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Damage Potential and Vulnerability Functions of Strategic buildings in the City of Algiers

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Abstract

The estimation of losses resulting from an earthquake requires that for each building class, the relationship between the intensity of ground shaking and damage degree must be known or developed. Potential earthquake damage to structures, human beings and personal property have been the scope of numerous studies. Different approaches have been employed so far to estimate earthquake casualties and damage. This paper describe the basic concept for development of analytical vulnerability functions based essentially on so called damage model which was performed from probabilistic studies on seismic capacity of existing buildings in the city of Algiers (Algeria). Regarding the developed model for assessing the seismic damage, vulnerability functions of specific losses (potential losses for a specific urban area in terms of meter square area of building slabs which may involve causalities) were developed in order to predict the expected seismic risk for a given ground motion scenario.

Keywords: *vulnerability curves, risk analysis, building damage, loss assessment*

1. Introduction

It is very important to evaluate the seismic risk of existing buildings in a prone area, in order to reduce the expected damages when a severe earthquake takes place (Murao and Yamazaki, 1999; Benedetti *et al.*, 1988). For specific needs of evaluation and reduction of the seismic risk in the urban zones (Fajfar and Kreslin, 2010), the present study introduces a complete procedure for seismic vulnerability evaluation and prediction of the damage/loss ratio of existing buildings based on analytical vulnerability functions versus ground motion intensity (Kaplan and Sen, 2008). The concept suggested for the development of vulnerability functions of existing buildings, is based primarily on an analytical evaluation method of the seismic damage of this kind of buildings (Esteva *et al.*, 2010; Parodi *et al.*, 2008), introducing a nonlinear model for a given structure by using preliminary existing results. An application of this concept for strategic buildings in the city of Algiers (Fig. 1) has been done, in order to define an acceptable level of seismic risk by developing vulnerability functions for various classes of buildings (represented by various blocks in Figs. 2-5), chosen based on the typological classification according to the basic parameters such as the number of stories, the structural type etc.

Those various functions allowed the development of the specific functions of losses in terms of losses per square meter of slabs area necessary for the quantification of the level of risk which has occurred at the time of an earthquake by using two levels of expected seismic actions. The first level corresponding to moderate earthquakes that are expected to happen many times during the life of the building, with a return period of 100 years, the behaviour of the structures should remain in the elastic range, without any damage and the building can be used immediately. The second one, corresponding to major earthquakes that are expected once during the life of the building; with a return period of 500 years; the structure may behave in the non linear range, with a controlled level of damage. No heavy damage or collapse is allowed, and the building should be reused after inspection and slight repairs.

2. Prediction and Estimation of Earthquake Losses

2.1 Methodological Approach and Model Output

Uncontrolled development and urbanization of seismic prone regions increase rapidly their vulnerability and seismic risk if no appropriate measures are undertaken for protecting human lives and material properties. Therefore, the process of pre-disaster seismic risk mitigation, reduction and management should start at the level of physical and urban planning and should be constantly implemented at all stages of development (ASCE 31-03 (FEMA310), 2003).

For the planning of new developments or post-earthquake reconstruction, earthquake preparedness and properties insurance

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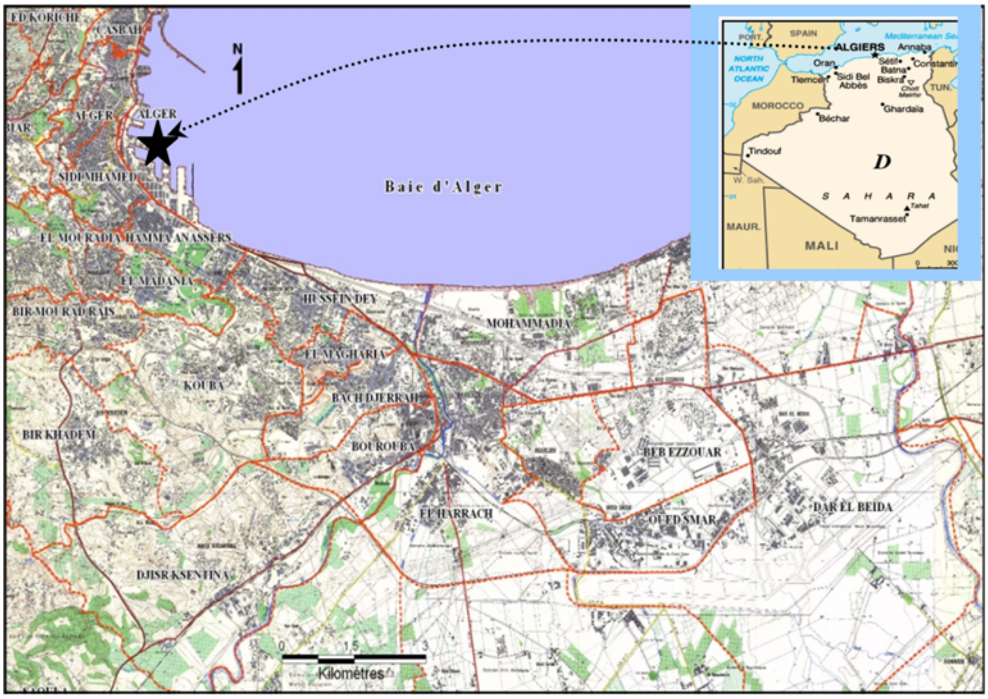

Fig. 1. Algiers Map – CGS Source (Algeria)

Fig. 2. Bloc I, Algiers Hospital "Mustapha Pacha" – Google Map-CGS Source (37 Buildings)

Fig. 3. Bloc II, Department of Telecommunications - Google Map-CGS Source (12 Buildings)

as well as for decision-making, the quantitative seismic risk assessment tools are needed for different building classes and locations. Recently, efforts have been made in the development of quantitative loss prediction procedures.

Loss evaluation is presently made with various degrees of rigor. However, all proposed theoretically or empirically based models for predicting seismic losses of an urban area share the common necessity of performing a series of complex procedures requiring extensive computations and proper acquisition and manipulation of the building data. A systematic approach is indispensable and the problem of prediction and estimation should, therefore, be assessed through the following basic steps (see Fig. 6.):

- Zonation of the region and classification with inventory of material property (elements at risk)
- Identification of the effects of local site-soil conditions in modifying the severity of the event at a given location.
- Prediction of the ground motion parameters, in this particu-

Fig. 4. Bloc III, Algiers City Hall Department - Google Map-CGS source (04 Buildings)

Fig. 5. Bloc IV, Fire Fighters Department - Google Map (17 Buildings)

Fig. 6. Inventory Methodology for a City or Region

lar case, affecting the earthquake damage potential for each zone

- Prediction of losses to any individual element at risk for each zone as well as prediction of cumulative losses for all considered elements at risk in the entire region/city.

The different stages necessary in the prediction of the seismic losses and the collection of the various structures which can be exposed to a severe ground motion in an urban area, take into account several types of structures sensitive to various modes of rupture and levels of vulnerability. Generally, most of structures are masonry buildings which will be damage during an expected earthquake.

In order to predict and estimate the losses associated with each structure, a classification in type of buildings must be established according to their physical and mechanical characteristics, to the type of construction material, age of the building etc

2.2 Overview of Building Damage in Algiers City due to Boumerdes Earthquake

On May 21st, 2003, at 19:45 local time, a strong earthquake with a magnitude of 6.8 hit the northern-center part of Algeria, where the epicenter was located in the Mediterranean Sea, seven kilometers north of Zemmouri city, and 60 kilometers east of the capital Algiers. The main shock was followed by severe tremors with high magnitudes. The main shock and aftershocks induced a lot of damages and disturbed and/or disrupted the health services, school buildings, some roads, water supply lines, electricity, and telecommunications in the region. The worst-affected prefectures are Boumerdes in the first position and then come Algiers in the second position (Ousalem and Bechtoula, 2005; Benouar, 2008). The most damaged cities include Bourmedes, Zemmouri, Thenia, Bordj-menail, Belouizdad, Bordj-el-bahri, Rouiba, and Reghaia. Other neighbouring regions to Algiers and Boumerdes, like the prefectures of Tizi-ouzou, Bouira, Blida, Tipaza and Chlef were also affected by the enormity of the earthquake, however, the catastrophe and damage level were far below those of Algiers and Boumerdes.

Officially, 2,278 persons died 11,450 human casualties, more than 180,000 homeless, 10,280 collapsed constructions and US$5 billions as a direct total loss.

In Algiers prefecture, the most affected areas were also the nearest to the epicenter, as shown in Fig. 7 and Fig. 8 to 11, where the number of damaged buildings in the sub-prefectures of Dar el-beida and Rouiba was very high compared to other

Fig. 7. Algiers Sub-Prefectures

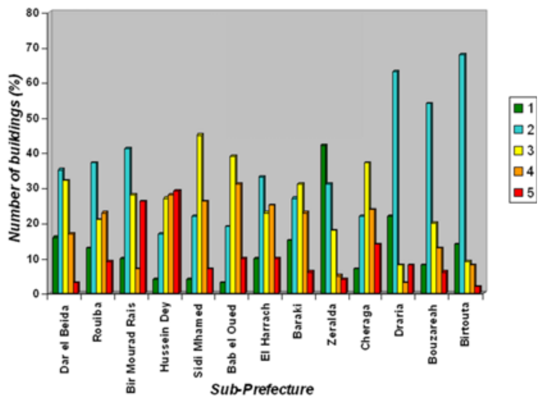

Fig. 8. Inventoried Buildings and Damage Level (1 Green to 5 Red) for each Sub-prefecture in Algiers Prefecture

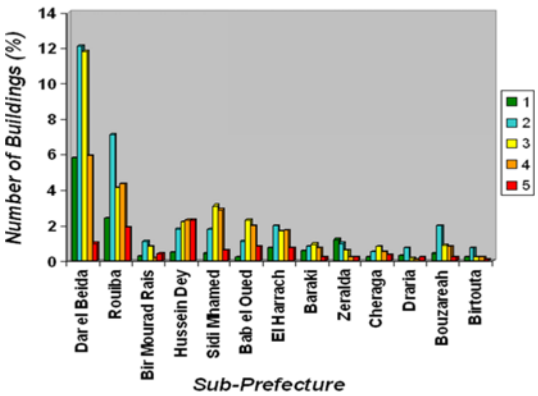

Fig. 10. Damage Level as Percentage to Total Inventoried Buildings in Algiers prefecture

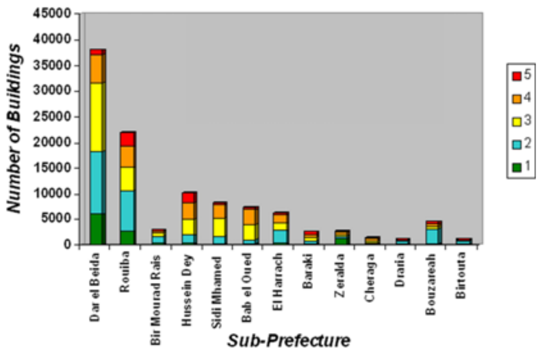

Fig. 9. Damage Level as Percentage to Total Inventoried Buildings in each Sub-prefecture

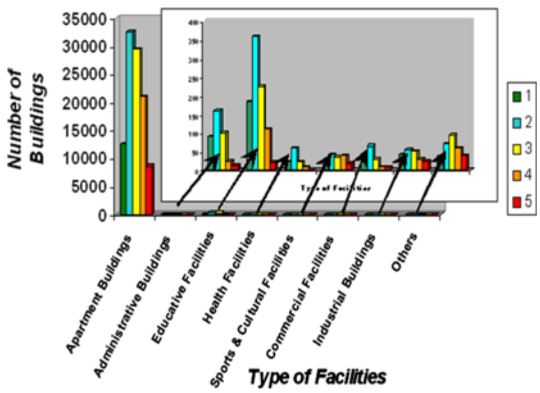

Fig. 11. Damage Level and Number of inventoried Buildings by Type of Facility

neighbouring areas in the prefecture. The results are given in term of number of inventoried buildings (Fig. 8), in percentage as to the total number of inventoried buildings in each sub-prefecture (Fig. 9) and in percentage as to the total number of inventoried buildings in the prefecture of Algiers (Fig. 10). The number of investigated buildings reached a very high numbers. Like Boumerdes prefecture, number of investigated apartment buildings was very high among other types of facilities (Fig. 11). Actually, around 55% of inventoried constructions in Algiers prefecture were moderate to heavily damaged where around 28% of apartment buildings, 12% of administrative buildings, more than 15% of educative facilities, more than 10% of health facilities, more than 30% of sport and cultural facilities, around

12% of commercial buildings and more than 25% of industrial buildings were heavily to very heavily damaged.

2.3 Damage Model

The experience from passed earthquakes showed that certain levels of damage are inevitable. Building designed against earthquakes should allow in some stages a certain level of damage. The model of damage proposed, limits explicitly the structural damage to a tolerable level. The structural damage is expressed quantitatively in terms of damage index, as a linear combination of the maximum deformation and energy dissipated during a cyclic loading whereas the acceptable index of damage was defined on the basis of calibration with the data of the damage observed at the time of an earthquake (Park *et al*., 1987). However, an empirical relation has been developed in order to estimate the nonlinear seismic responses of the building. The damage index of the structural elements under a seismic loading is generally caused by the combination of the effect of the maximum deformation and dissipated energy, given as follow:

$$D = \frac{U_m}{U_f} + \frac{\varepsilon}{Q_u \cdot U_f} \cdot \int dE \tag{1}$$

Where:

Q_u = Ultimate shear force
U_m = Maximum deformation
U_f = Deformation at failure
$\int dE$ = Cumulative hysterical energy
ε = Constant (also called parameter of the damage index = 0.075)

Equation (1) causes a linear damage surface; a random vibration method using a nonlinear hysteretic restoring force model to describe the load-deformation behavior is adopted to evaluate the response statistics required for damage assessment. The proposed damage model is calibrated using the damages of number of buildings damaged during past earthquakes. In accordance with the behavior of structures during past earthquakes, and the analyses of collected data from the damaged structures; Park *et al.* (1987) deduced that the seismic damage of structures is due mainly to some characteristics parameters such as, the peak ground acceleration, the structural period, the duration of the strong motion and so on.

Hence, the damage of structures is evaluated in terms of ratio of the seismic load (L) to the structural strength (R). The seismic force is defined by effective acceleration, the duration of the strong motion and the predominant period of the ground motion, whereas the structural strength is defined by the capacity in ultimate shearing strength at the base, by the ratio of the maximum deformation under the seismic load and the ultimate deformation of the structure and by the cumulated dissipated energy, whose general expression is given by the following equation:

$$D = \frac{L(PGA, t_d, T/T_g)}{R(T, U_u)} \tag{2}$$

Where:

PGA = Peak ground acceleration
t_d = Duration of strong motion
T = Structural period
T_g = Predominant period of ground motion
U_n = Ultimate displacement

From a regression analysis Ang *et al.* (1985) proposes the following relationships:

$$L = \beta_1 \cdot h_{T_g} \cdot (E_a)^{\alpha 1} \cdot (t_d)^{\alpha 2} \text{ and } R = \beta_2 \cdot (T)^{\alpha 3} \cdot (U_u)^{\alpha 4} \tag{3}$$

Where β_1 and β_2 are constants; h_{T_g} is function of the ratio T/T_g and α_1, α_2, α_3 and α_4 are exponents to be determined.

$$h_{T_g} = \begin{cases} 1.0 & : T/T_g \le 0.70 \\ \dfrac{1}{(0.80(T/T_g) + 0.44)} & : T/T_g > 0.70 \end{cases} \tag{4}$$

This method of assessment of the damage index to a single degree of freedom can be generalized to the case of several degree of freedom systems, assuming only that the previous relationships applied to the sum of the indices of damaged floors S_D gives:

$$S_D = \sum_{i=1}^{N} D_i = \gamma_N \cdot h_{T_g} \cdot \frac{(E_a)^{\alpha 1} \cdot (t_d)^{\alpha 2}}{(T)^{\alpha 3} \cdot (U_{ue})^{\alpha 4}} \tag{5}$$

In which, γ_N a constant and U_{ue} the ultimate equivalent displacement; expressed as being the sum of ultimate displacements of stories, each one weighted by the component of the corresponding vector of distribution, i.e,

$$U_{ue} = \sum_{i=1}^{N} U_i \cdot R_{Di} \tag{6}$$

According to the study of the variation of the S_D of several buildings, the following formulas (Park *et al.,* 1987) were selected for the values of the exponents:

$$\alpha_1 = \alpha_4 = \frac{\alpha_2 - \alpha_3}{2};\ \alpha_2 = 0.35;\ \alpha_3 = -3.40 + 0.10.N \text{ and}$$

$$\gamma_N = 0.057.N^{-0.2} \tag{7}$$

N = Stories number

For different structural systems, T_g varies from 0.2 second for a firm soil to 0.8 second for a soft soil.

Once the sum of damage indices S_D and the damage distribution vector R_D are known, the damage of the i^{th} floor will therefore be:

$$D_i = R_{Di} \cdot S_D = R_{Di} \cdot \gamma_N \cdot h_{T_g} \cdot \frac{(E_a)^{\alpha 1} \cdot (t_d)^{\alpha 2}}{(T)^{\alpha 3} \cdot (U_{ue})^{\alpha 4}} \tag{8}$$

2.4 Development of Vulnerability Functions

The estimation of losses resulting from an earthquake requires that for each building class the relationships (vulnerability functions) between the intensity of ground shaking and damage degree should be known or developed. Potential earthquake damage to structures, human beings and personal property has been the scope of numerous studies (Kumitani *et al*., 2008; Rota *et al*., 2010; Oropeza *et al*., 2010). Different approaches have been employed so far to estimate earthquake casualties and damages. These approaches have combined in various ways the important input or determinant factors, including data from relevant historical and recent damaging earthquake, different steps have been used to estimate the seismic vulnerability of existing buildings mainly based on:

- Data on damages suffered by individual buildings in a considered region during recent earthquakes
- The damage state is expressed on a standard scale
- Buildings are classified according to structural type and material used
- Vulnerability functions, relating damage degree to the intensity of ground motion, are derived for each building class.

The methodological approach used in this study for the development of vulnerability functions (See Fig. 12), is based primarily on the quantification of the seismic damage of a building according to what is called "damage index for various types of buildings constituting in a dominant way the urban nuclei of Algiers city (see Fig. 1), mostly represented by some of its strategic buildings as shown in Figs. 2-4 and 5.

A building is considered strategic by its function and by the equipments that it contains. This damage index was formulated on the basis of nonlinear analytical model.

As shown on Fig. 12, several acceleration time histories taken from a worldwide earthquake data base have been used, based on their peak ground acceleration values. Three (03) computer programs have been used for the non linear dynamic response analysis, SDUAMB (Bozinovski and Gavrilovic, 1993a); UARCS (Bozinovski and Gavrilovic, 1993b) and DRABS (Bozinovski and Gavrilovic, 1993c). Buildings used in this study were designed using the computer programs mentioned above, either for masonry buildings or RC structures in which the maximum

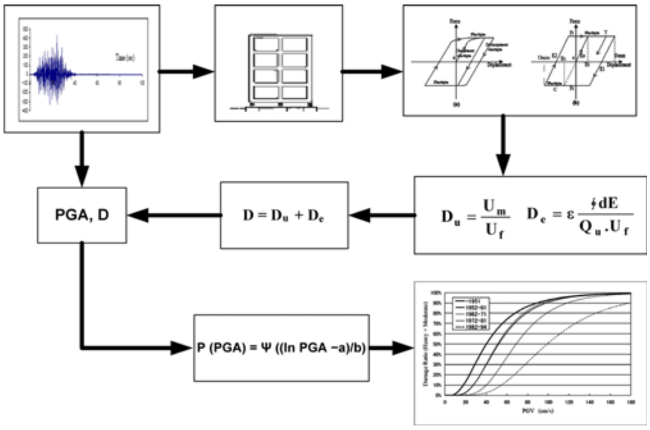

Fig. 12. Steps used to Construct Vulnerability Functions

displacement U_m, the displacement at failure U_f and the ultimate shear force Q_u are obtained. For the non linear dynamic response analysis, the PGA of the selected records was normalized to different excitation level from 0.1 g to 1.0 g having 10 excitation levels with equal intervals. The damage index D will be then estimated. Finally, the obtained damage index and the corresponding ground motion are combined to develop the analytical fragility curves for different structural systems used in this study.

Results in terms of the structural type, number of stories, total surface of floors as well as the number of buildings to carry out this study well are represented in Tables 1 and 2. These various data made it possible to make a typological classification of the various buildings represented in the blocs I, II, III and IV, while being based on certain characteristic parameters which influence the seismic behaviour.

The analytical vulnerability functions are developed while being based on more than 65 nonlinear dynamic analyses made for the various following structural types:

Table 1. Predicted Specific Loss for a PGA of 0.15 g

Bloc	Nbre of buildings	URM System		R.C Frame System		Dual System		R.C Walls System		Total Damage Area.	
		Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)
I	37	4762	27.5	15164	11.25	8483.5	24.16	/	/	28409	17.8
II	12	/	/	19929	/	/		3972	5.41	23901	10.3
III	04	14900	27.5	5750	/	/	/	/	/	20650	22.9
IV	17	/	/	8217.5	/	/	/	/	/	8217.5	11.3
Total	70	19662	27.5	49060	11.25	8483.5	24.16	3972	5.41	81178	15.6

Table 2. Predicted Specific Loss for a PGA of 0.25 g

Bloc	Nbre of buildings	URM System		R.C Frame System		Dual System		R.C Walls System		Total Damage Area.	
		Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)	Total area (m^2)	Damage (%)
I	37	4762	45.8	15164	20	8483.5	38.7	/	/	28409	29.9
II	12	/	/	19929	/	/		3972	10.4	23901	18.4
III	04	14900	45.8	5750	/	/	/	/	/	20650	38.6
IV	17	/	/	8217.5	/	/	/	/	/	8217.5	20
Total	70	19662	45.8	49060	20	8483.5	38.7	3972	10.4	81178	20.7

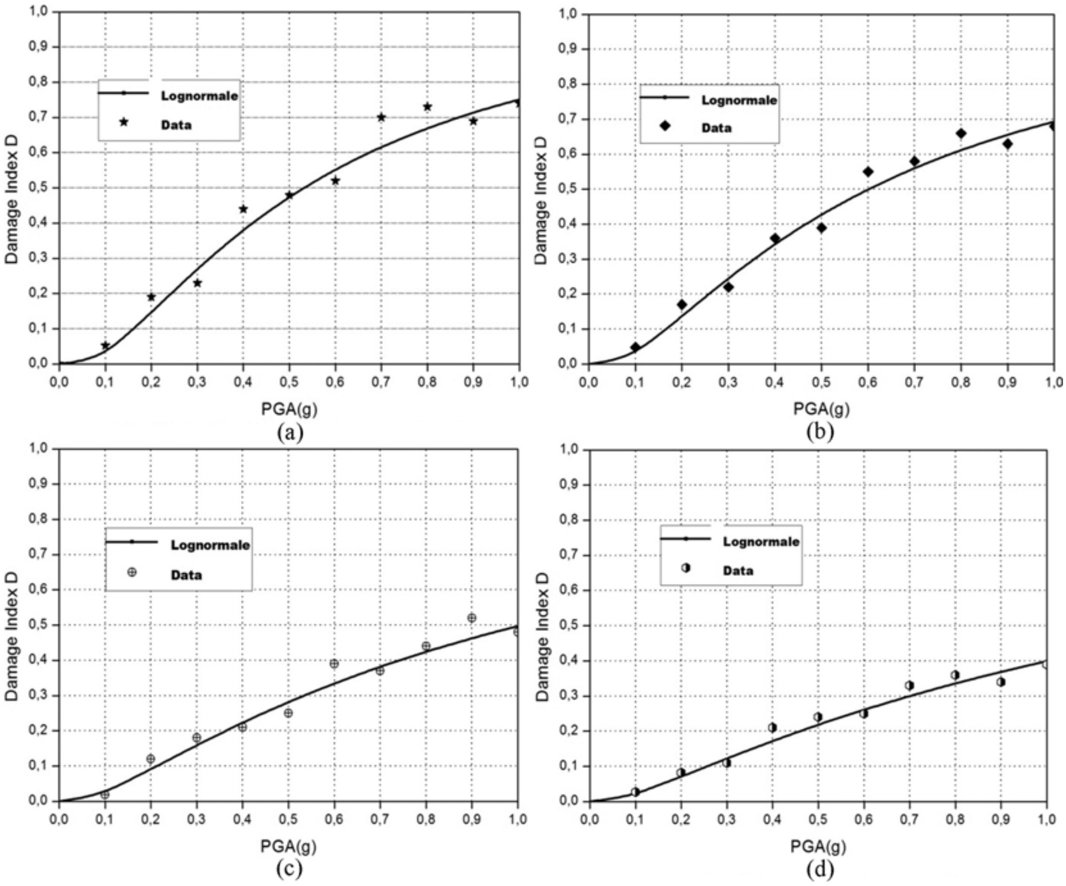

Fig. 13. Fragility Curves for Different Structural Systems using Regression Analysis: (a) Vulnerablility Curve for URM Buildings, (b) Vulnerability Curve for Dual System Buildings, (c) Vulnerability Curve for RC System, (d) Vulnerability Curve for RC Wall Buildings

- URM system: By considering unreinforced masonry buildings of more than 03 stories (standard BM) existing in a dominant way in the city of Algiers.
- Reinforced concrete frame system: By considering the buildings whose superstructure is composed of beam-column frames of more than 03 stories (standard BP).
- Dual system Buildings: By considering buildings made up of two types of bearing elements, reinforced concrete structures and unreinforced masonry bearing walls of more than 02 stories (standard BX).
- RC wall system: By considering buildings with RC walls as bearing elements of more than 03 stories of class D (standard BV).

Based on the collected data, regression analyses for the considered buildings according to their structural type were carried out. This phase was done by implementing the lognormal distribution that links the degree of damage D to the intensity of the ground motion represented by the peak ground acceleration PGA implementing the lognormal analysis using the mean and the standard deviation.

For a specific value of PGA, the cumulative probability P (PGA) of the occurrence of a certain damage equal or higher than rank D is assumed to follow a lognormal distribution given by:

$$P\,(PGA) = \Psi\,((\ln PGA - a)/b) \quad (9)$$

In which Ψ is the standard normal distribution and, a and b are the mean and the standard deviation of *ln PGA*. The two parameters of the distributions, a and b, have been determined by the least square method on lognormal probability state. Fig. 13 shows the fragility curves, for each structural system.

3. Results Interpretation

Although the characteristics of the soil and the number of stories have a certain influence on seismic vulnerability, the results showed that the type of construction plays a significant contribution in the quantification of the vulnerability. In fact, masonry buildings which exist in dominant way in the north of Algeria (specially in the city of Algiers with 70% URM system) have been designed without any regulations or seismic codes, this kind of structural system exhibits brittle behaviour, that is why, the most significant vulnerability is allotted to masonry buildings of BM type which present a much degraded state (see Figs. 14 and 15), and decreases for the other types of buildings.

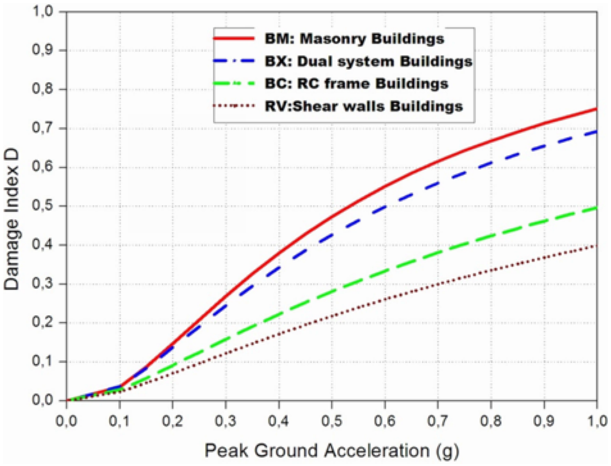

Fig. 14. Vulnerability Functions with Respect to PGA for Different Structural Types

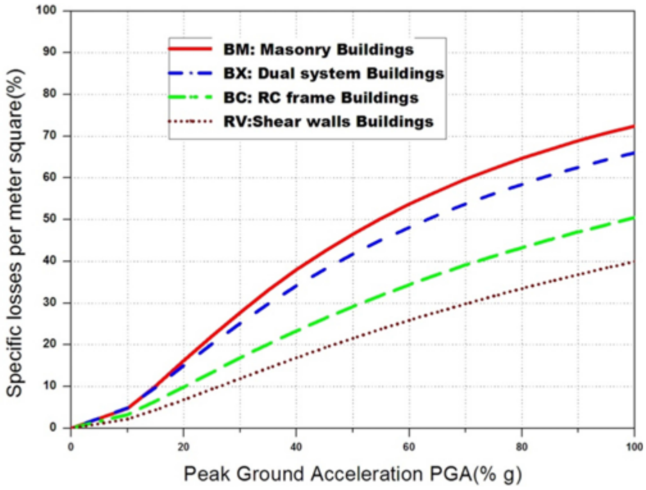

Fig. 15. Vulnerability Functions of Specific Losses with Respect to PGA for Different Structural Types

This very significant potential damage can be explained in term of dependence of the damage according to the maximum peak ground acceleration PGA. For the most vulnerable structures of BM type, it was noted that for a PGA of 0.15 g, 23% of the buildings will be damaged, by increasing the value of the PGA with 0.30 g, 52% of buildings BM will be damaged by giving a difference of 29% for a significant increase of 0.15 g of the PGA, as illustrated in Fig. 14.

In addition, this model which allowed the development of vulnerability functions does not take into account certain critical parameters in relation to the structure such as the age of the building, dimensions in plan and details of construction. By taking into account those various factors in the analysis, the vulnerability of various types of structures decreases and the model of calculation will be more reliable.

4. Conclusions

The quantitative evaluation of seismic risk on a regional level indisputably constitutes the necessary condition to an objective perception of the seismic risk. In this study, an evaluation of the seismic vulnerability of existing buildings was implemented starting from the damage analysis of different structures constitute the Algerian inheritance, based primarily on the "damage index" model proposed. Curves of vulnerability were developed for different types of structures in order to implement seismic risk reduction of a given area. It should be noted that these curves were limited for quite specific areas where a detailed dynamic nonlinear analysis of each structure was carried out. The curves obtained show that the level of vulnerability of masonry buildings which present a much degraded stage is very high and decreases for the other types of structures. This very significant potential damage can be explained in term of the larger dependence of the damage according to the peak ground acceleration PGA. A quantification of the seismic risk level expected at the time with a certain level has been carried out by using two levels of earthquake; a moderate earthquake whose peak ground acceleration is 0.15 g at bedrock for a return period of 100 years and a major earthquake whose peak ground acceleration is 0.25 g at bedrock for a return period of 500 years and also based on vulnerability functions for specific losses in terms of meter square area (m^2) of building slabs (Fig. 15) that have been developed. It was also noted that the majority of losses evaluated for the quantification of the risk were allotted to the very rigid buildings. This is due primarily to the dominating structural type whose design was not based on seismic codes and regulations.

The approach developed in this context is a basic tool for a quantitative evaluation of risks even though; it will be used just as an indicative value.

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References

ASCE 31-03 (FEMA310) (2003). *Seismic evaluation of existing buildings*, American Society of Civil Engineers-ASCE Standard USA.

Benedetti, D., Benzoni, G., and Parisi, M. A. (1988). "Seismic vulnerability and risk evaluation for old urban nuclei." *Earthquake Engineering and Structural Dynamics*, Vol. 16, No. 2, pp. 183-201.

Benouar, D. (2008). "Seismic vulnerability evaluation in the city of Algiers-Algeria." *4th World Urban Forum Nanjing (China)*, 3-6 November.

Bozinovski, Z. and Gavrilovic, P. (1993a). *Computer program for static, dynamic and ultimate analysis of masonry buildings SDUAMB*, Institute of Earthquake Engineering and Engineering Seismology, Skopje Republic of Macedonia.

Bozinovski, Z. and Gavrilovic, P. (1993b). *Computer program for* *analysis of ultimate state of reinforced concrete systems UARCS,* Institute of Earthquake Engineering and Engineering Seismology, Skopje Republic of Macedonia.

Bozinovski, Z. and Gavrilovic, P. (1993c). *Computer program for dynamic response analysis of buildings structures DRABS*, Institute of Earthquake Engineering and Engineering Seismology, Skopje Republic of Macedonia.

Esteva, L., Diaz-Lopez, O., and Hernandez, E. I. (2010). "Seismic vulnerability functions of multi-storey buildings: Estimation and applications." *Structure & Infrastructure Engineering: Maintenance, Managemen*t, Life-Cycle Design & Performance Vol. 6, Issue 1, pp. 3-16.

Fajfar, P. and Kreslin, M. (2010). "Seismic evaluation of an existing complex RC building." *Bulletin of Earthquake Engineering,* Vol. 8, No. 2, pp. 363-385.

Kaplan, E., Yilmaz, E. Akyol, and Sen, G. (2008). "A new rapid seismic vulnerability assessment method for Turkey." *The 14th World Conference on Earthquake Engineering,* October 12-17, Beijing, China.

Kumitani, S. and Takada, T. (2008). "Probability assessment of buildings damage considering aftershocks of earthquakes." *The 14th World Conference on Earthquake Engineering*, October 12-17, Beijing, China.

Kwok, Y. H. and Ang, H. S. (1985). *Seismic damage analysis and design of unreinforced masonry buildings*, Technical Report of Research Supported by the National Science Foundation, University of Illinois.

Murao, O. and Yamazaki, F. (1999). "Development of fragility curves for buildings based on damage data due to the hyogoken-nanbu earthquake." *Proceedings of APSSR and Its Applications*, pp. 259-269.

Oropeza, M., Michel, C., and Lestuzzi, P. (2010). "Fragility functions for seismic risk in regions with moderate seismicity." *Proceedings of the Ninth US National and Tenth Canadian Conference on Earthquake Engineering*, Toronto, Canada, July 25-29.

Ousalem, H. and Bechtoula, H. (2005). "Inventory survey of the 2003 zemmouri (Algeria) earthquake: Case study of dergana city." *Journal of Advanced Concrete Technology*, Vol. 3, No. 1, pp. 175-183.

Park, Y. J., Ang, A. H.-S., Eeri, M. and Wen, Y. K. (1987). "Damage-limiting aseismic design of buildings." *Earthquake Spectra EERI,* Vol. 3, No. 1, pp. 1-26.

Parodi, S., Milano, L., Martinelli, A., Manella, A., Lagomasirno, S., and Bernardini, A. (2008). "Vulnerability and damage assessment of current buildings in Italy: Application to Sulmona town." *The 14th World Conference on Earthquake Engineering*, October 12-17, Beijing, China.

Rota, M., Penna, A., and Magenes, G. (2010). "A methodology for deriving analytical fragility curves for masonry buildings based on stochastic nonlinear analyses." *Engineering Structures*, Vol. 32, Issue 5, pp. 1312-1323.