- *Technical Paper-*

SEISMIC RESPONSE OF REINFORCED CONCRETE WALLS WITH OPENING: EXPERIMENT AND STRUT-AND-TIE METHOD

Zasiah TAFHEEM*1, Hamood ALWASHALI *2, Masaki MAEDA, *3 and Kazuya TSURUGAI *4

ABSTRACT

The influences of different opening parameters on the seismic response of RC walls are still poorly understood. Therefore, this study aims to investigate the effect of two parameters - opening size, and additional reinforcement around the opening on the seismic performance of the RC wall. In addition, a conceptually simple grid-type strut-and-tie model has been proposed for better understanding the seismic response in the RC walls with opening. Shear strengths of RC walls predicted by the strut-and-tie method are compared with the test results to verify the effectiveness of the proposed method.

Keywords : Influence of opening, seismic response, opening parameters, strut-and-tie method

1. INTRODUCTION

RC walls in buildings resist gravity load as well as lateral loads. Those walls feature various types of opening for functional requirements. The presence of an opening alters the seismic behavior of RC walls. Several investigations by past research studies [1-6] were carried out to investigate the influence of opening on seismic capacity. For instance, the Japanese design standard (AIJ, 2018) suggested a reduction factor for RC wall shear strength ($r_{strength}$) due to opening. Fig.1 illustrates the comparison of strength reduction factors obtained from several past test results and AIJ standard [7]. Even though AIJ standard [7] shows a conservative estimation of strength reduction due to opening, there is a large variation observed between test results and the analytical values by AIJ (strength reduction factor ratio-$r_{AIJ/experiment}$:0.69). Several parameters are influencing such variations, such as the influence of opening size, shape, location, etc. In summary, even though several investigations were carried out to evaluate the influence of opening on seismic capacity, however, the effect of each parameter, such as the influence of opening size, shape, location, etc. are still poorly understood. In order to understand the influence of opening on RC walls, each influencing parameter should be investigated separately from other parameters. Therefore, the objective of this study is to investigate the influence of two parameters: 1. opening size and 2. additional reinforcement around the opening on the seismic performance of RC walls. This study at first presents an experimental study of six small-scaled RC walls with opening tested under pure shear static cyclic loading.

The second objective is to predict the behavior of the RC wall with opening, using simple analysis by strut-and-tie method (STM). In this study, a simple grid-type strut-and-tie model has been developed to reduce the complexities in modeling and analysis in case of non-linear finite element analysis (NLFEA). Even though several past studies such as [8] estimated the capacity of RC wall with opening using strut-and-tie model, this study includes a non-linear approach to the strut and tie model as well as a more detailed grid system for the model. The proposed methodology is undertaken to investigate the estimation of strength using STM for opening of different sizes as well as the applicability of the STM method to estimate the yielding propagation of steel rebars and predicting the backbone curve of RC walls with opening.

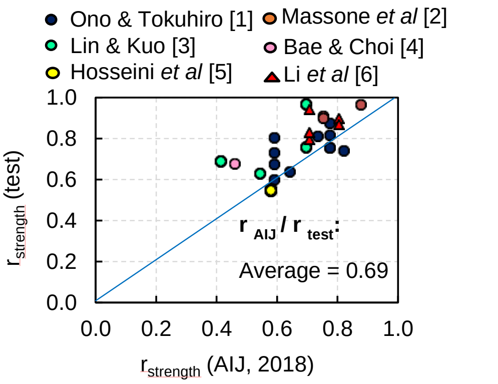

Fig.1 Comparison of the strength reduction factor

2. EXPERIMENTAL PROGRAM

2.1. Test setup

To understand the behavior of RC walls with an opening under lateral load, it is needed first to understand its behavior under pure shear load. The loading setup was inspired by past research work [9], where pure shear loading was applied to RC walls without opening. The new point here is that the idea of pure shear is applied to panels with an opening. The photograph of the test setup is shown in Fig.2. Four

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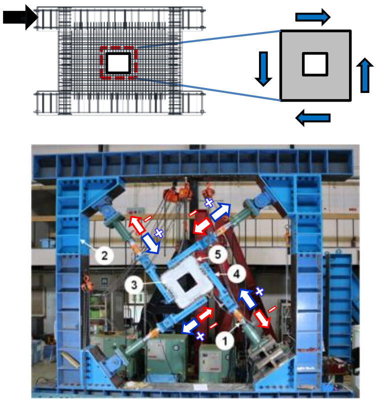
hydraulic jacks were used to apply reverse cyclic loads to resemble the seismic load and the loads were controlled by shear strain % (discussed in section 2.3). The lateral loading program consisted of two cycles for each shear strain of 0.0125%, 0.025%,0.05%, 0.1%, 0.2%, 0.4%, 0.6, 0.8%, and 1.5%. Specimens, that did not significantly degrade in strength, were then pushed monotonically.



[1. Hydraulic jack 2. Reaction frame 3. RC wall with opening 4. Loading plate attached with hydraulic jack 5. Steel plate attached at the edge of RC wall]

Fig.2 Test setup

2.2 Test Specimen detail

This study presents an experimental study of six small RC walls of length and height of 600mm×600mm and thickness of 60mm provided with a single layer of reinforcement. One wall specimen without opening and the other five specimens focus on two parameters: the size of the opening and additional reinforcement around the opening.

To measure the opening size, an equivalent opening area ratio (OAR) is used that is calculated using Eq. 1, as per AIJ [7]. The size of opening was designed to reflect three different opening area ratios as illustrated in Fig.3, where the specimen with the largest opening (S240) represents the case of opening larger than the limits (opening area ratio of 0.4) proposed in AIJ standard [7]. According to AIJ [7], if the equivalent opening area ratio is greater than 0.4, the wall should be modeled as a frame instead without the need for considering the strength reduction factor calculated by Eq.2 as per AIJ [7].

$$\text{Equivalent opening area ratio}=\sqrt{\frac{\sum h_0\, l_0}{h\, l}} \qquad (1)$$

$$r_{strength} = \text{minimum of } \{r_1, r_2, r_3\} \qquad (2)$$

$$r_1 = 1 - 1.1\left(\frac{\sum l_0}{l}\right);$$

$$r_2 = 1 - 1.1\sqrt{\frac{\sum h_0 l_0}{hl}};$$

$$r_3 = 1 - \lambda\frac{\sum h_0}{h};$$

where $r_{strength}$: reduction factor for lateral strength; l_0, h_0: horizontal and vertical length of opening; h, l: height and length of the wall. Fig.5 shows the dimensions, reinforcement details of six test specimens in which the main reinforcing bars were placed in a single layer of D6 with a spacing of 40mm with a reinforcement ratio of 1.3%. The reinforcement is decided to represent a full-scale solid RC wall that was tested by a past study [10].

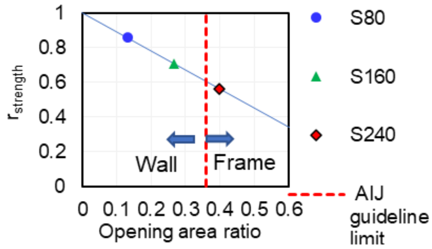


Fig. 3 Relation between opening size and AIJ reduction factor

As for the parameter of additional reinforcement around opening, the calculation of additional reinforcement of two specimens S80A and S160A was based on AIJ [7] using Eq.3.

$$A_d f_t + \frac{A_v f_t}{\sqrt{2}} + \frac{A_h f_t}{\sqrt{2}} \geq \frac{h_0 + l_0}{2\sqrt{2}l} Q_d \qquad (3)$$

A_d : cross-sectional area of diagonal reinforcement at a corner of the opening ; A_v and A_h: cross-sectional area of additional bars around an opening in vertical and horizontal directions, respectively ; f_t: allowable tensile stress of reinforcement ; Q_d: reduced lateral strength of wall with an opening. To avoid congestion of reinforcement in small-sized specimen, the additional reinforcement D10 replaced D6 just beside the opening, taking into consideration the necessary steel area calculated as per AIJ [7].

The details of the specimens are shown in Table 1 and the mechanical properties of reinforcement are shown in Table 2.

Table 1: Summary of specimen detail and parameters

Specimen name	S80	S80A	S160	S160A	S240	SS
Panel dimensions (mm) $h \times l \times t$	600 × 600 × 60					
opening size (mm × mm) $h_o \times l_o$	80×80		160×160		240×240	-
opening ratio $\sqrt{((\sum h_o\, l_o)/(h\, l))}$	0.13	0.13	0.27	0.27	0.40	-
Main reinforcement	D6@40mm (SD295)					
Main reinforcement ratio, ρ_w (%)	1.33					
Additional steel at each opening side A_v or A_h	-	1D10*	-	2D10*	-	-
Additional steel provided (A_v+A_h) at each corner of opening (mm^2)	-	78*	-	156*	-	-
Minimum additional steel area (A_v+A_h) calculated by AIJ [7] (mm^2)	-	55	-	91	-	-
Concrete compressive strength (MPa)	32.2					

The stress-strain responses of the compression test of three concrete cylinders are shown in Fig.4. The average of those three cylinders are taken into consideration.

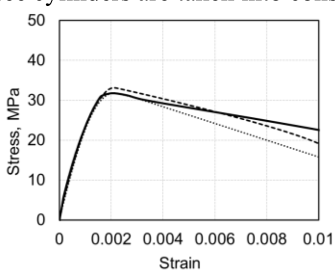


Fig. 4 Stress-strain response of compression test

The summary of additional reinforcement provided, and minimum required steel area are also shown in Table 1. Among six test specimens, one was a RC wall specimen without opening (SS), three specimens namely, S80, S160, S240, focused on three different sizes:80×80mm (OAR:0.13), 160×160mm (OAR:0.27), 240×240mm

(OAR:0.4); other two specimens S80A, S160A were provided with additional rebar around opening.

Table 2: Mechanical properties of reinforcing bars

Steel rebar	Nominal strength	E_s (MPa)	f_y (MPa)	f_u (MPa)
D6	SD295	1.56×10^5	315	525
D10	SD295	1.84×10^5	353	515

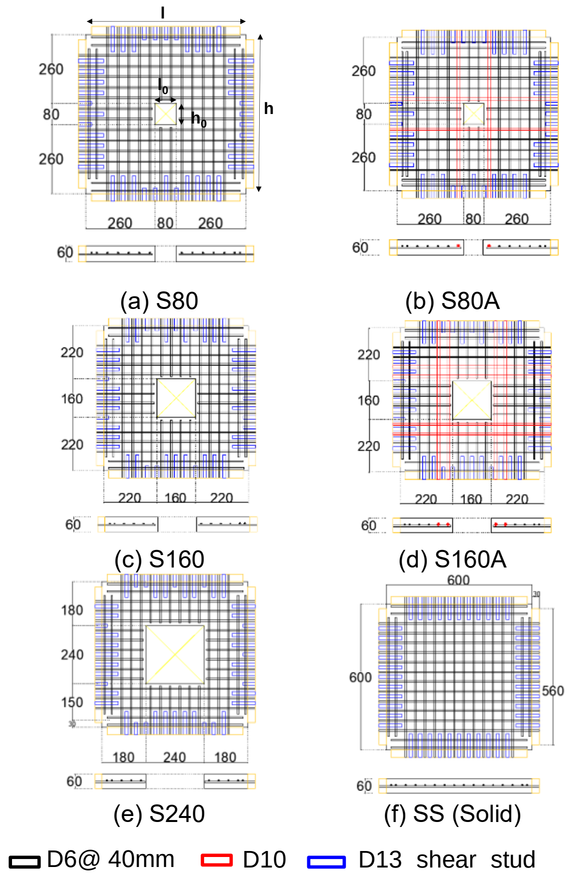
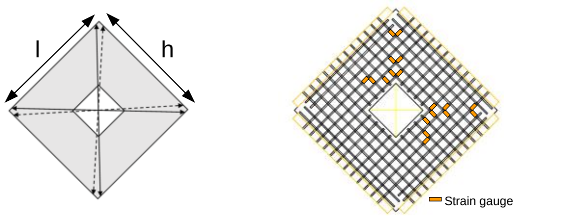


Fig.5 Detail of test specimens

A steel plate was attached to each of the four sides of the specimen to connect the specimen with hydraulic jacks. Shear studs of D13 were provided along with the steel plate and specimen for connection as shown in Fig. 5.

2.3 Instrumentation

Four displacement transducers (LVDTs) were attached diagonally shown in Fig.6a on both front and backside to calculate shear strain (γ) as calculated from Eq.4.



(a) Attached LVDTs (b) Attached strain gauges

Fig.6 Instrumentation of S160

In addition, strain gauges were attached to steel rebars around opening as shown in Fig.6b.

$$\gamma = \frac{\sqrt{h^2+l^2}}{2hl}(\Delta v - \Delta h) \tag{4}$$

where Δh, Δv are the deformation measured from two diagonal LVDTs along horizontal and vertical direction.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Failure modes

Fig.7 shows the failure modes of six specimens along with observed cracks. For walls with opening, final failure was accompanied by sudden abrupt degradation of strength caused by the crushing of concrete along the corner of the opening. The failure process of the specimens followed the development of diagonal cracks as expected by pure shear loading. Specimen S240 with the largest opening size (see Fig.7f) had relatively few numbers of cracks with large crack width.

3.2 Load-deformation hysteretic curves

The lateral load versus shear strain graphs of six test specimens are shown in Fig.8. The first cracks appeared at a shear strain of 0.0125~0.025% accompanied by gradual degradation of stiffness. The first yield of reinforcement observed by strain gauges was in the range of shear strain of 0.08% ~0.15%. At shear strain of 0.4%~0.6%, almost all reinforcement yielded.

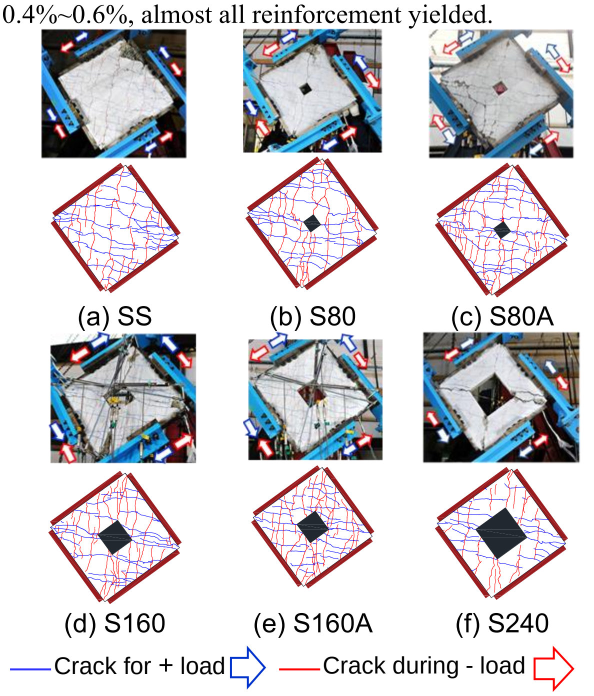


Fig.7 Crack observed with photos of failed specimens

3.3 Effect of opening size

A comparison of backbone curves of specimens (SS, S80, S160, S240) for +cycle load with the variable opening size is shown in Fig.9a. The reduction in strength was found about 12%, 22%, and 38% for RC walls with OAR of 0.13, 0.27, and 0.40, respectively. A comparison of secant stiffness with the opening size is shown in Fig.9b. There is a gradual decrease in stiffness and strength as the opening gets larger. However, the specimen S240 with an opening area ratio of 0.4, had a larger degradation in stiffness as well as strength while compared to S80 and S160. A comparison of reduction in strength, recommended by the AIJ guideline [7] with test results (walls without additional reinforcement) is shown in Fig.10. The AIJ [7] gave a conservative estimation even for specimens without the required additional reinforcement.

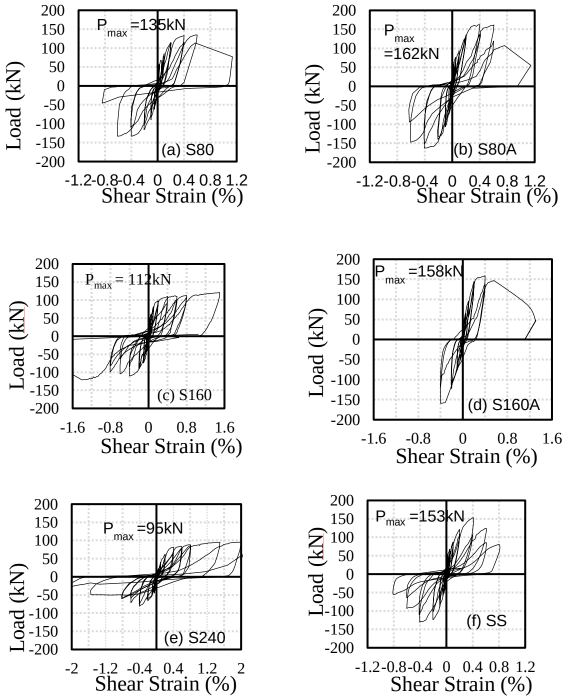


Fig.8 Lateral load-shear strain hysteretic curves

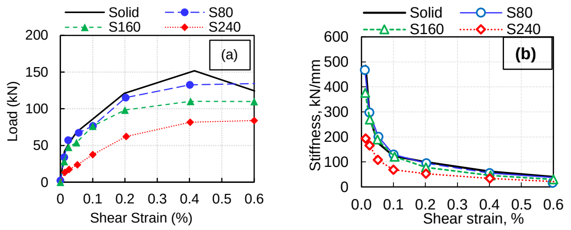


Fig.9 Comparison of (a) backbone curves (b) secant stiffness for different opening size

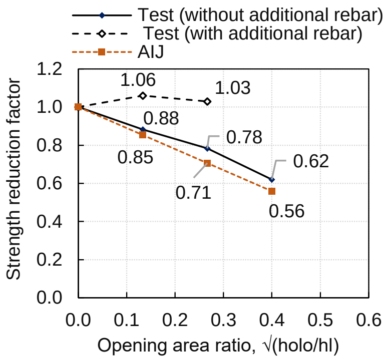


Fig.10 Strength variation for different opening size

3.4 Effect of additional rebar around opening

Fig.11a, 11b show the strength variation for RC walls with and without additional rebar around opening (S80& S80A, S160&S160A). It is found from Fig.9 that specimens with additional reinforcement around the opening had strength almost like that of the wall specimen without opening. However, the additional rebars around the opening were found insignificant in enhancing the initial stiffness (see Fig.11).

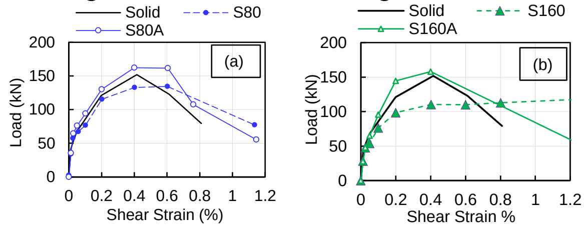


Fig. 11. Comparison of backbone curves of (a) SS, S80, S80A (b) SS, S160, S160A

4. METHODOLOGY OF STRUT-TIE METHOD

Although several past studies [8] performed a strut-and-tie approach to predict the capacity of a deep beam or RC walls, no study has been found so far focusing on investigating the applicability of strut and tie model on RC wall with opening considering different parameters of opening. In this study, a simple grid-type strut-and-tie model has been developed for capturing the seismic response of RC walls considering different opening sizes, and additional reinforcement around the opening. The objective is investigating the estimation of strength using STM for opening of different sizes as well as verifying the applicability of STM to estimate the yielding propagation of steel rebars and predicting the backbone curves. The strut-and-tie model (STM) is created by a set of diagonal struts and tension ties (see Fig.12) modeled as simple truss members. Even though the analysis of truss elements can be done using complex hand calculation, it requires much computational time and effort. Therefore, a simple truss model was constructed using a computer-aided program [11]. The proposed methodology is based on the principle that the compression forces are transferred through the diagonal concrete struts, and the tension forces are carried by the steel ties. In addition, the nonlinear load-deformation behavior has been incorporated in the struts and ties.

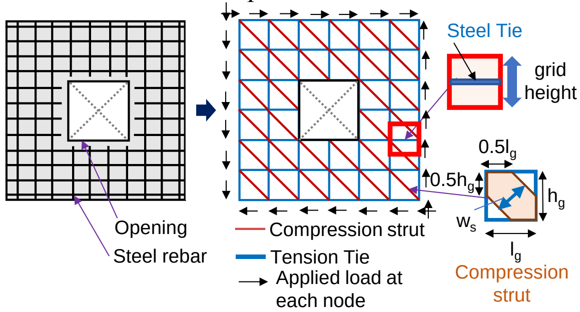


Fig.12 Idealized grid type strut-and-tie model (STM)

4.1 Formation of grid system

A grid strut-tie model is composed of several grids, and each grid consists of two horizontal, two vertical, and one inclined element. The model is shown color-coded (see Fig.12) where blue represents the ties, red represents the struts, and their intersections represent the nodes. A steel tie represents all the steel rebars exist between half the distance of each grid as indicated in Fig.12. The width of a compression strut is assumed by taking half of the width ($0.5l_g$) and half of the height ($0.5h_g$) of a grid as shown in Fig.12. The strut width was assumed by taking half of the width and height, this is just an assumption in this study for simplification and was assumed based on REF [12], which showed a good correlation with their experimental results. Further calibration of the strut width is needed in future studies for further improvement of calibration. The number of grids has been chosen in such a way so that the seismic response of the RC wall structure can be captured properly. It should be noted, the grid size here was assumed to be a simple STM model where two grids (two struts) exist on each side of the opening. This is an assumption that was used to simplify the analysis. The sensitivity of the size of the grid is an important point, that needs further investigation and is not presented in this study. Aspect ratio of wall is also expected to have some impact on the result of analytical model. As all studied specimens are square in shape, hence further study is needed to reflect the effect of shape of wall.

4.2 Application of load

The load is applied at each node of top, bottom, right, and left edge of the wall using static pushover analysis so that a pure shear condition can be achieved (see Fig.12).

4.3 Assumptions for tie

Fig.13a illustrates the bilinear inelastic stress-strain behavior of tension ties for simplicity. The yield strength of a steel tie is calculated using Eq. 5 shown below.

$$F_t = f_y \cdot A_{tie} \quad (5)$$

where f_y: yield strength of steel rebar, A_{tie}: cross-sectional area of each tie.

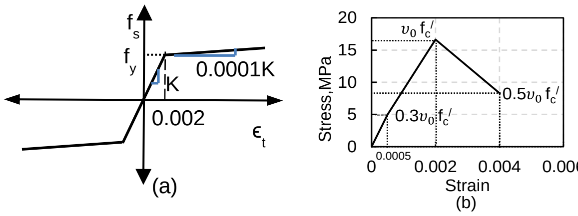


Fig.13 σ-ϵ behavior for (a) steel tie (b) concrete strut

4.4 Assumptions for strut

Fig.13b illustrates the nonlinear inelastic stress-strain behavior of compression struts. The strength of the concrete strut is assumed using Eq.6 shown below.

$$F_c = (\upsilon_0 f_c').w_s\, t \quad (6)$$

where $\upsilon_0 f_c'$: effective concrete strength w_s: strut width, t: wall thickness. The effective strength of a concrete strut is chosen as fraction of uniaxial compressive strength of concrete f_c' due to tension stiffening effect. Coefficient of effective strength of concrete strut (υ_0) is calculated using Eq.7 as per AIJ [7]. The cracking is assumed to occur at $0.3\times\upsilon_0 f_c'$, failure state at $0.5\times \upsilon_0 f_c'$. The strut width is assumed using Eq.8 (see Fig.12).

$$\upsilon_0 = 0.7 - \frac{f_c'}{200} \quad (7)$$

$$w_s = \sqrt{(0.5h_g)^2 + (0.5l_g)^2} \quad (8)$$

where h_g, l_g: height and length of each grid respectively.

5. COMPARISON OF THE STRUT-TIE MODEL

5.1 Ultimate strength and backbone curve

Fig.14 depicts the load-shear strain responses obtained from the test and strut-tie model of six investigated RC walls.

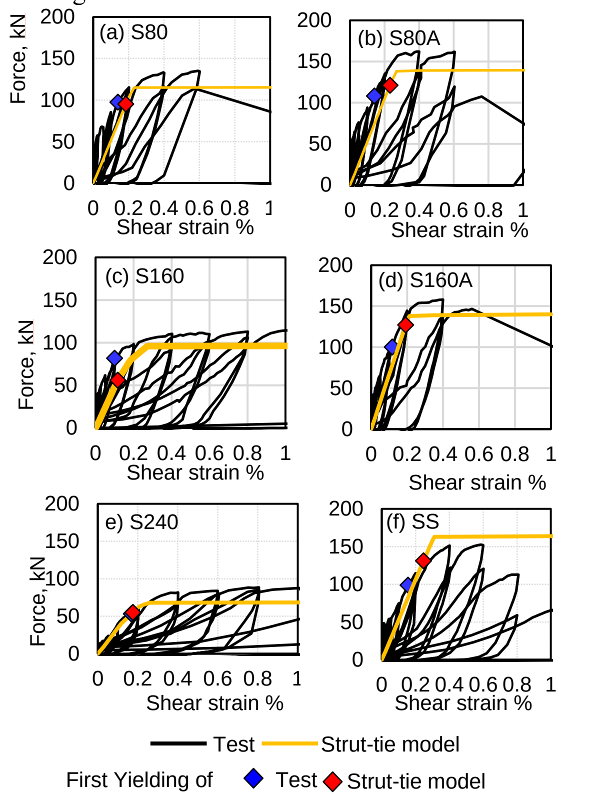


Fig.14 Load-Shear strain graphs from test and STM

As shown in Fig.14, the backbone curves obtained from strut-tie models can conservatively estimate the peak strength. In the case of the strut-tie model, the shear strain has been calculated using Eq.4 (mentioned in section 2.3), and the applied loads were obtained from different load steps of pushover analysis. Fig.15 illustrates the comparison of lateral strengths obtained from the test and strut-and-tie models. The average ratio of lateral strengths obtained from the strut-and-tie method and the test has been found 0.89 which shows conservative estimation and close to test results within the range between 5-15%. The Strut and tie model can approximately estimate the backbone curve. However, as shown by Fig.14, further calibration of the model is needed to capture the initial stiffness and its softening effect. The initial stiffnesses while using the STM were greatly underestimated compared to those from the test (see Fig.14). However, the initial stiffness in the proposed model underestimates because STM considers ties by only reinforcement; but concrete also works as well in tension until the concrete reaches its cracking strength. The incorporation of the concrete tensile strength (until cracking load) could be added to ties to improve the accuracy of estimating initial stiffness from STM in future investigations.

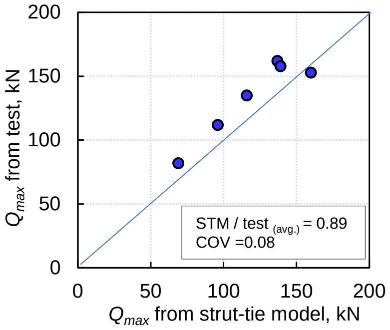


Fig.15 Comparison of strength between test and STM

5.2 Propagation of yielding

The yielding propagation of steel rebars (or ties) of two test specimens SS (solid) and S160, and the corresponding strut-tie models are presented in Fig.16. It is observed from Fig.16a-16b that for both wall without opening, test specimens and strut-tie models, yielding started near the corner of wall and progressed toward the center of wall, whereas for wall with opening (see Fig.16c-16d), yielding initiated near the corner of opening, and then diagonally propagated toward the corner of wall. The strut and tie models can capture the tendency of yielding propagation in wall with opening. Other walls with opening have the similar tendency of yielding propagation as S160, but due to space limitations, only one wall with opening is presented here.

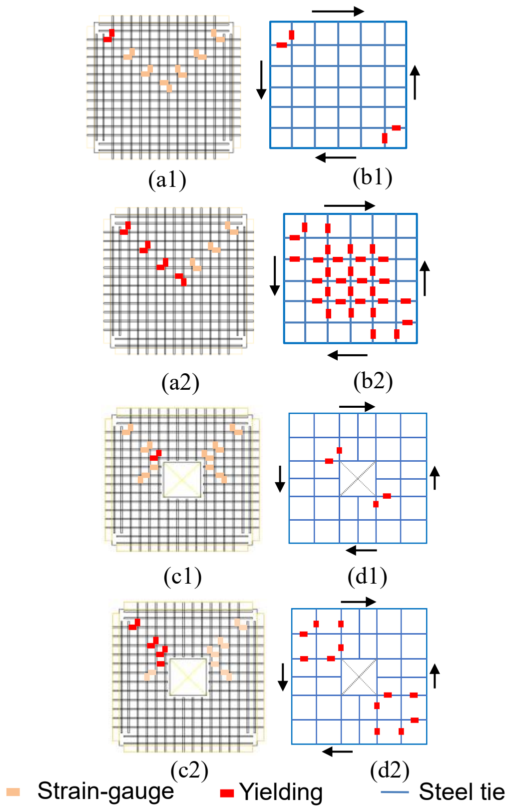


Fig.16 Onset of yielding (1), yielding at Q_{max} (2) of SS (a-b), S160 (c-d) test specimens (left) and STM (right)

6. CONCLUSIONS

In the present study, experimental investigation has been carried out on the seismic response of RC wall with opening considering two parameters- opening size, and additional reinforcement around opening. A simple grid-type strut-and-tie model is proposed to predict the seismic response of RC walls with opening. The following conclusions can be drawn –

1) It was found from the test that the reduction in strength follows a linear tendency with the increase in opening area ratio. The test results showed that the lateral strength was reduced by 12% to 38% for the opening area ratio ranging from 0.13 -0.4. In addition, the ultimate strengths of walls with additional reinforcement around opening were greatly increased compared to walls without additional reinforcement.
2) A simple grid-type strut-and-tie model has been proposed to predict the seismic response of RC walls with opening. Lateral strengths of RC walls with opening predicted by the proposed strut-tie method agree well with test results, and it gave almost conservative prediction within 5-15%.

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