World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:9, No:6, 2015

Earthquake Vulnerability and Repair Cost Estimation of Masonry Buildings in the Old City Center of Annaba, Algeria

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Open Science Index, Civil and Environmental Engineering Vol:9, No:6, 2015 publications.waset.org/10001437.pdf

***Abstract*—**The seismic risk mitigation from the perspective of the old buildings stock is truly essential in Algerian urban areas, particularly those located in seismic prone regions, such as Annaba city, and which the old buildings present high levels of degradation associated with no seismic strengthening and/or rehabilitation concerns. In this sense, the present paper approaches the issue of the seismic vulnerability assessment of old masonry building stocks through the adaptation of a simplified methodology developed for a European context area similar to that of Annaba city, Algeria. Therefore, this method is used for the first level of seismic vulnerability assessment of the masonry buildings stock of the old city center of Annaba. This methodology is based on a vulnerability index that is suitable for the evaluation of damage and for the creation of large-scale loss scenarios. Over 380 buildings were evaluated in accordance with the referred methodology and the results obtained were then integrated into a Geographical Information System (GIS) tool. Such results can be used by the Annaba city council for supporting management decisions, based on a global view of the site under analysis, which led to more accurate and faster decisions for the risk mitigation strategies and rehabilitation plans.

***Keywords*—**Damage scenarios, masonry buildings, old city center, seismic vulnerability, vulnerability index.

I. INTRODUCTION

WHEN analyzing large-scale seismic vulnerability of individual buildings through simplified methodologies it is required a significant level of knowledge on each single building, which even so is still incomparably lower than more detailed methodologies such as numerical analysis [1]. It would be unreasonable and unaffordable to perform numerical analysis of each single building within historical centers. In this sense, to evaluate the overall vulnerability of the built-up area under study is it worth adopting a vulnerability index method mainly applied in the Euro-Mediterranean region that Algeria belongs to. The main motivation behind this assumption, is reflecting on the basis of the thesis that, accounting for the structural characteristics and urban organizations of the Algerian buildings, they can be considered similar to those which have been studied in Europe [2]. In this research paper it is presented and discussed the proposed methodology, which is adopted for the vulnerability and damage assessment and for the creation of loss scenarios for the old masonry buildings of Annaba city, in Algeria. Such vulnerability assessment study of the historical city center of Annaba can be conducted aiming both to identify building fragilities and to reduce seismic risk, therefore such results and conclusions offer a great opportunity to guide the action and decision making in seismic risk prevention and mitigation strategies.

II. OLD CITY CENTRE OF ANNABA

A. Inspection and Appraisal - Database

The Direction of Urban Planning and Construction of Habitation (DUCH) launched a general program aimed at evaluating the vulnerability of the old buildings in 12 (out of 29) districts of the Annaba municipality, which have been declared as historical and heritage areas [3]. In this regard, a detailed field survey was used to obtain the data in the selected regions of Annaba city. This in-situ work was carried out by the members of expert structural engineers of the Technical Control of Construction organism of Annaba city [4] using check lists from the outside and the inside envelope of the various elements at every floor of each individual building. The main ingredients of CTC's datasheets are listed in Fig. 1 to give an overview of the type of items surveyed. The synthesis of CTC data was used to classify buildings in one of the four classes of degradation (good state, slightly degraded, moderately degraded and highly degraded) to propose the types of interventions to be undertaken (repairs, strengthen, etc.) according to their degree of classification (slight, moderate and heavy) (Fig. 1). Despite that the data was not originally developed for seismic purposes, however, such special engineering expertise on structural vulnerability is valuable and of great importance to obtain valid risk outputs especially if a good thesis and interpretation are done [5].

B. Architectural and Structural Context

According to the 2011 census, Annaba city has a population of over 260.199 people [6]. The historical centers dominate the city's building stock and constitute a priceless and irreplaceable urban heritage (Fig. 2). The old historical center of Annaba city, usually called as "Place d'arme", is located in the middle region of Annaba city. In term of population, the old town of Annaba city shelters about 12.000 inhabitants. Its first settlements started in the Arab-Turkish period before the 18th century. Later, in the 19th century, the town experienced

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a large extension during the colonial French era between 1830 and 1964. In this period, many modifications have been brought over the islets and buildings blocks, when some of them have been replaced by colonial buildings [7]. The old town is also known by its narrow alleys and streets (Fig. 2). Taking advantage of the vast set of data obtained from the surveys, the authors assessed the seismic vulnerability of 380 buildings over a total of 602. Stone and adobe are widely used as construction materials for residential buildings in the area under study. Some of these buildings present a regular structural layout with thick walls (usually ranging from 40 to 50cm), containing a commercial ground floor and residential apartments above [8]. Brick masonry was also used for buildings and its structural layout is frequently irregular. The floors are usually of timber structures, sometimes on stone or brick vaults, not well attached to the walls [8]. Timber floor construction includes wooden beams covered with wooden planks, ballast fill and tile flooring. Mixed floors with steel beams, which are used to support brick masonry arches and concrete slabs are also observed [8]. The building stock is in very poor condition, revealing high levels of deterioration in the interior and the exterior envelope of the constructions, which were built with poor quality mortars and low resistant materials. Moreover, the connections between the various structural elements are often insufficient [8].

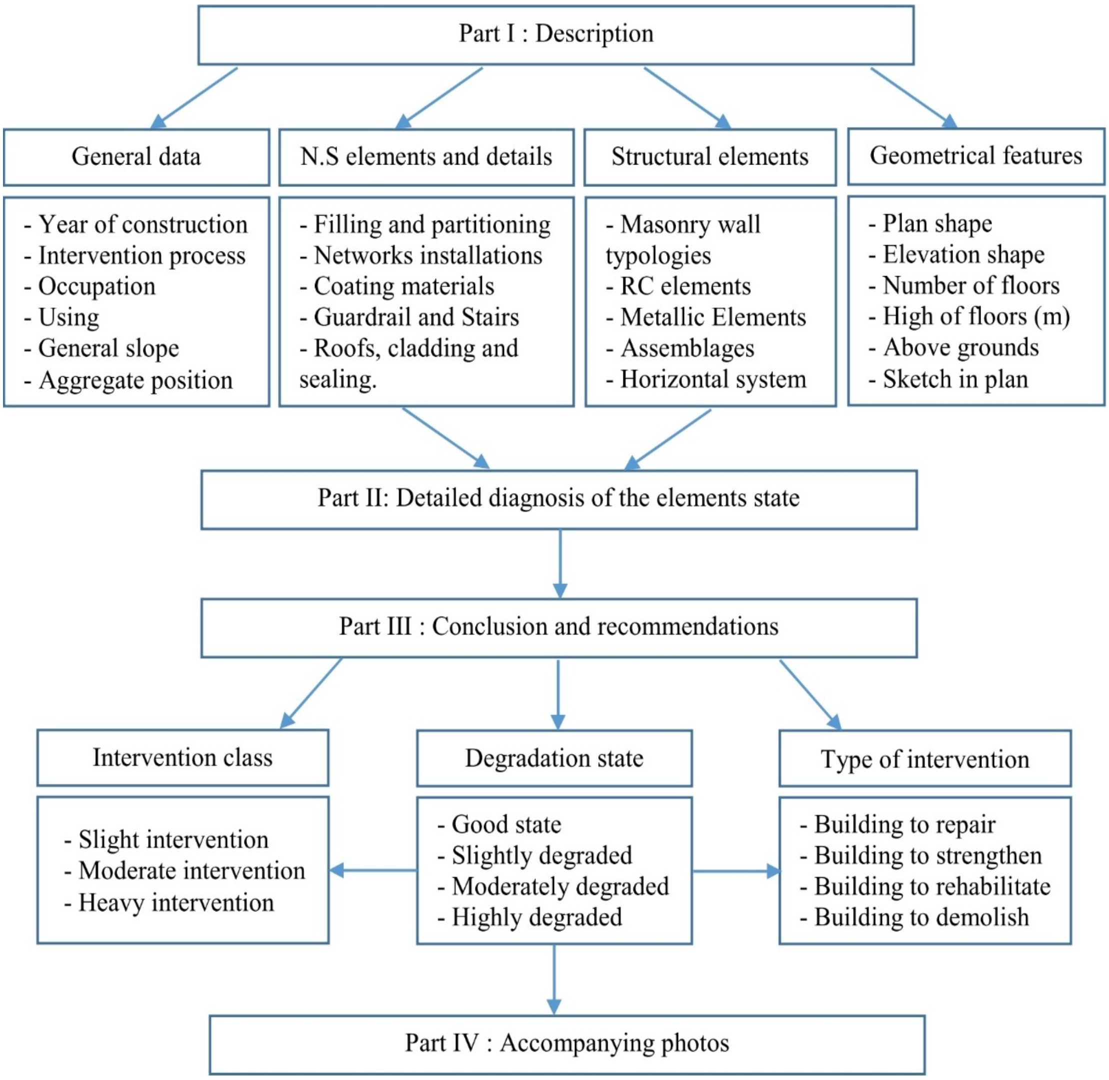


Fig. 1 The different parameters taken into account in the CTC data survey

The underlying ground consists of three main geological rock units: the upper part of the town is characterized by “Gneiss”, whereas the majority of the area from the middle to the northwest part is above “Micaschistes” and “Cipolins” layers. Over the whole study area, the soil conditions can be considered stiff to very stiff, presenting an average capacity of 200 KPa [7].

Fig. 2 Geography and overview of the old city center of Annaba

III. SEISMIC SCENARIOS FOR THE MASONRY BUILDING OF THE OLD CITY CENTRE OF ANNABA

A. Vulnerability Index Methodology

As already mentioned, the seismic vulnerability method selected to fit the number of buildings that composed the old city center of Annaba is developed for an European area. Among the existing methodologies, that developed for the Portuguese masonry buildings by Vicente [9] are selected in our case. Too close to the GNDT II approach [10], to evaluate the vulnerability of the buildings, this selected method uses a vulnerability index score for each building as the weighted sum of 14 parameters. These parameters are related to 4 classes (C_{vi}) 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 pi 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 I. 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 [11, 12].

$$I_v^* = \sum_{i=1}^{14} C_{vi} \times P_i \qquad (1)$$

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 in terms of structural behavior and level of connections amongst walls, fabric and quality of masonry [11]. Parameter P3, 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. The second group includes the building location and interaction parameter (P7), wherein the historical buildings of Annaba city are usually 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 [11], [13]. 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.

TABLE I
PARAMETERS AND VULNERABILITY INDEX (I_V)

PARAMETERS		Vulnerability class Cvi				Weight	Vulnerability Index
		A	B	C	D	*Pi*	
1. Structural building system							
P1	Type of resisting system	0	5	20	50	0.75	
P2	Quality of the resisting system	0	5	20	50	1.00	$I_V{}^* = \sum_{i=1}^{14} C_{V\,i} \times P_i$
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	
P6	Location and soil conditions	0	5	20	50	0.75	
2. Irregularities and interactions							
P7	Aggregate position and interaction	0	5	20	50	1.50	
P8	Plan configuration	0	5	20	50	0.75	$0 \leq I^*_v \leq 650$
P9	Regularity in height	0	5	20	50	0.75	
P10	Wall façade opening and alignment	0	5	20	50	0.50	
3. Floor slabs and roofs							
P11	Horizontal diaphragms	0	5	20	50	1.00	
P12	Roof system	0	5	20	50	1.00	
4. **Conservation status and other elements**							
P13	Fragilities and conservation state	0	5	20	50	1.00	Normalized index
P14	Non-structural elements	0	5	20	50	0.50	$0 \leq I_V \leq 100$

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 [14].

B. Vulnerability Curve and Damage Estimation

Finally, the associated expected average damage is computed as a function of the macro seismic intensity IEMS-98 (according to EMS-98 scale [15]) and the final vulnerability index *Iv*. This index, can be related to the vulnerability index, *V* (used in the Macro seismic Method, (1)), enabling the calculation of the mean damage grades and the subsequent estimation of physical principal and economic loss [13].

$$V = 0.592 + 0.0057 \times I_v \tag{2}$$

Therefore, once defined the vulnerability I_v, using (1), and translated into the macro seismic index *V* via (2), the mean damage grade, $\mu_D (0<\mu_D<5)$ can be calculated for different macro seismic intensities using an analytical expression [16]:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \tag{3}$$

where *I* is the seismic hazard described in terms of macro seismic intensity, *V* the vulnerability index (2) and *Q* a ductility factor which describes the ductility of a certain constructive typology (ranging from 1 to 4). In this research a ductility factor, *Q*, of 2.3 was adopted, as suggested by various authors [17], [18]. The *V* value defines the position of the vulnerability function, and the ductility coefficient (*Q*) defines the slope of the vulnerability function, that is, the growth of the damage with the seismic intensity.

The vulnerability curves are another way to represent the estimated damage expressed in EMS-98 scale [15]. This curves is directly obtained from the physical building damage distributions derived from the mean damage grade computed resorting to the applied methodology (2) for the mean value of the vulnerability index, $I_{v,mean}$, as well as for the upper and lower bound ranges $I_{v,mean} - 2\sigma_{Iv}, I_{v,mean} - 1\sigma_{Iv}, I_{v,mean} + 1\sigma_{Iv}, I_{v,mean} + 2\sigma_{Iv}$ for events of different macroseismic intensities [15].

IV. APPLICATIONS AND RESULTS

A. Vulnerability Assessment

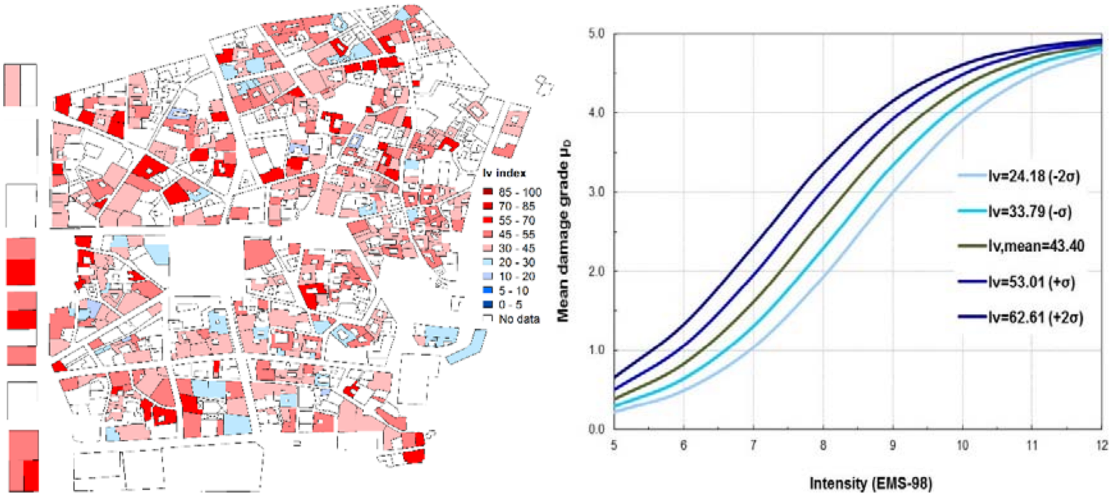
Fig. 3 shows the spatial distribution of building stock's seismic vulnerability in the old town of Annaba city. These results allowed for the identification of areas where more vulnerable buildings were located and also to identify the most vulnerable buildings or typologies. Approximately 66% of the assessed buildings had a vulnerability index value over 40 (see Fig. 3) and 42% over 45 (equivalent to vulnerability class A in the EMS-98 scale [15]. Only 2% of the buildings had an *I* below 20 (equivalent to vulnerability class B). The maximum and minimum *I* values obtained from the detailed assessment were 65.7 and 16.9, respectively.

It is important to stress that the outputs from this methodology must be interpreted statistically, by identifying a representative mean value which was 43.42 and defining the upper and lower bounds of the vulnerability index by mean of the associated standard deviation value, σ_{Iv}= 9.61. These results were well adjusted to the building characteristics and fragilities to construct the representative vulnerability curves for EMS-98 intensities between V and XII (Fig. 3).

B. Mean Damage Grade Distribution

The damage assessment presented above was carried out using the selected method and is shown as damage scenarios for earthquake intensities between I(EMS-98) = VII and

I(EMS-98) = X.



(a) (b)

Fig. 3 Mean damage grade: a) Spatial distribution; b) Vulnerability curves

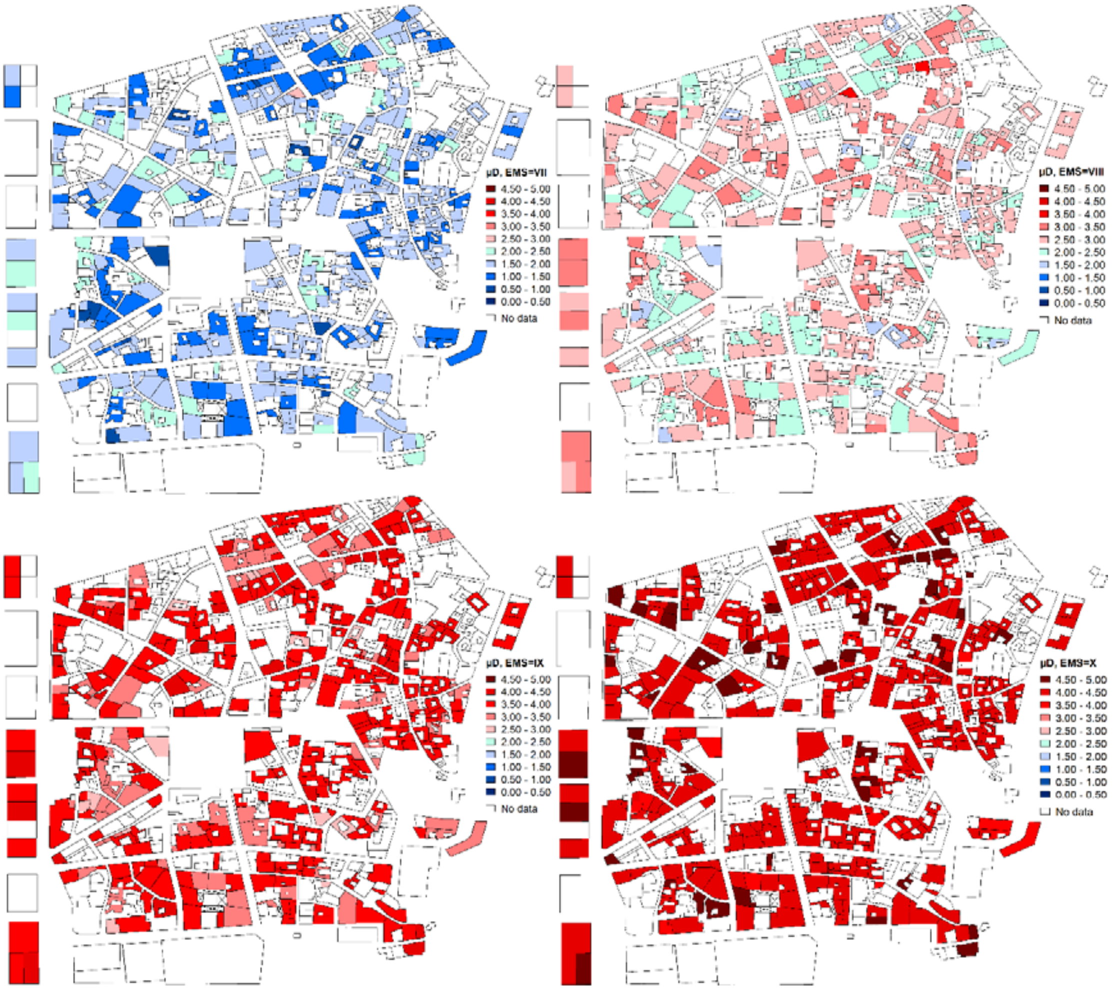


Fig. 4 Seismic scenarios of different intensities (VII to X) according to the EMS-98 scale

Such seismic vulnerability maps enable damage appraisal, and are therefore very useful tools for the focused implementation of both individual or/and larger-scale urban retro fitting processes and strengthening strategies.

Regarding the seismic scenario for the intensity I(EMS-98) = VII the distribution of the mean damage grade μ_D ranges between D2 and D3 with a of 83.42 and 13.68% respectively. Only 2.89% of the buildings stock expected to affect by a damage grad D1. The minimum and the maximum values of the μ_D are 0.87 and 2.51 respectively. For the seismic scenario of the intensity I(EMS-98) = VIII, the majority of masonry buildings have a mean damage grade lying between 1.67 and 3.53 ($1 < \mu_D < 4$), which refers to a probable damage between D3 and D4 (expressed in terms of the EMS-98 scale) with a rate of 76.05% and 19.21%, respectively. Moreover, rates of masonry buildings of 4.74% are expected to suffer a damage grade D2. The results shows that for the seismic scenario I(EMS-98) = IX, the expected damage grades computed with the proposed method range from D4 to D5 ($2 < \mu_D < 5$), wherein severe damages and potential local collapses are expected for about 87.89 and 8.68% of buildings, respectively. Only 3.42% of the analyzed buildings present a damage grade D3. The minimum and the maximum values obtained for μ_D are 2.72-4.26. Regarding the last considered scenario I(EMS-98) = X, the great majority of the masonry buildings have a mean damage grade ranging between D4 and D5 ($3 < \mu_D \leq 5$), which refers to a probable damage between D4 and D5 (expressed in terms of the EMS-98 scale). Considering such intensity, the majority of masonry buildings located in the old city center of Annaba should be collapsed at a percentage of about 6.32 and 93.68% for damage grades D4 and D5, respectively. The values of 3.70 and 4.66 were the peak values (minimum and maximum) for this damage scenario.

V. 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 [19]. 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 [20] and the known conditional probability of the damage grade to the building vulnerability, Iv and seismic intensity, I, given by $P[D_k|I_v, I]$:

$$P[R \mid I] = \sum_{D_k=1}^{5} \sum_{I_v=0}^{100} P[R \mid D_k] \times P[D_k \mid I_v, I] \tag{4}$$

Computing these values for the mean vulnerability value and the lower and upper bounds (I_v-σI_v; I_v; I_v+σI_v), 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 Annaba are shown in Fig. 5.

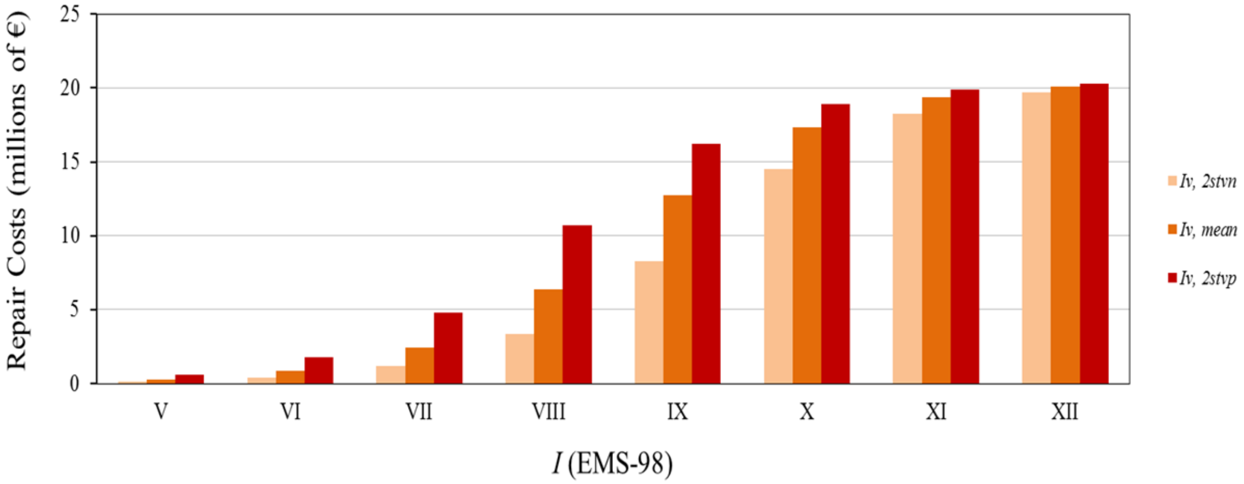


Fig. 5 Estimation of global repair costs

VI. FINAL COMMENTS

The vulnerability methodologies based on statistical methods and damage observation developed especially in the Euro-Mediterranean areas are far more interesting in the large-scale analysis in Algeria, essentially for two reasons: less resource requirements and simplified mechanical still need experimental testing validation.

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. Therefore, the results obtained in this work correlate well with the observed buildings construction features and general fragilities of built-up environment, proofing the reliability of the seismic vulnerability assessment methodology used. Even though the old city of Annaba is located in a moderate seismic hazard region, the high seismic building vulnerability brings up the considerable global seismic risk for building stock and historical area. The level of damage estimated for these buildings is an indicator of its low resistance against seismic actions and the moderate to high values of damage and loss obtained for different intensities (VII to X) are consequence of the high vulnerability of these buildings.

The integration of the results in a GIS tool is fundamental in a vulnerability assessment at this urban scale, thus being useful for its management and analysis. The possibility of spatial presentation of results is a significant tool in the support of the mitigation strategies and management of seismic risk.

ACKNOWLEDGMENT

The authors thank also the Annaba city council (technical organism in charge of the Technical Control of Construction, CTC) and DUCH (Direction of Urban planning and Construction of Habitation) for the data provision.

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