



SHEAR DESIGN METHOD FOR MULTI-STORY PRECAST CONCRETE STRUCTURAL WALLS WITH SLIPPAGE AT THE HORIZONTAL JOINTS

Toshio MATSUMOTO¹, Hiroshi NISHIHARA², Masato NAKAO³ and Hiroshi IMAI⁴

SUMMARY

This study presents a new methodology for the structural design of multi-story precast concrete (PCa) structural walls with boundary columns, based on the truss-arch theory.

First, we present a method of calculating with ease the shear strength of RC multi-story structural walls on the assumption that the ratio of the horizontal forces to be carried by the multi-story truss and arch mechanisms is constant.

Next, we present a shear design method of the PCa multi-story structural wall that is easy and on the safe side. The method assumes that shear resistance mechanism with arch mechanism on each story is provided when slippage takes place at the horizontal joint of any story of PCa multi-story structural walls due to horizontal force. In the design model, the failure of the each-story arch mechanism is considered to govern the shear strength of the PCa multi-story structural wall where slippage is caused at its horizontal joint, as well as govern the failure type. In addition, a design sample using the proposed design method for PCa multi-story structural walls is presented.

INTRODUCTION

Taking the collective housings using precast structures in Japan as an example, pure rigid-frame structures of full or half PCa are employed in longitudinal direction, while multi-story structural walls using PCa wall panels (PCa multi-story structural walls) are used in span direction in most cases. The construction practice in the recent years shows the tendency to use bedding mortar for horizontal joints of the PCa wall panels, mainly because of their simplicity.

The PCa structural walls are calculated as if they were conventional monolithic structures, independently of the horizontal jointing method. However, several researches reported that the PCa structural walls with

¹ Technical Research Institute, ANDO Corporation, Saitama, Japan. Email: LDZ06301@nifty.com

² General Manager, Technical Research Institute, ANDO Corporation, Saitama, Japan.

³ Research Associate, Yokohama National University, Kanagawa, Japan.

⁴ Professor, University of Tsukuba, Ibaragi, Japan.

mortar bedding jointing type, presented slip deformations at the horizontal joints even under relatively low shear stresses. Therefore the shear resistant and failure mechanisms are in fact very different from those presented by the conventional RC structural walls.

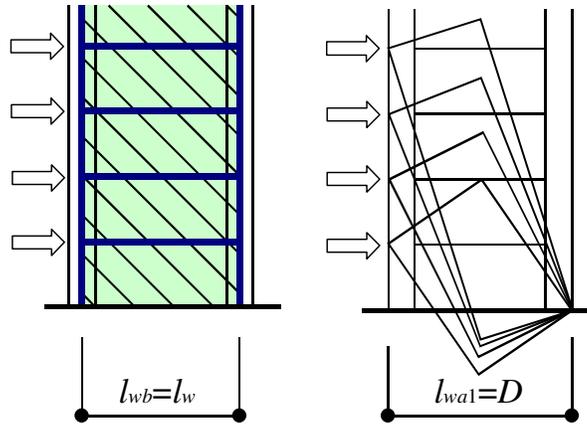
The proposed model is that in the case of PCa structural walls, the shear resistance mechanism transfers progressively from the multi-story truss and arch resistance mechanisms before slippage, to the each-story arch mechanism after the slippage of the horizontal joints. When any story is considered to have slippage at the horizontal joint, the shear resistance mechanism of the whole multi-story PCa structural walls is modeled as it is formed by the each-story arch mechanism at all stories.

To verify the applicability of the proposed model, a trial design of an actual structure was carried out, considering that the slippage at the horizontal joint is a kind of shear failure.

It must be noted that this study is based on the premise that no failure occurs at any vertical joint before the PCa multi-story structural wall reaches its shear strength.

SIMPLIFIED CALCULATION METHOD FOR SHEAR STRENGTH OF RC MULTI-STORY STRUCTURAL WALLS

Figures 1 (a) and (b) show the shear resistance mechanisms of RC multi-story structural walls, in other words multi-story truss and arch mechanisms. Multi-story truss mechanism is a truss mechanism which takes into consideration the main reinforcement of the frame beam between stories and slab reinforcement within the effective width. On the other hand, multi-story arch mechanism is an arch mechanism consisting of the working point of seismic force through the upper edge of the footing beam. These resistance mechanisms are proposed as an integral part of designing a multi-story structural wall[1].



(a) Multi-story truss mechanism (b) Multi-story arch mechanism
Figure 1: Shear resistance mechanism of multi-story RC structural walls

The shear strength $V_{u(RC)}$ in this case is obtained from equation(Eq.) (1) below, as the summation of the shear force carried by the multi-story truss and arch mechanisms.

$$V_{u(RC)} = V_t + V_a \tag{1}$$

Where, $V_{u(RC)}$ = shear strength of multi-story structural wall, V_t = shear force carried by the multi-story truss mechanism and V_a = shear force carried by the multi-story arch mechanism.

Multi-story truss mechanism

The shear force carried by the i^{th} -story in a multi-story truss mechanism (V_{ti}) is expressed by Eq. (2) below, with a truss angle of 45-degrees assumed. In this case, frame beam main reinforcements are included in the calculation in addition to the wall-horizontal shear reinforcements.

$$V_{ti} \leq l_{wbi} / h_{wi} \cdot (A_t \cdot \sigma_y)_i \quad (2)$$

Where, $l_{wbi}(\equiv l_w)$ = equivalent width of the i^{th} -story wall panel in the truss mechanism (center-to-center distance boundary columns), h_{wi} = height of i^{th} -story and $(A_t \cdot \sigma_y)_i$ = sum of tensile yield strength of wall-horizontal shear reinforcements and beam main reinforcements on i^{th} -story.

The concrete compressive stress σ_{ti} used in the truss mechanism of the i^{th} -story is given by Eq. (3) below.

$$\sigma_{ti} = 2V_{ti} / (t_{wi} l_w) \quad (3)$$

Where, t_{wi} = wall thickness of i^{th} -story.

Multi-story arch mechanism

The compressive stress generated in the concrete on the i^{th} -story of the multi-story arch mechanism σ_{aij} is given by Eq. (4) as the sum of the concrete stress of the compression strut generated by distributed external force. Note that $\sum_{j=i}^N$ is substituted by Σ in following equations.

$$\Sigma \sigma_{aij} = 2 / (t_{wi} l_{wa1}) \cdot \Sigma P_{aj} / \tan \theta_j \quad (4)$$

Where, σ_{aij} = concrete compressive stress generated on the i^{th} -story due to the multi-story arch mechanism on the j^{th} -story, $l_{wa1}(\equiv D)$ = equivalent width of the first story wall panel in the arch mechanism (\equiv total length of the structural wall), P_{aj} = distributed external force carried by the multi-story arch mechanism on the j^{th} -story, θ_j = angle of the multi-story arch mechanism on the j^{th} -story given by the following Eq. (5) and h_j = height from the top of the footing beam to the top of the j^{th} -story.

$$\tan \theta_j = \sqrt{(h_j / l_{wa1})^2 + 1} - h_j / l_{wa1} \quad (5)$$

Furthermore, since the sum of the concrete stress generated in the compression strut in the multi-story truss and arch mechanisms on the i^{th} -story is equal to or less than the effective compressive concrete strength, the following Eq. (6) is established.

$$\sigma_{ti} + \Sigma \sigma_{aij} \leq v \sigma_{Bi} \quad (6)$$

Where, $v \sigma_{Bi}$ = effective compressive concrete strength on the i^{th} -story, unit: N/mm² and $v_0(=0.7 \cdot \sigma_{Bi} / 200)$ = effective factor for the compressive concrete strength in a non-hinged member.

Ratio of shear forces carried by multi-story truss and arch mechanisms

In practical designing procedure, variations in both shear forces carried by multi-story truss and arch mechanisms make the design extremely complicated. So for the purpose of this study, the ratio of the shear force to be carried by the multi-story truss mechanism is assumed to be given uniquely by the maximum value of the Eq. (2) on the basis of the bar arrangement condition on the story (the lowest story

in most cases) where the shear force becomes highest in the design. Taking $i=1$ (the lowest story), the following Eq. (7) results from the Eq. (4) and Eq. (6).

$$2 l(t_{w1} D) \cdot \Sigma P_{aj} / \tan \theta_j = (1-\beta_1) v \sigma_{B1} \quad (7)$$

Where, β_1 = ratio of concrete compressive stress applied to the truss mechanism on the first story.

On the other hand, the horizontal external force P_j applied to each story is imposed at a constant ratio of external forces to the multi-story truss and arch mechanisms, and follows the distribution coefficient of force a_j , which is determined in accordance with the distribution mode of the external force assumed upon designing. P_j is given by the following Eq. (8).

$$P_j = P_{ij} + P_{aj} = (P_t + P_a) \cdot a_j \quad (8)$$

Where, P_j = horizontal external force applied to the j^{th} -story, P_{ij} = distributed external force carried by the multi-story truss mechanism on the j^{th} -story, P_t (P_a) = standard value of the external force carried by the multi-story truss mechanism (multi-story arch mechanism) on the j^{th} -story and distributed external force on the first story and a_j = distribution coefficient of the external force applied to the j^{th} -story (1.0 on the first story).

The distributed external force carried by the multi-story arch mechanism on the j^{th} -story P_{aj} is given by the following Eq. (9) on the basis of the assumption expressed in Eq. (8).

$$P_{aj} = P_a \cdot a_j \quad (9)$$

Substitution of Eq. (9) into Eq. (7) yields the following Eq. (10).

$$P_a = (1-\beta_1) t_{w1} D v \sigma_{B1} l (2 \Sigma a_j / \tan \theta_j) \quad (10)$$

As a result, the shear force provided by the multi-story arch mechanism on the i^{th} -story (V_{ai}) is given by the following Eq. (11) as a sum of distributed external force P_{aj} .

$$V_{ai} = \Sigma P_{aj} = P_a \Sigma a_j \quad (11)$$

The simplified calculation method for shear strength of RC multi-story structural walls proposed in this paper gives shear strength on the assumption that the multi-story structural wall is an integral part of the story where the design shear force is at the maximum level. In addition, the method is a shear design method to confirm that no shear failure occurs on other stories.

SIMPLIFIED CALCULATION METHOD FOR SHEAR STRENGTH OF PRECAST CONCRETE MULTI-STORY STRUCTURAL WALLS

Load-carrying mechanism of PCa multi-story structural walls with slippage at horizontal joint

PCa multi-story structural walls are likely to have slippage at the horizontal joints especially if PCa wall panels are erected using mortar bedding. In case the slippage at horizontal joint occurs on any story, shear resistance mechanism composed of arch on each story (each-story arch mechanism) is applied to all stories as shown in Figure 2. Actually all the stories will never be subjected to slippage in the same manner and at the same time. However, a mixture of stories with or without slippage at horizontal joints in one PCa multi-story structural wall makes the design procedure extremely complicated. For the purpose of this

study, a simplified analytical model, which gives an underestimation of the shear strength is proposed as shown in Figure 2.

The authors' past studies[2] present the load-carrying mechanism of PCa multi-story structural wall with slippage at the horizontal joints as shown in Figure 3. In short, the shear strength of PCa multi-story structural walls is the summation of the shear force carried by the multi-story truss and arch mechanisms before slippage and the shear force carried by the each-story arch mechanism after slippage and given by the following Eq. (12).

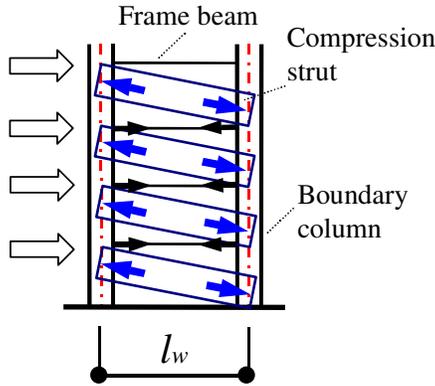


Figure 2: Shear resistance mechanism of multi-story PCa structural walls after slippage (each-story arch mechanism)

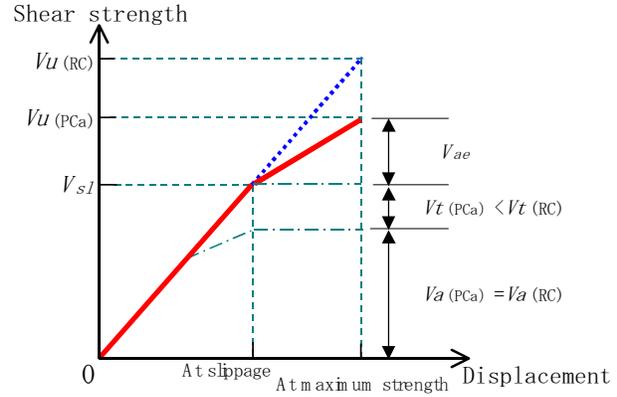


Figure 3: Concept of shear resistance mechanism of multi-story PCa structural walls

$$V_{u(PCa)} = V_{sl} + V_{ae} = V_{t(PCa)} + V_{a(PCa)} + V_{ae} \quad (12)$$

Where, $V_{u(PCa)}$ = shear strength of PCa multi-story structural wall, V_{sl} = shear strength at the slippage occurs at horizontal joint (shear slip strength at horizontal joint), $V_{t(PCa)}$ ($V_{a(PCa)}$) = shear force carried by multi-story truss (arch) mechanism before slippage and V_{ae} = shear force carried by each-story arch mechanism.

Also in consideration of the resistance mechanism by each-story arch mechanism, the sum of the concrete stress generated in the compression strut of the multi-story truss mechanism, multi-story arch mechanism, and each-story arch mechanism of the i^{th} -story is equal to or less than the effective compressive concrete strength. The following Eq. (13) holds for compressive stress.

$$\sigma_{t(PCa)i} + \sigma_{a(PCa)i} + \sigma_{aei} \leq V\sigma_{Bi} \quad (13)$$

Where, $\sigma_{t(PCa)i}$ = concrete compressive stress applicable to the multi-story truss mechanism of the i^{th} -story before slippage, $\sigma_{a(PCa)i}$ = concrete compressive stress applicable to the multi-story arch mechanism of the i^{th} -story before slippage and σ_{aei} = concrete compressive stress applicable to the each-story arch mechanism of the i^{th} -story.

Ratio of shear force carried by multi-story truss, multi-story arch and each-story arch mechanisms

In the same manner just as discussed in connection with RC multi-story structural walls, PCa multi-story structural walls with slippage at the horizontal joints are assumed to be always given the maximum value

obtained from Eq. (13) in the story where the design shear force becomes the largest (usually the lowest story). Taking $i = 1$ (the lowest story) for Eq. (13) yields the following Eq. (14).

$$\sigma_{t(PCa)1} + \sigma_{a(PCa)1} + \sigma_{ae1} = v\sigma_{B1} \quad (14)$$

Where, $\sigma_{t(PCa)1} = 2V_{t(PCa)1} / (t_{w1} l_w)$ (15)

$$\sigma_{a(PCa)1} = 2 / (t_{w1} D) \cdot \Sigma P_{a(PCa)j} / \tan \theta_j \quad (16)$$

$$\sigma_{ae1} = 2T_{y1} / (t_{w1} h_{w1}) \quad (17)$$

T_{y1} = tensile yield strength of horizontal reinforcement of the each-story arch mechanism of the first story.

At the same time, on the assumption that all horizontal reinforcement of the PCa multi-story structural wall with slippage at the horizontal joints reach the yield strength on the first story as in the case of the RC multi-story structural walls, the following Eq. (18) is established.

$$V_{t1} = V_{t(PCa)1} + T_{y1} (l_w / h_{w1}) \quad (18)$$

Substitution of Eq. (15) through Eq. (17) into Eq. (14) and setting up simultaneous equations together with Eq. (18) delete T_{y1} and yield the following Eq. (19).

$$\Sigma P_{a(PCa)j} / \tan \theta_j = (1 - \beta_1) t_{w1} D v \sigma_{B1} / 2 \quad (19)$$

The assumption that Eq. (20) holds for the left side of Eq. (19) in the same manner as Eq. (9) yields the Eq. (21) below.

$$P_{a(PCa)j} = P_{a(PCa)} \cdot a_j \quad (20)$$

$$P_{a(PCa)} = (1 - \beta_1) t_{w1} D v \sigma_{B1} / (2 \Sigma a_j / \tan \theta_j) = P_a \quad (21)$$

On the basis of Eq. (21) above, the shear force carried by the multi-story arch mechanism of PCa multi-story structural wall, on the story where the design shear force becomes largest, is identical with that on the lowest story of monolithic RC multi-story structural wall. The ratio of the horizontal reinforcing bars used for the multi-story truss and the each-story arch mechanisms on the lowest story determine the shear force carried by each mechanism. The concrete stress of the compression strut used in each mechanism establishes the following Eq. (22) and Eq. (23) for the first story.

$$\sigma_{a(PCa)1} = \Sigma \sigma_{a1j} \quad (22)$$

$$\sigma_{t(PCa)1} + \sigma_{ae1} = \sigma_{t1} \quad (23)$$

As for stories other than the first story, the shear force carried by each mechanism is assumed to depend on the distribution coefficient of the external force.

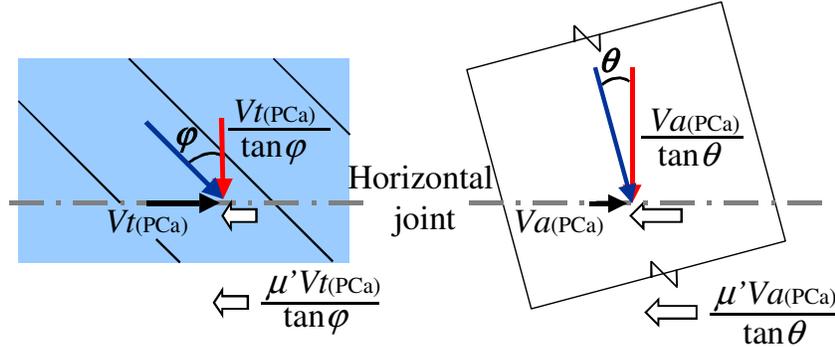
Shear strength of PCa multi-story structural wall with slippage at the horizontal joint

The shear strength of PCa multi-story structural wall with slippage at the horizontal joint is given by Eq. (12). The shear slip strength V_{sli} for the identification of slippage at the horizontal joint on the i^{th} -story of PCa multi-story structural wall[2] is determined by the following Eq. (24).

$$V_{sli} = \mu' (V_{t(PCa)i} / \tan \phi + V_{a(PCa)i} / \tan \theta_j) + D o_i + C_i = \mu' (V_{t(PCa)i} + \Sigma P_{a,j} / \tan \theta_j) + D o_i + C_i \quad (24)$$

Where, $\phi = 45$ -degrees, $V_{a(PCa)i} = V_{ai} = \Sigma P_{a,j}$, μ' = friction coefficient at horizontal joint and $D o_i$, C_i = dowel resistance force of the vertical joint bar and shear key at horizontal joint on the i^{th} -story.

In the Eq. (24) above, the vertical component of the concrete compression strut stress of the multi-story truss and arch mechanisms, which are resistance mechanisms generated in response to the horizontal force at the horizontal joint of the PCa multi-story structural wall before slippage, is assumed to be the axial force working on the horizontal joint, as shown in Figures 4 (a) and (b). The equation also takes into consideration the dowel effect of the vertical joint bar at the horizontal joint as well as the effect of a shear key set at the bottom of the PCa wall panel.



(a) Compression strut of the multi-story truss mechanism (b) Compression strut of the multi-story arch mechanism

Figure 4: Compression force acting on the horizontal joint of PCa wall panel

Eq. (12) shows $V_{sli} = V_{t(PCa)i} + V_{a(PCa)i}$, while Eq. (21) indicates $V_{a(PCa)i} = V_{ai}$. Therefore, based on the results of Eq. (24), the shear force carried by the multi-story truss mechanism on the i^{th} -story before slippage $V_{t(PCa)i}$ is given by the following Eq. (25).

$$V_{t(PCa)i} = (\mu' \Sigma P_{aj} / \tan \theta_j + D_{oi} + C_i - \Sigma P_{aj}) / (1 - \mu') \quad (25)$$

As for the shear force carried by each-story arch mechanism of the i^{th} -story (V_{aei}), the value is determined from the smaller of either the tensile strength carried by the horizontal reinforcement which serves as the path of stress after slippage at the horizontal joint T_{yi} or the shear strength of the compressing column ${}_c V_{cui}$, as expressed by the following Eq. (26).

$$V_{aei} = \min.(T_{yi}, {}_c V_{cui}) \quad (26)$$

$$T_{yi} \leq (V_{ti} - V_{t(PCa)i}) \cdot h_{wi} / l_w \quad (27)$$

Where, T_{yi} = tensile strength carried by the horizontal reinforcement of each-story arch mechanism of the i^{th} -story and ${}_c V_{cui}$ = shear strength of the compressing column on the i^{th} -story, where the shear span is 1/4 of the height of the story[2].

The simplified calculation method proposed in this paper gives shear strength, on the assumption that the PCa multi-story structural wall is an integral member, to the story where the design shear force becomes the largest. In addition, the method is a shear design method to confirm that no shear failure occurs even in the event of slippage on other stories.

SAMPLE DESIGN OF PRECAST CONCRETE MULTI-STORY STRUCTURAL WALL AND EVALUATION OF THE DESIGN

Outline

The multi-story structural walls in the span direction of 6-stories RC building are the object of the sample design for the purpose of this study[3]. Shear design is first worked by assuming that this structural wall is

a RC multi-story structural wall without opening and then examined by assuming that the wall panels are PCa panels with beams. The vertical joint in this case is assumed to remain without failure, even until the ultimate state.

Figure 5 and Table 1 show the cross-sectional view and specifications of the sample multi-story structural wall. The thickness of the wall panels of all stories is 210mm. Figure 6 shows the details of the horizontal joint, where bedding mortar having a thickness of 20mm is used for erecting PCa wall panel and a mortar-filled sleeve connection is used for the vertical joint bars. The arrangement for the vertical joint bar at the horizontal joint is D16 (SD295A) or D19 (SD345) -@ 600.

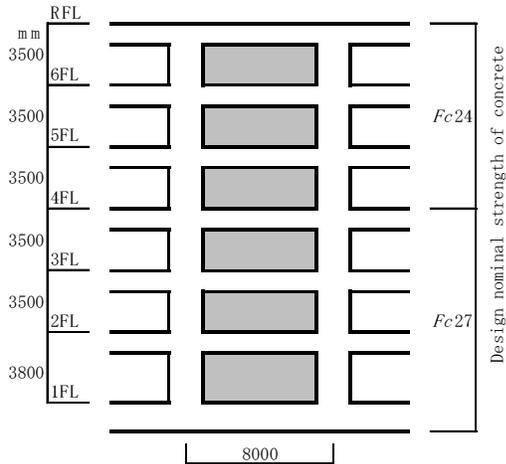


Figure 5: Skeleton of multi-story structural walls

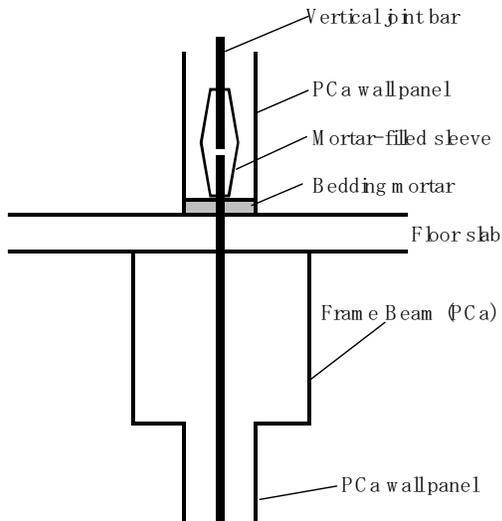


Figure 6: Detail of the bedding mortar type at the horizontal joint

Table 1: Sectional list of multi-story RC structural walls

Fbor	Wallpanel		Frame beam		Boundary column	
	tw (mm)	Reinforcing bar	Section (mm)	Main bar	Section (mm)	Main bar
RF			450x950			
6F	210	D 10@200W	450x850	8-D 25	750□	12-D 25
5F						32-D 25
4F					30-D 25	
3F					34-D 25	
2F					34-D 25	
1F					40-D 25	

Main reinforcement: SD 345, Shear reinforcement: SD 295A

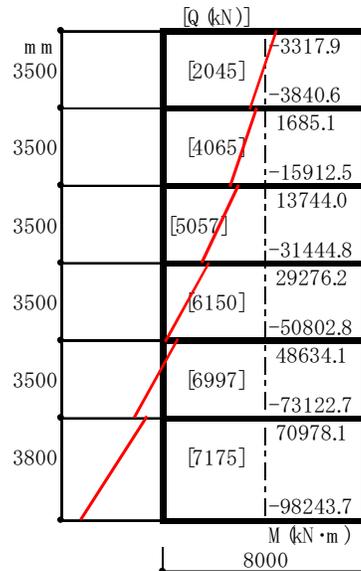


Figure 7: Ultimate shear force for design of multi-story structural walls

Shear design for PCa multi-story structural wall

Shear strength as a RC multi-story structural wall

Figure 7 shows the shear force for the ultimate design of the multi-story structural wall shown in Figure 5 on the assumption that the structural wall on the first story is subject to shear failure. The structural characteristics factor (D_s) is assumed to be 0.55, same as in the conventional RC structure. Then, a PCa

multi-story structural wall using PCa wall panels with beams in place of the wall panels of RC multi-story structural wall is taken into consideration. Even with a PCa multi-story structural wall in this instance, the shear strength is determined by the calculation method by assuming the wall as a RC multi-story structural wall having the same cross section.

The shear force carried by the multi-story truss mechanism takes into consideration all of the horizontal joint bars in the vertical joint and frame beam main reinforcements. Using Eq. (2), Table 2 shows the maximum value of the shear force carried by the multi-story truss mechanism on each story.

The shear strength $V_{u(RC)}$ is the summation value of the shear force carried by the multi-story arch mechanism V_{a1} and the shear force carried by the multi-story truss mechanism V_{t1} of the lowest (first) story. The $V_{u(RC)}$ is determined by assuming that the shear force carried by other stories follow the distribution of the design shear force. Table 3 (b) shows the results of the calculation. According to Table 3 (c), it is confirmed that the sum of the concrete stress of the compression strut reaches the effective compressive concrete strength on the first story and the compressive stress is lower than effective compressive strength on the second and higher stories.

Table 2: Shear force carried by the multi-story truss mechanism

Story	t_w (cm)	l_v (cm)	h_w (cm)	Horizontal reinforcement (SD295A)	$V_t(RC)$ (kN) Eq. (2)	Q_D (kN) Fig. 7
6			350	13-D 10	3823	2045
5			350	13-D 10	3823	4065
4	21	800	350	26-D 10	4448	5057
3			350	26-D 13	5425	6150
2			350	26-D 13	5425	6997
1			380	28-D 13	5154	7175

Q_D = Ultimate shear force for design

Table 3: Shear strength as multi-story RC structural walls

(a)	D (cm)	P_j (kN)	a_j	σ_B (N/mm ²)	$\nu = \nu_0$	$\tan \theta_j$ Eq. (5)	(b)	Story	Eq. (10)	P_{aj} (kN) Eq. (9)	V_a (kN) Eq. (11)	$V_u(RC)$ (kN)
	Story	Eq. (10)	Eq. (9)	Eq. (11)								
6	875	2045	11.49	24	0.58	0.20	6	$\beta 1$	632	632	2101	
5	875	2020	11.35	24	0.58	0.24	5		624	1256	4176	
4	880	992	5.57	24	0.58	0.28	4	0.402	307	1563	5195	
3	880	1093	6.14	27	0.57	0.36	3	P_a	338	1900	6318	
2	880	847	4.76	27	0.57	0.47	2	(kN)	262	2162	7188	
1	885	178	1.00	27	0.57	0.66	1	55.0	55	2217	7371	

$(V_{u1} = V_{a1} + V_{t1})$

(c)	V_t (kN)	σ_t (N/mm ²)	σ_a (N/mm ²)	$\sigma_t + \sigma_a$ (N/mm ²) Eq. (6)	$\nu \sigma_B$ (N/mm ²)
	Story	$V_u(RC) - V_a$			
6	1469	1.75	3.40	5.15	13.92
5	2920	3.48	6.26	9.74	13.92
4	3633	4.33	7.42	11.74	13.92
3	4418	5.26	8.43	13.69	15.26
2	5026	5.98	9.03	15.01	15.26
1	5154	6.14	9.12	15.26	15.26

Shear strength of a PCa multi-story structural wall

The shear strength (shear slip strength) when the slippage occurs at the horizontal joint V_{sl} is determined by Eq. (24). The friction coefficient μ' in Eq. (24) is set at 0.5 which is the design friction coefficient value for smooth-surface concrete that contains mortar in the joints[4].

The dowel resistance force in the vertical joint bars D_o is obtained by the following Eq. (28) as the shear resistance of the joint bars when the slip displacement is 2mm (which is equivalent to the value at the slippage occurrence in the horizontal joint shown in Figure 3) [5].

$$D_o = 3.52na_s\sqrt{\sigma_{sy} \cdot \sigma_B \cdot E_c / E_s} \quad [\text{kgf}] \quad (28)$$

Where, n = number of joint bars, a_s = cross-sectional area of a joint bar, σ_{sy} = yield strength of joint bar and E_c/E_s = reciprocal number of ratio of Young's modulus.

$C = 0$ is used in Eq. (24) since there is no shear key provided at the bottom edge of the PCa wall panels.

The shear force carried by the multi-story truss mechanism before slippage $V_{t(PCa)i}$ is determined by Eq. (25) as indicated in Table 4. The shear slip strength of the horizontal joint V_{sl} is the summation of the $V_{t(PCa)i}$ and the shear force carried by the multi-story arch mechanism V_{ai} . Table 5 (a) shows the results of the calculation.

Comparison between $V_{u(RC)}$ in Table 3 (b) and V_{sl} in Table 5 (a) yields the relationship $V_{sl} < V_{u(RC)}$ for the first and second stories, which occurs slippage at the horizontal joints. As the analytical model after slippage, each-story arch mechanism for all the stories is assumed as shown in Figure 2. As a result, the shear strength of the PCa multi-story structural wall $V_{u(PCa)}$ on the first story is the summation of both the V_{sl1} and the V_{ae1} . The shear force carried by other higher stories is determined on the assumption that it follows the distribution of the design shear force. The results are shown in Table 5 (a).

Table 5 (b) shows the relationship between the concrete stresses of the compression struts that consist of the respective mechanisms of the PCa multi-story structural wall. Table 5 (b) has confirmed that Eq. (22) and Eq. (23) hold for the first story and the sum of the compressive stress is lower than the effective compressive concrete strength on other higher stories. It thus becomes certain that slippage may develop on the second story according to this proposed design, however, no shear failure of wall panel will occur on the second story.

Table 4: Shear force carried by the multi-story truss mechanism of PCa structural walls

Story	Vertical joint bar	D_o (kN) Eq. (28)	$\mu'Va/\tan\theta_j$ (kN)	$V_{t(PCa)}$ (kN) Eq. (25)
6	12-D16	232	1588	2375
5	(SD295A)	232	2916	3782
4		232	3455	4248
3	12-D19	394	3928	4844
2	(SD345)	394	4206	4876
1		394	4248	4849

Table 5: Shear and slip strength of multi-story PCa structural walls

(a)	V_{sl} (kN) Eq. (11)+(25)		$V_u(RC)$ (kN)	Slip or not	$V_u(PCa)$ (kN)	(b)	σ_a (N/mm ²)	$\sigma_{t(PCa)}$ (N/mm ²)	σ_{ae} (N/mm ²)	σ_{sum} (N/mm ²) Eq. (13)	$\nu\sigma_B$ (N/mm ²)
6	3006	>	2101	not	2055	6	3.40	1.64	0.12	5.16	13.92
5	5038	>	4176	not	4086	5	6.26	3.26	0.23	9.75	13.92
4	5811	>	5195	not	5082	4	7.42	4.06	0.29	11.77	13.92
3	6744	>	6318	not	6181	3	8.43	4.93	0.36	13.72	15.26
2	7038	<	7188	slip !	7032	2	9.03	5.61	0.40	15.05	15.26
1	7066	<	7371	slip !	7211	1	9.12	5.76	0.38	15.26	15.26

$V_u(PCa)_1 = V_{sl1} + T_{y1}$ $\sigma_{sum} = \sigma_a + \sigma_{t(PCa)} + \sigma_{ae}$

CONCLUSIONS

This study has confirmed the following findings in connection with the shear design method for PCa multi-story structural walls with slippage at horizontal joints.

- 1) A method for easy calculation of the shear strength is proposed by regarding the multi-story structural wall as an integral member, and placing special attention paid to the story where the design shear force becomes largest (usually the lowest story).
- 2) An analytical model for the easy design of PCa multi-story structural walls is proposed, on the assumption that in case of slippage at the horizontal joint at any story, arch mechanism will be formed at every story. Since there is very uncertain that all of the horizontal joints will have slippage at once, the model gives an underestimation (safe value) of the shear strength of the PCa multi-story structural walls.
- 3) Though the PCa multi-story structural wall modeled for the sample design in this study is subject to slippage at the horizontal joint on the lower story for which resistance by each-story arch mechanism must be provided, the method proposed in this study allows to calculate the design shear force taking into consideration shear resistance and failure mechanisms.

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