CYCLIC LOADING TEST ON REAL-SCALED RC COLUMN EXTERNALLY RETROFITTED BY PC BAR PRESTRESSING

Y. Shinjo[1], M. L. Lin[2], P. C. Chen[2], K. C. Tsai[2] and T. Yamakawa[1]

[1]*University of the Ryukyus, Okinawa, Japan*
[2]*Center for Research on Earthquake Engineering (NCREE), Taipei, Chinese Taiwan*
Email: yamakawa@tec.u-ryukyu.ac.jp

ABSTRACT:

A permanent and/or an emergency seismic retrofit technique of PC bar prestressing using corner blocks for shear critical RC columns that proposed by T. Yamakawa in 1999 was verified through the cyclic loading tests on RC column specimens with a scale factor of 1/2.4. To verify the effectiveness of the proposed retrofit technique for real cases, loading tests on full-scaled column specimens were conducted under a joint-research project by the collaboration with the Center for Research on Earthquake Engineering (NCREE), Taiwan University, and University of the Ryukyus, Japan. In this paper, the experimental investigation of the full-scaled specimens and their seismic performance are compared with that of the small-scaled specimens. Experimentally it was observed that the failure mode of the full-scaled specimen retrofitted by the proposed technique shifted from shear to ductile flexural one. Moreover, by emergency retrofitting of the shear-damaged full-scaled column, the experimental lateral force capacity almost recovered with keeping the ductility and sustaining of the vertical load.

KEYWORDS: Retrofit, RC column, PC bar, Prestressing, Full-scale, Cyclic loading test

1. INTRODUCTION

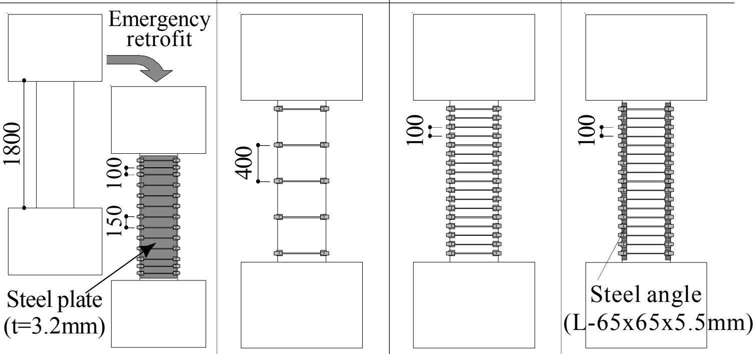
It is well-known fact that the strength and ductility of RC column can be extremely enhanced by transverse confinement. Considering this fact, a seismic retrofit technique of PC bar prestressing for shear critical RC column was proposed by T. Yamakawa in 1999 [1-2]. In this retrofit technique, the RC column is externally confined by PC bars with the help of corner blocks that placed at four corners of column, and initial prestressing is applied to column concrete by applying tension force into PC bars. The main features of this technique are the active and passive confinement effects by PC bar. It is possible that the failure mode of the extremely short column can easily be converted from brittle shear to ductile flexural one through this retrofit technique.

To verify the effectiveness of the proposed retrofit technique, the cyclic loading tests were carried out on specimens with a scale factor of 1/2.4. However, tests on full-scaled specimens are also necessary to verify the effectiveness of the proposed technique for real cases. A joint-research project was conducted by the collaboration with the Center for Research on Earthquake Engineering (NCREE), Taiwan University, and University of the Ryukyus, Japan. Cyclic loading tests of full-scaled RC columns retrofitted by PC bar prestressing were carried out in Taiwan since 2006 until 2007. In this paper, the seismic performance of the real-scaled columns retrofitted by the proposed technique was confirmed by the cyclic loading test. Furthermore, to ensure the seismic performance recovery of the shear-damaged non-retrofitted specimen, the cyclic loading test was also conducted after applying the emergency retrofit to it by the proposed retrofit technique.

2. TEST PLAN

The details of the full-scaled specimens are shown in Table 1. The real-scaled corner block and the application of PC bar retrofit technique applied in real columns as well as full-scaled test specimens are presented in Fig. 1. The properties of steel materials and the details of reinforcement are presented in Table 2 and Fig. 2 respectively. The column specimen is 600mm square section, and its height is 1800mm (shear span to depth ratio=1.5), the shear reinforcement ratio, p_w=0.09% (D10-@250mm) and the longitudinal reinforcement ratio, p_g=1.69% (12-D25). The column specimen is the original RC column of the school building designed by the inadequate old seismic design code before 1971. One of the specimens was planned for shear failure test to check the shear strength of column

Table 1 Details of full-scaled specimens

Specimen	R06-BM	R06-PC1	R06-PC2	R06-PC3
Elevation (mm)				
σ_B (MPa)	23.5	24.0	23.5	23.5
PC bar	- / end: @100, mid.: @150	9.2ϕ-@400 ($_Pp$=0.06%)	9.2ϕ-@100 ($_Pp$=0.22%)	9.2ϕ-@100 ($_Pp$=0.22%)
Pretension strain level	- / 2450μ (490MPa)	2450μ (490MPa)	2450μ (490MPa)	0μ (0MPa)
Longitudinal reinforcement	12-D25 (p_g=1.69%)	20-D29 (p_g=3.57%)	12-D25 (p_g=1.69%)	12-D25 (p_g=1.69%)
Common details	M/(VD)=1.5, Axial force ratio=0.3 Transeverse reinforcement : D10-@250 (p_w=0.09%)			

Notes : σ_B=cylinder strength, $_Pp$=shear reinforcement ratio of PC bar.

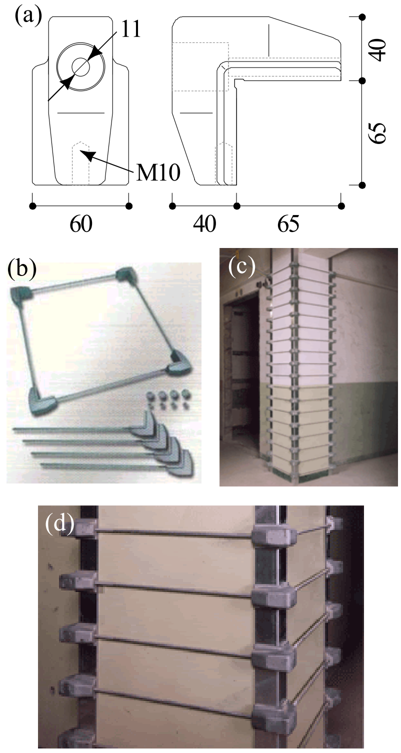


Fig. 1 Details of real-scaled corner block and its application

Table 2 Mechanical properties of materials

Reinforcement		a (mm²)	σ_y (MPa)	ε_y (%)	E (GPa)
Hoop	D10	71	374	0.19	200
Rebar	D25	507	490	0.24	200
	D29	642	489	0.24	200
PC bar	9.2ϕ	66	1080	0.54	200
Steel plate	t=3.2mm	-	312	0.15	213

Notes: a=cross section area, σ_y=yield strength of steel,
E=Young's modulus of elasticity.

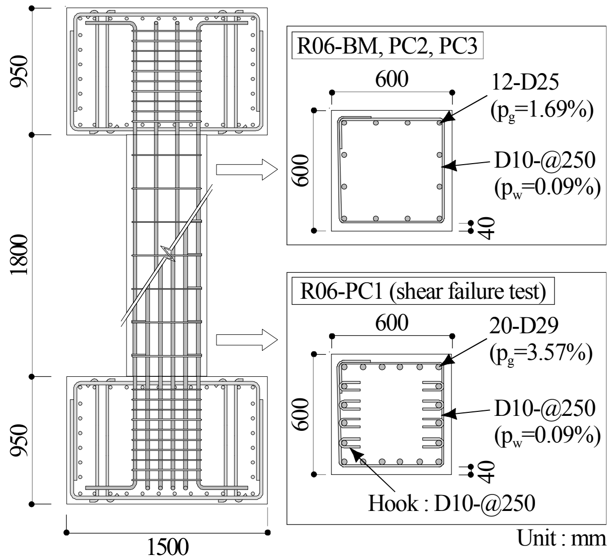


Fig. 2 Details of reinforcement

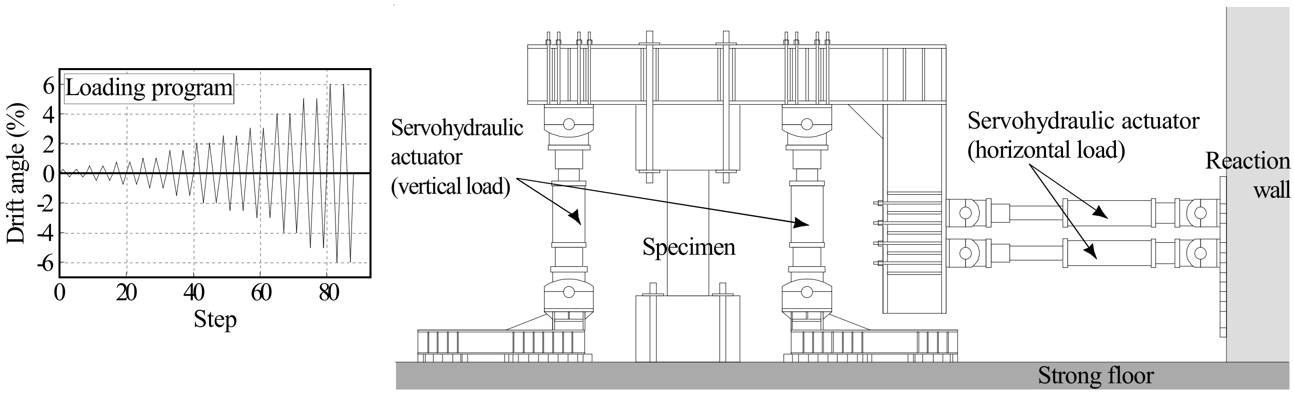


Fig. 3 Test setup and loading program

retrofitted with PC bars. In this case, a large amount of longitudinal reinforcement (20-D29, p_g=3.57%) was provided to ensure the shear failure. Furthermore, the bond strengthening hooks (D10-@250mm) proposed by K. Nagatomo *et al.*[3] were also provided to prevent the bond failure. The ends of each hoop was made at 90^0.

The specimen R06-BM is the non-retrofitted standard specimen in which shear failure is likely to happen. This shear-damaged column was then emergency retrofitted using steel plates and PC bar prestressing [2]. In specimen R06-PC1, the column was retrofitted by PC bars with a large interval of 400mm to make predetermined shear failure. The specimen R06-PC2 was retrofitted by PC bar at a interval of 100mm with initial prestressing in order to shift the failure mode from shear to flexural one. The specimen R06-PC3 was also retrofitted by PC bars but without initial prestressing and at the same interval of 100mm. In this case, steel angles (L-65 x 65 x 5.5mm) were also attached at four corners of column. The pretension strain level was about 2450μ (at a stress of 490 MPa), which was equal to approximately 1/2 of the yield strain of PC bar.

The test setup and loading program are illustrated in Fig. 3. In this setup, the constant vertical load was applied through the servohydraulic actuators and the cyclic lateral forces were applied through a double acting double actuators system. Under a constant axial compression ratio of 0.3 of the axial strength of column concrete, the cyclic loading tests were carried out. Since two horizontal actuators were controlled by the same displacement, the loading beam always remained parallel to the strong floor. Lateral loading cycles include two successive cycles at each drift angle with the values of R=0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0%.

3. TESTS RESULTS OF FULL-SCALED SPECIMENS

The experimental results on the relationship between the shear force V and the drift angle R, and the variation of average longitudinal strain ε_v along the column axis with the drift angle for full-scaled specimens are illustrated in Fig 4. The observed cracking patterns (web side) are presented in Fig. 5.

In non-retrofitted specimen R06-BM, the longitudinal rebar did not yield and the lateral force capacity dropped suddenly at R=-1.0% with brittle shear failure, but the capacity reached near to the calculated flexural strength.

In specimen R06-PC1, shear crack generated at R=0.5%, and the lateral force capacity reached to the maximum value at R=1.0%; but after that, the capacity decreased gradually. Then, at a drift angle prior to 2.0%, this specimen failed in a shear manner with the fracture of PC bar located at the second level from the top (see Fig. 6). Since the specimen was confined by PC bars, the hoop did not yield at peak strength. Again, longitudinal rebar did not yield and no flexural crack was observed, therefore, it was considered that the shear failure happened.

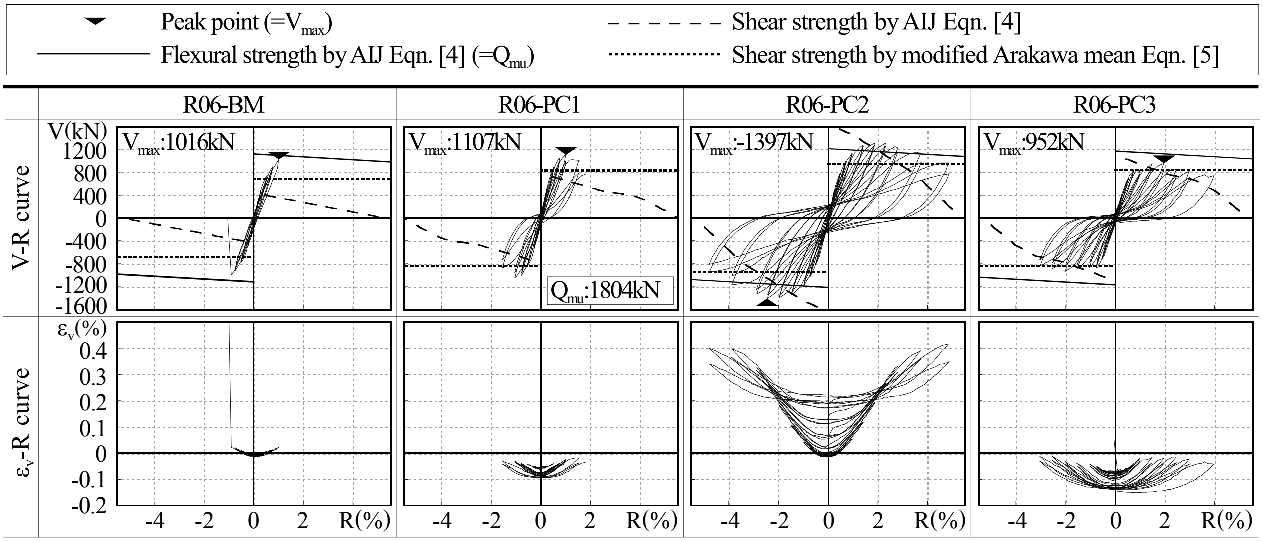


Fig. 4 Measured V-R and ε_v-R relationships of full-scaled specimens

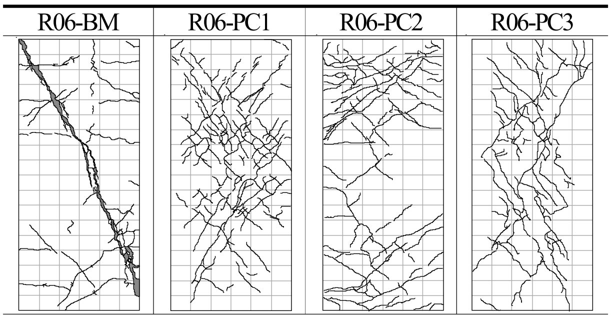


Fig. 5 Observed cracking patterns

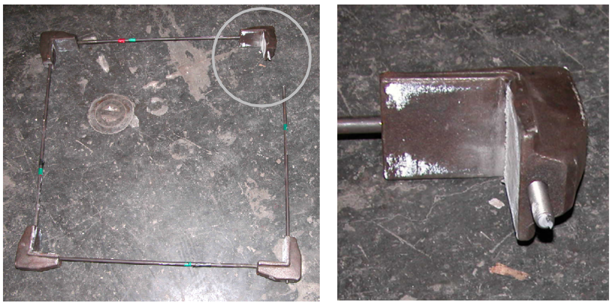


Fig. 6 Broken PC bar (R06-PC1)

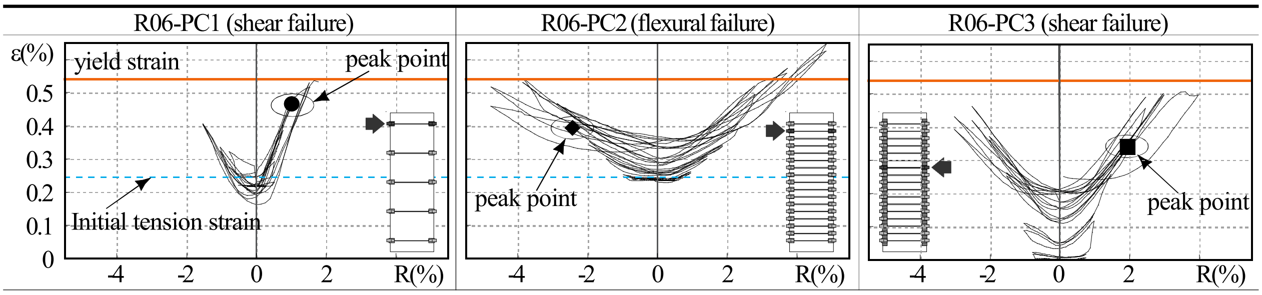


Fig. 7 Measured strain of PC bar

In specimen R06-PC2, at *R*=1.0%, longitudinal rebar yielded and at *R*=-2.5%, the lateral force capacity reached to the maximum value. The failure mode was flexural type. The average longitudinal strain was also tensile (see Fig. 4). The test result agreed well with the calculated flexural strength by AIJ simplified equation [4].

In specimen R06-PC3, the lateral force capacity reached to the maximum value at *R*=2.0%, and its hoop also yielded. However, the capacity did not reach to the calculated flexural strength and no flexural crack was observed. Therefore, it was considered that the shear failure happened, but the failure was not so brittle.

The variation of strain of PC bar that placed on the web side with drift angle is presented in Fig. 7. In specimens R06-PC1 and R06-PC3 in which shear failure occurred, PC bars did not yield at the experimental peak shear force.

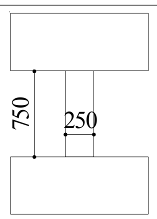
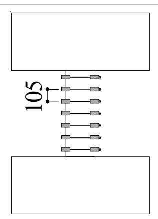
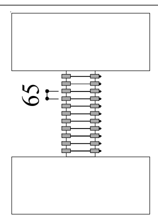
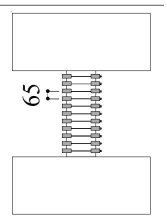
4. COMPARISON OF SMALL-SCALED AND FULL-SCALED SPECIMENS

The test results of full-scaled and small-scaled specimens are compared here. The details of small-scaled specimens [6] are presented in Table 3. The details of small-scaled corner block are presented in Fig. 8. The experimental *V*-*R* and ε_v-*R* relationships of small-scaled specimens are presented in Fig. 9. The small-scaled specimens were 1/2.4 of the original RC column (600mm x 600mm square section). The cross sectional dimension of the column was 250mm x 250mm for all test specimens. The diameter of PC bar was 3.8mm and it was about 1/2.4 times the diameter of 9.2mm which was used in the full-scaled specimens. The cyclic loading tests were carried out under a constant axial compression force ratio of 0.2 corresponding to the axial force in the long term. Lateral loading cycles include three successive cycles at each drift angle with the values of R=0.5, 1.0, 1.5, 2.0, 2.5 and 3.0%.

In non-retrofitted standard specimen R98M-P0, the lateral force capacity reached to the calculated flexural strength. After that, this specimen failed in a brittle shear manner. In case of specimen R98M-P105, due to poor amount of shear reinforcement, shear cracks widened gradually and at a drift angle before 2.0%, this specimen failed in a shear manner with the fracture of PC bar. The similar behavior was appeared in the full-scaled specimen R06-PC1. In other retrofitted specimens R98M-P65 and R98M-P65N, the experimental lateral force capacity increased significantly and also maintained even at large drift angles. However, without initial prestressing, the axial compression strain increased gradually. The failure mode of these specimens was flexural type.

The relationship of PC bar strain and drift angle is presented in Fig. 10. Here, the increment of PC bar strain of the small-scaled flexural failure specimen R98M-P65 was small although the increment of PC bar strain of the full-scaled flexural failure specimen R06-PC2 was large (see Fig. 7). Due to the difference in size of corner blocks used in small-scaled and full-scaled specimens and due to the presence of same gap of 3mm between the column surface and PC bars, the unsupported region of the full-scaled specimen was larger than the small-scaled specimen. So, the volume of the spalling of cover concrete and the pressure exerted by this concrete are relatively larger in full-scaled specimen than that of the small-scaled specimen. The comparison of corner blocks is illustrated in Fig. 11. Since the full-scaled specimen is 2.4 times the small-scaled specimen, small-scaled corner blocks as shown in Fig. 11 are enlarged to 2.4 times. In the full-scaled flexural failure specimen R06-PC2, reinforcement ratio of PC bar is larger than that of the small-scaled flexural failure specimen R98M-P65 (see Tables 1 & 3). However the bearing area of full-scaled corner block is about 55% of the 2.4 times the bearing area of the small-scaled specimen. So, the confinement effect in the full-scaled specimen was relatively smaller than the small-scaled specimen.

Table 3 Details of retrofitted specimens

Specimen	R98M-P0	R98M-P105	R98M-P65	R98M-P65N
Elevation (mm)				
PC bar	-	3.8ϕ-@105 ($_{P}p$=0.09%)	3.8ϕ-@65 ($_{P}p$=0.14%)	3.8ϕ-@65 ($_{P}p$=0.14%)
Pre-tension strain level	-	2450μ (492MPa)	2450μ (492MPa)	0μ (0MPa)
Common details	σ_B=27.4MPa, M/(VD)=1.5, Axial force ratio=0.2 Longitudinal reinforcement : 12-D10 (p_g=1.36%) Transeverse reinforcement : 3.7ϕ-@105 (p_w=0.08%)			

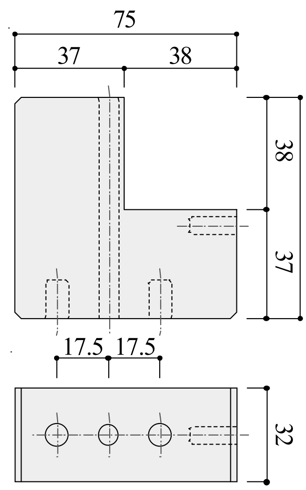


Fig. 8 Details of small-scaled corner block

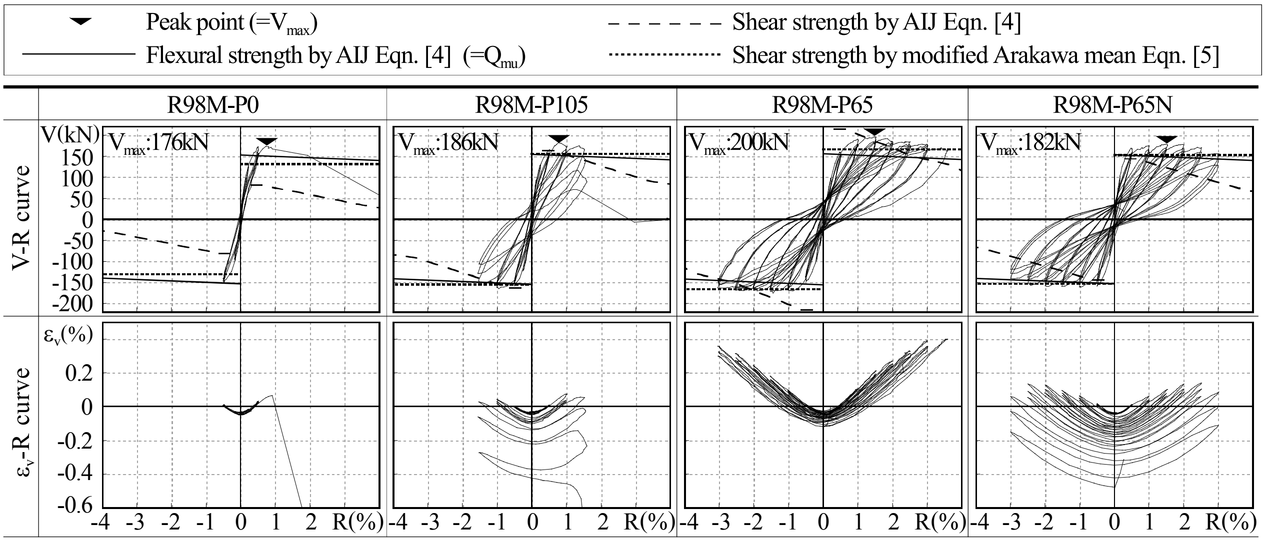


Fig. 9 Measured V-R and ε_v-R relationships of small-scaled specimens

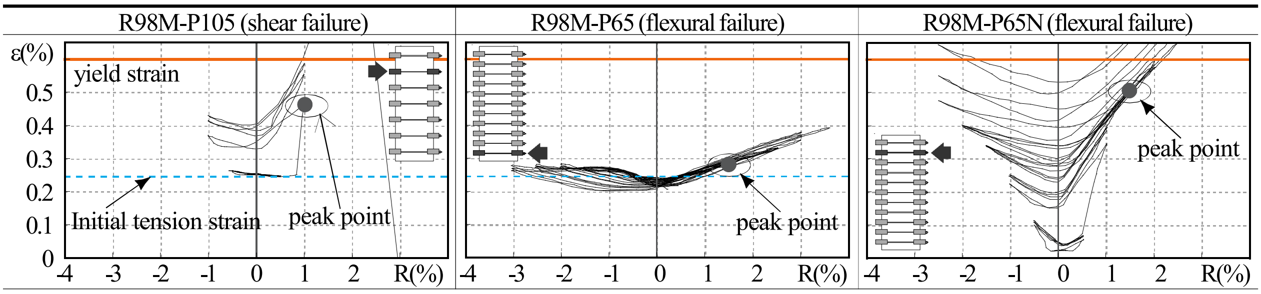


Fig. 10 Measured strain of PC bar of small-scaled specimens

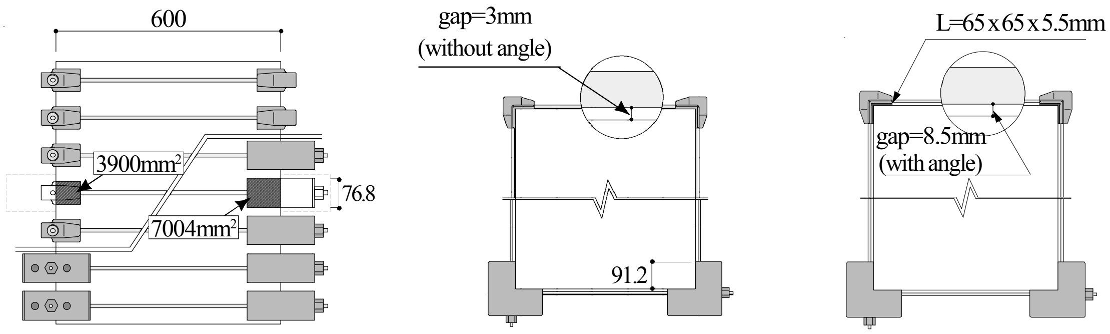


Fig. 11 Comparison of corner blocks

Therefore, the experimental lateral force capacity of the retrofitted full-scaled specimen R06-PC2 was not maintained at large drift angle although the shear reinforcement ratio of PC bar was large. In specimen R98M-P65N, although the failure mode was flexural type, the increment of PC bar strain was larger than that of R98M-P65. This may be due to the increase of axial compression strain (see Fig. 9). In specimen R06-PC3, due to the presence of steel angles (L-65 x 65 x 5.5mm), the gap between the column surface and PC bar was large. Therefore, even with the lateral expanding of column with the increase of drift angles, no out of plane bending of PC bars was observed. As a result PC bar did not yield at a large drift angle (see Fig. 7).

5. TEST RESULTS OF EMERGENCY RETROFITTED SPECIMEN

After emergency retrofitting the shear damaged standard specimen R06-BM, the cyclic loading test was carried out again. However, due to large damage, the axial force was not applied during the emergency retrofit test. In the emergency retrofitted specimen, corner blocks were located at four corners of the damaged column, PC bars with a diameter of 9.2mm were installed to connect them, and the specified prestress was introduced with a torque wrench. Four steel plates (570 x 1740 x 3.2mm) were also simply attached to the four faces of a damaged column and no welding was done. The pretension strain level was about 2450μ, which was equal to approximately 1/2 of the yield strain of PC bar. The steel plates did not resist the axial force due to the presence of clearance of 30mm between steel plate and stubs. The interval of PC bar at the middle zone of column was 150mm and at the end zones that was100mm.

The experimental *V-R* and ε_v-*R* relationships of emergency retrofitted specimen (R06-BM) are presented in Fig. 12. The relationships of PC bar strain and drift angle are presented in Fig. 13. The solid lines drawn in the *V-R* curve are the calculated flexural strength by the AIJ simplified equation without considering the lateral confinement effect of retrofit, and taking into account the P-Δ effect. The axial strain of emergency retrofitted specimen was started from ε_v=0 (see Fig. 12). But actually, the axial compression strain remained, because the shear failure happened.

The experimental lateral force capacity of the emergency retrofitted specimen reached to the calculated flexural strength at the negative side only. Experimentally, it was observed that the pretensioned strain in PC bars decreased with the increase of drift angle. This may be due to the closing of cracks through PC bar prestressing. However, the increase in axial compression strain was not able to restrain (see Fig. 12). One of the reasons is that the axial compression force ratio was comparatively high (0.3). However, in case of full-scaled RC column, the seismic performance was recovered by applying emergency retrofit. To check the initial stiffness of the specimen (R06-BM) before and after the emergency retrofit, a part of the *V-R* curve at *R*=-0.25% is presented in Fig. 14. This figure shows that, by emergency retrofitting, the lateral stiffness was not recovered to sound state. The variation of lateral stiffness with drift angles are presented in Fig. 15. Here, the stiffness is measured as the secant stiffness.

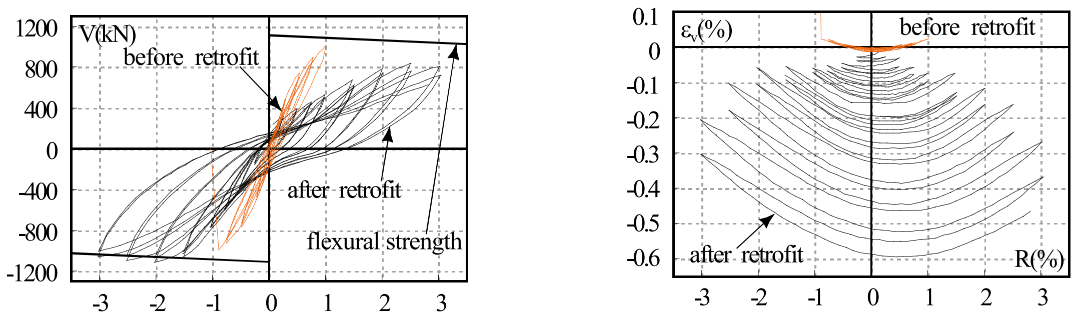


Fig. 12 Measured V-R and ε_v-R relationship (R06-BM)

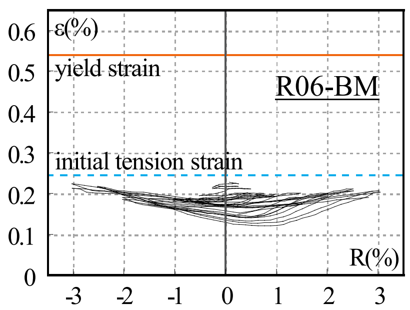


Fig. 13 Measured strain of PC bar

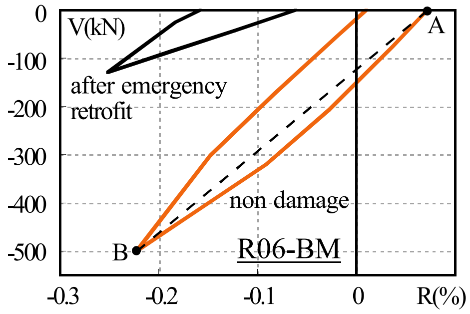


Fig. 14 Comparison of hysteresis loop

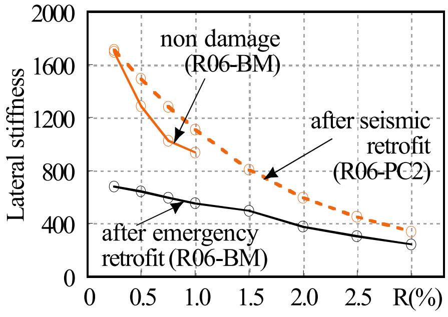


Fig. 15 Comparison of lateral stiffness

To compare with the flexural failure specimen, test results of the specimen R06-PC2 are also presented. Each test data in Fig. 15 is plotted based on the *V-R* curve at the negative side. It is observed that with the increase of drift angles, the degradation of lateral stiffness of emergency retrofitted specimen is relatively smaller than that of specimens R06-BM and R06-PC2. This may be due to the closing of cracks through PC bar prestressing and due to the protection of cover concrete by steel plates.

6. CONCLUSIONS

1) By retrofitting through PC bars and with initial prestressing, the failure mode of full-scaled column shifted from shear to ductile flexural one but the performance was not as good as small-scaled specimen due to the effect of size of corner block. Again, without initial prestressing, the lateral strength did not reach to the flexural strength and also the failure was not so brittle.

2) In specimens in which even shear failure occurred, no yielding of PC bars observed at experimental peak shear force. In full-scaled shear failure specimens, the increment of PC bar strain at peak strength also remained at the range of that of small-scaled shear failure specimens.

3) By emergency retrofitting of the shear-damaged column, the experimental lateral strength almost recovered with keeping the ductility and sustaining of vertical load.

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