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Seismic Design and Behaviour of Precast Concrete Wall Type Column with Mechanical Connection

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ABSTRACT

The present paper is discussed about the seismic behavior of precast concrete column type wall consisted in the high rise dwelling house by means of lateral loading test. The behavior of failure, hysteresis curve of load and displacement, slip deformation at the bottom and ductility were primarily investigated here. The maximum loads were compared with the ultimate strength calculated by the modelling of the compressive strut−tie, arch and dowel actions. It is thought that the formula of the ultimate strength derived from this model is very effective for the evaluation of that of precast concrete wall type column when we carry out the earthquake resistant design.

1. INTRODUCTION

The project of design and construction method for high−rise wall type column framed system were performed by the Japan Housing Corporation for the collective dwelling house. This system was developed with the purpose to turn into precast structure the high rise frame type of reinforced concrete wall system which possessed the earthquake resistant structural performance. The seismic behavior of the leg part of the intermediate wall type column of ridge direction in the first floor of the eleven story precast reinforced concrete system was studied here.The combined flexural and shearing experiment was conducted under the method of cantilever loading form. The influence of the lateral aspect ratio (ratio of length to the thickness of wall type column) of PCa specimens and the placed mortar to the seismic behavior is investigated here. Furthermore, the shear transfer mechanism at the horizontal connection of PCa wall type column is represented by the model of friction and dowel actions, and is examined comparing with the experimental results.

2. SUMMARY OF THE EXPERIMENT

2.1 Test specimens

The specimens used in this experiment are made in a half scale of the intermediate PCa wall type column in actural structural design. The total number of specimens is nine, the eight among them is precast reinforced concrete(abbreviated as PCa below) and the another one is an ordinary

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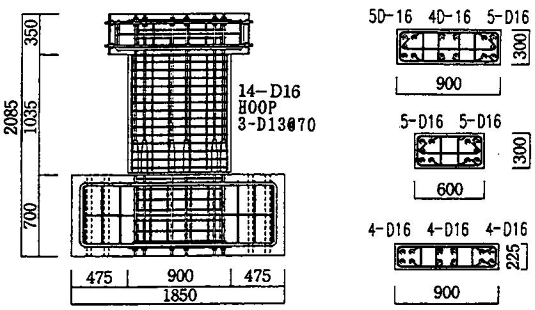
Table−1 Structural characteristics of specimen

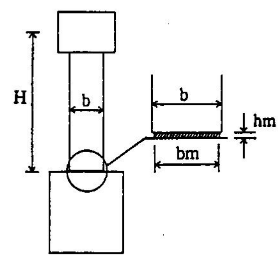
Specimen	Width b (mm)	Depth D (mm)	Height H (mm)	Depth of joint mortar layer hm (mm)	$\frac{bm^{3)} \times 100}{b}$ (%)	Ratio of tensile reinforcement Pt(at/bD) (%)	Ratio of shear reinforcement Pw (%)	Ratio of axial force $N/bD \cdot \sigma_B$ (%)	Remark
WPC−01					100		1.01		Proto type [1]
WPC−02				10	100	0.37			
WPC−03	300	900	1035		80 [2]			0.1	
WPC−04				15	100		1.81		
WPC−05				10	100	0.53			14−D19
WRC−06					100	0.37			Monolithic
WPC−07	300	600	1035	10	100	0.55	1.01	0.1	Proto type
WPC−08							1.81		
WPC−09	225	900	1035	10	100	0.39	1.05	0.1	Proto type

Note: 1) Shear reinforcement is the same as that in actural design.
2) Placed mortar is decreased by 20% at the direction of width of specimen.
3) bm is width of placed mortar.

reinforced concrete (called RC below). The specified concrete compressive strength is 330kgf/cm^2. The list of each structural characteristics of specimens is displayed in Table−1, and detail of steel bar arrangement is shown in Figure−1. Also the illustration of the shape for placed mortar in the connection is shown in Figure−2.



Figure−1 Detail of bar arrangement of specimen



Figure−2 Shape of placed mortar

2.2 Loading method and measurement

As shown in Figure−3, the horizotal and axial forces are given at the same time by oiljacks. The height of loading point is 121cm, and positive−negative cyclic loadings are applied to the specimens by the control of displacement. And axial compressive stress σ_0=33 kgf/cm^2 is applied to them. The displacements of various positions was measured by the displacement meter with high performance, and the strain of main and shear reinforcements were measured by wire strain gauge. The state of crack was observed by human eye.

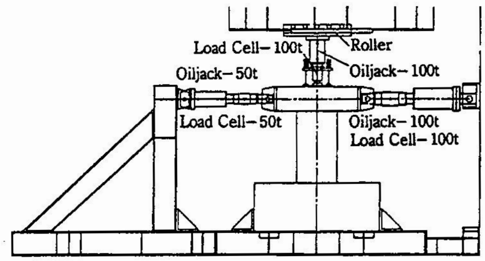
3. TEST RESULTS AND CONSIDERATION

3.1 Properties of material

The mechanical properties of the reinforcing bar used in the specimen are shown in Table−2(a), and the test results of concrete material are also shown in Table−2(b).

3.2 States of crack and failure

The states of failure of the specimens WPC−02 and WPC−06, are shown in Figure−4. For all of them, after the tensile reinforcement attained the yield point, the compressive failure of concrete occured at compressive fiber, after that, hardly have the strength increased. The pattern of failure for all the specimens is considered to be of flexural failure.The cracks occurred in RC specimen were more multiple than that in PCa ones.



Figure−3 Apparatus of test

3.3 Strength and hysteresis curve

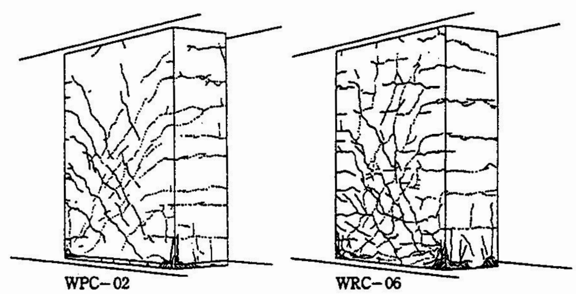
The hysteresis curves of load and translation angle for specimen with the value D/b=3 are shown in Figure−5. For all the specimens, the strength hardly deteriorates till the last cycle. Comparing WRC−02 with WPC−06, however the hysteretic loops are almost the same untill the tensile reinforcement attain the yield, after that the increase of strength for PCa specimen is greater than that for RC one, and the maximum strength of PCa specimen is greater in the ultimate state. It is considered that the dowel effect appeared at the connecting main reinforcing bar in compression zone of horizotal connection. But the deterioration of strength were not observed till the last cycle both in PCa and RC specimens, and the difference between the both specimens was not found when considering ductility. As for the influence of placed mortar, comparing the specimen

Table−2(a) Mechanical properties of reinforcement

Type	Nominal strength	Tensile strength (kg/cm²)	Yield strength (kg/cm²)	Young's modulus (× 10⁵ kg/cm²)	Elongation (%)
D10	SD295A	5270	3735	2.31	16.0
D13	SD295A	5118	3572	2.18	18.0
D13	SD390	5690	4065	2.06	15.2
D16	SD390	5711	3924	1.96	16.8
D19	SD390	5615	4094	1.98	18.8

Table−2(b) Test results of concrete material

Specimen	Concrete			Placed mortar			Grout mortar	
	Compressive strength (kg/cm²)	Splitted strength (kg/cm²)	Young's modulus (×10⁵kg/cm²)	Compressive strength (kg/cm²)	Splitted strength (kg/cm²)	Young's modulus (×10⁵kg/cm²)	Compressive strength (kg/cm²)	Young's modulus (×10 kg/cm²)
WPC−01	337	22.49	2.59	429	31.96	2.50	588	3.24
WPC−02	284	22.25	2.66	391	26.20	2.94	463	2.18
WPC−03	380	27.20	2.61	374	34.74	2.38	691	3.65
WPC−04	386	25.90	2.63	399	38.28	2.74	812	3.68
WPC−05	429	28.90	3.22	340	36.19	2.62	768	3.40
WRC−06	439	26.83	2.88	—	—	—	—	—
WPC−07	344	21.75	2.25	449	25.75	2.52	—	—
WPC−08	313	21.45	2.38	448	28.58	2.73	—	—
WPC−09	317	20.09	2.33	415	25.29	2.67	—	—

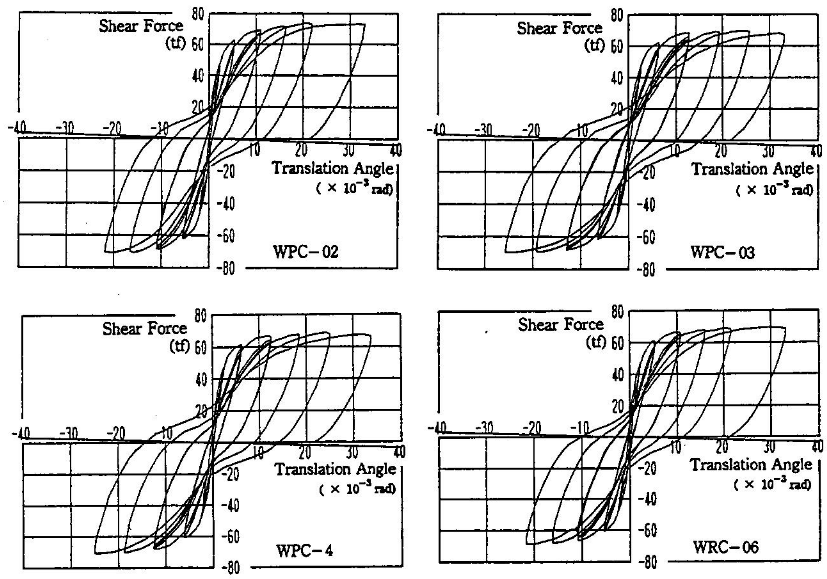


Figure−4 The states of cracks and failure

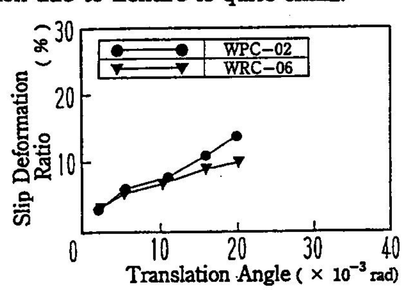
WPC−03 in which the setting area of placed mortar was decreased by 20%, which supposed the construction error, with specimen WPC−04 in which the thickness of placed mortar is 15mm, the former ultimate strength is somewhat lower, and however the deterioration of strength were not found till the last cycle. It is considered from this fact that there was also no problem in ductility.

3.4 Deformation characteristics

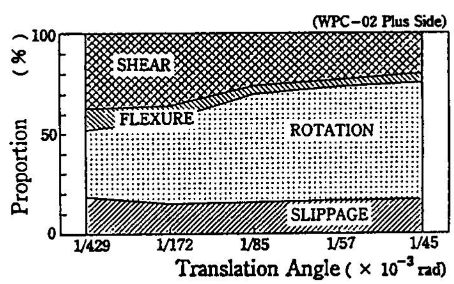
The relationship of translation angle and slip deformation ratio are shown in Figure−6. The slip deformation ratio [1] is the value of slip deformation devided by the value of horizontal displacement at the loading point. Comparing RC specimen with PCa one, the maximum value of WRC−06 is approximatly 10 %, while that of WPC−02 is approximately 15%. The influence of the characteristic of placed mortar to slip deformation ratio is not so much visible. Regarding from the point of view of difference of lateral aspect ratio, the greater the value of D/b is, the smaller slip deformation will be. Furthermore, the graph of Figure−7 shows the proportion of four deformation components such as flexure,shear,rotation and slippage to the whole horizontal displacement. We can see from the figure that about half of the whole horizontal dislpacement is caused by rotation due to the opening at the connection, and the proportion of deflection due to flexure is quite small.



Figure−5 The hysteresis curves of load and translation angle



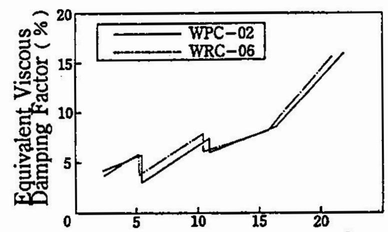
Figure−6 Relation of translation angle and slip deformation ratio



Figure−7 Proportion of various deformation components

3.5 The equivalent viscous damping factor

The equivalent viscous damping factor was calculated in order to investigate the hysteresis characteristic. The relationship between the translation angle and the equivalent viscous damping factor is shown in Figure−8 separated by the different influence factors. All of the specimens present almost the same level in the hysteresis characterestic, and the notable difference of PCa and RC specimens was not found. Moreover, the influence of placed mortar were not seen almost in the former.



Figure−8 Relation between translation angle and equivalent viscous damping factor

4. SHEAR TRANSFER MECHANISM

While PCa specimen is subjected to flexure and shear, the shear force acted in the leg portion of PCa one is transfered to the connecting precast unit through the joint mortar by the friction force occurred on the interface of connection and the dowel force of main reinforcement in the compression zone. When the shear resistance mechanism is formed on the interface of compression zone, the assumption can be made that in PCa specimen an inclined compressive strut (called compressive strut−tie action below) is formed with the equilibrium to the yielding forces of main reinforcement in side and middle of the specimen, as well as another inclined compressive strut sloping to the axial load direction (called arch action below) is also generated. The friction force on the interface of connection in compression zone is generated depending on these compressive strut. Furthermore, when the shearing force is applied to the interface of connection and the slip deformation is caused, dowel action is derived from the main reinforcement across the interface of connection.

We describe the compressive strut−tie、arch and dowel actions based on this analytical model as follow.

4.1 Compressive strut−tie action

When the main reinforcements in side and middle of PCa specimen reached the yield point and yielding mechanism is constituted, just as shown in Figure−9, in the field above grout−filled coupling sleeve, the inclined compressive strut which has an angle ϕ with the axis of specimen, is formed with the equilibrium to the yielding forces of each main reinforcement towards the interface of joint mortar where the compression block is constructed. Owing to the compression in the strut, the friction force Qt works on the interface of connection.

The normal stress σt and shearing stress τt act in this compresive strut ABCD. Nearby the interface of connection a plane stress field is derived by normal stress σx、σy and shearing stress τxy. And the relation between the two components can be described as :

$$\begin{aligned} \sigma x &= \sigma t \cdot \sin^2\phi - 2\tau t \cdot \sin\phi \cdot \cos\phi \\ \sigma y &= \sigma t \cdot \cos^2\phi + 2\tau t \cdot \sin\phi \cdot \cos\phi \qquad (1) \\ \tau xy &= \sigma t \cdot \sin\phi \cdot \cos\phi - \tau t\,(\cos^2\phi - \sin^2\phi) \end{aligned}$$

Shearing stress τt in the compressive strut can be disregarded here. Using $\tau xy = Qt/b \cdot kD$、

$\sigma y = \beta \cdot \sigma_B$ and the relations of $\sin\phi = \tan\phi / \sqrt{1+\tan^2\phi}$ and $\cos\phi = 1/\sqrt{1+\tan^2\phi}$, from the 2nd and the 3rd equation of (1), we can get :

$$Qt/k \cdot b \cdot D = \beta \cdot \sigma_B \cdot \tan\phi \qquad (2)$$

where kD is the length of compression zone (k : factor), b and D are the width and the length of specimen respectively, β is coefficient, σ_B is the compressive strength of concrete.

The yielding tensile force of the main reinforcements in the side and middle Ty and Tym respectively and the resultant of compression force have the equilibrium Ct=Ty+Tym. Substitute $Ty = a_t \cdot \sigma y$, $Tym = a_{tm} \cdot \sigma y$ and $Ct = \beta \cdot \sigma_B \cdot k \cdot b \cdot D$ into the equilibrium above :

$$k \cdot \beta \cdot \sigma_B \cdot b \cdot D = a_t \cdot \sigma y + \gamma \cdot a_{tm} \cdot \sigma y \qquad (3)$$

where a_t and a_{tm} are the sectional area of main reinforcement in the side and middle respectively. σy is the strength of reinforcement at yield point, and γ is the effective coefficient related to the position of main reinforcement in the middle.

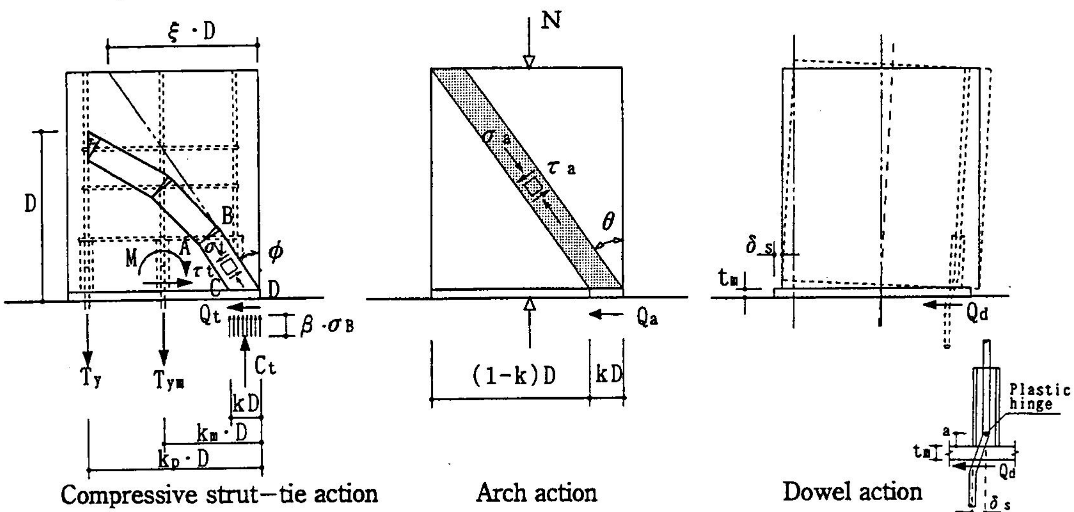
From equation (2) and (3), the shear transfer capacity Qt due to the compressive strut–tie action can be described as :

$$Qt = \mu t\,(a_t + \gamma \cdot a_{tm}) \cdot \sigma y \qquad (4)$$

where, $\mu t = \tan\phi = \xi \cdot D/H = \xi / \lambda$ (λ: ratio of shear span, H : the height of loading point) is the appearant friction coefficient. The coefficient γ is supposed 0.5. In the formula (4), coefficient ξ is assumed as 0.68 for the present analysis.

4.2 Arch action

When axial load N is applied to PCa specimen, as shown in Figure–9, the comperessive strut is formed with angle θ to the axis of spcimen towards the interface of joint mortar of compression zone, and then produced arch action. Depending on the arch action, shear force Qa may be derived at the interface of connection, and shear force is transferred through the joint mortar. In this compressive strut, the normal stress σa and the shearing stress τa act. The relationship between σa、τa and the normal stress σx、σy as well as shearing stress τxy



Figure–9 Model of compressive strut

which act nearby the interface of connection, can be developed from replacing σt、τt and ϕ in equation (1) with σa、τa and θ respectively. And using the relations of $\sigma x=0$, $\sigma y=N/k\cdot b\cdot D$, $\tau xy=Qa/k\cdot b\cdot D$ and $\tan\theta=(1-k)\cdot D/H$, we can get :

$$N/k\cdot b\cdot D=\sigma a$$

$$Qa/k\cdot b\cdot d=\sigma a+(1-k)\cdot D/2H \quad (5)$$

When the normal stress σa of compressive strut reaches the comressive strength of concrete σ_B, regarding that the mechanism of arch action is formed, we can remove the coefficient k in equation (5), and then shear transfer capacity Qa produced at the interface of connection due to arch action can be written as :

$$Qa=\mu a\cdot N \quad (6)$$

where, by introducing the symbol $\eta=N/b\cdot D\cdot\sigma_B$, the appearant friction coefficient is shown as $\mu a=(1-\eta)\cdot D/2H=(1-\eta)/2\lambda$.

4.3 Dowel action

The dowel action of main reinforcement cross the interface of connection of PCa specimen having a certain joint width, shown as Figure−9, is dependent upon the local compressive stress of concrete. This is called as the bearing compressive stress of concrete which is generated within the distance a from the interface of connection to the plastic hinge. The bearing compressive stress of concrete σcc get greater depending on the restraint of surrrounging concrete,and can get several times greater than the uniaxial compressive strength of concrete σ_B. This had been verified by direct shearing test. Supposing that shear transfer capacity Qd due to dowel action have a equilibrium with the resultant force of bearing compressive stress of concrete, we can get :

$$Qd=\phi c\cdot Cd\cdot\sigma_B\cdot a\cdot\Sigma dr \quad (7)$$

where, Cd is the coefficient of bearing compressive strength. ϕc is the decrease coefficient, and in this case, we assumed Cd=3.0, and $\phi c=0.2$ and 0.5 for the case with and without the main reinforcement in the middle respectively [2]. a corresponds to the distance from the interface of connection to the position where maximum bending moment is produced in the reinforcement, and is calculated using the theory of elastic support of beam. Taking joint width t into accout, it can be written as :

$$a=\frac{1}{\beta}\tan^{-1}\left(\frac{1}{1+\beta\cdot t}\right) \quad (8)$$

where, $\beta=(kc/4EsIs)^{1/4}$ means the relative stiffness of reinforcement and concrete. From direct shearing test, we can get the formula described through σ_B as follow [3] :

$$\beta=\frac{1.50}{dr}\left(\frac{\alpha\sqrt{\sigma_B}\times10^4}{Es}\right)^{1/4}$$

where, $\alpha=0.203+0.0013\sigma_B$, Es and Σdr is the Young's modulus and sum of diameter of main reinforcement in the compressive zone respectively.

4.4 Suggestion for the formula of shear transfer capacity

When main reinforcement yield and the resistance mechanism is formed in PCa specimen subjected to flexural moment, shearing force and axial force, the shear transfer capacity Qu can be represented from the friction forces such as Qt and Qa due to the compressive strut−tie action and arch action respectively as well as dowel action Qd due to main reinforcement. Thus, using equation (4)、(6) and (7), we can get :

$$Qu = \mu t\,(a_t + 0.5\,a_{tm})\,\sigma y + \mu a \cdot N + \phi c \cdot Cd \cdot \sigma y \cdot a \cdot dr \qquad (9)$$

4.5 The consideration of theoretical analysis

The experimental result and theoretical calculation are shown in Table-3. The maximum error of PCa specimens is 8%, which shows well agreement of the experimental result with the theoretical calculation, and the formula of theoretical analysis is quite suitable for the present experimental result. Furthermore, the percentage of dowel force to shear transfer capacity for PCa specimens is within 17−26%, which shows that dowel action contributes to the increase of strength after the tensile reinforcements yield.

Table−3 Comparation of experemental results with theoretical analysis (unit:tf)

Specimen	Experimental results	Analysis for shear transfer capacity				
	Maximum strength	Ultimate shearing strength		Dowel force		Friction force
	eQu	cQu	eQu／cQu	cQd	cQd／cQu	cQf
WPC−01	73.7	71.8	1.03	14.3	0.20	57.5
WPC−02	74.0	73.3	1.01	16.4	0.22	56.9
WPC−03	69.8	73.0	0.96	15.9	0.22	57.1
WPC−04	71.1	73.0	0.97	15.1	0.21	57.9
WPC−05	89.4	97.6	0.92	25.4	0.26	72.2
WRC−06	69.4	80.0	0.87	21.7	0.27	58.3
WPC−07	33.3	32.3	1.03	5.8	0.18	26.5
WPC−08	34.2	31.8	1.08	5.4	0.17	26.4
WPC−09	57.7	56.9	1.01	10.9	0.19	46.0

Note: cQu is the result calculated from equation (9). cQu = cQd + cQf.

5. CONCLUSION

The following items are suggested from the experimental and theoretical results :

(1) Comparing PCa specimens with RC one, PCa specimen indicated higher strength, greater slip deformation in connection and higher ductile property.

(2) The specimens which have 80% and 100% of setting area of placed mortar respectively showed almost the same mechanical behavior.

(3) As for the shear transfer mechanism of the connection of PCa specimen in which the yield due to flexure has occurred, the shear force which is described by the sum of friction forces due to tie action and arch action as well as dowel force due to main reinforcement in compression zone, is well agreed with the experimental results. And the formula for shear transfer capacity is very effective to calculate the ultimate strength. Depending on the present experiment, the dowel action owned a proportion of 17%−26% of the shear transfer capacity.

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