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Urban seismic vulnerability analysis: The case of Algeria

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ABSTRACT: A key aspect of earthquake risk mitigation is to develop tools which would help to identify high risk areas, where risk mitigation efforts have to be concentrated. There are a number of earthquake loss estimate studies undertaken world-wide, but most of the vulnerability functions and damage matrices developed are inadequate for Algeria which has a building stock with a large proportion of non-engineered and sub-standard buildings. The present paper gives the results of a research into building vulnerability in Algeria, based on damage data from local earthquakes. This empirical methodology is likely to give a more faithful picture of seismic vulnerability of Algerian buildings, and the built environment of developing countries.

1. RISK AND URBANISATION

The world population is increasing at an unprecedented rate of 100 million per year, with 75% of the growth taking place in cities of developing countries, adding pressure to an already stretched urban infrastructure, and decaying overcrowded building stock. In addition, many of these cities are prone to natural disasters. Mexico City, and Beijing exposed to earthquakes, Calcutta and Delhi threatened by cyclones and flooding, are such examples. As a result, not only this urban population has very low living standards, but also a large proportion is living in vulnerable and unsafe buildings from natural hazards. The main aim of this paper is to contribute to means of assessing and quantifying risk to urban built environments in developing countries, through a case study of earthquake risk to buildings in Algeria.

Algerian major cities share many of the problems of Third-World cities listed above. First, a large proportion of the Algerian population lives in a narrow fertile coastal plain. As a consequence, 87.5% of the total population lives on 7.8% of the total surface of the country, which lies on the most seismically active zones. The urban population growth which is estimated at 5.3% per year, also means that there is a constant increase of the population exposed to earthquake risk. This also resulted in great pressure on the building stock, especially housing where the occupation rate has exceeded 7 persons per dwelling *(ONS, 1985)*.

In addition, a large proportion of the existing old building stock is in an advanced state of decay, and the newly built stock suffers from low construction and design standards. Although 20% of the workers are employed in the construction industry, only a small proportion is trained to use modern techniques of construction. The low availability of professionals also led to a lack of quality control. These characteristics *resulted in a very vulnerable building stock as* demonstrated by recent earthquakes. The present research therefore aimed to assess and quantify the vulnerability of buildings in Algeria, which can then be used as a tool to develop strategies to reduce this vulnerability.

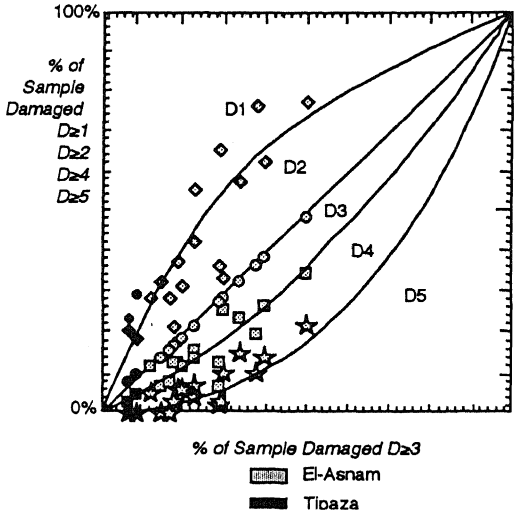

Figure 1: Earthquake damage distribution of reinforced concrete frame buildings in El-Asnam and Tipaza.

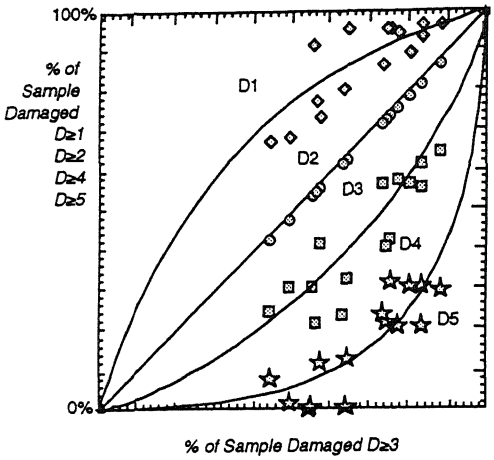

Figure 2: Earthquake damage distribution of all masonry walls buildings in El-Asnam.

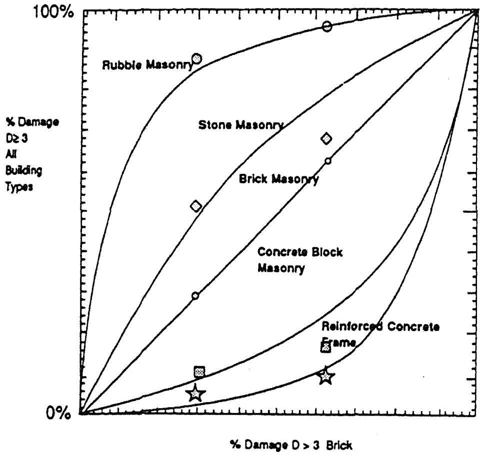

Figure 3: Earthquake damage distribution of all building types in Tipaza.

2 STATE OF SEISMIC RISK MITIGATION IN ALGERIA

Algeria is a country which has a short history of seismic risk mitigation. Although it has suffered from many devastating earthquakes in its history, the actions taken to reduce their effects during the last three centuries have been relatively minor until the 1950s.

2.1 Evolution of Building Codes

The first seismic design measures were published during the French period, following the 1954 Orleansville earthquake (this town was renamed El-Asnam after independence, then Ech-Cheliff after 1980). These are referred to as 'Recommendations AS55'. The French then produced an improved code in 1969 known as PS69. This code was designed for France only but it was adopted in Algeria.

The first Algerian seismic code (RPA) was published in 1983 by the CTC (Organisation of Technical Control of Construction). This code was the result of a research project started in 1978, which also incorporated the lessons learned from the 1980 El-Asnam earthquake. This building code was further modified in 1989 to provide more adequate seismic coefficients. However, the question of the extent of its enforcement remains.

2.2 Hazard Studies

There have been a number of hazard studies in Algeria. Most of these studies consist of compilations of historical records, and cover a period of about 300 years. Some of the most important catalogues are those by Roussel (1973) for the period 1716-1970, Grandjean (1957) for the period 1790-1957, and Rothe (1955) for events up to 1950. Most of these catalogues consisted of a basic account of the different events, and lack accuracy in the location of and the strength of the events. A more detailed study was carried out by Morgat and Shah (Morgat & Shah, 1978), who summarised and cross-checked all existing catalogues. Missing information on elements such as the magnitude and depth of the epicentre was generated using theoretical relationships. The main outcome of these studies is that Algeria suffered many destructive earthquakes in the past, and that events of at least the same strength (magnitudes up to 7) are likely to occur in the future, but they have not provided accurate hazard estimates in time and space.

There is only one comprehensive hazard study in Algeria, it was carried out for the region of Ech-Cheliff. This microzonation study consisted of detailed mapping of all hazard types, and surface faults as well as estimations of ground shaking (Woodward-Clyde Consultants, 1984). Complementary investigations provided information on soil strength, as well as probabilistic seismic exposure (Power et al, 1984; Swan et al, 1984).

2.3 Studies of Vulnerability

Seismic vulnerability of buildings is a subject has not been well covered in Algeria. Except for post earthquake observations of building performance (EERI, 1983; CTC, 1981), there are only two studies of vulnerability in Algeria known to the author. The first one by Tebal attempted to evaluate the vulnerability of the buildings in an area of Algiers. The probable losses for this settlement were estimated by applying vulnerability relationships developed by Shah for California (Tebal, 1985). This approach is questionable because the vulnerability of buildings in California is likely to be very different to that of the Algerian buildings.

The second study carried out by Liu was much more comprehensive. The functions of vulnerability were based on the damage data from the 1980 El-Asnam earthquake (Liu et al, 1986). The purpose of Liu's study was to evaluate the possible damage to buildings in the small town of Djelfa. Because this town is relatively new, only those buildings built after 1954 were considered in the damage analysis. The functions developed are therefore not appropriate for other towns with a building stock made of a large proportion of old and non-engineered buildings. The analysis in the present study will use the same database of damage, but all types and ages of buildings will be considered.

3. METHODOLOGIES FOR EARTHQUAKE RISK ASSESSMENT

In order to quantify the seismic vulnerability of buildings in Algeria, it was necessary to review ongoing research in the field. Most existing methodologies rely on the United Nations Disaster Relief co-Ordinator definition of seismic risk (UNDRO, 1979). This was expressed by the formula:

[R] = [H] x [V] x [SL]

Where for a given element at risk (population, buildings, economic activity), the expected risk [R] is quantified by defining a relationship between the damageability or vulnerability [V] of buildings, their structural characteristics, and the level of seismic hazard [H] to which they are likely to be exposed. The specific loss [SL] is expressed in terms of monetary units, human losses, or damage to property.

Current methods for the assessment of seismic performance range from very approximate screening methods, to detailed analytical approaches which involve a dynamic analysis of their structures. In the proceedings of the conference on 'Building Construction Under Seismic Conditions in the Balkan Region' (UNDP/UNIDO, 1985) these methods were classified into four categories, which are the Categorization, Inspection and Rating, Analytical, and Experimental methods.

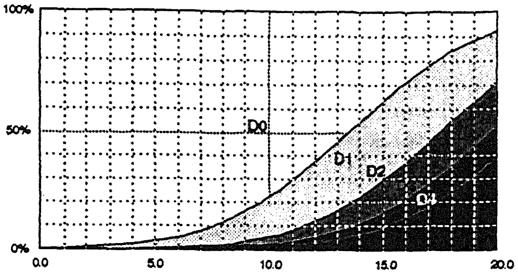

Figure 4: Vulnerability functions for damage levels D1 to D5 for RC frame buildings.

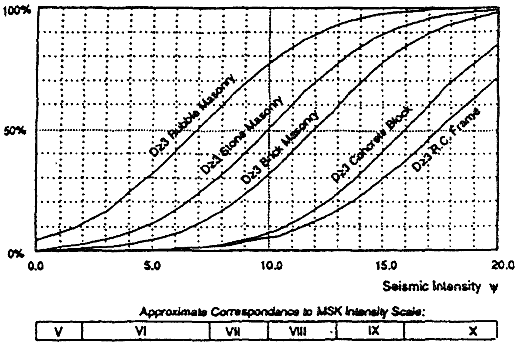

Figure 5: Vulnerability functions for damage level D>=3 for all building types.

Table 1: Structural categories in El-Asnam

Structure	Frequency	Percentage
Wood Columns	19	0.3%
Steel Columns	329	5.1%
RC Columns	2072	32.0%
RC & Steel Columns	18	0.3%
Concrete Walls	57	0.9%
Concrete Walls & Columns	48	0.7%
Masonry Walls	2331	36.0%
Masonry Walls & RC Columns	1119	17.3%
Masonry Walls & Steel Columns	57	0.9%
Other Combinations	75	1.1%
Missing Values	353	5.4%
Total	6478	100%

3.1 The Categorization Method

The categorization method, or primary screening is a very common method of vulnerability evaluation (Algermissen et al., 1978; Boissonade, 1985; Dolce, 1984; Sauter et al., 1978; Scawthorn et al., 1981; Shah, 1979; Whitman, 1973; Wiggins et al., 1973). This technique consists of classifying a given building stock into categories of buildings that are likely to perform in a similar way during a seismic event, then the potential damage to each category is estimated. The most common classification is based on the type of vertical load-bearing system and structural material. Other variables such as lateral stiffness, height, age and condition of the building, are sometimes considered.

3.2 The Inspection and Rating Method

In principle, this method uses a similar approach to that of the categorization method, but it concentrates on those elements of the structure that may be critical in a seismic event. A rating system is developed based on the physical characteristics of the building, and sometimes integrate seismicity information. Studies using this method include (Beneditti & Benzoni, 1985; Sheppard & Lutman, 1988; White & Gergely, 1988; Wiggins et al., 1973).

3.3 The Analytical Method

This method consists of a detailed analysis of the potential seismic response of a structure using an analytical model. For example in the Culver method called Detailed Analytical Method, the resistance of an existing building is evaluated by determining the stress ratio produced by seismic loading to critical structural elements (Culver, 1975). Detailed structural plans as well as an appropriate building code which can be used as the criteria for the analytical evaluation are needed. Other studies express damage as functions of ductility, displacement or tensile change of the structure (Aoyama, 1981; Blume 1977; Oliviera, 1977).

3.4 The Experimental Method

This method relies on physical experiments and testings of structures. For existing buildings the results from the experiments, such as those suggested by Angeletti (1984) and Noland (1982), can provide the complementary information to the outcomes of the analytical method. Laboratory testings can also be used to assess the performance of improved construction techniques in new buildings.

4. PROPOSED METHOD OF VULNERABILITY ANALYSIS

The previous section has outlined several methods that have been developed for the evaluation of building vulnerability. The selection of a methodology largely depends on the objectives of the study (urban planning, civil defence purposes, improvement of existing buildings codes). Section 2.3 also emphasised the fact that there are very few studies of vulnerability for Algeria to build upon. Therefore the present study will concentrate on a very general analysis of building vulnerability, using a statistical method such as the categorisation method discussed in section 3.1 based on an analysis of damage data from past earthquakes. This empirical method seems particularly appropriate in the case of Algeria, first because reliable damage data for the country is available (see section 5), second the wide range of non-engineered structures, the quality of workmanship, and the lack of building control means that the use of analytical methods is inadequate. The analysis of damage to buildings will lead to the establishment of graphical or mathematical relationships expressing the damageability of buildings in relation to their structural characteristics and the severity of the ground motion to which they have been exposed. These relationships are known as 'vulnerability functions'. The proposed methodology consists of the following steps.

4.1 Compilation of a damage database

Since the method is empirical, the first step consists of compiling databases of damage data for all possible categories of buildings. Given the characteristics of the Algerian building stock, only damage data from Algerian earthquakes will be considered. These databases which have been compiled after the 1980 El-Asnam and the 1989 Tipaza earthquakes are discussed in section 6.

4.2 Building classification for vulnerability analysis

As mentioned in section 3 most existing studies of vulnerability use the vertical structural system and structural material as the first criteria of classification, because they directly affects building failure. This is the main classification that will be used in this study. Although the analysis of the effect of other characteristics is desirable, these will not be considered due to inadequate data.

4.3 Damage distribution diagrams

The damage data used in this study was recorded on a 5 level damage scale (D1 to D5) such as those used in the MMI and MSK scales. The first step of the damage analysis will consist of looking at frequencies of each damage level for each of the structural categories defined. It will also look at the distribution of these damage levels across the zones of various levels of ground motion. The results will be presented in the form of damage distribution diagrams, which will illustrate the performance of each building type. The same procedure can also be used to compare the distribution of damage for two distinct building types. For example the performance of RC and masonry buildings can be compared by plotting the percentage of each damage level (ie. D2, D3, D4) for brick masonry against the percentage of the same damage levels for RC in each location. The defined points are then joined by a curve representing the 'relative vulnerability' (RVF) of brick masonry and RC frame.

4.4 Best fit vulnerability functions

This step is a synthesis of the damage distribution diagrams, and the RVFs for all building types. The results are compiled in a single graph showing the comparative vulnerability of all building types in the studied building stock. In such a graph a unique function is obtained for each damage level of each building type.

4.5 Relating the vulnerability to the ground motion

The vulnerability functions which are developed as the result of the previous steps constitute an important tool for comparing the damageability of two or more building types. However, these can only be used to forecast future losses to a given building stock if these relationships are related to a known parameter of seismic hazard. Existing studies usually use intensity scales or instrumentally recorded parameters such as the PGA. In the El-Asnam earthquake on which most of this study is based, the assigned intensity is found to be inconsistent (see section 6), and there were no instrumental records of the earthquake. In this study, recorded damage for all building types will be plotted against a new arbitrary index of severity. An attempt will then be made to correlate this new index to the MSK scale.

4.6 Modelling the losses

One important use of the developed vulnerability functions is in forecasting earthquake effects on a settlement through scenarios. Provided that there is sufficient information on the building stock to be tested and the level of seismic hazard to which it is likely to be exposed. These functions constitute a powerful tool not only to quantify losses for a given event, but also to assess the effectiveness of various risk mitigation strategies by quantifying the level of loss reduction achieved by each measure. Loss scenarios can be run using computerised models such as the Seismic Impact Simulation Model (SISMA) developed by Cambridge Architectural Research (CAR) for similar studies.

5 THE EARTHQUAKES AND DAMAGE DATABASES

The methodology of vulnerability analysis presented in the previous section will use damage data from the two most recent earthquakes in Algeria. The 1980 El-Asnam, and the 1989 Tipaza earthquakes.

5.1 The 1980 El-Asnam earthquake and damage data

The El-Asnam earthquake occurred on the 10 October 1980, it measured 7.2 on the Richter scale, and was very shallow depth (5 to 20 km). Although there were no strong-motion recordings, the peak ground acceleration was estimated at 0.59 g in the horizontal direction, and a vertical component of 0.89 g (CTC, 1981). The earthquake affected a total area of 7,000 square kilometres. Because the fault break was only 7km from the town of El-Asnam which had 900,000 inhabitants, 2,500 people were killed, another 7,000 were injured, and 25,000 housing units were destroyed.

The strongest effects on structures were observed in the town of El-Asnam and within a radius of 60 kilometres around the epicentre. The earthquake caused the collapse 20% of the buildings, and a further 60% suffered damage. The reasons for such extensive destruction were related to the severity of the ground motion, construction defects, and ignorance of fundamental principles of earthquake design (EERI, 1983). The causes of damage included inappropriate structural design (use of soft storeys, building irregularities, lack of shear walls, use of non-tied masonry, inadequate proportioning of structural elements), as well as the low quality of structural material (CTC, 1981; EERI, 1983).

Table 2: Vulnerability function parameters for all building types derived from the El-Asnam and Tipaza damage data.

	Stone	Brick	Rubble	C.Block	R.C.Frame
D1: Mean	**5.5**	**7.2**	**3.5**	**10.5**	**13.5**
Standard Deviation	**4.0**	**4.0**	**4.0**	**4.0**	**4.5**
D2: Mean	**8.0**	**10.0**	**6.0**	**14.0**	**15.7**
Standard Deviation	**4.0**	**4.0**	**4.0**	**4.0**	**4.5**
D3: Mean	**10.0**	**12.0**	**7.0**	**16.0**	**17.5**
Standard Deviation	**4.0**	**4.0**	**4.0**	**4.0**	**4.5**
D4: Mean	**13.0**	**14.5**	**9.5**	**17.0**	**19.8**
Standard Deviation	**4.0**	**4.0**	**4.0**	**4.0**	**4.5**
D5: Mean	**15.0**	**16.5**	**12.0**	**18.5**	**21.3**
Standard Deviation	**4.0**	**4.0**	**4.0**	**4.0**	**4.5**

After this earthquake, a systematic technical appraisal of all buildings in the affected area was carried out by the CTC engineers, and a total of 6,538 buildings were surveyed. In this survey characteristics of the buildings such as the address, use, age, height, configuration, and structural system were recorded, together with the level of damage sustained by structural and non-structural members. A preliminary analysis of the data showed that 4,859 buildings (79%) were residential. It also showed that although two sets of building regulations were introduced in 1954 and 1969, (AS55 and PS69), only 188 buildings (2.9%) were identified as being designed according to one of these two codes.

5.2 Building classes in El-Asnam

As discussed in the methodology in section 4, the first step is to classify the buildings in El-Asnam according to the available information on their vertical structural system. The identified systems are summarised in table 1. From this analysis two inadequacies of the data can be highlighted. First, in the "concrete columns and masonry walls" category, it is not clear whether the masonry walls are load-bearing or just infill panels. Second, there is no distinction between the structural material of masonry walls. Structures like rubble, stone and brick masonry, reinforced and unreinforced, all fall into the same category. Therefore the damage analysis has to be done within these limitations.

5.3 The 1989 Tipaza earthquake and damage data

An estimation by the US NEIC gave the following characteristics for the two shocks. The first one was located at 36.788 N 2.448E, h = 6Km, Msz = 5.7, and the second one at 36.745 N 2.443 E, h =10Km, Msz = 5.6. The nearest ground motion instrument that was triggered recorded a peak horizontal acceleration of 0.28g. The earthquake affected the towns of Tipaza and Cherchell, about 60 kilometres west of the capital Algiers. It caused about 30 deaths, 250 injuries and substantial damage to the old building stock. After the earthquake the CTC and CGS carried out a damage survey of all buildings in the area. A total number of 11938 buildings have been surveyed, of these 6142 (51.5%) suffered minor damage, 1701 (14%) sustained considerable damage, and 4095 (34.5%) collapsed or were damaged beyond repair (CGS, 1990). The main reason for such extensive damage is that most of the buildings were very old and non-engineered with a predominance of masonry buildings.

This earthquake provided an opportunity to look at the behaviour of various types of masonry buildings. However, not only the database from this survey was not released at the time of this research, but also the methodology used was the same as in the El-Asnam earthquake which means that the structural material of masonry structures was not differentiated, and the inadequacies discussed in section 5.2 apply to this data. I therefore carried out a small survey of about 350 buildings in the three most affected localities, using a methodology where both the structural system and structural material were recorded.

5.4 Building classes in Tipaza and related damage

This classification is based on the small survey carried out by the author after the earthquake. Because the Tipaza region is not very urbanized, there was a predominance of masonry structures which constituted up to 80% of the total building stock. The main structural categories identified were first the engineered buildings which were mainly RC frame structures built in the last three decades. Second, four types of masonry structures with rubble, stone, brick, and concrete blocks walls.

6 STRUCTURAL DAMAGE ANALYSIS TO DERIVE BUILDING VULNERABILITY

The present analysis of damage data to derive building vulnerability for Algeria will be mainly based on the data from the El-Asnam earthquake, as it is more comprehensive. However given the inadequacies of this database for masonry structures, the survey carried out after the Tipaza earthquake will be used to supplement the analysis for these categories of structures. The methodology described in section 4 will be applied to analyse and quantify the damage recorded for different structural categories in these two earthquakes, based on the performance of their vertical structural system.

To carry out the damage survey after the El-Asnam earthquake, the region was subdivided into 16 zones. Zones 1 to 10 were all contained within an area which was assigned an intensity 9, however, the analysis showed that the amount of damage varied considerably. For instance the damage level D=5 varied from 1.4% in sector 7 to 23.1% in sector 4. Similarly damage level D=1 varied from 21.8% in sector 4 to 78% in sector 9. This highlights the inconsistency of the assigned intensities after the earthquake. Therefore in the following analysis, each of the 16 zones will be considered as being exposed to a uniform value of ground motion, but the assigned intensities will not be considered.

6.1 Damage to RC frame structures in El-Asnam

This category consisted of 2065 buildings which were distributed over all the 16 zones. The damage histogram for RC frame structures shows that about 50% of these constructions suffered some damage (D>=2); of these nearly 18% collapsed or were damaged beyond repair (D>=4). The damage distribution diagram illustrated in figure 1 shows a relatively low performance of RC buildings in Algeria.

6.2 Damage to masonry wall structures in El-Asnam

The El-Asnam database included 2329 masonry wall structures. The results of the damage analysis for this building type is illustrated in figure 2, which clearly shows a lower performance of masonry structures compared to RC ones. The damage distribution diagram shows that in most zones 55% to 87% of masonry buildings sustained a damage level D>=3, while for RC no zone reached 50% of buildings damaged at level D>=3. Ideally, this analysis should also look at the difference in the performance of various types of masonry, but the database is inadequate (see section 5.2).

6.3 Damage to steel frame & concrete wall structures in El-Asnam

The total number of steel frame buildings was 327, most of which had a good overall performance. 74% of the buildings had a damage level D<=1, and only 13 structures (4%) suffered a damage level D>=4. There were only 61 concrete wall structures in the whole El-Asnam database; and none of these had a damage level D=5, and in most zones, 75% to 83% of the buildings suffered minor damage (D<=1). In general both steel frame structures and concrete wall structures had a better performance than RC and Masonry.

6.4 Damage to masonry structures in Tipaza

The various types of masonry performed differently. The survey showed that all buildings (100%) with rubble walls suffered structural damage D>=3. Stone masonry also sustained heavy damage with 54% of buildings damaged at level D>=3, and being responsible for most of the deaths. Brick buildings (which were unreinforced) had a similar performance with 50% of buildings damaged at level D>=3. Those building with concrete block walls performed much better, as 80% of such buildings had damage level D<=2. This was mainly because these buildings were recent, and horizontal reinforcements often introduced. The relative performance of these various masonry structures are shown by the diagram in figure 3.

6.5 Damage to reinforced concrete frame structures in Tipaza

In comparison with the masonry structures, reinforced concrete frame buildings which were well designed sustained the shock with no or minor damage. In the survey sample, 90% of such buildings suffered a damage level D<=2. However, in the epicentral area there were a few cases of serious structural damage. It was clear that the failures were caused by inadequate design, and bad execution on the site rather than any excessive lateral loadings. Common errors included lack of shear walls, soft storeys, and poor quality of concrete. As shown by the diagram in figure 1 the recorded damage for RC buildings in Tipaza fits reasonably well with the recorded damage to RC in the El-Asnam.

7 THE DERIVED VULNERABILITY FUNCTIONS

Once the damageability of each building type is analysed, the next step is to look at the relative performance of the different building types for similar values of the ground motion. This can be achieved by plotting the amount of damage levels D1 to D5 for a building type A (ie. RC) in relation to the sustained damage for a building type B (ie. brick masonry) in zones of various ground motion. The points obtained form the 'relative vulnerability' curve for building types A and B. These curves of relative vulnerability are then used to translate all the damage distribution diagrams for the building types onto a single graph showing the comparative performance of all the analysed building types. S-shaped cumulative normal distribution curves are obtained of each of damage level, and each building type. As an example, figure 4 shows the functions for all damage levels of RC buildings, and figure 5 shows the damage level D>=3 for all the building types on a single graph. On this graph the curves show the expected percentage of damage level D>=3 for all the building types in relation to an arbitrary intensity scale. The vulnerability functions obtained in this procedure are assumed to be of a normal or Gaussian distribution in the form:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left[-\frac{1}{2}\left(\frac{x-M}{\sigma}\right)^{2}\right] dx$$

Where: M, is the mean value, and σ, is the standard deviation.

In this formula the mean value M corresponds to the value of ground motion corresponding to a 50% probability of a structure suffering damage level D, and the standard deviation can be interpreted as the difference between the value of ground motion corresponding to 50% and the 16% probability of a structure suffering damage level D. The characteristics of all the curves are given in table 2.

The vulnerability functions derived from the present analysis not only give a clearer idea about the performance of building types in El-Asnam and Tipaza, but also constitute an important tool for the mitigation of future losses to any settlement with similar building types, provided that sufficient data on the number and distribution of the various building types, as well as some seismicity data are available. Such losses which can be expressed as amount of damage sustained by buildings, can be rapidly estimated for various building stocks using a computerised simulation model.

8. CONCLUSIONS

This research aimed to contribute to seismic risk mitigation in Algeria by providing a methodology to quantify the seismic vulnerability of buildings.

1. To date there are many databases of damage data which have been and are being compiled world wide, and many loss estimates methodologies expressed as vulnerability functions or matrixes have been published. However, the urban building stock of Algeria which is characterised by a large proportion of non-engineered and probably substandard construction, means that estimations of vulnerability based on theoretically similar building types in other countries, or analytical estimations would be inappropriate.

2. The present study is empirical and based on the analysis of damage data from Algeria, the developed vulnerability functions are therefore likely to be more realistic.

3. The study was restrained by nature of the data. The analysis only covered building types for which there was sufficient data, therefore steel frame and concrete wall, and any new type of structures have not been covered.

4. The methodological approach itself, which is based on a mathematical model placed restrictions on the study, because any non-quantifiable variables such as quality of workmanship or condition of the building could not be considered.

5. Finally the main limitation of the methodology is in relating the potential damage to hazard estimates,

however this can be improved should more data, or research in the field become available.

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