

OPTIMIZING EARTHQUAKE-RESISTANT BUILDING DESIGN: THE INTERPLAY OF SHEAR WALL PLACEMENT AND BRACING SYSTEMS

OPTIMISATION DE LA CONCEPTION DES BÂTIMENTS RÉSISTANTS AUX SÉISMES : INTERACTION ENTRE LA DISPOSITION DES VOILES ET LES SYSTÈMES DE CONTREVENTEMENT

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Abstract - In civil engineering, the design and construction of earthquake-resistant structures remain a top priority, particularly in regions prone to seismic activity. This study examines the dynamic relationship between the positioning and dimensions of shear walls and their influence on the selection of appropriate bracing systems, aiming to optimize structural performance and cost-effectiveness. The central issue addressed in this study is the complex decision-making process faced by civil engineers and architects when designing earthquake-resistant buildings. While the seismic role of shear wall positioning is well recognized, the interaction between their dimensions and the choice of bracing systems has been less comprehensively explored. This study aims to tackle the complex challenge of shear wall positioning and stiffness in relation to bracing system selection, ultimately promoting improved seismic design practices in civil engineering. The aim of this work is to establish optimization models for the quantity of shear walls in each individual seismic direction. This prediction is carried out using the machine learning method, with estimation performed by the artificial neural network (ANN) algorithm. Additionally, a parametric study is conducted to determine the quantity of shear walls while selecting the bracing system based on the vertical and horizontal loads supported by the shear walls. The study revealed that for optimal layout, shear walls should be placed along the perimeter of the architectural plan, allowing for better distribution of seismic forces and reduced torsional effects. Moreover, it is crucial to combine frames with shear walls positioned in the opposite seismic direction. This configuration ensures that the bracing system remains in category (4b), thereby maximizing seismic resistance efficiency.

Keywords: Shear walls, Position, Stiffness, Seismic Resistance, Bracing System.

Résumé - En génie civil, la conception et la construction de structures résistantes aux séismes restent une priorité, en particulier dans les régions sujettes à une forte activité sismique. Cette étude examine la relation dynamique entre la position et les dimensions des voiles et leur influence sur le choix des systèmes de contreventement appropriés dans le but d'optimiser les performances structurelles et la rentabilité. La problématique centrale abordée dans cette recherche est le processus décisionnel complexe auquel sont confrontés les ingénieurs civils et les architectes lors de la conception de bâtiments résistants aux séismes. Bien que le rôle sismique de la position des murs de cisaillement soit largement reconnu, l'interaction entre leurs dimensions et le choix des systèmes de contreventement a été moins explorée en profondeur. Cette étude vise à relever le défi complexe de la disposition et de la rigidité des murs de cisaillement en lien avec la sélection des systèmes de contreventement, dans l'objectif d'améliorer les pratiques de conception sismique en génie civil. Le but de ce travail est de développer des modèles d'optimisation pour la quantité de voiles dans chaque direction sismique spécifique. Cette prévision est réalisée en utilisant la méthode d'apprentissage automatique, avec une estimation effectuée par l'algorithme du réseau de neurones artificiels (ANN). En outre, une étude paramétrique est menée pour déterminer la quantité des voiles tout en choisissant le système de

contreventement en fonction des charges verticales et horizontales supportées par les murs de cisaillement. L'étude a révélé que, pour une disposition optimale, les murs de cisaillement devraient être placés le long du périmètre du plan architectural, permettant ainsi une meilleure répartition des forces sismiques et une réduction des effets de torsion. De plus, il est crucial de combiner des cadres avec des voiles placés dans la direction sismique opposée. Cette configuration garantit que le système de contreventement reste dans la catégorie (4b), maximisant ainsi l'efficacité de la résistance sismique.

Mots - clés : voiles, Position, Rigidité, Résistance sismique, Système de contreventement.

1-Introduction

The optimization of earthquake-resistant building design is a critical concern in civil engineering, particularly in regions prone to seismic activity [1]. Structural bracing often employs reinforced concrete walls due to their strong resistance to lateral forces. While the importance of shear wall positioning in enhancing the seismic performance of structures is well-established [2-3], the complex interplay between the dimensions of these walls and the choice of bracing systems remains less thoroughly examined. The capacity of a building to withstand seismic loads is not only dependent on the presence of shear walls but also on how their dimensions and arrangement interact with other structural elements, such as bracing systems. In the international technical literature, it is possible to find numerous references involving seismic studies [4-13]. Tarigan et al. (2018) examined the impact of shear wall placement on the seismic resistance of RC buildings. The study found that placing shear walls symmetrically at the core significantly reduced lateral displacement and story drift, offering the best performance compared to other configurations [14]. Research by Chen et al. (2020) highlights that appropriately sized shear walls significantly improve energy dissipation and overall stiffness, which are key to better performance during seismic events [15]. Similarly, Mangalathu et al. (2020) emphasize the importance of carefully considering wall dimensions to prevent catastrophic failures [16]. Bracing systems also play a vital role in stabilizing structures against lateral forces, with their selection often guided by building characteristics and specific seismic demands. Chen et al. further demonstrate that combining shear walls with energy dissipators enhances the ability to absorb seismic energy, while Mangalathu et al.'s use of machine learning to identify optimal bracing configurations that

complement shear wall dimensions underscores the importance of these elements working in synergy [15-16]. In a study conducted by Sayed (2021), the seismic performance of symmetrical multistory reinforced-concrete (RC) buildings was evaluated with a focus on the effects of various in-plane shear wall configurations. The analysis revealed that central core configurations increase seismic demands, while perimeter configurations better reduce forces. The study highlights the importance of strategic shear wall placement for improved seismic resilience and cost efficiency [17]. The study by Khelaifia et al. (2024) highlights the importance of both the position and quantity of shear walls in optimizing a structure's ability to withstand seismic activity. Their research shows that strategically placed and appropriately distributed shear walls significantly improve a building's resistance to seismic forces. However, adding too many shear walls can lead to diminishing returns, suggesting an optimal balance is necessary [18].

Current research has primarily focused on the benefits of placing shear walls symmetrically to balance seismic forces and minimize torsional effects, contributing to overall structural stability. However, the critical role of wall stiffness and how it integrates with the selected bracing system to influence the building's seismic response has been underexplored. An overly stiff shear wall can lead to stress concentrations and potential failure at specific points, particularly at the base, whereas an insufficiently stiff wall may not adequately control lateral displacements, risking structural collapse. This research aims to fill the gap by examining the interaction between the dimensions of shear walls and the selection of bracing systems to optimize the seismic resistance of buildings. Understanding this interplay is essential for developing design strategies that not only ensure safety and

stability but also adhere to practical design and cost constraints.

2- Reference structure description

The structure studied in this paper is a six-story reinforced concrete building, designed to be braced with shear walls, as shown in Fig. 1, with a storey height of 3,06m. It is located in a seismic zone III, following the standards of the Algerian seismic code RPA99/V2003 [19]. The numerical modeling of this structure was conducted using the ETABS V9 software [20], allowing for an analysis of its dynamic behavior. The characteristics of the materials initially considered are, 25 MPa for the compressive strength of the concrete and 400 MPa for the yield strength of the reinforcement. The floors are composed of beams and hollow blocks (16+4) cm, which are considered as infinitely rigid diaphragms, contributing to the overall stability of the building. The structural elements, such as columns and beams, were dimensioned in accordance with the applicable regulations [21], with particular attention given to seismic resistance. The geometric configurations and the quantities of reinforcement obtained for the load-bearing elements of the building are presented in Fig. 2. The structure exhibits irregularities in its plan, necessitating complex and precise modeling to accurately assess the natural frequencies of vibration and the forces induced by seismic activity.

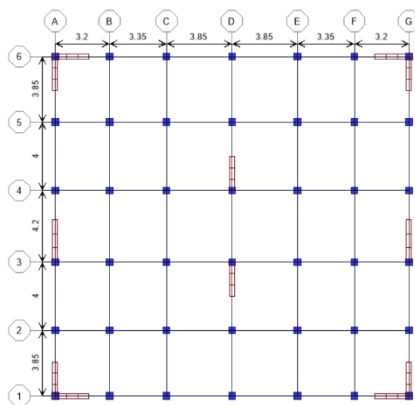
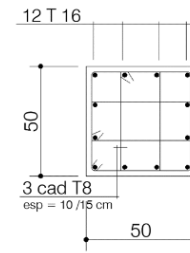
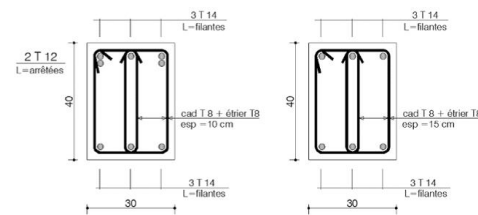


Figure 1: Plan view of the studied structure

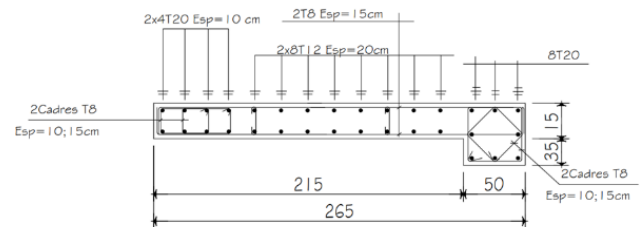
Figure 1 : Vue en plan de la structure étudiée



(a) Columns (Poteaux)



(b) Beams (Poutres)



(c) Shear Walls (Voiles)

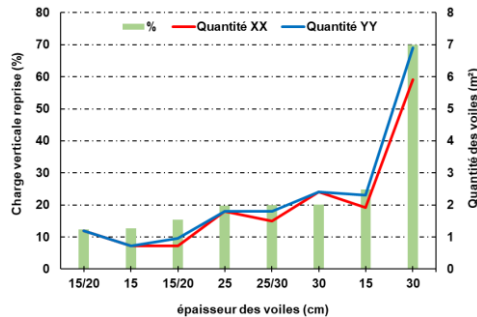
Figure 2: Reinforcement Details

Figure 2 : Détails des armatures

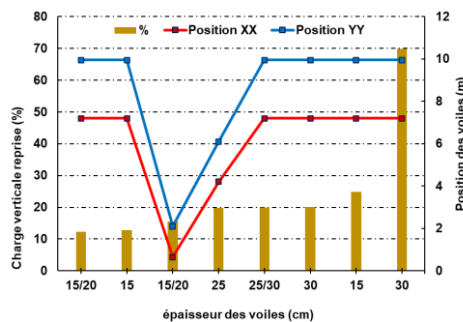
3- Justification of the bracing system

The RPA 99 - 2003 Version [19] stipulates that for bracing system 2, the shear walls carry more than 20% of the stresses caused by vertical loads. In contrast, for systems 4a and 4b, the shear walls carry at most 20% of the stresses caused by vertical loads. In fact, in the event of a strong earthquake, when the structure undergoes nonlinear deformations, significant vertical loads (more than 20% according to the RPA) on the shear walls can cause instabilities that may lead to a reduction in ductility and deformation capacity. These instabilities can manifest as buckling of the compressed ends of the shear walls or as buckling of the longitudinal reinforcements at the ends. As a result, bracing system 2 is considered the least ductile ($R=3.5$) compared to systems 4.a ($R=5$) and 4.b ($R=4$).

Fig. 5a indicates that increasing the number of walls improves vertical load distribution. Fig. 5b demonstrates that while increasing wall thickness generally improves vertical load support, the increase in horizontal load capacity is not always linear, with only slight differences observed between 15/20 cm and 25 cm thicknesses.



(a) according to quantity (selon la quantité)



(b) according to position (selon la position)

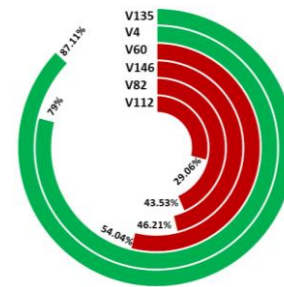
Figure 5: Comparison of the vertical load taken by the walls

Figure 5 : Comparaison de la charge verticale supportée par les voiles

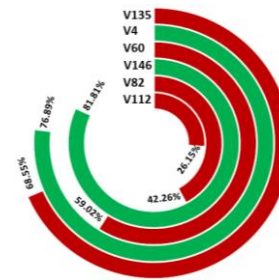
4.2- Horizontal load taken by the walls

In the second phase of our study, we examined a new regulatory condition for the 190 variants that passed the first phase. These variants were designed using a category (4b) bracing system under the Algerian seismic code. We specifically verified that the entire horizontal load is supported exclusively by the bracing walls. If a variant failed this requirement, it was reclassified to category (2), where the walls act as load-bearing elements. Figs. 6-7-8 illustrate the effectiveness of bracing walls in supporting horizontal seismic loads. Higher percentages in pie charts indicate

better efficiency, with variants below 75% reclassified to a different category. Thicker bracing walls generally improve load support but also increase material usage. The position of the walls within the structure affects their ability to carry horizontal loads, with the XX direction showing higher load support than the YY direction. Wall thickness and position are crucial factors in designing earthquake-resistant structures.



(a) XX



(b) YY

Figure 6: Percentage of the vertical load taken by the walls of the optimal and sub-optimal variants

Figure 6 : Pourcentage de la charge verticale supportée par les voiles dans les variantes optimales et sous-optimales

The study found that out of 190 variants, 154 did not meet the second seismic regulation condition, which requires bracing walls to support all horizontal loads. Variants V3 and V4 fully complied, while V134, V135, and V161 only met the condition in the XX direction, and 31 other variants only in the YY direction (see Appendix A). The 36 compliant variants had walls placed exclusively at the ends of the architectural plan, optimizing seismic resistance and stability while minimizing the impact on interior space flexibility.

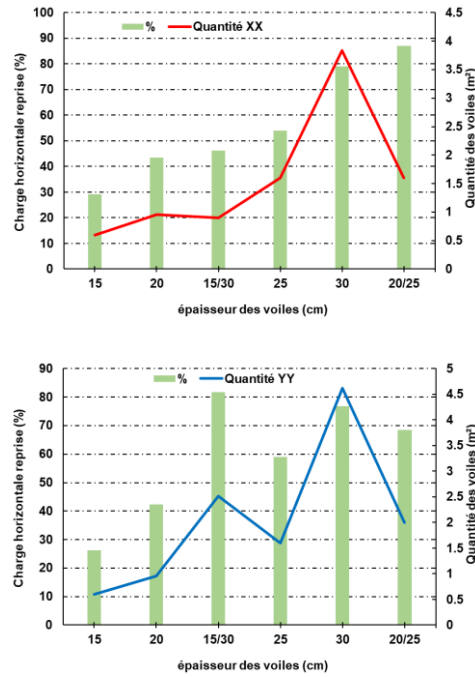


Figure 7: Comparison of the vertical load taken by the walls according to quantity

Figure 7 : Comparaison de la charge verticale supportée par les voiles en fonction de la quantité

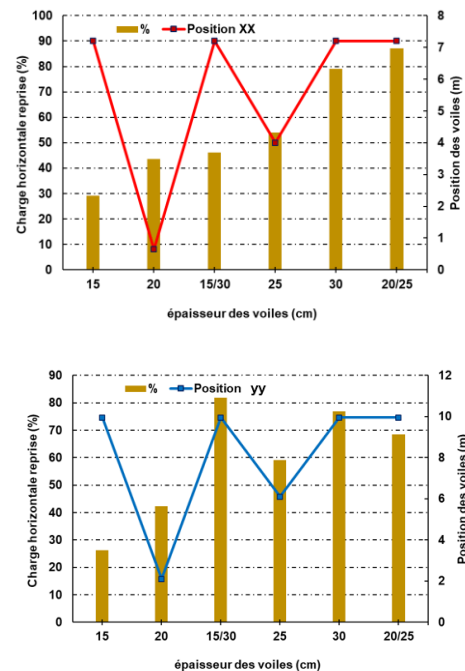


Figure 8: Comparison of the vertical load taken by the walls according to position

Figure 8 : Comparaison de la charge verticale supportée par les voiles en fonction de leur position

4.3- Checking gables for reduced seismicity

In the third phase of the study, the focus is on verifying the third regulatory condition for 36 category (4b) bracing system variants that have already met the first two conditions under the Algerian seismic code. This phase aims to assess the frames' ability to withstand horizontal loads representing 25% of the total horizontal effort [19]. For each seismic direction meeting the initial conditions of seismic regulations, we follow a modeling procedure that involves: first, removing shear walls to isolate the effect of frames in that direction; second, applying a reduction factor of 0.25 to the initial seismic load, which only affects the frames and ensures that any remaining shear walls support at least 75% of the load; and finally, verifying the stability and shear resistance at the base of the frames to ensure the structure can withstand seismic forces effectively. The results indicate that among the 36 variants tested, frames braced by load-bearing shear walls met the seismic regulations effectively. For frames to withstand 25% of the total seismic load, they must be paired with shear walls in the opposite seismic direction. This strategic configuration ensures optimal force distribution and enhances the structure's stability and resistance by utilizing the combined strengths of the shear walls and frames.

5- Predictive ANN models

The performance of artificial neural network (ANN) models is influenced by network topology and learning parameters [22-28]. Topology includes the number of inputs, outputs, hidden layers, and neurons per hidden layer, while learning parameters involve the algorithm, performance function, transfer functions, maximum error, and learning cycles [29-31]. There are no fixed rules for setting these parameters, so trial and error is often used. The backpropagation network, trained with the Levenberg-Marquardt algorithm, was used for developing models [32]. ANNs, inspired by the human brain, consist of interconnected nodes organized in layers [33-35]. Optimal performance for predicting bracing shear wall quantities is achieved with an architecture of two hidden layers, each with

10 neurons (Fig. 9). Input parameters are the ratios of vertical and horizontal loads, with shear wall quantity as the output.

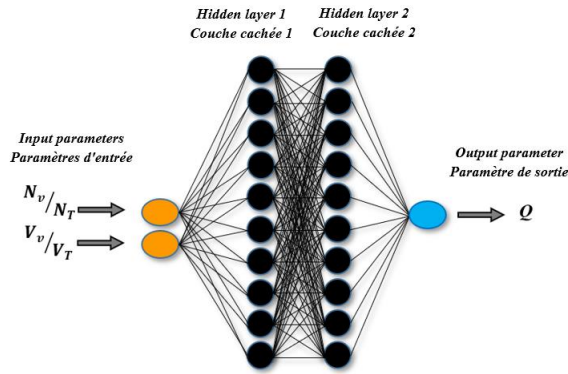
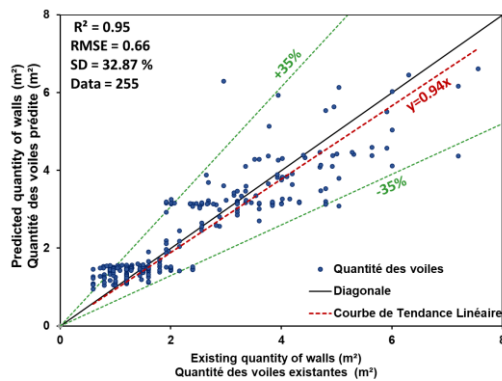


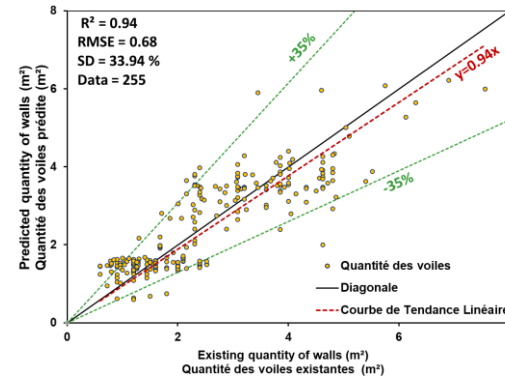
Figure 9: Architecture used in the ANN model

Figure 9 : Architecture utilisée dans le modèle ANN

Fig. 10 effectively illustrates this performance for each seismic direction XX and YY, respectively. From these figures, it is clear that the good distribution of data points is along the diagonal ($X=Y$) of the best-fit line, where an ideal agreement between prediction points and experimental results is achieved. This is confirmed by the slope of the linear trend line being equal to 0.94. This distribution falls within an error margin not exceeding 35% relative to the best-fit line. The results also show that these predictions provide a better coefficient of determination $R^2 = 0.95$ and 0.94 , as well as a better error in terms of root mean square error (RMSE) = 0.66 and 0.68, and a standard deviation (SD) = 32.87% and 33.94% for the X and Y directions, respectively.



(a) XX



(b) YY

Figure 10: Performance of the ANN models for predicting shear wall quantities

Figure 10 : Performance des modèles (ANN) pour prédire les quantités des voiles

4- Parametric study

In this section, we conduct a parametric analysis of the input variables to explore their correlations with the quantity of bracing shear wall, regardless of the bracing system. Using an artificial neural network (ANN) to predict models for each seismic direction, we precisely examine the impact of parameters such as the vertical load ratio and the horizontal load supported by the bracing shear walls on the quantity of shear walls, in order to facilitate the selection of the bracing system.

Figs. 11 and 12 show how the horizontal load ratio affects the quantity of bracing shear walls for two bracing system categories (4b and 2) across two seismic directions (XX and YY). For the analysis, vertical load values are kept constant at three levels for each system type. Results indicate that increasing both the vertical and horizontal load ratios increases the quantity of bracing shear walls. Specifically, for system (4b), the number of shear walls remains constant for horizontal loads below 85%, while for system (2), it remains unchanged for horizontal loads above 95% and 90%, regardless of vertical load.

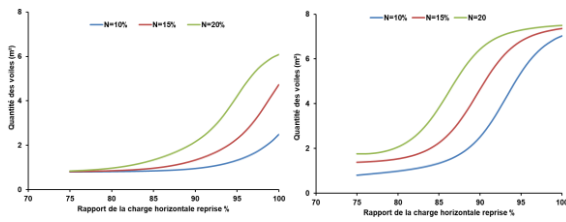


Figure 11: Effect of the vertical load ratio for a bracing system (4a)

Figure 11 : Effet du rapport de charge verticale pour un système de contreventement (4a)

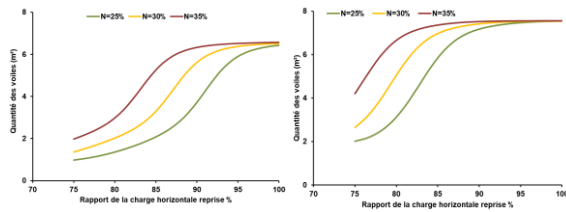


Figure 12: Effect of the vertical load ratio for a bracing system (2)

Figure 12 : Effet du rapport de charge verticale pour un système de contreventement (2)

Figs 13 and 14 show how the vertical load ratio affects the quantity of bracing shear walls for two bracing system categories (4b and 2) in seismic directions XX and YY. Increasing both vertical and horizontal load ratios leads to a proportional increase in the quantity of bracing shear walls. For system (4b), the number of shear walls varies by up to 12% with a maximum increase of 1.8 m². For system (2), the quantity remains constant for horizontal loads in direction XX but can increase significantly (up to 5 m²) by 39% in direction YY.

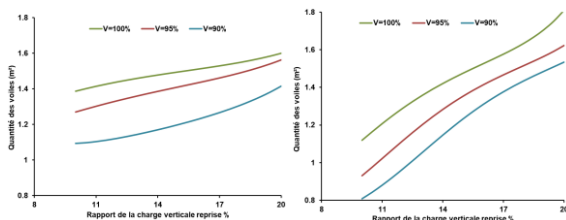


Figure 13: Effect of the horizontal load ratio for a bracing system (4a)

Figure 13 : Effet du rapport de charge horizontale pour un système de contreventement (4a)

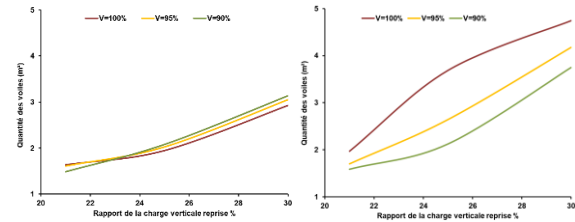


Figure 14: Effect of the horizontal load ratio for a bracing system (2)

Figure 14 : Effet du rapport de charge horizontale pour un système de contreventement (2)

4- Conclusion

This research has focused on optimizing the design of earthquake-resistant buildings by examining the interplay between shear wall placement, wall dimensions, and bracing systems. The study involved a comprehensive analysis of 310 building variants, taking into consideration the effects of both vertical and horizontal loads on the seismic performance of structures. Through the use of artificial neural networks (ANNs) and a detailed parametric study, we have provided insights into how these variables influence the overall stability and resistance of buildings in seismic zones. The principal findings of this study are summarized as follows:

- The study confirmed that placing shear walls along the perimeter of the architectural plan significantly enhances the distribution of seismic forces and reduces torsional effects. Specifically, variants with shear walls at the ends of the plan demonstrated superior seismic resistance.

- The research indicated that increasing the thickness of shear walls generally improves their ability to support vertical loads. For instance, variants with wall thicknesses of 25 cm and 30 cm showed better performance in both vertical and horizontal load support, with a reduction in the reclassification from category 4b to category 2.

- The analysis revealed that bracing systems categorized under 4b are more effective in supporting seismic loads when the shear walls carry less than 20% of the total vertical load. Approximately 190 of the 310 variants

met this condition, ensuring optimal structural performance.

- The study found that increasing the number of shear walls improved the distribution of vertical loads, with optimal variants carrying less than 20% of the vertical load. The horizontal load capacity also showed improvement, particularly in the XX seismic direction, where a wall thickness increase from 15 cm to 30 cm resulted in a more stable load distribution.

- The use of artificial neural networks demonstrated high accuracy in predicting the quantity of shear walls required for optimal seismic resistance. The ANN model achieved a coefficient of determination R^2 of 0.95 and 0.94 in the XX and YY directions, respectively, with a root mean square error (RMSE) of 0.66 and 0.68, indicating a strong correlation between predicted and actual results. In this section, we conduct a parametric analysis of the input variables to explore their correlations with the quantity of bracing shear wall, regardless of the bracing system. Using an artificial neural network (ANN) to predict models for each seismic direction, we precisely examine the impact of parameters such as the vertical load ratio and the horizontal load supported by the bracing shear walls on the quantity of shear walls, in order to facilitate the selection of the bracing system.

References

- [1] Seruti, C. A., Lima, E. F., Lima, S. D. S., & Santos, S. H. D. C. (2023). Influence of shear walls on the structural behavior of a multi-storey concrete building according to Brazilian Technical Code ABNT NBR 15421: 2006. *Revista IBRACON de Estruturas e Materiais*, 16(5), e16504. <https://doi.org/10.1590/S1983-41952023000500004>
- [2] Brencich, A., & Gnecco, M. (2012). Failure case studies in structural engineering courses and professional practice. *Arabian Journal for Science and Engineering*, 37, 2113-2126. <https://doi.org/10.1007/s13369-012-0292-4>
- [3] Tuken, A., & Siddiqui, N. A. (2013). Assessment of shear wall quantity in seismic-resistant design of reinforced concrete buildings. *Arabian journal for science and engineering*, 38, 2639-2648. <https://doi.org/10.1007/s13369-012-0482-0>
- [4] Beedalah, M. H., & Mohaisen, S. K. (2021). Performance of reinforced concrete building with shear wall under the effect of seismic loads. *Int. J. Modern Res. Eng. Technol*, 6(21), 367-375.
- [5] Elwi, M. A., & Hussein, W. G. A. (2021). Study of effect of shear wall in the seismic response of the existing buildings. *Periodicals of Engineering and Natural Sciences*, 9(3), 494-508. <http://dx.doi.org/10.21533/pen.v9i3.2157>
- [6] Hossain, S. A., & Bagchi, A. (2020). Seismic performance of existing buildings concrete shear wall. *5th World Cong. Civil, Structural, Environmental Eng.*, 1-10.
- [7] Ugalde, D., & Lopez-Garcia, D. (2020). Analysis of the seismic capacity of Chilean residential RC shear wall buildings. *Journal of Building Engineering*, 31, 101369. <https://doi.org/10.1016/j.jobbe.2020.101369>
- [8] Ahamad, S. A., & Pratap, K. V. (2021). Dynamic analysis of G+ 20 multi storied building by using shear walls in various locations for different seismic zones by using Etabs. *Materials Today: Proceedings*, 43, 1043-1048. <https://doi.org/10.1016/j.matpr.2020.08.014>
- [9] Alimohammadi, H., Esfahani, M. D., & Yaghin, M. L. (2019). Effects of openings on the seismic behavior and performance level of concrete shear walls. *International Journal of Engineering and Applied Sciences*, 6(10), 34-39. <https://www.researchgate.net/publication/337596926>
- [10] Ozkul, T. A., Kurtbeyoglu, A., Borekci, M., Zengin, B., & Kocak, A. (2019). Effect of shear wall on seismic performance of RC frame buildings. *Engineering Failure Analysis*, 100, 60-75. <https://doi.org/10.1016/j.engfailanal.2019.02.032>
- [11] Jamnani, H. H., Amiri, J. V., & Rajabnejad, H. (2018). Energy distribution in RC shear wall-frame structures subject to repeated earthquakes. *Soil Dynamics and Earthquake Engineering*, 107, 116-128. <https://doi.org/10.1016/j.soildyn.2018.01.010>
- [12] Ugalde, D., & Lopez-Garcia, D. (2017). Behavior of reinforced concrete shear wall buildings subjected to large earthquakes. *Procedia engineering*, 199, 3582-3587. <https://doi.org/10.1016/j.proeng.2017.09.524>
- [13] Peña, L. A. P., & CARVALHO, G. D. (2015). Estudo da influência da configuração estrutural na resposta sísmica de uma estrutura de concreto armado. *Revista Ibracon de estruturas e materiais*, 8(06), 813-826. <https://doi.org/10.1590/S1983-41952015000600005>

- [14] Tarigan, J., Manggala, J., & Sitorus, T. (2018, February). The effect of shear wall location in resisting earthquake. In IOP Conference Series: Materials Science and Engineering (Vol. 309, No. 1, p. 012077). IOP Publishing. [DOI 10.1088/1757-899X/309/1/012077](https://doi.org/10.1088/1757-899X/309/1/012077)
- [15] Chen, Z., Popovski, M., & Iqbal, A. (2020). Structural Performance of Post-Tensioned CLT Shear Walls with Energy Dissipators. *Journal of Structural Engineering*, 146(4), American Society of Civil Engineers (ASCE). [https://doi.org/10.1061/\(asce\)st.1943-541x.0002569](https://doi.org/10.1061/(asce)st.1943-541x.0002569)
- [16] Mangalathu, S., Jang, H., Hwang, S.-H., & Jeon, J.-S. (2020). Data-driven machine-learning-based seismic failure mode identification of reinforced concrete shear walls. *Engineering Structures*, 208, Elsevier BV. <https://doi.org/10.1016/j.engstruct.2020.110331>
- [17] Mahmoud, S. (2021). In-plane shear-wall configuration effects on the seismic performance of symmetrical multistory reinforced-concrete buildings. *International Journal of Civil Engineering*, 19(10), 1195-1208. <https://doi.org/10.1007/s40999-021-00634-8>
- [18] Khelaifia, A., Chebili, R., & Zine, A. (2024). Impact of the position and quantity of shear walls in buildings on the seismic performance. *Asian Journal of Civil Engineering*, 25(1), 953-964. <https://doi.org/10.1007/s42107-023-00824-w>
- [19] RPA-99/v2003 (2004), Algerian seismic regulation 1999-version2003. DTR-BC 248 - National Center for Applied Research in Seismic Engineering, Alger, Algeria.
- [20] CSI (Computer and Structure Inc) ETABS/V9.7.0 Software, Integrated Finite Element Analysis and Design of Structures. CSI, Berkeley.
- [21] D.T.R. – B.C. 2-41. Règles de conception et de calcul des structures en béton armé, CBA93. Ministère de l'habitat. Algérie.
- [22] Cascardi A, Micelli F, Aiello MA. An Artificial Neural Networks model for the prediction of the compressive strength of FRP-confined concrete circular columns. *Eng. Struct.* 2017, 140 : 199-208. <https://doi.org/10.1016/j.engstruct.2017.02.047>
- [23] Naderpour H, Kheyroddin A, Ghodrati-Amiri G. Prediction of FRP-confined compressive strength of concrete using artificial neural networks. *Comp. Struct.* 2010, 92(12): 2817-2829. <https://doi.org/10.1016/j.compstruct.2010.04.008>
- [24] Y Basalo FJDC, Matta F, Nanni A. Fiber reinforced cement-based composite system for concrete confinement. *Constr. Build. Mater.* 2012, 32: 55–65. <https://doi.org/10.1016/j.conbuildmat.2010.12.063>
- [25] Hajela P, Berke L. Neural networks in structural analysis and design: An overview. *Comp. Syst. Eng.* 1992, 3(1–4) : 525–538. [https://doi.org/10.1016/0956-0521\(92\)90138-9](https://doi.org/10.1016/0956-0521(92)90138-9)
- [26] Pu Y, Mesbahi E. Application of artificial neural networks to evaluation of ultimate strength of steel panels. *Eng. Struct.* 2006, 28(8): 1190–1196. <https://doi.org/10.1016/j.engstruct.2005.12.009>
- [27] Plevris V, Asteris PG. Modeling of masonry failure surface under biaxial compressive stress using Neural Networks. *Constr. Build. Mater.* 2014, 55 : 447–461. <https://doi.org/10.1016/j.conbuildmat.2014.01.041>
- [28] Waszczyszyn Z, Ziemiański L. Neural networks in mechanics of structures and materials—New results and prospects of applications. *Comp. Struct.* 2001, 79(22–25): 2261–2276. [https://doi.org/10.1016/S0045-7949\(01\)00083-9](https://doi.org/10.1016/S0045-7949(01)00083-9)
- [29] Le-Nguyen K, Minh QC, Ahmad A, et al. Development of deep neural network model to predict the compressive strength of FRCM confined columns. *Front. Struct. Civ. Eng.* 2022, 16(10): 1213-1232. <https://doi.org/10.1007/s11709-022-0880-7>
- [30] Ahmad A, Elchalakani M, Elmesalami N, et al. Reliability analysis of strength models for short-concrete columns under concentric loading with FRP rebars through artificial neural network. *Build. Eng.* 2021, 42: 102497. <https://doi.org/10.1016/j.jobbe.2021.102497>
- [31] Raza A, Khan QUZ, Ahmad A. Investigation of HFRC columns reinforced with GFRP bars and spirals under concentric and eccentric loadings. *Eng. Struct.* 2021, 227: 111461. <https://doi.org/10.1016/j.engstruct.2020.111461>
- [32] Taleb Bahmed, I., Harichane, K., Ghrici, M., Boukhatem, B., Rebouh, R., & Gadouri, H. (2019). Prediction of geotechnical properties of clayey soils stabilised with lime using artificial neural networks (ANNs). *International Journal of Geotechnical Engineering*, 13(2), 191-203. <https://doi.org/10.1080/19386362.2017.1329966>
- [33] Yalciner H, Hedayat AA. Repairing and strengthening of an existing reinforced concrete building: A north cyprus perspective. *Amer. Eng. App. Scien.* 2010, 3(1): 109–116. <https://doi.org/10.3844/ajeassp.2010.109.116>
- [34] Triantafillou TC. 13-Strengthening of existing concrete structures: Concepts and structural behavior. *Text. Fib. Comp. Civ. Eng.* 2016,

303–322. <https://doi.org/10.1016/B978-1-78242-446-8.00014-8>

- [35] Bournas DA, Triantafillou TC, Zygouris K, et al. Textile-reinforced mortar versus FRP jacketing in seismic retrofitting of RC columns with continuous or lap-spliced deformed bars. *Comp. Constr.* 2009, 13(5): 360–371. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000028](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000028)

Appendix A. Description of the final 36 variants

Fig. A1 shows the 36 variants with wall arrangements exclusively at the ends of the architectural plan that satisfy the second regulatory condition. This specific configuration is chosen to optimize the structure's resistance and stability against seismic loads.

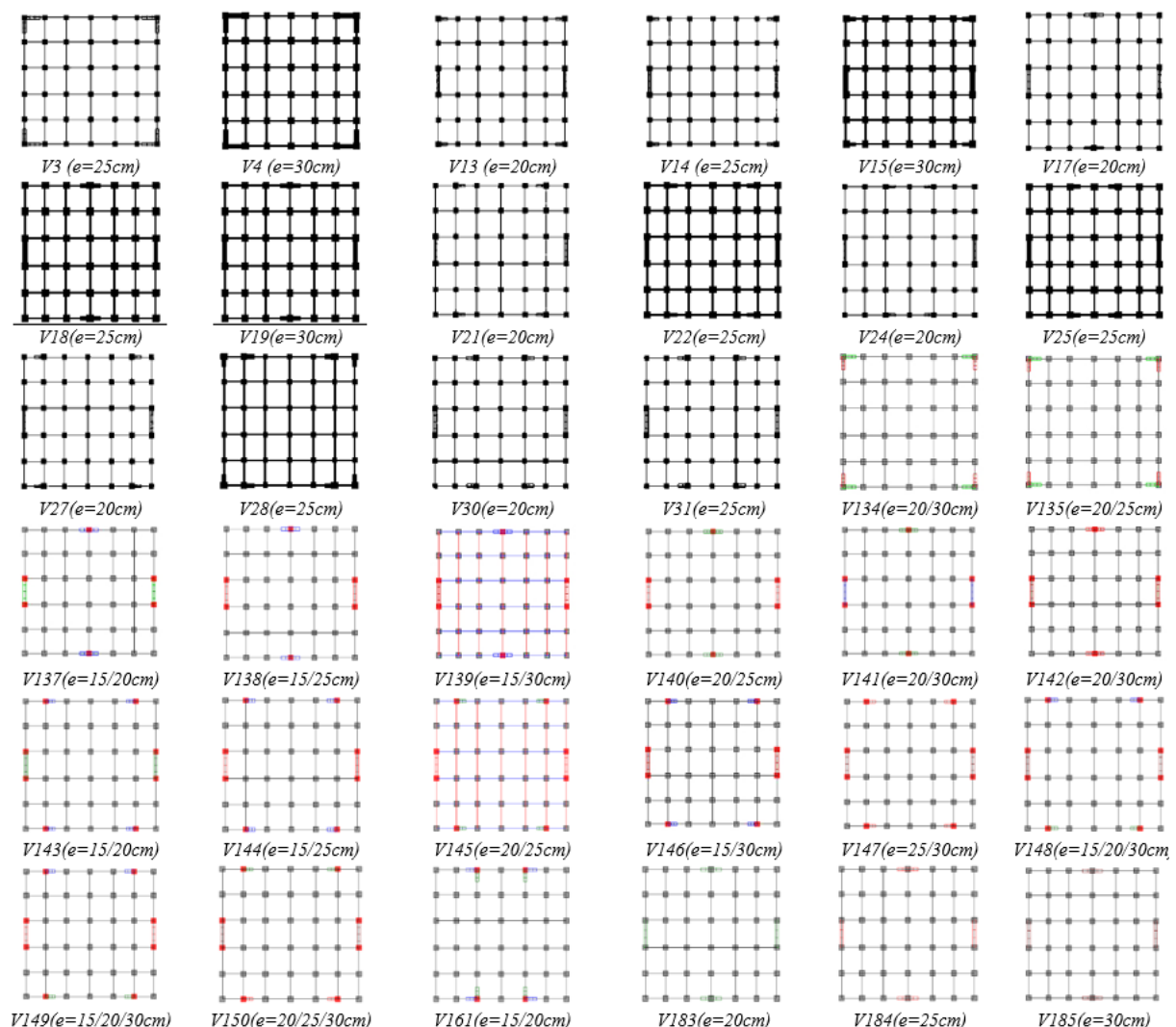


Figure A1: Variants satisfying the first two regulatory conditions of the bracing system (4b)

Figure A1 : Variantes satisfaisant les deux premières conditions réglementaires du système de contreventement (4b)