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Fragility Curves – Seismic Damage of Reinforced Concrete Frame Buildings

Fatiha Cherifi*, Mohammed Farsi**, Salah Kaci***
*(Civil Engineering Department, University Mouloud Mammeri, Tizi-Ouzou, Algeria.
Email: fatiha.cherifi@ummto.dz)
**(National Center for Applied Research in Earthquake Engineering (CGS), Algiers, Algeria.
Email: mnfarsi@gmail.com)
***(Civil Engineering Department, University Mouloud Mammeri, Tizi-Ouzou, Algeria.
Email: salah.kaci@ummto.dz)

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Abstract:

For a complete seismic risk analysis, a good knowledge of the hazard, that's to say the probability that an event occurs, and the vulnerability assessment are necessary. Once the most adverse seismic action level has been determined, fragility curves can be used to assess seismic vulnerability of structures. These curves offer valuable information about the relationship between the intensity of ground motion and the probability of exceeding damage grades: slight damage (S), moderate damage (M), extensive damage (E), and complete damage (C) even leading to collapse. The damage probabilities of the analyzed buildings are obtained in five main steps: 1. Structural characterization of buildings according to typological classes (seismic design level, construction material, structural system, number of levels). 2. Modeling and analyzing structures in the non-linear domain to obtain a response curve (capacity curve) using the Pushover method. 3. Determining the seismic excitation to be considered and identifying an appropriate seismic intensity parameter (spectral form). 4. The response curve and seismic demand are combined to identify performance points and corresponding spectral displacements. 5. Drawing fragility curves for different types of structures and assessing the probability of damage. Technical files and field visits were used to establish a database for this assessment.

Keywords — Seismic vulnerability, push-over, capacity curves, fragility curves, seismic damage.

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I. INTRODUCTION

Seismic activity remains high in northern Algeria. As many as 30 earthquakes a month are recorded in the region. Analysis of damage suffered in recent earthquakes (Algiers, 1996 ; Ain Temouchent, 1999 ; Beni Ouartilane, 2000 and Boumerdes-Alger, 2003) has highlighted the seismic vulnerability of existing buildings. Although seismicity in Algeria is considered significant, the seismic vulnerability of existing buildings in many urban areas remains largely unknown. The main objective of this project is to assess the vulnerability of existing buildings in Tizi-Ouzou city, located in northern Algeria, in order to raise awareness of the risks and challenges that an earthquake can bring to the region. To estimate seismic damage and resulting potential losses, several parameters such as site's hazard level and existing building type are necessary. Generally, when designing a building, all data and characteristics that affect its seismic behavior are known. The absence of these characteristics in existing buildings often leads to uncertainty at multiple levels. Information gathered from past earthquake damage is generally used to assess the seismic vulnerability of existing buildings.

Expert judgment-based methods require a survey in which multiple sets of questionnaires are distributed. Damage probability Matrixes are presented by combining expert responses on the probability of a structure having a state of damage for a given intensity [2, 8, and 13]. Due to the subjective nature of the experts' opinions, the random nature of ground movements, the uncertainty about the structural response, and the variety of structural classes, these curves are not reliable.

The use of empirical methods based on post-seismic observations to identify damage levels observed according to the construction's nature is more realistic than the previous approach [9, 11, 15, 16, and 18]. Fragility curves can be created by statistically converting the collected information. These approaches require a lot of data and are only applicable to the study area or a similar region.

Analytical models [1, 5, 10, 12, 17, 19, and 20] are an interesting option when there isn't enough data (observation and expert opinion data). Seismic vulnerability can be expressed in terms of the probability that a degree of damage will be achieved for a building class at a given seismic intensity (fragility curves). The main steps used in this work to estimate damage are as follows: build the capacity curves using static non-linear push-over, estimate seismic hazard, determinate performance points and fragility curves, and, finally, assess the damage. The results obtained are presented as probabilities of reaching or exceeding four damage levels (slight, moderate, extensive, and complete damage) for each building typology. The statistical distribution model used to represent the structure's fragility functions is a cumulative lognormal distribution.

To make this assessment, a database was created by conducting an inventory of buildings based on researching plans with specific organizations and conducting field visits. Different characteristic types have been assigned to the existing buildings to define typologies.

II. TYPOLOGY PARAMETERS

The first step in the analysis is to define the typologies that describe the study area buildings. These typologies are based on structural criteria that are significant for the building's seismic behavior. The elements that allow us to distinguish between the different types are generally: the construction material of the load-bearing system (concrete, masonry, wood, steel); the load-bearing system (reinforced concrete frames, and walls); and the seismic design level. Only parameters that have a significant impact on building earthquake resistance are considered. Buildings whose operation is vital for civil protection, defense or the maintenance of public order require a targeted approach due to their strategic importance.

A. *Seismic Design Level*

Buildings are classified according to the construction year, that is, before 1981, $1981-1999, 19999-2003$, and after 2003. These dates define the main periods in the evolution of seismic rules applied in Algeria [6]. The seismic coefficients have been strengthened after several revisions of these regulations. Structures without seismic design ($SDL = 0$) were built before 1981, date of the first Algerian seismic regulation ($RPA81$). The low seismic design level ($SDL = 1$) refers to structures built between 1981 and 1999, calculated according to $RPA88$ rules. The moderate seismic design level ($SDL = 2$) is assigned to all buildings constructed between 1999 and 2003 and calculated according to the $RPA99$ rules. Structures built after 2003, in accordance with $RPA99$ version 2003, and subject to control, are assumed to have a high seismic design level ($SDL = 3$).

B. *Structural System*

The structural system ensures the transmission of forces from the superstructure to the foundations, and characterizes the overall rigidity of the building. In the study area, there are mainly reinforced concrete frame structures, constructions with reinforced concrete walls and slabs, and structures made of reinforced concrete frames and walls (Fig.

1). Masonry structures, relatively old, are less common. The use of steel structures remains rare. These are limited to commercial, industrial and storage sheds.

C. Number of Levels (height)

The height of the building partly determines its frequency, its mass and consequently the forces to be taken up by the structural elements. Classification, according to the number of levels, depends on the type of structure (Table I). The methodology breaks down buildings into height ranges and defines three classes according to the number of levels: Low-Rise $(1-3)$, Mid-Rise $(4-7)$, and High-Rise $(8+)$ (Fig. 2).

TABLE I
CLASSIFICATION BY STRUCTURE HEIGHT

Typology	Classes According to Number of Levels		
Reinforced Concrete Structures	1-3	4-7	8+
Masonry Structures	1-2	3+	

D. Construction Materials

The type of materials used determines the structure's stiffness, allowable stresses and strains, and stress redistribution. Three basic materials are used in Tizi-Ouzou: reinforced concrete, masonry and steel (Fig. 3).

E. Building Inventory

Before proceeding with the vulnerability survey, documents (plans, soil reports, concrete crushing reports, calculation notes) are collected from various organizations (CTC, OPGI, ENPI, DUC), and examined. The data obtained concerns 819 public and private buildings. For each building, we recorded the ground plan, construction year, structural system, number of levels, height, dimensions in plan, concrete and soil characteristics. To complete this analysis, an on-site inventory survey is conducted. A survey form (Fig. 4), including several headings, is used. The buildings surveyed were selected to represent the main existing typologies. The number of inventoried structures is 2240. Only 2213 of them have been classified. We note that the most representative building typologies in Tizi-Ouzou city, in descending order, are as follows:

1. Individual houses, built before 2003, without seismic design;
2. Private buildings of reinforced concrete frames with masonry infill, built before 2003 without seismic design, not exceeding seven stories;
3. Reinforced concrete wall structures with a low seismic design level, not exceeding seven levels;
4. Unreinforced masonry structures, not exceeding two levels;
5. Structures with reinforced concrete frames and walls, without seismic design;
6. Reinforced concrete wall structures, without seismic design, not exceeding seven levels.

This paper focuses on reinforced concrete frame buildings with masonry infill (Table II), which account for over 60% of the city's building stock. The seismic design level of these structures varies from 0 (no seismic design) to 1 (low seismic design level) (Fig. 5).

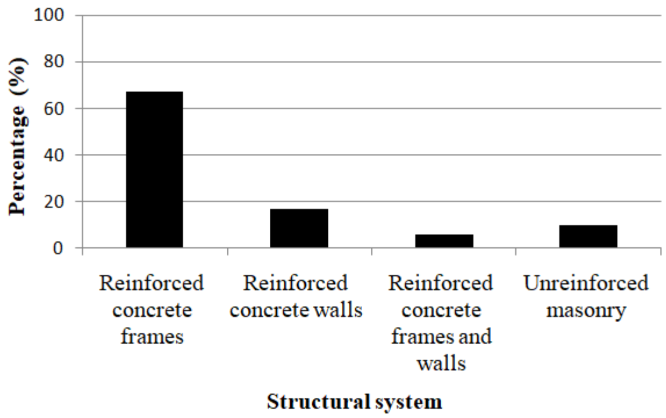

Fig. 1 Classification of the buildings in Tizi-Ouzou city according to the structural system.

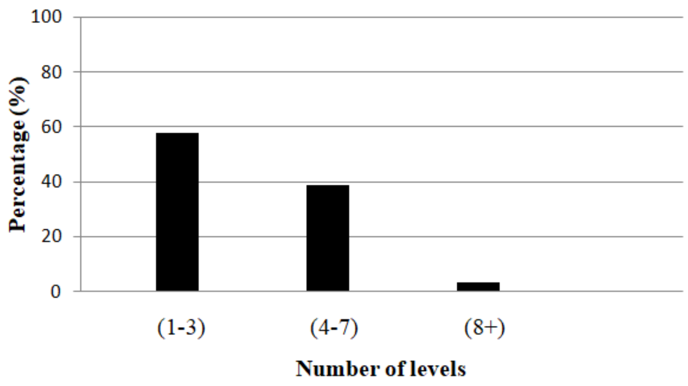

Fig. 2 Building height classification.

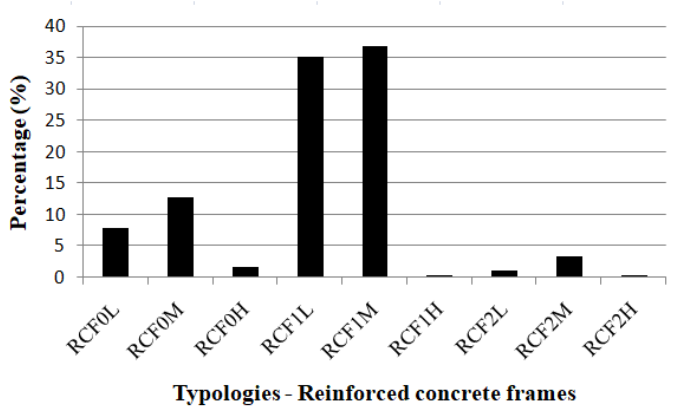

Fig. 5 Reinforced concrete frame structure typologies.

Fig. 3 Classification according to the building material.

TABLE II
TYPOLOGIES ADOPTED

Description	Seismic Design Level (SDL)	Number of Levels		Typology
Reinforced Concrete Frames	Without ($SDL = 0$)	Low-Rise	1 – 3	RCF0L
		Mid-Rise	4 – 7	RCF0M
		High-Rise	8 +	RCF0H
	Low ($SDL = 1$)	Low-Rise	1 – 3	RCF1L
		Mid-Rise	4 – 7	RCF1M
		High-Rise	8 +	RCF1H
	Moderate ($SDL = 2$)	Low-Rise	1 – 3	RCF2L
		Mid-Rise	4 – 7	RCF2M
		High-Rise	8 +	RCF2H
	High ($SDL = 3$)	Low-Rise	1 – 3	RCF3L
		Mid-Rise	4 – 7	RCF3M
		High-Rise	8+	RCF3H

Survey Form

Construction type: building ☐ detached house ☐ other ☐
Address...
Building year: ....
property: public ☐ private ☐
Use: residential ☐ commercial ☐ offices ☐ other ☐
Structure type: RC frames ☐ RC walls ☐ RC frames & walls ☐
Masonry ☐ steel ☐
Number of levels: ....
Existence of : crawl spaces ☐ basement ☐ number ☐
Irregularity: in plan ☐ in elevation ☐
Roof: accessible terrace ☐ Non-accessible terrace ☐ sloping roof ☐
Position: corner ☐ middle ☐ isolated ☐
Site on a slope: yes ☐ no ☐

Fig. 4 Survey form.

III. CAPACITY CURVE – RESPONSE SPECTRUM

The elastic response spectra are based on estimating the seismic coefficients C_A and C_V defined in ATC-40 [3]. These two coefficients depend essentially on seismic intensity (zone acceleration coefficient) and soil characteristics. The zone acceleration coefficient is given by the Algerian paraseismic rules (RPA 99 version 2003) [6] according to the seismic zone (Zone 0: negligible seismicity; Zone I: low seismicity; Zones IIa and IIb: medium seismicity and Zone III: high seismicity), and the building use group (Group 1A: structures of vital importance; Group 1B: structures of major importance; Group 2: structures of medium importance and Group 3: structures of minor importance). The main site types, classified according to the mechanical properties of their constituent soils, are characterized by a shear wave velocity [6].

The structure capacity is represented by a force-displacement curve (capacity curve), which characterizes the structure's behavior under progressive loading. This curve is obtained from a nonlinear static calculation (pushover) with a finite element model where vertical loads are constant and horizontal forces increase and have a distribution similar to the displacements in the fundamental mode. The main data used can be summarized as follows:

- The dimensions of the various elements of the modeled structures and the steel sections are taken from the plans.
- Material characteristics (Reinforced concrete density, concrete compressive strength, concrete Young's modulus, steel yield strength) are derived from design notes and concrete crush reports.
- Geotechnical reports provide soil properties.
- Overloads are defined in the regulatory technical documents [7].

The two curves (capacity - response spectrum) are superposed in a graph of type (spectral acceleration S_a - spectral displacement S_d). The intersection of these curves provides the performance point, which defines the maximum spectral displacement S_d^p the structure can have under the effect of the seismic action considered (Table III).

TABLE III
SPECTRAL DISPLACEMENTS AT PERFORMANCE POINTS

Typology	*Performance points*			
	Base shear force $V_p[t]$	*Top Displacement D_p [m]*	*Spectral acceleration S_a/g [-]*	*Spectral displacement $S_d^p[m]$*
RCF1L	105.449	0.059	0.200	0.051
RCF2L	97.436	0.038	0.219	0.048
RCF3L	279.835	0.087	0.239	0.069
RCF1M	126.142	0.074	0.254	0.057
RCF2M	83.749	0.188	0.064	0.149
RCF3M	192.529	0.078	0.134	0.062
RCF1H	219.760	0.120	0.163	0.099

IV. LOGNORMAL DISTRIBUTION PARAMETERS

The fragility curves describe the probability of reaching or exceeding each damage state for the given level of ground shaking. This probability is modeled as a cumulative lognormal distribution. The use of the lognormal distribution can be justified by the principle of proportional effects, which states that if the rate of growth of a variable at each step of the process is randomly proportional to its value, then the value of the variable at step n will be approximately distributed according to the lognormal distribution.

The fragility curve represents the probability that the seismic demand (D) exceeds or equals the capacity of the structure (C) (Equation 1). This probability is conditioned to a given seismic motion intensity (S_d) representing the seismic action level, for a specific damage limit state (ds).

$$Fragility = P[D \geq C] \qquad (1)$$

Assuming that the fragility curve is a cumulative function of the lognormal distribution, it is thus necessary to determine two characteristic parameters of this law ($\bar{S}_d, \beta$), $\bar{S}_d$ is the median spectral displacement value where the structure reaches the damage state threshold ds, β is the natural logarithm standard deviation of displacement for damage state ds. The lognormal distribution parameters (Table IV) are derived using the HAZUS method [11] based on experience feedback and summary building structural characteristics. Application of the Hazus method requires correspondence between the building types considered by this method and the typologies defined for the city under study.

Median values of structural component fragility are based on building drift ratios that describe the threshold of damage states. Damage-state drift ratios are converted to spectral displacement (Equation 2).

TABLE IV
LOGNORMAL DISTRIBUTION PARAMETERS

Typology	Damage grade							
	S		M		E		C	
	$\bar{S}_{d,ds}$ [cm]	β_{ds} [-]	$\bar{S}_{d,ds}$ [cm]	β_{ds} [-]	$\bar{S}_{d,ds}$ [cm]	β_{ds} [-]	$\bar{S}_{d,ds}$ [cm]	β_{ds} [-]
RCF3L	2.286	0.81	4.572	0.84	13.716	0.86	36.576	0.81
RCF3M	3.810	0.68	7.620	0.67	22.860	0.68	60.960	0.81
RCF3H	5.486	0.66	10.973	0.64	32.918	0.67	87.782	0.70
RCF2L	2.286	0.89	3.962	0.90	10.668	0.90	27.432	0.89
RCF2M	3.81	0.70	6.604	0.70	17.780	0.70	45.720	0.89
RCF2H	5.486	0.66	9.500	0.66	25.603	0.76	65.837	0.91
RCF1L	2.286	0.95	3.658	0.91	9.144	0.85	22.860	0.97
RCF1M	3.810	0.70	6.096	0.74	15.240	0.86	38.100	0.98
RCF1H	5.486	0.70	8.788	0.81	21.946	0.89	54.864	0.98
RCF0L	1.829	0.98	2.921	0.94	7.315	0.90	18.288	0.97
RCF0M	3.048	0.73	4.877	0.77	12.192	0.83	30.480	0.98
RCF0H	4.3942	0.71	7.0104	0.80	17.5514	0.94	43.8912	1.01

$$\bar{S}_d = \delta \cdot \alpha \cdot h \qquad (2)$$

$\bar{S}_d$ the median spectral displacement for structural damage state, ds;
δ the drift ratio at the threshold of structural damage state, ds;
h the typical roof height of the model building type of interest;
α the fraction of the building (roof) height at the location of push over mode displacement.

Fragility curves' variability is described by the standard deviation β of the natural logarithm displacement for the structural damage state ds[11].

The structures studied represent over 67% of the building stock of Tizi-Ouzou city [4], and consist of reinforced concrete frames with rigid masonry infill. In this case, frames must be able to withstand all horizontal and vertical loads. To dissipate by plastic deformation the maximum seismic energy without collapsing, the Algerian seismic regulations RPA 99 [6] recommend designing these structures so that plastic hinges form in the beams rather than in the columns.

Table IV summarizes the fragility curve parameters associated with the different typologies, and corresponding to the four damage grades considered (Slight S, Moderate M, extensive E, and complete C). The building's elastic level is correlated with the absence of damage. This condition characterizes superficial, nonstructural damage. Level S represents controlled damage, building stability is assured but minor structural damage has occurred. M and E represent advanced damage levels, where stability is somewhat assured and the safety of a structure part is limited. The building's load-bearing capacity and stability are at collapse risk beyond Level C.

V. FRAGILITY CURVES

Once the fragility function parameters are known, the fragility curves (Fig. 6 - Fig. 17) are constructed by numerically implementing the method in MATLAB software.

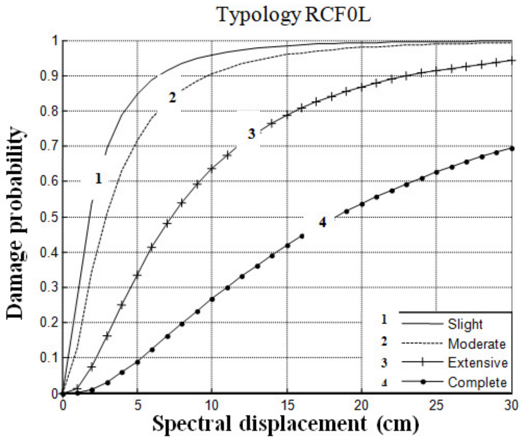

Fig. 6 Fragility curves for low-rise reinforced concrete frame structures, without seismic design.

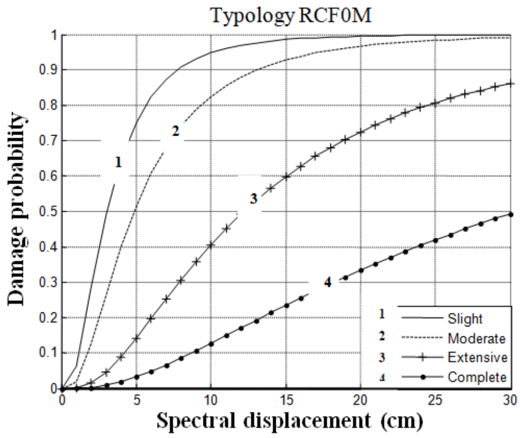

Fig. 7 Fragility curves for mid-rise reinforced concrete frame structures, without seismic design.

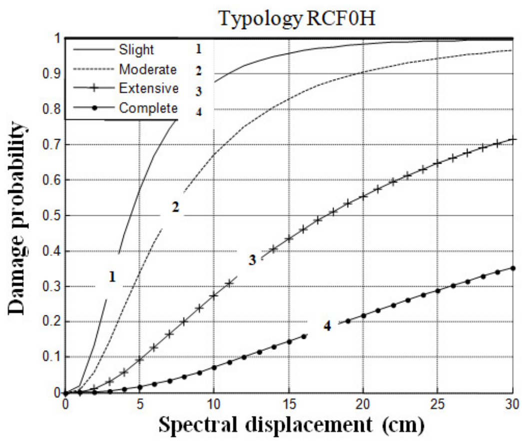

Fig. 8 Fragility curves for high-rise reinforced concrete frame structures, without seismic design.

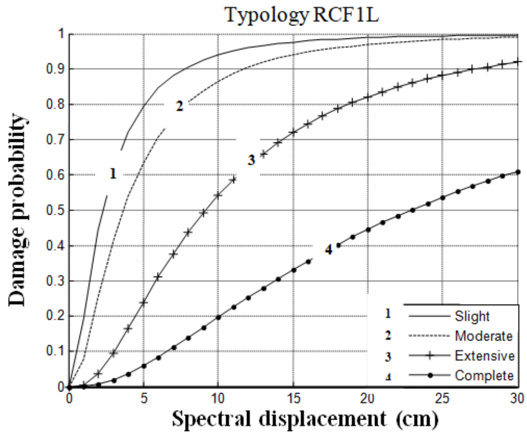

Fig. 9 Fragility curves for low-rise reinforced concrete frame structures, with low seismic design level.

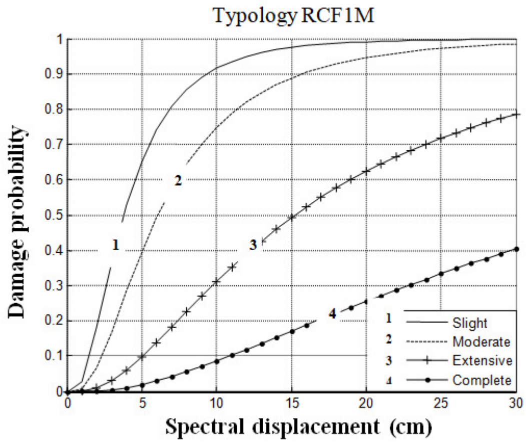

Fig. 10 Fragility curves for mid-rise reinforced concrete frame structures, with low seismic design level.

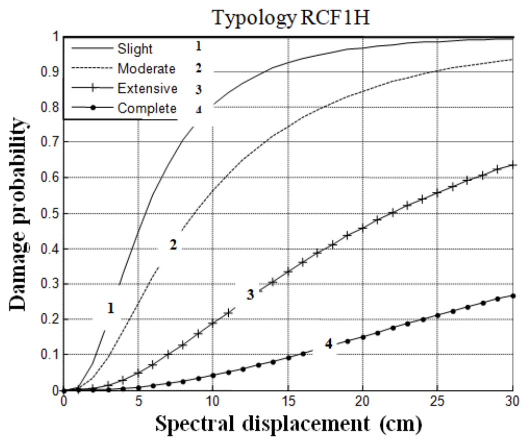

Fig. 11 Fragility curves for high-rise reinforced concrete frame structures, with low seismic design level.

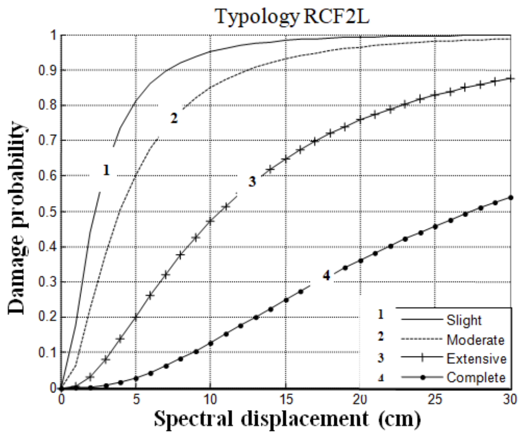

Fig. 12 Fragility curves for low-rise reinforced concrete frame structures, with moderate seismic design level.

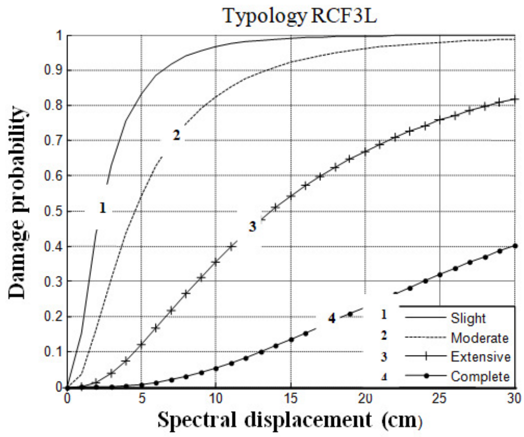

Fig. 15 Fragility curves for low-rise reinforced concrete frame structures, with high seismic design level.

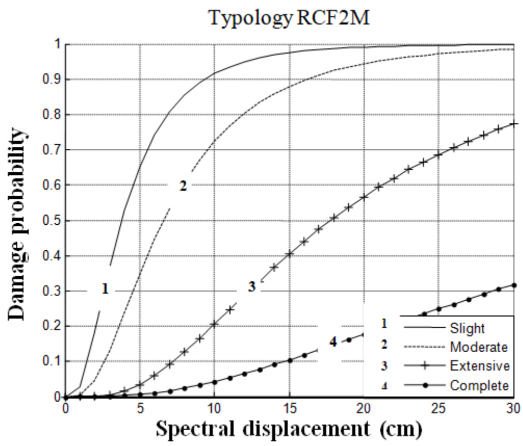

Fig. 13 Fragility curves for mid-rise reinforced concrete frame structures, with moderate seismic design level.

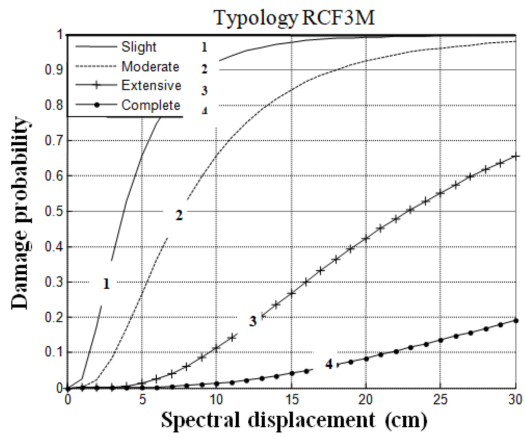

Fig. 16 Fragility curves for mid-rise reinforced concrete frame structures, with high seismic design level.

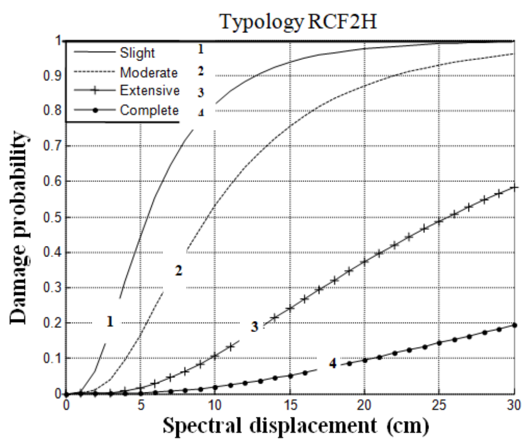

Fig. 14 Fragility curves for high-rise reinforced concrete frame structures, with moderate seismic design level.

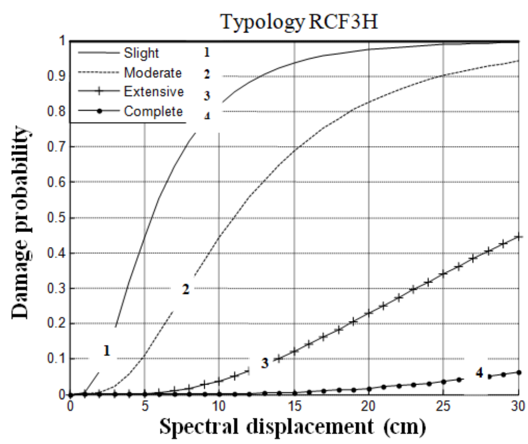

Fig. 17 Fragility curves for high-rise reinforced concrete frame structures, with high seismic design level.

VI. DAMAGE PROBABILITIES

Knowing the maximum spectral displacement S_d^p, it is possible to estimate the damage probabilities to a given type of building, based on the four damage grades, by projection on the fragility curves (Fig. 18 – Fig. 24). Theses curves, combined with the building inventories (Fig. 25), permit the quantification of the damage suffered in a seismic event (Fig. 26).

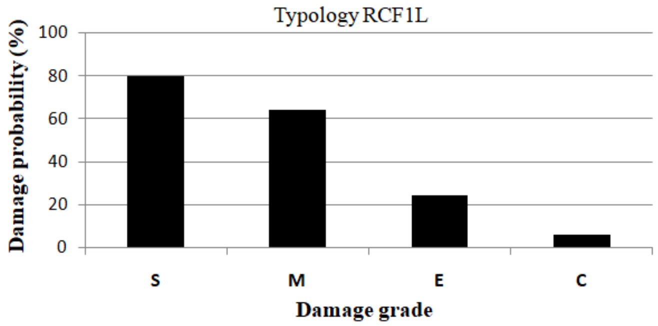

Fig. 18 Damage probabilities for low-rise reinforced concrete frame structures, with a low seismic design level.

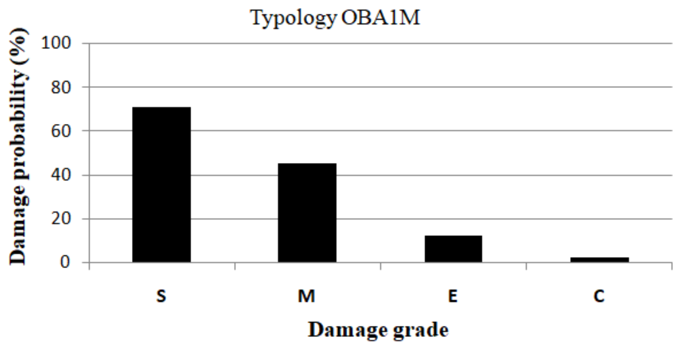

Fig. 19 Damage probabilities for mid-rise reinforced concrete frame structures, with a low seismic design level.

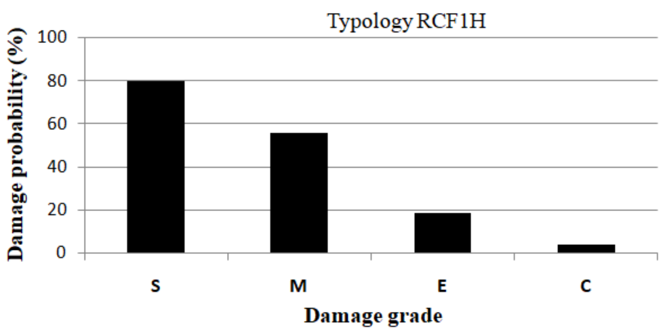

Fig. 20 Damage probabilities for high-rise reinforced concrete frame structures, with a low seismic design level.

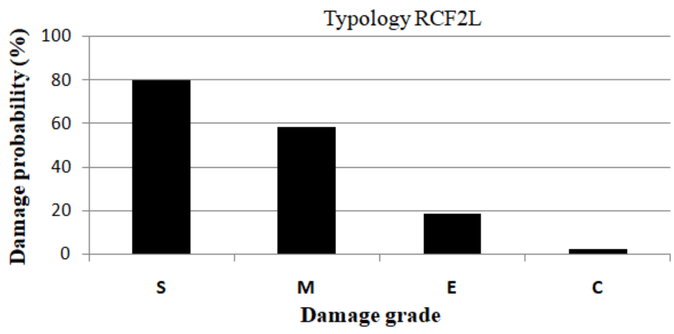

Fig. 21 Damage probabilities for low-rise reinforced concrete frame structures, with moderate seismic design level.

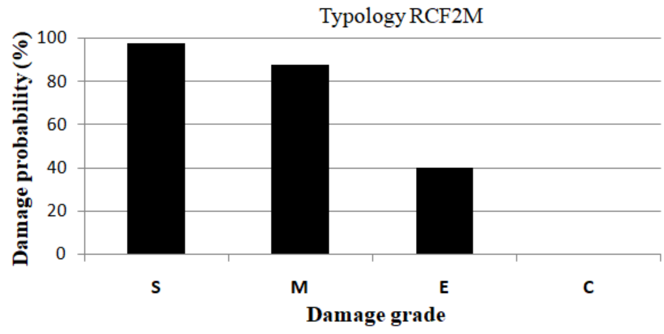

Fig. 22 Damage probabilities for mid-rise reinforced concrete frame structures, with moderate seismic design level.

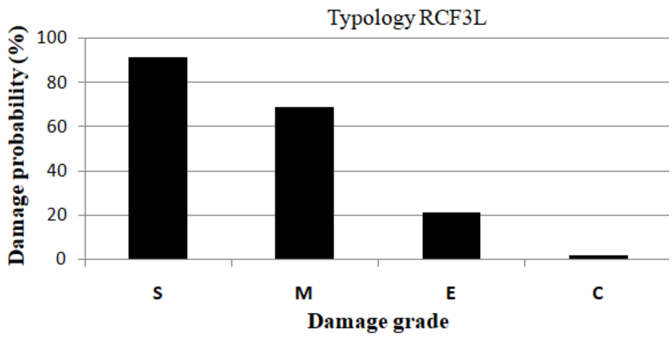

Fig. 23 Damage probabilities for low-rise reinforced concrete frame structures, with high seismic design level.

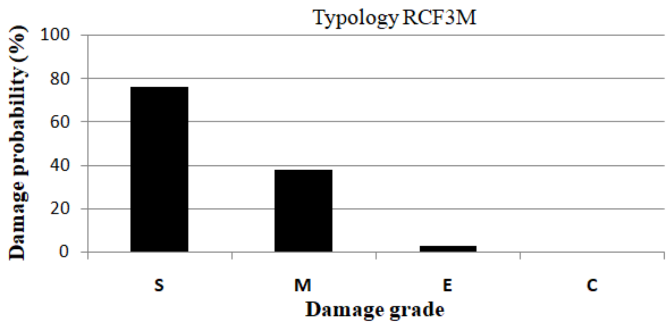

Fig. 24 Damage probabilities for mid-rise reinforced concrete frame structures, with moderate seismic design level.

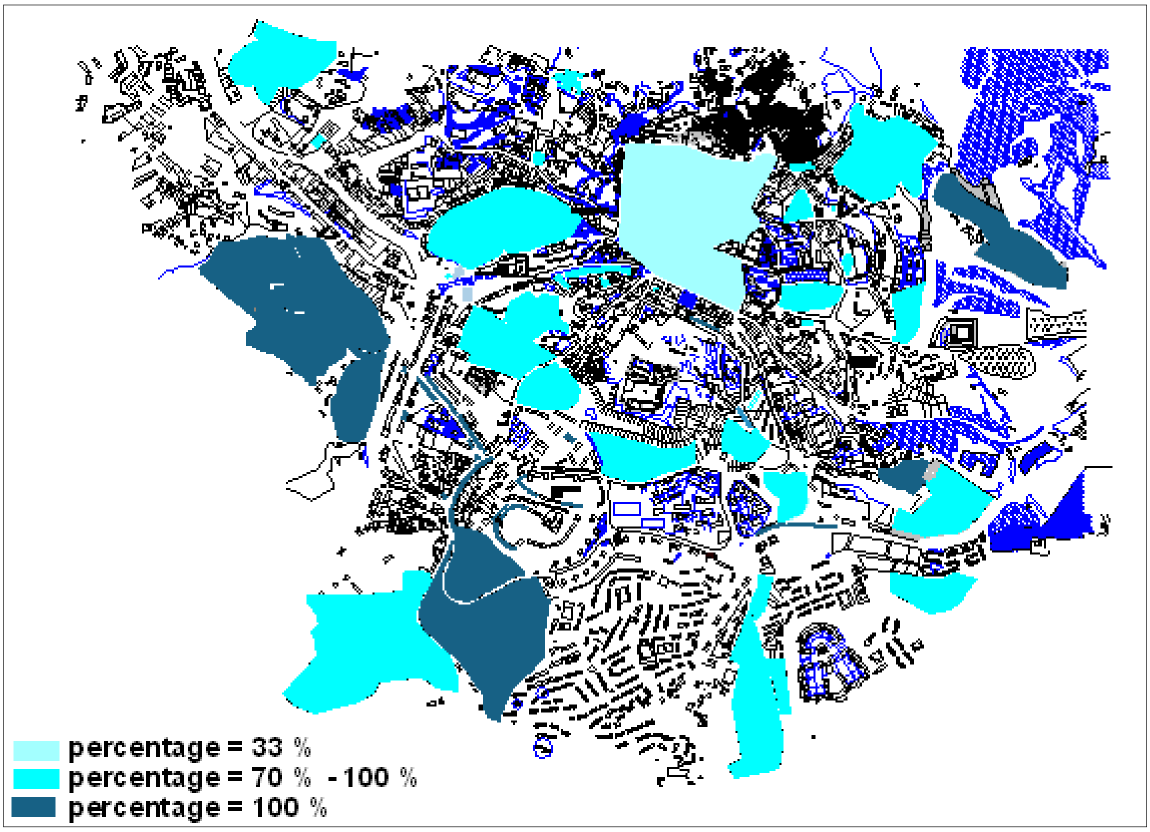

Fig. 25 Reinforced concrete frame structures distribution in Tizi-Ouzou city, according to the inventory survey carried out.

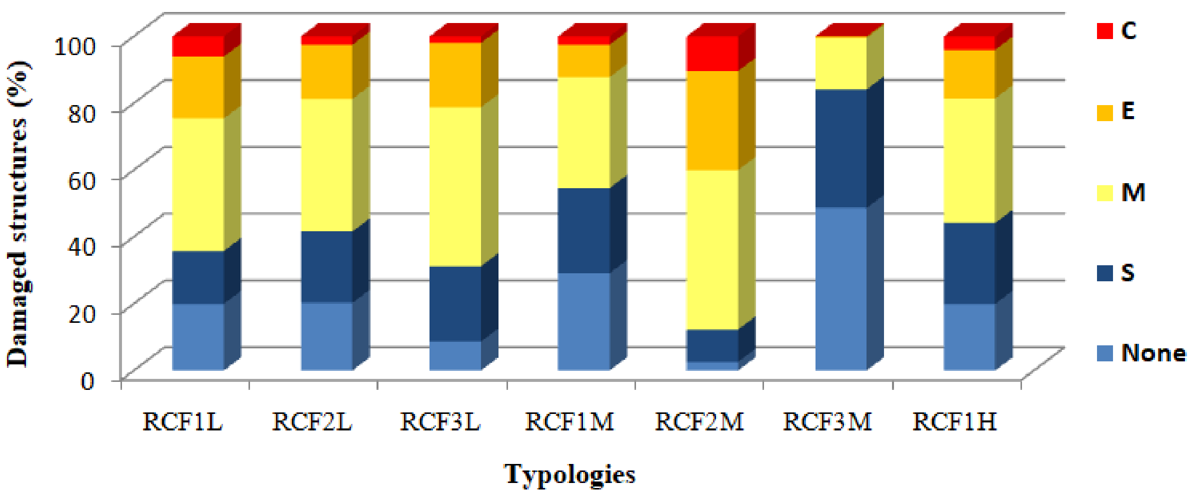

Fig. 26 Damaged structures percentages obtained for the four damage states (slight S, moderate M, extensive E, and complete C).

VII. CONCLUSION

We investigated the seismic vulnerability of reinforced concrete frame structures by fragility curves considered as cumulative functions of the log-normal distribution. These curves indicate the probability of a building reaching a certain damage grade, for a seismic demand expressed by the spectral displacement S_d . Calculating damage probabilities necessitates knowledge of maximum spectral displacements, which can be obtained by performing a pushover calculation.

Several criteria affect the accuracy of this analysis, including the shape of the lateral load that is supposed to represent the inertia forces in the seismic calculation. The difficulty of this assessment also lies in the great number of structures, the variability of construction types, and the unfamiliarity with existing structure behavior.

The model used to determine the capacity curves assumes that the mass is concentrated at the floor level. Considering a single mass per floor means that floors are infinitely rigid and will not deform. This is undoubtedly a good approximation for buildings with concrete floors, but more questionable for buildings with wooden floors, for example. This model is considered perfectly embedded at the base and does not consider soil-structure interaction. It should also be noted that masonry infills are neglected in calculations because of the difficulties in developing models that accurately represent masonry (Uncertainties about materials and element geometries, complex interaction between frame and wall, need to account for openings, asymmetric and unorganized arrangement of masonry panels), especially in the case of large-scale analysis.

Nonlinear static analysis is based on the assumption that the response of the structure can be assimilated to the response of a system with a single equivalent degree of freedom, which implies that the response is essentially controlled by a single vibration mode and that the shape of this mode remains constant during the earthquake. These two assumptions are not correct, but previous studies have shown that they provide good predictions of the maximum seismic response of a multi-degree-of-freedom system, and that the response is largely governed by the first vibration mode [13]. The second limitation of this analysis stems from the static nature of the loading, which cannot perfectly represent the phenomena that occur during dynamic cycles. Clearly, the most accurate approach is time-incremental dynamic analysis, which uses specific ground motion records to determine the relationship between structural responses and earthquake intensity levels. It has the advantage of considering the dynamic properties of the structure, taking into account the change in stiffness and eigenperiod of the structure under dynamic loading. However, temporal analysis is complicated and time-consuming, and cannot be applied to large-scale studies.

This analysis highlighted the high vulnerability to seismic action of structures with a low seismic design level, especially when the soils are soft or very soft. These structures can lose more than 50 % of their initial stiffness and suffer maximum damage.

The capacity curves obtained for structures without seismic design are significantly lower than the seismic requirement and the performance points are non-existent. Thus, the displacement generated by the earthquake exceeds the capacity of the structure, leading to partial or total collapse. By increasing the seismic design level, the performing point approaches the elastic domain, making the structure safer from collapse.

The probability of reaching or exceeding grade C, where damage is very significant and may even lead to ruin, is about 2 % for structures with a good seismic design level. This can exceed 10 % for the remaining structures.

The probability of exceeding grade E, where damage is significant, is less than 25% for low-rise structures and up to 40 % for the rest of the typologies.

The probability of exceeding the moderate damage grade M can reach 88 %.

In conclusion, Tizi-Ouzou city as a whole poses a problem in terms of its seismic vulnerability. Significant structural damage can occur, especially in reinforced concrete frame structures without any seismic design level. In the future, we hope to extend the analysis to all the typologies of this city. The results can be improved for the most vulnerable structures. A more detailed study would allow us to map the damage and estimate the economic costs.

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