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# EFFECT OF OPENING SIZE ON COMPRESSIVE STRUT OF RC SHEAR WALLS WITH OPENINGS BASED ON FEM ANALYSIS

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## *Abstract*

In this paper, applicability of the model for wider range of the opening ratio is examined. A 2D non-linear finite element (FE) analysis for shear walls with or without openings is conducted to investigate the effect of opening sizes on their internal compressive struts. All the analytical models in this study assume almost the same opening shape, and the parameters are the layout of openings and their widths corresponding to the opening ratio from 0.05 to 0.5.

The analytical results show that compressive diagonal struts are formed between openings and transfer shear in walls in similar way to the previous studies depending on the opening ratio. In the range of the opening ratio up to 0.4, calculated strength agrees well with those obtained from the conventional method based on the practically used opening ratio. But, as for the larger opening ratio than 0.4, remarkable concentrated stress in strut ends is observed at the connections to the columns, and this stress concentration makes it difficult to accurately predict the failure mechanism. It is concluded that further investigations are necessary to precisely estimate the strength of shear walls with the larger opening ratios, taking account of struts formations and their ultimate state criteria.

*Keywords: RC shear wall, FE analysis, opening size, compressive strut, shear strength*

## 1. Introduction

In Japanese practice, the shear strength of RC walls with openings is generally estimated as reduced strength of the walls without opening having the same configuration and bar arrangement. The reduction factor is basically defined by the equivalent perimeter ratio of openings, which is the ratio of the opening area to the total wall surface area evaluated by the equation below[1].

$$\eta = \sqrt{\frac{\sum h_{op} l_{op}}{hl}} \tag{1}$$

where, $h$ : story height(mm), $l$ : wall lengh including both boundary columns (mm)
$h_{op}$, $l_{op}$ : opening height and opening lemgth (mm), $\eta$ : equivalent perimeter ratio of openings

The locations of openings in the wall should be also taken into account. However, according to past structural test results and actual seismic damages of shear walls with openings, their failure mechanisms are complicated and cannot be simply estimated by the reduction factor. The reason for the complexity is that the behavior of the shear walls with openings is significantly affected by the differences of the number and the layout of openings. In fact, few cases of studies have been conducted focusing on the seismic performance of the shear walls with multi-openings. Main objective of this study is to develop a reasonable evaluation method for the shear strength of the RC walls with multi-openings.

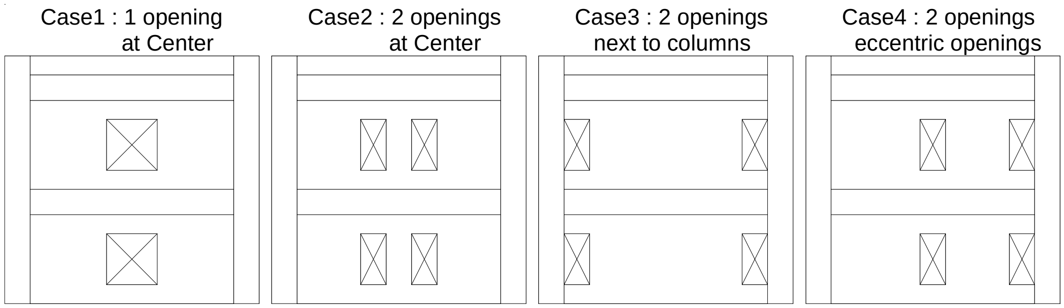


Fig. 1 – Opening Types

The author constructed a simplified shear resistant model of shear walls with multi-openings referring to previous studies. The proposed model was based on an analytical method in which compressive diagonal struts transferring shear were assumed to be formed between individual wall elements around openings. The model showed a good agreement with the experimental results regardless of the opening layouts and loading directions. However, the proposed model was focusing on the shear walls with the constant opening ratio of 0.4. Therefore, the plactical application of the proposed model has not been examined in detail.

In this paper, a two dimensional non-linear finite element (FE) analysis for the shear walls with two openings were parametrically conducted for the shear walls with several opening sizes and layouts to investigate the influence of the opening size and location. Then, the applicable ranges of the proposed shear resistant model are examined.

## 2. FEM Parametrical Analysis

### 2.1 Analytical Models

Parametrical analyses were conducted for the RC shear walls with several opening layouts to investigate influence of opening size on stress transferring mechanisms in RC shear walls. Examples of the configuration of analytical models are shown in Fig.1. Examined parameters are shown in Table 1. The specifications of sections and the mechanical properties of materials used in the analysis are listed in Table 2 and 3

In the previous studies by the authors, the static loading tests on RC shear walls with openings were carried out to investigate the influence of different number and arrangement of the openings [2, 3]. Test specimens were designed to simulate the lower 2 stories of multi-story shear wall in medium-rise RC buildings and scaled to one third of the prototype wall. The variables investigated were the size and arrangements of the openings, and the opening ratio were equally 0.4.

The analytical models were designed based on the specimens used in the previous tests. In this study, a total of 25 RC shear walls were analyzed including 4 specimens previously tested by the authors (Case1 to Case3: [2], Case4: [3]). The equivalent perimeter ratio of opening in this study varied from 0.1 to 0.5. The models are named as [Opening type] – [value of the equivalent perimeter ratio]. For an example, a model with opening type Case1 and equivalent perimeter ratio 0.4 is named as Case1-0.4. Opening type Case1 has one opening at center, while Opening Types Case2, Case3 and Case4 have two openings. The two openings in Type Case2 are positioned close to another at center, those in Type Case3 are on both sides, while those in Type Case4 are eccentrically located as shown in Fig.1.

### 2.2 Analytical Method

The finite element mesh layout for analytical model Case1-0.1 is shown in Fig.2. A quadrilateral plane stress element was used for concrete. Reinforcing bars in the wall panels and transverse reinforcements of boundary columns and beams are substituted by equivalent layers with stiffness in the bar direction and superposed on the quadrilateral elements. Longitudinal reinforcing bars in boundary columns and beams were modeled by truss elements. Line elements were used between truss elements and quadrilateral elements to consider the bond slip behavior.

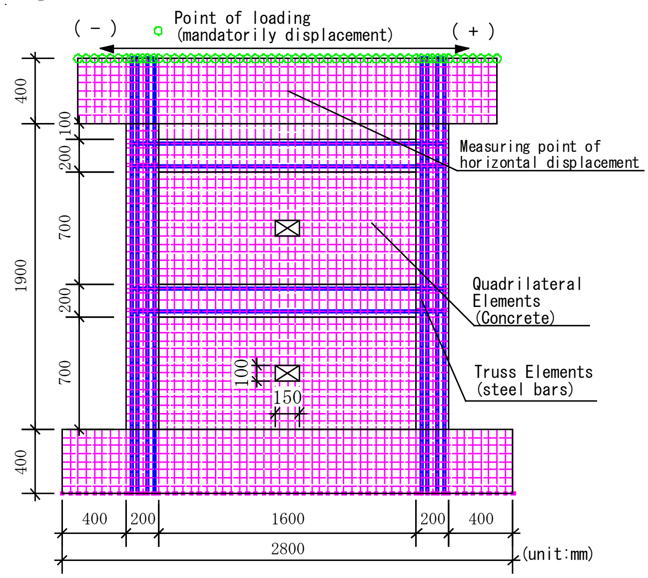


Fig. 2 – Finite element Mesh (Case1-0.1)

Each node at the end of the lower stub had pin support to restrain vertical and lateral displacement. A node at the top of the upper stub was subjected to lateral displacement reversals with applying a constant initial axial force. The FEM non-linear analysis software "FINAL" was used in this analysis [4].

Table 1 – Examined parameters

| Equivalent Perimeter Ratio | Case1 | | Case2 ～ Case4 | |
|---|---|---|---|---|
| | Size(mm) | Number | Size(mm) | Number |
| 0.09 | 100*150 | 1 | 100*75 | 2 |
| 0.15 | 200*200 | | 200*100 | |
| 0.2 | 250*200 | | 250*150 | |
| 0.3 | 400*400 | | 400*200 | |
| 0.41 | 500*600 | | 500*300 | |
| 0.48 | 700*600 | | 700*300 | |

Table 2 – Specification of section

| | | |
|---|---|---|
| Column | B×D | 200*200 |
| | Longitudinal bar | 12-D13 ($p_g$=3.8%) |
| | Tie | 2-D6@60 ($p_w$=0.53%) |
| | Sub-tie | 2-D6@120 ($p_w$=0.27%) |
| Beam | B×D | 150*200 |
| | Longitudinal bar | 4-D10 ($p_t$=0.54%) |
| | Stirrup | 2-D6@100 ($p_w$=0.42%) |
| Wall | Thickness | 80 (mm) |
| | Longitudinal bar | D6@100zigzag ($p_s$=0.4%) |
| | Transverse bar | D6@100zigzag ($p_s$=0.4%) |
| | Bar around opening | D10 (longitudinal, horizontal, diagonal) |

Table 3 – Propaties of material in analysis

| Concrete | | |
|---|---|---|
| $\sigma_B$ (N/mm$^2$) | 1st story | 25.0 |
| | 2nd story | 25.0 |

| Steel bars | | | |
|---|---|---|---|
| Type | Loacaton | $\sigma_y$ (N/mm$^2$) | $E_s$ (kN/mm$^2$) |
| D6 | Wall bars, Ties, Stirrups | 325 | 210 |
| D10 | Beam/Opening reinforcement | 380 | 210 |
| D13 | Column reinforcement | 380 | 210 |

2.3 Constitutive Laws of Materials

Concrete is idealized using the orthotropic model based on the strain concept. The smeared crack model for concrete elements was determined non-orthotropically crack model considered that it is able to represent multi-directional cracking [5]. As for the stress-strain relationships of concrete, a modified Ahmad model was adopted for the stress-strain curve as shown in Fig.3. Kupher-Gerstle's criterion [6] was applied for failure in biaxial compression and in tension-compression. Degradation of compressive strength and strain after cracking were incorporated. The compressive reduction factor was defined as a function of uniaxial compressive strength of concrete and acting normal stresses along reinforcing directions modeled on basis of RC panel tests by Naganuma [7]. In the tensile zone, the tension stiffening envelope after cracking determined as a function of the compressive stress and reinforcement ratio proposed by Yamaguchi and Naganuma [8]. The hysteric rule on the shear stress - shear strain relationship was modeled as shown in Fig.4. Shear transferring action is expressed by the average shear stress-shear strain relationship along the crack direction. The shear stress - shear strain envelope was determined as a function of the concrete strength, the amount of reinforcing steel crossing the cracks, and tensile strain perpendicular to the crack direction as shown in Fig.5 [7]. The bond stresses between reinforcing bars and concrete versus slip deformation relationships are shown in Fig.6. The maximum bond stress of concrete calculated by the AIJ design standard for RC buildings based on inelastic displacement concept [9] and the sliding at the maximum bond stress was assumed to be 1.0mm. The reversal loading model of bond behavior was represented by the modified Elmorsi model as shown in Fig.7 [10].

The material model of reinforcing bars was a plasticity model, which is the Von Mises model failure surface with associated plastic rule. The stress-strain curve of the reinforcing bars under stress reversal was idealized by Ciampi's model [11], and the isotropic hardening rule was adopted as the hysterical model.

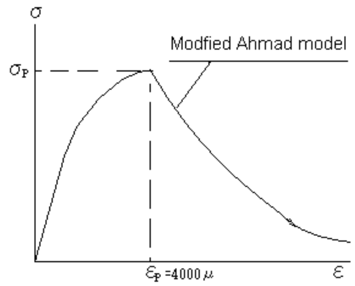


Fig. 3 – Stress – strain relationships

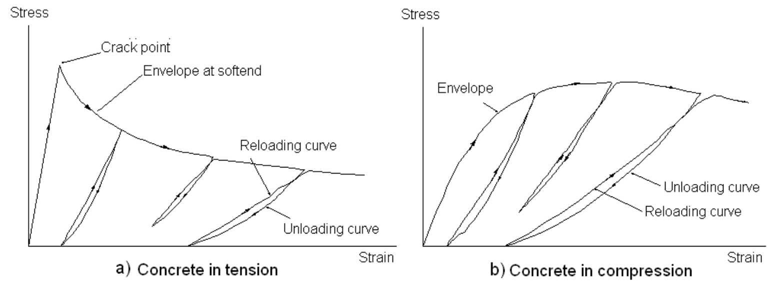


Fig. 4 – Reversal loading model of concrete shear along crack direction

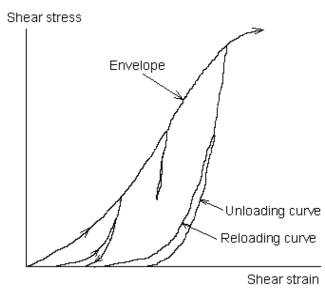


Fig. 5 – Reversal loading model of concrete shear along crack direction

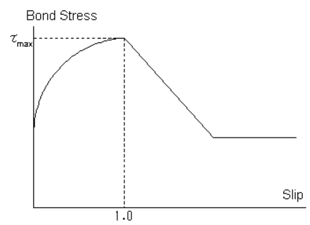


Fig. 6 – Bond stress– slip relationships

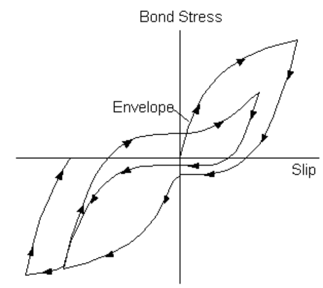


Fig. 7 – Reversal loading model of bond behavior

## 3. Analytical Results

### 3.1 Hysteresis Loops and Cracking Patterns

For analytical models which the equivalent perimeter ratios are 0.1, 0.3 and 0.5, the analytical results on the shear force versus drift angle relationships until the drift angle, the R, of 0.8% and the cracking patterns at peak capacity are shown in Fig.8 and Fig.9. In Fig.8, light gray color elements mean the softing in compressive stress-strain relationships for concrete, and gray color elements are occurring in compressive failure.

Each analytical model reached the maximum strength until the drift angle, the R of 0.5% or 0.75% and then destabilized under the influence of the damaged elements. In the shear force versus drift angle relationships, analytical models with the equivalent perimeter ratios of 0.1, the smallest opening ratio, have shown the highest shear strength. According to the cracking pattern, Analytical model Case3-0.1 has shown a typical damage in compression occurred bellow the openings on the 1st story. However, other analytical models have shown the damage in compression concentrated at the bottom of the compressive side columns on the 1st story. On the other hand, analytical models with the equivalent perimeter ratios of 0.5 shows the smallest shear strength proportional to the equivalent perimeter ratio of openings. Thus, the results show that damages in compression occur at the region in which the stress flow changes suddenly such as bottom ends of walls close to the openings in the 1st story and/or the top ends of walls close the beam on the 2nd story. As for, analytical models which have the equivalent perimeter ratios of 0.5 fail in heavily concentrated compression zone ca used by the decrease of the cross sections due to the existence of large openings. This suggests that the formation of the stress flow in the wall panels affects the ultimate states of RC walls with multi-openings.

### 3.2 Stress Flow in Wall Panels

Principal compressive stress distributions of concrete elements at R of 0.5% for analytical models with the equivalent perimeter ratios of 0.1, 0.3 and 0.5 are shown in Fig.10. For analytical models with the equivalent perimeter ratios equal to 0.3, the principal compressive stresses concentrate in diagonal direction, and the struts are formed between the top and the bottom of columns on both sides through wing walls and central panels,

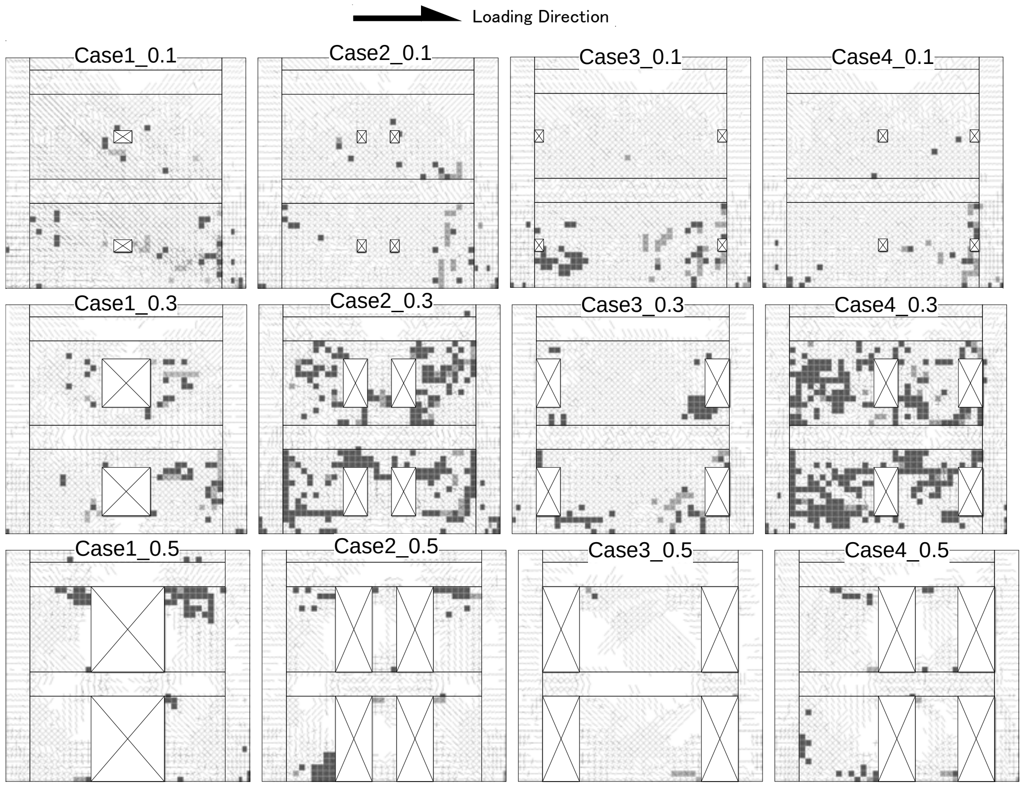

Fig. 8– Cracking pattern (peak capacity)

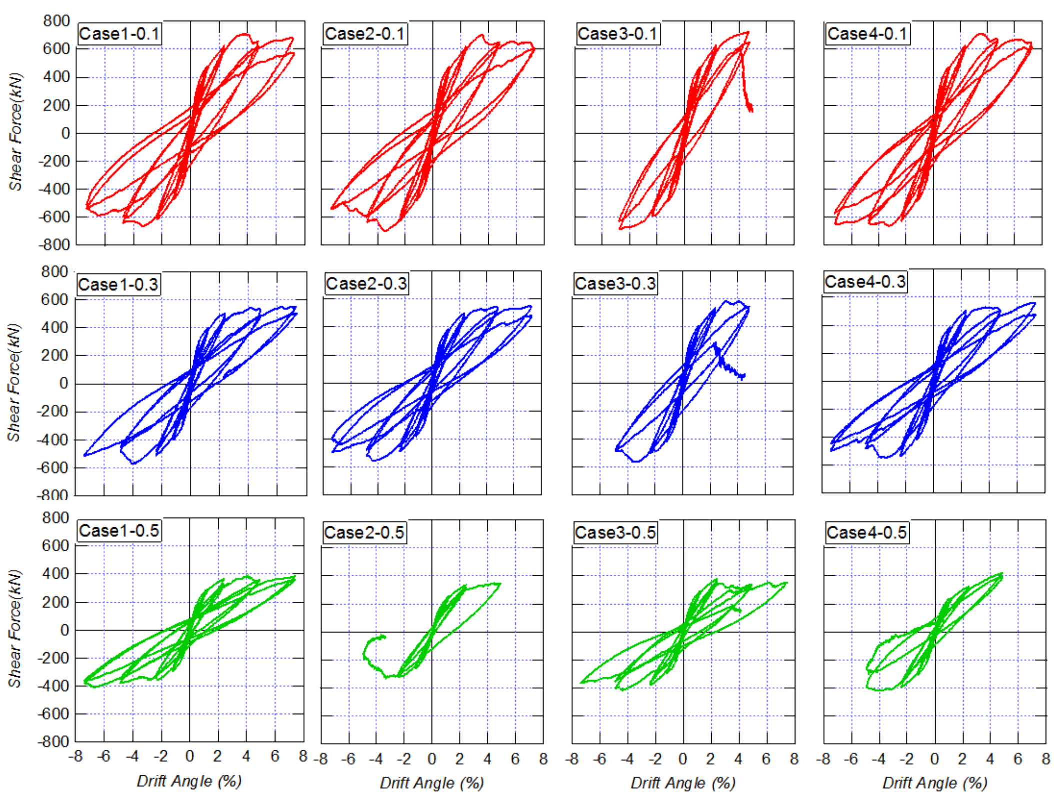

Fig. 9 – Q–R relationships

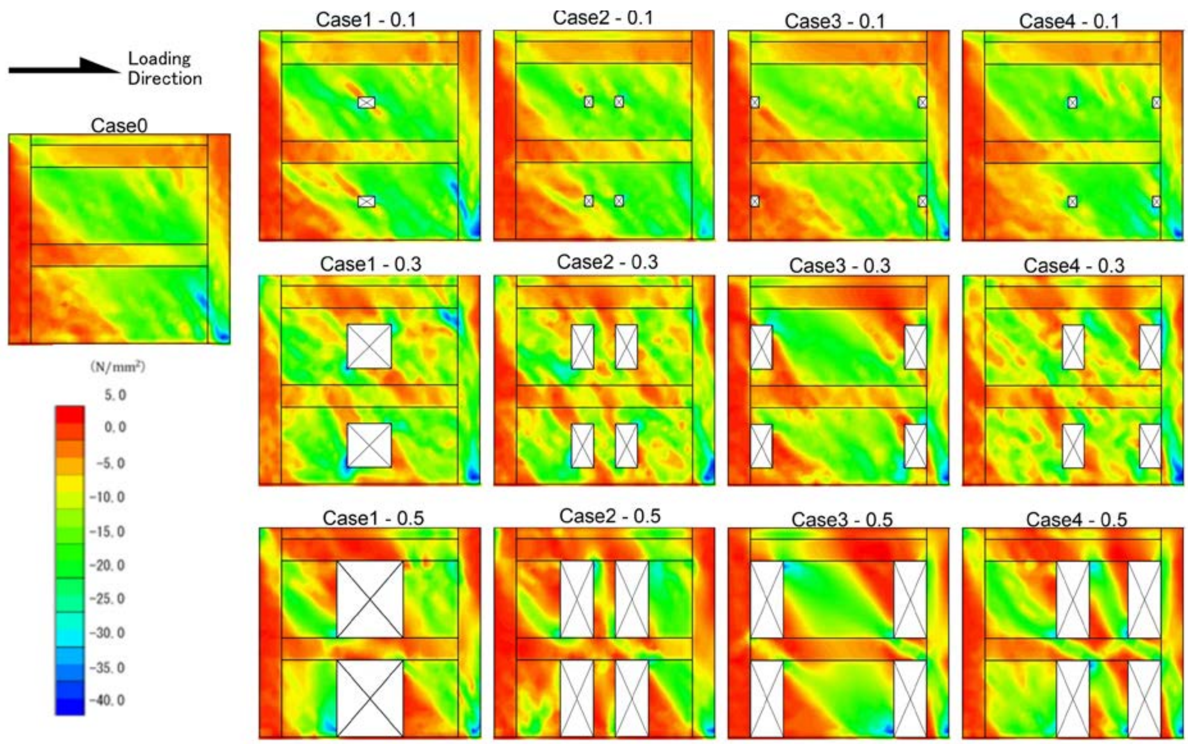


Fig. 10 – Principal compressive stress distributions of concrete elements (R=0.5%)

along cracking directions. In case of the analytical models with the equivalent perimeter ratios of 0.1, the struts are clearly formed between the top of the tensile column on the 2nd story and the bottom of the compressive column on the 1st story, similarly to those in non-opening shear walls as shown in Case0. Meanwhile, those in the equivalent perimeter ratios of 0.5 are formed in narrow area of wall panels or beams avoiding large openings, and remarkable concentrated stresses in strut ends are observed at the connections to the columns. This tendency with the cracking pattern. Therefore, the stress concentrated regions becomes the plastic hinge at early stage, and the failure modes of such walls are similar to frame structures excepting their poor ductility.

As described above, if the equivalent perimeter ratios are small, say less than 0.3, RC shear walls with openings show similar behavior as RC shear walls without openings. Meanwhile, if the ratios become larger, the structural behavior becomes poor. That is, the ductility is small, and the shear capacity is almost same as frame structures without shear walls.

## 4. Comparison of Proposed Model and Conventional Method

### 4.1 Verification of Proposed method in the range of small opening ratios

Reduction factors for the shear capacity versus the equivalent perimeter ratios of openings for all analytical cases shown in Fig.11. Reduction factor calculate to divide calculated shear strength for each analytical models by those one for analytical model of RC shear wall without openings. In Fig.11, the calculated reduction factors for Japanese standard by Eq.(2) are shown.

$$\gamma_2 = 1 - 1.1\sqrt{\frac{\sum h_{op} l_{op}}{hl}} \tag{2}$$

where, $\gamma_2$ : reduction factor for raito of the opening area and the total wall surface area

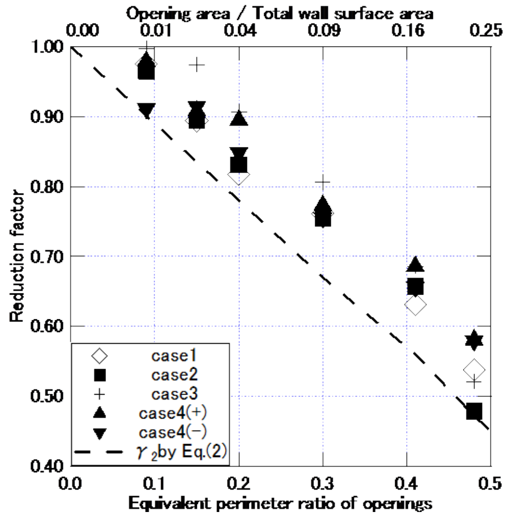


Fig. 11 – Reduction factor – Equivalent perimeter ratio openings rerationships

In Fig.11, calculated reduction factor by FE for each model exceeds the calculated by Eq.(2), and it is confirmed that reduction factors for Japanese standard calculated by Eq.(2) can safely estimates shear strength for shear wall with openings. Calculated reduction factor for analytical models which have eccentric openings makes difference between positive loadings and negative loadings. From the relationships between reduction factor ratio and equivalent perimeter ratio, the decreases of reduction factor are observed, depending on the increase of equivalent perimeter ratios. On the other hand, in analytical models with the equivalent perimeter ratios of 0.1, in which the shear transmission mechanisms are similar to shear walls without opening, calculated reduction factor by FE are from 0.91 to 0.99. Therefore, these models show slightly smaller shear strength against shear walls without opening. As described above, when the ratios of the opening area to the total wall surface area are about 2%, the shear deteriorations are very small.

## 4.2 Validity of Proposed Models

The relationships between shear strength in analytical results by FE and calculated one for each analytical models are shown in Fig.14. The calculated shear strength, $Q_{wo}$ (Eq. (3), Eq. (4) and Eq. (5)), is proposed by the authors, where $Q_{wo}$ was considered on the basis of shear transferring struts in RC shear wall and can estimate the difference of shear strength depending on the opening arrangement. The shear resisting model proposed by equations Eq. (3), Eq. (4) and Eq. (5) are shown in Fig.12, and the assumptions of boundary columns are also shown in Fig.13.

$$Q_{wo} = \sum_{i=1}^{n+1} Q_{wi} \tag{3}$$

$$Q_{wi} = \nu\sigma_B \cdot \cos\theta_i \sin\theta_i \cdot 0.5 l_{p_i} \cdot t_i \tag{4}$$

$$\nu = -0.016\sigma_B - 0.16\frac{M}{QD} + 0.36\frac{N}{bD\sigma_B} + 0.27 p_W + 1.23 \tag{5}$$

where, $n$: number of openings, $\sigma_B$: concrete cylinder strength (N/mm$^2$)

$\theta_i$: the angle of strut at wall panel, $l_{pi}$: wall panel length (mm), $t_i$: wall panel width (mm)

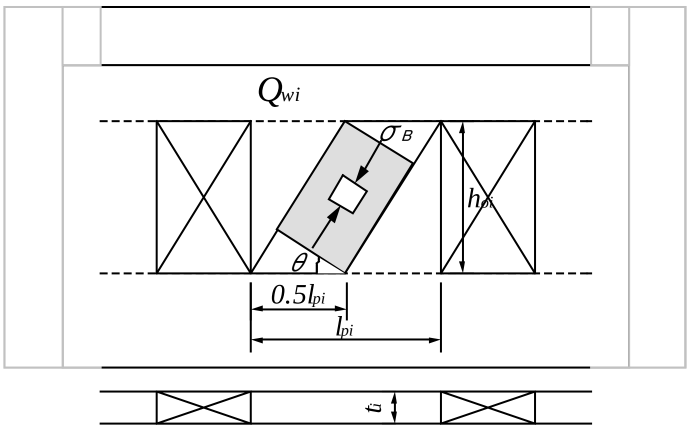


Fig. 12 – Proposed shear resisting model in wall panels

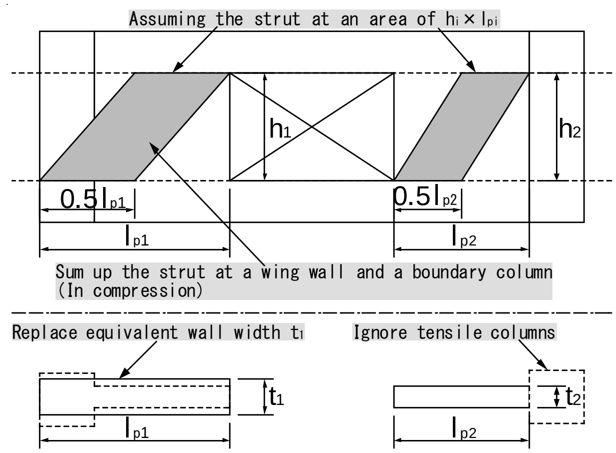


Fig. 13 – Assumption of boundary columns

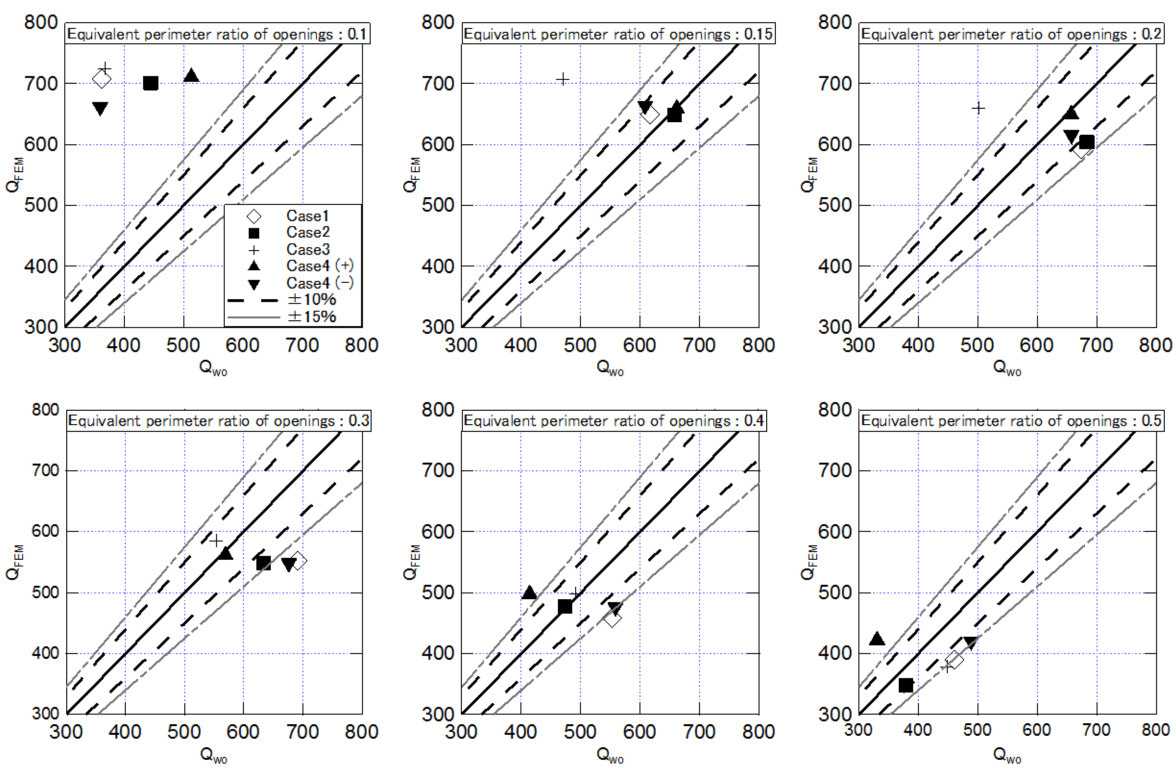


Fig. 14 – $Q_{FEM}$ – $Q_{wo}$ relationships

For analytical models in equivalent perimeter ratios from 0.15 to 0.5, ratios of the shear strengths obtained from the FE analysis to those calculated by the simplified model ($Q_{FEM}/Q_{wo}$) were approximately ranging from 0.85 to 1.15. Therefore, it is clarified that the shear strength of RC shear walls with multi-openings can be evaluated by the proposed model. This is because diagonal struts in each wall panel or boundary columns individually formed in these models.

On the other hand, for analytical models in equivalent perimeter ratios below 0.1, $Q_{FEM}/Q_{wo}$ were ranging from 0.49 to 0.71, and the proposed model underestimated analytical results. This is because shear transferring mechanisms in these models are similarly observed in RC shear wall without opening. Therefore, the assumption of formed struts for the proposed model disagree from effective internal struts.

## 5. Conclusion

In this paper, a two dimensional non-linear FE parametric analysis for the shear walls with two openings is conducted using the walls with several opening size and layout to investigate the influence of opening size. From calculated analytical shear, the investigation of the scope of application for the proposed shear resistant model of the shear walls with multi-openings was conducted. The following conclusions can be drawn.

(1) If the equivalent perimeter ratios of openings are small, say less than 0.3, RC shear walls with openings show similar behavior as RC shear walls without openings. Meanwhile, if the ratios become larger, the structural behavior becomes poor. That is, the ductility is small, and the shear capacity is almost same as frame structures without shear walls.

(2) When the ratios of the opening area to the total wall surface area for RC shear walls with openings are about 2%, the shear deteriorations are very small.

(3) For RC shear walls with openings in equivalent perimeter ratios from 0.15 to 0.5, the shear strength can be evaluated by the proposed simplified model.

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