

Chapter 4

Effect of size, shape and position of the opening on CBM walls

4.1 General Discussion

In building design, openings such as doors and windows are essential for providing natural light and ventilation, yet they have a considerable effect on the structural performance of masonry walls. These openings notably reduce both the strength and stiffness of the walls, making them more vulnerable to external forces. The in-plane response of masonry walls is particularly sensitive to the presence of openings, which can significantly weaken the overall structural integrity.

Although necessary for functional reasons, openings tend to decrease the load-bearing capacity and rigidity of masonry structures. Figure 4.1 illustrates a typical damage pattern seen in perforated walls during past seismic events [46]. The diagonal cracks shown in the figure are mainly the result of stress concentrations that occur around the corners of the openings. These localized stresses can initiate cracking and eventually lead to the failure of the masonry panels, making the walls less capable of withstanding lateral loads, such as those caused by earthquakes.

Several researchers have experimentally investigated the effect of openings on the in-plane

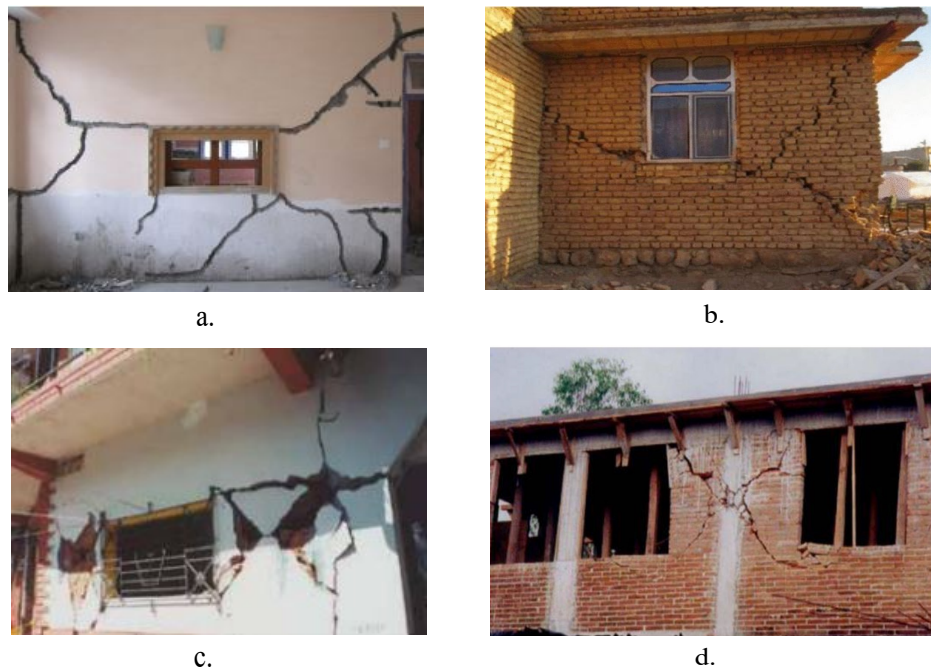


Figure 4.1: Typical damage to infill walls with openings observed during a. Sikkim, India (2011) earthquake [46], b. Sarpole Zahab, Iran (2017) earthquake [39], c. El-Salvador (2001) earthquake [5] and d. Oaxaca (1999) earthquake [135]

behaviour of masonry-infilled RC/steel frames [47], [49], [60], [61], [128]–[131]. Comprehensive reviews of these studies have been provided by Surendran and Kaushik [132] and Mohammadi and Nikfar [133]. The position and size of the openings can significantly reduce the lateral stiffness, strength, and energy dissipation capabilities of the infilled frames [130]. For example, Liauw [134] found that an opening covering 20-30% of the panel area could reduce its in-plane stiffness and strength by about 70-80% and 50-60%, respectively.

Research specifically focused on confined masonry walls with openings is limited. The experimental studies by Yáñez et al. [33] and Kuroki et al. [58] are among the few available. The location of openings can also adversely affect the load path, especially when they are present at either end of the loaded diagonal [47], [136]. Thus, openings should be strategically located to minimise interference with the diagonal load path. Some studies recommend placing openings at the center of the infill panel for optimal performance [47], [61], while Kakaletsis and Karayannis [130] suggest positioning openings near the edge of the infill. However, a comprehensive numerical analysis of how the shape, size, and positioning of window and door openings influence the ultimate strength, stiffness, and energy dissipation

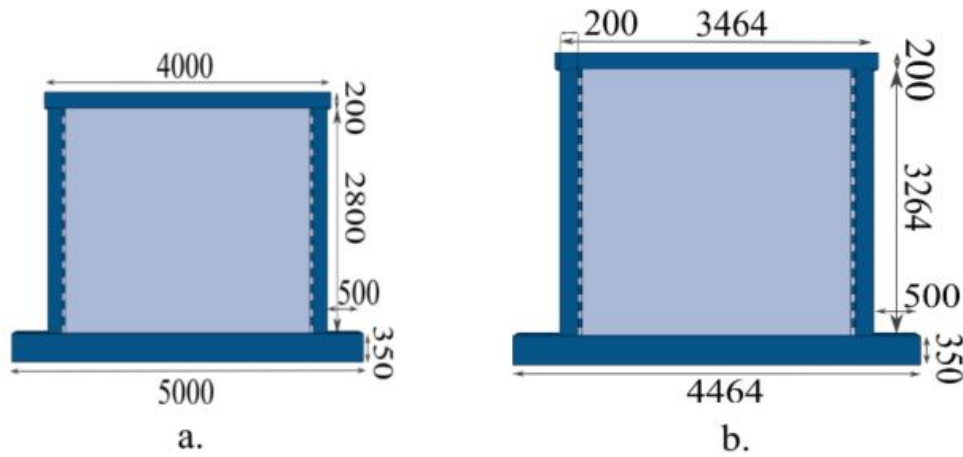


Figure 4.2: Dimensions of the wall considered in the study a. Rectangular wall (RW) with $AR=0.75$ and b. Square wall (SW) with $AR=1.0$

capabilities is crucial for understanding the seismic performance of the CBM walls. It is therefore imperative to establish a correlation between opening size and the ultimate strength of CBM walls and study the asymmetric positioning of openings.

4.2 Effect of opening shape and size in CBM walls

In this investigation, we comprehensively evaluate the effectiveness of CBM walls by analysing two distinct configurations: rectangular and square CBM walls, as illustrated in Figure 4.2. The rectangular walls are designed with an aspect ratio of 0.75, meaning their height is greater than their width by a ratio of 3:4. In contrast, the square walls have an aspect ratio of 1.0, indicating that their height and width are equal. Importantly, for the sake of a fair comparison, the square walls are designed to have an equivalent wall area to that of the rectangular walls.

To further explore the performance of these walls, each configuration is examined with centrally located window openings of varying shapes—either rectangular or square. The size of these window openings is systematically varied, ranging from 10% to 60% of the total masonry area of the wall panel. This variation allows us to assess how different sizes and shapes of openings affect the structural integrity and load-bearing capacity of CBM walls.

This investigation aims to provide a comprehensive understanding of how geometric configurations and window openings influence the overall behaviour of CBM walls when subjected

Table 4.1: Opening Sizes and percentage opening for rectangular wall

Wall-Opening Type	Opening size [$b \times h$] (mm)	Opening %	Opening case
RW – RO _(b)	1138.42 * 885.40	10%	RW – RO _(b) 1
	1609.97 * 1252.20	20%	RW – RO _(b) 2
	1971.80 * 1533.62	30%	RW – RO _(b) 3
	2276.84 * 1770.88	40%	RW – RO _(b) 4
	2545.58 * 1979.90	50%	RW – RO _(b) 5
	2788.55 * 2168.87	60%	RW – RO _(b) 6
RW – RO _(h)	885.40 * 1138.42	10%	RW – RO _(h) 1
	1252.20 * 1609.97	20%	RW – RO _(h) 2
	1533.62 * 1971.80	30%	RW – RO _(h) 3
	1770.88 * 2276.84	40%	RW – RO _(h) 4
	1979.90 * 2545.58	50%	RW – RO _(h) 5
	2168.87 * 2788.55	60%	RW – RO _(h) 6
RW – SO	1004 * 1004	10%	RW – SO1
	1419.86 * 1419.86	20%	RW – SO2
	1738.97 * 1738.97	30%	RW – SO3
	2007.98 * 2007.98	40%	RW – SO4
	2244.99 * 2244.99	50%	RW – SO5
	2459.27 * 2459.27	60%	RW – SO6

RW- Rectangular wall, RO_(b)- Rectangular opening with width > height, RO_(h)- Rectangular opening with height > width, SO- Square opening.

to various loading conditions. By examining different configurations and opening arrangements, the study seeks to uncover the key factors that impact the structural response of CBM walls, offering detailed insights into how these variables affect their performance, strength, and resilience under different types of loads. By systematically varying the aspect ratios and window opening sizes, this study aims to identify the most effective designs and construction techniques that enhance the structural performance and resilience of CBM walls. This methodical approach allows the investigation to pinpoint the critical factors that influence stability, strength, and durability. As a result, the study offers valuable insights into the key parameters that contribute to the improved behaviour of CBM walls, ultimately providing guidance on optimal practices for designing and constructing these structures to achieve maximum performance and longevity.

Table 4.2: Ultimate strength and stiffness for all opening sizes of rectangular wall

Opening Case	Ultimate strength (kN)	Stiffness (MN/m)
RW (no opening)	324.1	78.4
RW – RO _(b) 1	200.18	35.38
RW – RO _(b) 2	178.37	18.84
RW – RO _(b) 3	136.18	14.10
RW – RO _(b) 4	105.36	8.76
RW – RO _(b) 5	81.44	5.47
RW – RO _(b) 6	60.00	3.60
RW – RO _(h) 1	225.54	28.24
RW – RO _(h) 2	186.22	18.64
RW – RO _(h) 3	139.50	14.29
RW – RO _(h) 4	108.52	9.46
RW – RO _(h) 5	82.21	6.99
RW – RO _(h) 6	66.20	5.16
RW-SO1	212.47	31.95
RW-SO2	178.85	19.77
RW-SO3	138.87	13.57
RW-SO4	107.24	9.57
RW-SO5	81.88	6.44
RW-SO6	65.04	4.31

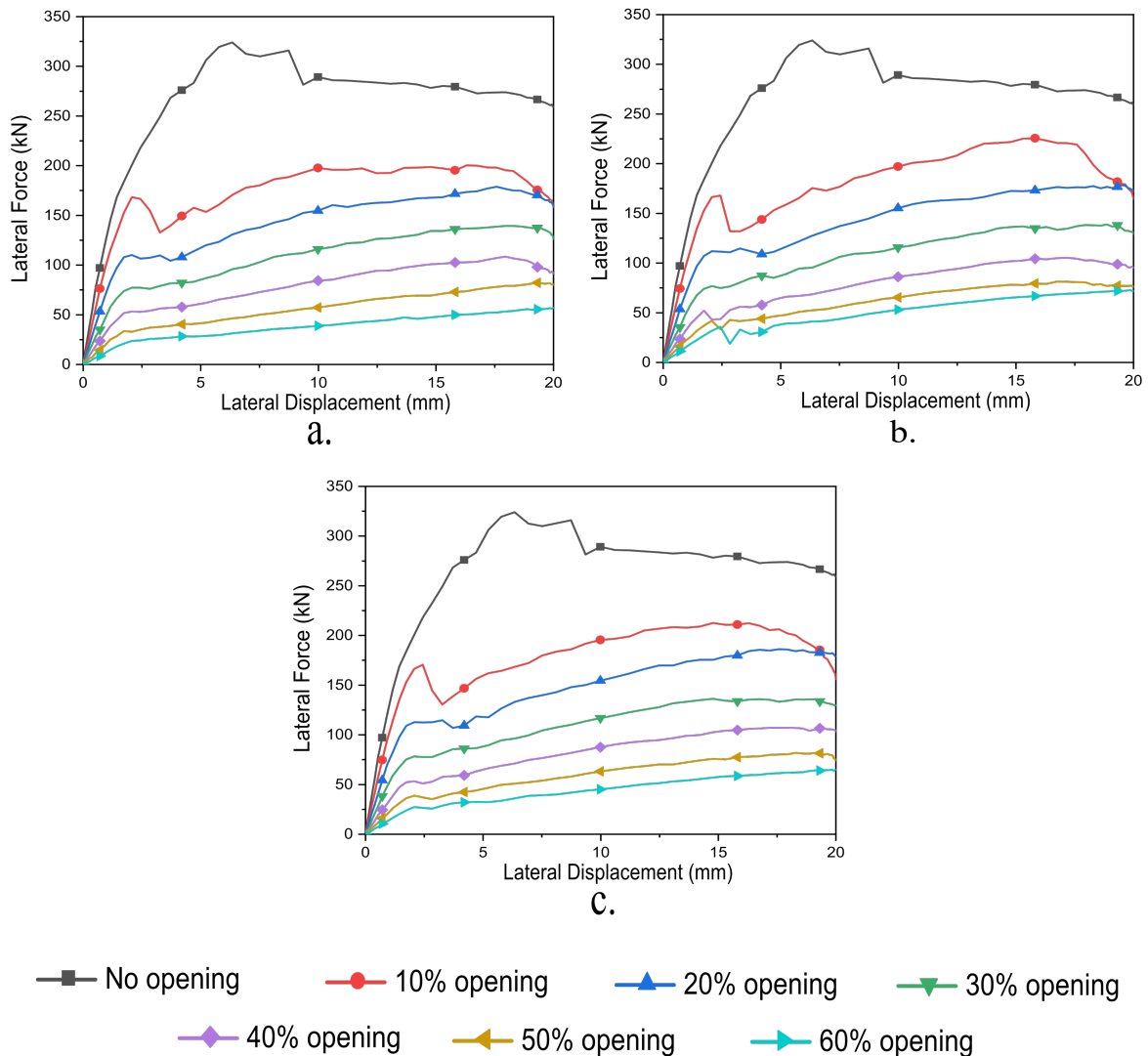


Figure 4.3: Pushover curve in rectangular wall for a. RW – RO_(b) b. RW – RO_(h) and, c. RW-SO

4.2.1 Effect of shape and size of the window opening on the CBM wall

a. Rectangular wall (RW)

This study investigates the response of rectangular and square window openings placed at the centre of the rectangular CBM wall. The dimension of the openings are specified in Table 4.1 where, RW refers as rectangular wall, RO_(b) stands for rectangular opening in which width is greater than height, RO_(h) refers as rectangular opening in which height is greater than width and SO stands for square opening. Pushover analyses are conducted on different models featuring window opening of varying shape and size in the rectangular CBM wall. The pushover curve obtained are presented in Figure 4.3. The calculated ultimate strength,

and stiffness of the FE models have been presented in Table 4.2.

It is observed that for the RW – RO_(h), the ultimate strength reduction ranges between 30.4% and 79.5% when the openings ranging from 10% to 60% are introduced. Similarly, for the RW-SO and RW – RO_(b) models, the ultimate strength decreased from 34.44% to 79.9% and from 38.23% to 81.5%, respectively.

Additionally, it have been observed that introducing opening of 10% to 60% decreases the stiffness by 54.9% to 95.4%, 59.25% to 94.5%, and 63.9% to 93.4% for RW – RO_(b), RW-SO, and RW – RO_(h) models, respectively.

Table 4.3: Opening Sizes and percentage opening for SW wall

Opening Type	Opening size [b^*h] (mm)	Opening %	Opening case
SW – RO _(b)	1134 * 882	10%	SW – RO _{(b)1}
	1603.7 * 1247.3	20%	SW – RO _{(b)2}
	1964.1 * 1527.6	30%	SW – RO _{(b)3}
	2268 * 1764	40%	SW – RO _{(b)4}
	2535.6 * 1972.2	50%	SW – RO _{(b)5}
	2777.7 * 2160.4	60%	SW – RO _{(b)6}
SW – RO _(h)	882 * 1134	10%	SW – RO _{(h)1}
	1247.3 * 1603.7	20%	SW – RO _{(h)2}
	1527.6 * 1964.1	30%	SW – RO _{(h)3}
	1764 * 2268	40%	SW – RO _{(h)4}
	1972.2 * 2535.6	50%	SW – RO _{(h)5}
	2160.4 * 2777.7	60%	SW – RO _{(h)6}
SW – SO	1000 * 1000	10%	SW – SO1
	1414.3 * 1414.3	20%	SW – SO2
	1732.2 * 1732.2	30%	SW – SO3
	2000 * 2000	40%	SW – SO4
	2236.2 * 2236.2	50%	SW – SO5
	2449.7 * 2449.7	60%	SW – SO6

b. Square wall (SW)

In this section, a square CBM wall is considered to study the effect of opening shape and size. The area of the square wall is equivalent to the rectangular wall, as shown in Figure 4.2 b. Detailed dimensions of the opening in the CBM wall have been shown in Table 4.3 where, SW stands for square wall with an equivalent wall area to rectangular wall (RW), $RO_{(b)}$ stands for rectangular opening in which width is greater than height, $RO_{(h)}$ stands for rectangular opening in which height is greater than width and SO stands for square opening.

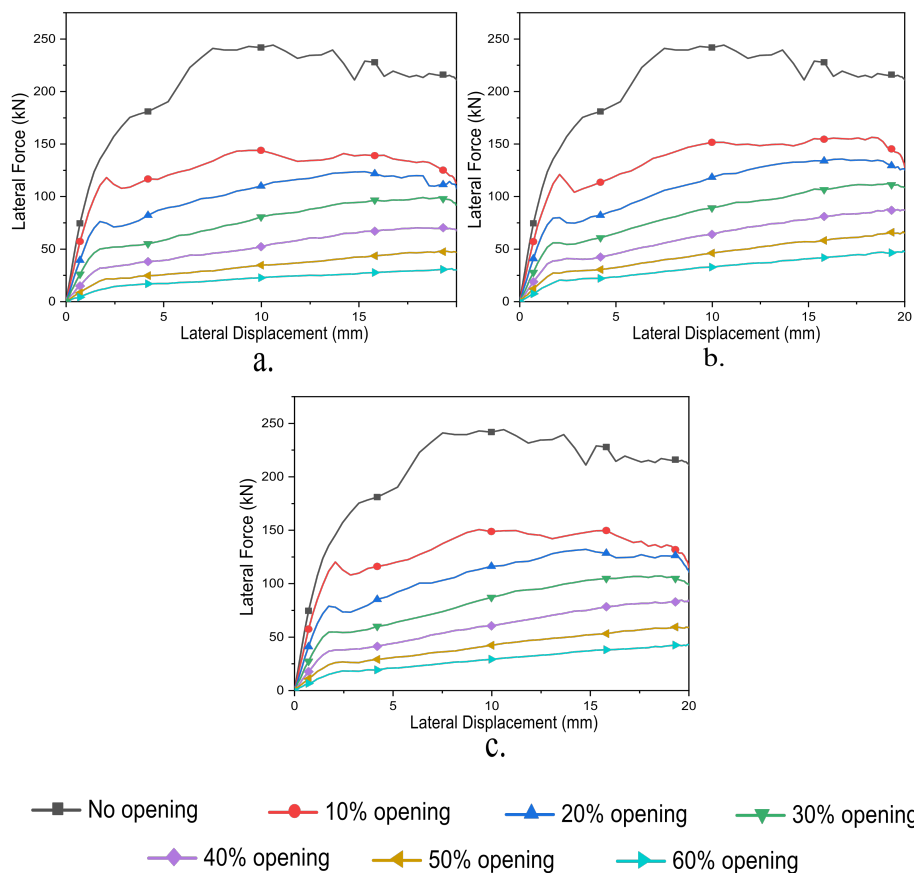


Figure 4.4: Pushover curve in square wall for a. SW – $RO_{(b)}$ b. SW – $RO_{(h)}$ and, c. SW – SO

The results of the pushover analyses are presented in Figure 4.4. Table 4.4 presents ultimate strength, and stiffness. The study's findings indicate that when openings ranging from 10% to 60% are introduced in the SW – $RO_{(h)}$ model, the ultimate strength decreased between 33.33% and 83.01%. Similarly, the ultimate strength of the SW-SO and SW – $RO_{(b)}$ models decreased by 34.04 to 84.04% and 38.5 to 89.13%, respectively. The study found that introducing openings ranging from 10% to 60% decreased the stiffness by 30 to 96.4%, 44.2 to

Table 4.4: Ultimate strength and stiffness for all opening sizes of SW wall

Opening Case	Ultimate strength (kN)	Stiffness (MN/m)
SW (no opening)	249.40	48.90
SW – RO _(b) 1	153.2	34.2
SW – RO _(b) 2	126.74	14.34
SW – RO _(b) 3	100.02	7.7
SW – RO _(b) 4	66.9	4.8
SW – RO _(b) 5	43.3	2.73
SW – RO _(b) 6	27.1	1.76
SW – RO _(h) 1	166.4	26.62
SW – RO _(h) 2	137.6	13.83
SW – RO _(h) 3	108.5	9.2
SW – RO _(h) 4	82.04	5.74
SW – RO _(h) 5	61.1	4
SW – RO _(h) 6	42.35	2.8
SW-SO1	164.5	27.3
SW-SO2	133.9	14.9
SW-SO3	106.8	9.2
SW-SO4	78.9	5.74
SW-SO5	56.4	3.53
SW-SO6	39.8	2.4

95.1% and 45.56 to 94.3% for the SW – RO_(b), SW-SO and SW – RO_(h) model respectively.

As expected, the ultimate strength of the wall decreases as the opening size increases, although the drop rate varies with individual cases. This reduction in ultimate strength can be attributed to the stress concentration around openings, which weakens the overall structural integrity. Figure 4.5, 4.6 shows the normalised ultimate strength of the walls for all opening shapes and increasing opening sizes. For the rectangular wall, as observed from Figure 4.5, it is noted that for 10% of the opening size, the decrease is highest in the rectangular opening in which the width is greater than the height (RO_(b)). Also, the decrease in ultimate strength is similar for 30%, 40%, 50%, and 60% opening sizes. For square wall, it is observed from Figure 4.6 that for different opening percentages, the decrease in ultimate strength is similar for the SO and RO_(h).

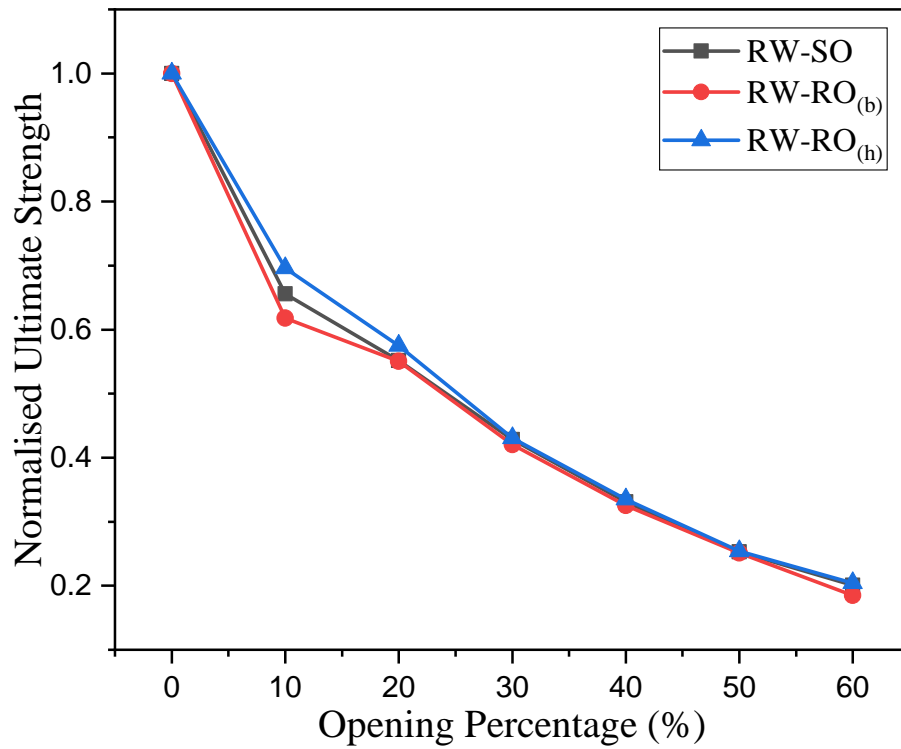


Figure 4.5: Normalised ultimate strength versus opening percentage for rectangular wall RW

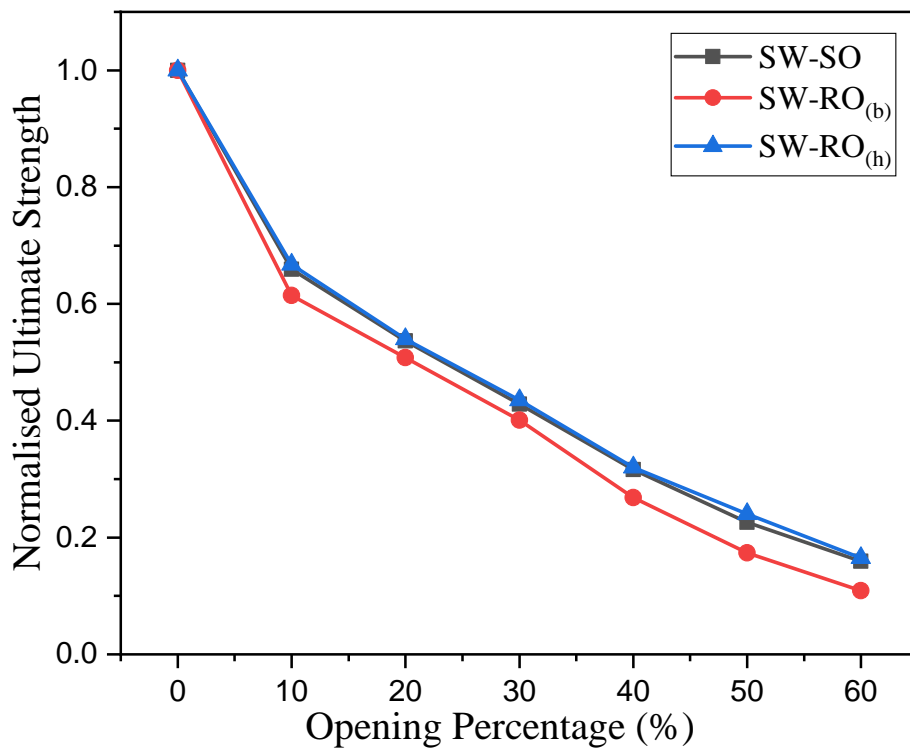


Figure 4.6: Normalised ultimate strength versus opening percentage for square wall SW

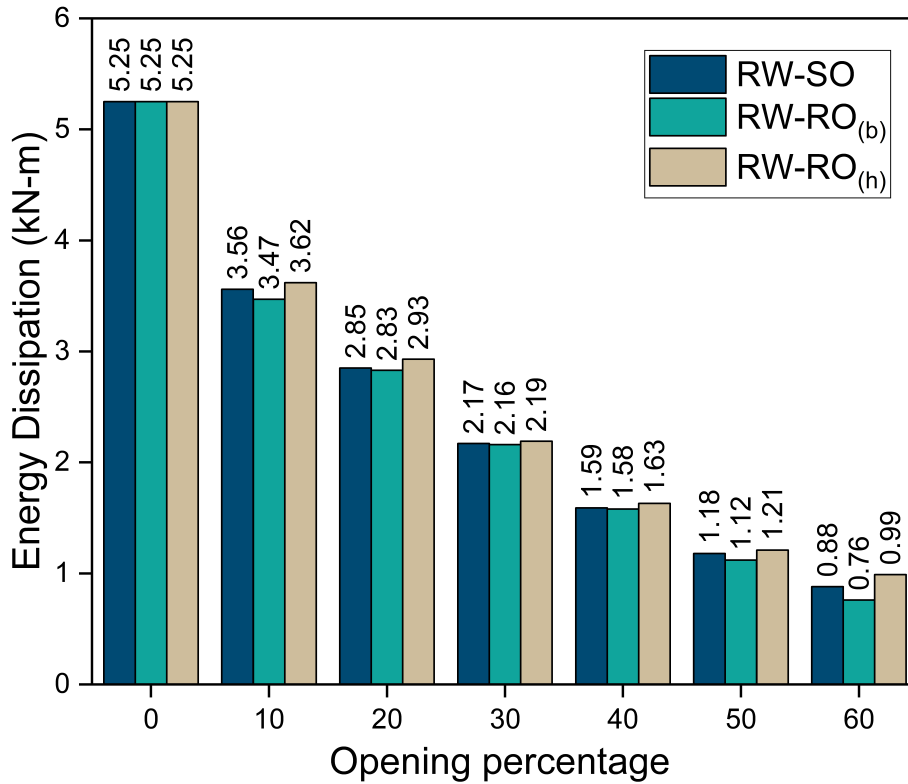


Figure 4.7: Energy dissipation in rectangular wall (RW) with variation of increased opening percentage

Figure 4.7, 4.8 compares the energy dissipation for the walls with all the opening shapes and sizes considered in this study. As the opening percentage increases, the energy dissipation of the CBM wall decreases. This decrease in energy dissipation clearly indicates that as the size of the opening increases, the structural capacity to mitigate seismic forces diminishes.

The impact of the opening size on the load path is particularly significant, as demonstrated by the stress contours in Figure 4.9. Comparing infill panels with and without openings of different sizes, it becomes evident that the size of the opening has a direct influence on the development of the diagonal compression strut mechanism (Borah et al. [137]). As the opening size increases, the ability of the diagonal compression strut mechanism to effectively distribute and withstand the applied load diminishes.

From Figure 4.9, it is visible that for 10% opening, the compression strut mechanism is not fully diminished, whereas, for 20% and 40%, the mechanism is not visible at all. According to the IS Code for confined masonry and a few literature's [138], [139] openings in the CBM wall are subdivided into two groups: a. small opening (i.e. area of opening $\leq 10\%$) and

b. large opening (i.e. area of opening > 10%). Therefore, this investigation indicates that smaller openings promote the development and efficiency of the diagonal compression strut mechanism, keeping intact the walls overall structural integrity and strength. Conversely, larger openings compromise the lateral load-bearing strength of the wall system, rendering it less capable of handling structural stresses.

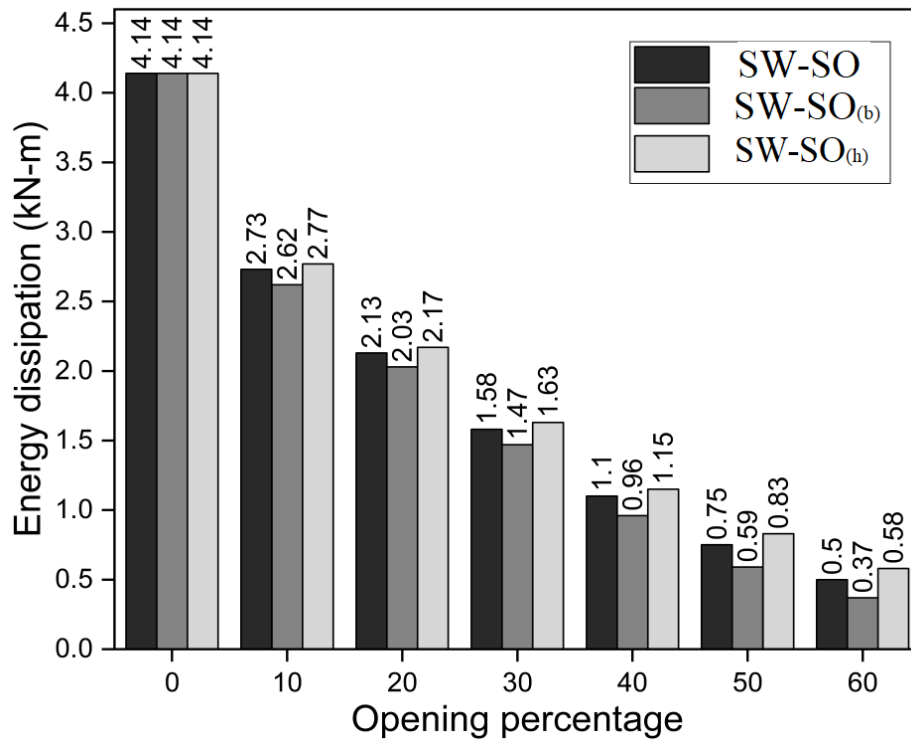


Figure 4.8: Energy dissipation in Square wall (SW) with variation of increased opening percentage

Furthermore, comprehensive observations indicate that for both wall types (RW and SW), the ultimate strength reaches its peak when the opening shape is RO_(h). Conversely, the ultimate strength is at its lowest when the opening shape is RO_(b). These results underscore the significant impact that both the shape and size of the openings have on the wall's ultimate strength and load-carrying capacity. The findings illustrate that the geometry of the openings plays a crucial role in influencing the structural performance of the walls, highlighting the importance of carefully considering these factors in the design process.

Several researchers have studied the effect of openings on the ultimate strength of CBM walls. To facilitate a comprehensive comparison, Table 4.5 summarises the findings from past literature alongside the results of the current study. Furthermore, Figure 4.10 illustrates

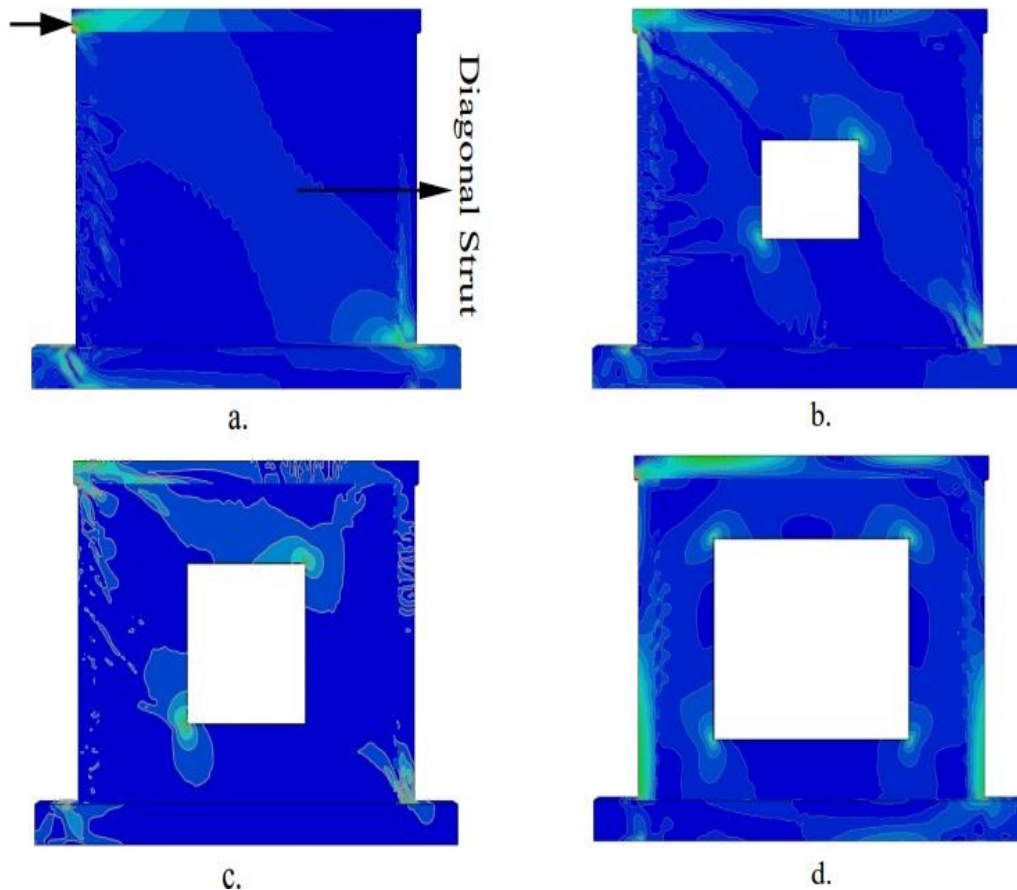


Figure 4.9: Stress contour plots of CBM wall with a. Solid infill panel, b. 10% opening, c. 20% opening and d. 40% opening.

the relationship between normalised ultimate strength and opening percentage. This plot clearly shows that the results from both previous research and the present study exhibit a consistent trend, reinforcing the validity and reliability of the observed patterns.

4.2.2 Co-relation between window opening percentage and ultimate strength

In accordance with the preceding section, it is conclusively determined that the opening within the CBM wall necessitates subdivision into two distinct categories: small and large openings. Consequently, it is imperative to formulate distinct correlations between the percentage of opening and the ultimate strength, addressing each category independently. In this study, we focus solely on square openings in both walls i.e. RW and SW. For smaller openings (with an area $\leq 10\%$), the dimensions and the observed ultimate strength is shown

Table 4.5: Ultimate strength obtained from existing studies and present study for opening percentages

Study	Specimen	Opening size		Opening %	Ultimate strength (kN)
		b (mm)	h (mm)		
Yanez et al. (2004)	Concrete pattern 1	0	0	0	123.5
	Concrete pattern 2	830	1230	12	120.75
	Concrete pattern 3	650	2050	16	101.75
	Concrete pattern 4	2060	1230	31	78.00
Singhal and Rai (2018)	SI	0	0	0	84.25
	SC-ODWB	500	1100	15	63.85
	SI-O2WA	1020	620	17	52.40
Okail (2016)	CLY S-CTRL	0	0	0	230
	CLY P-W	530	710	7	190
	CLY P-D	530	1690	17	130
Qin (2021)	S1	0	0	0	466.28
	O1	1000	1550	16	360.76
	O2	1000	2100	21	352.21
	O3	1500	1550	24	274.76
Kuroki (2012)	CMWO-07	0	0	0	79.70
	CMWO-05	430	560	9	63.72
	CMWO-11	430	1200	20	49.13
Present Study	RW – RO _(b)	As per the data provided in Table 2 and 4 of the present study			
	RW – RO _(h)				
	SW – RO _(b)				
	SW – RO _(h)				

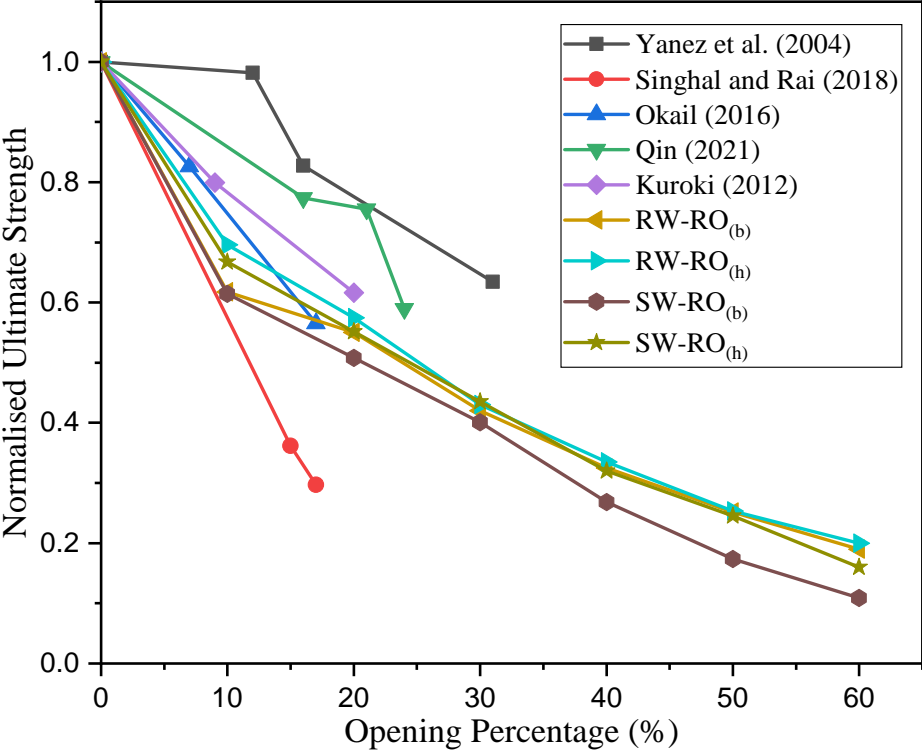


Figure 4.10: Comparing past and present studies on the effect of opening percentage on ultimate strength of CBM walls with openings.

in Table 4.6. For larger openings (with an area greater than 10%), the square opening dimensions and their corresponding ultimate strength is shown in Table 4.3, 4.4.

Extensive parametric studies were conducted using FE models to investigate the impact of opening size on ultimate strength in CBM walls. These studies involved analysing both large and small openings, while keeping all other variables constant to isolate the effect of opening size. By systematically varying the dimensions of the openings, we gained a thorough understanding of how changes in opening size influence the ultimate strength of CBM walls, providing valuable insights into the structural implications of different opening configurations.

To explain the effect of openings on the structural performance, a detailed analysis of the data is performed by plotting the ratio ' α ', which represents the ultimate strength of the CBM wall with various opening sizes compared to that of a solid CBM wall, against ' β ', which denotes the percentage of the opening. This method allows us to visually assess how variations in opening sizes and percentages influence the ultimate strength of the walls, faci-

Table 4.6: Opening size dimension and ultimate strength for small opening

Opening Type	Opening Size	Opening %	Ultimate strength (kN)
RW-SO	317.5 * 317.5	1%	320.2
	449 * 449	2%	311.8
	549.9 * 549.9	3%	297.8
	635 * 635	4%	269.3
	709.9 * 709.9	5%	238.4
	777.7 * 777.7	6%	219.2
	840 * 840	7%	216.4
	898 * 898	8%	213.9
	952.5 * 952.5	9%	213.1
	1004 * 1004	10%	212.47
SW-SO	316.2 * 316.2	1%	246.6
	447.2 * 447.2	2%	235
	547.8 * 547.8	3%	220.7
	632.5 * 632.5	4%	201.4
	707.2 * 707.2	5%	182.2
	774.7 * 774.7	6%	173.4
	836.7 * 836.7	7%	167.6
	894.5 * 894.5	8%	166.1
	948.8 * 948.8	9%	165.7
	1000 * 1000	10%	164.5

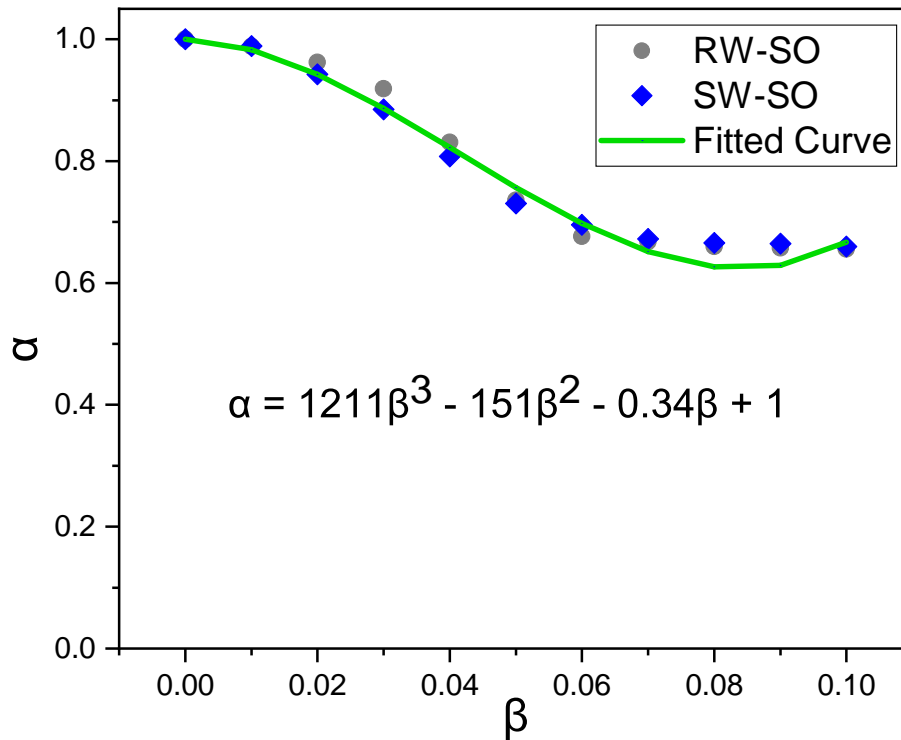


Figure 4.11: Effect of 0-10 percent opening on ultimate strength reduction of CBM wall

tating a clearer understanding of their impact on structural performance. A precise non-linear regression model for small opening and linear regression model for large opening to fit the numerical data have been used, as depicted in Figure 4.11, 4.12. For the large opening, the graph clearly demonstrates that as the opening size increases, there is a linear reduction in the ultimate strength of the solid specimen. However, it is essential to note that this correlation specifically pertains to square openings. Equation 4.1 is for small openings (with an area $\leq 10\%$) and Equation 4.2 is for large opening (with an area greater than 10%) in the CBM wall.

For small opening:

$$\alpha = 1211\beta^3 - 151\beta^2 - 0.34\beta + 1 \quad (4.1)$$

For large opening:

$$\alpha = -\beta + 0.74 \quad (4.2)$$

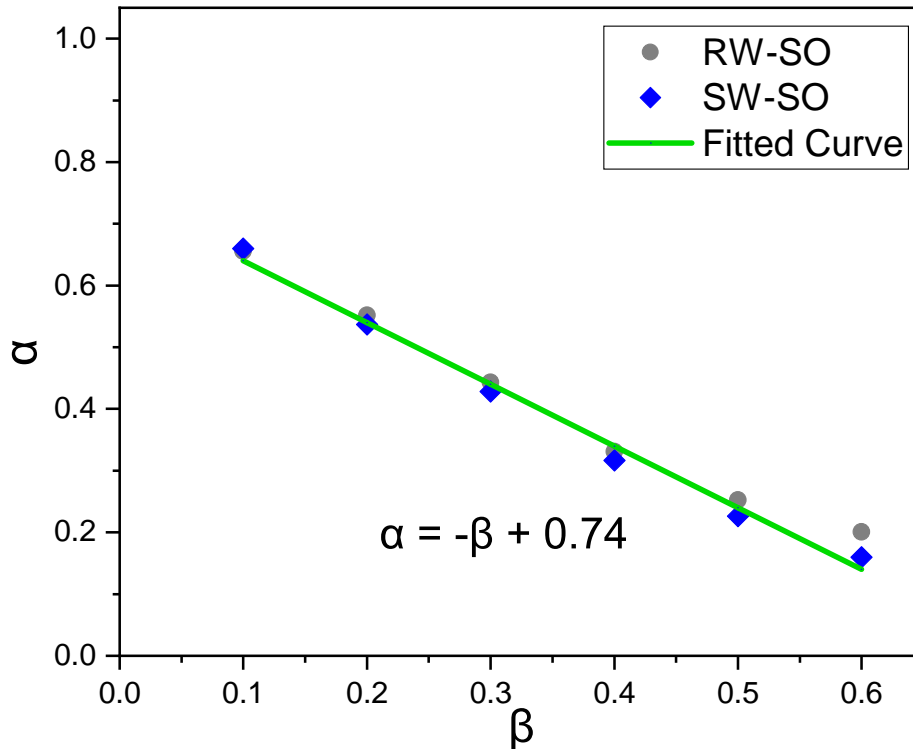


Figure 4.12: Effect of 10-60 percent opening on ultimate strength reduction of CBM wall

4.3 Effect of the position of opening in CBM wall

The position of openings in a confined brick masonry (CBM) wall has a significant impact on the wall's failure mechanism, often leading to localised failure that compromises the overall structural integrity. As a result, this study aims to evaluate how different opening positions affect the failure mechanisms of CBM walls, which is crucial for designing and constructing safe and resilient buildings.

To achieve this, we consider various positions for windows and doors both independently and in combination, and analyse them using displacement-based pushover analysis. This method enables us to assess the effects of localised failures and evaluate the overall integrity of the wall under different loading conditions.

In the following sections, we present a detailed discussion of our investigation into these opening positions and their impact on the performance of CBM walls.

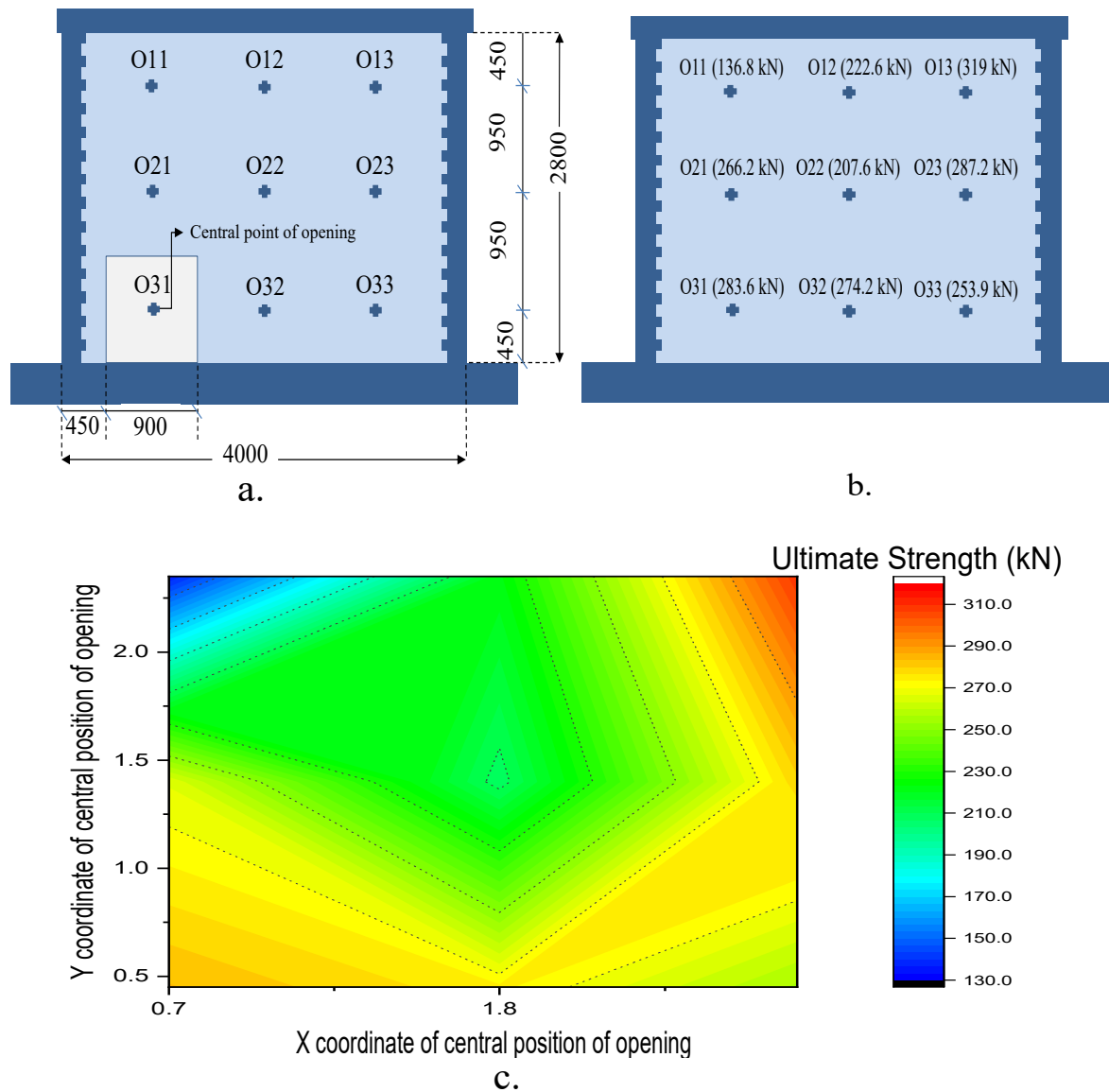


Figure 4.13: a. Window position considered b. Ultimate strength at different window position and c. contour plot for walls ultimate strength.

4.3.1 Effect of window opening positions in CBM walls

This study explores the effect of window opening positions on the ultimate strength of the CBM walls. The dimension of the window opening is considered to be 900*900 mm, which is 10% of the masonry area of the CBM wall, and its position is changed accordingly, as illustrated in Figure 4.13 a.

Initially, pushover analysis is conducted to examine the ultimate strength of the CBM wall for all nine opening positions. Figure 4.13 b, illustrates the values of ultimate strength, and Figure 4.14 presents the energy dissipation in the CBM wall for all window opening positions.

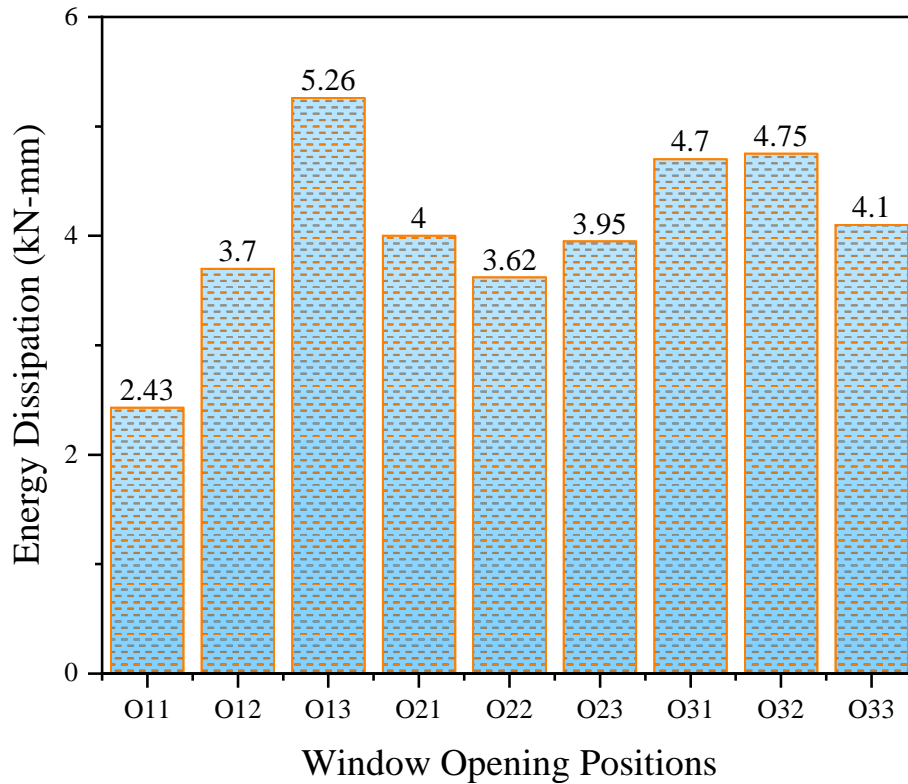


Figure 4.14: Energy dissipation due to window positions in a CBM wall.

The ultimate strength and energy dissipation increases as the opening position moves from O11 to O13, O11 to O31, and O11 to O33. This increase is attributed to the position of O11, which is near the loading point, preventing proper load propagation in the masonry and consequently requiring the RC-tie member to bear the load. It is also worth noting that as the opening position is shifted away from the loading point, the ultimate strength of the CBM wall improves.

To further explain the effect of opening positions on the ultimate strength of the CBM wall, contour plots (Figure 4.13 c) are generated based on the data of all the cases considered. Additionally, these plots enable comparing the wall's ultimate strength for the opening positions and identifying the position that yields the highest strength.

The study also assessed the maximum tensile damage (DAMAGET) in the CBM wall due to opening positions, with red indicating complete damage and blue showing no damage, as illustrated in Figure 4.15. Greater damage occurs in the RC components when the opening position intersects the loading diagonal.

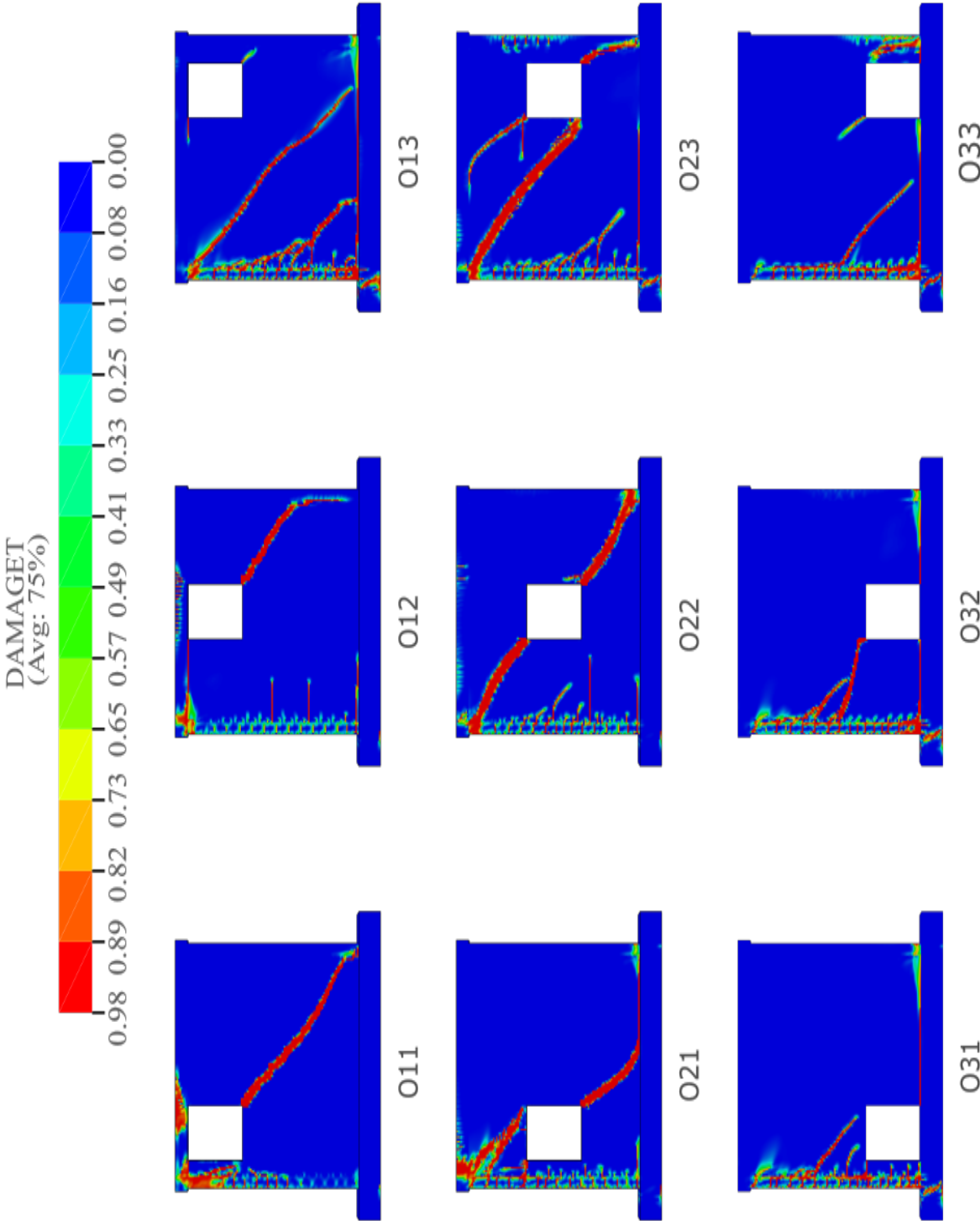


Figure 4.15: Damage propagation for window opening positions in CBM wall.

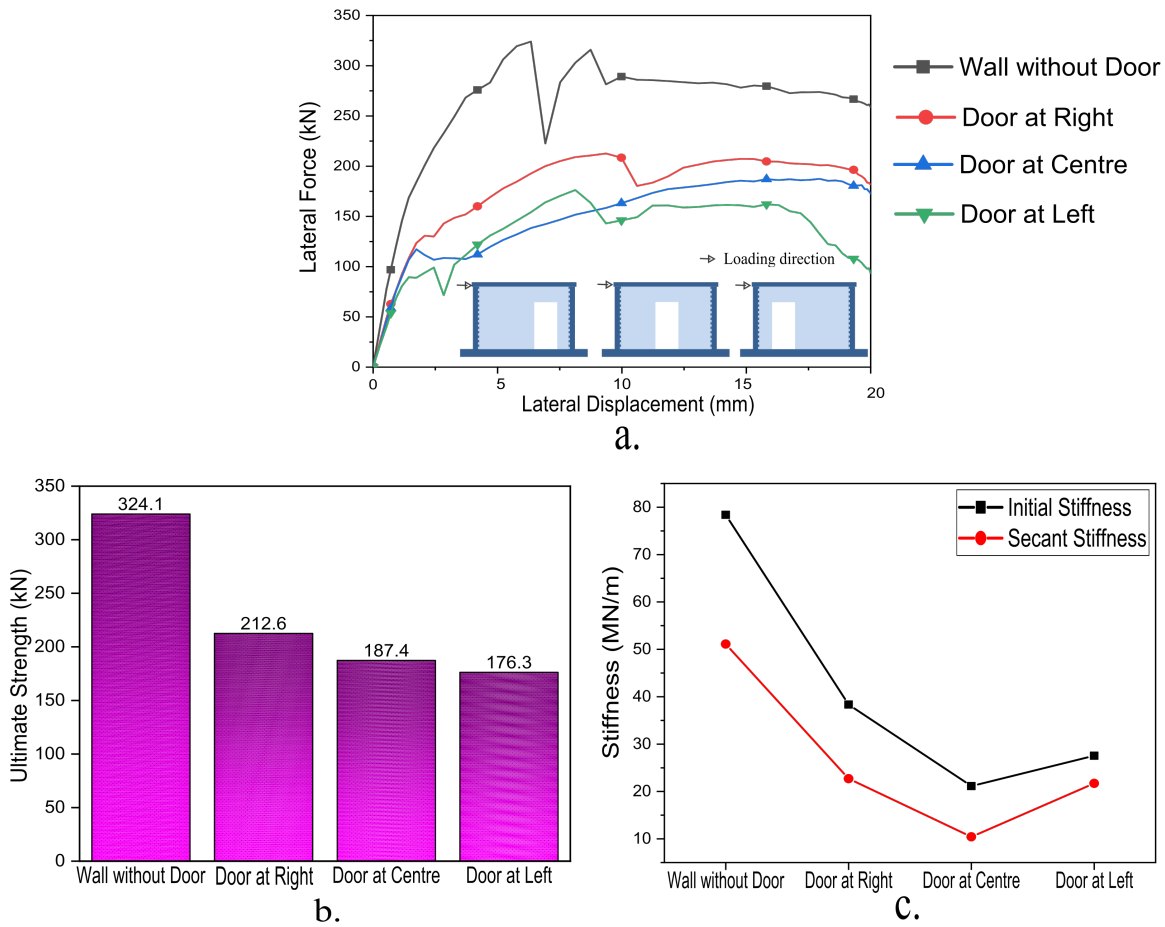


Figure 4.16: Door (900*2100 mm) opening position in a CBM wall a. Pushover Curve b. Ultimate strength and c. Stiffness.

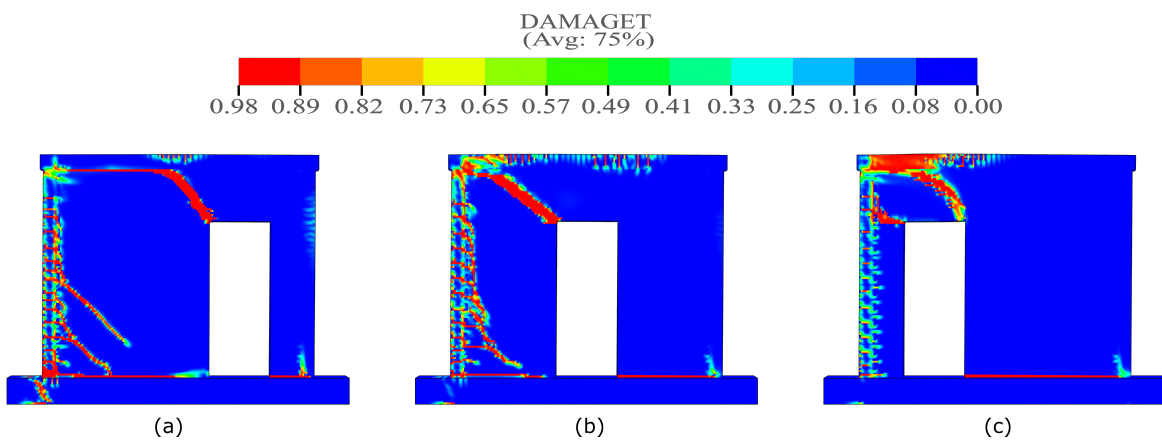


Figure 4.17: Damage propagation for a. Door at right, b. Door at centre, c. Door at left.

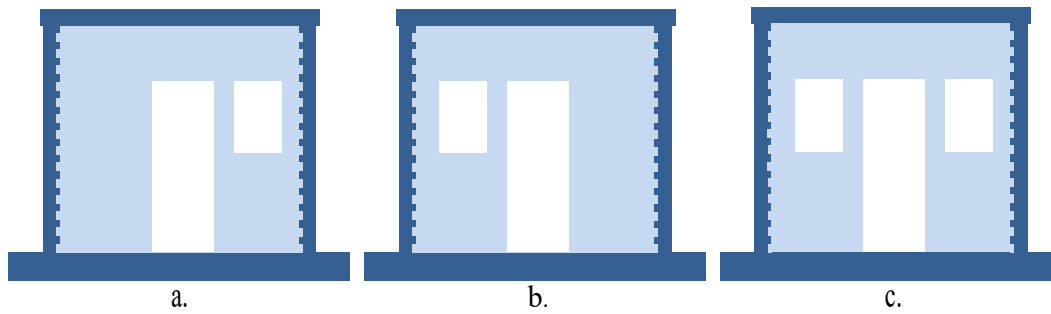


Figure 4.18: Combinations of door and window opening positions considered in the study as Set A; a. D-C, W-R, b. D-C, W-L, and c. D-C, W-L&R

4.3.2 Effect of door opening positions in the CBM wall

The present study investigates the impact of door position on the ultimate strength and stiffness of CBM walls. In this study, a 900 mm x 2100 mm door opening is introduced in the CBM wall, and FE analyses are performed to obtain a pushover curve Figure 4.16(a). The ultimate strength of the pushover curve is then analysed, as shown in Figure 4.16(b). The findings demonstrate a correlation between the position of the door opening and the ultimate strength of the wall. Notably, as the door opening shifts from the left to the right side of the wall, following the direction of load propagation, the ultimate strength of the wall increases. The reduction in ultimate strength, in comparison to a CBM wall without any doors is found to be 45.6% for a left-positioned door, 42.2% for a centrally located door, and 34.4% for a right-positioned door.

The impact of door position on CBM wall stiffness have been studied, revealing that the door's location affects stiffness. As the door position is moved from the right side of the CBM wall to the left, the initial and secant stiffness decrease until the door position reaches the centre of the CBM wall, after which the stiffness increases. This behaviour is depicted in Figure 4.16(c).

Figure 4.17 shows the CBM wall damage patterns for different door positions. Placing the door closer to the load point (left side) results in higher damage in the RC portion compared to the masonry portion due to interrupted load transfer. Moving the door away from the loading point improves the load transfer mechanism in the wall.

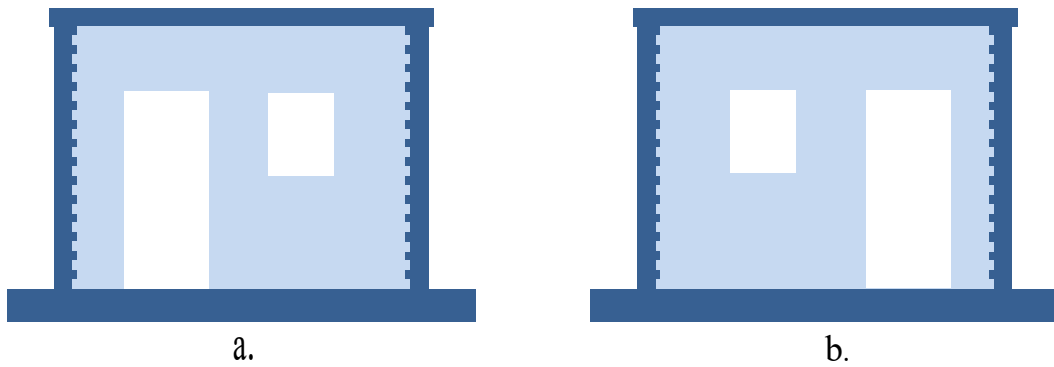


Figure 4.19: Combinations of door and window opening positions considered in the study as Set B; a. D-L, W-R, and b. D-R, W-L

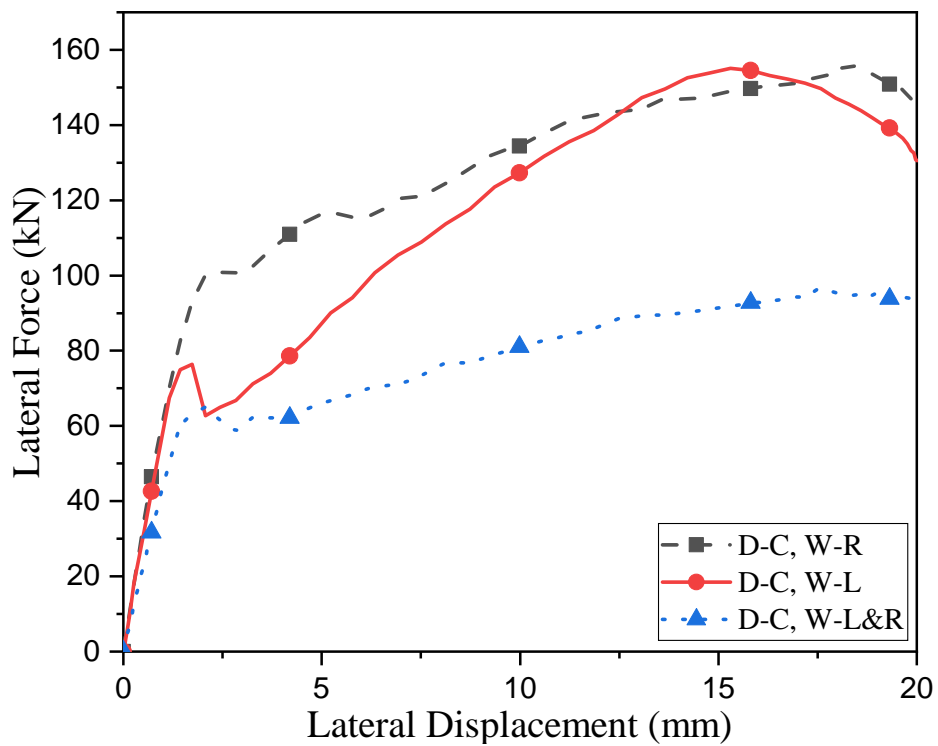


Figure 4.20: Pushover curve for Set A

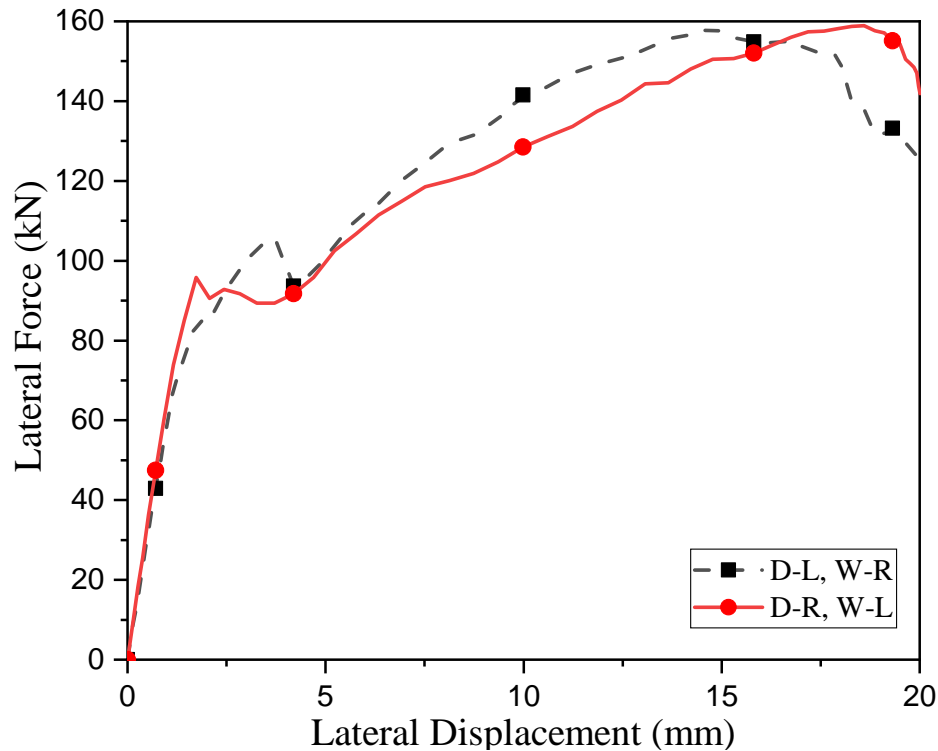


Figure 4.21: Pushover curve for Set B

4.3.3 Effect of the door and window positions combination in CBM wall

In typical construction practice, doors are often accompanied by windows, necessitating a combined evaluation of their positions to assess their overall impact on the strength and stiffness of CBM walls. To investigate how the placement of doors (900mm*2100mm) and windows (700mm*875mm) influences the structural performance of CBM walls, this study is divided into two distinct sets, as shown in Figure 4.18, 4.19, where, D-C: door at centre, D-L: door at left, D-R: door at right, W-L: window at left, W-R: window at right.

Set A involves positioning the door centrally, with windows placed either on the left, right, or both sides of the door. In contrast, Set B reverses the placement of these openings, interchanging the positions of the door and windows to explore how different configurations affect the wall's behaviour. This approach allows for a detailed assessment of the combined effects of door and window placement on the ultimate strength, stiffness, and overall resilience of CBM walls under various loading conditions. door and windows between the left and right sides of the wall.

Comprehensive numerical analyses have been conducted to examine the combined effect of

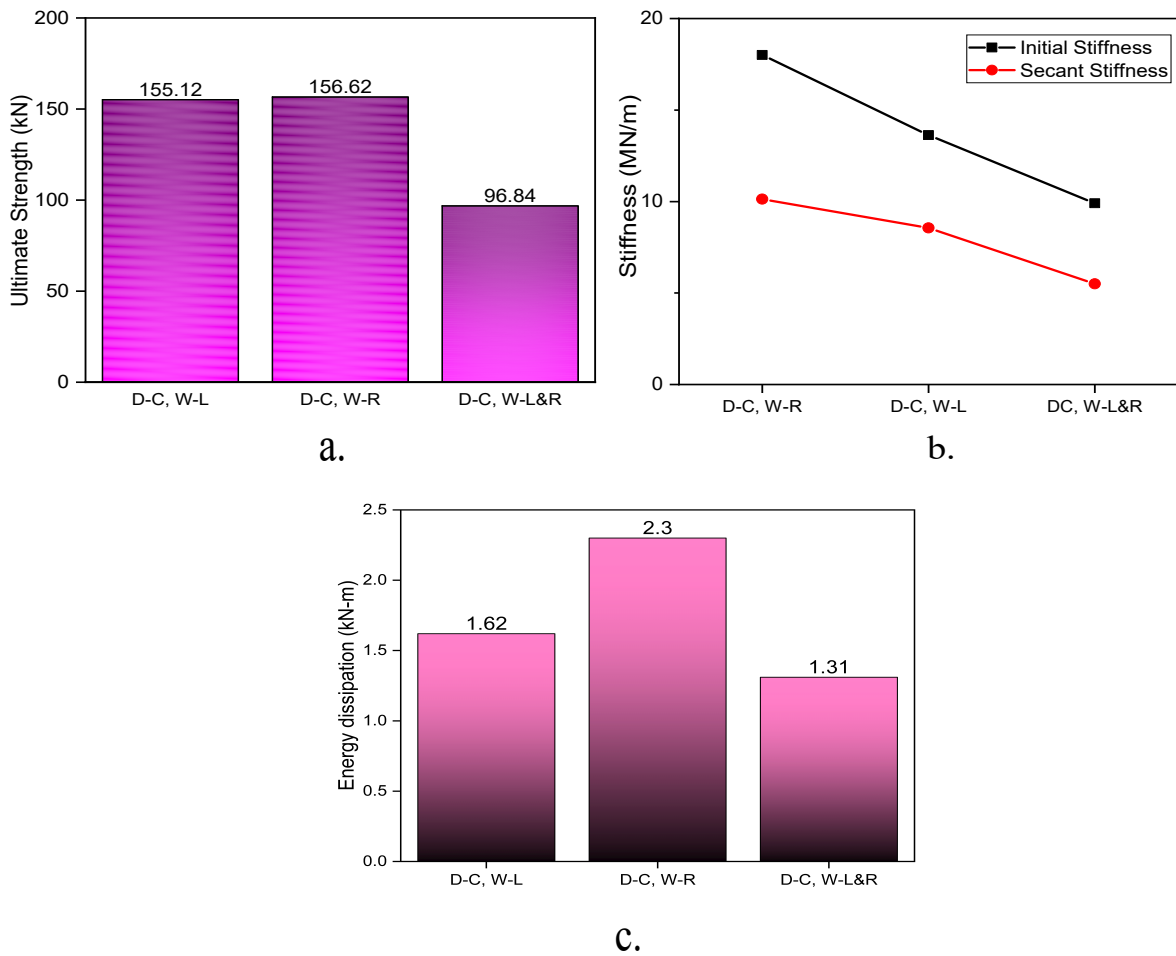


Figure 4.22: Ultimate strength, stiffness and energy dissipation for Set A

door and window opening positions on the ultimate strength, stiffness, and energy dissipation capacity of CBM walls. This investigation was performed for both sets of wall configurations, with a focus on understanding how the placement of openings influences the overall structural performance. Pushover curves were generated for both combinations of door and window openings, allowing for a detailed evaluation of the results. These curves, illustrated in Figure 4.20, 4.21, provide valuable insights into the behaviour of CBM walls under lateral loading, offering a clear visual representation of the structural response.

In Figure 4.22, it is observed that the ultimate strength remains relatively consistent for Set A when the window is located to the left or right of the door placed at the centre. However, a significant reduction of 38.19% in the ultimate strength is observed when the window openings are positioned on both sides of the door at the centre, compared to when the window opening is on only one side of the door opening at the centre. Additionally, the initial and

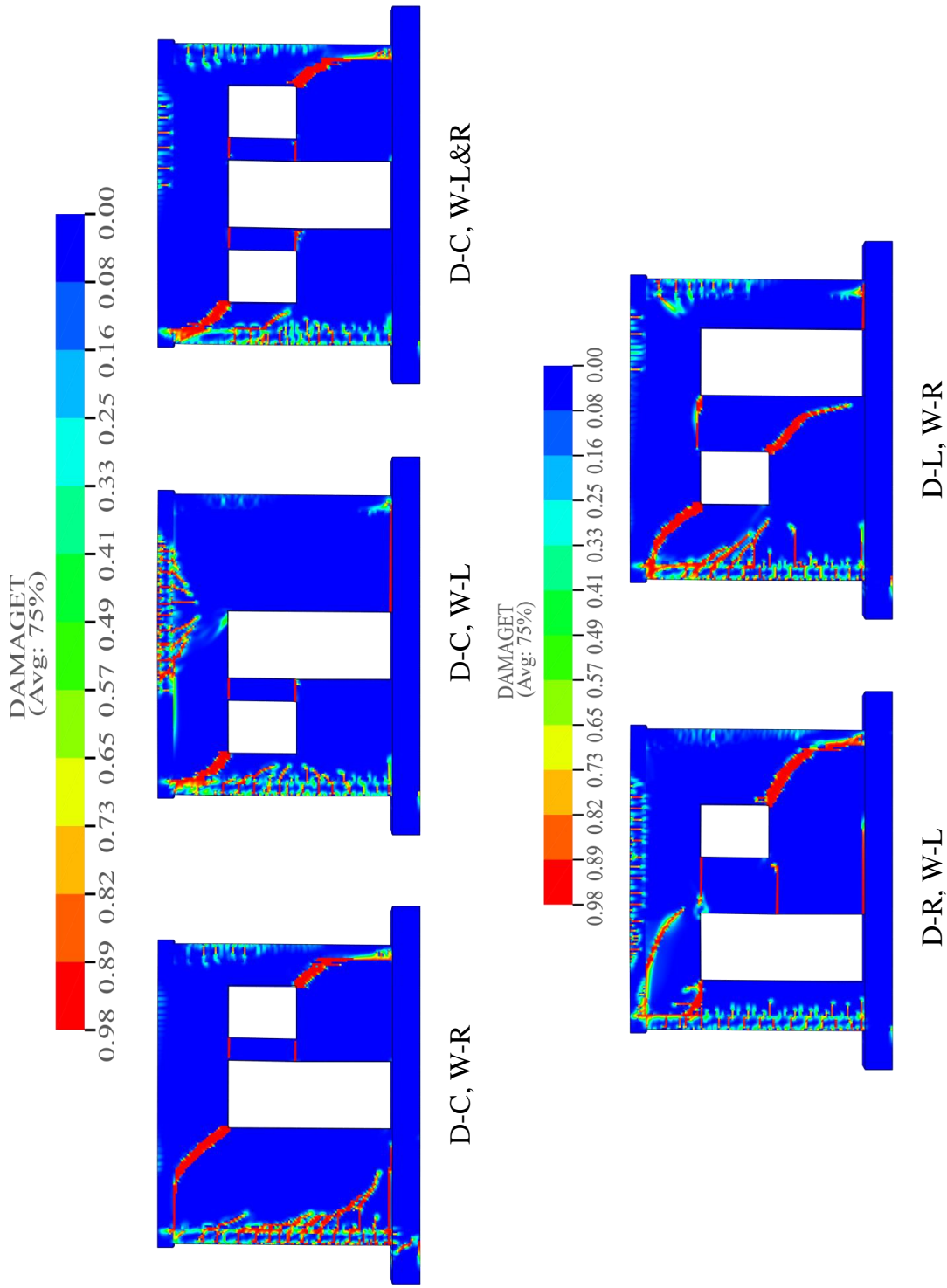


Figure 4.23: Damage propagation for Set A and Set B.

Table 4.7: Ultimate strength, stiffness and energy dissipation for Set B

Model	Ultimate strength (kN)	Stiffness (MN/m)		Energy dissipation (MN/m)
		Initial Stiff.	Secant Stiff.	
D-L, W-R	158.30	17.51	10.72	1.7
D-R, W-L	158.93	15.29	8.55	2.2

secant stiffness decreased by 24.31% and 15.58%, respectively, for D-C, W-L compared to D-C, W-R. The initial and secant stiffness also reduced by 45.03% and 45.6%, respectively, for D-C, W-L&R compared to D-C, W-R. Contrary to this, it is observed that the energy dissipation capacity of the D-C, W-R is much higher than that of the D-C, W-L, although the opening area and ultimate strength are the same for both cases.

For Set B, as presented in Table 4.7, interchanging the positions of the door and window in a CBM wall does not have a significant impact on the ultimate strength. However, a reduction of 12.67

Figures 4.23 illustrate the damage propagation for door and window openings in combinations A and B, respectively. Diagonal cracking is evident in the masonry regions surrounding the openings. Furthermore, the data reveals that when the opening is located near the loading point, there is an escalation in damage to the RC-tie members, highlighting the critical influence of opening placement on the structural response.

4.4 Conclusions

This study explores the influence of the size, shape, and position of openings in CBM walls on their ability to resist lateral forces. To conduct this analysis, we employ a macro-modelling approach using finite element methods, examining various CBM wall configurations with different opening arrangements. The investigation involves conducting pushover analyses with displacement-based methods to evaluate the ultimate strength, stiffness, and energy dissipation capacities of the walls. This approach provides a comprehensive assessment of how different opening configurations affect the structural performance of CBM walls under lateral

loading conditions. The key findings from this study are:

1. *Effect of Opening Size:* A comprehensive assessment reveals a correlation between the opening size and the ultimate strength, stiffness, and energy dissipation capacity of the CBM wall. As the opening size increases, these properties decrease due to the reduced effectiveness of the diagonal compression strut mechanism in distributing and resisting the applied load. Larger openings compromise the wall system's load-bearing capacity, making it less resilient to structural stresses. Additionally, openings introduce stress concentrations, particularly at the corners, which promote crack development and propagation along the wall's diagonal.

2. *Impact of Opening Area:* When the opening area is less than 10% of the masonry area, the load path remains significantly undisturbed compared to a solid CBM wall. Therefore, it is recommended to incorporate confining elements around larger openings, specifically those exceeding 10% of the masonry area, to ensure the continued stability and strength of the CBM wall, particularly where sizable openings compromise substantial portions of the wall.

3. *Aspect ratio of the opening:* Larger aspect ratios have been observed to enhance structural performance by improving the lateral load distribution capacity, enabling better resistance to seismic forces. Higher aspect ratios, i.e., larger height-to-width ratios, align better with vertical load paths, reducing stress concentrations around the corners. However, if the aspect ratio is too large, it could compromise strength due to the reduction in the effective masonry area. Therefore, optimising the opening aspect ratio is crucial to achieving a balance between efficient load transfer, improved deformation behaviour, and adequate strength. These findings underscore the need for careful design to enhance both stability and performance under seismic forces.

4. *Shape of the Opening:* Rectangular openings with a height greater than their width perform better than square openings or rectangular openings with a width greater than their height. Rectangular openings with greater height provide enhanced resistance to lateral forces. Taller openings relative to their width might improve performance by aligning better with the vertical load paths and minimising stress concentrations around the corners of the openings.

5. *Position of Window Openings:* The ultimate strength of the CBM wall improves as the

window position moves farther from the loading point. Openings positioned away from the loading diagonal of the walls show enhanced ultimate strength compared to those closer to the diagonal. This positioning allows for a more efficient distribution of forces within the wall, reducing stress concentration and improving load-bearing capacity.

6. *Position of Door Openings:* Like windows, the ultimate strength of the CBM wall increases as door openings are positioned farther from the loading point. However, placing a door at the center decreases stiffness due to its intersection with the loading diagonal, compromising its ability to distribute and withstand the applied load effectively.

7. *Combination of Window and Door Openings:* When combining window openings with a central door, the ultimate strength remains consistent regardless of whether the window is placed on the left or right side. However, stiffness is higher for right-side window openings. Additionally, having window openings on both sides results in a significant decrease in ultimate strength and stiffness.