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NATURAL FREQUENCY OF RC WALLS WITH VARIOUS SIZES AND LOCATIONS OF OPENING

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ABSTRACT

Reinforced concrete (RC) structural walls, also known as shear walls, are commonly employed as lateral force-resisting elements in structures located in areas with moderate-to-high seismic hazards. These walls significantly enhance a building's lateral strength and stiffness, enabling them to withstand heavy ground shaking. In certain cases, it may be necessary to incorporate openings in reinforced concrete shear walls to meet specific performance requirements. However, these openings can alter the force transmission mechanism, resistance, and stiffness of the wall, significantly impacting its response. This study evaluates the effect of opening size and placement location on the performance of reinforced concrete shear walls. The study quantifies the percentage change in natural frequency of RC walls when it increases or decreases. The investigation aims to identify openings that yield unfavorable outcomes and determine the optimal locations that meet the dynamic requirements of the walls more effectively efficiently. The findings reveal that the presence of openings, arranged in various configurations, can exert have both positive good and negative effects on the natural frequency of the walls. Consequently, this dynamic property can be subject to an increase of by up to 17% or a decrease of by up to 37%, depending on the arrangement of the openings.

KEYWORDS: Modal analysis, Natural frequency, Openings in walls, Reinforced concrete shear walls.

1. INTRODUCTION

Many low and medium-rise constructions consist of ductile moment-resisting frames. As the height of the structure increases, it becomes more effective to incorporate a frame system working in conjunction with structural walls to provide the necessary lateral strength and stiffness [1]. Reinforced concrete (RC) structural walls, also known as shear walls, are frequently employed as lateral force-resisting elements in buildings located in areas with moderate-to-high seismic hazards. This is because they significantly enhance a building's lateral strength and stiffness during intense ground shaking [2]. Shear walls are often positioned between column lines, stairwells, elevator shafts, and utility shafts. They resist lateral forces by transferring wind and seismic loads to the foundation while imparting lateral stiffness to the system and supporting gravity loads. The inclusion of a well-designed shear wall system within a building frame substantially improves its seismic performance, so shear walls are commonly utilized to increase the seismic strength of reinforced concrete structures [3, 4]. Many structural and architectural criteria, such as the height-to-length ratio, the presence of apertures, cross-sectional shapes, and materials, which may also change their behavior, significantly impact structural elements' capacity to support loads [5-7].

To meet functional requirements, openings may be introduced in reinforced concrete shear walls [8, 9]. From an architectural standpoint, these openings facilitate entrances, doors, ventilation, and windows in internal and external walls, often found in multi-story structures. From a structural engineering perspective, the placement of openings must consider the safety of the structural resisting elements against detrimental seismic impacts [10]. The influence of these openings in walls is often neglected by designers in order to simplify both designing and evaluating constructions using finite element programs. Neglecting these openings may result in unreal effects on the seismic design of structures. As a result, it is critical to measure these apertures' influence on the structures' lateral stiffness. It is discovered that the greatest window opening at concrete shear walls that

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might be neglected in modeling because of simplification will be up to 3% of the total wall area when 5% of the stiffness ratio RS decrease can be permitted [11].

These openings can significantly influence the behavior of the wall by altering its force transfer mechanism, reducing its resistance and stiffness, diminishing its ductility, and inducing stresses that are not accounted for in conventional wall design [12]. Saeed, Najm [13] conducted a comparative study on the impact of staggered and regular opening types on the building, examining properties such as story displacement, story drift, and base shear. The experiment showed that shear walls with periodic apertures exhibit seismic behavior similar to those with staggered openings. Another study by Kale and John [14] compared common and staggered opening types regarding displacement and base shear while also considering the period. However, their comparison only focused on two different opening types and did not explore a wider range of geometric variations.

To specify the reinforcement around pierced shear wall holes, current design provisions provide generally defined information. In order to correct this flaw, three-dimensional (3D) nonlinear pushover calculations on typical shear wall-dominating building systems were performed to examine the load capacity and stress distribution around the apertures by [15]; the study's conclusions show that the stress flow and crack patterns close to the apertures in the 3D samples were considerably dissimilar from those anticipated for the 2D situations. The tension-compression coupling effects caused by the interactions between walls and slabs greatly enhanced the overall lateral resistance. It can be concluded that the closer the openings are to the edge of the wall, the more decreased strength they show according to the seismic changes [16]. When the aspect ratio is significant, the shape of the opening also has a significant impact. Due to the supply of varying sizes of openings, the overall lateral displacement of the structures increases from 0.58% to 20.95%, and the inter-storey drift increases by roughly 1.04% to 23.63% [17]. In another investigation by [18], cyclic lateral stress was applied to five slender RC walls with small openings (one control specimen without openings and four specimens with varied openings); regardless of the opening's size and location, all specimens demonstrated the same sequence of action. There was flexural yielding in every specimen. Concrete crushing at the compressive side and buckling of the flexural reinforcement caused the test specimens to fail. Szczepanski, Manguri [19] conducted a comprehensive study on the effect of opening location and size on the natural frequency of wooden walls with various opening arrangements.

For both the design of new structures and the assessment of existing ones in the context of seismic risk evaluation and mitigation, an accurate method for determining the fundamental period of vibration is crucial Asteris, Repapis [20]. This is especially significant for studying the dynamic behavior of structures [21]. The weight, stiffness, and strength distribution in the building's horizontal and vertical planes determine how a structure will behave during an earthquake's motion [22]. In comparison to structures without shear walls or other lateral load resisting systems, buildings with shear walls with more robust lateral load resisting capability, evenly distributed mass, and stiffness in plan and elevation sustain significantly less damage [23]. However, openings may decrease their lateral capability, lowering their stiffness and lateral load capacity [24]. The fundamental period of vibration is influenced by the stiffness and mass distribution along the structure's height [20]. Modeling the wall as a vertical deep beam yields a relatively good result for determining the in-plane stiffness of a shear wall without openings. However, In the case of a shear wall with openings, it is problematic to model the wall as a deep beam because the wall cross section is not consistent over its length [25]. According to Szczepanski, Manguri [19], (1), f is directly proportional to K and inversely related to M. Consequently, when a wall contains an opening, mass, and stiffness decrease. However, the extent of their reduction depends on the size and placement of the opening. If the value is higher than that of non-opened walls, then f is increased.

$$f = \sqrt{\frac{K}{M}} \quad (1)$$

$$f = \frac{1}{T} \quad (2)$$

While f is the natural frequency, K is the stiffness and M represents the mass. And the relation of the natural frequency f and fundamental period is related in (2). The relation shows that the natural frequency for a system is linearly inverse to its time ~~p~~ period

In this paper, an investigation is conducted on the effect of opening size and location on the reinforced concrete walls. The study aims to establish the percentage change in the required property, whether it decreases or increases. Given the widespread use of reinforced concrete structures supported by shear walls globally, it is crucial to address this dynamic property to ensure enhanced safety. The data obtained from various geometries, arrangements, and locations of openings that may be necessary in buildings for architectural or mechanical purposes is considered.

2. SHEAR WALLS- A NUMERICAL MODEL

This paper investigates the structural behavior of walls with three different widths (4m, 6m, and 8m) using CSI SAP2000 software. Each wall has a height of 14m, representing a five-story building with each story having a height of 2.8m. The walls are constructed with a thickness of 300mm and are assumed to be supported by line fixes at the base. Figure1 illustrates the structural model of the walls, and Table 1 presents the properties of the reinforced concrete (RC) walls.

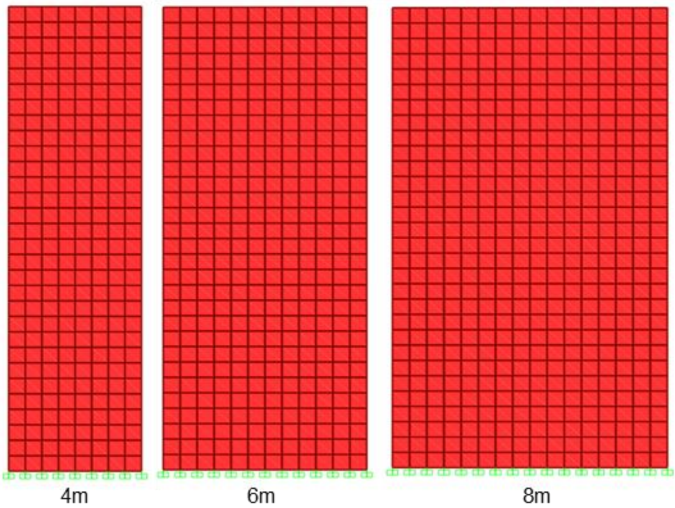

Fig. (1): - Numerical model of the structural walls without opening.

Table(1):-Material Properties For The Rc Walls In Sap2000

Element	Thickness (mm)	Material	Density (kg/m3)	Elasticity modules (MPa)
RC Walls	300	RC 35 MPa	2400	27805.574

The openings with different sizes of 1 m x 2 m and 2 m x 2m were created in different locations on the reinforced concrete walls in different cases of optimal locations, horizontal arrangements and vertical arrangements based on the Szczepanski, Manguri [19] locations to verify the most used cases in the practical constructions.

2.1 Optional cases of Opening

Ten optional cases were selected to determine the dynamic behavior of the three models at various locations with openings. Considering both opening sizes, analysis was conducted for three different natural frequencies for ~~all~~ the three walls. Figure. 2 illustrates the ten locations where 1 m x 2 m openings were placed for W1, which has a width of 4m.

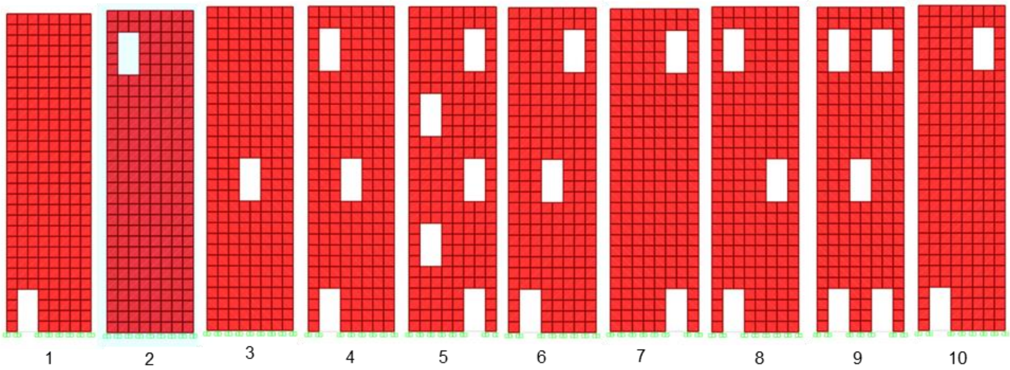

Fig. (2): - Ten optional cases of locations for opening have size 1 for in W1.

2.2 Horizontal opening

Another system used in this study is the horizontal arrangement of the openings (op) for walls (see Figures 3, 4, and 5). This arrangement was implemented across all five stories. In the W1 model, the spacing between op1 type openings is 1m, with an edge distance of 0.5m for op1 and 1m for op2. For the W2 model, the spacing between openings is 0.5m and 1m for op1 and op2 types respectively, while the edge distance is 1m for op1 and 0.5m for op2. In the W3 model, both op1 and op2 sizes have a spacing between openings and an edge distance of 1m.

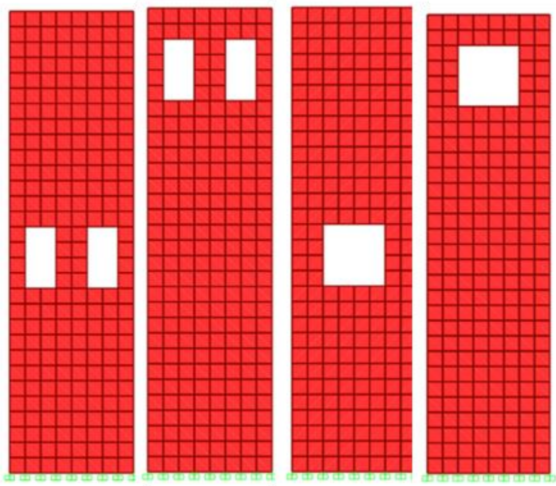

Fig. (3): - Horizontal cases of openings sizes 1 and 2 on the third and fifth floor for W1.

2.3 Vertical opening

The apertures for the vertical opening system were arranged in a stacked configuration on each floor (see Figure. 6). The initial aperture was located 0.5 meters away from the left edge of the wall. Subsequently, as the apertures approached the center, the distance from the edge was increased by 0.5 meters at each consecutive stage.

3. STRUCTURAL ANALYSIS

The modal analysis was conducted using CSI SAP2000 software to investigate the natural frequencies (NF) of realistic five-story buildings [19, 26] .This study focuses on examining the impact of openings on the natural frequencies of the walls. Table 2 presents the first three natural frequencies of vibration for the reinforced concrete (RC) walls without any openings. It is observed that the first natural frequency of the walls is the lowest among the three types of natural frequencies, with Wall 1 having the smallest NF1 value compared to the other walls. Furthermore, NF3 exhibits the highest vibration level for all types of walls, and among the three walls considered, Wall 1 has the highest natural frequency in the third mode of vibration. Subsequently, the analysis was performed for Wall 1 (W1), Wall 2 (W2), and Wall 3 (W3) with two types of openings. The NF1, NF2, and NF3 results for all walls with ten optional cases, horizontal cases, and vertical cases of openings are presented in Tables 2, 4, and 5, respectively.

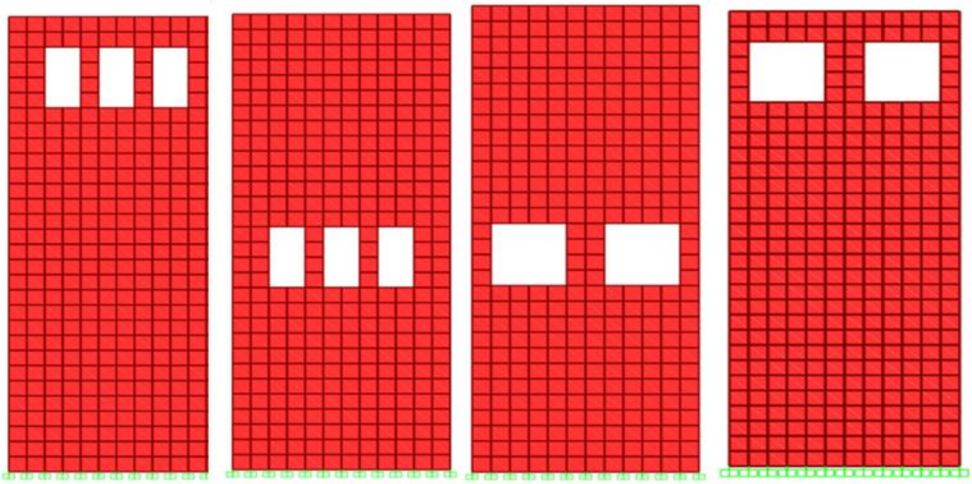

Fig. (4): - Horizontal cases of openings sizes 1 and 2 on the third and fifth floor for W2.

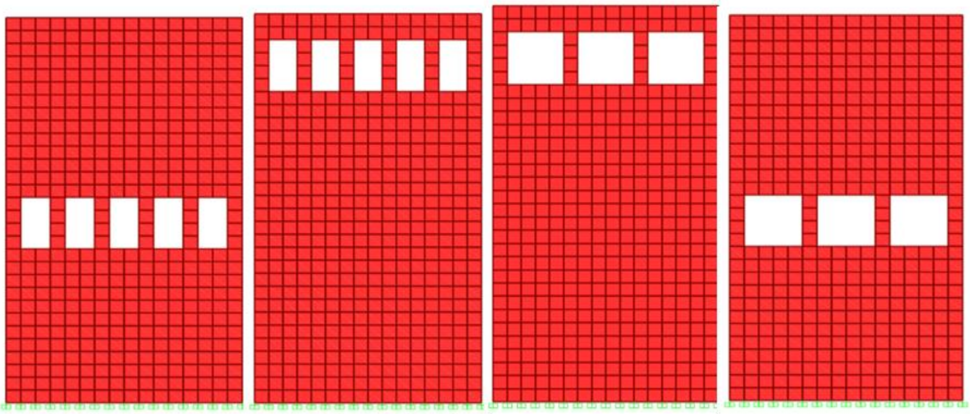

Fig. (5): - Horizontal cases of openings sizes 1 and 2 on the third and fifth floor for W3.

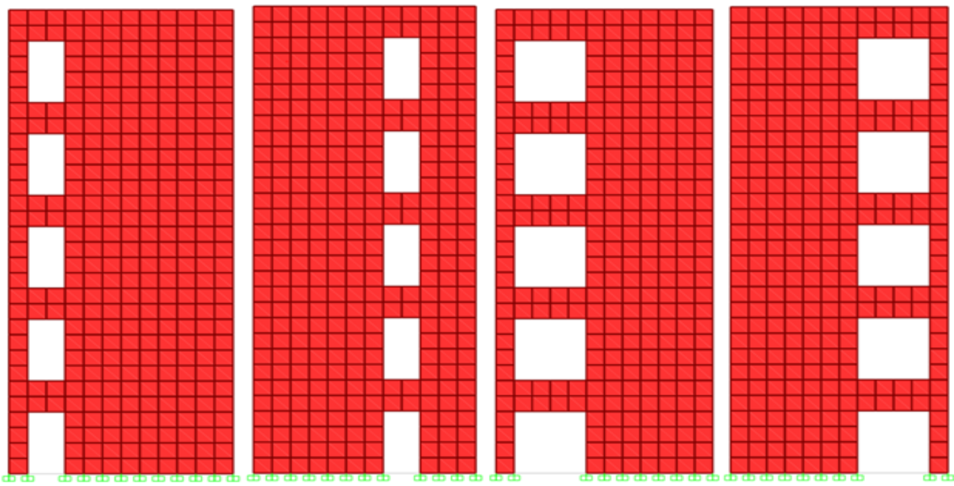

Fig. (6): - The vertical arrangement of openings sizes 1 and 2 for W2.

Table (2): - Natural Frequency of Rc Walls Without Opening (Hz)

Wall Length	NF1	NF2	NF3
4 m	0.731	4.570	5.718
6 m	0.733	3.986	4.578
8 m	0.734	3.111	4.582

Table (3): - Natural Frequency of the Rc Walls with The Ten Positions of Openings

Positions	4m Wall						6m Wall						8m Wall					
	2mx1m Opening			2mx2m Opening			2mx1m Opening			2mx2m Opening			2mx1m Opening			2mx2m Opening		
	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3
1	0.676	4.382	5.547	0.591	4.163	5.399	0.697	3.876	4.468	0.647	3.783	4.354	0.708	3.037	4.491	0.672	2.978	4.392
2	0.766	4.602	5.886	0.806	4.618	5.886	0.755	4.104	4.611	0.780	4.126	4.643	0.751	3.203	4.600	0.769	3.247	4.614
3	0.723	4.521	5.558	0.701	4.359	5.382	0.728	3.909	4.545	0.717	3.830	4.456	0.731	3.065	4.556	0.723	3.018	4.491
4	0.703	4.345	5.574	0.640	3.949	5.294	0.716	3.897	4.485	0.708	3.774	4.387	0.722	3.075	4.488	0.697	2.997	4.351
5	0.686	4.271	5.412	0.611	3.807	4.821	0.701	3.891	4.436	0.638	3.535	4.130	0.710	3.103	4.452	0.661	2.965	4.191
6	0.702	4.365	5.548	0.640	3.972	5.264	0.715	3.937	4.441	0.679	3.834	4.211	0.721	3.086	4.473	0.695	3.035	4.299
7	0.707	4.406	5.720	0.650	4.216	5.571	0.719	3.966	4.528	0.689	3.849	4.496	0.725	3.120	4.518	0.704	3.083	4.457
8	0.702	4.318	5.650	0.639	3.916	5.331	0.715	3.902	4.522	0.678	3.678	4.403	0.721	3.098	4.499	0.693	3.010	4.368
9	0.658	4.192	5.472	-	-	-	0.697	3.942	4.341	0.589	3.774	3.942	0.711	3.094	4.399	0.654	3.012	4.132
10	0.707	4.427	5.693	0.649	4.244	5.534	0.718	4.010	4.478	0.687	3.975	4.355	0.724	3.131	4.502	0.702	3.124	4.402

Table (4):- Natural Frequency Of The Rc Walls With The Horizontal Cases Of Openings

Floors	4m Wall						6m Wall						8m Wall					
	2mx1m Opening			2mx2m Opening			2mx1m Opening			2mx2m Opening			2mx1m Opening			2mx2m Opening		
	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3
First	0.600	4.181	5.331	0.593	4.182	5.444	0.598	3.808	4.189	0.518	3.628	4.014	0.546	2.869	4.065	0.465	2.802	3.916
Second	0.653	4.633	5.246	0.642	4.605	5.218	0.651	3.698	4.637	0.588	3.553	4.607	0.617	2.860	4.650	0.547	2.778	4.594
Third	0.707	4.418	5.460	0.701	4.359	5.382	0.707	3.797	4.407	0.676	3.720	4.204	0.693	2.950	4.318	0.653	2.890	4.070
Fourth	0.754	4.294	5.767	0.753	4.237	5.606	0.756	3.965	4.284	0.757	4.012	4.017	0.760	3.141	4.149	0.756	3.127	3.821
Fifth	0.806	4.644	6.019	0.806	4.629	5.783	0.808	4.106	4.649	0.838	4.294	4.634	0.832	3.332	4.662	0.856	3.376	4.612

Table (5): - Natural Frequency of the Rc Walls with The Vertical Cases of Openings

Edge Distance (m)	4m Wall						6m Wall						8m Wall					
	2mx1m Opening			2mx2m Opening			2mx1m Opening			2mx2m Opening			2mx1m Opening			2mx2m Opening		
	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3	NF1	NF2	NF3
0.5	0.693	4.338	5.541	0.625	3.913	4.966	0.709	4.011	4.429	0.672	3.850	4.191	0.717	3.154	4.471	0.691	3.115	4.300
1	0.693	4.340	5.288	0.625	3.921	4.795	0.709	3.892	4.430	0.671	3.670	4.197	0.717	3.098	4.472	0.691	3.012	4.306
1.5	0.693	4.340	5.211	0.625	3.913	4.966	0.708	3.814	4.430	0.671	3.574	4.199	0.716	3.053	4.473	0.690	2.938	4.310
2	0.693	4.340	5.288	-	-	-	0.708	3.769	4.430	0.671	3.544	4.200	0.716	3.019	4.473	0.690	2.890	4.312
2.5	0.693	4.338	5.541	-	-	-	0.708	3.754	4.430	0.671	3.574	4.199	0.716	2.996	4.473	0.690	2.862	4.313
3	-	-	-	-	-	-	0.708	3.769	4.430	0.671	3.670	4.197	0.715	2.983	4.473	0.690	2.853	4.313
3.5	-	-	-	-	-	-	0.708	3.814	4.430	0.672	3.850	4.191	0.715	2.978	4.473	0.690	2.862	4.313
4	-	-	-	-	-	-	0.709	3.892	4.430	-	-	-	0.715	2.983	4.473	0.690	2.890	4.312
4.5	-	-	-	-	-	-	0.709	4.011	4.429	-	-	-	0.716	2.996	4.473	0.690	2.938	4.310
5	-	-	-	-	-	-	-	-	-	-	-	-	0.716	3.019	4.473	0.690	3.012	4.306
5.5	-	-	-	-	-	-	-	-	-	-	-	-	0.716	3.053	4.473	0.691	3.115	4.300
6	-	-	-	-	-	-	-	-	-	-	-	-	0.717	3.098	4.472	-	-	-
6.5	-	-	-	-	-	-	-	-	-	-	-	-	0.717	3.154	4.471	-	-	-

4. CHANGES IN NATURAL FREQUENCY

A comparison was conducted between NF1, NF2, and NF3 for both walls without and with openings. This comparison aimed to assess the percentage change in frequencies, considering the size and location of each type. The percentage change in frequencies (f) was determined using (3), as previously used by Szczepanski, Manguri [19].

$$\%D = \frac{f_{oi-}f_i}{f_i} * 100, i = 1:3 \quad (3)$$

The f_{oi} shows the natural frequency of the wall with opening and f_i is the natural frequency of the wall without opening. The effect of the ten optional locations of both op1 and op2 is depicted in Figure. 7 for all three wall sizes. The maximum positive change observed was over 10%, recorded in W1 at the second location for op2 in the first natural frequency. This location represents the larger opening in the top left of the 4m wide wall. Conversely, the most significant negative impact was approximately 20%, recorded in the 6m wide wall in the same scenario, but this time at the 9th location. The 9th location represents the case of five openings in a single wall.

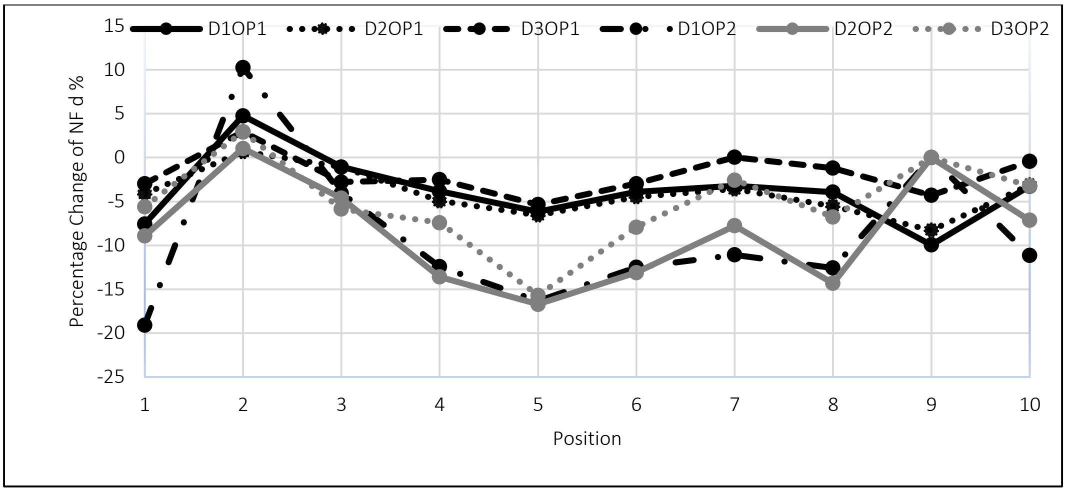

Fig. (7): - Changes in Natural Frequency for Wall 1 with optional openings.

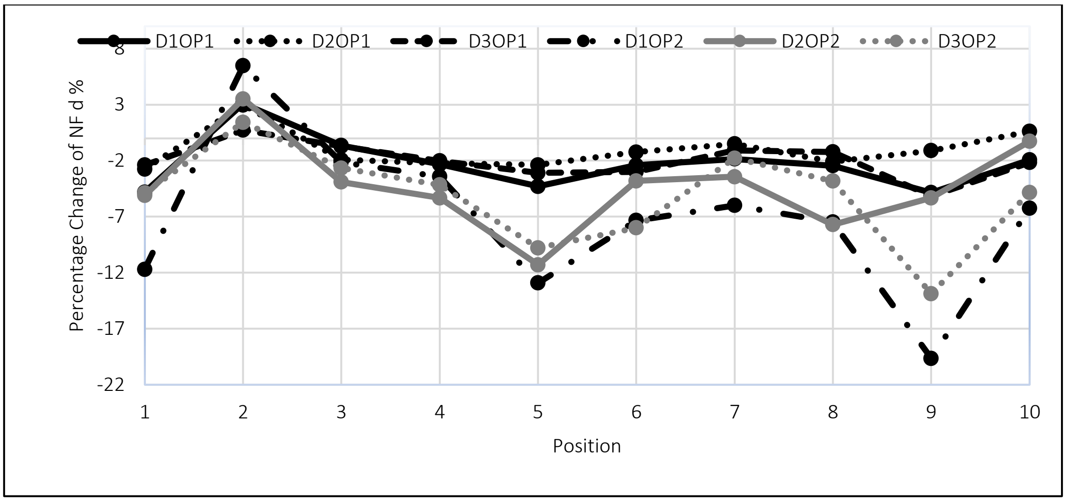

Fig. (8): - Changes in Natural Frequency for Wall 2 with optional openings.

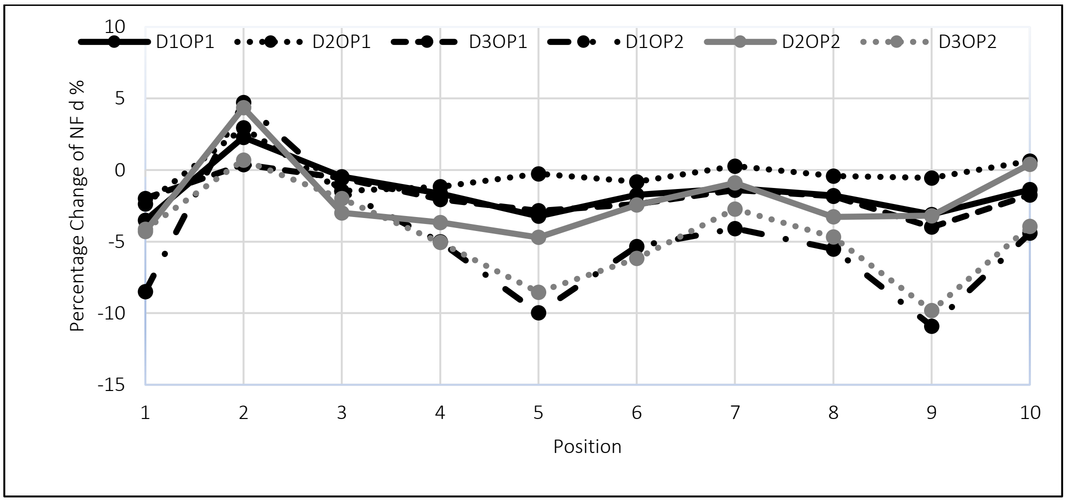

Fig. (9): - Changes in Natural Frequency for Wall 3 with optional openings.

Figures 10, 11 and 12 show the changes in natural frequencies of horizontal openings in 4m, 6m and 10m wide walls respectively. The same procedure as for optimal slots was conducted to determine the impact of openings on the natural frequencies of the walls in a horizontal arrangement. In this case, the most significant positive change was observed in W3 with op2 in the fifth story. The maximum increase was found in NF1, with an approximate effect of 17%. Conversely, the most significant decrease, exceeding 35%, was recorded for W3 in the first story in NF1, and this significant decrease occurred when using larger opening sizes. Most of the maximum decreases were observed in the lower stories when employing a horizontal arrangement, while the maximum increases were observed in the upper levels of the walls.

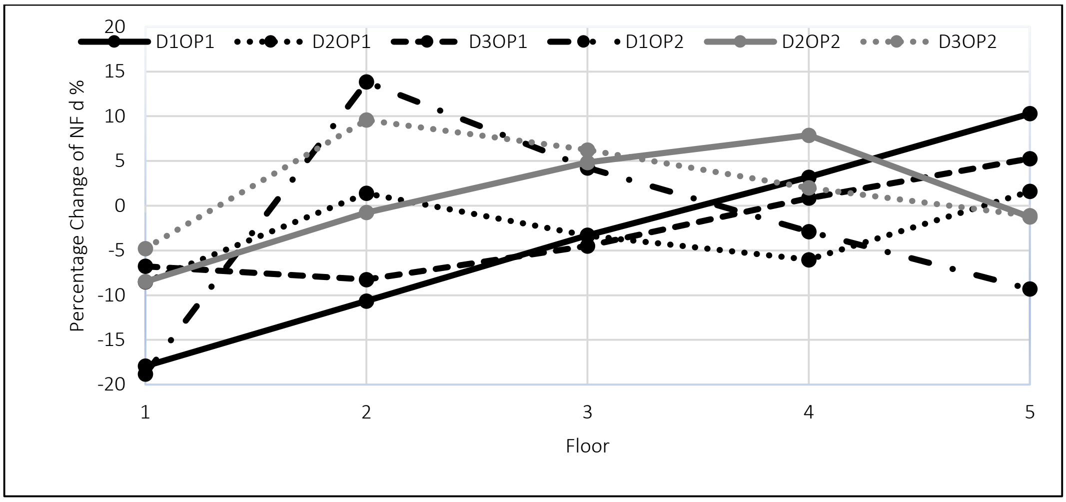

Fig. (10): - Changes in Natural Frequency for Wall 1 with horizontal openings.

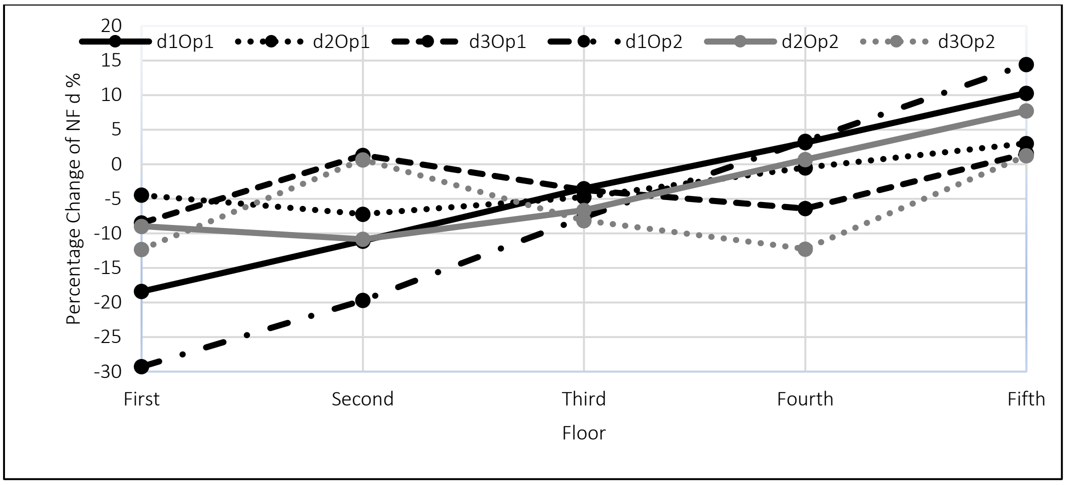

Fig. (11): - Changes in Natural Frequency for Wall 2 with horizontal openings.

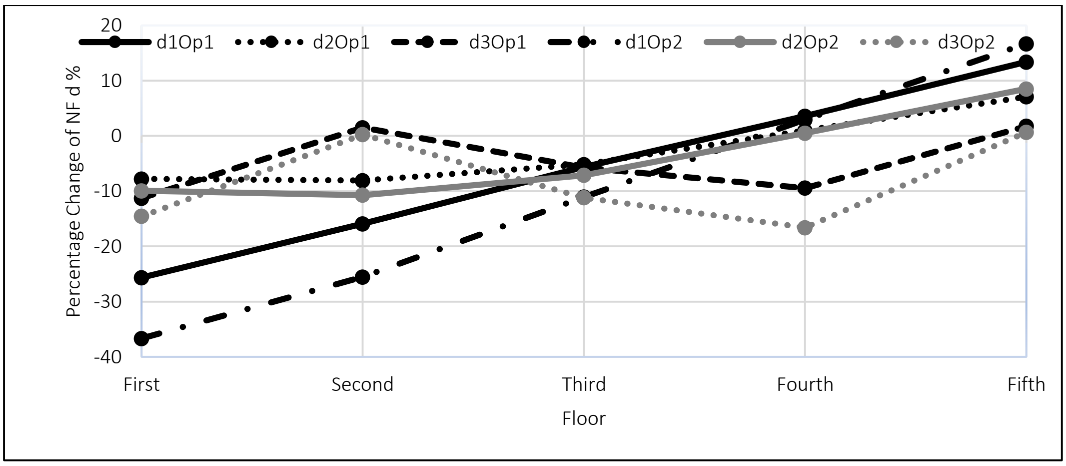

Fig. (12): - Changes in Natural Frequency for Wall 3 with horizontal openings.

Figures 13, 14 and 15 illustrate the fluctuation in the percentages of NF1, NF2, and NF3 for different opening sizes in the vertical arrangement for 4m, 6m, and 8m walls correspondingly. Most cases exhibit a linear trend, with minimal changes over time. However, some cases deviate from this pattern, displaying a curved form. In these instances, the frequencies experience an increase when the openings are positioned near the edges with the minimum and maximum edge distances. Conversely, the maximum decrease in frequencies is observed when the openings are located at the central positions of the wall. The results of Szczepanski, Manguri [19] also support our conclusions in terms of performance but in different amounts due to differences in materials and application methods on walls.

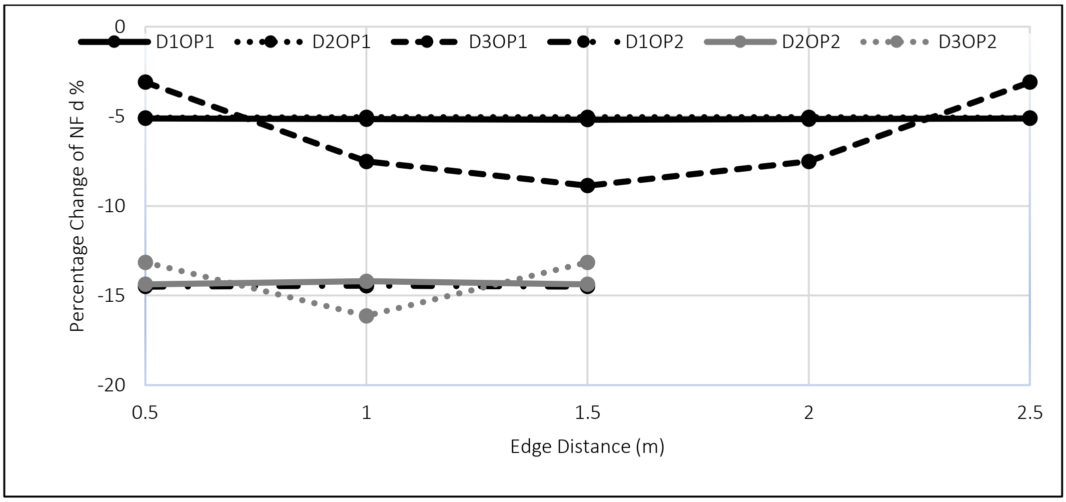

Fig. (13): - Changes in Natural Frequency for Wall 1 with vertical openings.

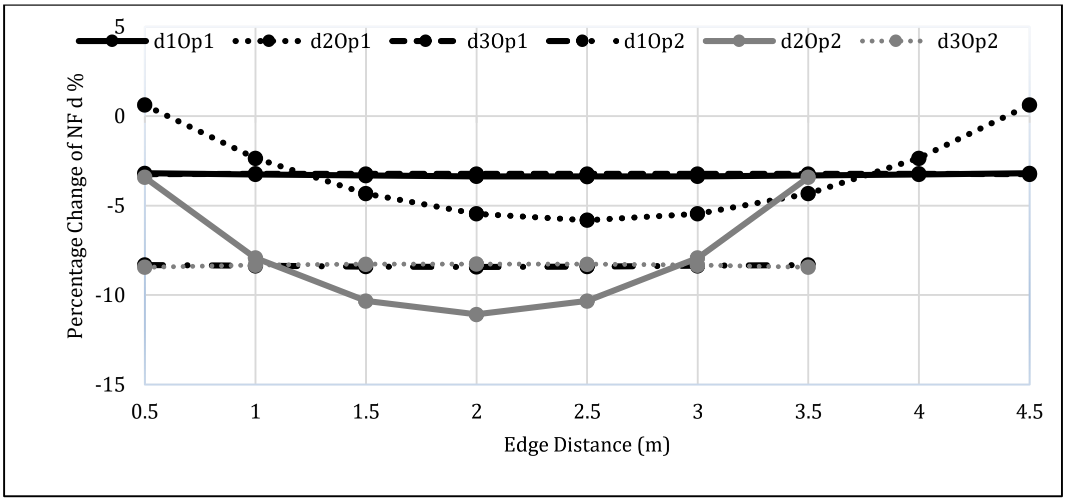

Fig. (14): - Changes in Natural Frequency for Wall 2 with vertical openings.

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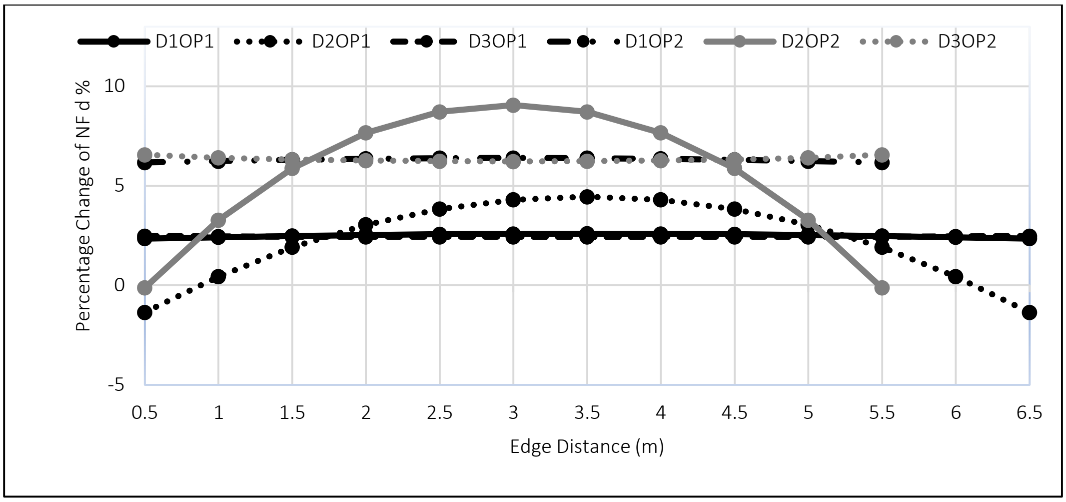

Fig. (15): - Changes in Natural Frequency for Wall 3 with vertical openings.

4. CONCLUSIONS

This paper determines the effect of the size and location of openings on the natural frequency of reinforced concrete walls using modal analysis. Different wall sizes are considered, and the following conclusions are drawn:

- The size of the walls affected the natural frequency due to variations in mass and stiffness.
- The opening size, location, and arrangement have positive and negative effects on the natural frequency of the walls.
- The study reveals a maximum increase of approximately 17% and a maximum decrease of about 37%, indicating that careful selection of locations can improve dynamic properties.
- Among the optional locations, the highest natural frequency is observed when the opening is in the top left. In contrast, the lowest natural frequency is recorded when the opening is simultaneously positioned at the bottom, center, and top of the wall.
- In terms of horizontally arranged openings, the top of the walls is the most favorable location for increasing the natural frequency. In contrast, the bottom of the walls poses the most significant risk, resulting in lower frequencies.
- vertical arrangement of openings have a lesser impact on altering the natural frequencies.
- For vertically oriented openings, the preferred locations for creating openings are the edges, as they yield higher frequencies. On the other hand, the least desirable location is the center of the walls.

REFERENCES

Jalali, A. and F. Dashti, "Nonlinear behavior of reinforced concrete shear walls using macroscopic and microscopic models." Engineering Structures, 32(9): p. 2959-2968. 2010, https://doi.org/10.1016/j.engstruct.2010.05.015

Abdullah, S.A., Reinforced concrete structural walls: Test database and modeling parameters. 2019: University of California, Los Angeles.

Nainan, N. and T. Alice, "Dynamic Response of seismo-resistant building frames." International Journal of Engineering Science and Technology, 4(5): p. 1865-1870. 2012,

Zainadeen, H., N. Saeed, and B. Haydar, "Optimum Location And Bracing System As Alternative To Shear Walls For Retrofitting Of RC Buildings Against Seismic Loading." The Eurasian Journal of Science and Engineering, 9(2). 2023, https://doi.org/10.23918/eajse.v9i3p6

Najm, H.M., et al., "Modelling of Cyclic Load Behaviour of Smart Composite Steel-Concrete Shear Wall Using Finite Element Analysis." 12(6): p. 850. 2022,

Hassan, A., et al., "Experimental test and finite element modelling prediction on geopolymer concrete beams subject to flexural loading." 7: p. 1-18. 2022,

Wang, K., et al., "Seismic analysis and design of composite shear wall with stiffened steel plate and infilled concrete." 15(1): p. 182. 2021,

Lin, C. and C. Kuo. "Behavior of shear wall with Opening". in Proceedings of ninth world conference on earthquake engineering. 2-9, 1988, (Conference proceedings)

Kim, H.-S. and D.-G.J.E.S. Lee, "Analysis of shear wall with openings using super elements." 25(8): p. 981-991. 2003,

Thakre, P., S. Jamle, and K. Meshram, "Opening Area

Effect of Shear Wall in Multistorey Building under Seismic Loading." International Journal of Advanced Engineering Research and Science,(ISSN: 2456-1908 (O), 2349-6495 (P)), 7(2): p. 122-129. 2020,

Fares, A.M.J.R.o.E.S. and Materials, "The impact of RC shear wall openings at the lateral stiffness of the cantilever shear walls." 7(1): p. 51-63. 2021,

Behfarnia, K. and A. Shirneshan, "A numerical study on behavior of CFRP strengthened shear wall with opening." Comput Concrete, 19(2): p. 179-189. 2017,

Saeed, A., et al., "A Comprehensive Study on the Effect of Regular and Staggered Openings on the Seismic Performance of Shear Walls." Buildings, 12(9): p. 1293. 2022, https://doi.org/10.3390/buildings12091293

Kale, P.B. and R. John, "The Effect Of Different Opening Configuration In Multi-Story Rc Building With Shear Wall." International Journal of Engineering Applied Sciences and Technology, ISSN, (2455-2143). 2019,

Balkaya, C. and E.J.J.o.s.e. Kalkan, "Three-dimensional effects on openings of laterally loaded pierced shear walls." 130(10): p. 1506-1514. 2004,

Alimohammadi, H., et al., "Effects of openings on the seismic behavior and performance level of concrete shear walls." 6(10): p. 34-39. 2019,

Sharma, R., J.A.J.J.o.M. Amin, and E.S. «JMES», "Effects of opening in shear walls of 30-storey building." 2(1): p. 44-55. 2015,

Yu, H.-J., et al., "Cyclic loading test of structural walls with small openings." 13(1): p. 1-14. 2019,

Szczepanski, M., et al., "The Effect of Openings' Size and Location on Selected Dynamical Properties of Typical Wood Frame Walls." J Polymers, 14(3): p. 497. 2022, https://doi.org/10.3390/polym14030497

Asteris, P.G., et al., "On the fundamental period of infilled RC frame buildings." Structural Engineering and Mechanics, 54(6): p. 1175-1200. 2015, https://doi.org/10.12989/sem.2015.54.6.1175

Ghanbari, A., E. Hoomaan, and M. Mojallal, "An analytycal method for calculating the natural frequency of retaining walls." International Journal of Civil Engineering, 11(1): p. 1-9. 2013,

LovaRaju, K. and D.K.J.I.A.R.J.S.E.T. Balaji, "Effective location of shear wall on performance of building frame subjected to earthquake load." 2(1). 2015,

Kankuntla, A., et al., "Effects of openings in shear wall." 13(1): p. 1-6. 2016,

Lin, Z., et al., "Effects of Openings and Axial Load Ratio on the Lateral Capacity of Steel-Fiber-Reinforced Concrete Shear Walls." 12(11): p. 2032. 2022,

Qamaruddin, M.J.B. and Environment, "In-plane stiffness of shear walls with openings." 34(2): p. 109-127. 1998,

Ciesielski, R., et al., "Empirical formulae for fundamental natural periods of buildings with load bearing walls." Archives of Civil Engineering, 38(4): p. 291-299. 1992,