Seismic 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. Regarding the developed model for assessing the seismic damage, vulnerability functions of specific losses were developed in order to define the expected seismic risk in case of particular ground motion.

Keywords: Vulnerability curves, Risk analysis, Building damage, loss assessment.

1. INTRODUCTION

It is very important to evaluate the seismic risk of existing buildings in prone area, in order to reduce expected damages when a severe earthquake takes place. For specific needs of evaluation and reduction of the seismic risk in the urban zones, 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. 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, introducing a nonlinear model for a given structure by using existing results as a preliminary. An application of this concept for strategic buildings in the city of Algiers (see Fig.1.1) 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 of figure 02, defined starting from a 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 meter square of slabs area necessary for the quantification of the level of risk which has occurred at the time of an earthquake by using the two levels of expected seismic actions. The first one 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 allowable, and the building must be reused after inspection and slight repairs.

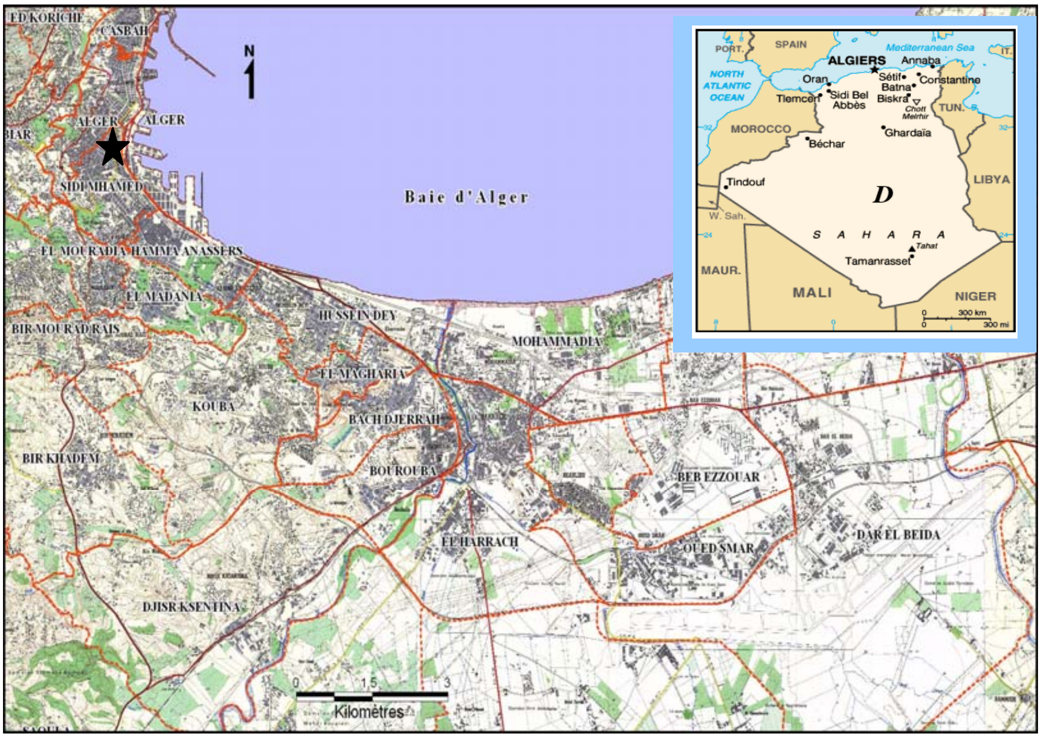

Figure 1.1. Algiers Map

2. PREDICTION AND ESTIMATION OF EARTHQUAKE LOSSES

2.1. Methodological Approach and Model Output

Rapid development and urbanization of seismic prone regions rapidly increase their vulnerability and seismic risk if no appropriate measures are undertaken for protecting human lives and material properties. The process of pre-disaster seismic risk mitigation, reduction and management therefore should start at the level of physical and urban planning and be constantly implemented at all stages of development.

For the planning of new developments or post-earthquake reconstruction, earthquake preparedness and insurance as well as for decision-making, the quantitative seismic risk assessment tools are needed for various building classes in various locations. Recently, efforts have been made in the development of quantitative loss prediction procedures (Petrovski et Al. 1994).

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. 2.1):

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

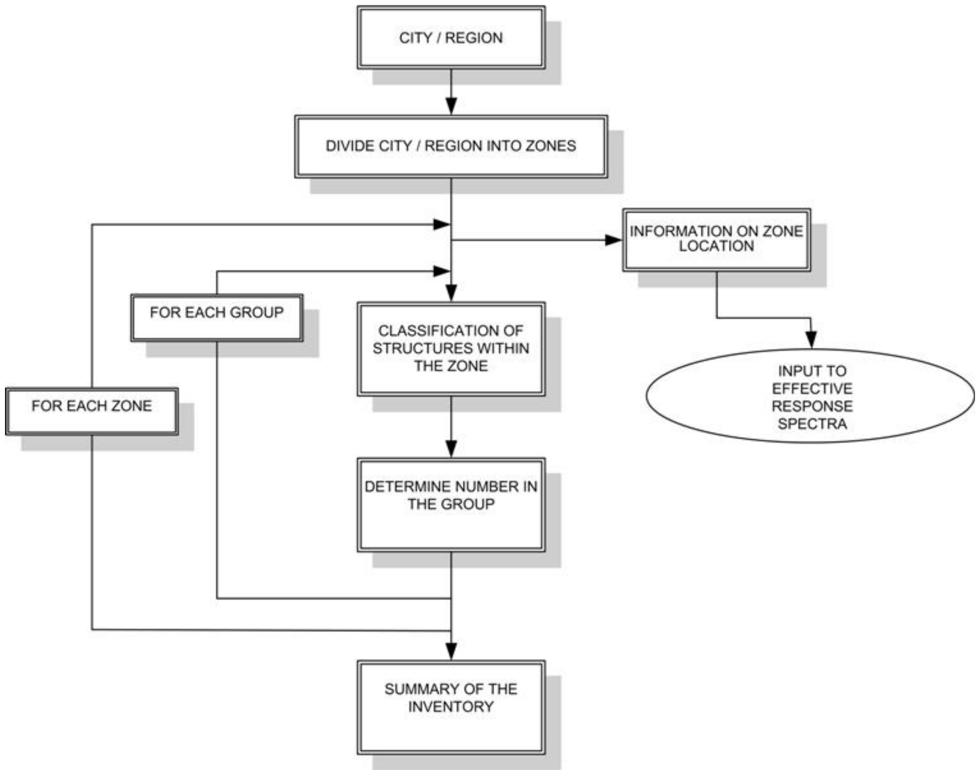

Figure 2.1. Inventory methodology for a City or Region

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

On May 21st, 2003, at 19:45 local time, a severe 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 (Ousalem et Al. 2005). The main shock and aftershocks induced severe 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. 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. 2.2., 2.3., 2.4. et 2.5., where the number of damaged buildings in the sub-prefectures of Dar el-beida and Rouiba was very high compared to other neighbouring areas in the prefecture. The results are given in term of number of inventoried buildings (Fig. 2.2), in percentage as to the total number of inventoried buildings in each sub-prefecture (Fig. 2.3) and in percentage as to the total number of inventoried buildings in the prefecture of Algiers (Fig. 2.4). The number of investigated buildings reached a very high numbers (Ousalem et Al. 2005). Like Boumerdes prefecture, number of investigated apartment buildings was very high among other types of facilities (Fig. 2.5). 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.

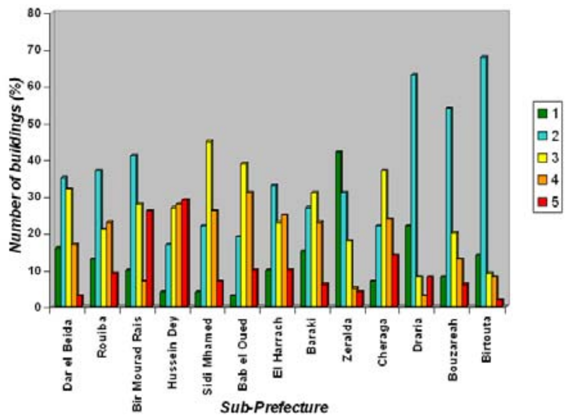

Figure. 2.2 : Inventoried buildings and damage level (1 green to 5 red) for each sub-prefecture in Algiers prefecture

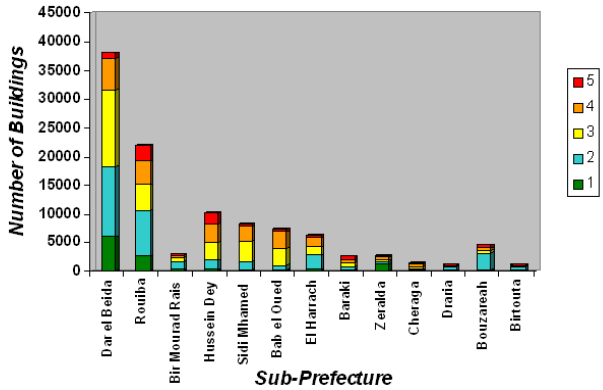

Figure. 2.3 : Damage level as percentage to total inventoried buildings in each sub-prefecture

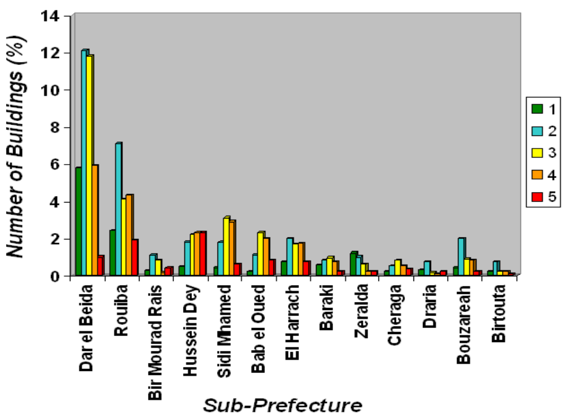

Figure. 2.4 : Damage level as percentage to total inventoried buildings in Algiers prefecture

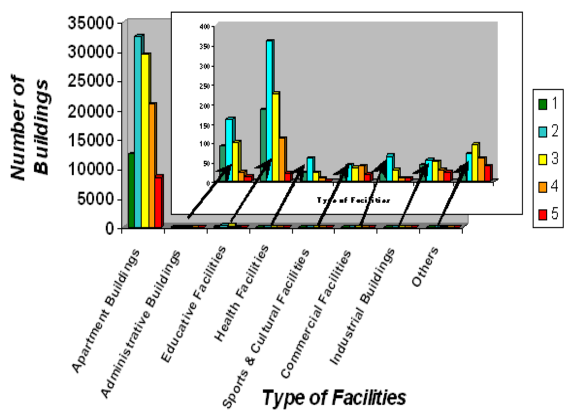

Figure. 2.5 : Damage level and number of inventoried buildings by type of facility

2.3 Damage model

The experience on the passed earthquake showed that certain levels of damage are inevitable. An earthquake design of buildings under the effect of a ground motion should allow in some stages a certain level of damage. The model of damage proposed, limits explicitly the structural damage on 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 & Ang 1987). However, an empirical relation has been developed in order to estimate the nonlinear seismic responses of the building. The damage of the structural elements under a seismic loading is generally caused by the combination of the effect of the maximum deformation and dissipated energy. This is expressed in terms of damage index as follow:

$$D = \frac{U_m}{U_f} + \frac{\varepsilon}{Q_u . U_f} . \int dE \qquad (2.1)$$

Where:

U_m : Maximum deformation
U_f : Deformation at failure
$\int dE$: Hysterical energy
ε : Constant

The damage is evaluated in terms of ratio of the seismic load to the structural strength. 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 in the base, by the ratio of the maximum deformation under the seismic load and the ultimate deformation of the structure and by the cumulated absorptive energy, whose general expression is given by the following equation:

$$D = \frac{L(PGA, t_d, T/T_g)}{R(T, U_u)} \qquad (2.2)$$

Where:

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

This model has been used for estimation of seismic vulnerability of several buildings structures by taking into account soil local conditions.

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. 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 (Petrovski 1994):

- 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, 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. 1.1), mostly represented by the strategic buildings (Fig. 2.6, 2.7, 2.8 and 2.9.). 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.

Figure 2.6: Bloc I, Algiers hospital "Mustapha Pacha" (37 buildings)

Figure 2.7: Bloc II, Department of telecommunications (12 buildings)

Figure 2.8: Bloc III, Algiers city hall department (04 buildings)

Figure 2.9: Bloc IV, Fire fighters department (17 buildings)

The data 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 2.1 and 2.2.. 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.

Table 2.1. Predicted specific loss for a PGA of 0.15g

Zone	Masonry buildings		R.C Frame Buildings		Mixed Buildings		R.C Walls		Total Damage Area.	
	Total Area (m²)	(%)	Total Area (m²)	(%)	Total Area (m²)	(%)	Total Area (m²)	(%)	Total Area (m²)	(%)
Bloc I	4762	27.5	15164	11.25	8483.5	24.16	/	/	28409	17.8
Bloc II	/	/	19929	11.25	/		3972	5.41	23901	10.3
Bloc III	14900	27.5	5750	11.20	/	/	/	/	20650	22.9
Bloc IV	/	/	8217.5	11.30	/	/	/	/	8217.5	11.3
Total	19662	27.5	49060.5	11.25	8483.5	24.16	3972	5.41	81178	15.6

Table 2.2. Predicted specific loss for a PGA of 0.25g

Zone	Masonry buildings		R.C Frame Buildings		Mixed Buildings		R.C Walls		Total Damage Area.	
	Total Area (m²)	(%)	Total Area (m²)	(%)	Total Area (m²)	(%)	Total Area (m²)	(%)	Total Area (m²)	(%)
Bloc I	4762	45.8	15164	20	8483.5	38.7	/	/	28409	29.9
Bloc II	/	/	19929	20	/		3972	10.4	23901	18.4
Bloc III	14900	45.8	5750	20	/	/	/	/	20650	38.6
Bloc IV	/	/	8217.5	20	/	/	/	/	8217.5	20
Total	19662	45.8	49060.5	20	8483.5	38.7	3972	10.4	81178	20.7

Those two (02) tables show expected economic loss in terms of total slabs area (m2) for two (02) different earthquake scenarios which could happen in the city of Algiers, and at the same time is specific tool for elaborating physical development plan or urban master plan for the city.
The analytical vulnerability functions are developed while being based on more than 65 nonlinear dynamic analyses made for the various following structural types:

- Masonry Buildings: By considering unreinforced masonry buildings of more than 3 levels (standard BM) existing in a dominant way in the city of Algiers.
- Reinforced concrete frame buildings: By considering the buildings whose superstructure is composed of beam-column frames of more than 3 levels (standard BP).
- Dual system Buildings: By considering buildings made up of two types of bearing elements,

reinforced concrete structures and unreinforced masonry bearing walls (standard BX).

- Shear walls buildings: By considering buildings with shear walls as bearing elements of more than 3 levels of class D (standard BV).

Based on all collected data, regression analyses for all buildings considered according to their structural type were developed, by implementing several formulas connecting 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 (Yamazaki et Al. 1999).
For a specific value of PGA, the cumulative probability P (PGA) of the occurrence of damage equal or higher than rank D is assumed to be lognormal as follows:

$$P\ (PGA) = \Psi\ ((\ln PGA - a)/b) \qquad (2.3)$$

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 paper.

Figure 2.10 shows the vulnerability curves, for each structural system.

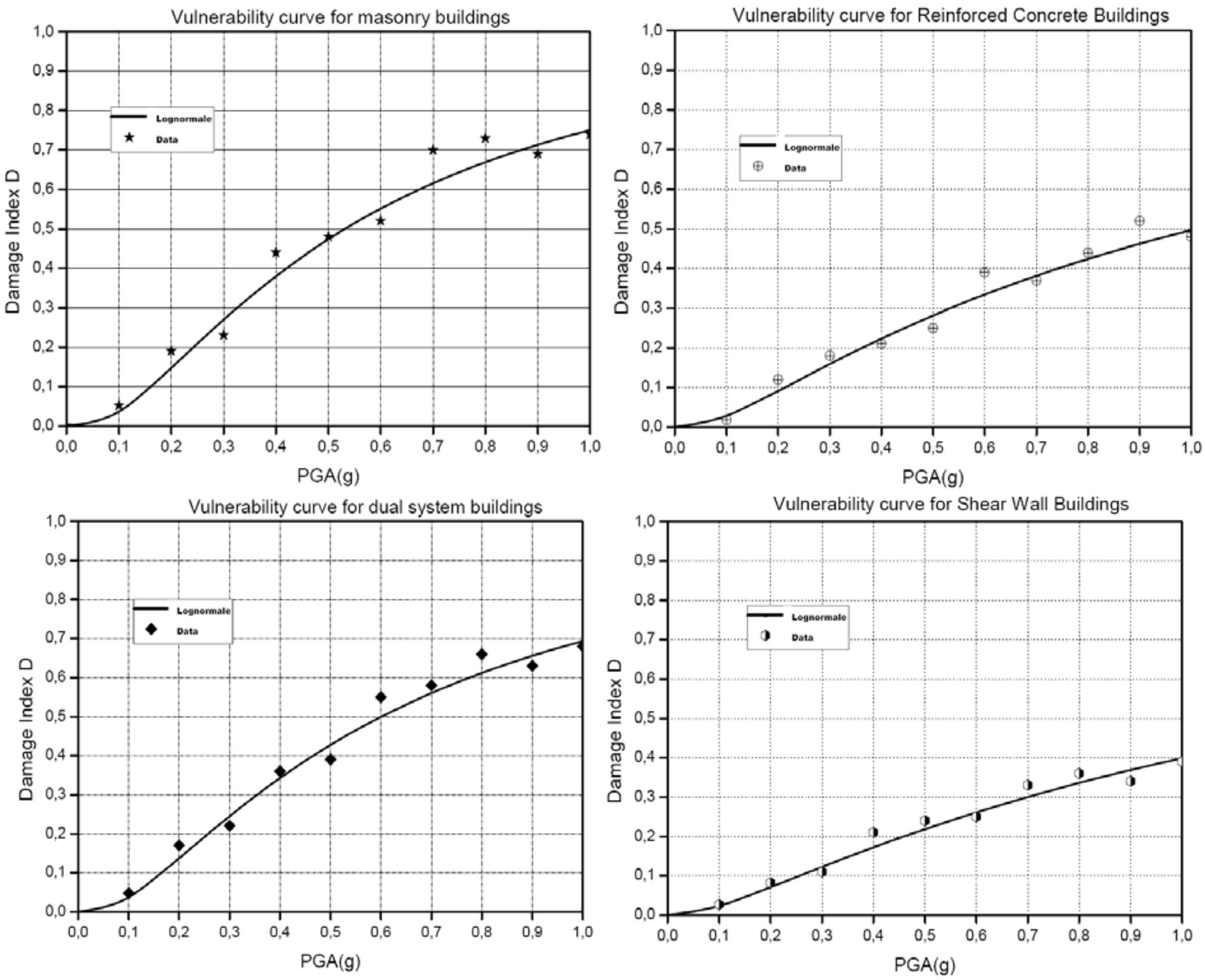

Figure 2.10: Vulnerability curves for different structural systems using regression analysis

3. RESULTS INTERPRETATION

Although the characteristics of the soil and the number of stories have a certain influence on seismic vulnerability, it was shown that the type of construction plays a significant role in the quantification of the vulnerability. The most significant vulnerability is allotted to masonry buildings of BM type which

present a much degraded state (see Fig. 3.1 and 3.2), and decreases for the other types of buildings. 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 15%g, 23% of the buildings will be damaged, by increasing the value of the PGA with 30% g, 52% of buildings BM will be damaged by giving a difference of 29% for a significant increase of 15%g of the PGA (see Fig. 3.1).
In addition, this model which allowed the development of vulnerability curves, 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.

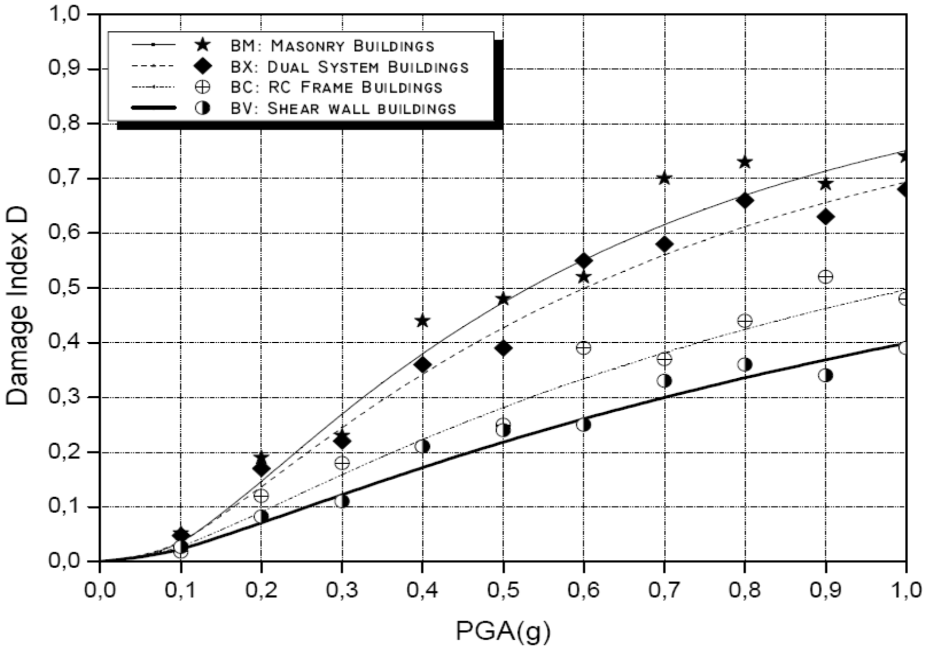

Figure 3.1: Vulnerability functions with respect to PGA for different structural types

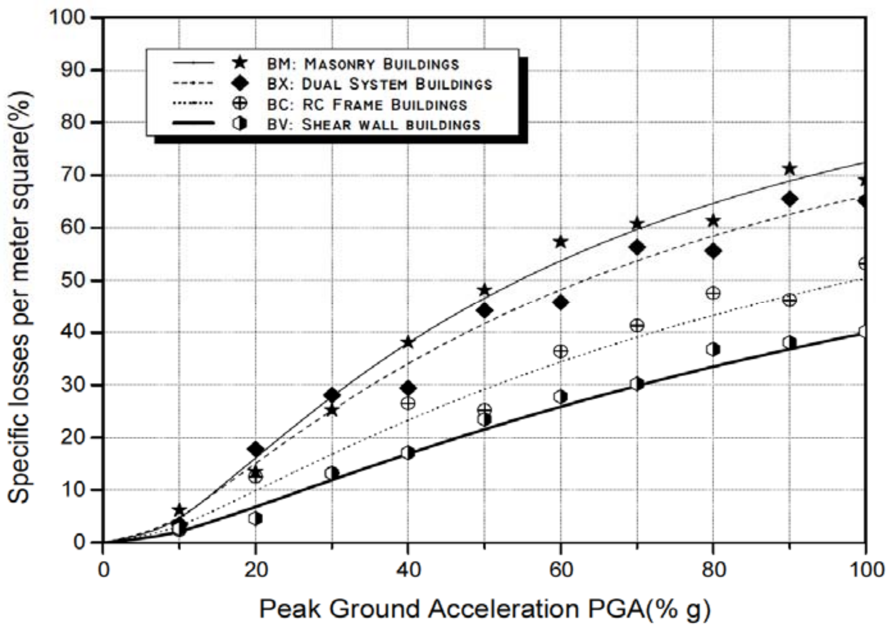

Figure 3.2: Vulnerability curves of specific losses with respect to PGA for different structural types

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. Fragility curves 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 0.15g at bedrock for a return period of 100 years and a major earthquake whose peak ground acceleration is 0.25g 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. 3.2) 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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