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Investigation into the Impact of L-Shaped RC Shear Wall Placement with Openings on the Behavior of Medium-Rise Buildings

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Abstract
This article aims to investigate the impact of regular openings in L-shaped reinforced concrete (RC) shear walls located at building corners. A comparison of different buildings and an estimation of the optimal percentage of openings were conducted. To accomplish this, various wall models, with and without openings, underwent numerical simulations using the ETABS program. The research focused on medium-rise ten-story buildings with opening rates of 0%, 15%, 20%, 25%, 30%, and 35% in the X and/or Y direction under high seismic loading conditions (Zone-III) following the Algerian Paraseismic Regulations (RPA 99/version 2003). The findings of this study indicate that openings have a noticeable impact on the overall behavior of buildings and on the shear wall's capacity to withstand earthquakes. However, opening ratios of 20.8%, 30%, and 31.8%, depending on the direction, are considered optimal opening percentages for L-shaped shear walls. These percentages ensure a suitable balance between architectural functionality and the effective structural performance of L-shaped shear walls. Thus, it is important to consider the placement of openings in the design of reinforced concrete structures braced by shear walls.
Keywords: Medium-rise building. Numerical simulations. L-shaped shear walls. Walls with openings. High seismicity.

1. Introduction

In recent years, Algeria has seen a significant increase in the construction of medium-rise buildings. This trend reflects the country's recent progress and development in the building sector. However, the structural safety of these buildings depends largely on the use of shear walls. For aesthetic and practical reasons, it is common practice to incorporate openings in these walls. The Algerian seismic code (RPA99/version 2003) does not specify a maximum percentage of openings in shear walls, hence the importance of determining the optimum percentage of openings while understanding how they can influence the overall behavior of buildings.

Reinforced concrete shear walls are commonly used in tall buildings to resist lateral loads (Fofiu *et al.,* 2015; Trifa and A. Cătărig, 2015; Tiwari *et al.,* 2023; Lina and Senlin, 2023; Mi *et al.,* 2023; Xu *et al*., 2023). L-shaped reinforced concrete shear walls with a short branch refer to specific concrete walls with a height-to-width ratio ranging from 5 to 8 (CMC, 2010). Walls of this kind offer considerable flexibility (Chen *et al.,* 2016; Dai, 2012). Several studies have analyzed the seismic behavior of rectangular shear walls (Cao *et al.* 2003; Kuang *et al.* 2008; Dashti *et al.* 2017; Terzioglu *et al.,* 2018). Previous research has shown that rectangular shear walls generally have poor seismic performance (Pilakoutas and Elnashai, 1995), especially those with a short branch (Wang *et al.,* 2014). Zhang *et al*. (2022) improved this type of wall by designing L-shaped shear walls with reinforced bars and high-strength concrete. The reinforced longitudinal bars enhance the load-carrying capacity, while the reinforced horizontal bars confine the concrete, delay the buckling of longitudinal bars, and increase ductility.

Karamlou *et al.* (2012) conducted simulations to study the behavior of slender reinforced concrete walls under cyclic lateral loads. They tested four walls, applying constant axial loads and cyclic lateral loads. On the other hand, Su and Wong (2007) verified the seismic behavior of slender reinforced concrete walls subjected to a high proportion of axial load. Pugh *et al*. developed an accurate and efficient simulation model to study the nonlinear cyclic response of flexural controlled concrete walls (Pugh *et al.,* 2015). Inada *et al.* (2008) conducted a study on the influence of load direction and section configuration on the seismic behavior of load-bearing walls. Ozkula *et al.* (2019) also concluded that shear walls have a significant impact on the seismic performance of reinforced concrete buildings, and their presence improves the performance of the buildings.

Shear walls may require openings for various reasons and considerations (Mohamed *et al.* 2018). However, creating openings in shear walls leads to a reduction in their structural capacity and overall integrity, as well as a concentration of stress around the openings (Berman and Bruneau, 2015; Lin *et al.* 1988). Recently, several studies have been conducted to assess the adaptability of shear walls with openings to different types of seismic loads (Meghdadaian and Ghalehnovi, 2019; Wang *et al*., 2019). Research by Pandey *et al.* (2017) revealed that the size of these openings can indeed influence the building's ability to withstand earthquakes. Additionally, the shape and number of openings have a significant impact on the seismic resistance of the building, particularly in terms of the stress that affects its overall performance (Kalpana *et al.,* 2016). Studies conducted by Daniel *et al*. showed that vertical reinforcements placed on the sides of the openings work well in earthquake-resistant buildings (Daniel *et al.,* 1986). Varma and Kumar also found that providing appropriate ductile reinforcement around the openings is essential to prevent crack propagation during an earthquake (Varma and Kumar, 2021).

Hosseinia *et al.* (2019) conducted an experimental study on the location of eccentric voids in concrete shear walls. They observed that the reduction in lateral stiffness was less for shear walls with eccentric openings than for those with cutouts. Another study by Varma and Kumar, (2021) focused on the effect of the size and location of openings in shear walls. Their findings demonstrated that walls placed at the corners of the building were more effective than those located at the center of the portico. Finally, Montazeri *et al.* (2018) analyzed reinforced concrete shear walls with vertically arranged openings; either staggered or ordered, and compared the results with experimental data. Their conclusion showed that walls with staggered openings exhibited higher load capacity and stiffness than walls with ordered openings.

Currently, despite the existence of a seismic code for buildings in Algeria, there are no specific recommendations regarding the percentage of openings in shear walls. This study aims to evaluate the dynamic behavior of a building reinforced with L-shaped reinforced concrete shear walls, which include regular openings at all four corners of the building in the X and/or Y directions, following the provisions of the Algerian paraseismic regulations (RPA99/version 2003). It seeks to contribute to the understanding of the impact of L-shaped shear wall openings on total displacement, inter-story displacement, and seismic forces.

2. Description of the studied building

This research focuses on examining the influence of openings in shear walls. Structural models with centered rectangular openings in the X and/or Y directions were created (see Table 1). Openings of different sizes (15%, 20%, 25%, 30%, and 35%) were introduced into the 15 cm walls. The walls in question are positioned at the four corners of the building. The height of the openings remained constant at 2 meters in all cases, while the width varied based on the percentage of the opening size. The studied buildings are medium-rise reinforced concrete structures, consisting of ten stories, located in seismic category III areas (high seismicity). These buildings are situated on soft soil (S3), requiring a thorough analysis of their dynamic behavior under seismic loads.

The three-dimensional software ETABS, commonly used for the study and design of civil engineering structures, was employed to conduct the dynamic analysis of these buildings. This software allows for precise analysis of the building's response to seismic loads, taking into account specific building characteristics, including geometry, material properties, and applied loads. It facilitates evaluating the seismic response of a building while adhering to Algerian seismic regulations, examining displacements, forces, and stress caused by seismic loads, and ensuring the building complies with Algerian safety standards (RPA99/version 2003) to guarantee its resistance and stability during seismic events. Through this software, the dynamic behavior of buildings can be accurately assessed, ensuring their earthquake resistance and stability.

Table 1 – Different building models studied.

Cases	0:0	1:0	0:1	1:1
Opening in wall	Without openings	Opening in X direction	Opening in Y direction	Opening in X and Y direction

The building under study measures 22.5 meters in length and 18 meters in width. It consists of bays of 4.5 meters in both directions and has a floor height of 3.06 meters. The building's construction includes hollow-core columns, beams, and slabs designed to withstand the operational and permanent loads associated with residential use. It is essential to emphasize that this study was conducted on a building with both a regular plan and an elevation layout.

The data needs to be analyzed to determine the influence of L-shaped openings on the shear walls and their impact on the overall building behavior. To achieve this, we are comparing shear forces, lateral displacements, inter-story drifts, and maximum stress on the shear walls for different models with various opening configurations. This comparison will help us understand the impact of the openings on these critical characteristics and enable us to draw meaningful conclusions.

3. Building and the variables studied

3.1. Story Displacement

The results indicate that the building without shear walls exhibits larger displacements compared to the other models. Shear walls with openings experience larger displacements than shear walls without openings (case 0:0). A shear wall without openings shows better performance compared to shear walls with openings.

Figures 1, 2, and 3 illustrate the maximum displacements observed in the studied cases. At the top floor, the results show that a building without shear walls has a displacement of approximately 68.28 mm compared to a building with shear walls, which has a displacement of 26.107 mm, representing a 62% reduction in the X direction. Interestingly, the displacement in the X direction on the top floor for model (1:0) with a 15% opening is approximately 24.40 mm, corresponding to an increase of about 2.28% compared to model (0:0). In models (0:1) and (1:1), this increase is 1.62% and 4.07%, respectively. Displacements are more significant when openings are created in both directions of the shear wall. However, among these two directions, the displacement is maximal in the direction where the opening is formed. This might be because the opening reduces the stiffness of the shear wall in that specific direction, resulting in greater deformation under applied loads.

In the case of walls with a 35% opening, the maximum displacement is observed to be approximately 28.44 mm. This represents an 8.15% increase compared to the model without openings in the (1:0) direction. For models (0:1) and (1:1), the increases are 5.65% and 13.38%, respectively. The results show that the higher the percentage of openings, the more significant the maximum displacements. Additionally, it is noteworthy that the (1:1) model exhibits larger displacements than the other models. This result implies that when openings are formed in both directions of the shear wall, the maximum displacements are more significant. To ensure adequate structural performance, this variation should be considered during the design and evaluation of buildings with openings, especially in the (1:1) model.

Similarly, in the Y direction, at the top floor, the results show that a building without shear walls has a displacement of 83.74 mm, while the building with shear walls without openings has a displacement of 27.65 mm, resulting in a difference of about 67%. A more substantial reduction in displacement is indeed observed in the Y direction. With a 15% opening, the displacement on the building's roof in the (1:0) model is 28.23 mm, representing an increase of about 2.11% compared to the (0:0) model. This indicates that the increase in displacement is more significant in the X direction. The models (0:1) and (1:1) increase by 2.79% and 4.61%, respectively. In reality, the displacements measured in the Y direction are higher than those measured in the X direction, which is due to the way the openings are designed. Increasing the wall openings to 35% resulted in a 6.62% increase for the (1:0) model, while the (0:1) and (1:1) models recorded displacements of 9.79% and 14.32%, respectively. It should be noted that maximum displacements are more significant in the direction of the wall opening. However, when openings are formed in both the X and Y directions, i.e, in the (1:1) model, the increase is more significant in the Y direction. These results emphasize the need to consider the arrangement of openings when planning and studying buildings.

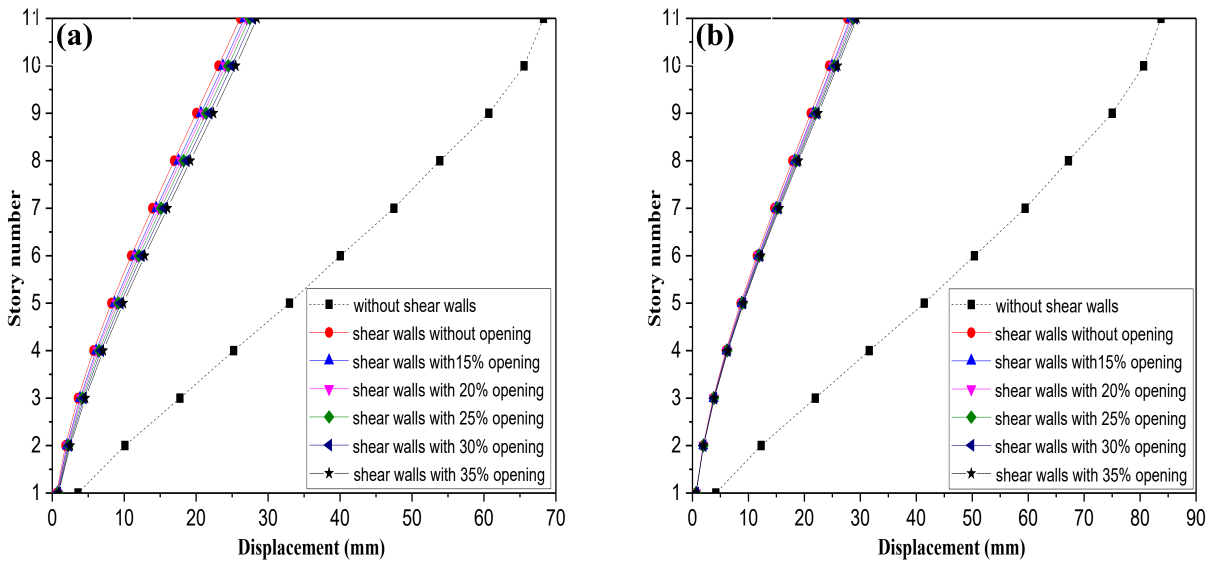

Figure 1 - Story displacement of the model cases 1:0: a) X-direction b) Y-direction.

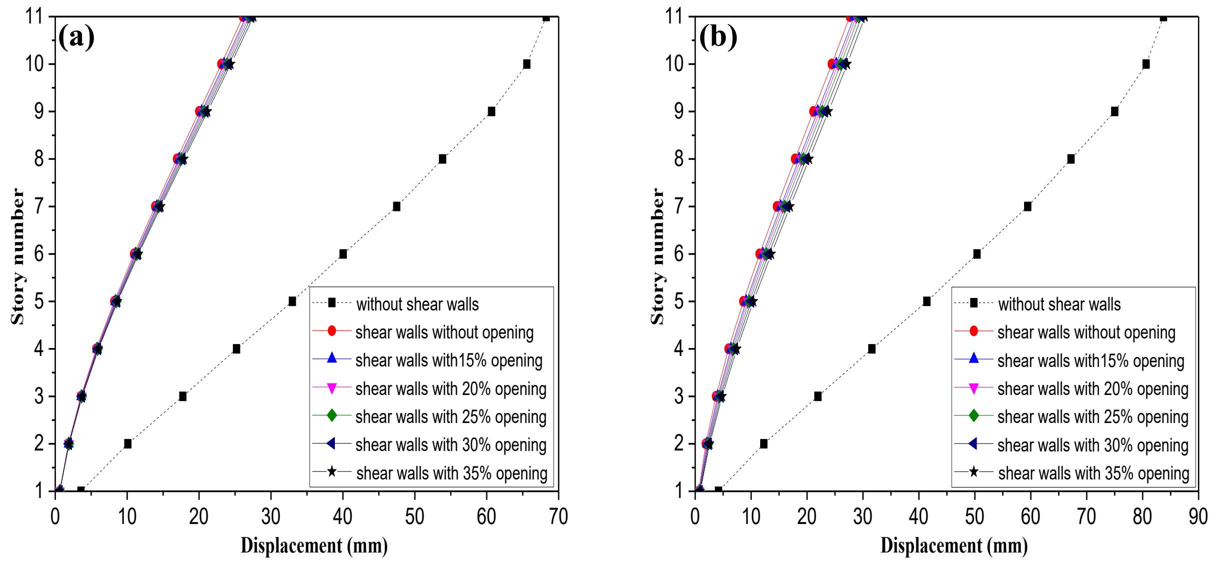

Figure 2 - Story displacement of the model cases 0:1: a) X-direction b) Y-direction.

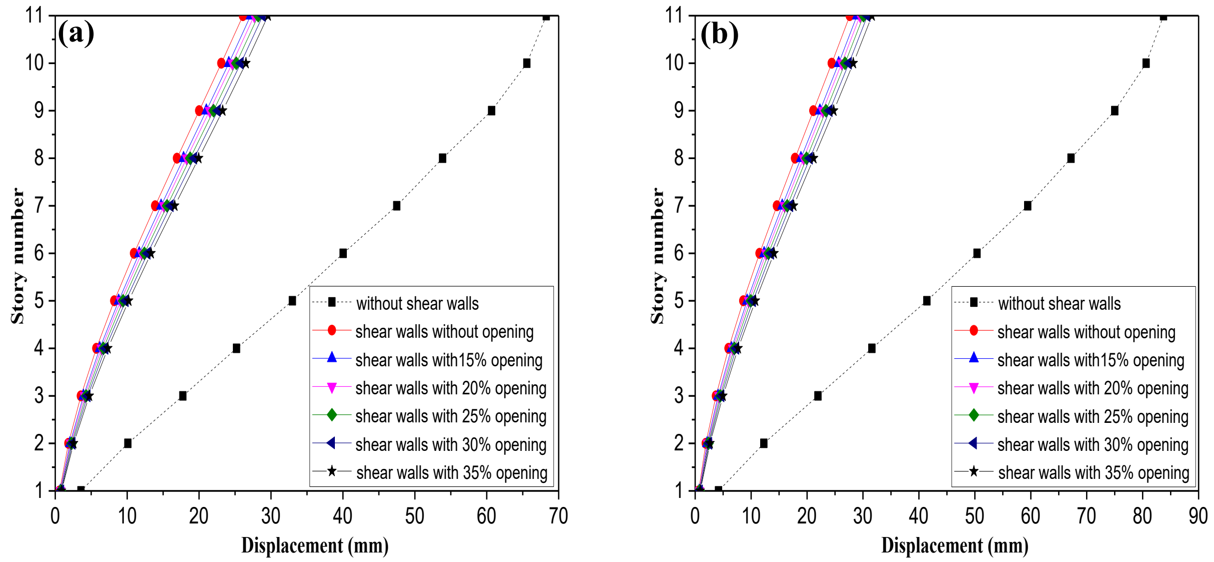

Figure 3 - Story displacement of the model cases 1:1: a) X-direction b) Y-direction.

3.2. Story Drift

Figures 4, 5, and 6 illustrate the inter-story displacements in the X and Y directions. Increasing the percentage of openings leads to an increase in inter-story displacements, whether in the X or Y direction. The results reveal that the maximum displacement on the fourth floor, due to the absence of shear walls, is 7.57 mm in the X direction and 9.63 mm in the Y direction. Similar observations were reported by Saeed *et al*. in a study on a ten-story building (Saeed *et al.* 2022).

Furthermore, it is observed that the maximum inter-story displacement in buildings with shear walls without openings occurs on the fourth floor. In contrast, when the building is equipped with walls with openings, the maximum inter-story displacement occurs on the eighth floor, regardless of the direction and percentage of openings. The largest inter-story displacement is observed in the Y direction, specifically in the (1:1) model, with a value of 1.82 mm.

The displacement is more significant in the Y direction, i.e, in the transverse direction, indicating that this direction is more sensitive to the effects of openings. Indeed, the building with 35% openings in the walls records an increase of approximately 9% in the X direction and 17% in the Y direction compared to buildings without openings. However, it is essential to remember that the obtained values remain within the limits of the current regulations. This compliance with safety standards is crucial to ensure the stability and resistance of the building against applied loads.

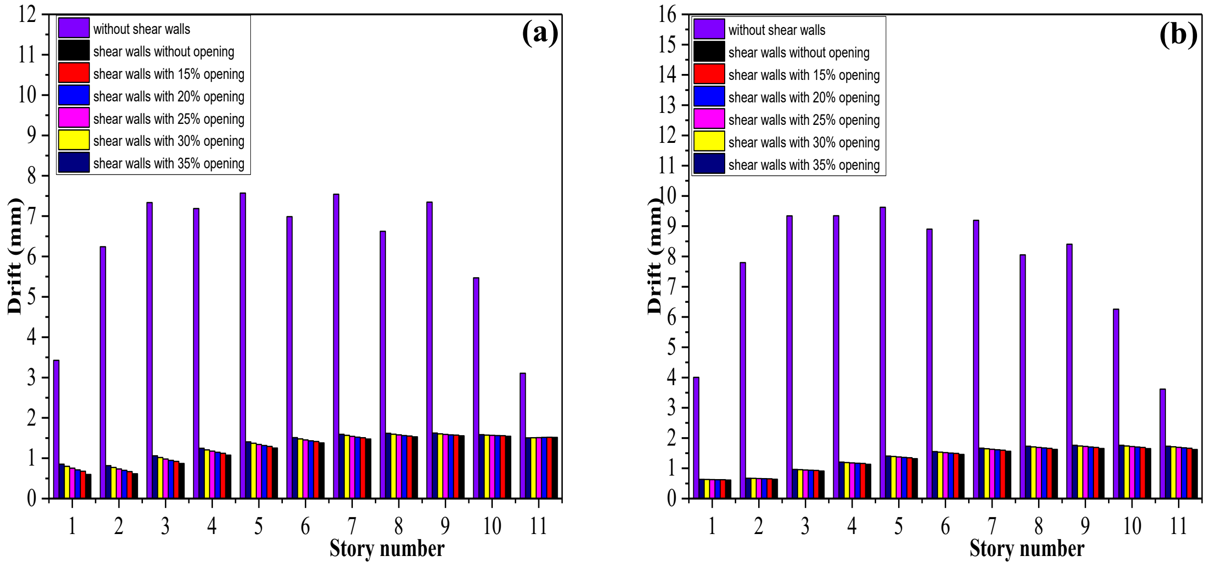

Figure 4 - Story drift of the model cases 1:0: a) X-direction, b) Y-direction.

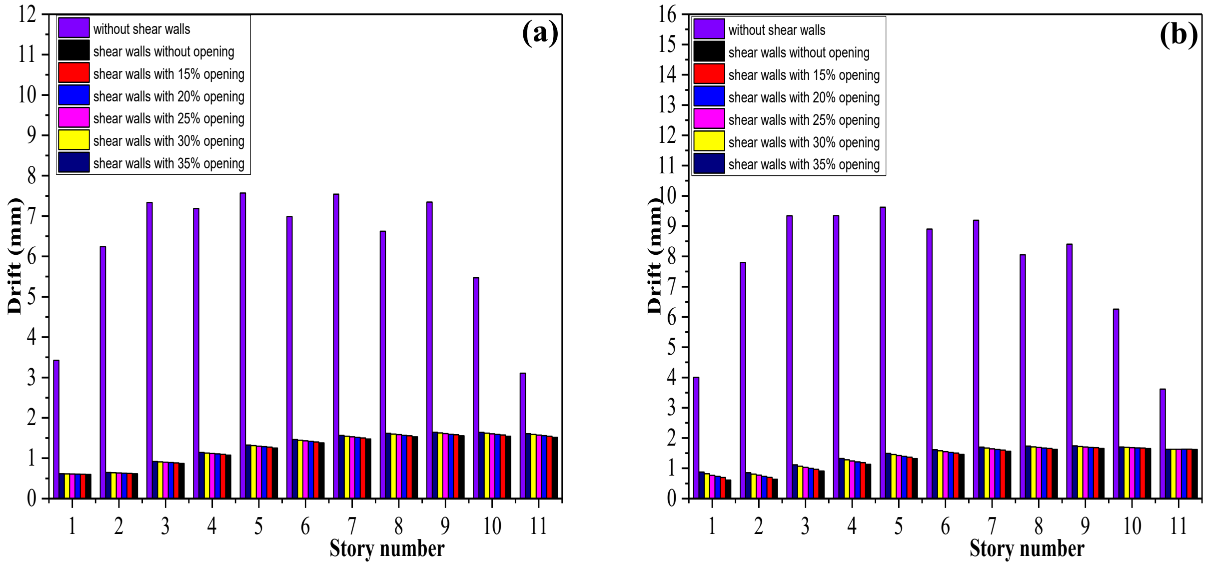

Figure 5 - Story drift of the model cases 0:1: a) X-direction, b) Y-direction.

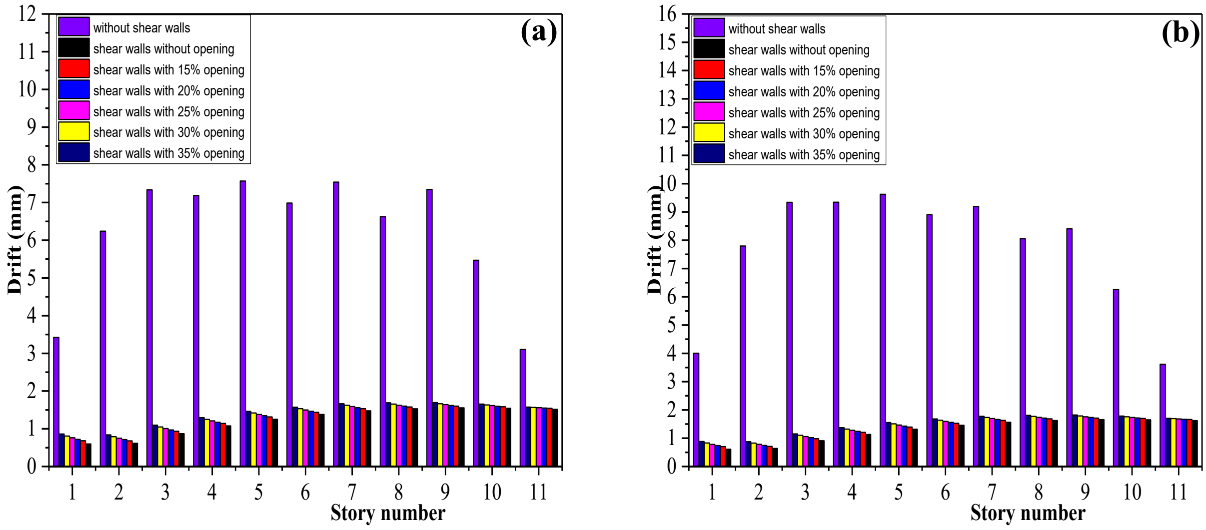

Figure 6 - Story drift of the model cases 1:1: a) X-direction, b) Y-direction.

3.3. Story Forces

The lateral forces are highest on the first floor and gradually decrease with increasing floors, reaching their minimum value on the tenth floor. At the first level in the X direction of the 1:0 model, the following values are recorded: 2252.22 KN for the building without shear walls, 3775.62 KN for the building with shear walls without openings, and 3714.59 KN for 15% openings in the shear walls, as shown in Figures 7, 8, and 9. It can be observed that the force value on the first floor of the building without shear walls is 40% lower than the building with shear walls. Introducing 15% openings leads to a reduction of approximately 7% in the lateral force value on the first floor compared to the (0:0) model. This reduction can even reach 4.21% when the shear walls have 35% openings. For the (0:1) and (1:1) models, a reduction of 4.26% and 7.63% is recorded for 35% openings, respectively. These forces are higher in the X direction. However, it is noteworthy that the reduction in lateral force is more significant in the Y direction for the (0:1) and (1:1) models. In the (0:1) model, the reduction is 4.42%, while in the (1:1) model, the reduction is 7.97%. This finding highlights the influence of the direction of openings on the lateral force of the building. The placement of the opening results in a reduction in this force. This could be due to the redistribution of weight and, consequently, the loads applied to the building.

In terms of impact on the lateral force of the building, openings formed in both the X and Y directions exhibit the most pronounced effect. In this configuration, openings have a greater potential for significantly reducing the lateral force compared to when they are formed in a single direction.

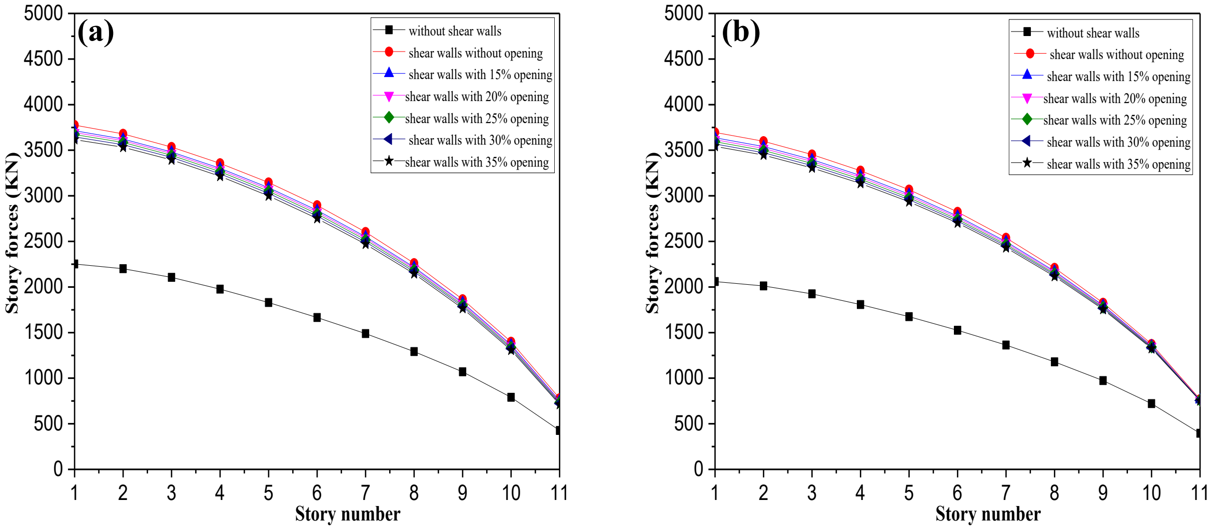

Figure 7 - Story forces of the model cases 1:0: a) X-direction, b) Y-direction.

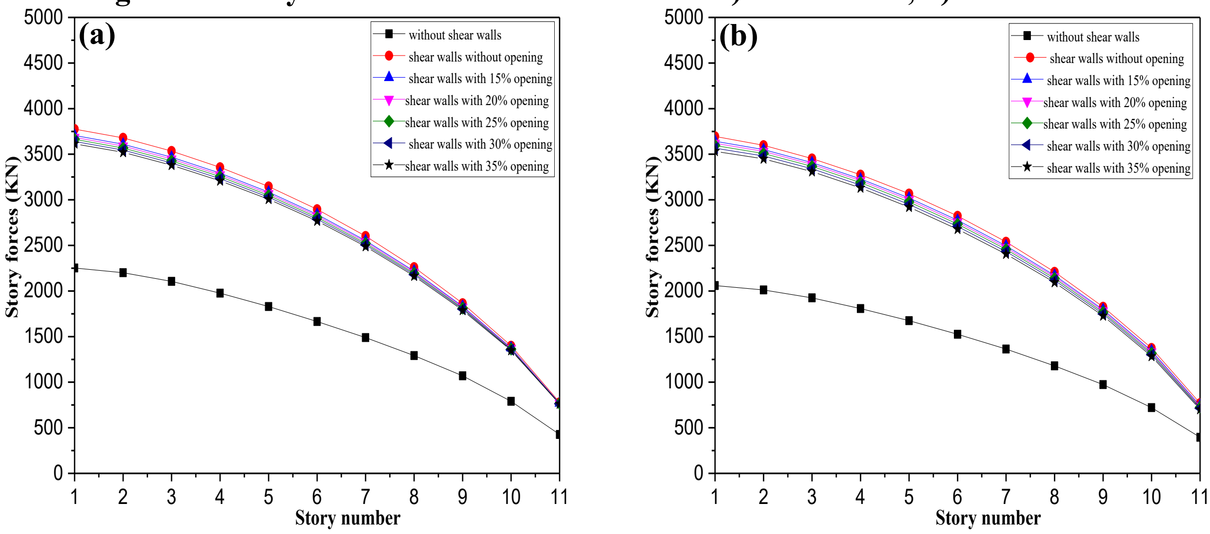

Figure 8 - Story forces of the model cases 0:1: a) X-direction, b) Y-direction.

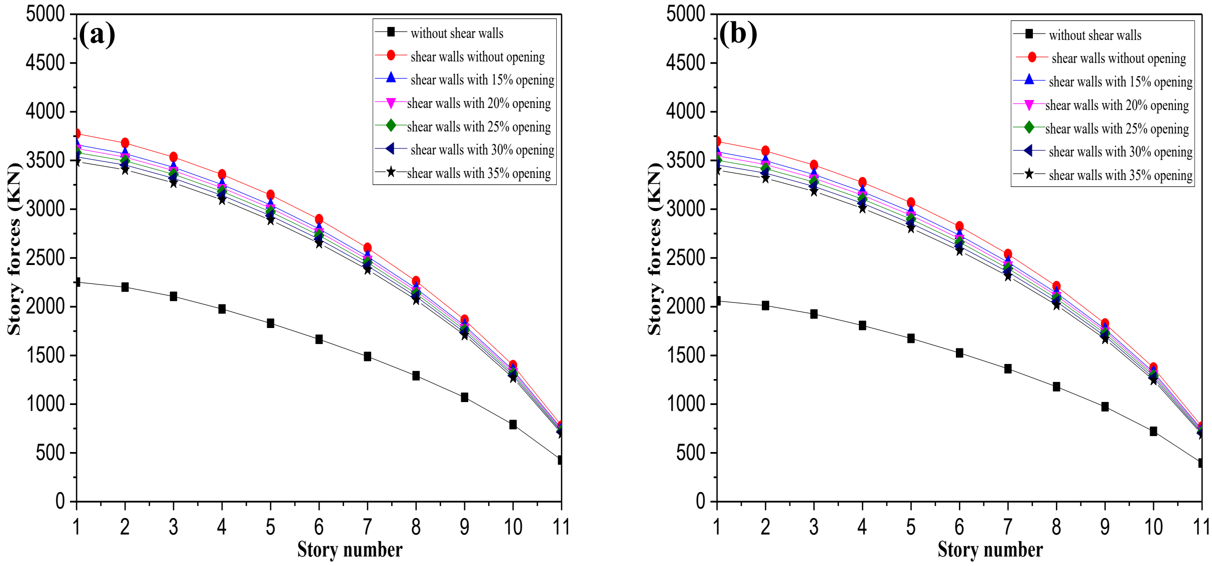

Figure 9 - Story forces of the model cases 1:1: a) X-direction, b) Y-direction.

3.4. Optimal opening percentages

After conducting a thorough study on several buildings, we have determined that the optimal percentages of openings in the shear walls vary among the different analyzed models. For the (1:0) model, we found that the optimal percentage of openings in the shear walls is 31.8%. This percentage has been identified as the most effective in ensuring satisfactory structural performance in the X direction. The ideal percentages of openings in the shear walls for the (0:1) and (1:1) models are 30% and 20.8%, respectively. These values have proven to be the most appropriate for ensuring adequate structural performance simultaneously in the X and Y axes.

It is important to note that in the (0:1) model, where the opening is made in the transverse direction, the obtained percentage of openings is 5.66% lower than in the X direction. It should be emphasized that site S3 and seismic zone-III considered in the study are the only ones to which these ideal percentages apply. These optima were determined while taking into account regulatory constraints and the specific characteristics of the studied constructions. It is essential to use them judiciously and adapt them to the specific conditions of other sites and seismic zones.

3.5. Stress in shear walls

A comprehensive numerical study was conducted to evaluate the stress at the base and top of the shear walls, with a particular focus on the maximum values. Our study also considered the influence of the percentage of openings in this analysis. The stress analysis in the building reveals several significant observations (Figure 10). Firstly, the values of compressive and tensile stress are higher than shear stress. It is important to note that the obtained stress remains within acceptable limits, with normal stress below 15 MPa and shear stress below 5 MPa, even with 35% openings in the shear walls.

The compressive stress in the (1:0) model is 3.66% higher than the (0:0) model, reaching a value of 11.65 MPa with a 35% opening, representing an increase of 9.39%. Remarkably, the increase in compressive stress in the (0:1) model is significantly higher, with an increase of 12.68% when the opening is 35%. This demonstrates that introducing openings in the Y direction leads to a notable increase in compressive stress. It is also noteworthy that an increase of 12.96% is recorded in the case of the (1:1) model. Regarding tensile stress, a comparison between different models revealed significant increases. The (1:0) model shows an increase of 4.85% compared to the (0:0) model. In contrast, the (0:1) and (1:1) models record higher increases, namely 10.79% and 6.76%, respectively, with a 35% opening. This observation clearly shows that introducing openings in the Y direction results in higher tensile stress.

The introduction of openings in the shear walls of the (0:1) model leads to a substantial increase in shear stress, reaching a peak of 154% compared to the (0:0) model when the opening is 15%. Likewise, the (0:1) and (1:1) models record respective increases of 149% and 151%. Interestingly, shear stress decreases with increasing openings by up to 30%, after which they begin to increase. This trend can be observed in all the models studied. Merabti *et al.* (2023) found the same percentage opening for shear walls of different thicknesses.

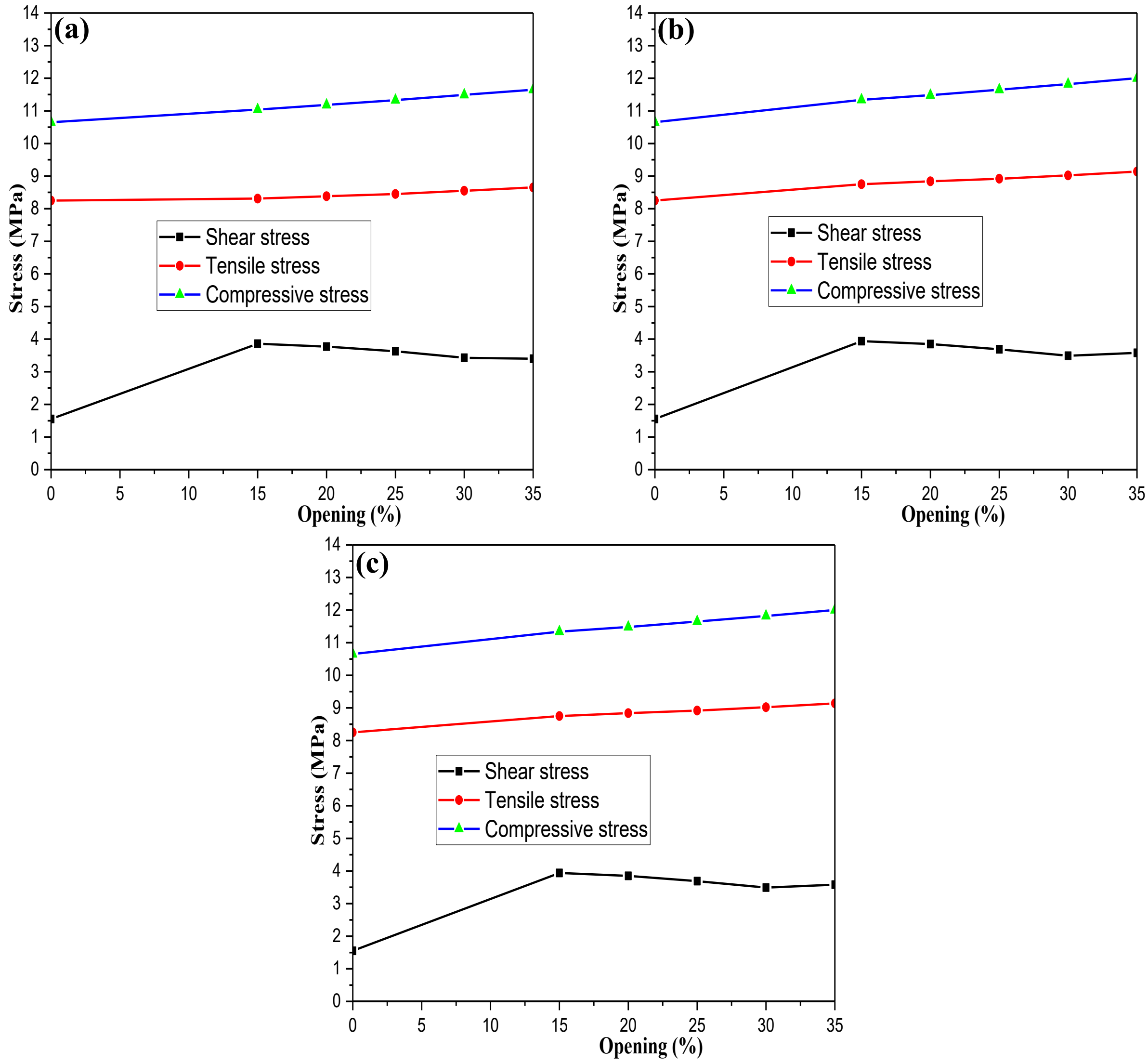

Figure 10 - Compressive, tensile, and shear stress in shear walls: a) Cases 1:0, b) Cases 0: 1, c) Cases 1:1.

4. Conclusions

The objective of this study is to analyze the behavior of mixed buildings, consisting of columns and beams, braced by L-shaped shear walls at the four corners of the building. We studied five different percentages of openings in these walls, namely 15%, 20%, 25%, 30%, and 35%. First, a comprehensive analysis of a building without openings was performed using the ETABS software. Subsequently, we introduced similar openings in the longitudinal and transverse directions at the center of the shear walls, varying their width while keeping the height constant for all studied openings. The analytical study of the effect of these openings on the seismic behavior of the shear walls led to the following conclusions:

- Buildings without shear walls exhibit larger displacements than those with shear walls. Openings in the shear walls result in increased displacements, especially in the direction of the openings. As the rigidity of the shear wall is reduced by the presence of openings in both directions, the maximum displacements are significant.

- The maximum inter-story displacements are observed on the fourth floor for buildings without shear walls and on the eighth floor for buildings with shear walls without or without openings. There is a direct relationship between the increase in the percentage of openings in the shear walls and the increase in inter-story displacements in the X and Y directions. The effect is particularly pronounced in the Y direction, where the displacements are more significant.
- The added openings in the shear walls further reduce the lateral loads in the buildings, which are already reduced by the presence of shear walls. Openings in the Y direction allow for a greater reduction of lateral forces, even though these forces are often stronger in the X direction. Models (0:1) and (1:1) lead to a reduction of forces by 4.42% and 7.97%, respectively. Openings that exhibit both X and Y directional characteristics have the greatest potential for reducing lateral forces.
- The optimal percentage of openings in the walls is 20.8%, 30%, and 31.8% for models (1:1), (0:1), and (1:0), respectively. These values are considered optimal for a medium-height building on site S3 in seismic zone-III.
- The compression and tensile stress continually increase when openings are added to the shear walls, mainly in the Y direction. This increase is significant for shear stress, reaching up to 151% for 15% openings in the (1:1) model. To ensure the building's resistance, it is crucial to conduct a rigorous check of the flexural behavior of the shear walls, especially for those with significant openings.

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