17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Structural performance of external frames using high-strength PCM in beam-column joints for seismic retrofitting

T. Abe(1), E. Inai(2), T. Akita(3) , J. Osaki(4) , K. Kitahara(5) and A. Oogami(6)

(1) *Graduate Student, Graduate School of Sciences and Technology for Innovation Yamaguchi Univ., b002ve@yamaguchi-u.ac.jp*
(2) *Professor Dr. Eng., Graduate School of Sciences and Technology for Innovation Yamaguchi Univ., inai@yamaguchi-u.ac.jp*
(3) *Lecture Dr. Eng., Graduate School of Sciences and Technology for Innovation Yamaguchi Univ., akita@yamaguchi-u.ac.jp*
(4) *General Manager Dr. Eng., Production Technology Division Hagimori Industries Ltd., j-osaki@hagimori.co.jp*
(5) *Tokyo Branch, Ube-Mitsubishi Cement Co. Ltd., 34904u@umcc.co.jp*
(6) *Design-fit Office Sales Department, UBE Construction Materials Co. Ltd., asahi.oogami@ube-ind.co.jp*

Abstract

Loading tests of five cross-shaped partial reinforced concrete frame specimens modeling for the external frame, which is used for the seismic retrofitting of existing reinforced concrete buildings, were conducted. The partial frame specimens have new low heat generation type high-strength polymer-cement-mortar (PCM) instead of concrete in the beam-column joints. Test parameters of the specimens are the flexural strength ratio of column and beam, shear strength margin of the column-beam joint, and with/without of special reinforcement in the column-beam joint. Test results indicated that the new PCM had a good performance as the material of the beam-column joint.

Keywords: Seismic Retrofitting, External Frame, Polymer-Cement-Mortar, Reinforced frame, Beam-column Joint

1. Introduction

The authors have been proposing the seismic retrofitting method for existing buildings by external frames using columns and beam members made of reinforced concrete and high-strength polymer-cement-mortar (PCM) in the beam-column joints. This PCM improves the anchorage performance of reinforcing bar, and enables the use of high-strength reinforcing bar. Therefore, the sections of the external frame can be small and thin.

PCM is supplied in the premixed powdery product by maker anywhere, even in place where there are no supply plants dealing with the high-strength concrete. Therefore, a strong external frames can be realized even in the countryside.

In this research program, new low heat generation type PCM has been developed for the purpose of suppressing cracks associated with the heat generation of PCM in the beam-column joints. In order to verify the structural performance of external frames having low heat generation type PCM in the beam-column joints, loading tests of five cross-shaped partial frame specimens modeling for the external frame were carried out. Three test parameters were set for the five specimens to obtain useful information for the structural design of the external frame.

2. Test program

2.1 Specimens and Test Parameters

A list of five specimens is shown in Table 1. The shapes and the arrangement of reinforcing bars of specimens are shown in Fig. 2 (1)~(5). The specimens are J-20, J-21, J-22, J-23 and J-24. All specimen is half scaled cross-shaped sub-assemblages that represents the external frame, and is designed to fail in the flexural mode of the column. J-20 specimen is the standard specimen. The column cross section of J-20 specimen is 280 mm × 350 mm, the beam cross section is 280 mm × 380 mm. The column main reinforcing bar is 12-D16 (SD390), the hoop is 2-U7.1@50 (SBPD1275). The beam main reinforcing bar is 6-D19

(SD390) in both the upper and lower ends, and the stirrup is 3-U7.1@50 (SBPD1275). J-20 specimen has a flexural strength ratio of beam to column of 1.54 and a shear strengh margin of the column-beam joint on the input shear force of 1.57. J-21 and J-22 specimens have the same amount of reinforcing bar and shear reinforcement in the colum and beam as J-20 specimen, howevere have the smaller cross section of the column and beam than J-20 specimen. As a result, J-21 specimen has a flexural strength ratio of 1.44 and a shear strengh margin of 1.29, and J-22 specimen has a flexural strength ratio of 1.29 and a shear strengh margin of 1.09. J-23 and J-24 specimens have the smaller amount of the beam main reinforcing bars than J-20 specimen, and have a flexural strength ratio of 1.09 and a shear strengh margin of about 1.50 as well as J-20 specimen. Further compared with the other specimens, J-24 specimen has also special stirrups in the beam-column joint.

The results of material test of concrete and PCM are shown in Table 2. The compressive strength of concrete in the column and beam is 44.6 to 49.0 N/mm². The compressive strength of PCM is 76.6 to 83.2 N/mm². The results of material test of reinforcing bars are shown in Table 3.

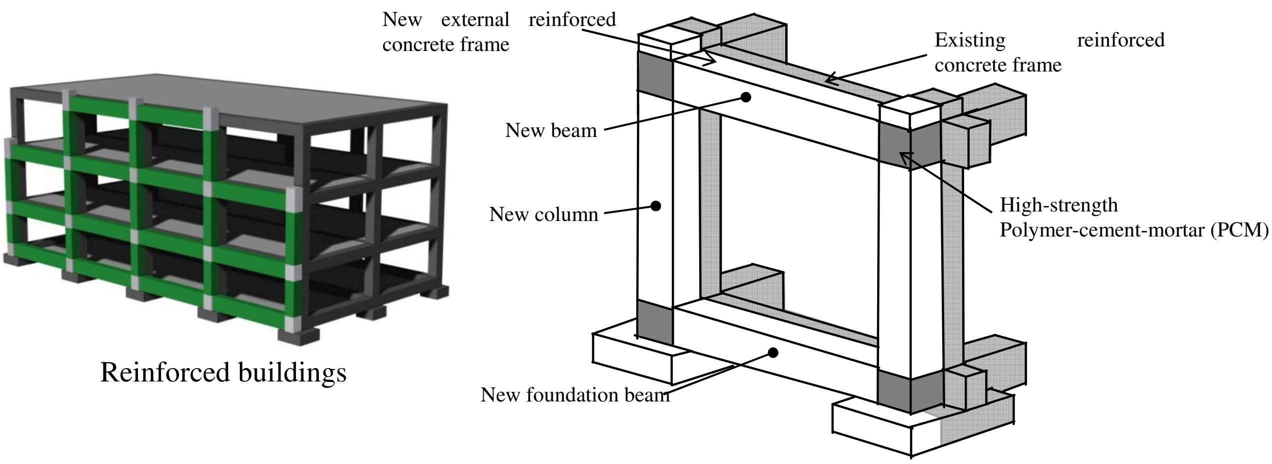
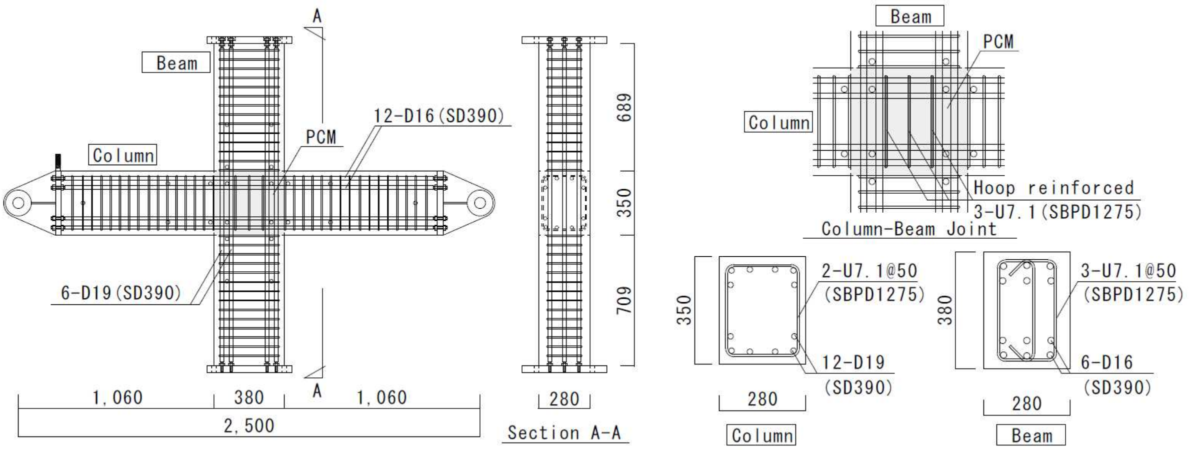


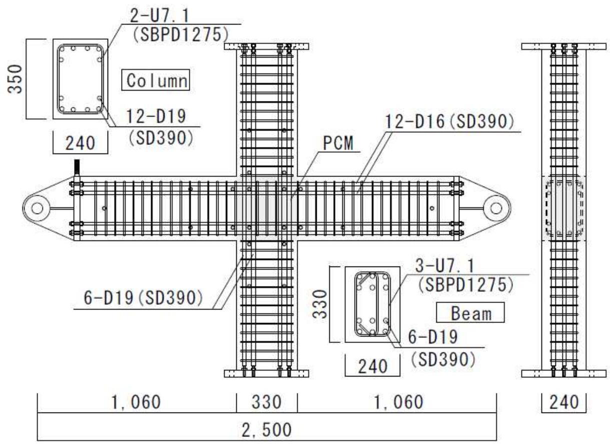
Fig. 1. Seismic retrofitting method using external frame

Table 1: A list of specimen

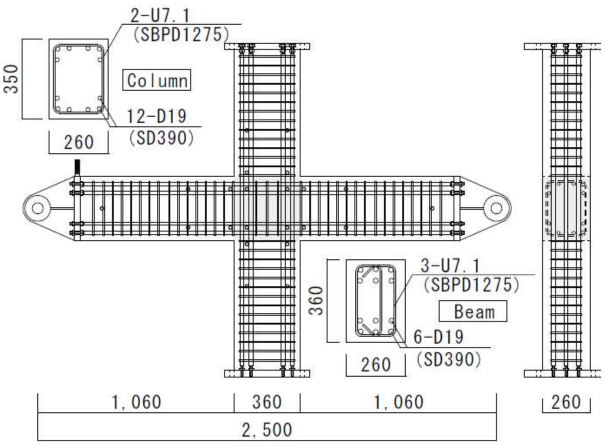
Specimen	Column			Beam			Lateral reinforcement in beam-column joint	Flexural strength ratio beam/column (column/beam)	Shear stlength margin of beam-column joint
	Section(㎟) bxD	Main reinforcing bar	Hoop	Section(㎟) bxD	Main reinforcing bar	Stirrup			
J-20	280×350	12-D16 (SD390)	2-U7.1@50 (SBPD1275) Pw=0.57%	280×380	6-D19 (SD390)	3-U7.1@50 (SBPD1275) Pw=0.86%	column 3-☐U7.1 (SBPD1275) beam nothing	1.54 (0.65)	1.57
J-21	260×350		Pw=0.62%	260×360		Pw=0.92%		1.44 (0.69)	1.29
J-22	240×350		Pw=0.67%	240×330		Pw=1.00%		1.29 (0.77)	1.09
J-23	280×350		Pw=0.57%	280×380	6-D16 (SD390)	3-U7.1@75 (SBPD1275) Pw=0.57%		1.09 (0.92)	1.49
J-24							column 3-☐U7.1 (SBPD1275) beam 3-◫ U7.1 (SBPD1275)	1.09 (0.92)	1.53



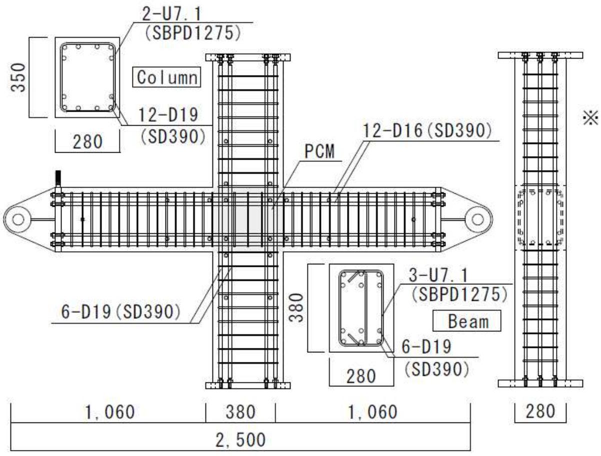
(1) J-20 Specimen



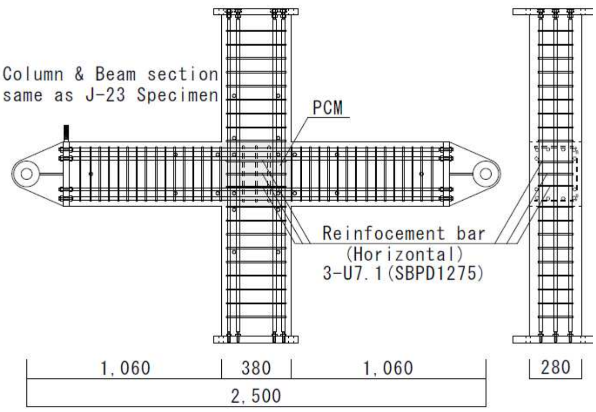
(2) J-21 Specimen



(3) J-22 Specimen



(4) J-23 Specimen



(5) J-24 Specimen

Fig. 2 . Shapes and the arrangement of reinforcing bars of specimens

Table 2: The results of material test of concrete and PCM

Specimen	Part	Material	Compressive Strength (N/mm^2)	Young's Modulus (kN/mm^2)
J-20	Lower beam ,Column	Ordinary concrete	47.6	32.1
	Upper beam	Ordinary concrete	48.0	33.3
	Column-beam joint	PCM	83.2	34.6
J-21	Lower beam ,Column	Ordinary concrete	48.6	31.0
	Upper beam	Ordinary concrete	44.9	30.4
	Column-beam joint	PCM	76.6	33.7
J-22	Lower beam ,Column	Ordinary concrete	45.1	32.0
	Upper beam	Ordinary concrete	44.6	32.5
	Column-beam joint	PCM	77.6	32.4
J-23	Lower beam ,Column	Ordinary concrete	49.0	32.8
	Upper beam	Ordinary concrete	46.6	32.2
	Column-beam joint	PCM	76.6	32.9
J-24	Lower beam ,Column	Ordinary concrete	49.0	33.1
	Upper beam	Ordinary concrete	47.4	32.7
	Column-beam joint	PCM	80.6	33.7

Table 3: The results of material test of reinforcing bars

Specimen	Part	Diameter (Spec)	Yield strength (N/㎟)	Tensile strength (N/㎟)	Young's modulus (kN/㎟)	Fracture elongation (%)	Yeild strain (μ)
J-20 J-21 J-22	Column main reinforcing bar	D16 (SD390)	447.8	608.5	195.3	18.2	2450
	Beam main reinforcing bar	D19 (SD390)	463.1	643.8	195.8	16.2	2761
	Shear reinforcement	U7.1 (SBPD1275)	1459	1517	202.2	8.6	9213
J-23 J-24	Column and beam main reinforcing bar	D16 (SD390)	448	609	195	18.2	2450
	Shear reinforcement	U7.1 (SBPD1275)	1459	1516	202	8.6	9213

2.2 Test procedure

A test setup is shown in Fig. 4. The bottom of the vertical member of the specimen was connected with the swivel device, and the both ends of the horizontal member were supported and restricted in the vertical direction by the clevis device. Then, the top of the vertical member was cyclically loaded by a horizontal hydraulic jack. The axial force of the vertical member was maintained to be zero under the loading. The horizontal loading was controlled by the story drift angle R.

The loading schedule of the test is shown in Fig. 5, the loading cycle was R=±0.00125 rad., R=±0.002 rad., R=±0.004 rad., R=±0.0067 rad., R=±0.01 rad., R=±0.015 rad., R=±0.02 rad., R=±0.03 rad., and R=±0.04 rad. The measurement of the story drift angle was carried out using a measuring frame. The loads were measured by the load cells which were installed in a horizontal hydraulic jack and the clevis device.

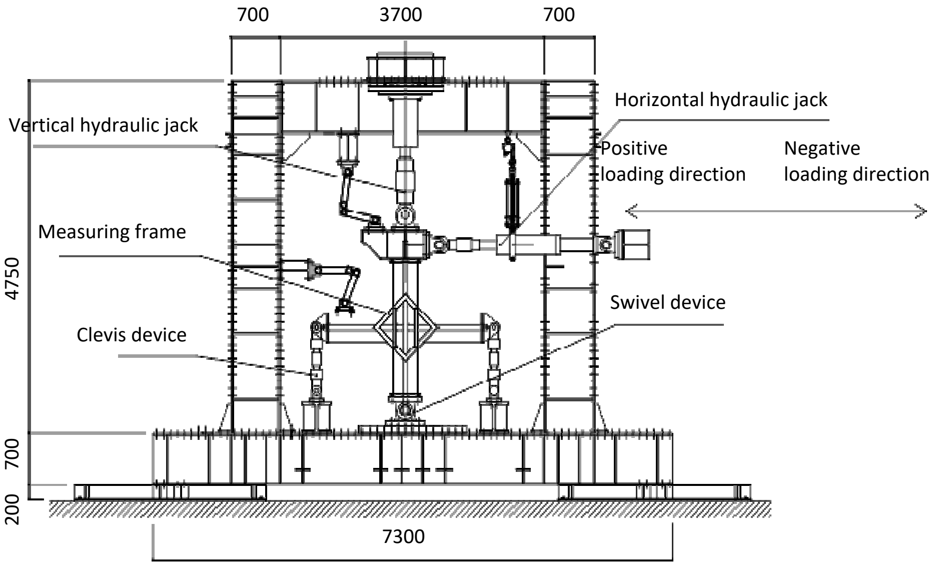


Fig. 4. A test setup

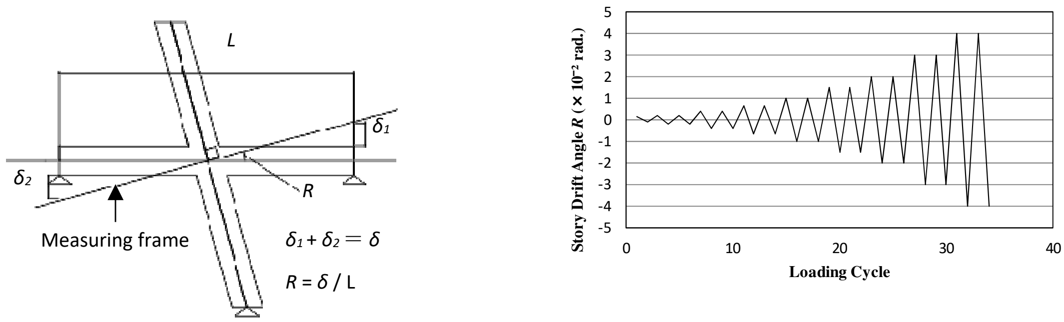


Fig. 5. Loading schedule

3. Test results

Shear force of the column Q - story drift angle R relationships are shown in Fig. 6. Equivalent viscous damping factors are shown in Fig. 7. Strain distributions of the main reinforcing bars of column and beam around the beam-column joint are shown in Fig. 8(1)~(10). Crack patterns of the specimens after the test are shown in Fig. 9(1)~(5).

J-20 specimen, after the column main reinforcing bars yield in the beam-column joint, also yield at the column ends, reached the maximum strength at R=3 %. Thereafter, the strength was reduced in the second loading cycle of R=4 %. The deterioration of shear force in the column was observed after R=3 % in J-21 specimen and R=2 % in J-22 specimen, respectively. There was no significant difference in performance up to R＝2 %. In the final loading stage, many cracks and peeling were observed at the beam-column joint. The column main reinforcing bars yield at the beam-column joint, but the yielding of the beam main reinforcing bar was not observed, as shown in Fig. 8. The yielding of the hoop in the beam-column joint did not occur.

In J-23 and J-24 specimens, the yielding of the beam main reinforcing bars were observed in the beam-column joint as well as the column main reinforcing bars. J-23 specimen had a slightly larger deterioration in strength compared to the J-24 specimen. There was no difference in the equivalent viscus damping factor. Many cracks are observed at the beam-column joint of both specimens in the final loading stage.

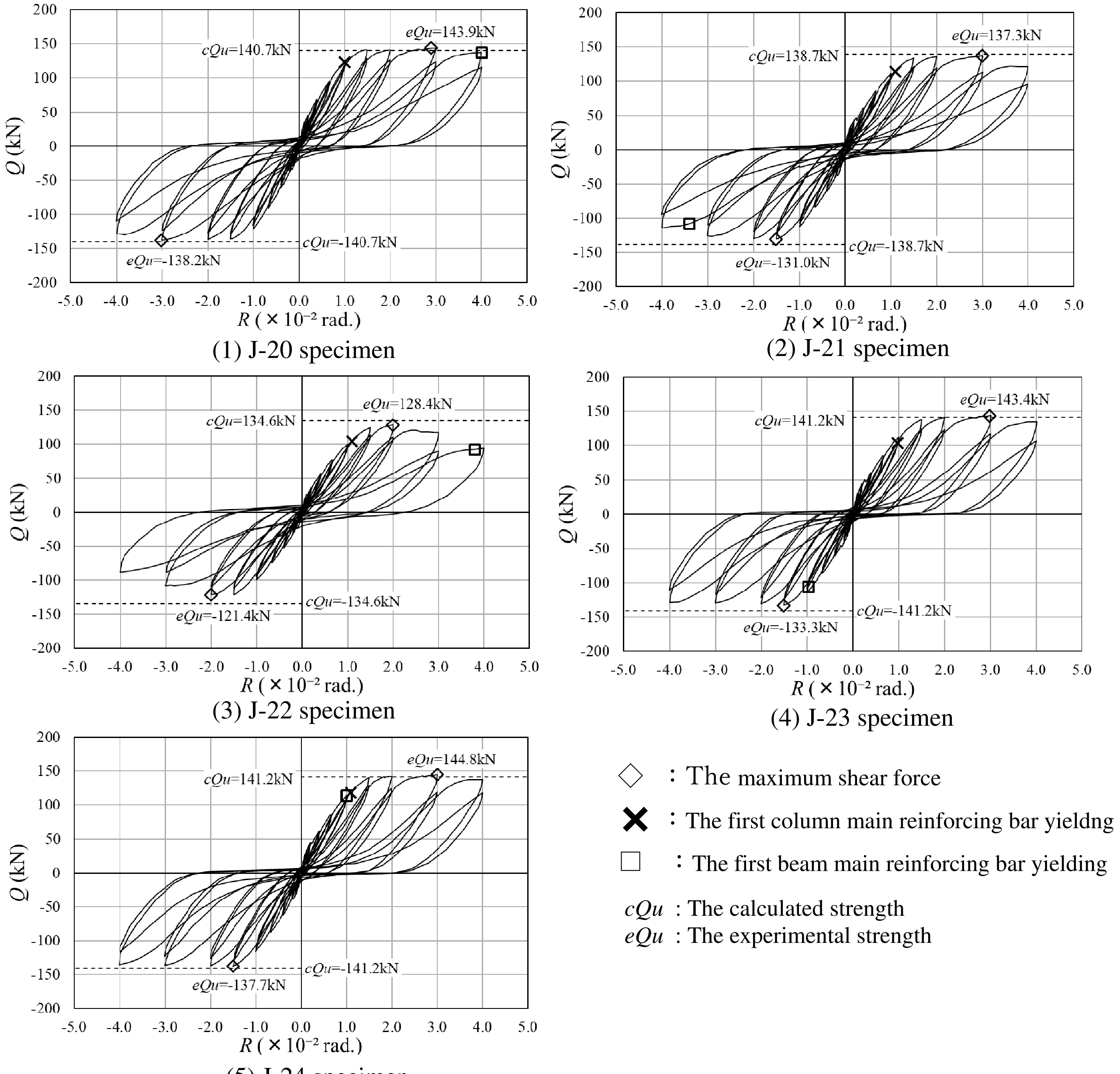


Fig.6. Shear force of the column Q(kN) - story drift angle R($\times10^{-2}$rad.)

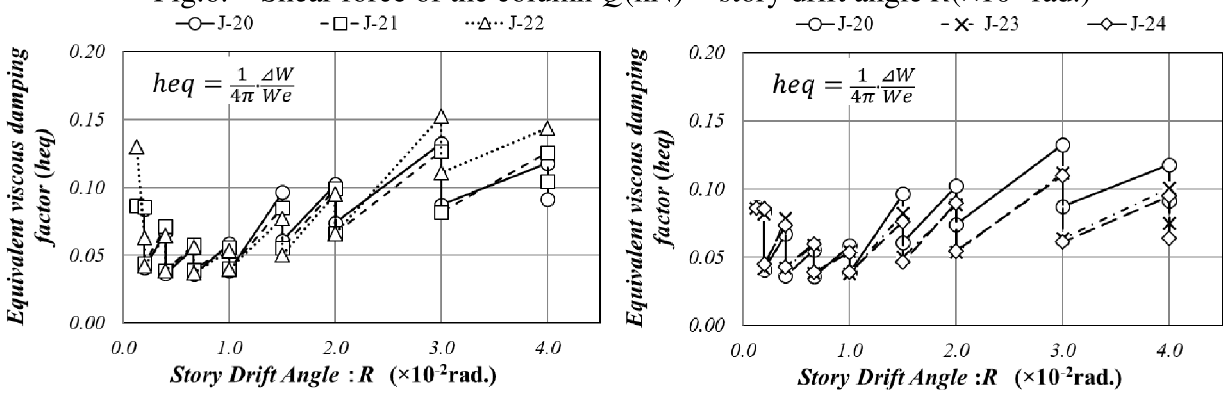
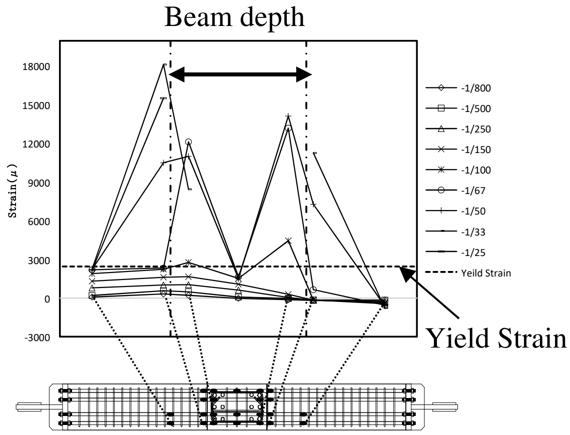
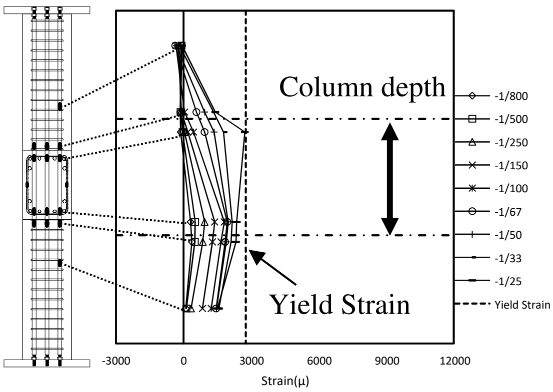


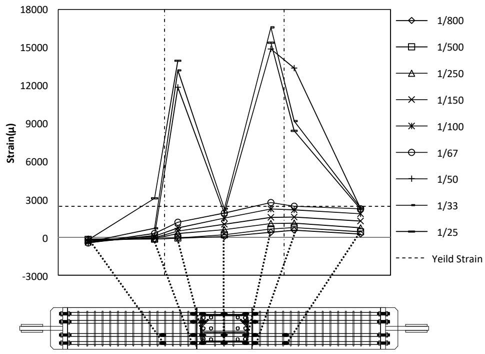
Fig. 7. Equivalent viscous damping factor



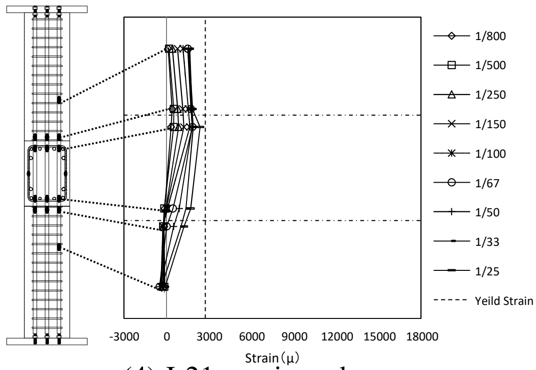
(1) J-20 specimen column



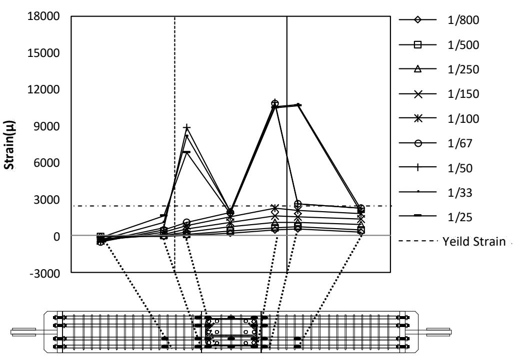
(2) J-20 specimen beam



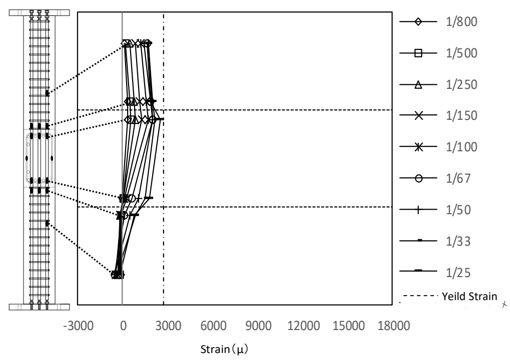
(3)J-21 specimen column



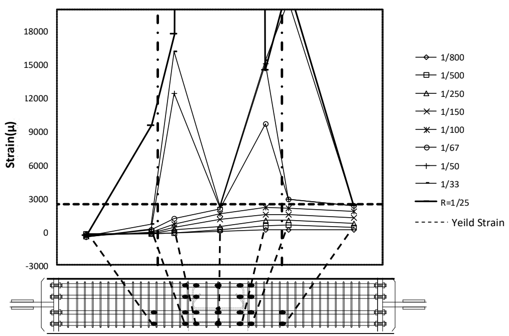
(4) J-21 specimen beam



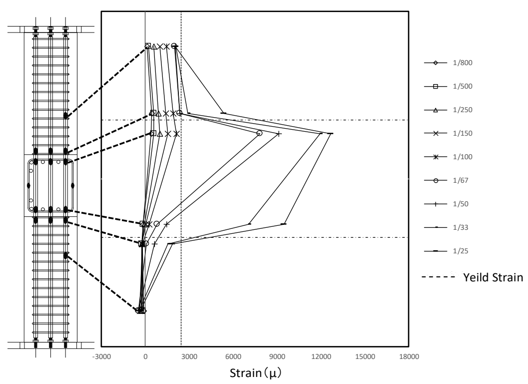
(5) J-22 specimen column



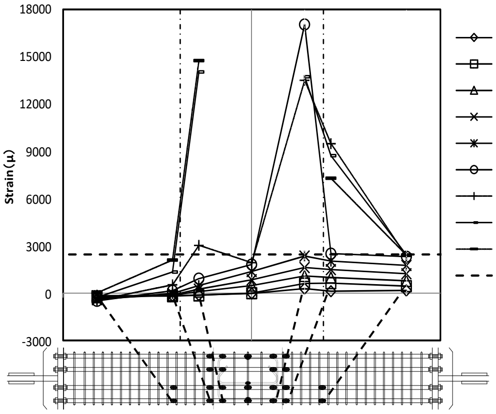
(6) J-22 specimen beam



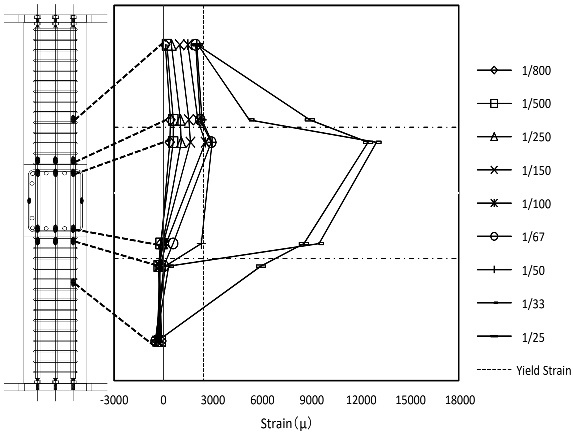
(7) J-23 specimen column



(8) J-23 specimen beam



(9) J-24 specimen column



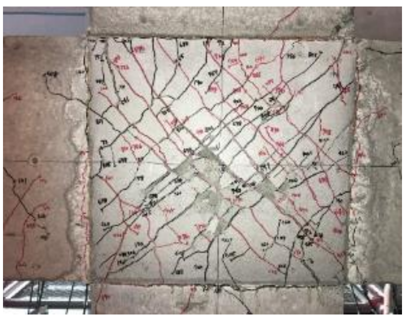
(10) J-24 specimen beam

Fig. 8. Strain distributions of the main reinforcing bars of column and beam around the beam-column joint

(1) J-20 specimen beam-column joints

(2) J-21 specimen beam-column joints

(3) J-22 specimen beam-column joints



(4) J-23 specimen beam-column joints

(5) J-24 specimen beam-column joints

Fig. 9. Crack patterns of the specimens after the test

4. Discussion on the test paramater

The calculated strength, the experimental strength and the failure mode of each specmen are shown in Table 4.

The failure mode of all specimens is computationally the flexural failure of the column, but the experimental failure mode of all specimens was the diagonal compression failure in the beam-column joint after the yielding of the column main reinforcing bar. In case that the flexural strength ratio is more than 1.29, the yielding of the beam main reinforcing bar was not occur as J-20, J-21 and J-22 specimen. In case that the flexural strength ratio is more than 1.29 and that the shear strength margin is more than 1.57, stable behavior can be expected up to R=3% after the yielding of the column main reinforcing bar, and the expected flexural strength can be achieved as J-20 specimen. However, the smaller the shear strength margin, the earlier the beam-column joint fails, and the strength is also less than the calculated value as J-21 and J-22 specimen.

Comparing J-23 and J-24 specimen, the stirrup of the beam-column joint has no significant effect on the improvement of the yield mechanism and the final failure mode.

Table 4: Calculated strength , experimental strength and the failure mode

Specimen	Calculated strength							Flexural strength ratio beam/column (column/beam)	Shear stlength margin of beam-column joint	Experimental strngth			$_eQ_u/_cQ_u$	
	$_cQ_{su}$ *1 kN	$_cQ_{mu}$ *2 kN	$_cQ_{bsu}$ *3 kN	$_cQ_{bmu}$ *4 kN	$_cQ_{jsu}$ *5 kN	*Calculated failure mode*	$_cQ_u$ *6 kN			*Experimental failure mode*	$_eQ_u$ *7 kN			
											positive	*negative*	*positive*	*negative*
J-20	262.6	140.7	291.1	217.1	220.2	Flexural failure of column	140.7	1.54 (0.65)	1.57	Joint failure after yielding of the column main reinforcement in the joint and column end	143.9	138.2	1.02	0.98
J-21	252.7	138.7	257.9	199.8	178.9	Flexural failure of column	138.7	1.44 (0.69)	1.29	Joint failure after yielding of the column main reinforcement in the joint	137.3	131.0	0.99	0.94
J-22	236.9	134.6	222.8	174.3	146.1	Flexural failure of column	134.6	1.29 (0.77)	1.09	Joint failure after yielding of the column main reinforcement in the joint	128.4	121.4	0.95	0.90
J-23	264.5	141.2	246.9	153.8	210.2	Flexural failure of column	141.2	1.09 (0.92)	1.49	Joint failure after yielding of the column and beam main reinforcement in the joint	143.4	133.3	1.02	0.94
J-24	262.4	141.2	248.0	154.1	216.4	Flexural failure of column	141.2	1.09 (0.92)	1.53	Joint failure after yielding of the column and beam main reinforcing bar in the joint	144.8	137.7	1.03	0.98

*1 $Q_{c,su}$: Column shear strength
*2 $Q_{c,mu}$: Column shear force at column flexural failure
*3 $Q_{b,su}$: Column shear force at beam shear failure
*4 $Q_{b,mu}$: Column shear force at beam flexural failure
*5 $Q_{j,u}$: Column shear force at shear failure of beam-column joint
*6 $Q_{c,u}$: Calculated strength (the minimum value among (*1~*5))
*7 $Q_{e,u}$: Experimental strength

The calculated strengths were based on the assumption that the flexural strength was developed at the beam end or column end. The shear strengths of the members were calculated by (1) to (3). The flexural strengths of column section and beam section were calculated by ACI 318-14 [1].

Shear strength of column cVu [2]

$$ {}_cV_u = \left\{ \frac{0.053 \cdot p_t^{0.23}(18+\sigma_B)}{M/(Q \cdot d)+0.12} + 0.85\sqrt{p_w \cdot \sigma_{wy}} + 0.1 \cdot \sigma_0 \right\} bj \quad (1) $$

Shear strength of beam bVu [2]

$$ {}_bV_u = \left\{ \frac{0.053 \cdot p_t^{0.23}(18+\sigma_B)}{M/(Q \cdot d)+0.12} + 0.85\sqrt{p_w \cdot \sigma_{wy}} \right\} bj \quad (2) $$

Shear strength of beam-column joint jVu [3]

$$ {}_jV_u = \kappa \cdot \varphi \cdot F_j \cdot b_j \cdot D_j \quad (3) $$

$$ F_j = 0.8 \cdot \sigma_B^{0.7} $$

κ=1.0 (for +-shaped)

φ=0.85 (for no transverse beam)

$F_j=0.8 \cdot (0.8 \cdot \sigma_B)^{0.7}$

5. Conclusions

The following conclusions can be derived from this research program on the behaviour of the cross-shaped partial reinforced concrete frame using new PCM in the beam-column joint.

- The failure mode of all specimens is computationally the flexural failure of the column, but the experimental failure mode of all specimens was the diagonal compression failure in the beam-column joint after the yielding of the column main reinforcing bar.
- In case that the flexural strength ratio is more than 1.29, the yielding of the beam main reinforcing bar does not occur. In case that the flexural strength ratio is more than 1.29 and that the shear strength margin is more than 1.57, stable behavior can be expected up to R=3% after the yielding of the column main reinforcing bar, and the ideal flexural strength can be achieved. However, the smaller the shear strength margin, the earlier the beam-column joint fails, and the strength is also less than the calculated value
- The stirrup of the beam-column joint has no significant effect on the improvement of the yield mechanism and the final failure mode.
- When the flexural strength ratio is more than 1.29 and the shear strength margin is more than 1.57, good performance can be obtained with new PCM.

6. References

[1] ACI committee 318, (2014), “Building code requirements for structural concrete (ACI 318-14)”.

[2] Building Guidance Division, Housing Bureau, the Ministry of Land, Infrastructure, Transport and Tourism, (2007), “Technical standards manual on the structure of buildings”.

[3] Architectural institute of Japan, (1999), “Design Guidelines for Earthquake Resistant Reinfoced Concrete Buildings Based on Inelastic Displacement Concept”.

