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Behavior of Shear Wall with Base Opening

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ABSTRACT

Provision of parking may require an opening to be kept at the base of a shear wall. In this paper, an attempt is made to establish the range of base opening that may be allowed without significantly affecting the strength and stiffness. The behavior of planar and box shear wall with varying percentages of base opening has been studied and compared to that of a shear wall without opening. Finite element package ANSYS has been used for modeling. A set of non-dimensional graphs has been prepared featuring important parameters which will guide the designer to choose an appropriate opening width. It is observed that the rate of decrease of stiffnessis is relatively low for up to 60% base opening. Beyond this limit, strength and stiffness degradations are excessive. Based on the findings of the study, it has been recommended that in high-rise constructions the provision of a base opening up to 50% of the length of the wall may be considered as a feasible option.

KEYWORDS: Concrete, Shear wall, Base opening, ANSYS, Finite element.

INTRODUCTION

Shear walls may be defined as structural elements, which provide strength, stiffness and stability against lateral loads deriving strength and stiffness mainly from their shape. In many cases, high-rise buildings are designed as a framed structure with shear walls that can effectively resist horizontal forces (Kim et al., 2005). Lateral forces generated either due to wind blowing against the building or due to the inertia forces induced by ground shaking tend to snap the building in shear and push it over in bending. These types of forces can be resisted by the use of a shear wall system which is one of the most efficient methods of ensuring the lateral stability of tall buildings (Norlizian, 2007). The use of shear wall structure has gained popularity in high-rise building construction, especially in the construction of service apartments or office/commercial towers. It has been proven that this system provides efficient structural systems for multi-storey buildings in the range of 30-35 storeys (Marsono and Subedi, 2000). Shear walls are frequently pierced for doors, windows and corridor openings. Those openings are usually located at every floor dividing the wall into two wall segments connected by coupling beams or floor segments, forming coupled shear walls. The behavior of this coupled wall is widely covered in various literature (Lu and Chen, 2005; Balkaya and Kalkan, 2004; Paulay, 2002; Doran, 2001; Park and Paulay, 1975). In addition, much research to study the behavior of shear walls without openings (Jalali and Dashti, 2008; Orakcal and Wallance, 2006; Orakcalet

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al., 2004) and shear walls with irregular openings at various locations (Li and Chen, 2010; Wang et al., 2010) has been conducted. However, little research has been conducted on the effect of openings at the base of a shear wall, a condition encountered to provide access for vehicular movement at the basement or ground floor level. The base is the most critical section of a shear wall as the entire lateral load acting on a shear wall is transmitted to the ground through the base. So, openings at that section will affect its overall stiffness as compared to shear walls without openings. Maximum top deflection and stresses at the base will be higher than those of shear walls without openings. The section will become more critical with the increase in opening width and shear wall height. It is important to establish the range of base opening that may be allowed without significant loss of strength and stiffness of a structural wall.

Table 1. Various ratios for varying % opening and H/B of both types of plane shear wall

% Base opening	**Type of shear wall**	**Maximum deflection ratio**		**Maximum flexural stress ratio**		**Maximum shear stress ratio**	
		H/B=3.75	**H/B=6**	**H/B=3.75**	**H/B=6**	**H/B=3.75**	**H/B=6**
90% base opening	Type-1	4.7	2.4	20	14.4	51.5	37
	Type-2	366	253	86	92	215	233
80% base opening	Type-1	2.2	1.7	7.6	4.6	15.2	5.6
	Type-2	45	30	20	22	100	116
60% base opening	Type-1	1.16	1.1	2.3	2	7.3	5.5
	Type-2	7	5.2	5.1	5.4	17.6	20.6
40% base opening	Type-1	1.1	1.06	1.85	1.2	5.1	3.8
20% base opening	Type-1	1.03	1.0	1.4	1.2	2.8	1.6

Table 2. Deflection and stress ratios for varying % of opening and storey height for both types of box shear wall

% base opening	**Type of box shear wall**	**Maximum deflection ratio**			**Flexural stress ratio**			**Shear stress ratio**		
		6 storeys	**10 storeys**	**15 storeys**	**6 storeys**	**10 storeys**	**15 storeys**	**6 storeys**	**10 storeys**	**15 storeys**
80% base opening	Type-1	1.225	1.061	1.027	2.1	2.2	2.6	1.5	1.2	1.2
	Type-2	1.062	1.050	1.057	1.7	1.8	1.9	1.0	1.0	1.0
60% base opening	Type-1	1.080	1.025	1.010	1.5	1.8	2.6	1.3	1.2	1.2
	Type-2	1.036	1.034	1.034	1.4	1.6	1.6	1.0	1.0	1.0
40% base opening	Type-1	1.036	1.012	1.005	1.3	1.5	2.6	1.3	1.2	1.2
	Type-2	1.019	1.018	1.018	1.1	1.3	1.3	1.0	1.0	1.0

In this paper, the behavior of planar and box type shear wall (core wall) with varying percentages of base opening has been studied. Finite element package ANSYS has been used for modeling the shear wall.

The behavior of the shear wall for different opening widths has been studied and compared to that of a shear wall without opening. Three parametric ratios such as deflection ratio, maximum shear stress ratio and maximum flexural stress ratio have been studied. A set of non-dimensional graphs has been prepared featuring important parameters which will guide the designer to choose appropriate opening width without significantly hampering the lateral stiffness. An investigation is also performed to show how the degradation of stiffness of plane shear wall with base opening can be compensated using an additional portion of the shear wall.

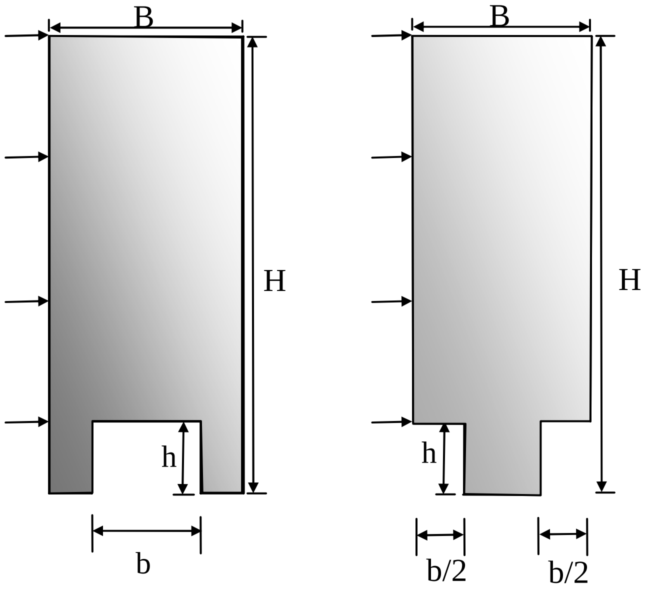
Table 3. Study of parameter ratios for varying % base opening of shear wall (H/B=3.75) for both 1st and 2nd alternative measures

% of base opening	Type of shear wall	Maximum deflection ratio	Maximum flexural stress ratio	Maximum shear stress ratio
60% base opening	without compensating measure	1.16	2.11	5.34
	with 1st alternative measure	0.88	0.74	4.27
	with 2nd alternative measure	0.89	0.90	2.18
40% base opening	without compensating measure	1.05	1.44	3.54
	with 1st alternative measure	0.90	0.87	3.14
	with 2nd alternative measure	0.87	0.88	1.57
20% base opening	without compensating measure	1.01	1.18	2.25
	with 1st alternative measure	0.94	0.92	2.10
	with 2nd alternative measure	0.90	0.86	1.33

The paper is structured as follows: details of finite element modeling and assumed parameters are presented. The parameters studied in this paper are then defined. Results and observations for both shear walls are given. An investigation with introducing a compensating measure on plane shear wall with base opening is presented. Finally, conclusions are drawn.

Modeling the Shear Wall

Finite Element (FE) technique has been used for modeling the shear wall with base opening. It is necessary to use fine mesh finite element models for an accurate analysis of structure with openings (Kim and Lee, 2003). The general purpose finite element package ANSYS has been the tool for modeling the shear wall and studying its behavior in terms of stress pattern and stiffness variation due to the incorporation of the opening at the base. For modeling the shear wall, a four-node element with two translational degrees of freedom per node is commonly used (Husain, 2011). Analysis has been conducted in several previous studies by using a four-node element with three (two translational and one rotational) degrees of freedom per node (Kim and Lee, 2003; Lee et al., 2002), an eight-node element with three translational degrees of freedom per node (Husain, 2011) and an eight-node element with five (three translational and two rotational) degrees of freedom per node (Guan et al., 2010). In this study, linear elastic analysis using three-dimensional membrane four-node shell element SHELL63 (ANSYS, 2000) has been used for suitable meshing. SHELL63 has both bending and membrane capabilities. Both in-plane and normal loads are permitted with this element. The element has six degrees of freedom at each node: translations in the nodal x, y and z directions and rotations about the nodal x, y and z axes. Stress stiffening and large deflection capabilities are included. A consistent tangent stiffness matrix option is available for use in large deflection analysis (ANSYS, 2000). A refined mesh has been used around the opening to capture the likely stress concentration at the juncture. The Young's Modulus of elasticity (Ex) of concrete is taken as $3.0\text{x}10^6$ psi; i.e., $20.7\text{x}10^6$ kN/m^2. The shear modulus and Poisson ratio have been assigned as $9.4\text{x}10^6$kN/m^2 and 0.1, respectively, for this analysis.



Shear wall Type-1 (T-1) Shear wall Type-2 (T-2)

Figure 1: Types of shear wall with base opening

Plane Shear Wall with Base Opening

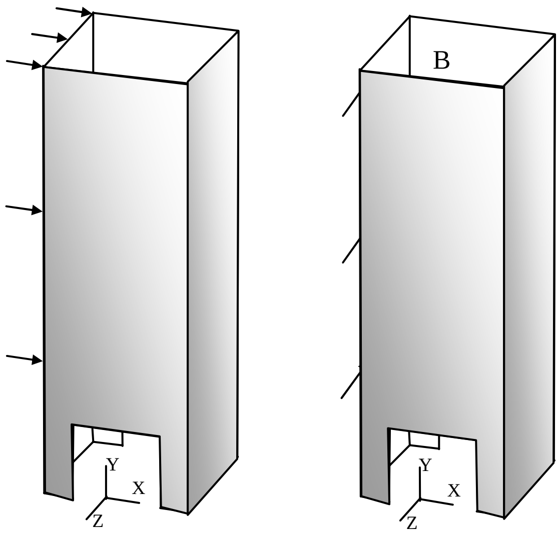
Two types of plane shear walls; double legged (Type-1) and single legged (Type-2) have been studied. In each case, the height of shear wall is H and the width of the opening is b. The width of shear wall (B), height of opening (h) and thickness have been taken to be 8m, 3m and 0.25m, respectively. A uniformly distributed load of 15 kN/m^2 has been applied on the shear wall, as shown in Figure 1.

Box Shear Wall with Base Opening

Box type shear wall is frequently used as a lift core in structure. A frame structure with a box shear wall is selected for the study where the opening is kept in two opposite parallel planes of the box (XY plane) as shown in Figure 2. Here, box shear walls have been classified into two types depending on the direction of the applied load. In Type-l, the load is applied along the X axis on the YZ plane. On the other hand, in Type-2, the load is applied along the negative Z axis on the XY plane where the opening is kept. In either case, the cross-section of the box shear wall has been considered to be square with the length of each side (B), and the wall thickness is 6m and 0.25m, respectively. Three different heights (H) of frame-box shear wall buildings have been considered for study: 6 storey, 10 storey and 15 storey buildings. Applied load is 1.5 kN/m^2, uniformly distributed on the wall plane for both cases.

Study Parameters

In this paper, the deflection ratio, maximum shear stress ratio and maximum flexural stress ratio for varying H/B values and % base openings have been studied. The results are calculated with respect to shear wall without base opening. These three ratios used in the subsequent presentations are described next.



Box shear wall (Type-1) Box shear wall (Type-2)

Figure 2: Two distinct loading types (depending on the loading direction) of box shear wall with base opening considered

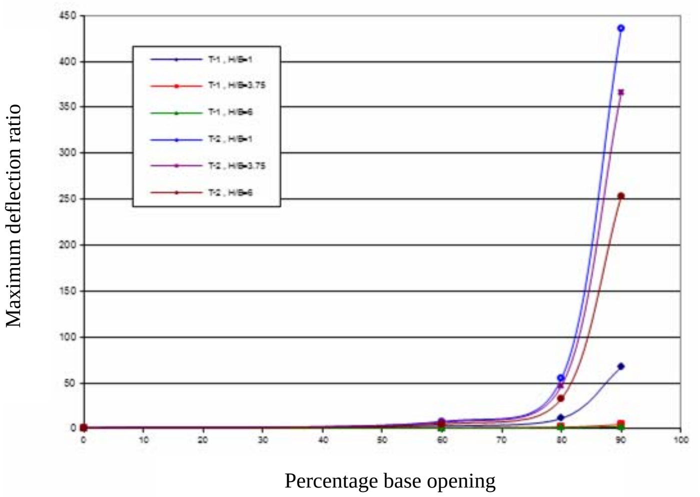
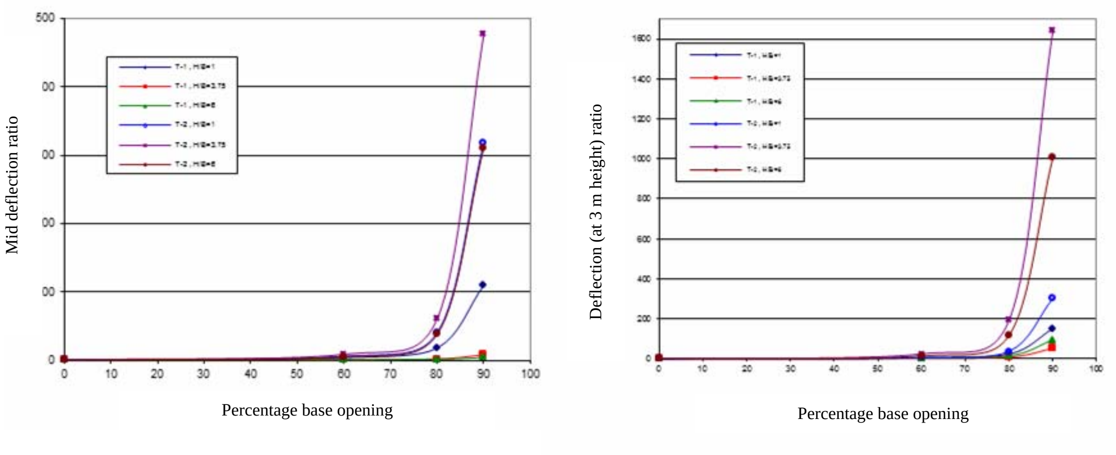


Figure 3: Effect of opening size on maximum deflection ratios for varying ratios of H/B

Deflection ratio: Deflections at three locations have been studied. These are: the top deflection (maximum deflection), deflection at mid height and at 3.0 m above the base. At a particular height of shear wall and with a particular percentage of base opening, the deflection ratio is the ratio between the deflection of the shear wall with base opening and the deflection of an identical shear wall without base opening. Similarly, the other two deflection ratios are also calculated.

Maximum shear stress ratio: With a particular percentage of base opening, maximum shear stress ratio is defined as the ratio between the maximum shear stress at the base of the shear wall with base opening and the maximum shear stress of an identical shear wall without base opening.

Maximum flexural stress ratio: With a particular percentage of base opening, maximum flexural stress ratio is the ratio between the maximum flexural stress at the base of the shear wall with base opening and the maximum flexural stress of an identical shear wall without base opening.



(a) Mid deflection ratios

(b) Deflection(at 3 m height) ratios

Figure 4: Effect of opening size on (a) mid deflection ratios (b) deflection(at 3 m height) ratios for varying ratios of H/B

Results of Parametric Study

Plane Shear Wall with Base Opening

Deflection ratios at three different floor levels for varying opening size (b/B), are presented in Figure 3 and Figure 4. It is observed that deflection increases with the increase of base opening. However, the rate of increase of deflection is very low up to 60% (i.e., b/B=0.60) base opening. Beyond 60% opening, wall stiffness decreases significantly. Maximum deflection of shear wall (Type-1) with 90% base opening and H/B= 1 is 67 times than that of solid shear wall, whereas in the case of shear wall with 60% base opening it is only 3 times. The influence of height of shear wall (i.e., H/B) in its stiffness is also observed here. For all values of H/B with 0 to 60% base opening, the effect is insignificant, but for base opening higher than 60% it is very high. This may be due to the reduction of moment of inertia. It is observed that beyond 60% opening moment of inertia of the wall is significantly reduced. For example, due to opening, the reduction of moment of inertia for 40% opening is 6.4%, for 60% opening is 21.6% and for 80% opening is 52%.

For very stiff wall (i.e., H/B=1), the loss of stiffness due to base opening is quite significant, whereas for relatively slender walls (H/B=3.75), the reduction in stiffness is only moderate. For example, with 90% base opening the top deflection ratio of shear wall (Type-1) with H/B = 1 is 67 and it is only 4.7 for shear wall with H/B = 3.75.

Comparisons of deflections at lower levels (i.e., at mid height and at 3 m height) are shown in Figure 4.

The general tendency of stiffness degradation due to base opening, as reflected in the computed deflection ratios, remains the same as in the case of maximum deflection ratios. However, deflection ratios at lower levels are higher than the maximum deflection ratio at the top of the wall. With 90% base opening, the mid deflection ratio of shear wall Type-1 (for H/B=1) is 112 and the deflection ratio at 3 m height stands at 153, whereas maximum deflection (at top) ratio is only 67. Still with 60% or lesser base opening, deflection ratios at lower levels are insignificant (close to 1.0).

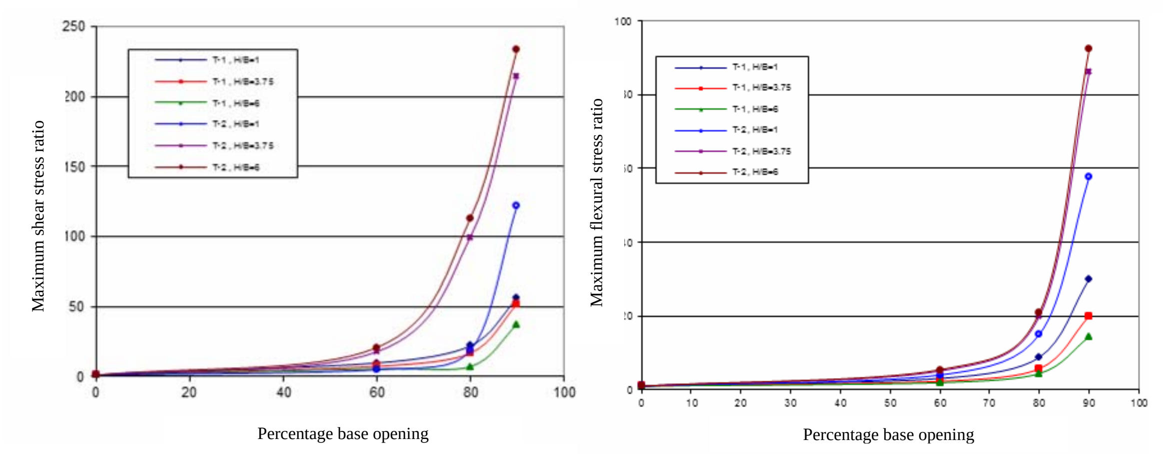


Figure 5: Effect of opening size on (a) maximum shear stress ratios (b)maximum flexural stress ratios for varying ratios of H/B

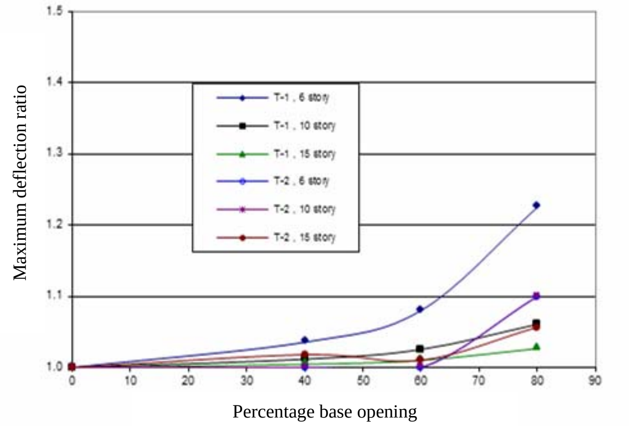
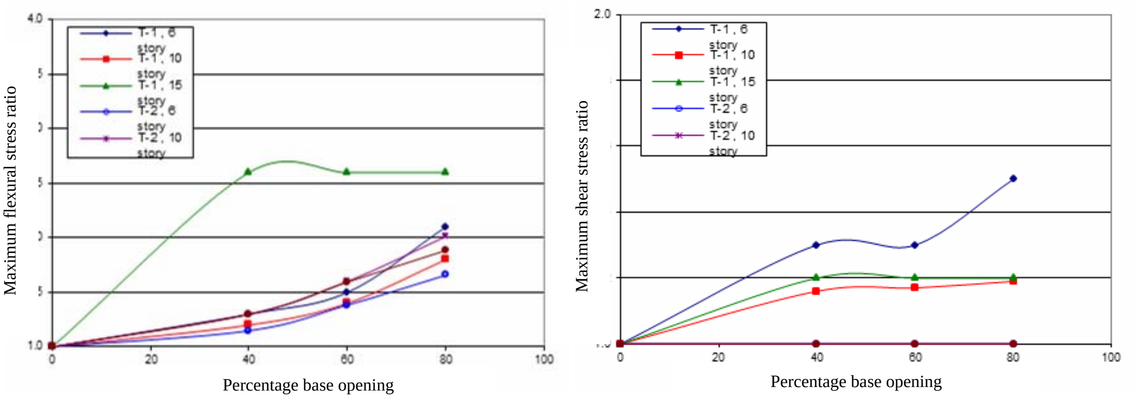


Figure 6: Effect of opening size on maximum deflection ratios for box shear wall with varying height of the building

Maximum shear stress ratios and maximum flexural stress ratios for varying base opening (b/B) are presented in Figure 5. Identical to the deflection pattern, similar behavior is observed in the stress pattern. It is seen that up to 60% base opening, the rate of increase of these ratios is low. But for more than 60% opening, the stress ratios increase rapidly. The increase in shear stress ratios for 60% opening appears to be 5 to 10 times in section at 3 m height for shear wall Type-1(shown in Figure 5(a)). This high concentration of shear stress needs to be carefully addressed from the design point of view and is dealt with in section. In the case of flexural stress ratios for 60% opening, the increase appears to be 2 to 3 times (shown in Figure 5(b)). It is seen from Figure 5 that shear stress is more affected than flexural stress due to the introduction of base opening in shear wall. For the same % of opening, shear stress ratio is more than flexural stress ratio.

For shear wall Type-2, it has been observed that stress (flexural and shear) ratios increase with the increase of shear wall height, while on the other hand in Type-1 these stress ratios decrease with the increase of shear wall height. Apart from this, all curves show almost similar behavior to the behavior of double legged shear wall (Type-1). Although general behaviors of Type-1 and Type-2 are similar, the absolute values of the ratios are quite high in the case of Type-2. This may be due to excessive reduction of moment of inertia for Type-2. For example, for 60% opening, the reduction of moment of inertia of Type-1 is 21.6%, whereas it is 94% for Type-2. A summary of the various ratios is presented in tabular form, in Table 1.



(a) Maximum flexural stress ratios

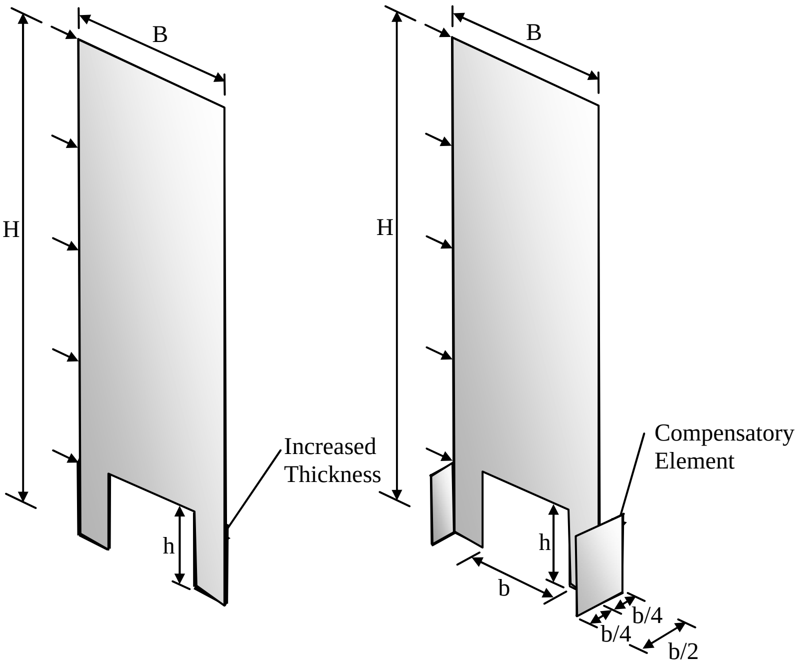
(b) Maximum shear stress ratios

Figure 7: Effect of opening size on (a) maximum flexural stress ratios (b) maximum shear stress ratios for box shear wall with varying height of the building

Box Shear Wall with Base Opening

Maximum deflection ratios for varying percentage of base opening are presented for both types of box shear wall, in Table 2 and Figure 6. The deflection ratios reported here are based on the relevant deflection at the wall rather than the deflection of the frame. It is observed that the deflection ratio increases with the increase of percentage base opening. However, the effect of base opening on deflection is not very significant (Figure 6). The influence of shear wall height in its stiffness is also observed here. The deflection ratios are reported to an accuracy of three decimal places. For both types of box shear wall, the ratio decreases with the increasing storey height. For example, with 80% base opening, the maximum deflection ratio of a 6 storied Type-1 shear wall is 1.225 and it is 1.027 for a 15 storied building. Another interesting feature is that the deflection ratio is virtually not affected for less than 60% base opening.

Maximum shear stress ratios and maximum flexural stress ratios for varying percentage of base opening are presented in Figure 7 and Table 2 for both types of box shear wall. For Type-1, the shear stress ratios for 60% opening are in the range of 1.0 to 1.3 at the top of the box shear wall. In the case of Type-1, the flexural stress ratios for 60% opening are in the range of 1.5 to 2.6. On the other hand, for Type-2 shear wall, all curves are almost similar to those of Type-1. Although general behaviors of Type-1 and Type-2 are similar, the absolute values of the ratios are smaller in the case of Type-2. For example, in the case of 15 storied Type-1 shear wall with 60% base opening, the maximum flexural stress ratio is 2.6, while it is only 1.6 for Type-2. Type-2 box shear wall is stiffer than Type-1 box shear wall. It is observed that shear stress ratios for Type-2 shear wall are nearly 1.0 which means that the effect of base opening on shear stress is insignificant for Type-2 shear wall.



(a) With 1st alternative (b) With 2nd alternative

Figure 8: Shear wall with compensatory element

It is seen from Figure 7 that flexural stress is more affected than the shear stress due to the introduction of base opening in box shear wall. For the same % of opening, the shear stress ratio is lower than the corresponding flexural stress ratio. For example, with 60% opening and 15 storied Type-1 shear wall, the flexural stress ratio is 2.6, whereas the shear stress ratio is 1.2. For the purpose of easy comparison, numerical values in tabular format have been presented in Table 2 with an accuracy of the numerical values up to three decimal places.

Compensating Measure on Plane Shear Wall with Base Opening

It has been shown that although the deflection ratios up to 60% base opening are reasonably low, the stress ratios (both flexural stress and shear stress) are adversely affected even with 60% base opening. In this context, it has been thought that to improve the stress scenario compensating elements might be introduced to account for the stress adversities due to base opening. To this end, a study has been conducted to observe the behavior of shear wall with base opening with compensatory measure. Two alternative compensatory measures have been taken for this study. First, the thickness of two legs of the shear wall has been increased, and in the second alternative, two compensatory elements have been introduced which are placed perpendicular to the shear wall at the two edges (Figure 8). The total area of the compensatory element is taken such that the resultant cross-sectional area of the pierced shear wall remains the same as that of the solid shear wall (i.e., without opening). That means, the total cut area for base opening is equally distributed at the two edges/legs of the shear wall. In this study, an attempt has been made to show the improvement of stiffness that might occur with introducing compensatory measures. Double legged shear wall (Type-1) with H/B=3.75 has been chosen for this study. Three parameter ratios of the shear wall for different opening widths have been calculated and presented in Table 3 as well as the graphical presentation shown in Figure 9.

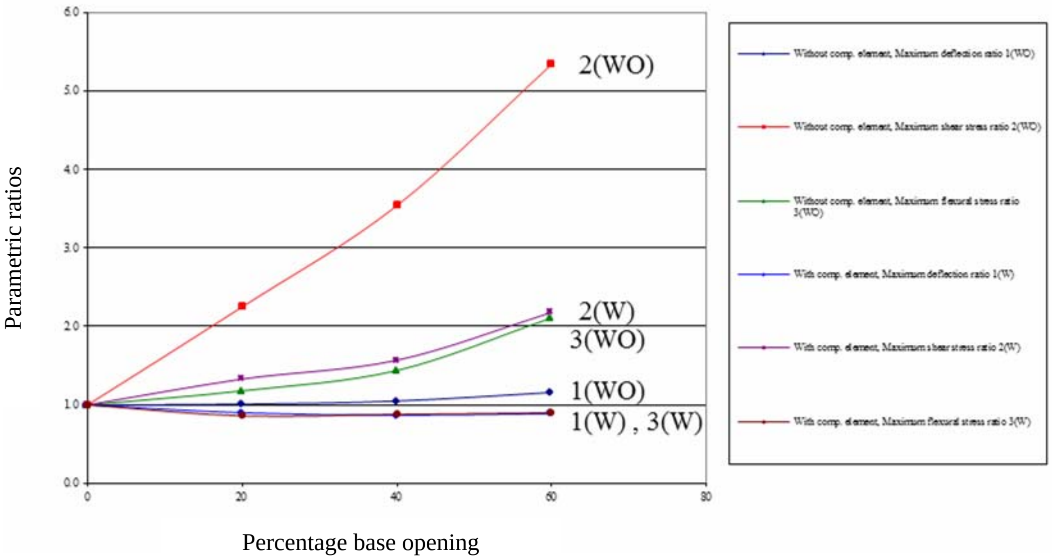


Figure 9: Effect of compensatory element (2nd alternative) on parametric ratios for varying percentage of base opening

It is seen that with compensating element, the maximum deflection ratio decreases as compared to that of shear wall without compensatory element. For example, with 40% base opening the ratio is 1.05 and with compensatory measure it is 0.90 for the 1st alternative and 0.87 for the 2nd alternative, indicating an improvement over the stiffness of the shear wall without base opening.

Maximum flexural stress ratio is also reduced with the introduction of compensatory measure. For shear wall with 60% base opening, this ratio is 2.11, whereas in the case of shear wall with compensatory measure it is only 0.74 (for the 1st alternative) and is 0.90 (for the 2nd alternative). It is seen that the use of compensatory elements, by providing an equivalent compensatory cross-sectional area as that of the opening, can be beneficial in offsetting the adverse effect of introducing the base opening.

Maximum shear stress ratio is also significantly improved with the introduction of compensatory element. The shear stress is decreased to almost a half. With 60% base opening this ratio is decreased from 5.34 to 4.27 (for the 1st alternative) and to 2.18 (for the 2nd alternative). It is noticed that shear stress ratio, the most adversely affected parameter due to the introduction of the base opening, can be significantly improved if compensatory elements are added.

It is observed that there is considerable impact of introducing compensatory measure on these parametric ratios. So, it can be concluded that the introduction of the compensating measure would fully compensate the deflection and flexural stress ratios and also bring about significant improvement in the shear stress ratio. It is also observed that the 2nd alternative measure is more effective than the 1st one to compensate the adverse effect of introducing the base opening. However, the overall planning need of the ground storey would dictate the choice between the two alternatives.

CONCLUSIONS

Within the limited scope of the study, the following conclusions may be drawn. These conclusions are grouped under two sub-headings and listed below:

Behavior of Plane Shear Wall with Base Opening

It is observed that deflection and stresses increase with the increase of % base opening. However, the rate of increase of deflection is relatively low up to 60% base opening. Beyond 60% base opening, the wall stiffness decreases significantly. It is seen that shear stress is more adversely affected than flexural stress due to the introduction of base opening in shear wall. In case of single legged shear wall, stress (flexural and shear) ratios increase with the increase of shear wall height, whereas in double legged shear wall these stress ratios decrease with the increase of shear wall height. Apart from this, almost similar behavior is observed for both types of plane shear wall. However, the absolute values of the ratios are significantly high in the case of single legged shear wall. Single legged shear wall, therefore, is not considered a feasible option. It is also observed that the introduction of the compensating measure placed perpendicular to double legged shear wall at the two edges would fully compensate the deflection and flexural stress ratios and also bring about significant improvement in the shear stress ratio.

For plane shear wall with central opening at the base, provision of base opening up to 50% of the wall width may be considered as a feasible option. It has been shown that for this level of opening, stiffness degradation is minimal. However, the flexural stress and shear stress would be magnified in the range of 2.0 to 2.5 and 5.0 to 7.0, respectively. These must be carefully taken care of by the designer with special reinforcement detailing. In extreme cases of stress concentration, compensatory walls would be helpful to reduce stresses.

Behavior of Box Shear Wall with Base Opening

In case of box shear wall, the effect of base opening on deflection is not very significant. General behaviors of both types of box shear walls are similar. However, the absolute values of the three ratios are lower in the case of Type-2 (openings are in the two parallel flange walls with the load being applied on one of the flange walls). This means Type-2 box shear wall is stiffer than Type-1 box shear wall.

For the range of structures considered in the study, it is seen that up to 40% base opening the stress ratios reached up to 2.6 for Type-1 and up to 1.4 for Type-2 shear wall. This can lead to the practical conclusion that with proper design and detail, it is feasible to have a box shear wall with base opening up to 40%.

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