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Impact Assessment of Structural and Non-Structural Components on the Vulnerability Level of Reinforced Concrete Buildings

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Abstract: Over the past four decades, Algeria has suffered considerable losses, due to several large earthquakes that hit its various northern parts. These destructive effects are amplified by the large volume of buildings constructed using imprecise and unfinished codes (before the appearance of the Algerian paraseismic code RPA99/03). Indeed, the majority of cities have developed in total ignorance of seismic risks. Also, these heavy losses recorded are the consequence of the use of poor materials as well as poor control of implementation. Furthermore, reducing human and economic losses during a disaster requires raising awareness among the population at risk. In this context, a study on the seismic vulnerability of constructions built before 2003 is carried out in our laboratory. Knowing that the "IV" vulnerability index level to be considered for a structure threatened by an earthquake is a combination of several parameters. This document proposes an approach to quantify the "IV" index level of column-beam buildings, based on the design of experiments method (DEM). The DEM is a correlation established between this "IV" index level and certain parameters considered sources of danger by several researchers. Two types of factors are distinguished: those designated as internal to the construction, such as: the age "Ag", the symmetry in plane "Sy", the regularity in elevation "Re", the quality of the bracing "Qc", the quality of the resistant system "Qr", the state of conservation "Ec", the secondary elements "Es", the infrastructure "If" and the redundancy of the rows "Rf" and those designated as external, such as: collision "And" and the ground condition "So". The resulting formula from this correlation allows managers to classify vulnerable buildings with a better approximation.

Keywords: Buildings, Reinforced concrete, Earthquake, Vulnerability, Design of experiments.

Introduction

In recent decades, Algeria has experienced earthquakes causing considerable human and material losses. These disasters have called into question the development process, causing disorganization at the level of the urban fabric and the economic fabric as well as the societal structure (Akkouche et al., 2020). Thus, the Chlef earthquake of 1980 and that of Boumerdes in 2003, creating a disaster and total upheaval in these regions; it is therefore important to undertake a real reflection on prevention, before investing in development programs

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which could be wiped out by a natural disaster (Schlupp et al., 2001). In this context, a number of studies have been carried out and reported in the literature dealing with knowledge on:

- The perception of seismic risk and the desire to take measures to reduce this risk (Kanti et al., 2010; Tekeli-Yesil et al., 2010; Isabelle et al., 2012; Bouzid et al., 2020).;
- The development of a vulnerability index (Lang et al., 2002; Mebarki et al, 2004; AFPS, 2005; Belheouane et al., 2009; Gulay et al., 2011);
- The development of new means of assessing vulnerability (Hamizi et al., 2007; Olson et al., 2010; Lutman et al., 2014; Nekmouche et al., 2017; Akkouche et al., 2019);
- The production of seismic scenarios (Boukri et al., 2014).

Despite the differences between these methods, they are based on the basic principle, which is the identification and estimation of seismic consequences. According to Gulay (2011), the vulnerability of a population is dominated by the most vulnerable buildings, it is therefore important to first determine what these buildings are, their number as well as their importance in relation to existing buildings.

In this perspective, based on the failure modes observed in reinforced concrete frames, Mitcheletll et al. (2001) and Mazare (2002) give a list of parameters most likely to cause significant damage. However, with such data, it is generally not easy to quantitatively identify the seismic capacities of existing structures, knowing in fact that these methods remain more or less simple, as they relate to simple visual inspections. To this end, in what follows, all the parameters judged to be influential factors on column-beam structures are studied: age “Ag”, symmetry in plane “Sy”, regularity in elevation “Re”, quality of the bracing “Qc”, quality of the resistant system “Qr”, state of conservation “Ec”, secondary elements “Es”, infrastructure “If”, redundancy of rows “Rf”, collision “Et” and ground condition “So”.

This study is based on post-seismic data processing based on the theory of experimental designs (Goupy,2006). For this purpose, a database of 508 post-seismic evaluation sheets is processed. Finally, an orientation allowing property managers to identify and prioritize high-risk buildings is given, and this, to be able to find the appropriate decisions with the objective to perform repairs or rehabilitation.

Methodology

The processing of feedback data (evaluation sheets) made it possible to show that the vulnerability of buildings varies greatly depending on the parameters characterizing the initial structural conditions. In this perspective, we seek to determine the factors and their degrees which can influence the overall behavior of column-beam structures. The experimental design method is carried out according to the following approach:

Identification of all the factors likely to weaken column-beam structures under the influence of seismic loads. Eleven factors were selected from a database made up of 508 files (constructions) (Hamizi et al., 2006), application of the Koshal screening experimental design, in order to distinguish the most influential factors. Application of the full factorial optimization experiment to develop a model for assessing the vulnerability of self-stable reinforced concrete frame buildings. Before discussing the results, a presentation, in the following two paragraphs, of some data specific to the Koshal and full factorial designs is performed.

KOSHAL Experiment and Full Factorial Experiment

KOSHAL designs: Koshal screening experimental designs make it possible to estimate the main effects or "weights" of k factors on a given property (response) in order to distinguish the truly influential factors. These experimental designs only admit a single first-degree polynomial model without interaction. For this purpose, the experiment matrix used, represents the beginning of the matrix of a complete factorial design (Goupy, 2006).

The matrices of the KOSHAL experimental design with N lines make it possible to study a number of k factors (k = N-1), each taking two levels. The latter, designated by Ri (inf) and Ri (sup) in natural variables, take the values -1 (denoted –) and +1 (denoted +) respectively in coded variables [Telford J.K et al, 2007]. The experience matrices are obtained by a circular permutation of a series of levels – and + given in the form of lines (Table 1).

Table 1. KOSHAL experiment matrix.

Configuration N°	Factors (Xi) X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	Response
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1,128
2	+1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	4,155
3	-1	+1	-1	-1	-1	-1	-1	-1	-1	-1	-1	4,319
4	-1	-1	+1	-1	-1	-1	-1	-1	-1	-1	-1	2,971
5	-1	-1	-1	+1	-1	-1	-1	-1	-1	-1	-1	3,741
6	-1	-1	-1	-1	+1	-1	-1	-1	-1	-1	-1	2
7	-1	-1	-1	-1	-1	+1	-1	-1	-1	-1	-1	3,624
8	-1	-1	-1	-1	-1	-1	+1	-1	-1	-1	-1	3,758
9	-1	-1	-1	-1	-1	-1	-1	+1	-1	-1	-1	1,882
10	-1	-1	-1	-1	-1	-1	-1	-1	+1	-1	-1	3,706
11	-1	-1	-1	-1	-1	-1	-1	-1	-1	+1	-1	3,802
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+1	3,867

The student statistical test of significance (Goupy, 2009; Kamoun et al, 2011) is used to choose whether significant effects are taken into account. PFC Full Factorial Designs: Two-level full factorial designs allow all possible combinations to be studied with a minimum number of configurations. In other words, these plans make it possible to determine the effects of factors and all the interactions that may exist between them. In this case, the experiment matrix has a dimension of k columns (Factors) and 2k rows (configurations). This matrix takes two levels for each factor k: -1 and +1. The experiment matrix is thus obtained by a classic arrangement of the experimental points (Table 2).

Table 2: PFC experiment matrix.

Configuration	Factor (Xi) X_1	X_2	X_3	X_4	.	.	X_N
1	-1	-1	-1	-1	.	.	-1
2	+1	-1	-1	-1	.	.	-1
3	-1	+1	-1	-1	.	.	-1
4	+1	+1	-1	-1	.	.	-1
5	-1	-1	+1	-1	.	.	-1
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
2^{N-1}	-1	+1	+1	+1	.	.	+1
2^N	+1	+1	+1	+1	.	.	+1

In the case where the factors are continuous, the mathematical model associated with the two-level Complete Factorial Experiment is of the additive polynomial type (of first or second degree and with interactions):

$$Y = a_0 + \sum_{i=1}^{N} a_i X_i + \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij} X_i X_j + \dots \dots . + \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} \sum_{l=1}^{N} a_{ijkl} X_i X_j X_k X_l \quad (1)$$

Where: Y: the response (damage state), X: the factor influencing the structure and a: the model coefficient.

Note: in the case where no factor appears in the structure (configuration No. 1: all factors are fixed at their lower level), assuming that the construction is healthy. For this purpose, the coefficient a_0=0.

Identification of Vulnerable Components

The identification of vulnerable components is established on a sample of structures assessed in the area affected by the 2003 Boumerdes earthquake, Algeria. Potential losses are quantified for each significant source of vulnerability. The classification of the sample of 508 structures is carried out by typologies, as indicated in Figure 1. The study is carried out on the typology representing more than 70% of residential use constructions, which are the structures made of reinforced concrete columns and beams. The degrees of damage relating to the 340 free-standing structures are given in the Figure 2.

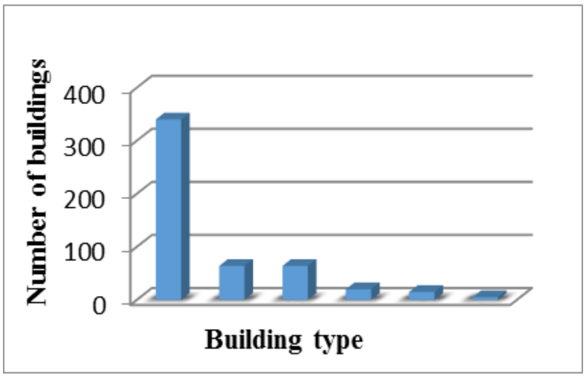

Figure 1. Classification according to the structures typology.

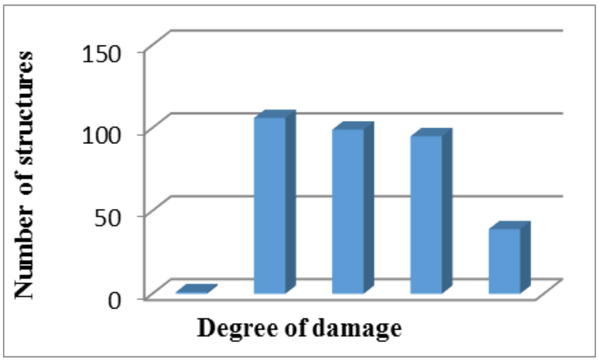

Figure 2. Classification of the 340 buildings according to the degree of damage

After inventorying the 340 column-beam buildings, the following process is carried out:

- Choice of 11 pathological factors for each structure (each survey sheet).
- Accounting for the factors having suffered damage, for each structure

Results

Application of the Koshal Experimental Design

The eleven factors likely to have a bad influence on the proper behavior of column-beam constructions as well as the levels assigned to them are given in Table 3. The lower and upper levels represent the two limits of the evaluation domain of the factors (as shown on the post-seismic evaluation sheet in the context of Algerian buildings).

Table 3. Factor levels following the Koshal experimental design.

Factors	Constructions classified in [D1-D2] Lower level		Constructions classified in [D3-D5] Higher level	
	Natural	coded	Natural	coded
Qr	D1	-1	D5	+1
Qc	D1	-1	D5	+1
Ag	After RPA 99	-1	Before RPA 99	+1
Ec	Good (D1)	-1	Bad (D5)	+1
Et	No	-1	Yes	+1
Es	D1	-1	D5	+1
So	D1	-1	D5	+1
If	D1	-1	D5	+1
Sy	Yes (D1)	-1	No (D5)	+1
Re	Yes (D1)	-1	No (D5)	+1
Rf	Yes (D1)	-1	No (D5)	+1

The overall damage levels are indicated in the last column of Table 3. Note that each of the 12 configurations were replicated several times. The values shown in Table 3 represent the test averages. The effects of the factors were estimated using the least squares method, as presented in Table 4.

Table 4. Estimated effects of Koshal experimental design factors.

Factor	Coefficient	Weight	Standard deviation	Significance test
Qr	a1	-0,72818	0,0033	***
Qc	a2	-0,63156	0,0033	*
Ag	a3	-0,6156	0,0033	NS
Ec	a4	-0,68772	0,0033	**
Et	a5	-0,62562	0,0033	NS
Es	a6	- 0,67839	0,0033	**
So	a7	-0,64934	0,0033	*
If	a8	-0,7331	0,0033	***
Sy	a9	-0,6231	0,0033	NS
Re	a10	-0,61 34	0,0033	NS
Rf	a11	-0,61039	0,0033	NS

With: NS: not significant; *: significant with a 95% confidence level; **: significant with a 99% confidence level; ***: significant with a confidence level of 99.9%

The results obtained made it possible to estimate the standard deviations of the coefficients [D. MATHIEU et al, 2000] and to distinguish, using the STUDENT test, the effects of statistically significant factors with a 95% confidence level (Table 4). Considering the confidence interval of the coefficient values, one can state that at most six factors can induce a vulnerable behavior in column-beam buildings. Those factors are: the quality of the resistant system (Qr), the quality of the bracing (Qc), the state of conservation (Ec), the secondary elements (Es), the ground conditions (So) and the infrastructure (If).

Note: We consider the two factors Qr and Qc to be comparable in a self-stable frame structure. Therefore, only the Qr factor is taken into account in this study.

Application of the Full Factorial Design

The two levels assigned to each of the five factors are the same as those indicated in Table 3. This is equivalent to considering a two-level system of five factors with 25 possible states (32 Configurations). Following the recommendations given in Goupy (2006), only the main effects and first-order interactions are taken into consideration. The results of the studied configurations are given in Table 5:

Table 5. Results of the different configurations

Configuration	1	2	3	4	5	6	7	9
Response	1,29	3,42	2,37	3,61	2,89	4,11	3,08	3,43
Configuration	10	11	12	17	18	19	20	21
Response	4,05	3,59	3,88	3,93	4,67	4,02	4,21	3,97

The analysis of the results is performed with the classic tools of experimental designs. Under these conditions, the model coefficients are estimated using the least squares method. The results obtained are illustrated in the Table 6.

Table 6**.** Importance of factors and interactions.

Main effects		Order interactions 1			
Effect	Weight	Interaction	Weight	Interaction	Weight
E1	-0,208	I12	0,0512	I24	0,0114
E2	-0,105	I13	0,0518	I25	-0,0265
E3	0,097	I14	-0,035	I34	0,0554
E4	-0,085	I15	0,0537	I35	0,0348
E5	-0,115	I23	0,0643	I45	0,0649

From the results presented above, a mathematical model making it possible to quantify the vulnerability of existing column-beam buildings was developed and given by the following formula:

$$
\begin{aligned}
V_{pp} = {} & -0{,}208 * Q_R - 0{,}105 * E_C + 0{,}097 * E_S - 0{,}085 * S_O - 0{,}115 * I_F + 0{,}0512 * Q_R * E_C + 0{,}0518 Q_R \\
& * E_S - 0{,}035 Q_R * S_O + 0{,}0537 * Q_R * I_F + 0{,}064 * E_C * E_S + 0{,}0114 * E_C * S_O - 0{,}0265 \\
& * E_C * I_F + 0{,}0554 E_S * S_O + 0{,}0348 E_S * I_F + 0{,}0649 * S_O * I_F
\end{aligned}
$$

Conclusions

The statistical procedure bringing together seismic vulnerability and structural characteristics, in the form of a mathematical model, offers a reliable possibility and capacity to provide real data on the structural state in the face of earthquakes. This is done by introducing data collected on site and taking into consideration the internal and external parameters of the construction.

The present work evaluates and quantifies the seismic vulnerability of a specific reinforced concrete structure, in this case: self-stable. The method of experimental designs, following the application of the Koshal design and the full factorial design, makes it possible to classify this typology of construction into two categories:

- Vulnerable when VPP= [3; 5]: encompassing structures that require intervention for reinforcement and rehabilitation. These are buildings with low earthquake resistance.
- Not vulnerable VPP= [0; 2]: encompassing healthy buildings, which do not require any intervention.

Therefore, this model can be used to translate a master plan on the vulnerability and fragility of the structures and buildings of the Algerian real estate stock.

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