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NUMERICAL SIMULATION OF THE BEHAVIOR OF L-SHAPED RC SHEAR WALLS WITH STAGGERED OPENINGS

SIMULAÇÃO NUMÉRICA DO COMPORTAMENTO DE PAREDES DE CISALHAMENTO DE CONCRETO ARMADO EM FORMA DE L COM ABERTURAS ESCALONADAS

SIMULACIÓN NUMÉRICA DEL COMPORTAMIENTO DE MUROS DE CORTE DE HORMIGÓN ARMADO EN FORMA DE L CON ABERTURAS ESCALONADAS

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ABSTRACT

Reinforced concrete shear walls in an L-shape are highly valued in modern architecture for their ability to withstand lateral loads. However, incorporating openings, necessary for functional reasons, can compromise their structural integrity. Our study investigates the effects of offset openings on compression, tension, and shear stresses in these walls, aiming to provide design recommendations. We also analyzed shear forces and top-floor displacements in buildings with various opening configurations through numerical simulations conducted on ten-story structures. The results indicate that shear stresses increase when openings are off-center. Nevertheless, regardless of their position, the optimal proportion of openings is found to be 30% of the shear wall surface.

RESUMO

As paredes de cisalhamento de concreto armado em forma de L são altamente valorizadas na arquitetura moderna por sua capacidade de suportar cargas laterais. No entanto, a incorporação de aberturas, necessárias por razões funcionais, pode comprometer sua integridade estrutural. Nosso estudo investiga os efeitos das aberturas desalinhadas nas tensões de compressão, tração e cisalhamento nessas paredes, com o objetivo de fornecer recomendações de design. Também analisamos as forças de cisalhamento e os deslocamentos no topo de edifícios com várias configurações de abertura por meio de simulações numéricas realizadas em estruturas de dez andares. Os resultados indicam que as tensões de cisalhamento aumentam quando as aberturas estão fora do centro. No entanto, independentemente da sua posição, a proporção ideal de aberturas é de 30% da superfície da parede de cisalhamento.

RESUMEN

Las paredes de cortante de hormigón armado en forma de L son muy valoradas en la arquitectura moderna por su capacidad para resistir cargas laterales. Sin embargo, la incorporación de aberturas, necesarias por razones funcionales, puede comprometer su integridad estructural. Nuestro estudio investiga los efectos de las aberturas desalineadas en las tensiones de compresión, tracción y cortante en estas paredes, con el objetivo de proporcionar recomendaciones de diseño. También analizamos las fuerzas de cortante y los desplazamientos en la parte superior de edificios con diversas configuraciones de apertura mediante simulaciones numéricas realizadas en estructuras de diez pisos. Los resultados indican que las tensiones de cortante aumentan cuando las aberturas están descentradas. Sin embargo, independientemente de su posición, la proporción óptima de aberturas se encuentra en el 30% de la superficie de la pared de cortante.

1.INTRODUCTION

Algeria has recently embarked on the construction of high-rise buildings, with several projects completed and others planned to meet the population's needs (Merabti, 2022). These buildings rely heavily on reinforced concrete shear walls, crucial for their stability and structural resilience (Merabti and Guelmine., 2024; Merabti et al., 2023). Such walls offer numerous structural advantages (Galal and El-Sokkarry., 2008), providing adequate rigidity and ductility to withstand seismic lateral forces (Zhou et al., 2023). They can take various forms (U, T, I, L) to enhance load-bearing capacity without significantly increasing the structure's weight (Merabti and Bezari., 2023; Rong et al., 2023; Wang et al., 2022).

Previous studies have predominantly focused on L-shaped walls (Najmet al., 2022; Liuet al., 2024; Guoet al., 2023; Wang et al., 2022) and their performance under various loads, including seismic forces (Benbellil et al., 2019; Najm et al., 2022). However, the Algerian design code 99/version 2003, (2003) lacks specific guidelines for walls with openings, posing practical challenges during design.

Recent research highlights that the width of openings in shear walls has a more pronounced effect than their height (Varma and Kumar., 2021), a finding supported by Saeed et al., (2022) and Pandey et al., (2017). Montazeri et al., (2018) demonstrated that walls with varied opening configurations exhibit improved load capacity and stiffness. Conversely, Hosseinia et al. (2019) observed reduced stiffness with off-center openings, a result confirmed experimentally by Mosoarca (2014).

Despite these advancements, research on centered and off-center openings in L-shaped reinforced concrete shear walls remains limited, particularly concerning variations in opening width at different locations. This study aims to address this gap and propose design recommendations for such walls subjected to seismic forces.

2. BUILDING DESCRIPTION AND ANALYZED VARIABLES

Our study focuses on the numerical analysis of a ten-story reinforced concrete building, measuring 24.8 m in length and 20.8 m in width. The structure features L-shaped walls situated at all four corners, incorporating openings of 15%, 20%, 25%, 30%, and 35%. These openings are located at the center of the wall, at the intersection of the two wings, and the end of the L-shaped wall (see Figure 1). We specifically investigated scenarios where openings are present in both directions of the L-shaped walls. The dimensions of the building are as follows:

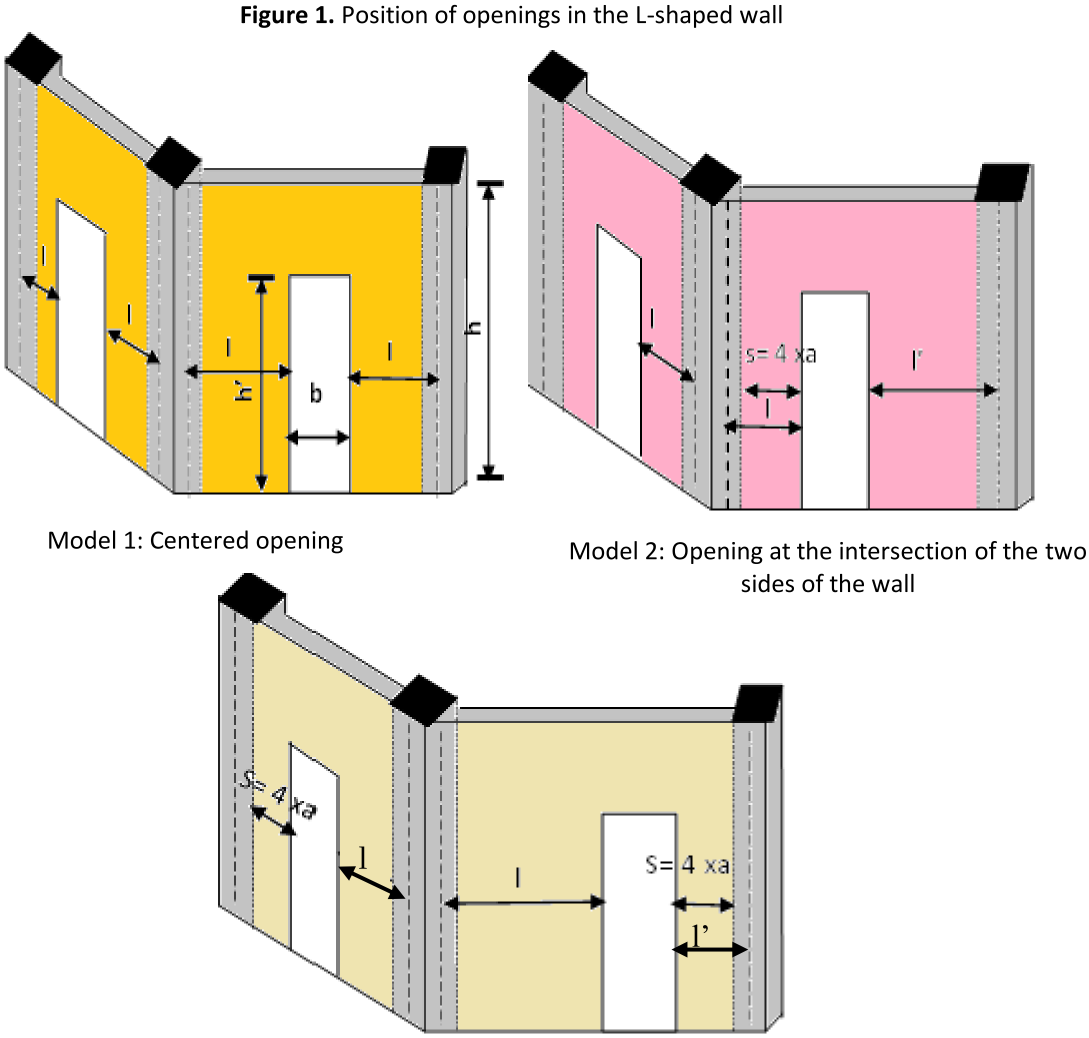
- Six spans of 4.8 m on the X-axis (longitudinal)
- Five spans of 4.8 m on the Y-axis (transversal)
- Uniform floor height: 3.06 m
- Fixed opening height: 2.1 m (variable width)
- Concrete with a compressive strength of 25MPa

Our analysis focused on the following parameters:

1. The position of the openings
2. The width of the openings (percentage of openings in the shear wall)
3. Analytical Stresses (compression, tension, and shear)
4. Shear Forces
5. Top Displacements

To ensure the accuracy of our analyses, we refined the meshing of the shear walls. The software used offers adaptive automatic refinement based on a preliminary analysis, concentrating the fine mesh in high-stress areas. The final mesh was determined once the result stability was achieved.

Figure 1. Position of openings in the L-shaped wall



Model 1: Centered opening

Model 2: Opening at the intersection of the two sides of the wall

Model 3: Opening at both ends of the wall

Sources: The authors (2024)

In our study, the wall thickness (a) is maintained at a constant 20 cm for all three analysed cases. According to the recommendations of RPA 99/version 2003., (2023), openings located at the end of the wall are positioned at a distance equal to four times the wall thickness, or 80 cm. Table 1 presents the wall lengths relative to the column situated at the intersection of the wings of the L-shaped wall. These geometric specifications are essential for understanding the structural layout of our model and its compliance with current building standards. They directly influence stress distribution and the overall structural response to lateral loads, particularly seismic forces. The uniformity in wall thickness and precise placement of openings enable a consistent comparison across the various cases studied while meeting local regulatory requirements.

Table 1. Wall dimensions according to opening percentages (m)

Openings (%)					
Wall length (l)					
Cas étudiés	15	20	25	30	35
Model 1	1.88	1.70	1.53	1.35	1.18
Model 2	1.05	1.05	1.05	1.05	1.05
Model 3	2.70	2.35	2.00	1.65	1.30
Wall length (l')					
Model 2	2.70	2.35	2.00	1.65	1.30
Model 3	1.05	1.05	1.05	1.05	1.05
Opening width (b)					
Model 1, 2 et 3	1,05	1,40	1,75	2,10	2,45

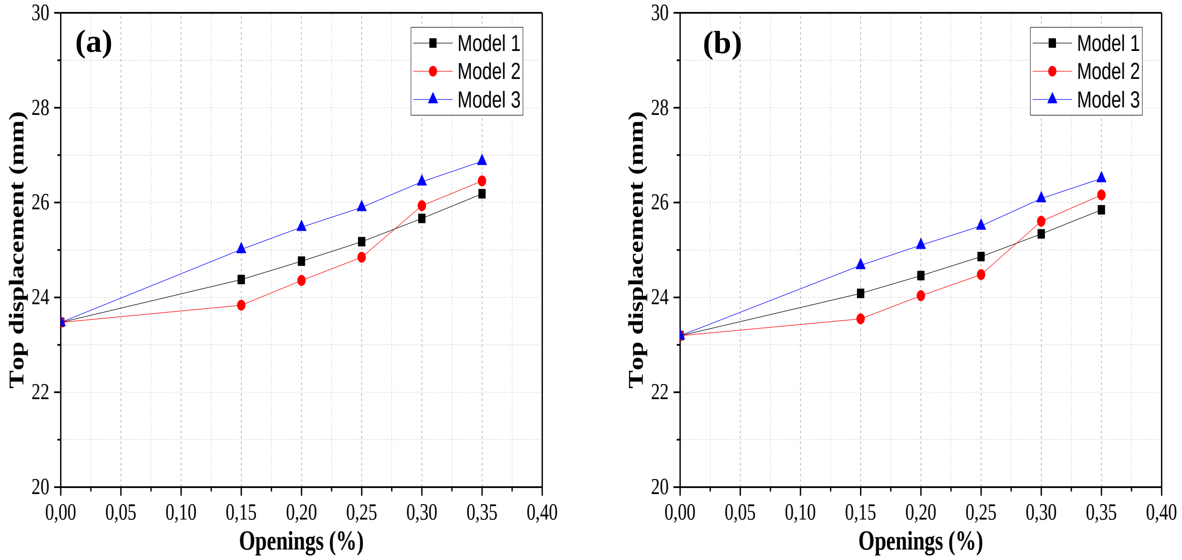
Sources: Authors (2024).

3. RESULTS AND DISCUSSION

3.1. DISPLACEMENTS AT THE TOP OF THE BUILDING

Figure 2 illustrates the evolution of top displacements of the buildings as a function of the percentage of openings for the three models studied. There is a general increase in displacements as the percentage of openings increases. Model 2 exhibits the lowest displacements up to approximately 28% of openings, beyond which its displacements exceed those of Model 1. In contrast, Model 3 consistently shows greater displacements than the other two models. This analysis leads to the conclusion that Model 3 represents the least favorable configuration in terms of displacements for the buildings studied in this research.

Figure 2. Maximum displacements as a function of the percentage of openings: a) X-direction, b) Y-direction

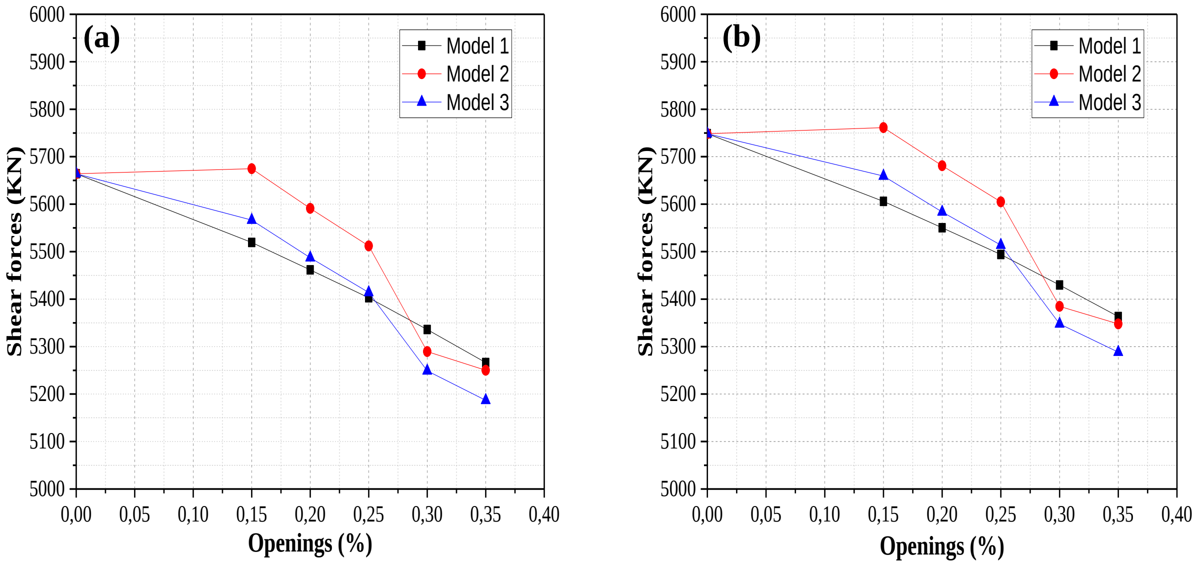


Sources: Authors (2024).

3.2. SHEAR FORCES AT THE BASE

Figure 3 illustrates the evolution of shear forces with the percentage of openings in the L-shaped concrete wall. Initially, there is an increase in shear force at a 15% opening rate, followed by a gradual decrease as the percentage of openings increases. Model 2 exhibits the highest shear forces in both directions up to approximately 28% openings. Conversely, Model 3 demonstrates higher shear forces compared to Model 1 up to 25% openings, after which these forces decrease and become lower than those of the other models. This analysis highlights the complex influence of openings on the distribution of shear forces in L-shaped shear walls.

Figure 3. Shear forces as a function of the percentage of openings:
a) X-direction, b) Y-direction



Sources: Authors (2024)

3.3. COMPRESSION STRESSES, TENSILE STRESSES, AND SHEAR STRESSES

A comprehensive study evaluated the maximum stresses in L-shaped shear walls based on the percentage of openings. In all cases, the maximum concentration of shear stresses shifted from the intersection of the wings towards the column-wing interface of the wall without openings, and then towards the openings, particularly at lintels, piers, and corners. This phenomenon, also observed by Sharma and Jignesh., (2015) and Balkaya et al., (2024), is accompanied by a significant increase in maximum stresses and a broader distribution of these stresses.

Table 2 and Figure 4 illustrate the evolution of compression, tensile, and shear stresses concerning the percentage of openings. Compression and tensile stresses exceed shear stresses, remaining within acceptable limits (below 15 MPa for normal stresses). The introduction of openings in Models 2 and 3 results in a notable increase in shear stresses, reaching 6.28 MPa for Model 2 and 5.53 MPa for Model 3. These stresses increase with the percentage of openings for these two models, unlike Model 1 where they decrease.

Table. 2. Stresses as a function of the percentage of openings (MPa)

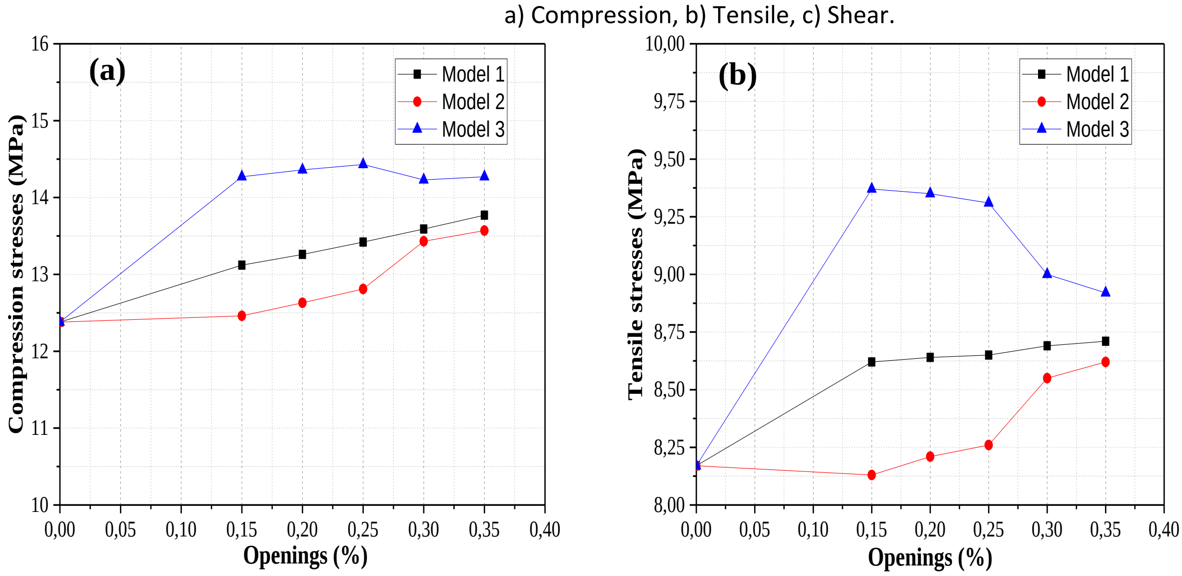
	Opening (%)					
	Compression					
Cases studied	**0**	**15**	**20**	**25**	**30**	**35**
Model 1	12,38	13,12	13,26	13,42	13,59	13,77
Model 2	12,38	12,46	12,63	12,81	13,43	13,57
Model 3	12,38	14,27	14,36	14,43	14,23	14,27
	Tensile					
Model 1	8,17	8,62	8,64	8,65	8,69	8,71
Model 2	8,17	8,13	8,21	8,26	8,55	8,62
Model 3	8,17	9,37	9,35	9,31	9,00	8,92
	Shear					
Model 1	1,93	4,76	4,68	4,53	4,32	4,8
Model 2	1,93	5,43	6,02	6,28	4,25	4,39
Model 3	1,93	4,71	5,25	5,53	4,00	4,11

Sources: Authors (2024)

The analysis reveals that compression stresses increase proportionally with the percentage of openings in the L-shaped wall. Model 3 stands out by approaching values near the 15 MPa limit. In contrast, tensile stresses decrease with increasing percentages of openings.

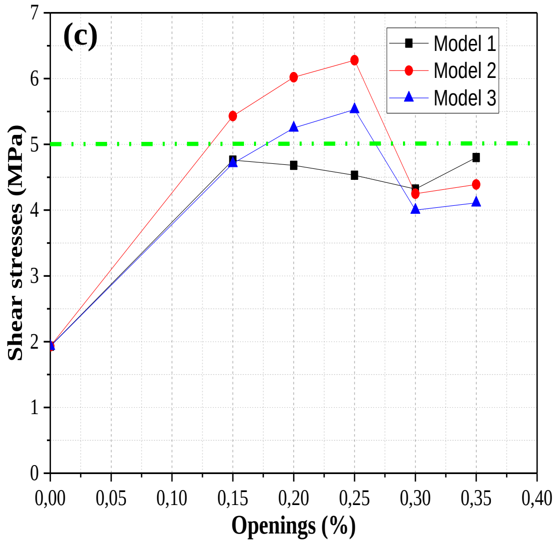
This opening configuration generates higher tensile stresses for Model 3 compared to the other two models. For Models 1 and 2, there is an increase in tensile stresses correlated with the percentage of openings or the width of the openings, while the height remains constant across all three models.

Figure 4. Evolution of stresses as a function of the percentage of openings: a) Compression, b) Tensile, c) Shear.



Sources: Authors (2024)

Sources: Authors (2024)



Sources: Authors (2024)

Model 2 stands out with the lowest tensile and compression stresses compared to Models 1 and 3. However, its shear stresses exceed the permissible value. Models 2 and 3 exhibit shear stresses above 5 MPa for opening rates of 15%, 20%, and 25%, with Model 3 reaching these values for rates of 20% and 25%.

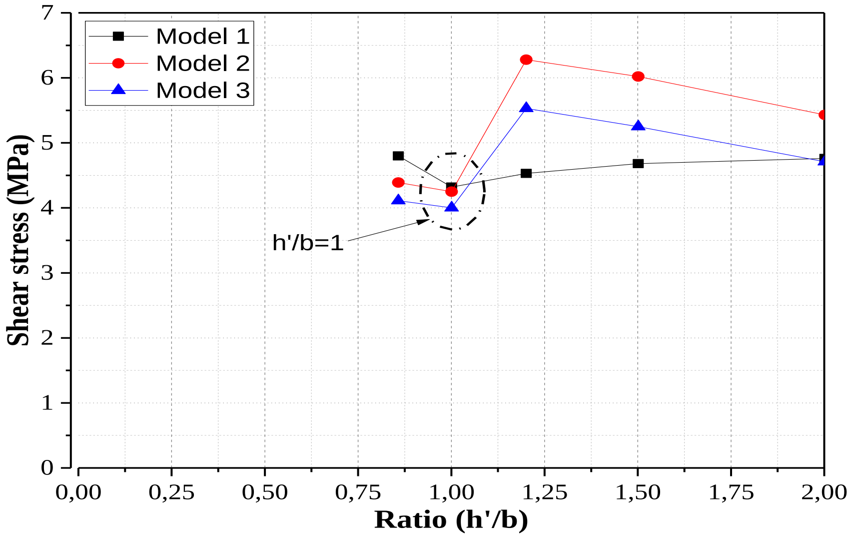
Despite the increase in opening width, there is a decrease in shear stresses for rates of 30% and 35%. This analysis reveals that the optimal opening rate for the three models studied is 30%. These results underscore the importance of balancing the percentage of openings with stress distribution in L-shaped shear walls, with an identified optimum of 30% openings for the studied configurations.

3.4. SHEAR STRESS AS A FUNCTION OF THE RATIO (h'/b)

Figure 5 illustrates the variation of shear stresses as a function of the height-to-width ratio (h'/b) of openings in 20 cm thick walls. For the studied buildings, the maximum shear stress is reached when the ratio (h'/b) reaches 0.86 for Model 1 and 1.2 for Models 2 and 3. This stress reaches a minimum value for all three models when (h'/b) equals 1, corresponding to an opening rate of 30%.

The analysis reveals that the optimal reduction of shear stress in L-shaped walls, particularly for Models 1 and 3, is achieved with square openings (where height equals width) or rectangular openings (where width is double the height). These results underscore the crucial importance of opening proportions in the design of L-shaped shear walls to optimize their structural performance.

Figure 5. Evolution of shear stress as a function of the aspect ratio (h'/b)



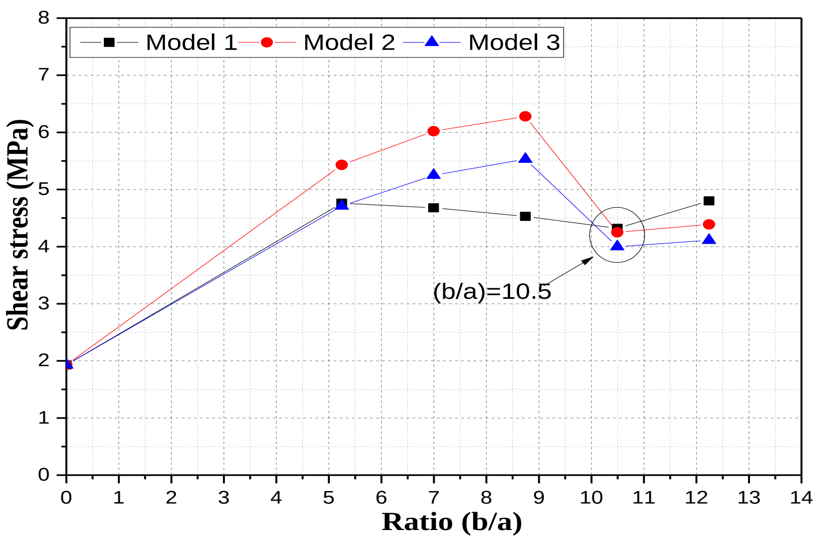
Sources: Authors (2024)

3.5. CONTRAINTE DE CISAILLEMENT EN FONCTION OF THE RATIO (b/a)

Figure 6 illustrates the variations in shear stresses as a function of the ratio between the width of openings (b) and the thickness (a) of the shear wall. The ratios (b/a) of 10.5 and 12.24, corresponding to opening rates of 30% and 35% respectively, satisfy the permissible shear stress of 5 MPa for all three models. However, the ratio (b/a) of 10.5 is considered optimal. Model 2 proves to be the least favorable, while the ratios (b/a) of 7 and 8.74 for Model 3 do not meet the tolerated shear stress limits.

The analysis reveals that the width of openings significantly influences shear stresses, especially for staggered openings near the edges of the walls. These observations corroborate the findings of Varma and Kumar (2021), emphasizing the crucial importance of sizing and positioning openings in the design of L-shaped shear walls to optimize their structural performance.

Figure 6. Evolution of shear stress as a function of the ratio (b/a)



Sources: Authors (2024)

4. CONCLUSIONS

This study examines the seismic behavior of ten-story buildings braced by L-shaped shear walls with openings located at all four corners. Openings of similar sizes were introduced in both longitudinal and transverse directions, positioned at the center, corners, and ends of the two wings of the L-shaped wall. The analysis reveals that all three models comply with compression and tensile stress constraints, but Models 2 and 3 do not meet shear stress constraints for certain opening percentages. The width and location of the openings significantly influences structural stresses. An optimal opening rate of 30% is recommended, corresponding to an aspect ratio (height/width) of the opening (h'/b) of 1 and a ratio of opening width to wall thickness (b/a) of 10.5. Centered openings offer the best compromise among the different stresses studied. These results underscore the crucial importance of sizing and positioning openings in the design of L-shaped shear walls to optimize their structural performance. Further studies on buildings of varying heights and wall thicknesses would help deepen this research and generalize these conclusions.

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