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Influence of Concrete Compressive Strength on L-Shaped Shear Wall Performance in Buildings within High-Seismicity Zones

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Abstract
Reinforced concrete mid-rise structures are supported by shear walls to withstand lateral forces resulting from earthquakes. In this context, the presence of openings in these walls is essential both functionally and aesthetically. This study employed L-shaped shear walls with varying vertical opening ratios, ranging from 15% to 50%, and compressive strengths ranging from 20MPa to 40MPa in a ten-story building. The study results demonstrate the significant role played by openings and the compressive strength of concrete in reinforced concrete walls to ensure buildings withstand earthquake forces. In this regard, we have developed reference models that adhere to seismic design principles and utilize optimized dimensions for openings based on the compressive strength of the concrete.
Keywords: High seismicity. Buildings. Concrete. Shear wall. Openings. ETABS.

1. Introduction

The concrete shear walls, also referred to as bracing walls, are specifically designed for tall structures (Farzampour *et al*., 2015; Naderpour *et al*., 2022). Their role is crucial to counteract shear forces and limit horizontal displacements, as indicated by Lu *et al.* (2015) and Najm *et al.* (2022). These reinforced concrete walls are symmetrically arranged to prevent the adverse effects of torsion (Fintel., 2014). Indeed, they play a vital role in multi-story buildings in high seismicity areas (Abualreesh *et al.*, 2022). These shear walls cannot be displaced or cut, as they are structural. Otherwise, the building's safety is compromised (Saeed *et al*., 2022). Openings may be integrated into concrete shear walls, whether for architectural, aesthetic, or other reasons (Erbaş *et al*., 2022; Saeed *et al*., 2022**)**. However, these openings reduce the load-bearing capacity of the walls. In addition, stresses concentrate around the openings (Berman *et al*., 2005; Merabti *et al*., 2023; Merabti and Bezari., 2023). The width of these shear walls, according to the Algerian seismic code (RPA99/V2003) (DTR B.C 2.48., 2003), is four times the thickness of the shear wall. The dimensions of these walls vary depending on the floor height and their stiffness at the ends. This code recommends a minimum thickness of 15 cm.

Studies on reinforced concrete shear walls integrated into buildings have been conducted (Liu *et al*., 2023; Rong *et al.*, 2023). These walls can take different shapes, such as T-, H- or U-shaped cross-sections (Chen *et al.*, 2016; El Ouni *et al.*, 2018; Alarcón *et al.*, 2023). Additionally, they may also have a rectangular form (Ugalde *et al.*, 2017); Moroz *et al.*, 2014). Other research focuses more on reinforced concrete shear walls with an L-shaped configuration to better understand their significance (Kezmane *et al.*, 2016; Karamlou and Kabir., 2012). These walls are capable of withstanding seismic forces when carefully designed (Husain *et al.,* 2019; Dou *et al.*, 2016).

The efficiency of the concrete element is inherently linked to the quality of the concrete (Kišiček *et al*., 2020). Indeed, the assessment of concrete efficiency relies largely on compressive strength, which is one of the key indicators (Merabti., 2022). Authors (Wood., 1990; Gulec *et al*., 2007) indicate that the shear strength of shear walls depends on several factors such as compressive strength, the yield limit of transverse and vertical reinforcements, the thickness of the shear wall, and the shape of the wall. Dabbagh (2005) highlights that high-strength concrete makes the material more brittle, leading to a reduction in ductility. Conversely, the experimental study conducted by Su *et al*. demonstrates that the section of high-strength concrete reinforced with steel bars behaves like a plane section in an L-shaped shear wall (Su *et al.,* 2012). According to Eurocode 8 (EN 1998-1) (Eurocode 8., 2004), medium to high ductility is recommended for buildings located in seismic zones. Furthermore, buildings designed with high ductility exhibit a reduction in compressive strength, following this standard. However, some authors suggest the use of ultra-high performance concrete (UHPC) containing a quantity of steel fibers for shear walls, which reduces cracking and also promotes energy absorption (Ding *et al*., 2024; Wood., 2015).

In this study, the behaviors of medium-sized buildings are investigated using the ETABS software. This document facilitates the understanding of the behavior of L-shaped shear walls, whether or not they have openings, in a ten-story structure with varying percentages of openings and different compressive strengths of concrete. The analysis was conducted on over fifty buildings, thereby allowing for a thorough exploration of the relationships between opening percentages, concrete strengths, and their impact on the performance of shear walls.

2. Building description

The seismic behavior of a ten-story reinforced concrete structure was studied using the finite element simulation software ETABS. This software is employed for finite element analyses (FEM). The structure was constructed using columns and beams; with bracing provided by L-shaped shear walls. The foundation rests on firm soil (S2). These walls are positioned only at the corners of the structure, both with and without openings. The plan geometry of the structure was intentionally chosen to be regular, with square-sectioned columns, to eliminate any factors that could interfere with result interpretation. Each floor consists of five frames in the longitudinal direction and four frames in the transverse direction. The structure is located in a high seismicity zone (Zone III), according to the Algerian seismic code RPA99/V2003 (DTR B.C 2.48., 2003). All loads, including seismic data, were input into the ETABS software. To ensure compliance with the RPA (DTR B.C 2.48., 2003), multiple load combinations were introduced into the software.

$$1.35G + 1.5Q \quad (1)$$
$$G + Q + Ex \quad (2)$$
$$G + Q + Ey \quad (3)$$
$$0.8G + Ex \quad (4)$$
$$0.8G + Ey \quad (5)$$
$$0.8G - Ex \quad (6)$$
$$0.8G - Ey \quad (7)$$

With:
G: Permanent loads
Q: Unfactored live loads
E: Seismic action

3. Parameters studied

The analysis focused on the behavior of L-shaped shear walls with and without vertical openings. All walls had a thickness of 200 mm, a length of 4000mm, and a height of 2610mm. The shear walls were positioned at the building's corners, as mentioned earlier, both with and without openings. Openings were centrally located on the wall panel, and their height was uniform for all cases studied, fixed at 2100 mm.

Seven levels of vertical openings in the shear walls were considered, starting at 15%, corresponding to a door opening, and gradually increasing to 20%, 25%, 30%, 35%, 40%, 45%, and 50%. Additionally, different compressive strengths of concrete were considered for the shear walls, namely 20MPa, 25MPa, 30MPa, 35MPa, and 40MPa, incorporated into the structural models.

4. Results & Discussion

4. 1. Shear force

The shear forces at the base of buildings braced by L-shaped shear walls, with or without openings, are depicted in Figure 1. The increase in the size of openings and the compressive strength of the concrete used in the shear walls impact the shear forces at the base of the building. Indeed, it is observed that increasing the size of openings reduces shear forces, and this holds for all analysed compressive strengths, except for a specific scenario. Specifically, for a compressive strength of 20MPa and an opening equivalent to 15%, it is noted that the shear force in the wall is higher than that of the wall with a compressive strength of 25MPa. This holds for both longitudinal (X-Direction) and transverse (Y-Direction) orientations.

Shear walls with 50% openings exhibit lower shear forces compared to smaller openings, and increasing compressive strength raises the shear forces at the base. Other studies have also demonstrated a decrease in shear force with an increase in the opening rate in shear walls (Merabti *et al.*, 2023). The simulation results provide a value of 3036.079KN for a compressive strength of 20MPa and a 50% opening. This is 1.79% lower for the same opening rate and a compressive strength of 40MPa. This result indicates that shear forces are more affected by the increase in the percentage of openings in shear walls, despite the use of high-strength compressive concrete.

The difference in shear force between 15% and 50% for a compressive strength of 20MPa in X-Direction is 12.13%. These findings underscore the importance of considering opening percentages in shear walls when designing a building of this height. Regarding the difference in shear forces between X and Y directions, it is evident that shear forces are higher in X-Direction.

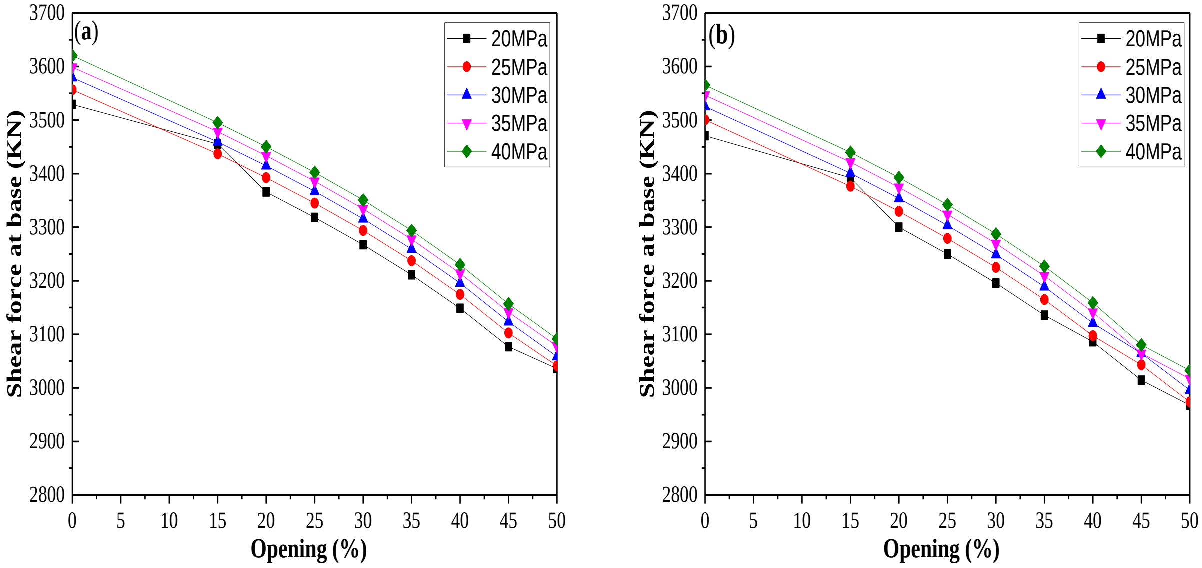

Figure 1. Evolution of shear forces in buildings based on openings in shear walls: (a) X-Direction, (b) Y-Direction.

4.2. Maximum displacement

The displacement at the top floor based on the percentage of openings in the shear walls for X and Y direction are illustrated in Figure 2. Buildings with shear walls having a compressive strength of 20MPa and no openings recorded a maximum displacement of 21.72mm and 22.974mm in the X and Y directions, respectively. Increasing the compressive strength of the walls decreases the maximum displacement of the structure. Indeed, with strength of 40MPa, there is a decrease of 7.24% in the X-Direction and 8.09% in the Y-Direction compared to a compressive strength of 20MPa. This displacement difference narrows with the increase in openings in the shear walls. Conversely, incorporating openings in the walls increases the maximum displacement in the studied structures.

In the X-Direction, a maximum displacement of 27.057mm is induced for the building with shear walls having 50% openings and a compressive strength of 20MPa. The structure exhibits a displacement of 29.076mm in the Y direction. As observed, the displacement in the transverse direction (Y-Direction) is higher compared to the longitudinal direction (X-Direction). This observation remains consistent for irregular buildings, as demonstrated in a study conducted by Laissy *et al*. (2023).

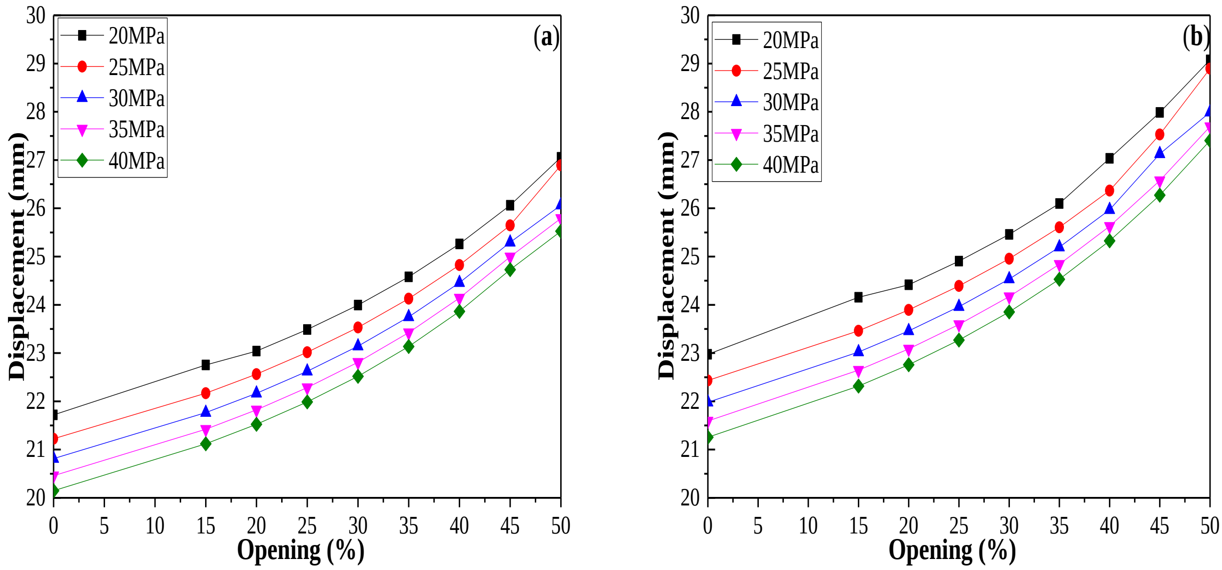

Figure 2. Evolution of total displacements in buildings based on openings in shear walls: (a) X-Direction, (b) Y-Direction.

4.3. Maximum stresses

4.3.1. Exploration of maximum compressive stress

Maximum compressive stresses are obtained through Equation 3. They are reached at the ground floor, regardless of the compressive strength of the shear wall and the percentage of openings in the walls. These stresses manifest at the base of the L-shaped wall in the X-Direction, while they are observed at the opposite end of the wall in the Y-Direction. The work conducted by Merabti and Bezari (2023) led to the same conclusion. In the Y direction, the compressive stress decreases as it approaches the openings. However, an increase in compressive stress occurs as one approaches the openings in the shear walls in the X-Direction. This allows us to observe that the distribution of compressive stresses is not symmetrical in both directions. Similarly, compressive stresses on walls without openings are observed at the lower part of the wall, and their distributions are not symmetrical. This result is also noted by Benbellil *et al*. (2019).

The maximum compressive stresses based on the percentage of openings are presented in Figure 3. The results show that the maximum compressive stress increases with the percentage of openings in the wall. Similarly, compressive stresses gradually increase with the increase in the compressive strength of the shear wall. A compressive stress of 12.86MPa is observed for the wall with 50% opening and compressive strength of 40MPa. This compressive stress represents an increase of 22.63% compared to the building equipped with a shear wall without openings. It is observed that, for the same buildings with different compressive strengths and a constant percentage of openings, the difference in compressive stress increases as the percentage of openings increases.

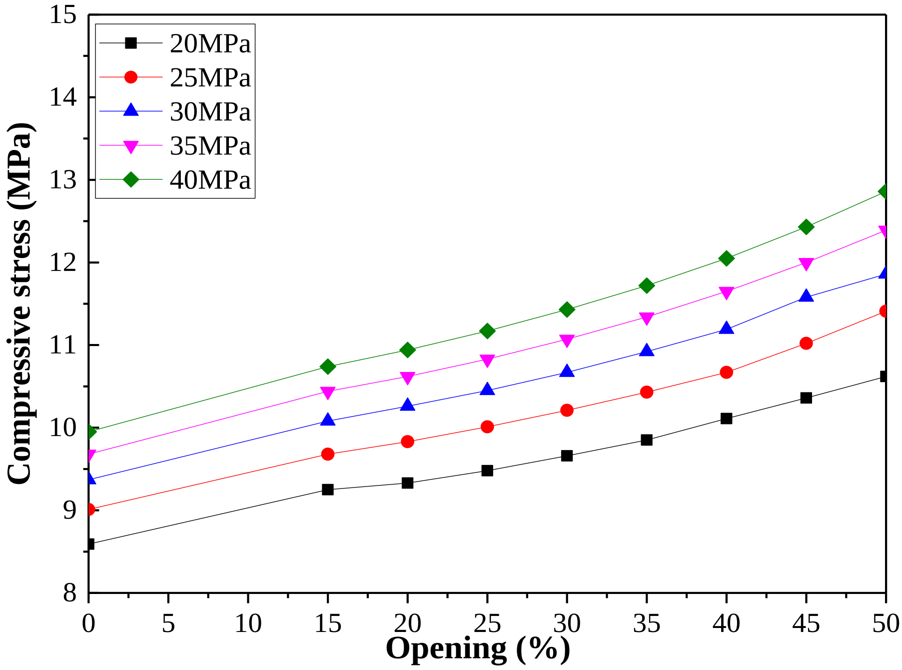

Figure 3. Compression stresses based on openings in shear walls.

4.3.2. Exploration of maximum tensile stress

The maximum tensile stresses are distributed at the same locations as the compressive stresses, but they are obtained under the seismic action Ey. However, the values obtained remain lower, regardless of the proportion of openings and the compressive strength of the shear wall.

It is observed that increasing the compressive strength of the shear wall increases the tensile stress. According to the tensile stress curve based on openings (Figure 4), buildings braced with shear walls with a compressive strength of 40 MPa and 50% opening reached a maximum stress of 8.74MPa. When reducing the percentage of openings, this tensile stress decreases to reach 7.72 MPa for the building without openings, representing a decrease of 11.67%. Compared to compressive stress, there is an approximately halved reduction in the evolution of tensile stress with an increase in the percentage of openings.

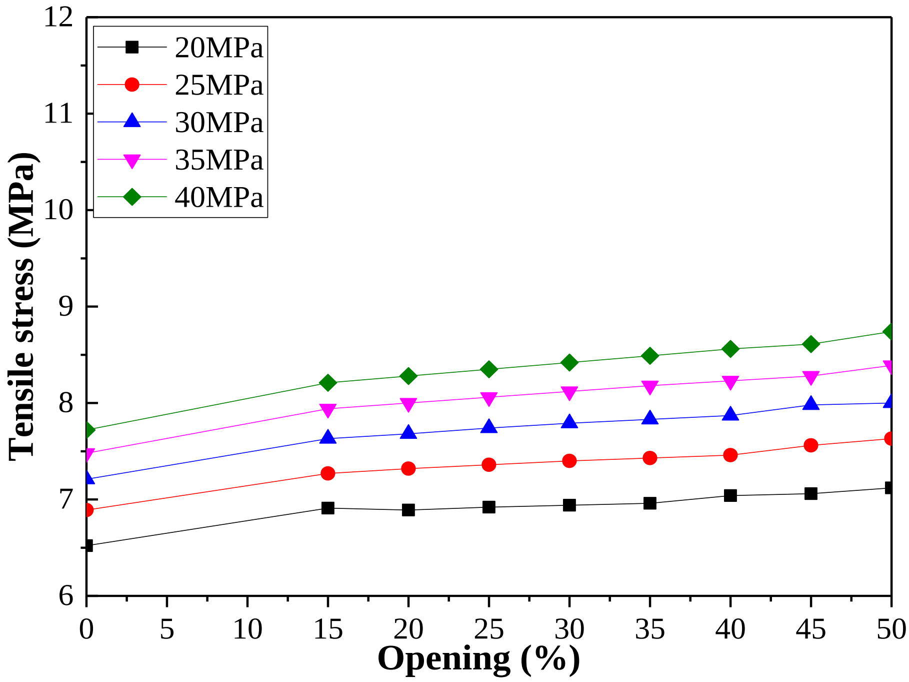

Figure 4. Tensile stresses based on openings in shear walls.

4.3.3. Tensile and compressive stresses

The relationship between tensile and compressive stresses is illustrated in Figure 5. This depiction highlights all concrete strengths as well as all openings made in the shear walls. It is noticeable that an increase in compressive stress consistently leads to an increase in tensile stress, regardless of the concrete strength level used in the shear wall. It should be emphasized that both tensile and compressive stresses consistently remain below the permissible limit of concrete, which is 15MPa.

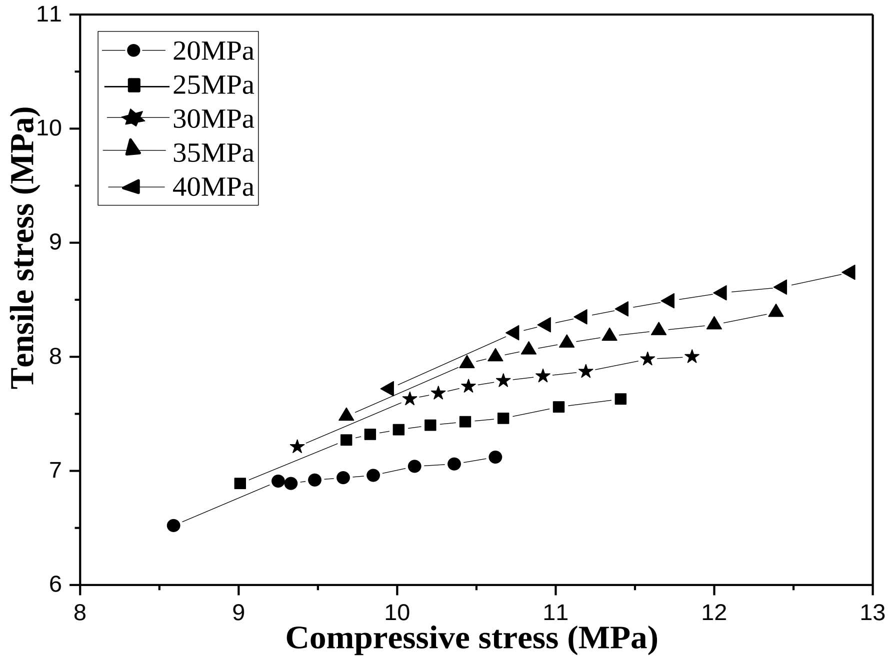

Figure 5. Evolution of tensile stress vs compressive stress.

A correlation between tensile and compressive stresses has been established for shear wall compressive strengths of 20MPa, 25MPa, 30MPa, 35MPa, and 40MPa. The relationships above, based on the concrete strength, have been obtained with very satisfactory determination coefficients (R^2). It can be argued that there is a significant relationship between the stresses studied, the concrete strength, and the percentage of openings in the shear walls.

$$T_s = -0.129C_S^2 + 2.747C_S - 7.512 \quad (R^2 = 0.955) \tag{8}$$

$$T_s = -0.100C_S^2 + 2.324C_S - 5.900 \quad (R^2 = 0.974) \tag{9}$$

$$T_s = -0.111C_S^2 + 2.651C_S - 7.881 \quad (R^2 = 0.985) \tag{10}$$

$$T_s = -0.103C_S^2 + 2.578C_S - 7.803 \quad (R^2 = 0.984) \tag{11}$$

$$T_s = -0.093C_S^2 + 2.451C_S - 7.395 \quad (R^2 = 0.986) \tag{12}$$

4.3.4. Exploration of maximum shear stress

The shear stresses based on the percentage of openings are illustrated in Figure 6. Comparing each compressive strength used in the shear wall, it is observed that its increase has little influence on the shear stresses. However, increasing the thickness of the shear walls reduces shear stresses, as reported in (Merabti and Bezari., 2023). The optimal percentage of openings in reinforced concrete shear walls is 30%. These findings align with the research conducted by (Merabti and Bezari., 2023; Merabti *et al*., 2023).

The maximum shear stresses in walls without openings are observed at the base of the wall, especially in the X-Direction. There is a distribution of stresses along the entire length of the wall. In contrast, there is a concentration of these shear stresses on the side opposite the angle of the shear wall. Concrete spalling at the base of the wall is confirmed by an experimental study conducted by Inada *et al*. (2008) and numerically by Benbellil *et al*. (2019).

The behavior of the shear wall element with openings is different from that without openings. The distribution of shear stresses in this case also focuses on the lintel level, requiring the use of special reinforcement in this part of the wall (Merabti and Bezari., 2023). The maximum stresses are obtained according to Equation 3 on the ground floor, except for walls with openings of 15%, 20%, and 25%, for which they are obtained on the first floor.

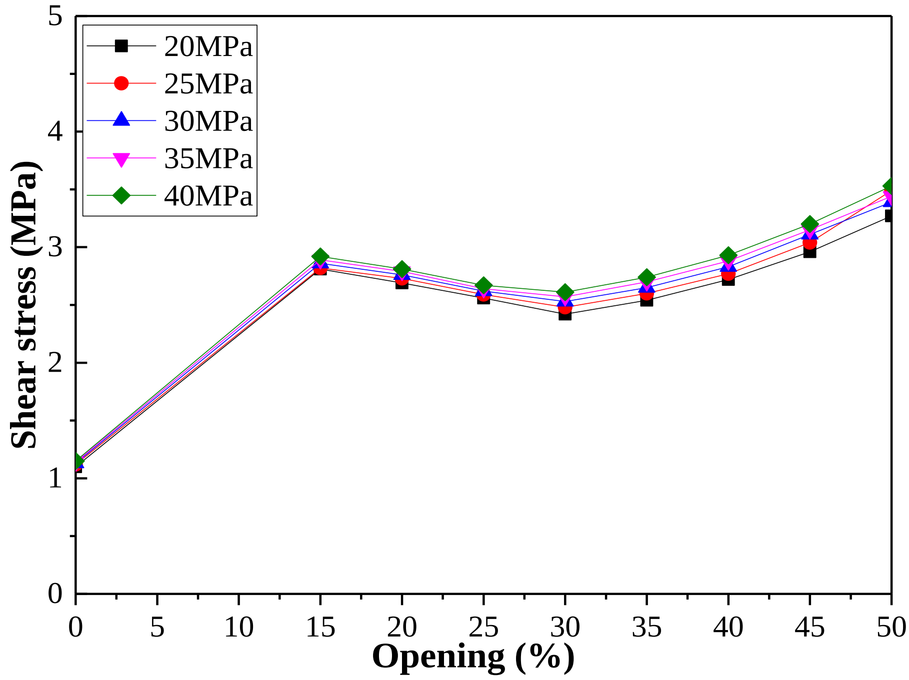

Figure 6. Shear stresses are based on openings in shear walls.

4. 4. Evolution of openings based on the compressive strength of the walls

Figure 7 illustrates the evolution of openings based on the compressive strength of the shear walls. For each compressive strength of the shear wall, we determined the optimal percentage of openings while adhering to the requirements of the Algerian seismic code (DTR B.C 2.48., 2023). As observed, the increase in compressive strength leads to an increase in the percentage of openings in the wall. A shear wall with a compressive strength of 40 MPa reaches an opening rate of 45%, surpassing that of the wall with strength of 20MPa by 18.67% (36.6%). There is a significant linear correlation between the compressive strength of the walls and the optimal openings, with a determination coefficient of 0.98.

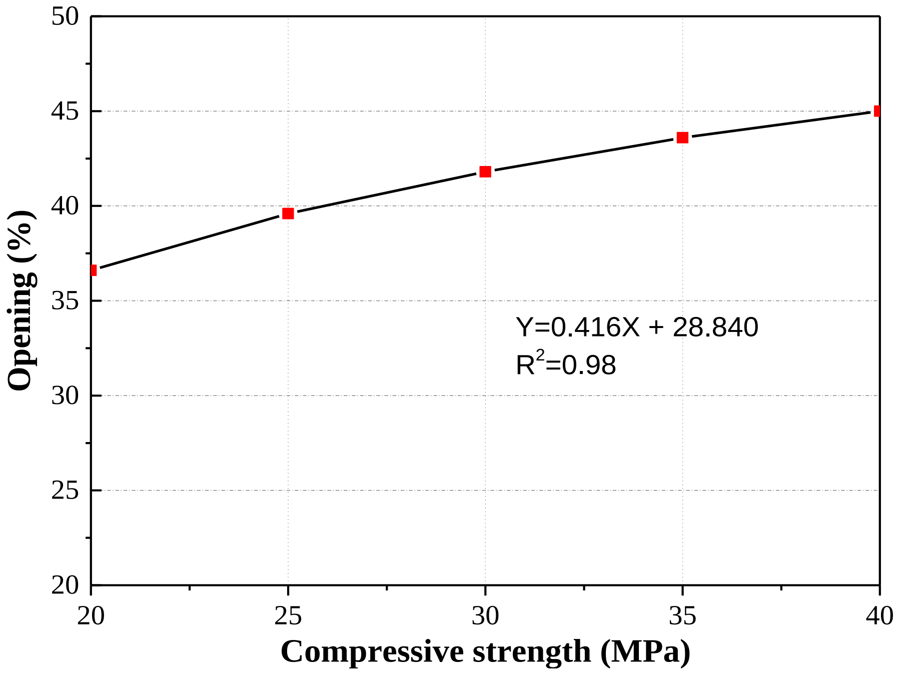

Figure 7. Optimization of openings in shear walls based on compressive strength.

5. Conclusion

The analysis conducted in this study focuses on the interaction between the compressive strength of the concrete in shear walls and the presence of openings. From the obtained results, the following conclusions can be drawn:

- Shear forces are more influenced by the percentage of openings than by an increase in the compressive strength of the concrete in shear walls.
- The total displacement is affected by the compressive strength of the walls and the opening ratio in the shear walls. Increasing the concrete strength reduces the total displacement of the structure.
- Maximum compression and tension stress increase with the percentage of opening and the compressive strength of the concrete in the walls. As the concrete strength increases, the shear walls are more stressed by compression and tension stresses. However, it is observed that the evolution of compression stresses is more significant with opening percentages.
- The compressive strength of the concrete in shear walls does not exert a substantial influence on the shear stresses of the shear walls. Other parameters need to be examined to identify the most influential factors, especially for shear stresses.
- The opening percentages obtained for different compressive strengths exceed 30%, automatically leading to an increase in shear stresses.

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