VULNERABILITY CURVES FOR ALGIERS MASONRY STRUCTURES

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Abstract

The amount of damage which masonry structures can undertake in a case of a seismic event with a given intensity can be estimated using the vulnerability curves. The latest are of a major importance before any technical decision is taken, such as reinforcement or demolition. For this purpose, vulnerability curves for masonry constructions using vulnerability index were developed. Within this paper, the state of the existing structures is assessed using "the vulnerability index” method. This method allows the classification of masonry buildings taking into account both, structural and non structural parameters, considered to be ones of the main parameters governing the vulnerability of the structure. Vulnerability curves for Algerian unreinforced masonry structures (URM) using vulnerability index are constructed by the use of a translation method, allowing the determination of the vulnerability curves from one region to another. Analytical functions linking the mean damage ratio to the seismic intensity and the vulnerability index are given. The obtained vulnerability curves were compared to those provided by Risk-UE project.

Keywords: URM structures; Seismic; Vulnerability index; Vulnerability curves, Analytical function

1. Introduction

Most of the buildings constructed before the sixties in Algiers and its suburbs are typically low and mid rise multi-storey buildings, made of stone and/or brick masonry walls or infill light steel framing. These buildings were constructed according to construction procedures where seismic regulations were not fully implemented. These types of constructions are known to be vulnerable to seismic hazard. This was particularly visible during the recent earthquakes that stroke many regions in Algeria such as, Ain-Temouchent in 1999 and Boumerdes in 2003. The post-seismic investigations have shown extensive damages to such masonry structures.
In order to undertake any reinforcement actions to lower the seismic risk, it is essential to estimate at a large scale the seismic resistance capacity of these constructions. One of the methods used to perform this task is the method of the seismic vulnerability index. In this method, the vulnerability index is established individually for each construction. The vulnerability index is an indicator of the structure state. This allows knowing the seismic capability of the constructions of a given area to withstand the seismic forces and consequently classify them. One of the first studies carried out on vulnerability index was initiated by the GNDT (Group of National Defense against earthquake) [1, 2], named as the methodology of level II. This method is based upon observation and given data relative to the constructions. The structural and non structural parameters playing a significant role in the seismic response of the structure should belong to one of the four vulnerability classes (A, B, C or D) described by [3, 4]. A methodology called "Level 1", allowing the estimation of the vulnerability construction of several European cities within the framework of the European project RISK-UE [5] was developed. The classification used in the RISK-UE project was based on EMS-98 [6]. In Portugal, inspection survey of the old masonry buildings of the old city centre of Coimbra has been carried out. A proposed method which determines the level of vulnerability is presented by [7]. In Italy, the ReLUIS Project had the aim to evaluate and to reduce the seismic vulnerability of existing masonry buildings [8].

In Algeria, work relating to the estimate of the masonry constructions vulnerability using vulnerability index was undertaken. These studies allowed the classification of buildings in vulnerability class translating its seismic quality [9, 10, 11, 12, 13]. Each class of vulnerability is consequently associated to a relation between the seismic intensity and the damage rate which a structure can undergo. This relation is known as the vulnerability function which is generally developed from the “Damage Probability Matrix” (DPM) [14, 15]. Several DPM and vulnerability functions were used or developed throughout the world by different authors [16, 17, 18]. This paper uses the principle of vulnerability index to develop vulnerability curves specific to the city of Algiers and takes into account, the characteristics of masonry constructions and the seismic experience feedback which will enable to classify such structures in vulnerability classes.

2. Vulnerability index method

The method consists in attributing a numerical value to each building representing its “seismic quality”. This number is called vulnerability index (VI); it is obtained by a weighted sum of the numerical values expressing the “seismic quality” of the structural and non structural items which are deemed to play a significant role in the seismic response of the building. Each parameter considered can belong to one of the four defined categories C1, C2, C3 and C4. These categories are declined as follows:
C1 expresses that considered parameter reflects a good resistance, C4, expresses that considered parameter reflects a bad resistance, C2 and C3 represent intermediate situations.

For each parameter and each category considered, a coefficient (k) is identified expressing its seismic quality based on the feedback of seismic experience and statistical data from past earthquakes in Algeria (Ain Temouchent 1999 and Boumerdes 2003), Table 2. The feedback of seismic experience was prevailing in the sense that a statistical analysis relative to 617 buildings in the case of Ain Temouchent Earthquake (1999) and 768 buildings in the case of Boumerdes earthquake (2003) was performed, this allow to provide the coefficients given in Table 1.

To avoid another difficulty pointed out the “Details” parameter was specified as follows: studwork, dividing walls, balconies, railing, cornices, chimneys, ventilation space, electrical network, gas network, water network and sewage network.

Table 1- Parameters values for vulnerability index evaluation

Parameter	**Coefficient K**			
	C1	**C2**	**C3**	**C4**
1. Total shear resistance of walls	0	0.05	0.12	0.21
2. Plan regularity	0	0.01	0.04	0.07
3. Elevation regularity	0	0.01	0.04	0.07
4. Walls connection	0	0.03	0.07	0.10
5. Walls type	0	0.01	0.03	0.05
6. Floor	0	0.01	0.03	0.05
7. Roof	0	0.01	0.03	0.05
8. Soil conditions	0	0.02	0.06	0.10
9. Pounding effect	0	0.01	0.04	0.07
10. Modifications	0	0.01	0.04	0.07
11. Details	0	0.00	0.02	0.03
12. General maintenance conditions	0	0.03	0.08	0.13

All these parameters are predetermined, so the method could be used by engineers even they are beginner. The vulnerability index, VI, of a construction will be expressed according Eq. (1):

$$VI = \sum_{i=1}^{12} k_i \tag{1}$$

The parameters determination is done based on an in situ construction expertise. A chart including the whole data necessary to evaluate the various parameters used and determining their categories has been developed. According to the value obtained for the vulnerability index, three vulnerability ranges P1, P2 and P3 are proposed, Table 2:

Table 2 - Vulnerability index ranges

Ranges	**P1**	**P2**	**P3**
VI	0 – 0.20	0.20 – 0.60	0.60 – 1
Colour	Green	Orange	Red

The P1 range associated to the green colour classifies the construction to be resistant with no requirement to any repairs. The P2 range associated to the orange colour classifies the construction to be moderately resistant which require reinforcement. The P3 range associated to the red colour classifies the construction to be weak with low resistance which requires demolition. This ranges make the interpretation easy, in the sense of the engineer can classify the considered building according its vulnerability index. Especially, this index range from zero to one. Zero express a building with good seismic resistance (green) and 1 express a building with a bad seismic resistance (red). Table 3 was used to classify the construction of Belouizdad district (sub-paragraph 4.1).

3. Development of vulnerability functions

The evaluation of the seismic loss takes into account the hazard of the site and the vulnerability of the existing buildings. The damage distribution is obtained by convolution of the probability function of hazard distribution and the conditional probability function of the vulnerability distribution for a given stock of building. The damage rate (DR) is a variable related to the physical damage of a typology at the risk and depends on the factor of vulnerability V of this category as well as the intensity (I) of the seismic movement within the site (DR = f(I, V)). The latter, is a nondeterministic variable, because buildings of the same vulnerability on the level of the same site can suffer different damage with different intensity. This leads us to a conditional probability distribution of the rate of damage defined by P(DR/V, I) generally given by the damage probability matrix (DPM). The expected value of this distribution is the mean damage ratio (MDR) define as MDR(I) = E(DR/I)). The functions of the average damage rate are usually known as vulnerability curves.

The vulnerability curves express the average damage rate which a stock of buildings belonging to various vulnerability classes with respect to various seismic intensities could undergo. These curves are a function of the constructive system, of the site on which the city is built as well as certain numbers of local parameters. So each city has its own vulnerability curves. The methodology defined in [19] allows the translation of the buildings vulnerability functions from region to region or from area to area by systematically considering the differences in buildings design codes. This methodology was adopted in order to determine the vulnerability functions of masonry building for Algiers. Indeed these curves will be deduced from those obtained from damage matrices after Friuli earthquake (courtesy of Pr. D. Benedetti). This area in Italy is an area which is similar to Algiers (same kind of masonry, same geographic conditions...)

3.1 Principle of the method

In this method, the difference between earthquake vulnerability curves of a particular building type in two regions or areas can be considered through combination of a shift and a rotation from a reference curve. The values of shift and rotation are quantified based on the differences between building codes [19]. For the convenience of description, the vulnerability function to be determined for a region or area with insufficient damage data is referred to as the “target”, while that used as the basis for translation is referred to as the “reference”.

The design base shear and the ultimate displacement capacity of the building control the translation of the vulnerability functions from one region to the other. Under moderate levels of ground shaking, the vulnerability characteristics of the buildings in two areas or regions can be regarded as identical, except for a shift of the vulnerability curve along the Modified Mercalli Intensity (MMI) axis based on the difference between their design base shear. In buildings code, the design base shear (V) is proportional to the peak of the ground acceleration (PGA). The PGA can be related to MMI through an empirical relation. The relation established by Murphy and O' Brien was adopted. So that the shift along the MMI axis of the vulnerability functions [19] is:

$$\Delta I = \left(\frac{Log_{10}\left(V_C / V_R \right)}{0.25} \right) \tag{2}$$

ΔI is the MMI shift, V_C and V_R represent the target and the reference design base shear respectively.

In addition, for the same type of structural system and the same design base shear, the difference in the ultimate deformation capacity of two buildings to the translated vulnerability curve will be a rotation to the intermediate curve starting at the point of inelastic structural response $I_{Inelastic}$, and ending at the intensity corresponding to severe structural damage, I_{severe} . The difference between MDR’s of the reference and the target buildings at I_{severe} is given by:

$$\Delta MDR(I_{Severe}) = \left(K_2 \frac{\delta_R}{\delta_C} - 1 \right) . MDR_R(I_{Severe}) \tag{3}$$

Where: K_2 is the coefficient depending on the relationship of MDR with ultimate deformation capacity of a building. In practice, the inter-story drift or roof drift can be used as a measure of deformation capacity of the building. Due to the lack of detailed experimental data, K_2 is simply taken as 1 [19].
δ_R and δ_C represent the reference and target ultimate displacement capacities of the building respectively.
I_{Severe} is intensity for which severe damage is observed in the building. According to seismic code, the inelastic behaviour of the buildings starts at about MMI 7 and severe structural damage at about MMI 10.
In order to determine the vulnerability curves for Algiers town the Italian and Algerian seismic codes are used to obtain the parameters which control the translation of the curves. These parameters relate to the fundamental period of the structures, the behaviour factor and ultimate displacement. To properly implement the methodology, the construction practices related to the buildings whose vulnerability functions are served as references should be consistent with the effective edition of the code in the reference region. The 1986 edition of the Italian building code is used as reference code for translation from Italy [19], while the 1988 Algerian seismic code [20] is used for the target region it means Algiers. This choice is made because the two seismic codes are close, so they have quite the same level of knowledge and philosophy in their specification.
The seismic design base shear of the building in the reference area is written: $V_R = C_R W$.
The seismic design base shear of the building in the target area is written: $V_C = C_C W$.

3.2 Translation control parameters

The design base shear according to two codes quoted above is obtained by considering that the zone under study is of an average seismicity. The shear base coefficients C_C and C_R allow the calculation of ΔI by using Eq. (2). Table 4 gives the control values thus allowing the determination of Algerian vulnerability function.

Table 4 – Control parameters for the translation of the vulnerability curves

Construction	**Shear base coefficient C**		**MMI difference ΔI**	**Ultimate displacement δ Italian Code 86**	**Ultimate displacement δ Algerian Code 88**
	Italy C_R	Algiers C_C	Algiers-Italy	1.5%	1%
Masonry	0.28	0.30	0.12		

By considering Eq. (2), Eq. (3) and Table 8 the MMI difference ΔI between the two countries is determined as well as the mean damage ratio (MDR), allowing to plot the Algerian vulnerability curves which will be presented in the next paragraph.

4. Application

As an application the district of Belouizdad has been considered. This district is located East of Algiers. The number of inhabitant is of 59248 people according to the census of 1998 (RGPH 1998) and number of masonry buildings is about 643. The latter are primarily made up of stone and/or brick walls. Their average thickness is about 60 cm. The floor is structured for the majority in an arch. For these masonry constructions, the vulnerability index VI and their classification will be determined. The vulnerability functions are then established giving the mean damage ratio (MDR) according to the seismic intensity (I) for various classes of vulnerability index VI. A data base is established and managed by a geographical information system.

4.1 Vulnerability index

In situ observations on structures are important information required to assess the vulnerability of structures. An investigation chart for a survey was elaborated. The chart contains:

a) General data , b) Geometric characteristics, c) Information on the structural system, d) Information on the ground, e) Details on the non structural elements, f) General maintenance conditions.

The vulnerability index calculated for the 643 buildings of the data base, enabled to have the results given in Fig.1.

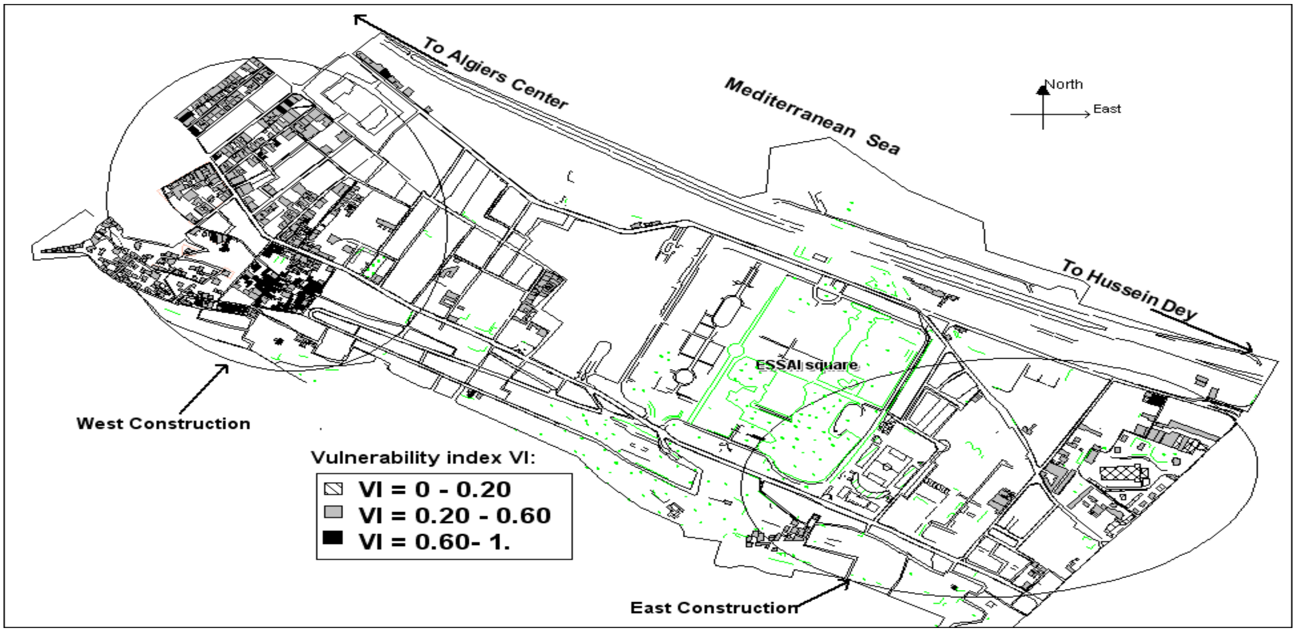

Fig. 1a - General view of masonry construction for Belouizdad district according their vulnerability index

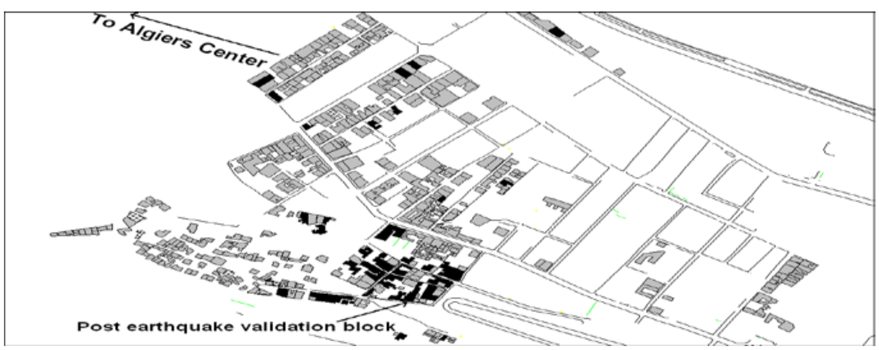

Fig. 1b - Zoom view of West Construction

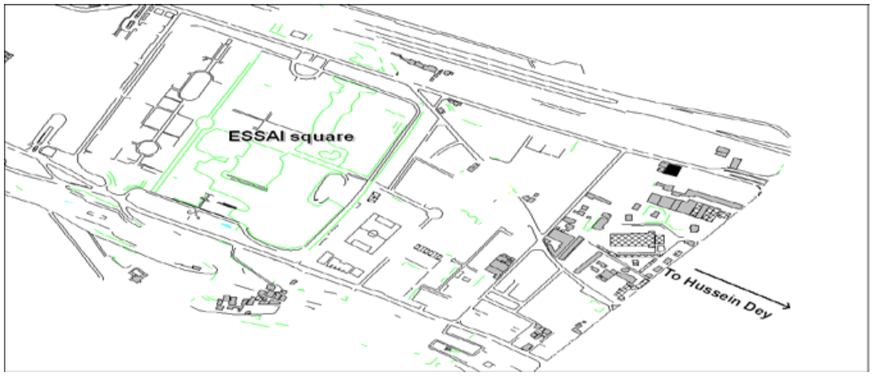

Fig. 1c - Zoom view of East Construction

In order to show the validity of vulnerability index values, the results are compared with those provided by the Structural Engineering Control (CTC: official organization in charge of control in Algeria) following the survey carried out on 179 buildings. The results are given in Fig. 2 and Fig. 3. The calculation of the vulnerability index of the buildings has led to the results given in Fig. 2, their classification is done according to Table 3. The vulnerability index calculated provide an estimate of the buildings state with a difference of 9% compared to the one given by the CTC survey. The CTC survey is done according to the engineer's experience. The main observed damages are listed and the reasons might be also given. Then an opinion on the state of the construction is given which led to its classification. The results show that approximately 80% of masonry constructions of the Belouizdad district have an average seismic quality. Indeed the vulnerability index for 508 buildings is included in P2 range which shows an average vulnerability. About 10% of the buildings are very vulnerable to the seismic action.

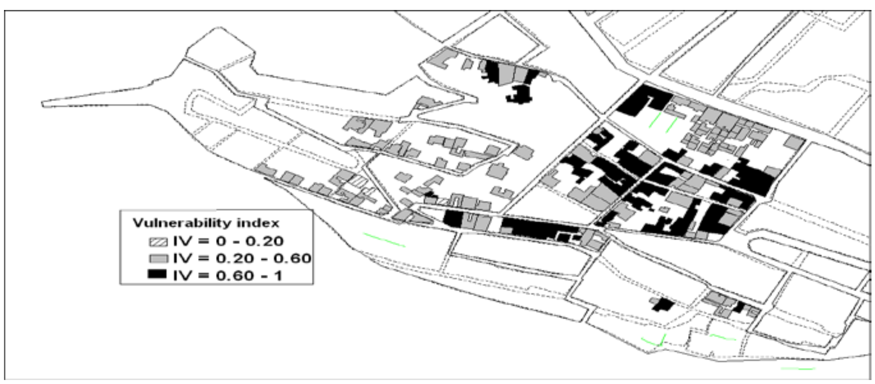

Fig. 2 - Vulnerability index distribution for studied buildings

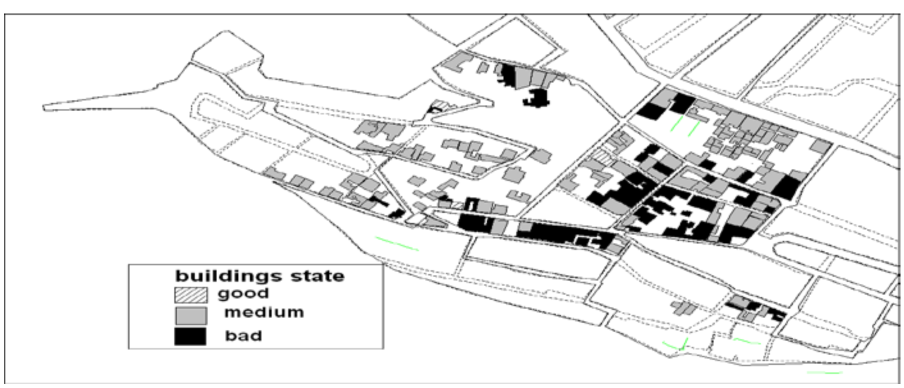

Fig. 3 - CTC survey

As a result, 90% of the buildings of Belouizdad district are vulnerable and require an intervention for reinforcement or replacement (Fig. 4).

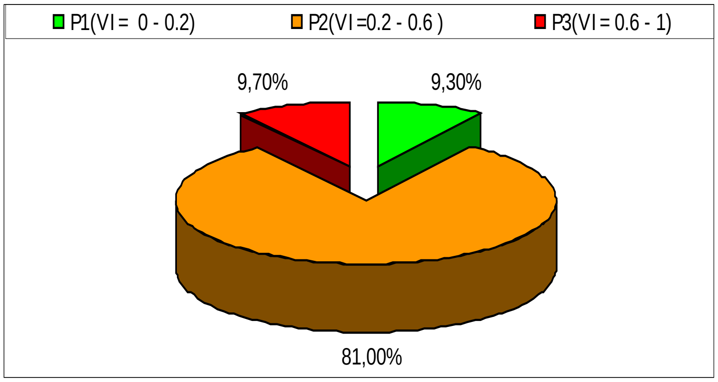

Fig. 4 - Vulnerability buildings distribution

These results can be explained by the age of constructions, the lack of maintenance of the buildings and the modifications made to the structures, increasing their vulnerabilities.

4.2 Vulnerability curves

In order to finely represent the vulnerability of masonry constructions of Belouizdad district, ten vulnerability classes have been considered. A step of 0.1 of vulnerability index was taken. Fig. 6 shows the distribution of masonry constructions according to vulnerability classes. The ten vulnerability classes CL1(IV = 0.-0.1), CL2(IV = 0.1-0.2), Cl3(IV = 0.2-0.3)...,CL9(IV = 0.8-0.9) and CL10(IV=0.9-1) are respectively representative of the buildings having a decreasing seismic quality.

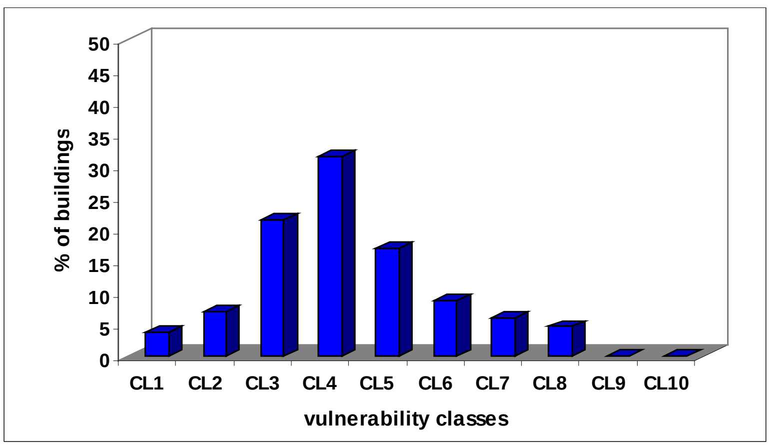

Fig. 6 - Constructions classification in Belouizdad district according to vulnerability index

For each classes (CL1, CL2,… CL10) a vulnerability function was derived (according § 3). Each curve is represented on figure 10 by dots. Three sets of curves can be identified belonging to the three defined vulnerability ranges. A polynomial interpolation was performed in order to obtain a representative curve for each range (see Fig. 7). This interpolation has a correlation of 0,978 for P3, 0,965 for P2 and 0,971 for P1.

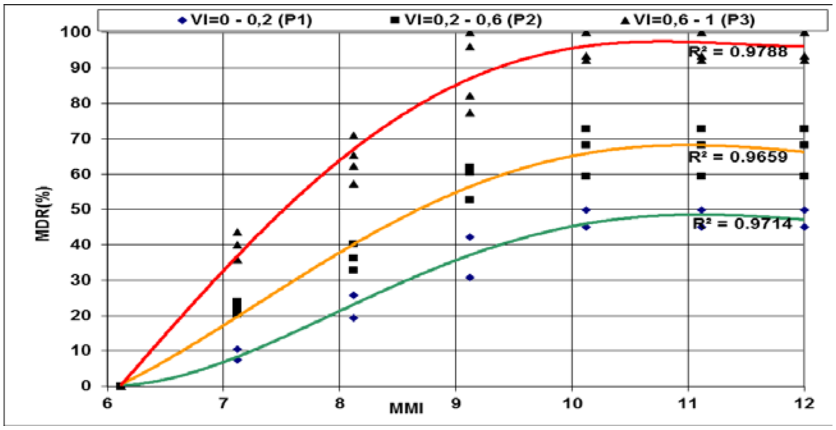

Fig. 7 - Algerian vulnerability curves for masonry constructions

The vulnerability curves (Fig. 7) show that the mean damage ratio for the same intensity I is more significant when constructions present a high index of vulnerability. As an example, the mean damage ratio (MDR) for intensity 8 is 20 % for a structure with lower vulnerability (P1 range), 40 % for vulnerable structures belonging to P2 and higher than 55% for very vulnerable structures belonging to P3.

4.3 Analytical proposal for a damage-intensity function

The analytical representation of the vulnerability curves allows the link between the mean damage ratio (MDR), the intensity and the vulnerability index VI. These analytical functions are obtained by interpolation of established vulnerability curves and represented on Fig. 12. To each vulnerability class, a relation, damage rate/seismic intensity is then associated, the following analytical functions are proposed:

$$\begin{cases} MDR(VI, I) = (-3.65VI - 0.56)[I + 1.52Ln(VI) - 15.77][I + 0.11Ln(VI) - 6.11] \\ I = 6.3,11 \end{cases} \quad (4)$$

5. Discussion

On the work carried out within the framework of the European program RISK-UE, an LM1 methodology was developed. LM1 method is favoured as suitable for vulnerability, damage and loss assessments in urban environments having not detailed site specific seismicity estimates but adequate estimates on the seismic intensity. The Level 1 (LM1) method is largely based on statistical FM/DPM method, i.e., statistical correlation between the macroseismic intensity and the apparent (observed) damage from past earthquakes. It is derived starting from the European Macroseismic Scale (EMS-98) – the modern macroseismic scale that implicitly includes a vulnerability model, although defined in an incomplete and qualitative way. The LM1 methodology recognizes no-damage state labeled None, and five damage grades termed as Slight, Moderate, Substantial to Heavy, Very Heavy, Destruction. Building Classification Matrix (BTM) systemizing the distinctive features of European current building stock comprises 23 principal building classes grouped by: structural types and material of construction. The LM1 method is used to define vulnerability classes, vulnerability indices and to develop DPMs pertinent to RISK-UE BTM.

Vulnerability Index (VI) is introduced to represent and quantify the belonging of a building to a certain vulnerability class. The index values are arbitrary (range 0-1) as they are only scores to quantify in a conventional way the building behaviour. The LM1 method defines mean semi-empirical vulnerability functions that correlate the mean damage grade μD with the macroseismic intensity I and the vulnerability index VI.

$$\mu_D = 2.5\left[1 + Tanh\left(\frac{I+6.25V_I-13.1}{2.3}\right)\right] \quad (9)$$

When a building typology is directly identified within BTM, the vulnerability index values (VI*, VI- ,VI+ ,VImin, VImax) are univocally attributed according a proposed table. Then a VI is calculated by adding coefficients (Regional Vulnerability Factor ΔV_R and Behaviour Modifier ΔV_m) increasing or decreasing the vulnerability of the structure depending on the considered parameter.

In this study, the VI is determined by in situ observed parameters, except one parameter (Lateral shear resistance); This one need calculation and considers numbers of factors (weight, dimensions, shear resistance), so it take into account implicitly the rise of the building under study. In this method the typology of the building is not considered directly.

The present work deals with unreinforced masonry structures (URM), the most found typologies in Algeria belong to buildings with stone and/or brick and composite steel and masonry slabs i.e. M1.2 and M3.3 Risk-UE classification. So in order to compare the vulnerability functions of these two classifications, the Mean Damage Ratio (MDR) will be derived using the LM1 method.

Considering VI* the most probable value of the Vulnerability Index VI and applying the eq. (9) the mean damage grade is obtained for the two typologies (Fig.8). As it can be seen the two curves are very close so the mean damage grade will be considered as the same for the two typologies.

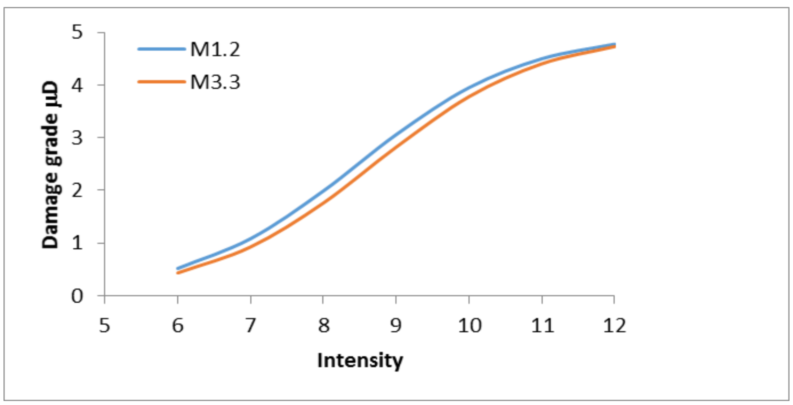

Fig. 8 - Mean semi-empirical vulnerability functions

Then using Table 5, MDR for M1.2 and M3.3 is obtained and represented on Fig. 9.

Table 5 - Damage grading and loss indices for URM structures

Damage state	**Damage state label**	**Range of loss Index-URM**	**Central index**
0	None	0	0
1	Slight	0 – 0,04	0,02
2	Moderate	0,04 – 0,20	0,12
3	Substantial to heavy	0,20 – 0,40	0,30
4	Very heavy	0,40 – 0,70	0,55
5	Collapse	0,70- 1	0,85

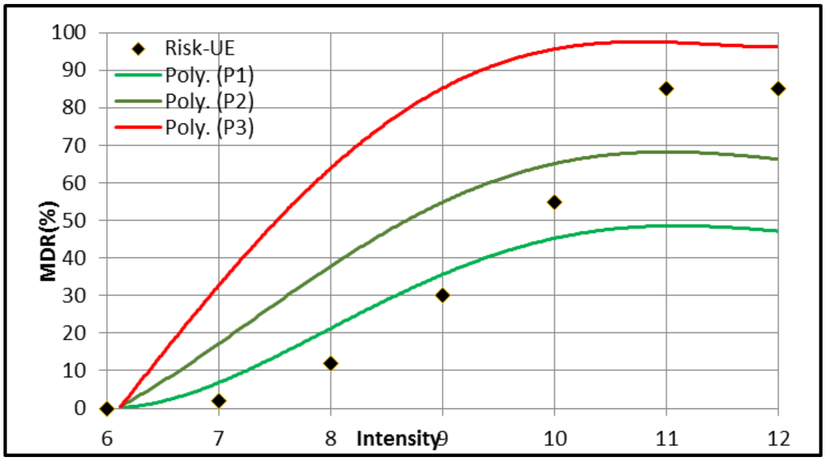

Fig. 9 - Mean damage ratio for M1.2 and M3.3 Risk-UE buildings typology

On the same figure are represented the vulnerability functions derived in this study. As it can be observed the developed vulnerability curves are more conservative than Risk-UE vulnerability function. This can be justified by the lack of maintenance and their intensive use due to the increase demography.

6. Conclusion

In this study, a vulnerability index method for URM was developed. A Delphi program was elaborated gathering the whole information necessary to calculate or deduce the parameters class. The information was stored in a Geographical Information System (GIS). Three classes of vulnerability were established and vulnerability curves for unreinforced masonry constructions were developed. A comparison with LM1 (Risk-UE) method shows also that there is a good correspondence between the two approaches. Note that the most important goal of this assessment tool is to be simple for application even for personnel with slight experience in behaviour of masonry structures under seismic action.

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