SHEAR STRENGTHENING USING POLYMER-CEMENT MORTAR FOR EXISTING REINFORCED CONCRETE COLUMNS WITH SIDEWALL

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ABSTRACT :

This paper proposes a seismic retrofitting technique for existing RC columns with cast-in-place RC sidewall using polymer-cement mortar. In the technique, additional shear reinforcement (deformed steel bar: prefabricated reinforcing unit) is adhered to the surface of existing RC columns with RC sidewall by using polymer-cement mortar. Shear-loading tests of the RC columns with RC sidewall were conducted to clarify the structural performance of the columns with sidewall strengthened by polymer-cement mortar. The results suggested that the technique improved the shear capacity and ductility of the RC columns with RC sidewall, and clarified the mechanism of shear resistance of the strengthened columns with sidewall. Furthermore, a method of estimating the capacity (shear strength) and ductility of RC columns with RC sidewall strengthened by polymer-cement mortar was proposed by modeling the shear resistance mechanism.

KEYWORDS: retrofit, polymer-cement mortar, R/C, column with sidewall, shear capacity

1. INTRODUCTION

In conventional cast-in-place reinforced concrete (RC) buildings in Japan, RC frames (columns and beams) and cast-in-place non-structural RC walls (mullions, spandrels and sidewalls) are constructed simultaneously and are connected rigidly. As a result, stress transfer exists between the RC frame and the cast-in-place non-structural walls (mullions, spandrels and sidewalls), and these walls influence the seismic behavior of the RC structure. In past earthquakes, shear failure of columns with non-structural walls (e.g. shear failure of short columns; columns with spandrels) was reported as one example of such influence. However, in cases where the shear reinforcement of the column is sufficient to resist the shear force, it was reported that damage to the columns and beams caused by failure of the cast-in-place non-structural RC walls, for example, was slight [example 1]. So, this paper suggests a seismic retrofitting technique that makes the most of cast-in-place RC sidewalls for existing RC columns by applying polymer-cement mortar (PCM).

In the technique, additional shear reinforcement (hoops of column and/or horizontal shear reinforcement of sidewall; prefabricated reinforcing unit) is adhered to the surfaces of existing RC columns with RC sidewall by applying PCM. The strengthened area (additional reinforcement and PCM) and existing member are strongly joined by the high adhesive strength of the PCM, so post-installed anchors need not be used in this technique.

This paper describes the improvement achieved by this seismic retrofitting technique and how to estimate the capacity (shear strength) and ductility of an RC column with RC sidewall strengthened by the technique.

2. IMPROVEMENT OF SHEAR CAPACITY (Series 1)

This series of tests was conducted to grasp the extent to which seismic retrofitting with PCM improved the shear capacity and ductility of RC columns with sidewall.

2.1 Test program

2.1.1 Specimens

The dimensions and arrangement are shown in Figure 1, and the parameters are listed in Table 1. Nine half-scale RC columns with RC sidewalls were prepared.

Each specimen was assumed to be a column with sidewall in an apartment house constructed before 1971. The cross section of the column (B_C x D_C) was 300 mm x 300 mm, and the height was 900 mm. The thickness (t) of RC sidewalls was 60 mm ($\alpha = t/B_C = 1/5$), and the length of RC sidewalls (lw) was 600 mm ($\beta = lw/D_C = 2.0$) in order to make the shear failure mode happen first.

The parameters of the tests were the strengthened area (W-type, C-type and WC-type) and the amount of shear reinforcement. No. 1-1 was planned to use conventional RC specimens without additional reinforcement. W-type specimens were strengthened on one surface of the RC sidewalls, and C-type specimens were strengthened on both sides of the column. WC-type specimens were strengthened on both the sidewall and the column. The column was reinforced using the closed type by combining U-type hoops, which were placed through the hole of the sidewall near the column, and were spliced by lap-splicing. The amount of shear reinforcement was set as the amount of hoops in the column and the amount of horizontal reinforcement in RC sidewalls, and was the total of the existing shear reinforcement and the additional shear reinforcement. The reinforcement bars were deformed bars and the yield stresses of deformed bars (D6, D10 and D13) were 317–384 N/mm2. Figure 2 shows a typical stress-strain curve of the PCM. The compressive strength of PCM was similar to that of concrete, and Young's modulus of PCM was about 0.7 times that of concrete. In the tensile test shown in Fig. 3, the adhesive strength of PCM to concrete was 2.5 N/mm2 or more.

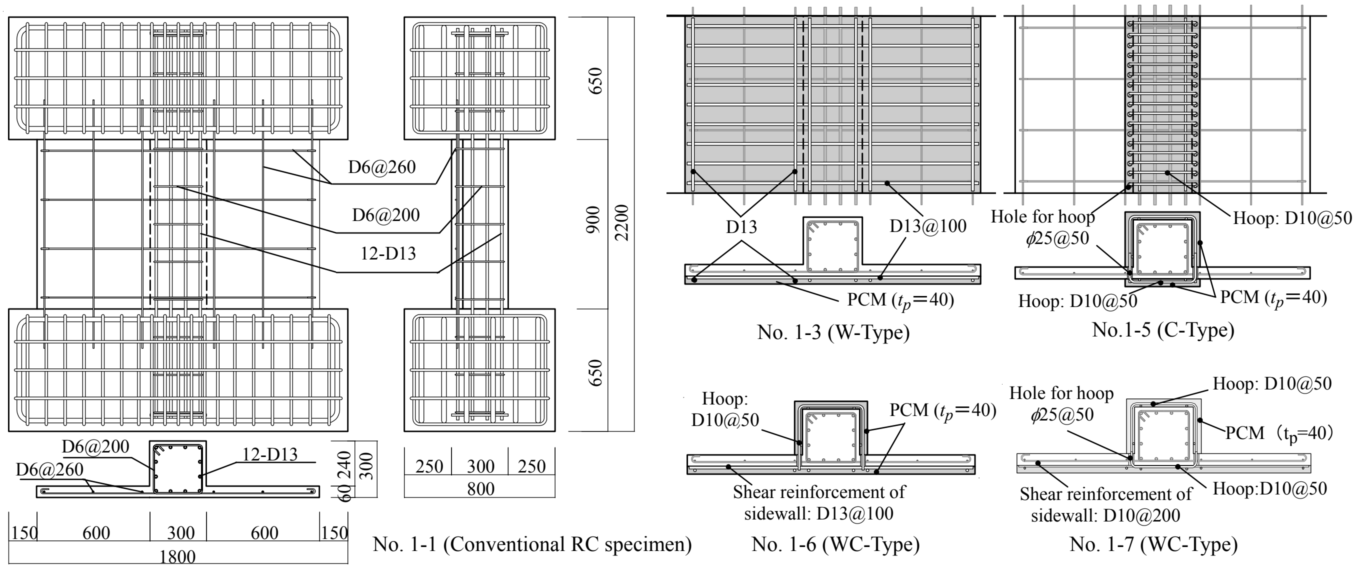


Fig. 1 Configuration and bar arrangement of specimens (Series 1)

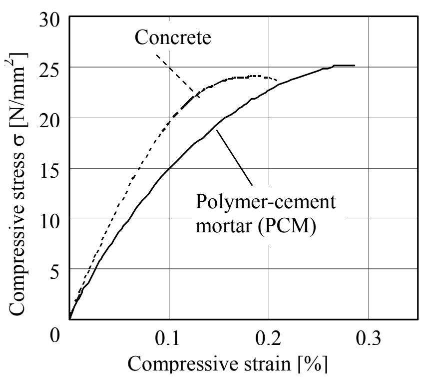


Fig. 2 Stress-strain relationship

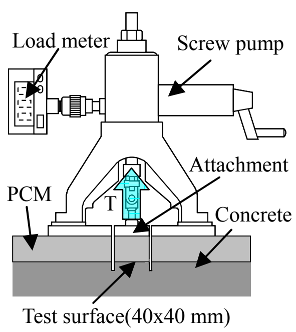


Fig. 3 Tensile test apparatus for adhesive strength

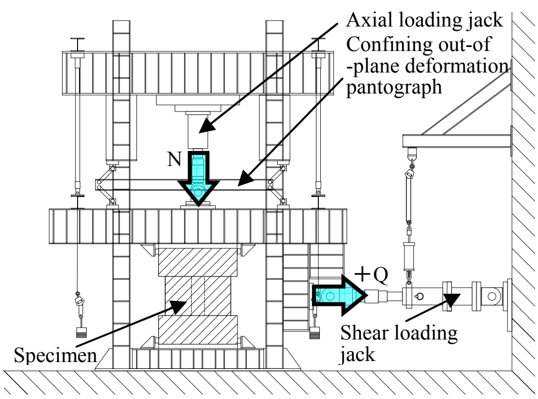


Fig. 4 Loading apparatus

Table 1 List of specimen parameters and test results (series 1)

No.	Existing member			Additional reinforcement (Strengthened by PCM)								Material properties		Test result	
	Hoop of column	*t* [mm]	Sidewall shear reinforce-ment	Column (U-shaped hoop)					Sidewall (horizontal)			*fc* [N/mm²]	*fpc* [N/mm²]	*eQmax* [kN] *2	Failure Mode*3
				Sidewall (Front) side	Column (Back) side	Ratio [%]			Surface shear reinforce-ment	Shear Ratio[%] (t=100mm)					
						ppw1 (Front)	*ppw2* (Back)	Σ*pw*		*pps*	Σ*ps*				
1-1				-	-	-	-	-	-	-	-	22.0	-	419	CWS
1-2				-	-	-	-	-	D13@200	0.64	0.75	22.0	23.8	661	CWS
1-3			D6@260	-	-	-	-	-	D13@100	1.27	1.38	22.0	23.8	773	CWS
1-4	D6@200	40		D10@100	D10@100	0.24	0.24	0.58	-	-	-	23.5	28.0	505	WS-CF
1-5	*pw*=0.11%		*ps*=0.21%	D10@50	D10@50	0.47	0.47	1.06	-	-	-	23.5	28.0	484	WS-CF
1-6			(t=60mm)	-	D10@50	-	0.47	0.58	D13@100	1.27	1.38	23.5	28.0	806	WS-CF
1-7				D10@50	D10@50	0.47	0.47	1.06	D10@200	0.36	0.48	29.5	29.7	904	WS-CF
1-8*1				D10@50	-	0.47	-	0.58	D13@100	1.27	1.38	32.3	36.6	728	CWS
1-9	D10@40 pw=1.18%	100	2-D6@60 ps=0.21%	-	-	-	-	-	-	-	-	27.1	-	946	WS-CF

Cross section of column (*Bc*x*Dc*)=300×300 [mm], Length of sidewall (*lw*)=600 [mm] (b=*lw*/*D*=2.0), *t*: Thickness of sidewall, Thickness of PCM＝40 [mm]
Main bar of column: 12-D13 (ϕ=13mm deformed bar), $\Sigma pw = pw + ppw1 + ppw2$, $\Sigma ps = ps + pps$
fc: Concrete compressive strength (cylinder test: ϕ=100mm, *h*=200mm), *fpc*: PCM compressive strength (cylinder test: ϕ=50mm, *h*=100mm)
*1: PCM was not applied to the head and foot of sidewalls like the "partial seismic slit".
*2: eQmax: Maximum shear load of test, *3: CWC: Shear failure of column with sidewall, WS: Shear failure of sidewall, CF: Flexural failure of column

2.1.2 Method of experiment

In this test, the specimens were subjected to a repeating horizontal force under constant axial force with the loading equipment shown in Fig. 4. This equipment provides loading conditions such that both end of the stubs of the specimen remain parallel with each other in the horizontal direction. The shear load, relative displacement between the upper and lower stubs, and strain of the reinforcement were measured.

2.2 Test results

2.2.1 Failure mode

Crack patterns are shown in Fig. 5. In the conventional RC specimen (No. 1-1), flexural cracks occurred in the RC sidewall first, and then diagonal shear cracks occurred in the RC sidewall. Finally, the shear crack width of the RC sidewall developed and specimen No. 1-1 resulted in shear failure mode. Furthermore, the shear failure of a column occurred immediately after the shear failure of the RC sidewall. The failure states of the strengthened specimens were similar to that of the conventional RC specimen (No. 1-1). In the strengthened specimen, the number of shear cracks increased in the strengthened area of the sidewall, but crack widths were decreased by the additional reinforcement with PCM. The failure mode of the W-type strengthened specimen was the same as that of specimen No. 1-1. In the C-type strengthened specimen, the resistance of an independent column was observed after the shear failure of sidewalls that were not strengthened. Moreover, the failure states of the WC-type strengthened specimen were equivalent to the combination of C-type added to W-type. The polymer-cement mortar did not peel off from the surface of the existing RC column with RC sidewall.

2.2.2 Deformation properties

Figures 6 (a) and (b) show the shear force (Q) – displacement (δ) relationships. The initial stiffness of strengthened specimens was higher than that of the conventional specimen (No. 1-1). The shear strength of specimen No. 1-1 was determined by the shear failure of the column with sidewall when the drift angle (R) was about 1/200 rad. In the W-type strengthened specimen, the shear strength improved with the increase of additional horizontal shear reinforcement on the sidewall. In the C-type specimen, improvements of shear strength were small. However, after the maximum shear load was observed, the shear load decreased slowly, and it was rather higher than the flexural capacity of the independent column. Further, the ductility of the C-type specimen improved with the increase of additional hoops on the column. Moreover, the deformation properties of the WC-type strengthened specimen were equivalent to the combination of C-type added to W-type.

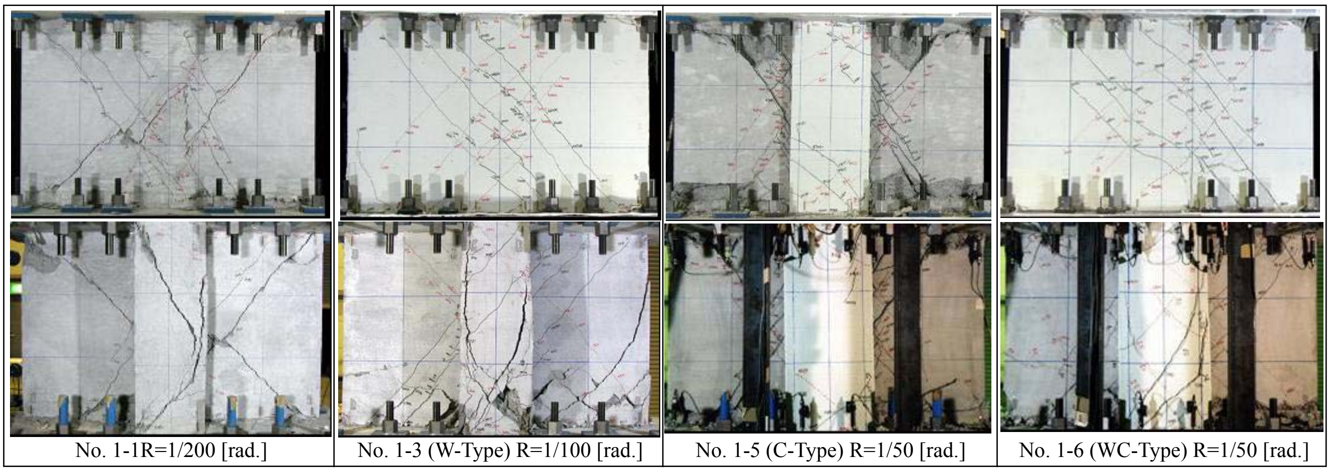
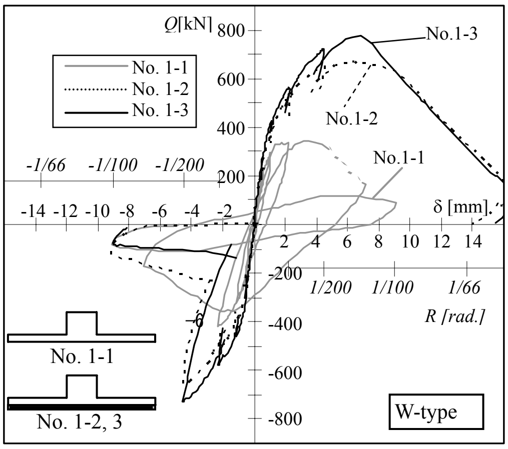
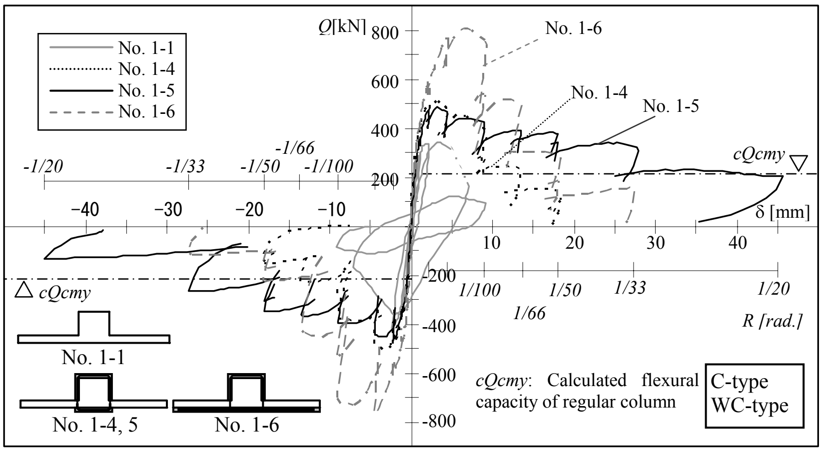


Fig. 5 Damage properties of series 1 (upper: wall side, lower: column side)



(a) W-type



(b) C-type and WC-type

Fig. 6 Shear load (Q) – drift displacement (δ) relationship

2.3 Seismic retrofitting effect

Figure 7 shows the strain distribution of shear reinforcement. The strain distribution shows the time of the maximum shear load (*eQmax*) as a solid line, and also shows the last cycle with a dashed line for the C-type and WC-type specimens. In the conventional specimen (No. 1-1) and W-type strengthened specimen (No. 1-2, 3), the value of horizontal reinforcement on the RC sidewall was near the yield strain at the maximum shear load. Although the strain of the hoops was about 0.1% at that time, the hoops yielded immediately thereafter. Thus, it is considered that the improved shear strength of the RC column with RC sidewall was the result of the horizontal reinforcement on the sidewall. In the C-type strengthened specimen, the strain of horizontal reinforcement on the RC sidewall was near the yield strain at the maximum shear load, and the strain of the hoops on the column was about 0.05% at that time. Further, the hoops of specimens No. 1-4 and No. 1-6 (pw = 0.58%) yielded in the last cycle, and that of specimen No. 1-5 (pw = 1.06%) was about 0.1% in the last cycle. Therefore, it is considered that the column with sidewall gained the resistance of an independent column by the additional hoops, so the structural performance (capacity and ductility) of the strengthened RC column with RC sidewall can be controlled by choosing the strengthened area and amount of additional shear reinforcement.

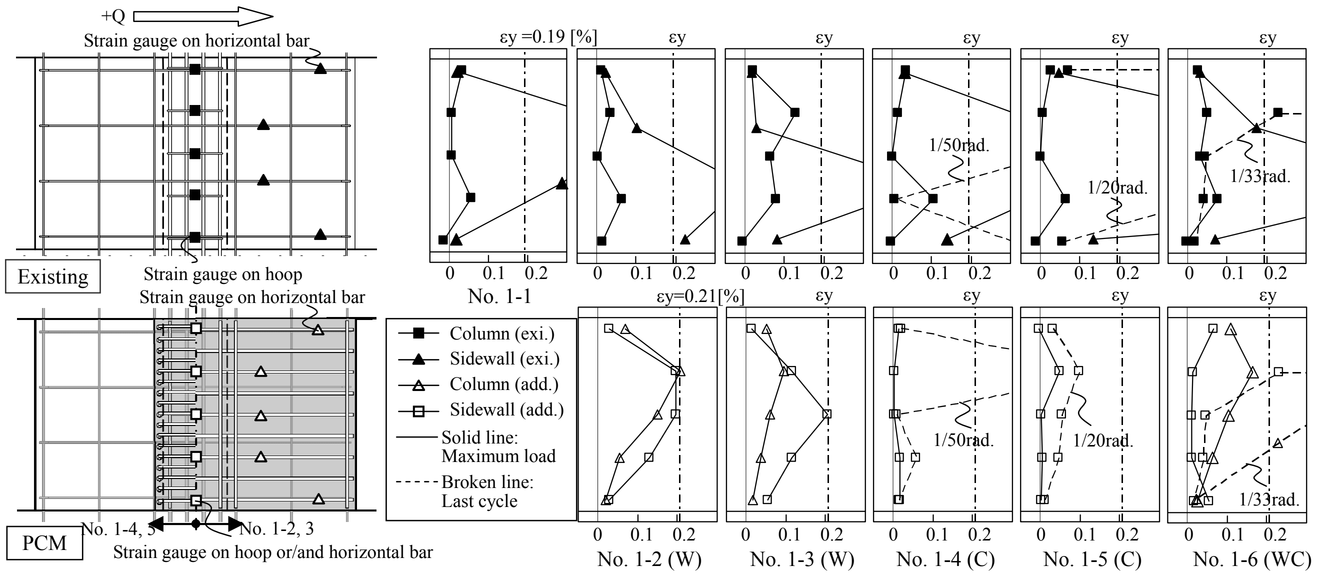


Fig. 7 Strain distribution of shear reinforcement (upper: existing reinforcement, lower: additional reinforcement)

3. IMPROVEMENT OF DUCTILITY

This series of tests was conducted in order to grasp the improvement of failure mode and ductility by shear strengthening with PCM.

3.1 Test program

3.1.1 Specimens

The dimensions and arrangement are shown in Figure 8, and the parameters are listed in Table 2. The main forms of the specimens were the same as those of series 1. Since the mode of failure of the column with sidewall was flexural failure previously, the RC sidewall length was set to 300 mm (β = lw/D_C = 1.0). The parameters of the tests were the strengthened area (WCO-type and WC-type), the amount of shear reinforcement and the sidewall position (eccentric side or center of column). In the WCO-type strengthened specimen, PCM was set on one side of the sidewalls and the column, and in the WC-type strengthened specimen, PCM was set on one side of the sidewall and both sides of the column. The WCO-type is a method of executing without residents' leaving.

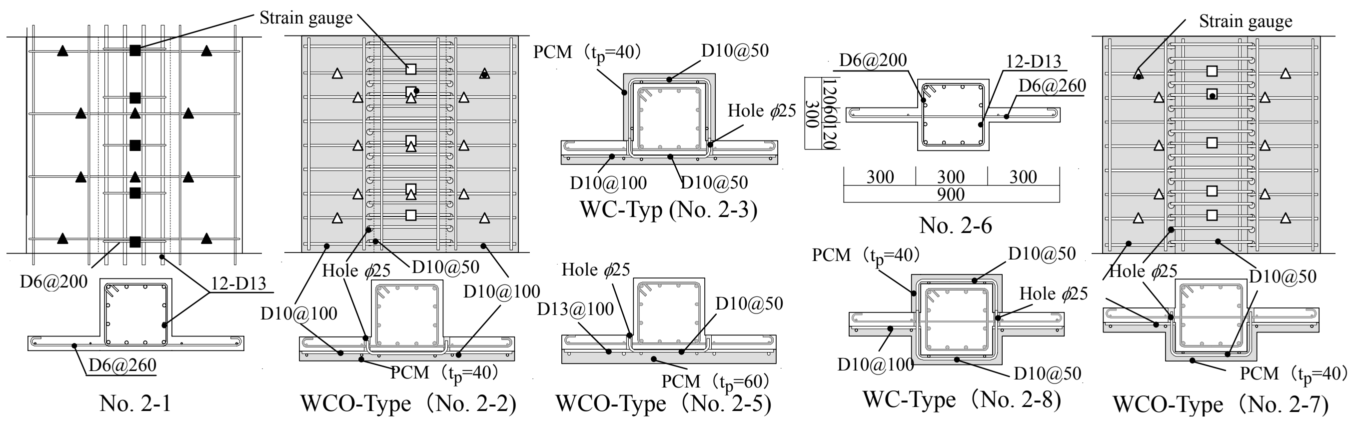


Fig. 8 Configuration and bar arrangement of specimens (Series 2)

Table 2 List of specimen parameters and test results (series 2)

No.	Existing member: Hoop of column	Existing member: Sidewall: Position	Existing member: Sidewall: Shear reinforce-ment	Additional reinforcement (Strengthened by PCM): Column (U-shaped hoop): Sidewall (Front) side	Column (U-shaped hoop): Column (Back) side	Ratio [%]: $ppw1$ (Front)	Ratio [%]: $ppw2$ (Back)	Ratio [%]: Σpw	Sidewall (horizontal): Surface shear reinforce-ment	Shear Ratio [%] (t=100mm): pps	Shear Ratio [%] (t=100mm): Σps	Material properties: fc [N/mm^2]	Material properties: fpc [N/mm^2]	Test result: $eQmax$ [kN]*3	Test result: Failure Mode*4
2-1	D6@200 pw=0.11%	Eccentric	D6@260 ps=0.21% (t=60mm)	-	-	-	-	-	-	-	-	29.8	-	417	CWS
2-2				D10@50	-	0.47	-	0.58	D10@100	0.71	0.83	29.8	28.7	605	CWF-CF
2-3					D10@50	0.47	0.47	1.06		0.71	0.83	29.8	28.7	656	CWF-CF
2-4					-	0.47	-	0.58	D13@100	1.27	1.38	29.4	27.9	509	CWF-CF
2-5*1					-	0.47	-	0.58		1.06	1.16	29.4	27.9	561	CWF-CF
2-6		Center		-	-	-	-	-	-	-	-	29.5	-	422	CWS
2-7				D10@50	-	0.47	-	0.58	D10@100	0.71	0.83	29.5	29.7	561	CWF-CF
2-8					D10@50	0.47	0.47	1.06	D10@100	0.71	0.83	29.5	29.7	590	CWF-CF
2-9					-	0.47	-	0.58	D13@100	1.27	1.38	29.4	27.9	516	CWF-CF
2-10				D13@50	-	0.84	-	0.95	D10@100	0.71	0.83	29.4	27.9	482	CWF-CF
2-11*2				D10@50	-	0.47	-	0.58	D13@100	1.27	1.38	29.4	27.9	615	CWF-CF

Cross section of column ($BcxDc$)=300×300[mm], Length of sidewall (lw)=300 [mm] (b=lw/D=1.0), t: Thickness of sidewall, Thickness of PCM＝40 [mm]
Main bar of column: 12-D13 (ϕ=13mm deformed bar), $\Sigma pw = pw + ppw1 + ppw2$, $\Sigma ps = ps + pps$
fc: Concrete compressive strength (cylinder test: ϕ=100mm, h=200mm), fpc: PCM compressive strength (cylinder test: ϕ=50mm, h=100mm)
*1: Thickness of PCM＝60 [mm], *2: Axial load N = 0.4xfcxBcxDc
*3: eQmax: Maximum shear load of test, *4: CWC: Shear failure of column with sidewall, WS: Shear failure of sidewall, CF: Flexural failure of column

2.1.2 Method of experiment

The same load system as in the first series was used.

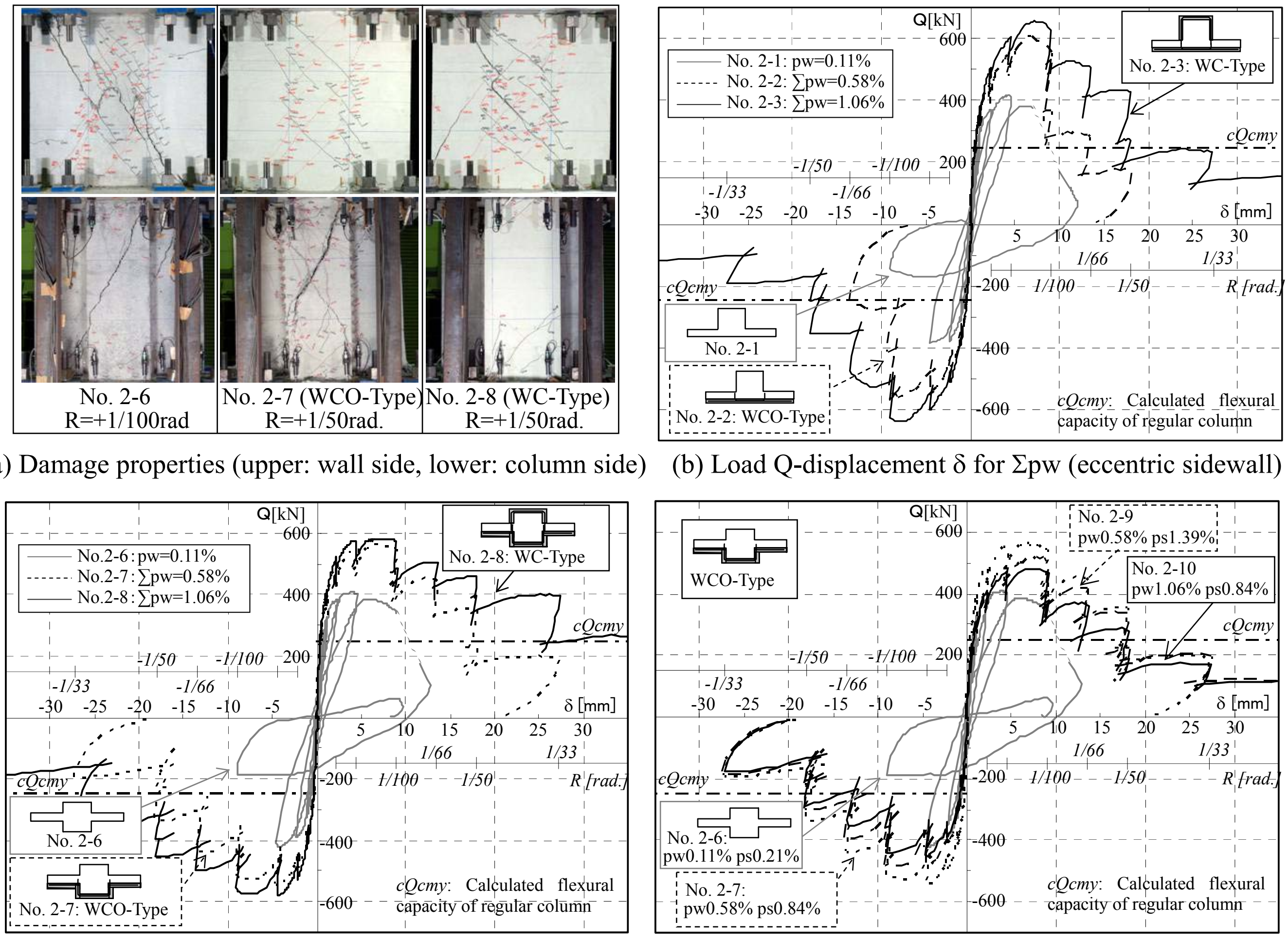
3.2 Test results

3.2.1 Failure mode

Crack patterns are shown in Fig. 9 (a). The failure states of this series were similar to that of series 1, and the failure mode of the conventional RC specimen (No. 2-1 and No. 2-6) was shear failure of the column with sidewall. In the strengthened specimen, the failure mode was improved to flexural failure of the column with sidewall. After the maximum shear load (flexural capacity), the behavior of all strengthened specimens became that of an independent column by compressive failure of concrete in the sidewalls. In the WCO-type specimen, shear cracks on the surface of the column that had not been strengthened were observed after drift angle R = 1/100 rad. In the WC-type strengthened specimen, large shear cracks were not observed on the surface of PCM until the last cycle.

3.2.2 Deformation properties

Figures 9 (b) and (c) show the deformation properties. In the strengthened specimen, the shear strength was improved by the additional shear reinforcement and the shear load decreased slowly after the maximum load (flexural capacity) by the compressive failure of concrete in the sidewalls. When the amount of hoops on the column was increased, the reduction of shear load became small. Further, the ductility of the column was improved when the anchorage of hoops was lengthened (sidewall position; eccentric side or center of column). Figure 9 (d) shows the limit of the strengthening effect. In the case of flexural failure, the ultimate drift angle for the maximum shear load was not increased by the additional horizontal shear reinforcement on the sidewall. Further, in the WCO-type specimen, the ultimate drift angle on the independent column (flexural capacity of independent column) was limited by the reinforcement effect of the additional hoops.



(a) Damage properties (upper: wall side, lower: column side) (b) Load Q-displacement δ for Σpw (eccentric sidewall)

(C) Load Q-displacement δ for Σpw (center sidewall) (d) Load Q-displacement δ for Σpw and/or Σps

Fig. 9 Test result of series 2

4. Evaluation of shear load – drift angle relationship of RC columns with sidewall retrofitted by PCM

4.1 Outline of evaluation method

Here, the shear force (*Q*) – drift angle (*R*) curve of RC columns with RC sidewalls retrofitted by RCM is evaluated. *Q-R* is referred to as the "Standard for seismic evaluation of existing reinforced concrete buildings [3]" and is modeled as the relationship of strength index C – ductility index F. Figure 10 shows a C-F model of the RC column with RC sidewall, and the model is evaluated on the basis of sidewall length β = 1.0. The model shows the behavior of the RC column with RC sidewall at first, and when there is column reinforcement (hoops), the behavior shifts to that of an independent column. Furthermore, the strength (flexural capacity) at the time of the shift to the independent column from the column with sidewall decreases gradually. For intermediate flexural capacity, the case of β= 0.5 is used. As shown in Fig. 10, evaluation items are the flexural capacity of the column with sidewall (*Qcwmy*), the shear strength of the column with sidewall (*Qcwsu*), the flexural capacity of the independent column (*Qcmy*), the shear strength of the independent column (*Qcsu*), the ultimate drift angle of the column with sidewall (*Rcwu*) and the ultimate drift angle of the independent column (*Rcu*).

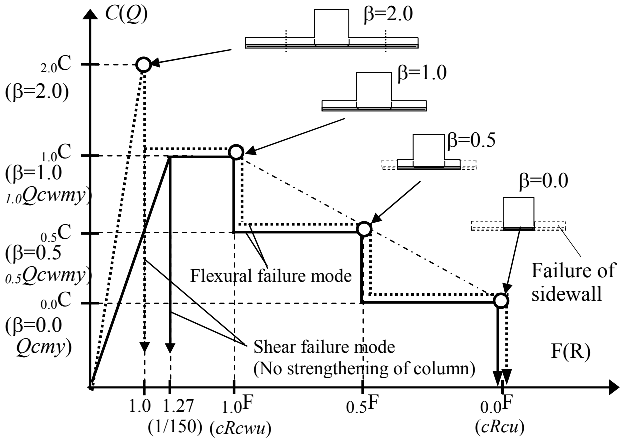


Fig. 10 C-F model for column with sidewall

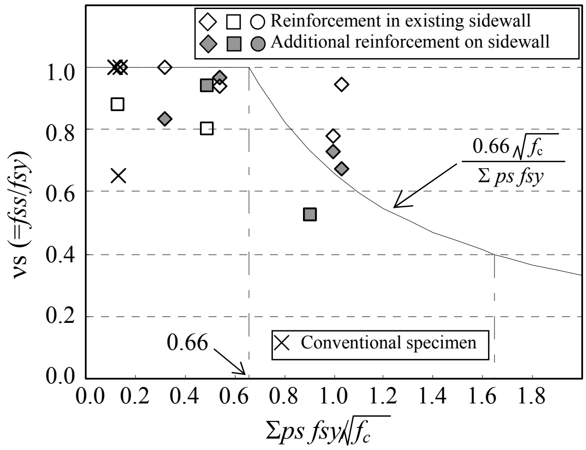


Fig. 12 Evaluation of ν_{ws}

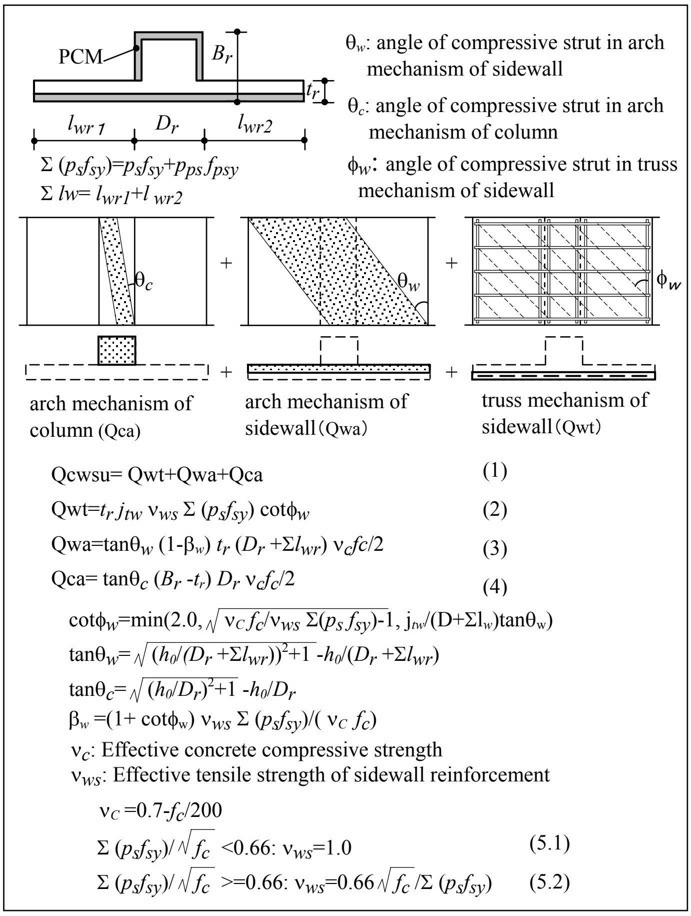


Fig. 11 Shear resistance mechanism and evaluation method for shear strength of column with sidewall strengthened by RCM

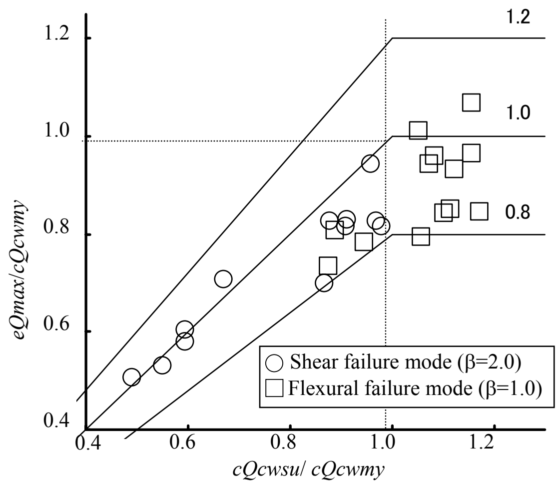


Fig. 13 Correspondence between calculated and measured values

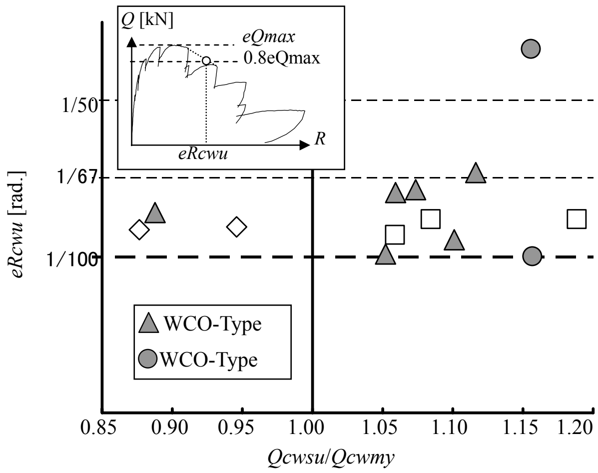


Fig. 14 Evaluation of ductility (*Rcwu*)

4.2 Strength and ductility of column with sidewall

The flexural capacity of the column with sidewall (*Qcwmy*) is calculated using the flexural capacity equation [4 and 2]. The shear strength of the column with sidewall (*Qcwsu*) is calculated using the shear strength equation in Fig. 11, which is derived based on "Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept [5]". Further, the shear strength is considered to accumulate in

the arch of sidewalls, the truss of sidewalls, and the truss of a column, since the shear strength is improved by the horizontal reinforcement on the sidewall. In the trusses of sidewalls, the actual stress of the horizontal reinforcement on the sidewalls is calculated by Eq. (5,1) and (5.2), and is determined from the test as shown in Fig. 12. The failure mode is classified as flexural failure if the flexural capacity is lower than the shear strength. Calculated results are plotted in Fig. 13. All values calculated by the suggested method agree with the test results. Also, the method can predict the failure (flexural or shear) mode of the test.
Figure 14 shows the ultimate drift angle of the column with sidewall in the test (*eRcwu*) – shear margin coefficient (*cQcwsu* / *cQcwmy*) relationship. The ultimate drift angle (*eRcwu*) has little effect on the shear margin coefficient (*cQcwsu* / *cQcwmy*), so it is evaluated as 1/100 radian.

4.3 Strength and ductility of independent column

The flexural capacity of the independent column (*Qcmy*) is calculated using the flexural capacity equation of AIJ [6], and the shear capacity of the independent column (*Qcsu*) is calculated using the shear strength equation of AIJ [5]. The ultimate drift angle of the independent column (*Rcu*) is calculated according to the "Standard for seismic evaluation of existing reinforced concrete buildings". Figure 15 shows the relationship of the actual stress ratio of additional hoops on the column (*fs*/*fy*) and the drift angle. The strain of additional hoops did not exceed the yield strain. Therefore, the actual stress of hoops is reduced by reduction coefficient vcs.
The ultimate drift angle of the test and the calculated values is shown in Fig. 16. The calculated values agree with the test results by using the reduction coefficient vcs for the actual hoop stress.

4.4 Agreement of proposed method and the test results

Figure 17 shows an example of calculated values compared with the test results. Good agreement between the calculation and the test can be seen in the capacities and the ductilites. Therefore, the proposed method can adequately evaluate the structural performance of the RC column with RC sidewall strengthened by PCM.

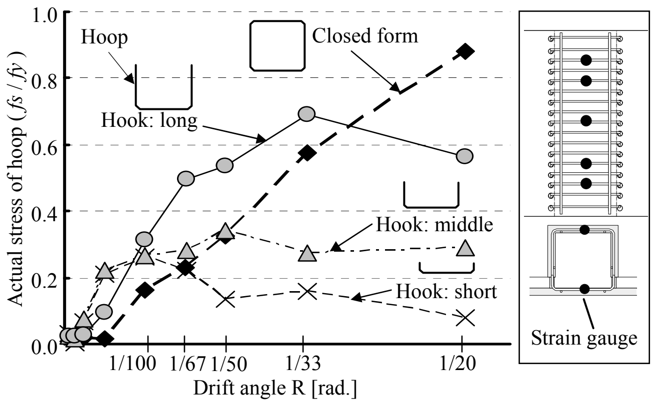


Fig. 15 Effect of actual stress of hook

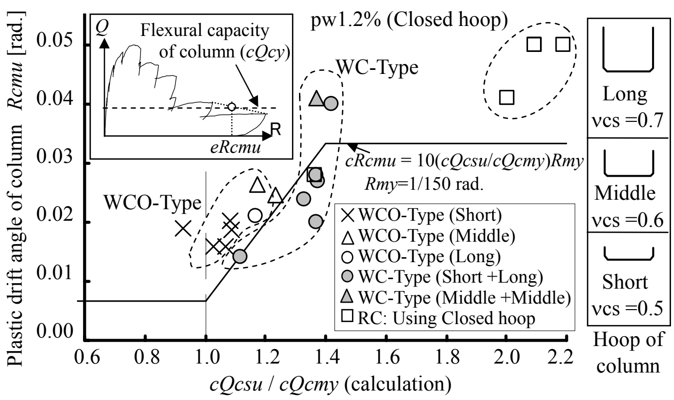
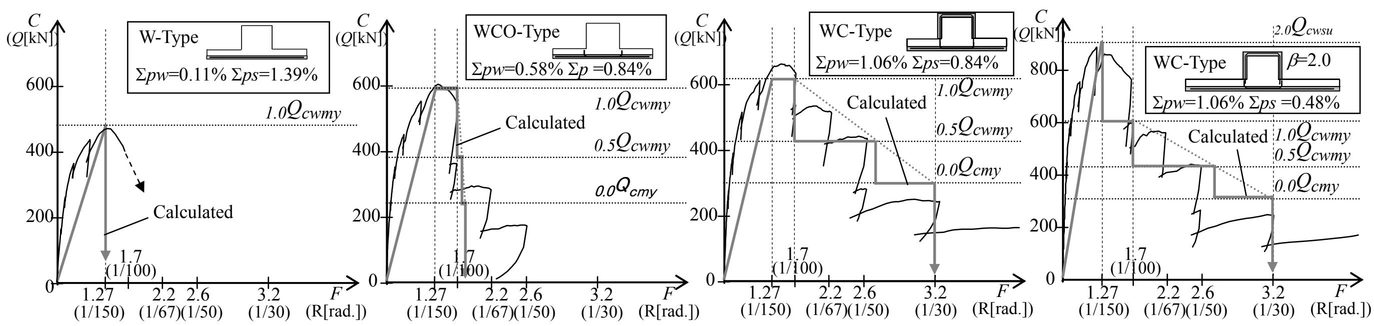


Fig. 16 Evaluation of plastic drift angle of column (*Rcmu*)



(a) W-Type (b) WCO-Type (c) WC-Type (d) WC-Type (β=2.0)

Fig. 17 Strength Index C (Shear load Q) – Ductility Index F (drift angle R) relationship

5. CONCLUSIONS

The conclusions of this study are as follows:

1) The polymer-cement mortar did not peel off from the existing RC column with sidewall, and the proposed seismic retrofitting technique improved the shear capacity and ductility of the RC column with sidewall.
2) The additional shear reinforcement on the sidewall (horizontal reinforcement bar) improved the shear strength of the RC column with RC sidewall, and the additional shear reinforcement on the column (hoop) improved the ductility of the RC column with RC sidewall.
3) The structural performance (capacity and ductility) of the strengthened RC column with RC sidewall could be controlled by choosing the strengthened area and the amount of shear reinforcement.
4) The mechanism of shear resistance of the strengthened RC column with RC sidewall was clarified from the test results.
5) A method of estimating the capacity (shear strength) and ductility of the RC column with RC sidewall strengthened by polymer-cement mortar was proposed by modeling the shear resistance mechanism.

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