

EMPIRICAL VULNERABILITY INDEX ASSESSMENT OF STRENGTHENED MASONRY STRUCTURES: CASE STUDY OF ALGIERS CITY

ÉVALUATION EMPIRIQUE DE L'INDICE DE VULNÉRABILITÉ DES STRUCTURES EN MAÇONNERIE CHAÎNÉE : CAS D'ÉTUDE DE LA VILLE D'ALGER

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Résumé - Cet article se concentre sur l'application de la méthode de l'indice de vulnérabilité sismique pour les bâtiments en maçonnerie chaînée (MC). Ce type de structures est connu pour être vulnérable aux tremblements de terre car, en pratique, il ne répond pas aux normes parasismiques en vigueur. A cet effet, une analyse empirique est appliquée aux bâtiments en maçonnerie chaînée afin d'évaluer cette catégorie de bâtiments selon le code parasismique algérien (RPA 99 version 2003). La méthode est appliquée à une base de données de 215 bâtiments situés dans la ville d'Alger expertisés après le séisme de Boumerdes (Mg. 6,8) qui a touché l'Algérie en 2003. Pour ce faire, les paramètres de vulnérabilité les plus importants influençant le comportement global de ce type de structures sont identifiés. Ensuite, trois classes de vulnérabilité (A, B et C) sont proposées pour exprimer l'état de chaque paramètre de vulnérabilité dans chaque classe de vulnérabilité. Ainsi, des facteurs de pondération sont attribués à chaque paramètre afin de calculer l'indice de vulnérabilité et de classer les bâtiments étudiés selon une classification proposée. La méthode a été insérée dans un programme Delphi. Ce programme appelé « Vulnerability Index Program » est dédié au calcul de l'indice de vulnérabilité pour plusieurs types de structures. Un système d'information géographique (SIG) est utilisé comme outil pour visualiser les résultats obtenus afin d'atténuer le risque sismique des bâtiments de la ville d'Alger.

Mots - clés : Indice de vulnérabilité, Séisme, Bâtiment en maçonnerie chaînée, Analyse empirique, Risque, Dommage.

Abstract - This paper is focused on the application of a seismic vulnerability index method for strengthened masonry buildings (SM). This kind of structures is known as being vulnerable to earthquakes as it does not comply with the seismic code in practice. With this purpose, an empirical analysis is applied for strengthened masonry buildings, in order to assess this category of buildings according to the Algerian seismic code (RPA 99 version 2003). The method is applied to a database of 215 buildings located in Algiers city and investigated after the Boumerdes earthquake (Mg. 6.8) which affected Algeria in 2003. To do this the most important vulnerability parameters influencing the global behaviour of this type of structures are identified. Then three vulnerability classes (A, B and C) are suggested to express the state of each vulnerability parameter in each vulnerability class. Therefore, weighting factors are assigned to each parameter in order to calculate the vulnerability index and classified the investigated buildings according to a proposed classification. The method was implemented in a Delphi program and applied to 215 buildings located in Algiers city. This program called "Vulnerability Index Program" is dedicated to the calculation of vulnerability index for several types of structures. A Geographic Information System (GIS) is used as a tool to visualize the obtained results, in order to mitigate the buildings seismic risk in Algiers city.

Keywords : Vulnerability index, Earthquake, Strengthened Masonry buildings, Empirical analysis, Risk, Damage.

1-Introduction

Algeria, which is located in a seismic zone, contains old urban nuclei that do not comply with the current seismic code. However, some macro vulnerability studies were elaborated and applied to Algiers city [1, 2], Boumerdes [3] and Blida city [4 - 6]. These studies targeted the existing buildings such as the unreinforced masonry (URM), reinforced concrete structures (RC), steel structures and lifelines such as roads and bridges. The present study deals with the vulnerability index method and applied to SM buildings, which are common in Algiers city. Several studies have been conducted using the vulnerability index method (VI). The method was improved and applied to different cities. The vulnerability parameters may influence the global behaviour of masonry buildings change from different suggested methods [7, 9 - 13, 15, 16]. On the other hand, some case studies have been elaborated targeting typical buildings [8, 14, 17]. In this method, parameters that may have an influence on the global seismic behaviour of SM buildings are identified. Then three vulnerability classes (A, B and C) are defined determining the state of each vulnerability parameter [18]. The weighting factors are determined using the empirical method. This method is based on a database of 100 buildings located in Algiers, which is situated in the highest seismic zone (Zone 3) [19]. The database has been established after the Boumerdes-Algiers earthquake magnitude 6.8 in 2003 [20]. The first Algerian earthquake regulations RPA was elaborated in 1981 after the major earthquake of El Asnam (Chlef) Mg. 7.1. Then the RPA was revised in 1983, 1988, 1999 and in 2003. On the other hand, in 1981 a data sheet was created just after the earthquake, and never has been updated. For this purpose, a new data sheet for the SM structures has been established in order to make the in-situ investigation and the building's classification according to the vulnerability index (VI). This data sheet has been implemented in a numerical program, to make easy and accurate the investigation of SM structures. Lastly, a Geographic Information System (GIS) is used to assess SM buildings and help to show which

area are most vulnerable to future earthquake. Therefore, the method is applied to a database in which 215 SM buildings has been inventoried in Algiers city.

2- Vulnerability Index method (VI)

The VI method is based on four important steps: [18, 21 - 24]

- First step: Selecting parameters influencing the seismic vulnerability of SM structures
- Second step: Defining vulnerability classes
- Third step: Assigning weighting parameters in each class
- Fourth step: Calculation of the VI and structure classification.

These steps are explained in the following paragraphs.

2.1- Selecting Parameters

Some influencing parameters on the structural response of SM buildings to seismic event were identified based on bibliography and statistical analysis based on the experience feedback in Algeria. Therefore, fourteen parameters have been identified in order to assess the seismic vulnerability of SM structures.

These parameters are Wall connections, seismic capacity, type of soil, steel's ductility, steel joints, horizontal diaphragm, modifications, plan regularity, elevation regularity, maintenance conditions, ground conditions, pounding effect, roof and details.

2.2- Defining Vulnerability Classes

Three vulnerability classes are considered: A, B and C. The class A shows that the parameter is consistent with the seismic code in use. The class C shows that the parameter is not consistent with the seismic code, while class B corresponds to an intermediate situation.

2.3- Defining Vulnerability Classes

An empirical analysis is used to define weighting parameters. The weighting factors have been obtained from seismic experience feedback and their direct influence on the global resistance of SM structures. A database of 100 SM buildings located in Algiers city has been used to determine factors assigned to each vulnerability parameter [20].

2.4- Calculation of VI and Structure Classification

To calculate the VI an equation is given based on the suggested strengthened masonry (SM) weighting factors. The VI is used to classify the investigated structures.

3-Application of the VI method to strengthened masonry (SM) buildings

Each parameter selected, is defined according to its influence on the behaviour of SM structures and each class is defined according to each parameter characteristics.

3.1- Wall connections parameter

Masonry buildings behaviour depends on the connection between masonry bearing walls. Several studies supported by the experience feedback have shown that a good connection between masonry walls can avoid the out of plan deformation and improve the global strength of the structures [14, 25, 26]. In the class A no wall connections damages or cracks appear, in the class B moderate wall connections damages appear while in the class C severe wall connections damages or total disconnection of walls appear.

3.2- Seismic capacity parameter

The seismic capacity is defined as the total base shear force of the structure. This force is calculated according to seismic Algerian code (RPA 99 version 2003) [19]. The number of the masonry walls and their thickness are the two main criteria taken into account to calculate the base shear force [27]. In the class A the base shear force (BSF) is greater than the seismic force (80%V) given by the seismic Algerian code, in the class B the

BSF is between 50% V and 80% V while in the class C the BSF is less than 50% V.

3.3- Type of soil

The classification of this parameter has been established according to the Algerian seismic code (RPA 99 version 2003), in which four types of soil are listed. The first type is the rock soils where the shear average wave velocity overtakes 800 m/s, the second type is the firm soils where the shear average wave velocity overtakes 400 m/s. The third type is the soft soils where the shear average wave velocity overtakes 200 m/s and the last type is the very soft soils where the shear average wave velocity is less than 200 m/s [19]. In the class A, rocky soil (S1) is considered, in the class B the firm soils (S2) is considered and in the class C the soft (S3) and very soft soils (S4) are considered.

3.4-Steel's ductility

The ductility of a material is the capacity to distort in the plastic range without reaching the failure. In the seismic code, the ductility is represented by the behaviour factor assigned to each structural system. The behaviour factor is between 2 and 6 for the different types of structures listed in the Algerian seismic code [19]. For the present study, only the ductility of the steel material existing in the masonry walls is taken into account. The evolution of the ductility is according to the material strain. In the class A steel frames undergo strains in elastic range, in the class B steel frames reach the plastic range and in the class C steel frames reach the failure [28].

3.5-Steel joints

Steel joints must transmit forces between different steel frames (columns and beams). Steel joints must strain in the elastic range; therefore, the classification of this parameter depends of the state of the connection between steel frames. In the class A steel joints undergo strains in the elastic range, in the class B steel joints reach the plastic range and in the class C steel joint reach the failure.

3.6-Horizontal diaphragm

Buildings diaphragms are the horizontal structures transmitting horizontal forces to the vertical walls. Floors must have diaphragm behaviour to ensure the forces transmission to vertical walls. Therefore, floors must be stiff and well connected to masonry vertical walls [29 - 31]. In the class A floors do not suffer damage and well connected to masonry walls, in the class C floors suffer damage and disconnected to masonry walls and in the class B one of the criteria of classification is observed.

3.7-Modifications

The modification refers to the change of the building's function and/or the structural system. This phenomenon is observed in many buildings in Algeria. People change the use of the building by increasing the loads on the structure, and make modifications in the structural system by creating openings in the masonry walls for instance. In the class A the building keeps its original structural system and the use, in the class B the building undergo modifications in the use or in the structural system and in the class C general modifications are made to the building as well as for the structural system.

3.8-Plan regularity

Criteria taken into account to classify this parameter are the building shape (L, H...etc.), the mass distribution in the same floor and the rigidity distribution (openings in the floor, different materials in the same floor...etc.). This phenomenon increases the horizontal eccentricity, which contributes to an inequality of forces distribution [30, 32]. In the class A the structure is horizontally regular according to the seismic code (RPA 99 version 2003), in the class B the structure is horizontally slightly irregular and in the class C the structure is horizontally irregular.

3.9-Elevation regularity

The same criteria of classification for the plan regularity parameter are used however; the comparison has been done between different floors vertically [33]. In the class A the structure is vertically regular according to the seismic code (RPA 99 version 2003), in the class B the structure is vertically slightly irregular and in the class C the structure is vertically irregular.

3.10-Maintenance

Each construction must be maintained regularly in order to keep as possible its initial state, especially the bracing system elements (Walls, frames...etc). In the class A the structure is periodically maintained (no cracks), in the class B the structure is occasionally maintained (slight cracks) and in the class C the structure never has been maintained (severe cracks).

3.11- Ground conditions

The experience feedback has shown that induced effect by earthquakes such as liquefaction [34 - 36], landslides [37, 38]...etc caused severe damages to buildings. Therefore, buildings located in a risk area such as near rivers, up or down cliffs, on a slope land with risk of landslide...etc are considered as vulnerable to earthquake and should be moved or protected by special countermeasures. In the class A the structure is located in secured area, in the class B the structure is located in moderate risk area and in the class C the structure is located in a high risk area.

3.12-Pounding effect

The Pounding effect can increase the structures vulnerability when these last are adjacent to other structures more or less stiff [40], and if any seismic joint exist but do not respect conditions required by the seismic regulations [20]. In the class A, the calculated seismic joint according to the seismic code exist, in the class B the seismic joint exist but do not comply with the seismic code and in the class C any seismic joint exist.

3.13-Roof

Roofs should have also diaphragm behaviour as floors; however, the design is usually different to current floors. Therefore, this part of the structure needs to be assessed separately to different floors, where same criteria as the horizontal diaphragm are applied.

3.14- Details

Detail parameter concerns elements that do not interfere in the structural system such as balcony, partition walls, handrail, acroterion, stairs...etc. In the class A more than 75% of existing non-structural elements do not suffer damages, in the class B less than 75% and more than 50% of non-structural elements do not suffer damages and in the class C less than 50% of non-structural elements do not suffer damages.

4- Strengthened masonry structures weighting factors

Weighting factors assigned to the different parameters have been obtained from experience feedback after the Boumerdes-Algiers earthquake in 2003. A database of 100 buildings has been used to determine weighting factors for each parameter in each vulnerability class [20]. The table 1 shows the weighting factors given by the empirical method. The weights are calculated so that the maximum vulnerability is equal to one (1).

Table 1: Empirical weighting factors (Ki)

Tableau 1 : Facteur de pondération empirique (Ki)

No.	Parameters	Classes		
		Class A	Class B	Class C
1	Walls connections	0.00	0.12	0.20
2	Seismic capacity	0.00	0.09	0.12
3	Type of soil	0.01	0.08	0.09
4	Steel's ductility	0.01	0.07	0.08
5	Steel joints	0.01	0.04	0.06
6	Horizontal diaphragm	0.01	0.04	0.05
7	Modifications	0.01	0.04	0.05
8	Plan regularity	0.01	0.04	0.05
9	Elevation regularity	0.01	0.04	0.05
10	Maintenance	0.01	0.04	0.05
11	Ground conditions	0.01	0.04	0.05
12	Pounding effect	0.01	0.04	0.05
13	Roof	0.01	0.04	0.05
14	Details	0.01	0.04	0.05

4.1- Vulnerability index (Vi) Calculation and Structure Classification

Three vulnerability classes are suggested (green, orange and red), explaining the state of strengthened masonry buildings. This classification is shown in table 2. The green class represents structures having a good resistance to earthquakes. The red class represents structures having a bad resistance to earthquakes, while the orange class is for an intermediate situation. Equation 1 shows how to calculate the Vi.

$$V_i = \sum_{n=1}^{n=14} K_i \quad (1)$$

Table2. Empirical RM structure classification according to the Vi

Tableau 2. Classification des structures en maçonnerie chaînée selon l'Iv empirique

Class	Green	Orange	Red
Vi	0.12-0.44	0.44-0.88	0.88-1.00

4.2- Digital implementation

4.2.1-Elaboration of the Data Sheet

The weighting factors assigned to each parameter will be established from a survey. For this purpose, a data sheet has been elaborated to regrouping all necessary information to calculate the building's VI. This sheet contains six parts as shown here after.

Part A: Structure identification

This part contains general information about the structure such as address, age, use, number of floors, basement and others details.

Part B: Geometric characteristics

This part describes building dimensions as length, width, height, plan and elevation shape.

Part C: Structural system

This part indicates the type and the structural system quality.

Part D: Soil and layout

Type of soil and layout of the building are found in this part.

Part E: Non-structural elements

This part contains information for non-structural elements such as balcony, partition walls, handrails, acroterion and stairs.

Part F: Maintenance and modifications

General information on the state of the structure is noticed, as well as modifications, which may influence the structure global behaviour.

A Delphi program has been performed in order to treat the collected information and to carry out the classification of the studied buildings.

4.2.2-Developed program

The developed program called VIP or Vulnerability Index Program version 4.5 can treat different types of structures (Masonry; RC structures; Steel and Strengthened Masonry (RM) structures). This program contains two

4.2.2.1-Interface Part

The visual part allows access to different menus and to fill in the necessary fields. It is made up of several pages. The home page and the handling page of the VIP are given in Figure 1 and 2.

4.2.2.2-Program Part

This part treats different information, carries out different calculations and assigns a weighting factor to each parameter. The calculation of the VI and the structure classification are carried out too.



Figure 1: Vulnerability Index Program home page

Figure 1 : Page d'accueil de programme de l'indice de vulnérabilité

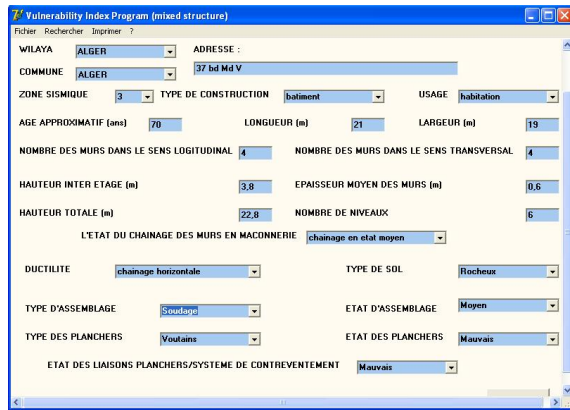


Figure 2: Vulnerability Index program handling page

Figure 2 : Page de manipulation de programme de l'indice de vulnérabilité

5-Application of the VI method to SM buildings

An in-situ survey of 215 SM buildings has been conducted in Algiers city centre. The database has been established after the Boumerdes-Algiers earthquake magnitude 6.8 in 2003, which affected 22665 buildings in Algiers and 66383 in Boumerdes city. The VIP helps to make easy the calculation of the VI, the classification and the recording of each building's data sheet. For this purpose and after the in-situ survey 196 (91.16%) buildings have been classified "Orange" ($0.44 < VI < 0.88$) and only 19 buildings (8.84%) have been classified "Green" ($0.00 < VI < 0.44$) as shown in Figure 3. Some reinforced concrete buildings shown in white colour exist in the study area (Fig. 4). The map shows the global view of the investigated buildings and their location using the GIS (Figure 4). Therefore, the study area is bounded by three important avenues, (Didouche Mourad, Mohamed V and Colonel Krim Belkacem) in which many important offices and ministries are located.

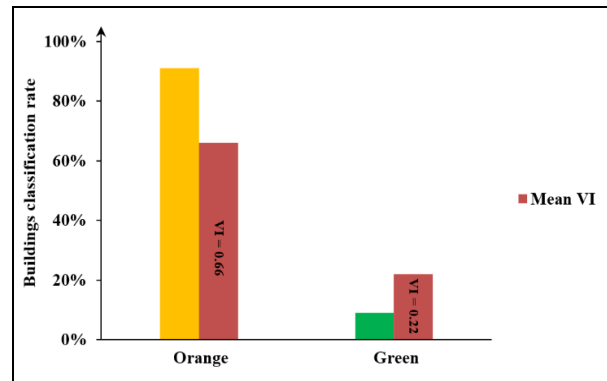


Figure 3: Strengthened masonry buildings classification

Figure 3 : Classification des bâtiments en maçonnerie chaînée



Figure 4: Strengthened masonry buildings classification map

Figure 4 : Carte de classification des bâtiments en maçonnerie chaînée

6-Conclusion

In this paper, a seismic vulnerability analysis has been conducted, using the vulnerability index method and has been applied to Algerian strengthened masonry structures. The aim of this study is the determination of weighting factors, which were obtained using an empirical analysis. A database of 100 strengthened masonry buildings was elaborated, which investigated by national experts after the major Boumerdes-Algiers earthquake in 2003. A data sheet has been worked out and implemented in a numerical program (VIP), in order to investigate with accuracy the SM buildings. For this purpose, a seismic scenario has been elaborated for the SM buildings, and applied to 215 of this type of building located in one of important district in Algiers city. This study showed that SM buildings need to be retrofit and updated according to the current seismic code.

Références bibliographiques

- [1] OYO-CGS, *Etude de vulnérabilité sismique de la ville d'Alger*, Japan international cooperation agency (JICA) - Centre National de Recherche Appliquée en Génie Parasismique (CGS), Algiers, 2006.
- [2] Yousfi, N., Bensaibi, M., Guessoum, N. and Boukri, M., *Seismic Scenario of Algiers City: Case Study of Strengthened Masonry Buildings*, Structural Engineering International, Vol. 32, n° 3, pp 328-336, 2022.
- [3] Sehili, F., Madani, S. and Meschinet de Richemond, N., *Vulnerabilities of cities to disaster: the 2003 earthquake in Boumerdes (Algeria)*, GeoJournal, Vol. 87, n° 1, pp 1759-1776, 2022.
- [4] Yousfi, N., Ait Belkacem, M., Guessoum, N. and Bensaibi, M., *Seismic resilience scenario of Algerian buildings context: Blida city case study*, Journal of Earthquake and tsunami, 2024.
- [5] Tadjer, K., and Bensaibi, M., *Earthquake risk assessment of Blida (Algeria) using GISproc*, of the Conf. on Mat. and Energy, La Rochelle, France, 2017.
- [6] Tadjer, K., Bensaibi, M. and Chaid, A., *Vulnerability assessment of Blida city*, proc. of the 15th World Conf. on Earthq. Eng., Lisboa, Portugal, 2012.
- [7] Chieffo, N., Clementi, F., Formisano and A., Lenci, S., *Comparative fragility methods for seismic assessment of masonry buildings located in Muccia (Italy)*. Journal of Building Engineering, Vol 25 pp 100813, 2019.
- [8] Hadzima-Nyarko, M., Misetic, V. and Moric, D., *Seismic vulnerability assessment of an old historical masonry building in Osijek, Croatia, using Damage Index*. Journal of Cultural Heritage, Vol 28 n° 7, pp 140-150, 2017.
- [9] Ferreira, T.M., Maio, R., Costa, A.A. and Vicente, R., *Seismic vulnerability assessment of stone masonry façade walls: Calibration using fragility-based results and observed damage*. Soil Dynamics and Earthquake Engineering, Vol 103 n° 12, pp 21-37, 2017.
- [10] Quagliarini, E., Lucasoli, M. and Bernardini, G., *Rapid tools for assessing building heritage's seismic vulnerability: a preliminary reliability analysis*. Journal of Cultural Heritage, Vol 39 n° 5, pp 130-139, 2019.
- [11] Ortega, J., Vasconcelos, G., Rodrigues, H. and Correia, M., *A vulnerability index formulation for the seismic vulnerability assessment of vernacular architecture*. Engineering Structures, Vol 39 n° 15, pp 109381, 2019.
- [12] Ortega, J., Vasconcelos, G., Rodrigues, H., Correia, M., Ferreira, T.M., and Vicente, R., *Use of post-earthquake damage data to calibrate, validate and compare two seismic vulnerability assessment methods for vernacular architecture*. International Journal of Disaster Risk Reduction, Vol 39 n° 10, pp 101242, 2019.
- [13] Kassem, M.M., Nazria, F.M. and Farsang, E.N., *The efficiency of an improved seismic vulnerability index under strong ground motions*, Structures, Vol 23 pp 366-382, 2020.
- [14] Uva, G., Sangiorgio, V., Ruggieri, S. and Fatiguso, F., *Structural vulnerability assessment of masonry churches supported by user-reported data and modern Internet of Things (IoT)*, Measurement, Vol 131 pp 183-192, 2019.

- [15] Zucconi, M., Sorrentino, L. and Ferlito, R., *Principal component analysis for a seismic usability model of unreinforced masonry buildings*, Soil Dynamics and Earthquake Engineering, Vol 96 n° 5 pp 64-75, 2017.
- [16] Khan, S.U., Qureshi, M.I., Rana, I.A. and Maqsoom, A., *An empirical relationship between seismic risk perception and physical vulnerability: A case study of Malakand, Pakistan*, International Journal of Disaster Risk Reduction, Vol 41 n° 12 pp 64-75, 2019.
- [17] Polese, M., Di Ludovico, M., d'Aragona, M.G., Prota, A. and Manfredi, G., *Regional vulnerability and risk assessment accounting for local building typologies*, International Journal of Disaster Risk Reduction, Vol 43 n° 2 pp 101400, 2020.
- [18] Yousfi, N. and Bensaibi, M., *Weighting assessment of vulnerability index parameters for reinforced masonry structures*, Structural Engineering International, Vol 27 n° 1, pp 79-87, 2017.
- [19] Ministry of Housing and Urban Planning, *Règles parasismique algériennes RPA 99/ version 2003, DTR-B.C.2.48*, Algeria, 2004.
- [20] CGS, *Statistical study on the damaged buildings following the Boumerdes earthquake of May 21st, 2003*, Report, Centre national de recherche appliquée en ingénierie parasismique, Algeria, 2003.
- [21] Bensaibi, M., Djaalali, F., Belheouane, F.I., Amellal, O. and Yousfi, N., *Seismic vulnerability index method: Algerian case studies*, Proc. of the 8th International Conf. on Urban Earthq. Eng., Tokyo, Japan, 2011.
- [22] Amellal, O., Bensaibi, M. and Grine, K., *Seismic vulnerability index method for steel structures*, Proc. of the 15th World Conf. on Earthq. Eng. (WCEE), Lisboa, Portugal, 2012.
- [23] Djaalali, F., Bensaibi, M. and Bourahla, N., *Evaluation of the vulnerability index for unreinforced masonry structures*, Applied Mechanics and Materials, Vol 166-169, pp 1387-1390, 2012.
- [24] Djaalali, F., Bensaibi, M., Bourahla, N. and Davenne, L., *Vulnerability curves of masonry constructions Algiers case study*, Structural Engineering and Mechanics, Vol 42 n° 5, pp 609-630, 2012.
- [25] Preciado, A., Ramirez-Gaytan, A., Santos, J.C. and Rodriguez, O., *Seismic vulnerability assessment and reduction at a territorial scale on masonry and adobe housing by rapid vulnerability indicators: The case of Tlajomulco, Mexico*, International Journal of Disaster Risk Reduction, Vol 44 n° 3, pp 101425, 2020.
- [26] Acito, M., Magrinelli, E., Milani, G. and Tiberti, S., *Seismic vulnerability of masonry buildings: Numerical insight on damage causes for residential buildings by the 2016 central Italy seismic sequence and evaluation of strengthening techniques*, Journal of Building Engineering, Vol 28 n° 2, pp 101081, 2020.
- [27] Yousfi, N. and Bensaibi, M., *Elaboration de courbes de vulnérabilité pour des structures mixte maçonnerie-charpente métallique*, Ph.D. thesis, Blida 1 university, 2017.
- [28] Association Française de Normalisation (AFNOR), *Eurocode 3, Calcul des Structures en Acier et Document d'Application AFNOR*: Paris, 1999.
- [29] Solarino, F., Oliveira D.V. and Giresini, L., *Wall-to-horizontal diaphragm connections in historical buildings: A state-of-the-art review*, Engineering Structures, Vol 199 n° 22, pp 109559, 2019.
- [30] Kollerathu, J.A. and Menon, A., *Role of diaphragm flexibility modelling in seismic analysis of existing masonry structures*, Structures, Vol 11 n° 3, pp 22-39, 2017.
- [31] Lin, T.J. and LaFave, J.M., *Experimental structural behavior of wall-diaphragm connections for older masonry buildings*, Construction and Building Materials, Vol 26 n° 1, pp 180-189, 2012.
- [32] Kalkbrenner, P., Pela, L. and Sandoval C., *Multi directional pushover analysis of irregular masonry buildings without box behavior*, Engineering Structures, Vol 201 n° 24 pp 109534, 2019.
- [33] Lin, J.L., Tsaur, C.C. and Tsai, K.C., *Two-degree-of-freedom modal response history analysis of buildings with specific vertical irregularities*, Engineering Structures, Vol 184 n° 7 pp 505-523, 2019.
- [34] Kokusho, T., *Earthquake-induced flow liquefaction in fines-containing sands under initial shear stress by lab tests and its implication in case histories*, Soil Dynamics and Earthquake Engineering, Vol 130 n° 3, pp 105983, 2020.

- [35] Papathanassiou, G., Mantovani, A., Tarabusi, A., Rapti, D. and Caputo, R., *Assessment of liquefaction potential for two liquefaction prone areas considering the May 20, 2012 Emilia (Italy) earthquake*, Engineering Geology, Vol 189 n°6, pp 1-16, 2015.
- [36] Chiaradonna, A., Tropeano, G., d'Onofrio, A. and Silvestri, F., *Interpreting the deformation phenomena of a levee damaged during the 2012 Emilia earthquake*, Soil Dynamics and Earthquake Engineering, Vol 124 n°9, pp 389-398, 2019.
- [37] Liu, W., Yan, S., He, S., *Landslide damage incurred to buildings: A case study of Shenzhen landslide*, Engineering Geology, Vol 247 n° 12, pp 69-83, 2018.
- [38] Infante, D., Di Martire, D., Confuorto, P., Tessitore, S., Tòmas, R., Calcaterra, D. and Ramondini, M., *Assessment of building behavior in slow-moving landslide-affected areas through DInSAR data and structural analysis*, Engineering Structures, Vol 199 n° 22, pp 109638 2019.
- [39] Guenidi, Z., Abdeddaim, M., Ounis, A., Shrimali, M.K. and Datta, T.K., *Control of Adjacent Buildings Using Shared Tuned Mass Damper*, Procedia Engineering, Vol 199 n° 30, pp 1568–1573, 2017.
- [40] Jankowski, R., *Non-linear FEM analysis of earthquake-induced pounding between the main building and the stairway tower of the Olive View Hospital*, Engineering Structures, Vol 31 n° 8, pp 1851-1864, 2009.