Evaluation of Shear Strength and Failure Mode of a Column with Installed Wing Walls

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SUMMARY
The objective of this study is to propose a method for strengthening columns by installing small wall panels which may not be considered to be shear wall. In this study, shear strength of a column with installed wing walls was evaluated though experiment and analysis using a column with installed wing walls on one or both sides. The experimental variables were vertical joint anchor ratio, shear reinforcement ratio of the column, length and width of the wing wall. The experimental results indicate that the most effective parameter of seismic performance of the column with one or both wing walls was vertical anchor ratio. The calculated strength achieved though the proposed method is correlated with the experimental maximum strength.

Keywords: Seismic Retrofit, Column with Installed Wing Wall, Shear Strength, Failure Mode

1. INTRODUCTION

In recent years, large earthquakes have occurred in Japan, including the 2011 Tohoku Earthquake off the Pacific Coast. Further large earthquakes are predicted in Japan. This means that the seismic strengthening of buildings needs serious consideration. Many urban middle-rise apartment buildings were built before the current seismic design code came into force and do not have sufficient seismic capacity. Buildings that have insufficient seismic capacity should be strengthened as soon as possible.

The objective of this study is to propose a strengthening method for existing columns by installing small wall panels which are not considered to be shear walls. This strengthening method can increase the seismic strength of the existing column by changing it to a column with wing walls (BRI 2005). The method does not require much cost and time, does not require conversion of the dwelling design and can be installed on resident. Therefore, this method is suitable for urban middle-rise residential buildings. However, the seismic capacity of a column with installed wing walls has not been clearly proven.
In this study, the shear strength and failure mode of a column with installed wing walls are evaluated though experiments and analysis.

2. RETROFIT METHOD

Details of the retrofitting of wing walls to an existing column are shown in Figure 2.1. The installed wing wall is attached to both-sides for the inside column, and on one-side of the outside column. The existing column and the installed wing wall are connected by a later installed anchor at the horizontal joint side and vertical joint side. The installed anchor should transfer shear stress of the installed wing wall to the column. The dimensions of the installed wing wall and the ratio of the installed anchor may be adjusted as required.

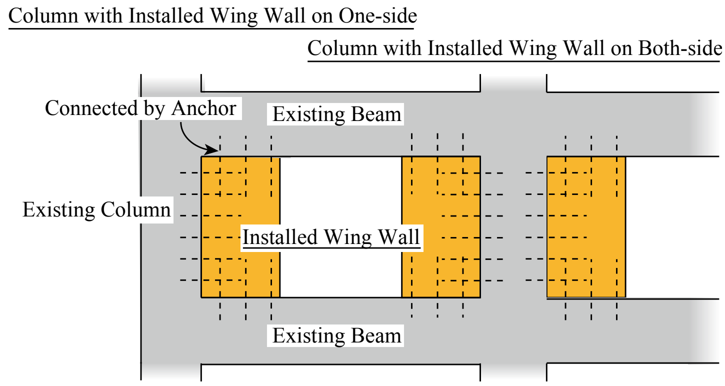


Figure 2.1. Detail of the retrofitting

3. EXPERIMENTAL PROGRAM

3.1 Specimen Description

One-half scale specimens are constructed (Nakamura et. al. 2011, Kokemae et. al. 2011). An overview of all test specimens is shown in Figure 3.1. The experiment has three types of specimens; a column with installed with wing walls in both-side (SW series, 12 specimens), a column with installed wing walls on existing wing walls (AW series, 1 specimens) and a column with a wing wall in one-side (OW series, 4 specimens). Parameters of specimens are shear reinforcement ratio of column, vertical anchor ratio between column and installed wing walls, the ratio of wall thickness to column width (α) and the ratio of wall length to column depth (β).

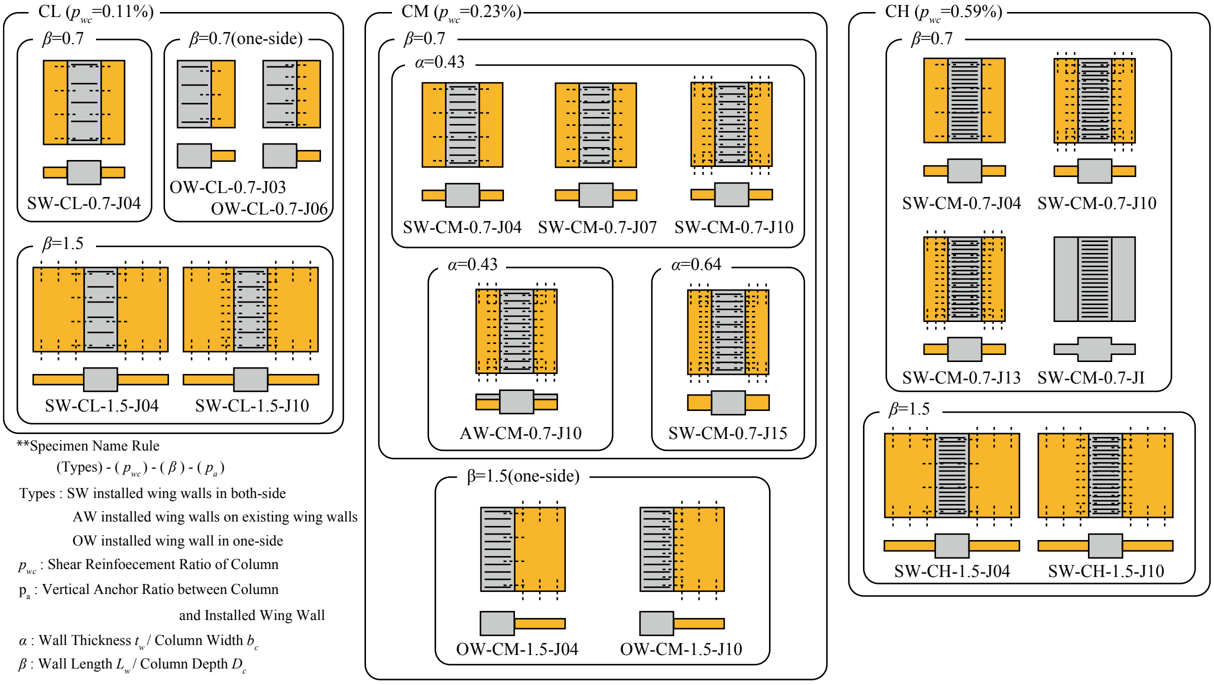
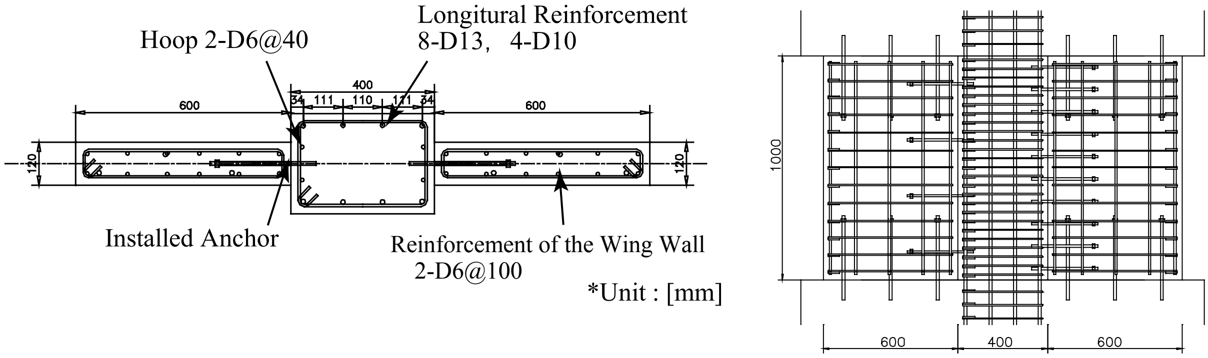


Figure 3.1. Overview of all test specimens

An example of bar arrangement drawings of test specimens is shown in Figure 3.2. The fabrication procedure of specimens is as follows: 1) arrange bars of the existing column and stabs, and cast concrete, 2) strip the form one week after casting, 3) roughen joint area between the installed wing walls and the column or stabs, 4) install vertical and horizontal anchors at the joint, 5) arrange bars of the installed wing wall, and cast concrete.



(a) Cross Section (b) Elevation View

Figure 3.2. Example of bar arrangement drawing of test specimens

(a) Roughing and Anchor installing (b) Bar Arrangement

Figure 3.3. Fabrication detail of installed wing wall

3.2 Material Properties

Characteristics of the concrete and steel used in this study are shown in Tab.3.1. A normal ready mixed concrete with 25mm maximum aggregate is used.

Table 3.1. Characteristics of materials

Grouping	Casted Position	E_c [N/mm²]	σ_B [N/mm²]	σ_t [N/mm²]	Diameter	Quality	E_s [N/mm²]	σ_y [N/mm²]	ε_y [μ]	σ_s [N/mm²]
A	Column	2.50×10^4	23.7	2.5	D6	SD295A	1.84×10^5	350	2968	498
	Wing Wall	2.61×10^4	23.1	2.4	D10	SD345	1.88×10^5	396	2265	566
	-	-	-	-	D13	SD345	1.90×10^5	403	2245	582
B	Column	2.40×10^4	21.7	2.2	D6	SD295A	1.85×10^5	352	2850	524
	Wing Wall	2.57×10^4	25.0	2.5	D10	SD345	1.90×10^5	391	2350	571
	-	-	-	-	D13	SD345	1.90×10^5	391	2280	566
C	Column	2.77×10^4	23.8	2.3	D6	SD295A	1.82×10^5	400※	4225※	518
	Wing Wall	2.76×10^4	23.0	2.3	D10	SD345	1.78×10^5	377	2630	572
	-	-	-	-	D13	SD345	1.82×10^5	403	2387	580

Group A: SW-CM-0.7-J10, SW-CH-0.7-J10, SW-CH-0.7-J13, SW-CH-0.7-JI ※ 0.2% offset

Group B: SW-CL-0.7-J04, SW-CM-0.7-J04, SW-CM-0.7-J07, SW-CH-0.7-J04, OW-CL-0.7-J03, OW-CL-0.7-J06

Group C: SW-CL-1.5-J04, SW-CL-1.5-J10, SW-CH-1.5-J04, SW-CH-1.5-J10, AW-CM-0.7-J10, SW-CM-0.7-J15, OW-CM-1.5-J04, OW-CM-1.5-J10

E_c, E_s : Young's Modulus of Concrete and Steel, σ_B : Compressive Strength of Concrete, σ_t : Tension Strength of Concrete

σ_y : Yield Strength of Steel, ε_y : Strain at Yield Point of Steel, σ_s : Tension Strength of Steel

3.3 Test Setup

The test setup is shown in Fig.3.4. A lateral cyclic load is applied at the middle height of the specimen with a constant axial stress. The ratio of axial force by compressive strength of the column is 0.15. The lateral load is controlled through the rotation angle. The rotation angle is defined as the deformation between the top and the bottom of the column divided by inside height. The rotation angle levels are 1/800(1), 1/400(1), 1/200(2), 1/100(2), 1/50(2), 1/33(1), 1/25(1). The number in parenthesis represents the number of repeating cycles.

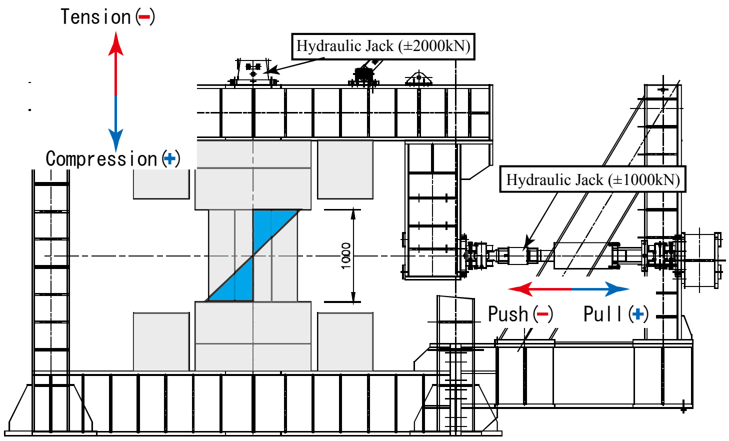


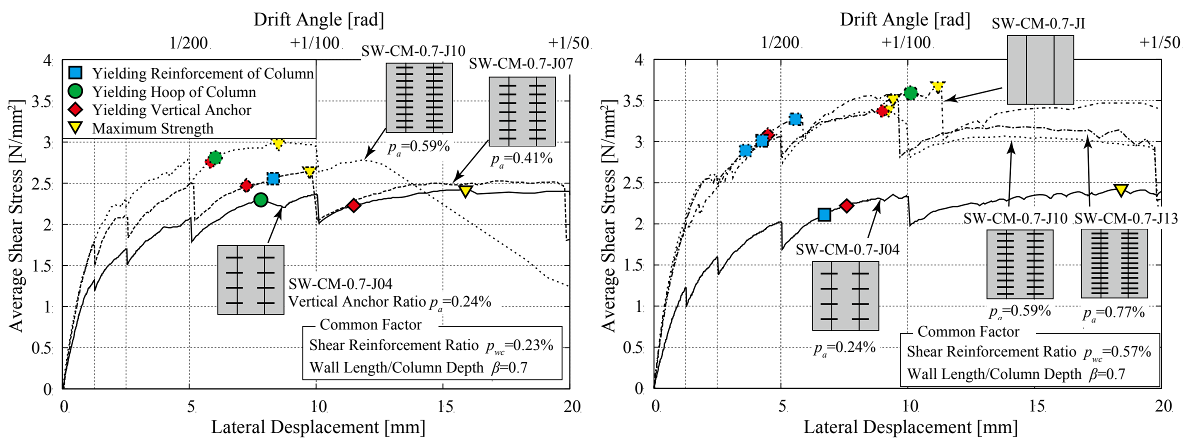
Figure 3.4. Test setup

4. EXPERIMENTAL RESULT

4.1 Observed Behaviour of Load-Displacement Relationship and Failure Mode

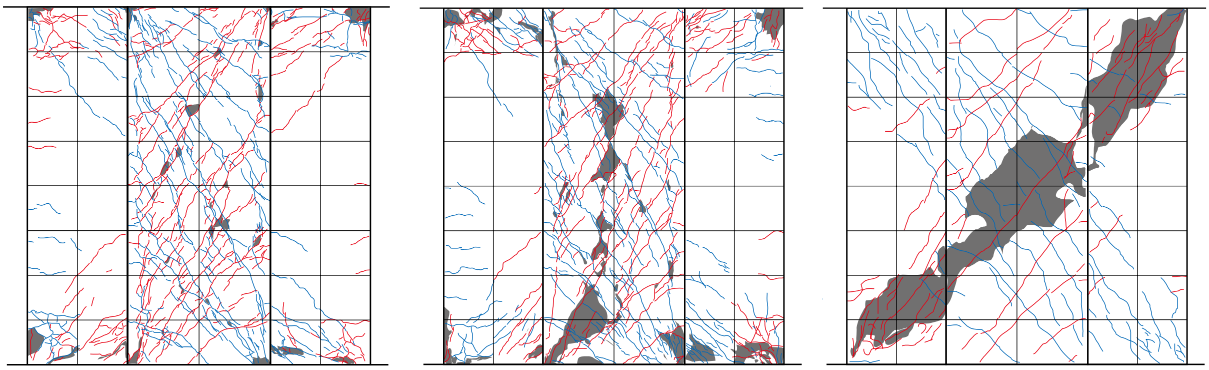
Comparison of load-displacement relationship among different vertical anchor ratio is shown in Fig.4.1. The Y axis of the graphs is average shear stress; lateral load divided by lateral dimension including wing walls. The average shear stress at the same rotation angle and the maximum average shear stress are raised by increasing the vertical anchor ratio. In addition, the column with integral wing walls (specimen SW-CM-0.7-JI) and the column with installed wing walls attached with high vertical joint anchor ratio (specimen SW-CM-0.7-J10) behave in almost the same manner.

Crack patterns after the loading cycle of 1/25 rad. are shown in Figs. 4.2, 4.3. Cracks in low vertical anchor ratio specimens are comparatively concentrated on the existing column. By contrast, cracks in the specimens with high vertical anchor ratio are comparatively concentrated on the wing wall.



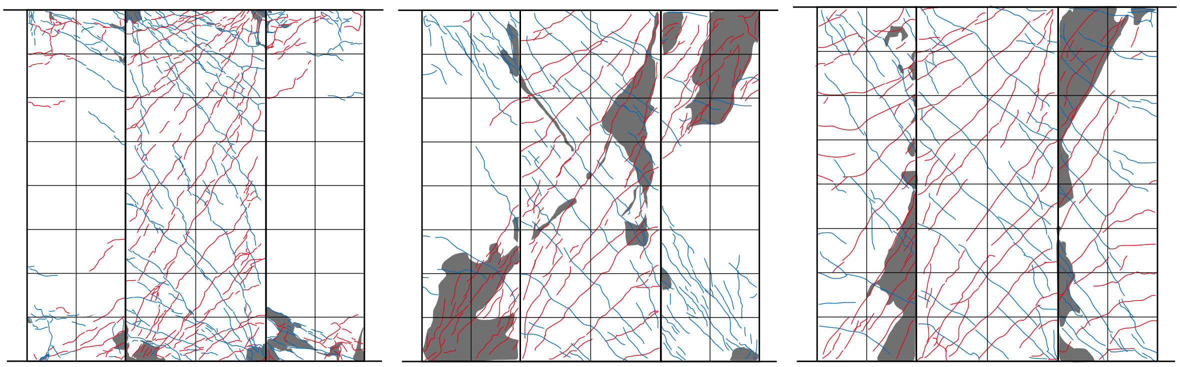
(a) CM-Series (b) CH-Series

Figure 4.1. Comparison of force-displacement relationship



(a) SW-CM-0.7-J04 (b) SW-CM-0.7-J07 (c) SW-CM-0.7-J10

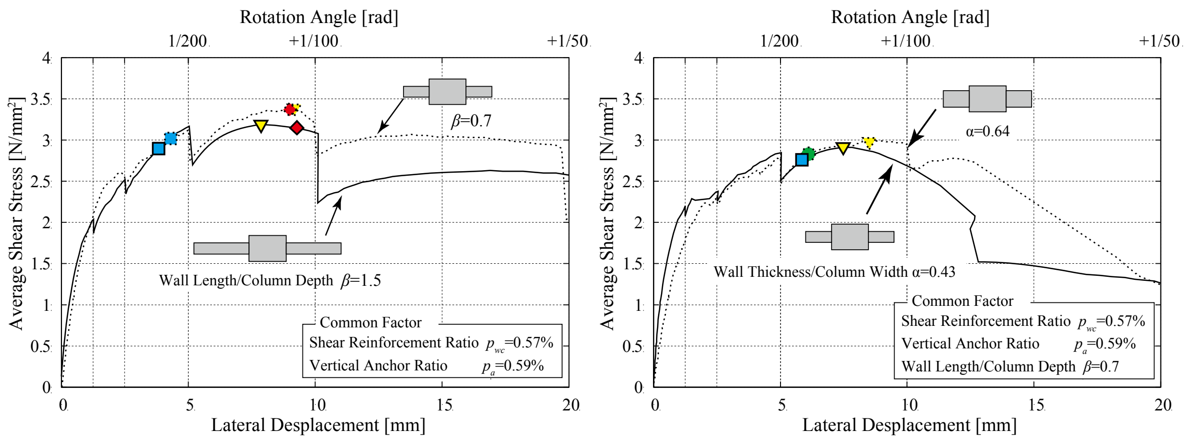
Figure 4.2. Crack patterns after 1/25 rad. cycle (CM-Series)



(a) SW-CH-0.7-J04 (b) SW-CH-0.7-J10 (c) SW-CH-0.7-JI

Figure 4.3. Crack patterns after 1/25 rad. cycle (CH-Series)

Comparison of load-displacement relationships among different wall thickness/column widths (α), wall length/column depths (β) is shown in Fig.4.4. Load-displacement relationship behavior is almost the same with the same vertical anchor ratio regardless of the dimension of wing wall. Consequently, the most effective index for the column with wing walls is the vertical anchor ratio.



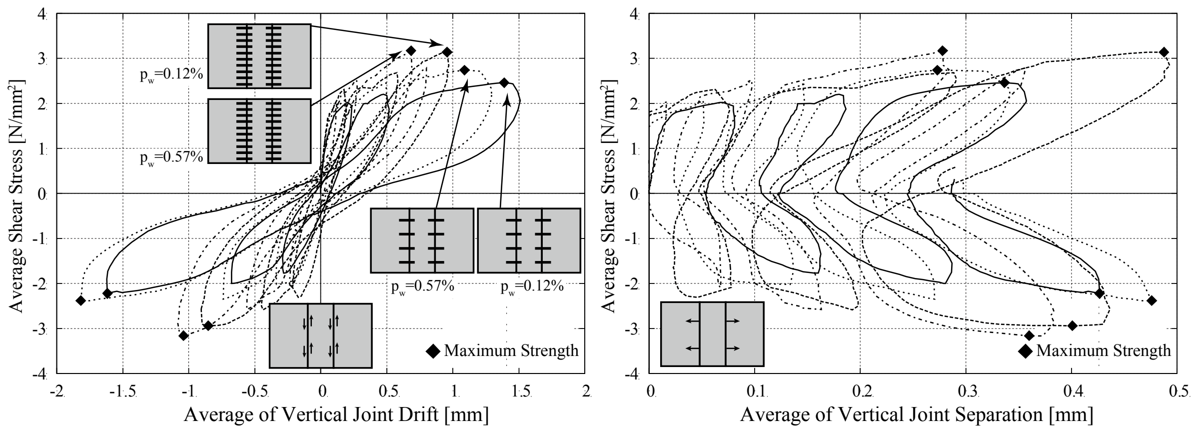
(a) CM-Series (b) CH-Series

Figure 4.4. Comparison of force-displacement relationship

4.2 Displacement Characteristics

In some specimens (wall length/column depth are β=1.5), separation at and slippage along the vertical joint between the existing column and installed wing wall are measured at four points illustrated in each of the above figures. In addition, pull-out displacement at the top and bottom of the column and the wing wall is measured.

The relationship between the average shear stress and vertical joint slippage and separation is shown in Fig. 4.6. The vertical joint of all specimens start to deform from the average shear stress of 2.0 N/mm^2. Vertical joint slippage of low vertical anchor ratio specimens is larger than that of high vertical anchor ratio specimens.
Pull-out displacement distribution at the bottom is shown in Fig.4.7. Pull-out distribution does not comply with the Navier hypothesis, especially on the compressive side. This is due to the vertical joint slippage.



(a) Average shear stress vs. vertical joint drift (b) Average shear stress vs. vertical joint separation

Figure 4.6. The relationship between the average shear stress and vertical joint drift and separation

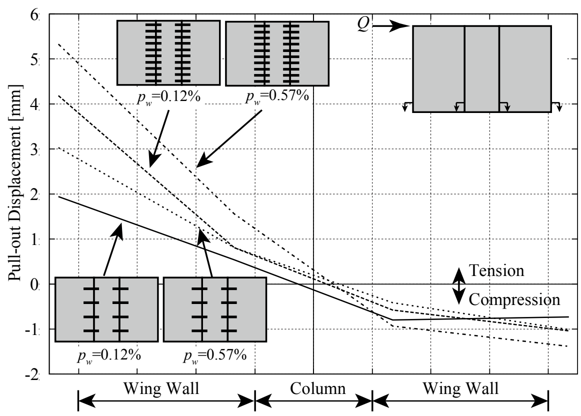


Figure 4.7. Pull-out displacement distributions at the bottom on maximum strength

5. EVALUATION MODEL

5.1 Shear Strength

To evaluate the shear strength of the column with wing wall on one or both side, an evaluation model based on the experimental results described in section 4 is proposed. In this model, shear force is transferred along two struts, wall strut and column strut as illustrated in Fig. 5.2. With this model, the shear strength is determined as follow. Each term on the right side in the Eq. (5.1) represents a mechanism shown in Fig. 5.2.

$$Q_u = p_a \sigma_{ay} \alpha b_c h + \left(C_w + T_w - p_a \sigma_{ay} \alpha b_c h\right) \tan\theta_w + p_{wc} \sigma_{wy} b_c j_c + \left(C_c + T_c - p_{wc} \sigma_{wy} b_c j_c\right) \tan\theta_c \quad (5.1)$$

where, p_a is vertical joint anchor ratio (%), σ_{ay} is yield strength of vertical joint anchor, b_c, D_c is width and depth of column, h is internal height, p_{wc} is hoop ratio (%), σ_{wy} is yield strength of hoop, T_c is tension force of tension reinforcement of column, T_w is tension force of horizontal joint anchor, θ_c is arch angle of column, θ_w is arch angle of wall.

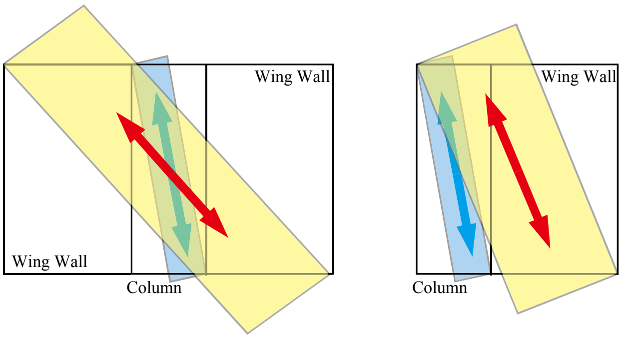


Figure 5.1. Assumption of strut model

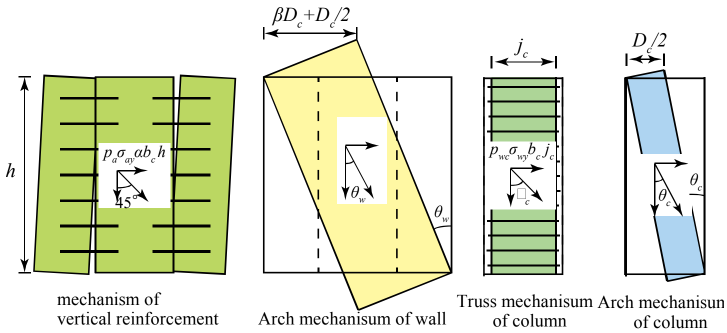


Figure 5.2. Shear resistant mechanisms

The ratio of the compressive force upon the wall strut C_w to that upon the column strut C_c is determined by axial force distribution at the critical section shown in Fig. 5.3. Equilibrium of the axial force and moment at the critical section is determined as follows.

$$C_w = \left(Q_{const}h_0 - N_{all}k - M_{const}\right)/K \tag{5.2}$$

$$C_c = N_{all} - C_w \tag{5.3}$$

where, $$N_{all} = N + T_c + T_{c,m} + T_w \tag{5.4}$$

$$M_{const} = T_c\left(D_c/2 - d_{st}\right) + T_w\left(1+\beta\right)D_c/2 \tag{5.5}$$

$$Q_{const} = p_a\sigma_{ay}\alpha b_c h\left(1-\tan\theta_w\right) + T_w\tan\theta_w + p_{wc}\sigma_{wy}b_c j_c\left(1-\tan\theta_c\right) + T_c\tan\theta_c \tag{5.6}$$

$$k = \left(D_c/2 - d_{sc}\right) - h_0\tan\theta_c \tag{5.7}$$

$$K = \left(2/3\right)\beta D_c + d_{sc} - h_0\left(\tan\theta_w - \tan\theta_c\right) \tag{5.8}$$

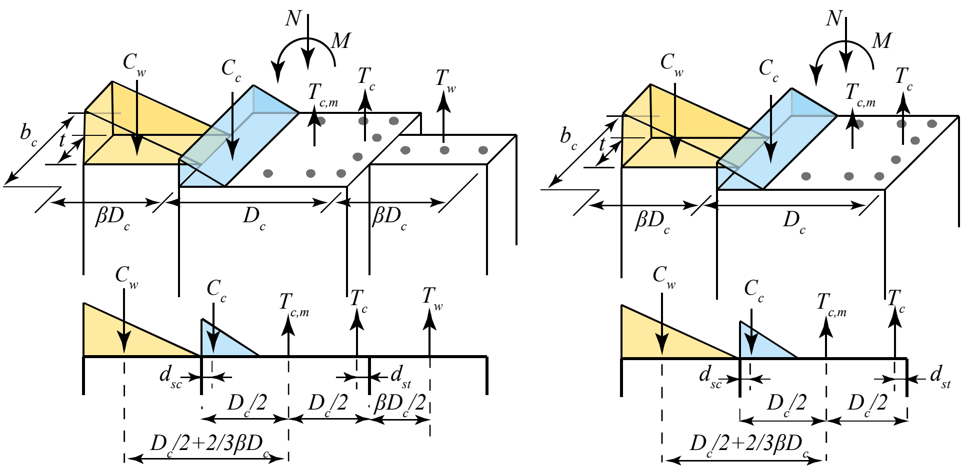


Figure 5.3. Distribution of axial force at the dangerous section

Due to increasing vertical joint anchor ratio, compressive force on the wall strut C_w and calculated shear strength is higher. The result agrees with the behavior observed in the experiment.

An effective range of vertical joint anchor ratio is needed. The maximum value for the vertical joint anchor ratio is determined according to the following provisions. If the designed vertical joint anchor ratio is higher than the maximum value, a valid vertical joint anchor ratio to calculate the shear strength is determined as the maximum value.

a) The compressive stress of the wall strut is lower than the valid compressive stress of concrete.

$$p_a \sigma_{ay} \alpha b_c h + \left(C_w + T_w - p_a \sigma_{ay} \alpha b_c h\right) \tan\theta_w \le Q_{w\max} = \nu \sigma_B \alpha b_c \left(1+2\beta\right) D_c \tan\theta_w / 2 \quad (5.9)$$

where, σ_B is compressive strength of concrete, ν is valid compressive strength value ($=1.7\sigma_B^{-1/3}$)

b) The compressive force on the column strut is a positive value.

$$C_c = N_{all} - C_w \ge 0 \quad (5.10)$$

The minimum value for the vertical joint anchor ratio is determined as the compressive force on the wall strut is a positive value.

$$C_w = \left(Q_{const} h_0 - N_{all} k - M_{const}\right) / K \ge 0 \quad (5.11)$$

If the designed vertical joint anchor ratio is lower than the minimum value, the shear strength is calculated according to the truss model (See Fig. 5.4). The shear strength as per the truss model is given by Eq. 5.12.

$$Q_{tr} = Q_c + Q_T \cdot n = \min({}_cQ_{su}, {}_cQ_{mu}) + 2t^2 F_c L_2 / H \quad (5.12)$$

Where, n: number of wing wall, ${}_cQ_{mu}$: shear force at yielding moment of column, ${}_cQ_{su}$: shear strength of column.

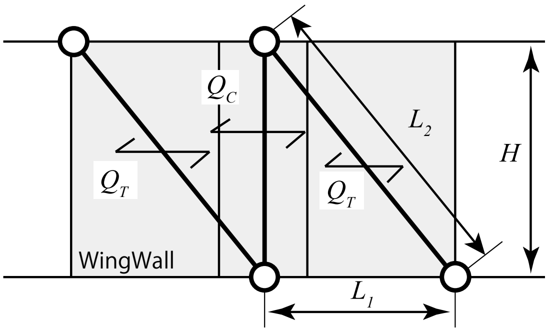


Figure 5.4. The truss model

Therefore, proposed calculation flow for the column with wing walls is shown in Fig. 5.5.

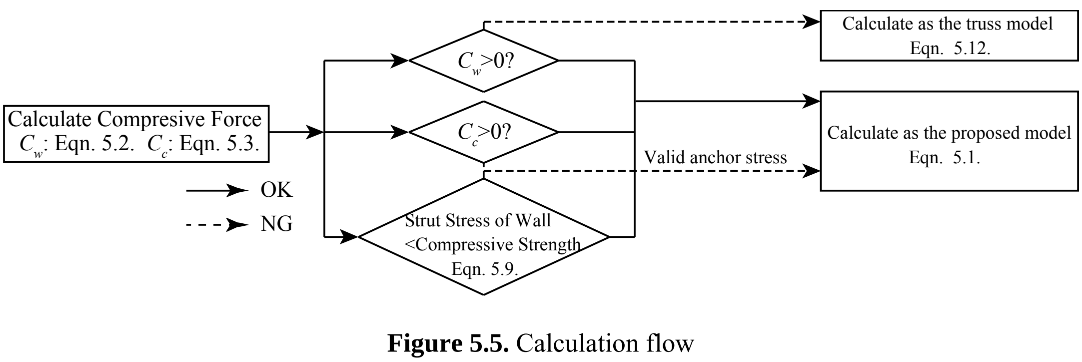


Figure 5.5. Calculation flow

5.2 Flexural Strength

The flexural strength of the column with wing walls is calculated according to strict plastic theory. In this theory, the horizontal dimension is divided into parts, and the material of each part is assumed to be yielding. The flexural strength is calculated as follows.

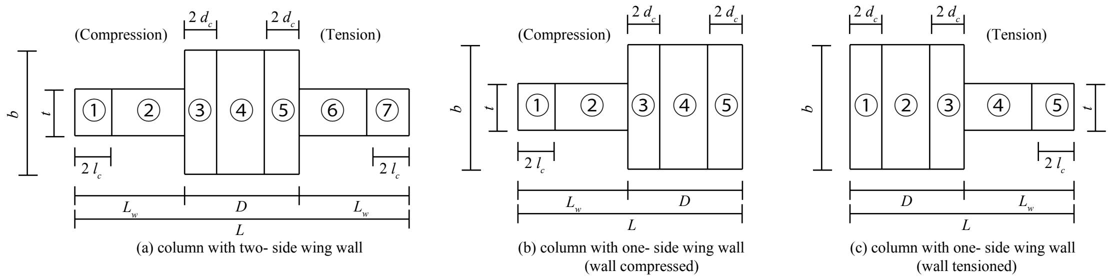


Figure 5.6. Divided horizontal dimension

$$M_u = \sum_{i=1}^{K}\left(A_i \cdot \sigma_{y,i} \cdot m + B_i \cdot\cdot F_{c,i} \cdot n\right) \cdot D_i \cdot L_i + N \cdot L_N + \left(2A_j \cdot \sigma_{y,i} + B_j \cdot F_{c,i}\right)\left(\sum_{i=1}^{j} D_i - x_n\right)\left(\sum_{i=1}^{j} D_i + x_n\right)\frac{1}{2} \quad (5.13)$$

$$\sum_{i=1}^{K} A_i \cdot D_i \cdot \sigma_{y,i} \cdot m + \sum_{i=1}^{K} B_i \cdot D_i \cdot F_{c,i} \cdot n + N + \left(2A_j \cdot \sigma_{y,i} + B_j \cdot F_{c,i}\right)\left(\sum_{i=1}^{j} D_i - x_n\right) = 0 \quad (5.14)$$

where, a subscript means the number of part, A_i is reinforcement ratio, B_i, D_i is width and depth, L_i is length from the compressive edge to the center of the part, $\sigma_{y,i}$ is yield strength of steel, $F_{c,i}$ is compressive strength of concrete, N is axial force, L_N is length from the compressive edge to center of action, x_n is neutral axis depth determined by Eqn. 5.14.

5.3 Accuracy of Evaluation

The proposed method is applied to the experimental results. The candidate specimens are the column with integral wing walls and installed wing walls conducted in Japan from 1973 to 2011, listed in the reference (Nakamura et. al. 2012). The range of each parameter is shown in Tab. 5.1. The experimental strength versus the calculated strength according to the proposed method is shown in Fig. 5.7. The result shows that the proposed method is applicable. The accuracy of evaluation on all specimens is at the average value 1.13 and the variance is 0.28.

Table 5.1. The range of each parameter

	Column wigh installed wing walls		Column wigh integral wing walls	
	Two-side	One-side	Two-side	One-side
Number of Specimens	23	11	100	20
Tension reinforcement ratio [%]	0.35-0.88	0.34-0.76	0.34-1.54	0.34-0.76
Shear Span Ratio	1.0-4.8	0.5-3.5	1.0-6.0	1.0-3.5
wall thickness/column width α	0.13-0.64	0.20-0.50	0.17-0.50	0.20-0.50
wall length/column depth β	0.5-1.5	0.7-2.7	0.5-2.0	1.0-2.7
Vertical Anchor ratio [%]	0.19-1.89	0.20-1.89	0.16-2.67	0.20-1.17
Axial stress ratio	0.06-0.17	0-0.25	0-0.26	0-0.24

Using the proposed method, accuracy of the determining failure mode is shown in Fig. 5.8. The calculated shear strength of shear failure specimens in area A is overestimated. The calculated flexural strength of shear failure specimens in area B is also overestimated. However, the failure mode of most specimens is determined exactly.

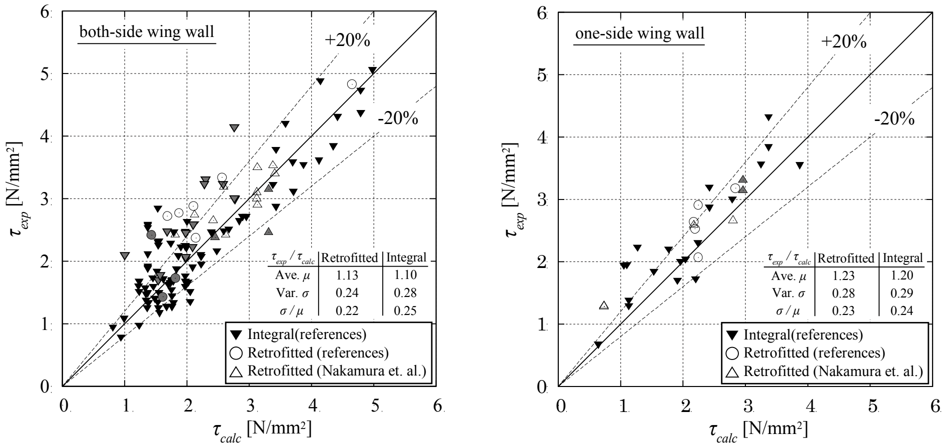


Figure 5.7. Experimental strength vs. calculated strength (proposed method)

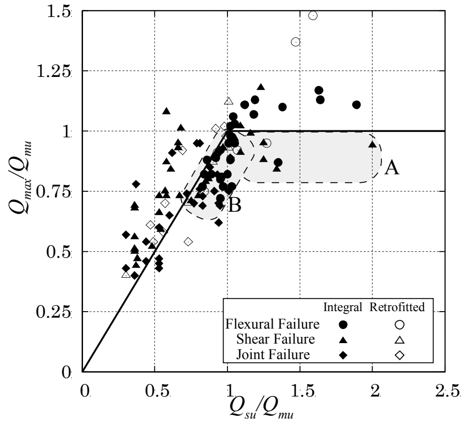


Figure 5.8. Failure mode determinations

6. CONCLUSION

In this paper, the authors analyze seismic characteristics of a column with installed wing walls, and propose an evaluation method for the shear strength. The conclusions are as follows;

1) In the experimental result, the average shear stress at the same rotation angle and the maximum average shear stress are raised by increasing vertical anchor ratio.
2) Load-displacement relationship behavior is almost the same at the same vertical anchor ratio regardless of the dimension of wing wall.
3) The proposed method to calculate the shear strength of the column with wing walls is applicable.

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