- *Technical Paper-*

# INVESTIGATION OF THE INFLUENCE OF OPENING PARAMETERS ON THE SEISMIC CAPACITY OF REINFORCED CONCRETE WALLS

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ABSTRACT

The presence of openings in RC walls leads to uncertainty in assessing the seismic response. The influence of opening parameters that can effect the seismic strength is still poorly understood. Therefore, this study aims to investigate the effect of different opening parameters on the lateral strength of RC wall using simplified approach. The parameters considered here are size, shape, location of opening, wall boundary elements. Another objective is to apply approach to past test specimens and investigate based on past test results.

Keywords： Influence of opening, seismic capacity, opening parameters.

## 1. INTRODUCTION

RC shear walls are popular structural systems to resist gravity load as well as lateral loads such as wind and earthquake loads. Those walls commonly feature various types of openings often provided for functional requirements of buildings. The opening in walls lead to significant uncertainty in the assessment of seismic behavior of the structure. The seismic response of RC wall including opening is influenced by different parameters of openings such as opening area, opening size, shape and location of opening. The influence of opening on the seismic performance of RC walls have been investigated by several researchers [1-7]. To evaluate the lateral strength of RC wall with opening, some analytical methods have already been developed for predicting lateral strength reduction factor due to opening. For example, reduction factor was developed by AIJ [8] that considers only the size of opening (i.e. length, height and area of opening). However, some other parameters of opening such as aspect ratio, location of opening had not been taken into account even though they have influence on the lateral strength.

Fig.1 illustrates the comparison of lateral strength reduction factor ($Q_{max,0}$ /$Q_{max,s}$) obtained from past test studies [1-6] with those calculated from AIJ code. Here. $Q_{max,s}$, $Q_{max,o}$ indicate lateral strength of solid wall and wall with opening respectively. The plot of Fig.1 shows that AIJ code gives conservative and safe evaluation of the reduction of strength. However, there is a large variation between strength reduction factor obtained from experiment and AIJ factor. This indicates that there are other parameters not included in the AIJ equation which gives this large variation of the experimental results. Which parameters have larger influence on seismic capacity is still topic with limited research and poorly understood. Therefore, the objective of this study is to investigate the influence of opening parameters using both AIJ code and a simplified approach. Then finally comparison has been done with some past experimental results.

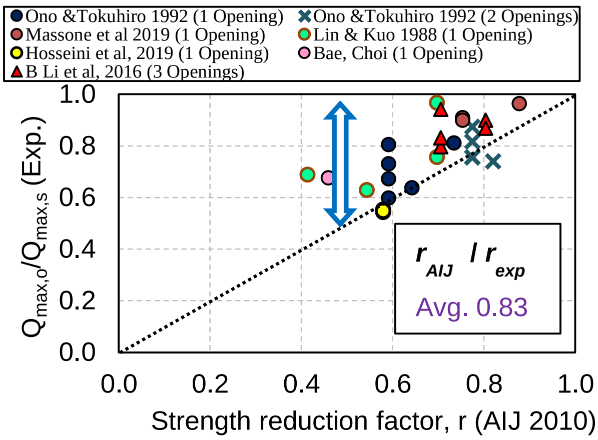


Fig.1 Comparison of strength reduction factor obtained from past experiment and AIJ code

Lateral strength reduction factor due to opening are calculated as per AIJ guideline [8] using Eqs. (1-4).

$$r = \text{minimum of } \{r_1, r_2, r_3\} \tag{1}$$

$$r_1 = 1 - 1.1\left(\frac{\Sigma l_o}{l}\right) \tag{2}$$

$$r_2 = 1 - 1.1\sqrt{\frac{\Sigma h_0\ l_o}{h\ l}} \tag{3}$$

$$r_3 = 1 - \lambda\frac{\Sigma h_0}{h} \tag{4}$$

where $l$, $l_o$ = length of wall (including two columns) and opening; $h$, $h_o$ = height of wall (including beam) and opening respectively (see Fig.2a).

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## 2. SIMPLIFIED APPROACH FOR LATERAL STRENGTH EVALUATION

In the present study, the lateral strength of RC wall surrounded by RC frame has been evaluated using a simplified approach. The novelty of the proposed method is that it can predict the strength of opening due to factors of variable aspect ratio of opening and location of opening using a simplified approach of dividing the wall into different segments. This approach is based on the fundamental wing wall concept as per JBDPA [9] in which the wall is separated by opening. The lateral strength of RC wall is calculated considering both shear strength ($Q_{su}$) and flexural strength ($Q_{mu}$) as per Eq.5.

$$Q_{max} = \text{Minimum of } Q_{su}, Q_{mu} \quad (5)$$

The following sections explains concept and assumptions used in the simplified approach.

### 2.1. Shear force ($Q_{su}$)

The shear capacity ($Q_{su}$) has been calculated considering both horizontal and vertical direction at the opening location and then minimum value has been taken for $Q_{su}$ as per Eq.6.

The schematic diagram of Fig.2 shows the shear strength ($Q_{su,h}$) considering horizontal direction. As for the calculation of shear strength along horizontal direction, the whole structure is divided into two parts-left and right separated by opening (see section AB in Fig.2a). Then, each part is assumed as a wing wall attached with a column for calculating shear strength using wing wall concept as per JBDPA [9]. The shear strength of each part is evaluated using Eq.8 and then the total strength has been calculated by adding the strength of left part and right part using Eq.7. The necessary equations for calculating shear strength have been given from Eqs. 6-9. For Eq. 8, $\frac{M}{Q.de}$ is taken between 1 and 2 as per JBDPA [9].

$$Q_{su} = \text{Minimum of } Q_{su,h}, Q_{su,v} \quad (6)$$

$$Qsu_h = Qsu_{left} + Qsu_{right} \quad (7)$$

$$Qsu = \left\{ \frac{0.068\ p_{te}^{0.23}(18+fc)}{\frac{M}{Q.de}+0.12} + 0.85\sqrt{\sigma_{wye} p_{we}} + 0.1\sigma_0 \right\} be.je \quad (8)$$

$$p_{we}\sigma_{wye} = \frac{p_{shc}\sigma_{scy}\, b_c d_c + p_{shw}\sigma_{swy}\, l_w t_w}{be\, l\, e} \quad (9)$$

where $\rho_{te}$ = tensile reinforcement ratio; $\sigma_{scy}$, $\sigma_{swy}$, =yield strength of shear reinforcement in column and wall; $\rho_{shc}, \rho_{shw}$ = shear reinforcement ratio in column and wall; $\sigma_o$ = axial vertical stress on column; $b_e$ = effective width of RC wall with column; $d_e$ = distance between centroid of tension force to the extreme face of compression side; $j_e$ = distance between centroid of compression and tension force; $b_c$, $d_c$ = width and depth of column; $l_e$ = length of each part including column; $l_w$ = length of wall of each part; $t_w$ = thickness of wall; $f_c$ = concrete compressive strength.

The schematic diagram of Fig.2b shows the shear strength considering vertical direction ($Q_{su,v}$). For shear strength in vertical direction, only the top part of

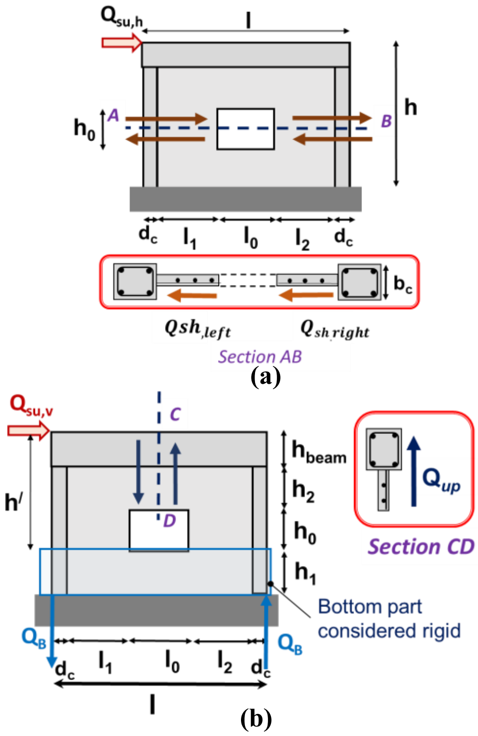


Fig.2: Shear strength of wall with opening considering (a) horizontal (b) vertical shear

the structure above the bottom edge of opening (see Fig.2b) is considered in the calculation. The bottom part marked in Fig. 2b is thought to be very rigid since the bottom part is attached with a rigid base beam (stub) and is thought not to fail in shear in the vertical direction in this case. Thus bottom part is not taken into account for calculation. It should be noted here that this assumption of rigid beam is considered here to compare with experimental results of past studies in the later section of this study. In the case that base-beam does not exist, then vertical direction for bottom part could be added in this case. The notations shown in Fig.2b are as follows- $h_1$, $h_2$ = height of top and bottom part of wall respectively; $h^/$ =height of wall without bottom part (see Fig.2b), $l_1$, $l_2$=length of left and right part of wall beside opening respectively; $Q_B$ = vertical reaction in column, $Q_{up}$ =vertical shear in upper part. At first, the shear strength of the upper part $Q_{up}$ (see Fig.2b) is calculated using Eq. 8 mentioned earlier. For this case, in Eq. 8, $\frac{M}{Q.de}$ is taken between 0.5 and 2 for beam with hanging wall as per JBDPA [9]. Then using moment equilibrium equation given in Eq.11, lateral strength $Q_{su,v}$ is calculated considering vertical directional shear ($Q_B$). The necessary equations for calculating shear strength $Q_{su,v}$ are given in Eqs. 10-13.

$$Q_B = Q_{up} \quad (10)$$

$$Q_{su,v}\ .h^/ = Q_{B.}\ l \quad (11)$$

$$h^/ = h_0 + h_2 + h_{beam} \quad (12)$$

$$l = l_1 + l_o + l_2 + 2d_c \qquad (13)$$

### 2.2 Flexural Shear ($Q_{mu}$)

Similar to the calculation of shear strength in the previous section, the flexural shear strength $Q_{mu}$ has been calculated considering both horizontal (h) and vertical (v) direction at the opening location and then minimum value between $Q_{mu,h}$, $Q_{mu,v}$ has been taken for $Q_{mu}$ as per Eq.14. The schematic diagram of Fig.3 shows the flexural shear ($Q_{mu,h}$) considering horizontal direction. As for the calculation of flexural shear strength along horizontal direction, the whole structure is divided into two parts- left and right. The flexural capacities ($M_{uh}^{/}+M_{uh}^{//}$) for left part and right part about horizontal direction have been found from a program Response 2000 [10] using sectional analysis. Then, flexural shear strength of left part has been calculated using Eq. 16 and finally total flexural shear force in horizontal direction is found by adding the shear from left part and right part as per Eq. 15. The necessary equations for the calculation of flexural shear strength are given from Eqs. 14-16.

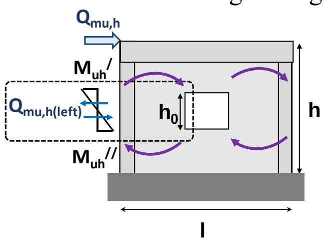


Fig.3: Flexural strength of wall with opening considering moment about horizontal direction

$$Q_{mu} = \text{Minimum of } Q_{mu,h}, Q_{mu,v} \qquad (14)$$

$$Qmu_h = Qmu_{hleft} + Qmu_{hright} \qquad (15)$$

$$Q_{mu,h(left)} = \frac{M_{uh}{'} + M_{uh}{''}}{h_o} \qquad (16)$$

Here $M_{uh}^{/}$ and $M_{uh}^{//}$ are moment capacity of the left pier beside opening at top and bottom respectively. The schematic diagram of Fig.4 shows the flexural shear ($Q_{mu,v}$) considering vertical direction.

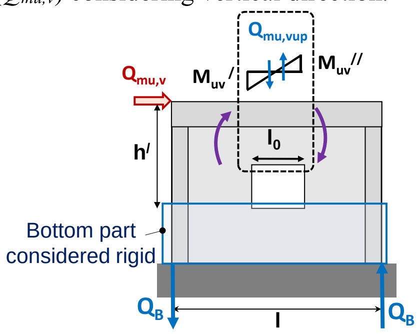


Fig.4: Flexural strength of wall with opening considering moment about vertical direction

In case of vertical direction, only top part above the opening is considered for flexural shear calculation (see Fig.4) and bottom part below the opening is not taken into account for rigid base beam described earlier in section 2.1. At first, flexural shear strength of the upper part $Qmu_{,v,up}$ in vertical direction (see Fig.4) is calculated using Eq. 18. It is to mention here that the moment capacities $M_{uv}^{/}$,$M_{uv}^{//}$ are found from response 2000 [10]. Then using moment equilibrium equation given in Eq. 19, the lateral strength $Q_{mu,v}$ is calculated considering vertical directional flexural shear ($Q_B$). The necessary equations for calculating $Q_{mu,v}$ are given in Eqs. 17-19.

$$Q_B = Q_{mu,v,up} \qquad (17)$$

$$Q_{mu,v(up)} = \frac{M_{uv}{'} + M_{uv}{''}}{l_o} \qquad (18)$$

$$Q_{mu,v}.h^{/} = Q_B.l \qquad (19)$$

Here $M_{uv}^{/}$ and $M_{uv}^{//}$ are moment capacity at left and right side of the top spandrel above opening respectively. $h^{/}$ , $l$ are calculated using Eqs. 12 and 13 respectively given in section 2.1.

## 3. INVESTIGATION OF THE ANALYTICAL APPROACH WITH PAST TEST RESULT

The simplified approach has been applied to some previous test specimens and then compare the strength reduction with the test results. It is to mention here that in this study, only single opening cases carried out by Ono and Tokuhiro [1] are taken into consideration. Other studies mentioned in Figure 1 are not all considered in the present study, due to unavailability of necessary information such as material properties, or due the presence multiple opening in other studies which is out of the scope of this study. Fig.5a and 5b illustrate the comparison of lateral strength reduction factor ($Q_{max,0}$ /$Q_{max,s}$) obtained from past test studies [1] with those calculated from AIJ code and simplified approach respectively.

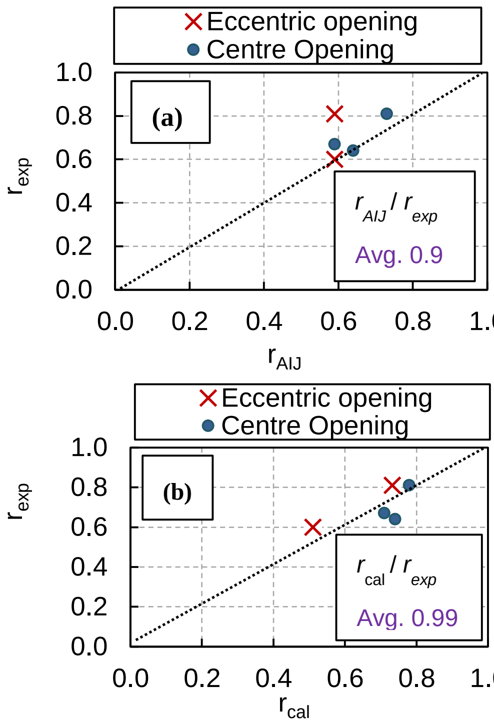


Fig.5: Comparing strength reduction factor between Ono's test and (a) AIJ code (b) simplified method

It has been observed that AIJ code [8] exhibits same strength reduction for all eccentric openings whereas simplified approach shows variation in strength for different opening location that matches well with the test results.

## 4. INVESTIGATING PARAMETERS USING SIMPLIFIED APPROACH

The detail of RC wall with frame considered in the present study is shown in Fig.6. In order to make the parametric study more practical and similar to real conditions, the basic RC wall is taken similar to a specimen from a previous study by Ono and Tokuhiro [1]. However, it should be noted that the reinforcement of columns, wall and beam are considered like the study by Ono and Tokuhiro [1], but other parameters such as aspect ratio, and opening size are investigated by choosing many several random cases due to limited test number and for better understanding. The assumptions of material are taken as following: for RC wall and frame, compressive strength of concrete: 27MPa and yield strength of steel rebars: 387MPa for D6, D10 and 344MPa for D13 rebar. The geometric dimension (in mm) of RC wall and other detail are given in Table 1.

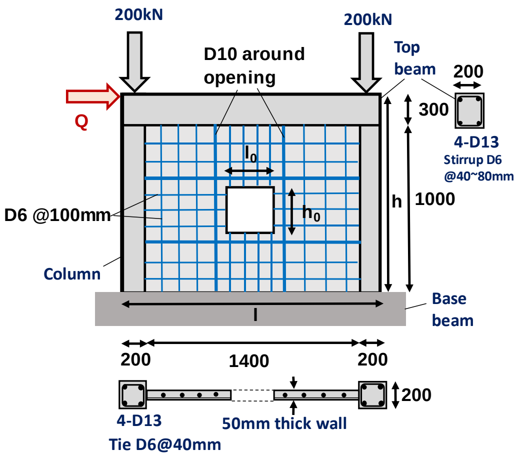


Fig.6: Geometric detail of RC wall with frame

Table 1: Geometric dimensions and other detail

| Component | x × y | Main Rebar | Shear steel |
|---|---|---|---|
| RC Column | 200×200 | 4-D13 | Tie D6 @ 40 |
| RC Beam | 200×300 | 4-D13 | Stirrup D6@40-80 |
| RC Wall | 1400×1000 | D6 @ 100 (horizontal & vertical) | |

*dimensions are in mm.*

In this section, the effect of different parameters of opening on the lateral strength of RC wall is going to be discussed using simplified approach described earlier. The parameters considered in this study are size, shape, location of opening and another parameter- the wall confinement.

### 4.1 Opening size

The schematic diagram of RC wall with different opening size has been shown in Fig.7. It is noted that the opening considered here are square and center located. The equivalent opening area ratio investigated for the analysis are listed in third column of Table 2. Fig.8 illustrates the effect of opening area on the lateral strength reduction of RC wall.

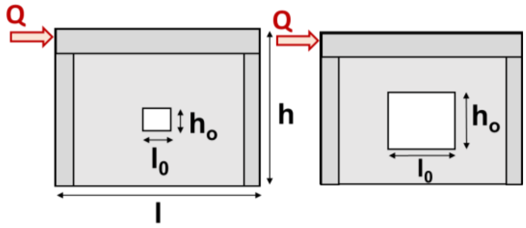


Fig.7: Different opening size considered for RC wall

Table 2: Equivalent opening area ratio for the study

| Case | $h_o \times l_0$ | $\sqrt{\frac{h_0 l_0}{hl}}$ |
|---|---|---|
| 1 | 170×170 | 0.11 |
| 2 | 370×370 | 0.20 |
| 3 | 470×470 | 0.31 |
| 4 | 570×570 | 0.37 |
| 5 | 670×670 | 0.44 |
| 6 | 770×770 | 0.50 |
| 7 | 820×820 | 0.54 |
| 8 | 870×870 | 0.57 |
| 9 | 920×920 | 0.60 |

*dimensions are in mm.*

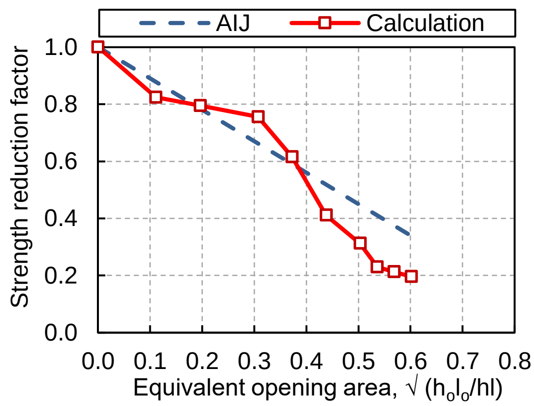


Fig.8: Strength reduction for different opening size

From Fig.8, a decreasing trend of lateral capacity has been observed with the increase in opening area, which is quite logical. There is a rapid decrease of strength from opening ratio of 0.3. This is thought to be due to the change of failure mechanism from shear failure to flexural failure, which is discussed in next paragraph. The values by simplified approach have similar tendency of strength reduction as shown in Fig.8. It should be noted that AIJ code have a limitation for reduction of strength ratio of opening of max as 0.4. Therefore, values plotted in Fig.8 for AIJ code is just plotted for comparison but not permitted in the code. Fig.9 presents the lateral strength variation of RC walls with opening area considering both shear ($Q_{su}$) and flexural ($Q_{mu}$) capacity. The investigated RC walls fail in flexure

($Q_{mu}$<$Q_{su}$) when equivalent opening area is above 0.35.

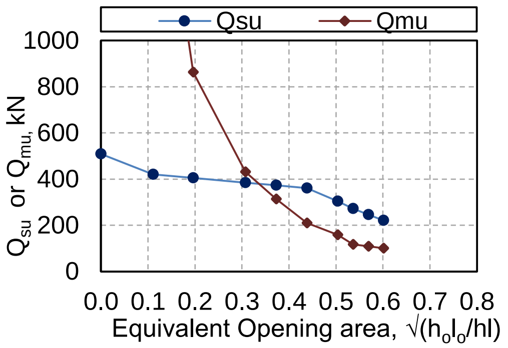


Fig.9: Comparing $Q_{su}$, $Q_{mu}$ for different opening area

## 4.2 Aspect ratio of opening

Aspect ratio is another important parameter that is thought to change the behaviors of the wall with opening. The schematic diagram of RC wall with different opening shape is shown in Fig.10. The parametric study of aspect ratio of opening considered in this study are listed in Table 3. All the cases have same opening area, but with different aspect ratio.

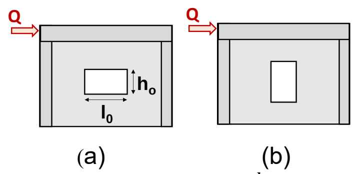


Fig.10: (a) Opening aspect ratio $\frac{h_0}{l_0} < 1$ (b) $\frac{h_0}{l_0} > 1$

Table 3: Aspect ratio of opening considered in the study

| Case | $h_o$ | $l_o$ | $\frac{h_0}{l_0}$ |
|---|---|---|---|
| 1 | 100 | 900 | 0.11 |
| 2 | 150 | 600 | 0.25 |
| 3 | 200 | 450 | 0.44 |
| 4 | 250 | 360 | 0.69 |
| 5 | 300 | 300 | 1.00 |
| 6 | 360 | 250 | 1.44 |
| 7 | 500 | 180 | 2.78 |
| 8 | 600 | 150 | 4.00 |
| 9 | 900 | 100 | 9.00 |

*dimensions are in mm.*

Fig.11 shows the variation in lateral strength with different aspect ratio of opening having same opening area for better understanding the influence of opening shape only. The strength variation pattern obtained from

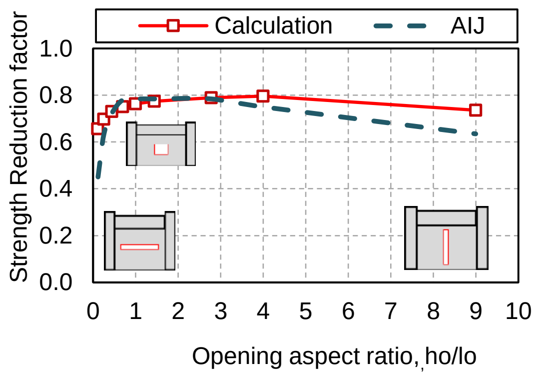


Fig.11: Strength variation with opening aspect ratio

simplified approach has similar tendency with the AIJ code. It has been found that for large opening length cases ($\frac{h_0}{l_0} < 1$), the walls fail in shear in horizontal direction because of small shear area along the wall length. Lateral strength increases visibly with the decrease of opening length but strength gradually decreases for large aspect ratio $\left(\frac{h_0}{l_0} > 1\right)$.

## 4.3 Opening location

RC walls with different opening locations considered in this study are shown in Fig.12. It is to mention that same opening has been considered here and the tests have been previously done by Ono and Tokuhiro [1], and is taken here to allow comparison with experimental results. Fig.13 shows the strength variation due to different position of opening. The simplified approach gives the tendency similar to that from the experiment. From figure 13, it is observed that AIJ code gives conservative estimate, however, the influence of opening location is not reflected in AIJ code [8].

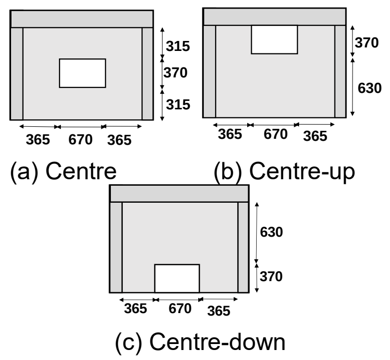


Fig.12 RC wall with same opening considered for different location *(dimensions are in mm.)*

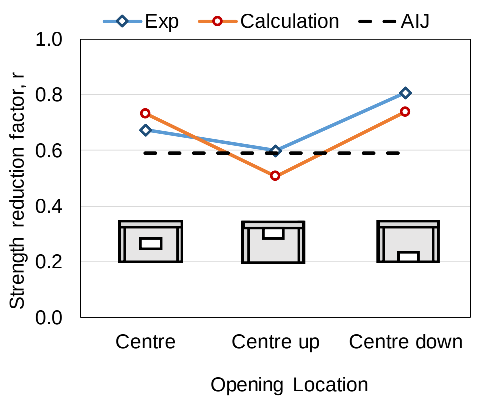


Fig.13: Strength variation with location of opening

It is noted here that the strength is reduced more when opening is located near the top of the wall while compared to centre opening from both test and simplified approach. For centre and centre up located opening (see Fig.13), $Q_{mu,v}$ that means flexural shear strength considering vertical direction has been found minimum from simplified approach. But in case of centre-down located opening, $Q_{su,h}$ , shear strength in horizontal direction has been found minimum which is very close to centre located opening case. However, this tendency does not look similar to previous test result.

### 4.4 Wall confinement

The boundary elements of the wall, (columns, flange walls) are thought to have large impact on shear strength of RC walls. The impact of those boundary elements is not clearly understood for walls with openings. RC walls with different wall confinement considered in this study are shown in Fig.14. One configuration taken here is square column and another one is flange with different dimensions (see Fig. 14).

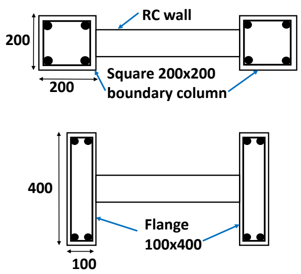


Fig.14: Different type of wall confinement *(dimensions in mm.)*

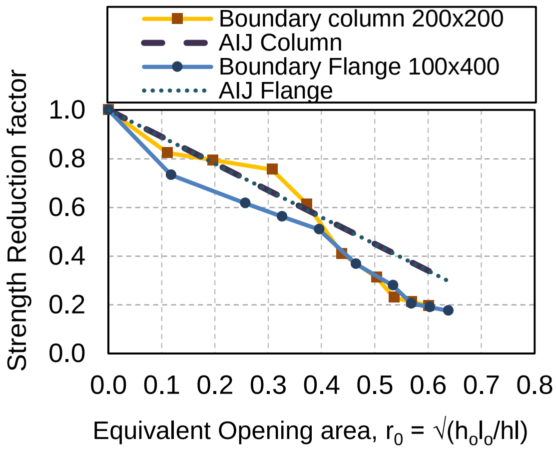


Fig.15: Comparison of strength reduction due to different boundary element

The boundary area and reinforcement are taken the same for both cases to allow comparison. Fig.15 presents the variation in lateral strength for different wall confinement. Reduction in lateral strength was found large up to opening area ratio of 0.4 in case of flange confinement while comparing to square column. After that, the strength reduction tendency was same for both cases. It is to mention that for both confinement cases, walls fail in flexure for opening ratio of 0.4 and above. It reveals that wall confinement does not effect much on the walls with very large opening that fail in flexure.

## 5. CONCLUSIONS

In the present study, a comprehensive investigation has been conducted on the lateral behavior of RC wall with opening considering different parameters. The following conclusions can be drawn -

a) *Opening size:* A decreasing trend of lateral capacity was observed with the increase in opening area. From simplified approach, RC walls fail in flexure for equivalent opening area of 0.35 and above.

b) *Aspect ratio of opening:* For lower aspect ratio of opening $\left(\frac{h_0}{l_0} < 1\right)$ , lateral strength increases with decrease of the length of opening whereas strength gradually decreases for large aspect ratio $\left(\frac{h_0}{l_0} > 1\right)$.

c) *Location of opening:* Location of opening is thought to have large impact on strength reduction. The simplified approach gives similar tendency with the experimental results. AIJ code gives a conservative estimate of strength reduction, however, the location of opening is not reflected in AIJ code.

d) *Wall confinement (boundary elements):* Wall panels with flange boundary have greater reduction than walls with column boundary having same boundary area up to opening are of 0.4. This might have happened due to comparatively less confinement at the wall end. Based on the simplified approach, the influence of boundary elements is not reflected in the AIJ code and this might give non-conservative results for walls with flange boundaries that needs further investigation.

It should be noted that other parameters not presented in this study might have influence on the performance of openings such as wall reinforcement ratio, influence of reinforcement around the opening. Those parameters are planned to be investigated in future studies.

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