the detailed procedure and the completion of the vulnerability assessment for the project perimeter using the simpler approach differ very little, from 9.12 to 7.86, representing a variance of 14%, although the mean value for the vulnerability index is very similar, 38.13 to 38.38. The use of this strategy seems reliable for a completion approach in cases in which the numbers of buildings of similar building typology, therefore not inspected in a detailed way are fewer and the level of quality and reliability of the detailed assessment is high.

3.1 Seismic hazard and physical damage

Once defined the vulnerability using Eqn. 2.2, the mean damage grade, μ_D, can be calculated for different macroseismic intensities using Eqn. 3.1, I(EMS-98)- μ_D vulnerability curves for different vulnerability index values can be calculated using mean value of I_v and upper and lower bound ranges by affecting the mean value by standard deviation can also be calculated. From these mean damage grade values, μ_D, we can define different damage distribution histograms for different intensities and representative vulnerability index values using a probabilistic basis, mainly using the known binomial probability mass function or of the beta probability density function. For the operational implementation of the methodology a analytical expression is proposed that correlates the hazard, I, and mean damage grade value ($0<\mu_D<5$) of the damage distribution (discrete beta distribution) in respect to the vulnerability value, V, and coefficient of ductility for the building type Q , as shown in Eqn 3.1.

$$\mu_D = 2.5\times\left[1+\tanh\left(\frac{I+6.25\times V-13.1}{Q}\right)\right] \quad 0\leq\mu_D\leq 5 \tag{3.1}$$

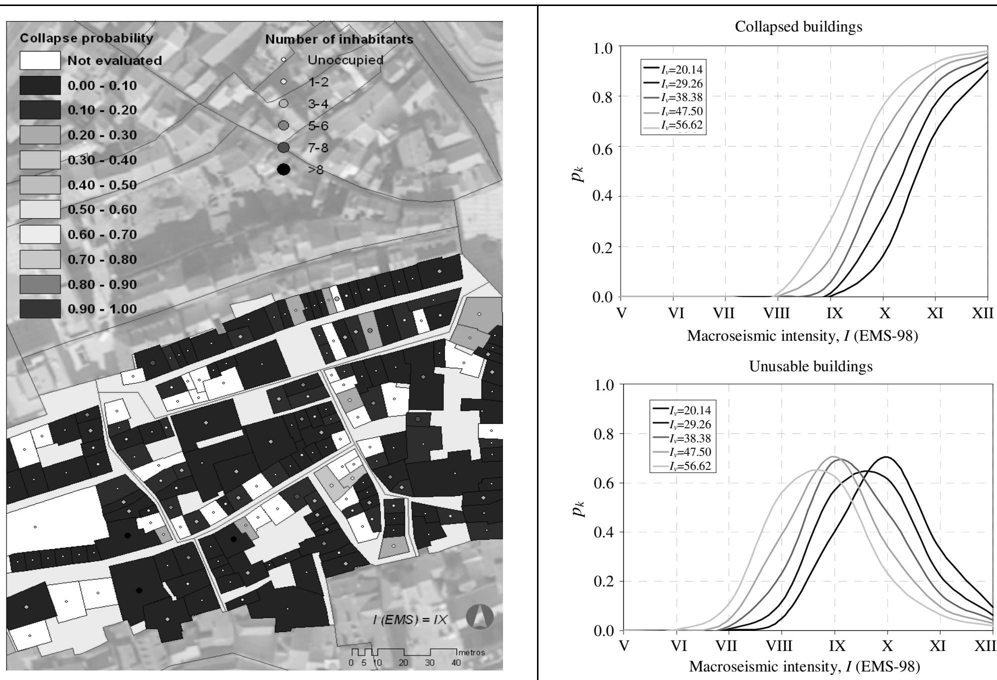
3.2 Seismic loss estimation and consequence

The development of the GIS tool has highlighted its potentially in the management of data, implementing a workable and progressive platform by integrating all the seismic risk evaluation, from the building characteristics to economical loss estimation. Vulnerability and loss algorithms (mathematical and probability functions) are programmed into the GIS tool. This allows enhancing the whole analysis process, enabling data editing of building information, inter-crossing of results of building features to occupation numbers with vulnerability results and loss estimations, to support responsible actions and decisions in the risk management.

3.2.1 Collapsed and unusable buildings

The expected mean damage grade μ_D has been evaluated, as a function of the macroseismic intensity I(EMS-98) and the vulnerability index I_v from the assessment. A beta function has been assumed to obtained the damage distribution, understood as the probability of reaching each damage grade, D_k ($k \in [0,5]$) for the assessed mean damage grade μ_D. Loss estimation models are then based on physical damage, correlating probability of certain damage levels with the probability of collapse and loss of functionality of buildings. The most used approaches are based on observed damage data such as the HAZUS [1999] proposal, Italian National Seismic Survey proposal based on Bramerini *et al.* [1995] work on data analysis associating the probability of unusable buildings to minor and moderate earthquakes that produce lower levels of structural and non-structural damage. Severe earthquakes lead to higher mean damage values and are associated to the collapse probability.

Basically the use of the probabilities of a certain damage grades are multiplied by factors ranging from 0 to 1 that differ from proposal to proposal and that have some statistical correlation to validate the algorithms used. In Italy the processing of data by the SSN has enabled the establishment of weighed factors and consequent expressions to estimate building loss. In Figure 4 is shown a plot result from the GIS tool, particularly for layering results (estimation of building collapse) and global results for different vulnerability values.



Collapse probability & Number of building inhabitants — Collapsed and unusable building probability

Figure 4 Mapping layer results and global results

3.2.2 Economical loss and repair costs

The correlation between damage grades and the repair costs have been obtained by the data processing after earthquakes and various correlations have been put forward [Dolce *et al.*, 2005]. The probability of the repair costs are computed as product of probabilities. The conditional probability of the repair cost to the damage level, $P[R|D_k]$, expressed by the values assumed [Bramerini *et al.*, 1995] and the known conditional probability of the damage grade to the building vulnerability, I_v and seismic intensity, I, given by $P[D_k|I_v, I\,]$:

$$P[R\,|\,I]=\sum_{D_k=1}^{5}\ \sum_{I_v=0}^{100} P[R\,|\,D_k]\times P[D_k\,|\,I_v,I] \qquad (3.2)$$

Computing these values for the mean vulnerability value and the lower and upper bounds (I_v-σ_{Iv}; I_v; I_v+σ_{Iv}), the repair costs for the building stock relative to the total building cost and building value in terms of unit area (800€/m^2) for Coimbra are shown in Figure 5. For the case of a seismic intensity of VIII, the total repair costs are about 60% of the 2007 annual budget of the Coimbra city council for the mean vulnerability (I_v=38.38).

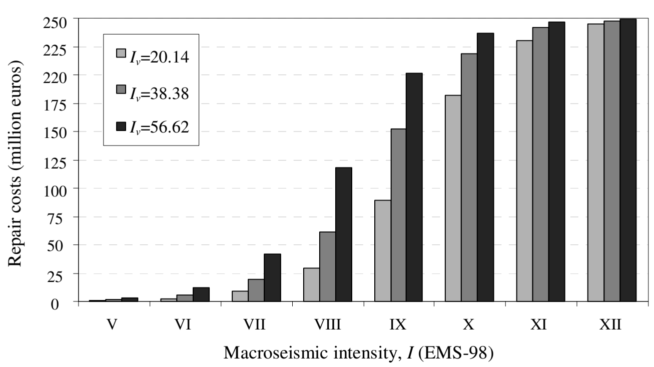


Figure 5 Estimation of global repair costs

4. CONCLUSIONS

The vulnerability assessment method development has revealed to be very exhaustive in analysis of the building constructive characteristics and therefore is of good reliability and consequently the results produced from the use of the vulnerability evaluation. The use and implementation of such vulnerability assessments integrated into a macroseismic methodology has enabled to put forward damage and loss scenarios for risk mitigation and management. The proposed vulnerability assessment method and risk scenario mapping intends to be applicable for other regions and old city centres, and if needed easily adapted and slightly modified for specific building features.

The GIS application and DB managing system enable to store building features and survey information, assess seismic vulnerability, as well as, damage and risk scenario prediction, allowing data upgrading and improvement. This integrated tool is essential in various activities, such as the development of strengthening strategies plans, cost-benefit analysis, civil protection and emergency planning.

For the damage scenarios studied, the results attained are very well correlated with the building constructive features and fragilities of the built-up environment. Even though the city of Coimbra is located in a low to moderate hazard region, the high seismic building vulnerability brings up the considerable global seismic risk for building stock and historical area. The seismic vulnerability of the old city centre Coimbra is relatively high and in account to this, optimized interventions for improving seismic response and conservation of old buildings assisted with mechanical and mathematical modelling are needed in the mitigation of seismic risk.

The vulnerability methodologies based on statistical methods and damage observation, are far more interesting in the large scale analysis, essentially for two reasons: less resource requirements and simplified mechanical still need experimental testing validation. However the uncertainty in the post-seismic data collection that establish empirical vulnerability curves and the vulnerability classification data quality itself are still issues that are being dealt with. In the risk mitigation, the reduction of loss is only possible by acting over vulnerability or exposure. Therefore evolving into more reliable vulnerability assessment models that can combine statistical and mechanical convergence, in the sense that they could lead to better results and bidirectional validation by adjusting criteria.

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