論文 Experimental Investigation of RC Short Columns Retrofitted by Prestressed Aramid Fiber Belts as External Transverse Reinforcement

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ABSTRACT: A new seismic retrofit method, in which aramid fiber belts are prestressed and used as external transverse reinforcement, is proposed in this paper. Five shear critical columns with shear span to depth ratio of 1.5 and poor transverse reinforcement, were retrofitted and tested under reversed cyclic lateral forces and constant axial load, simultaneously. The test results indicated the high efficiency of the retrofit technique. Moreover, the experimental results for a retrofitted earthquake-damaged column showed the efficiency of the proposed method as an emergency retrofit technique.
KEYWORDS: RC column, seismic retrofit, emergency retrofit, aramid fiber belt, prestress

1. INTRODUCTION

The 1995 Hanshin-Awaji earthquake disaster in Japan clearly demonstrated the need for developing retrofit techniques for the existing buildings and bridges. This fact is a common issue in earthquake hazard field all over the world, and it will be an important topic for twenty-first century. One category of these retrofit techniques is focused on improving the ductility of buildings. An effective way in order to enhance the ductility of RC columns in addition to the strength is well known to be the confinement of concrete. Considering this fact and based upon the investigation of previously proposed retrofit method utilizing PC bar prestressing [1] and retrofit by aramid fiber sheet [2], a new seismic retrofit technique is proposed. In this technique, aramid fiber belts surround the column like the external hoops which are supported on the steel blocks at four corners of the cross section. Then, the prestressing is applied into the AFRP belts through the prefabricated steel couplers. Because of prestressing, the method utilizes the benefits of active confinement in addition to shear reinforcement and passive confinement. Also, comparing with retrofit by aramid fiber sheets, the consumption of new expensive materials is much lower in this method. Furthermore, as an emergency retrofit of the earthquake-damaged concrete columns, this method seems to be suitable because the retrofit can be conveniently and rapidly applied without heavy machinery. In order to assess the effectiveness of this technique, the experimental results for six test specimens including a non-retrofitted column and an emergency-retrofitted column are presented in this paper.

2. TEST PLAN

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Six column specimens (shear span to depth ratio of 1.5) were tested under reversed cyclic lateral force and constant axial load, simultaneously. Lateral loading cycles included three successive cycles at each drift angle range of R= 0.5,1,1.5,2,2.5,3% and one cycle at R= 4, 5%. Properties of materials are listed in **Table 1**. Details of the specimens and a schematic figure of retrofit technique are presented in **Table 2** and **Fig. 1**. Test specimen ER00M-A65/3 is the emergency-retrofitted column.

Table 1 Properties of materials

Type	A (mm^2)	f_y(MPa)	ε_y(%)	E(GPa)
Aramid fiber belt	10.48*	2065	1.75	118
Steel bar D13 (SD295)	127	359	0.18	200
Steel bar 3.7 ϕ	11	333	0.17	196

* This is a value of one ply sheet which has a width of 17 mm and a thickness of 0.612 mm .

Notes: f_y and ε_y = tension yield strength and strain of steel or tension design strength and strain of AFRP belt, E= modulus of elasticity .

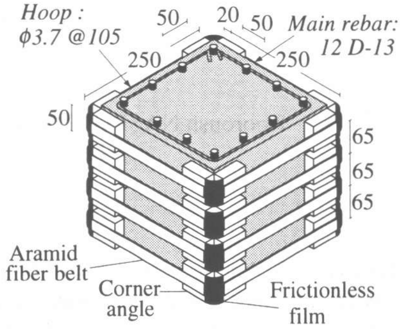
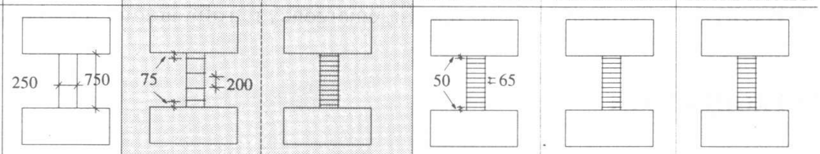


Fig. 1 Retrofit details *(unit : mm)*

Table 2 Details of test specimens

	R00M-A0	R00M-A200/3 →	ER00M-A65/3	R00M-A65/0	R00M-A65/2	R00M-A65h/3
Specimen $\frac{M}{VD}$ **=1.5**						
Aramid belt	—	**2-ply @200**	**2-ply @65**			
Prestress(MPa)	—	**fy/3**		**0**	**fy/2**	**fy/3**
Axial force ratio	**0.2**					**0.4**
σ_B (MPa)	**26.8**	**23.4**				
Common detail	Longitudinal reinforcement:12-D13 SD295A(pg=2.44%) Transverse reinforcement:ϕ3.7-@105(pw=0.08%) f_y = tension design strength of aramid fiber belt (f_y = 2065 MPa) unit : mm					

Steel angles, which are located at the corners of column, have width and length of 50 mm and thickness of 20 mm. An external radius of 20 mm is provided for the corner angle in order to decrease stress concentration in the belt. Moreover, a frictionless film, which is placed between corner angle and belt, reduces the friction between belt and corner angle. In this program, the aramid fiber belts were not impregnated by the epoxy resin. Prestressing can be applied by tightening the coupler manually. In order to control the prestressing level, strain gauges attached to the belt surface.

3. EXPERIMENTAL INVESTIGATION

The experimental results including crack patterns, lateral shear force V versus drift angle R curves and the variation of average vertical strain ε_v along the column axis, are presented in **Fig. 2**. The dotted lines drawn in the V-R curves are the calculated flexural strength taking into account the P-Δ effect by the simplified equation (based on yielding of two bar rows). **Table 3** summarizes the experimental shear capacity and failure modes.

The non-retrofitted column, R00M-A0, is shear failure type due to poor transverse reinforcement.

The loading test of column R00M-A200/3 retrofitted with only four belts (with 200 mm space),

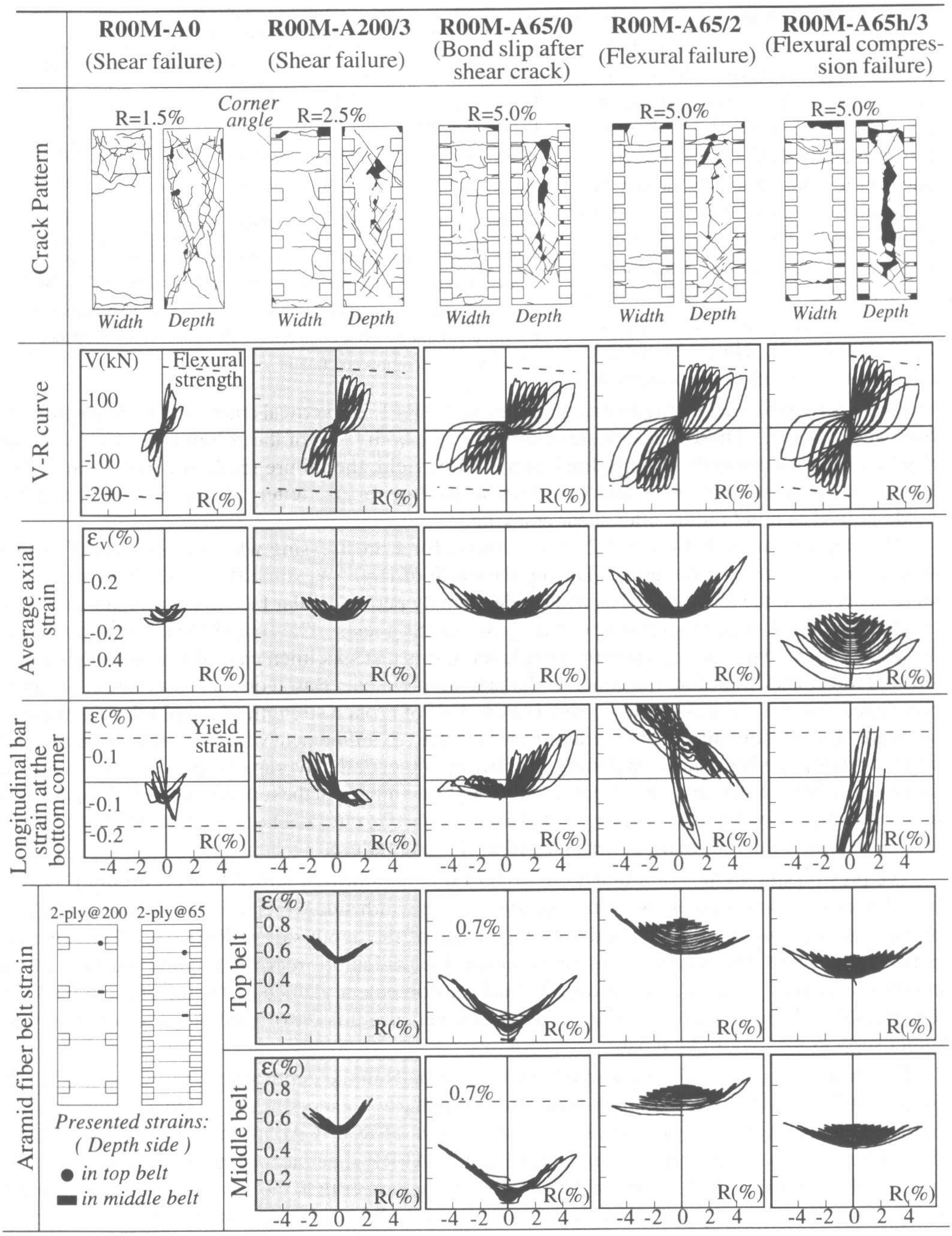


Fig. 2 Crack patterns and measured experimental results versus drift angle R

continued until R=2.5%, where the lateral capacity dropped more than 20% of the experimental peak shear force. The first shear crack occured at R=0.4%, and then, successive shear cracks happened with increasing the drift angle. At R=2%, some parts of cover concrete peeled off because of joining the shear cracks to each other. During the test, hoops yielded but longitudinal bars did not yield, showing shear failure mode.

The test specimen R00M-A65/0 was designed for the case of non-prestressing. Because of the lack of active confinement, this column can be compared with the columns retrofitted by AFRP sheet. The first shear crack happened in the depth side, namely parallel face to the lateral load, at R=0.5%. During R=1% cycle, some large shear cracks occured and then the peak in the hystereis diagram suddenly dropped, a little (see Fig. 2). However, spread of these shear cracks was protected by the belts, therefore with progressing of the test and at R=1.5%, vertical cracks along the longitudinal bars were formed. These cracks were observed in the both faces of the column, showing the bond degradation. Because the longitudinal bars did not yield, the failure mode was not flexural one. Moreover, the hysteresis curve was very narrow and like inverse letter 'S'. Therefore, the failure mode judged as bond failure after shear cracking.

Table 3 Summary of experimental results

Specimen	V_{exp} (kN)	R_{exp} (%)	R_f (%)	Failure mode
R00M-A0	147.6	0.54	0.79	S
R00M-A200/3	169.1	0.66	2.25	S
R00M-A65/0	155.5	0.73	5.00	SB
R00M-A65/2	193.6	1.49	5.00	F
R00M-A65h/3	213.8	0.98	2.87	FC

Notes : V_{exp} = experimental peak shear force in push direction R_{exp} = drift angle corresponding to V_{exp} , R_f = drift angle related to the shear force being 80% of V_{exp} , S = shear failure , F = flexural failure , SB = bond failure after shear crack happened , FC = flexural compression failure .

The test specimen R00M-A65/2 was designed for a prestressing which was a half of broken strength of aramid fiber material. During the cycle of R=0.5%, some flexural horizontal cracks were observed in the tension face of width side, namely perpendicular face to lateral load, and these cracks developed with progressing of the cyclic loading test. The first shear crack happened at R=0.9%. Moreover, the high prestressing level in this test specimen caused overlapping the two sides of the cracks, therefore the concrete damage accelerated. Based on this observation, it can be concluded that the prestressing level equal to one half of broken strength of aramid fiber material is too high. This prestressing level generated very high active confinement which accelerated developing concrete damage after cracks happened. Referring to Fig. 2, the average vertical strain was tensile in the larger drift angles, showing the formation of plastic hinges in the top and bottom of column. In addition, longitudinal reinforcement yielded at about R=1%, but steel hoops did not yield during the test. Therefore, the failure mode was judged as flexural failure.

The prestressing in the column R00M-A65h/3 was one-third of AFRP broken strength. In the R=0.5% cycle, horizontal cracks were observed in the width side which developed during the test. Shear cracks occured at the top and bottom surface of the depth side at R=0.7%. The concrete between the horizontal cracks in the top of width side peeled off, representing the crushing of the compression side. During the test, longitudinal reinforcement yielded and some of them buckled. The buckling of bar could be predicted in this test because this retrofit technique did not prepare direct support for longitudinal bar.

The strain variation in the top and middle aramid belts in the depth side is shown in Fig. 2. In R00M-A65/2, aramid fiber belt strain decreased during the test, endorsing the fact that the prestressing level was a high value. But strain in the aramid belts of R00M-A65/0 increased. In Fig. 2, the dotted line shows the passive strain design limit in AFRP sheet according to BDPAJ [3]. The measured aramid fiber belt strains in R00M-A65/0 were lower than the passive strain design limit, i.e. 0.7%. This fact suggests that strain concentration did not happen in the aramid fiber belts because of 20 mm space existing between column surface and belt. As a result, it can be concluded that the prestressing is a beneficial procedure and it can decrease the strain variation range in the aramid fiber belts. Also, the passive confinement and shear reinforcement can be expected.

4. EMERGENCY RETROFIT

For R00M-A200/3, which explained before, lateral loading cycles included three successive cycles at each drift angle range of 0.5, 1.0, 1.5, 2.0%. Then the drift angle incresed to 2.5% (push direction), in which the lateral load capacity dropped to less than 80% of the experimental peak. During the first cycle of R= 2.5%, and at the time that the shear force became zero in the pull direction, the test stopped. And then, six aramid fiber belts with prestressing strain of one-third (i.e. 0.6%) of broken strain, added to the column and the cyclic loading test continued from the point which was the end of first cycle of R=2.5% . Therefore, the loading test of the emergency-retrofitted column, ER00M-A65/3, started with residual lateral deformation and initial damage. The loading cycles were two successive cycles at R= 2.5% and three cycles at R= 3.0% and one cycle at R= 4.0 and 5.0%.

Figs. 3 and **4** present the experimental results. In R00M-A200/3 and at R=2.5% (first cycle in the push direction), shear capacity became 126.1 kN, which was less than 80% of the experimental peak value 169.1 kN (see **Table 3**). After emergency-retrofitting the column, the lateral capacity increased to 152.6 kN at R=3.0%. This lateral capacity decreased to 141 kN at R=5.0% (push direction), namely the decreasing amount was equal to about 7% during loading test of ER00M-A65/3. Therefore, emergency-retrofitting the column could stop decreasing in the lateral capacity and developed ductile behavior. Furthermore, when the emergency-retrofit was applied, some initial cracks closed. This is a reason why the gap in the aramid fiber belt strain is observed before and after emergency-retrofitting the column (see **Fig. 4**).

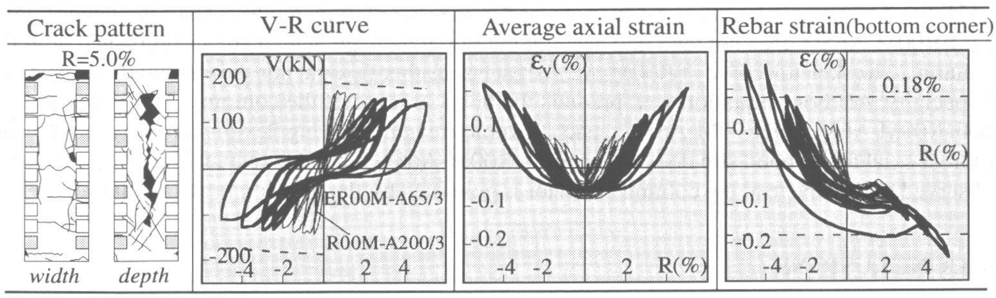


Fig. 3 Comparison of measured experimental results for emergency-retrofitted column

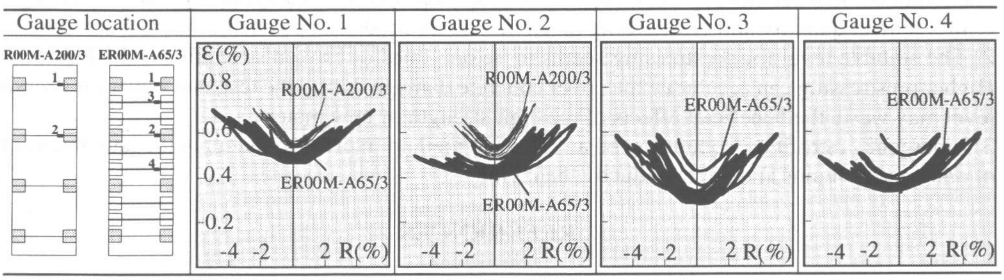


Fig. 4 Presentation of measured strains in the aramid fiber belts (depth side)

5. ANALYTICAL INVESTIGATION

The test results are evaluated by the analytical methods (see **Fig. 5**). A fiber model and Sakino & Sun's constitutive law are used to evaluate the flexural strength. Active confinement is considered as a uniform confined pressure corresponding to Richart's formula. And, shear capacities due to shear and bond failure are calculated by AIJ design guidelines' equations [4]. Referring to **Fig. 5,** the failure mode of R00M-A0 can be predicted by AIJ design guidelines' equations. However, in the case of poor transverse reinforcement, Arakawa's mean equation can better estimate the shear strength. For this column, shear capacity by Arakawa's mean equation is 146 kN. The calculated

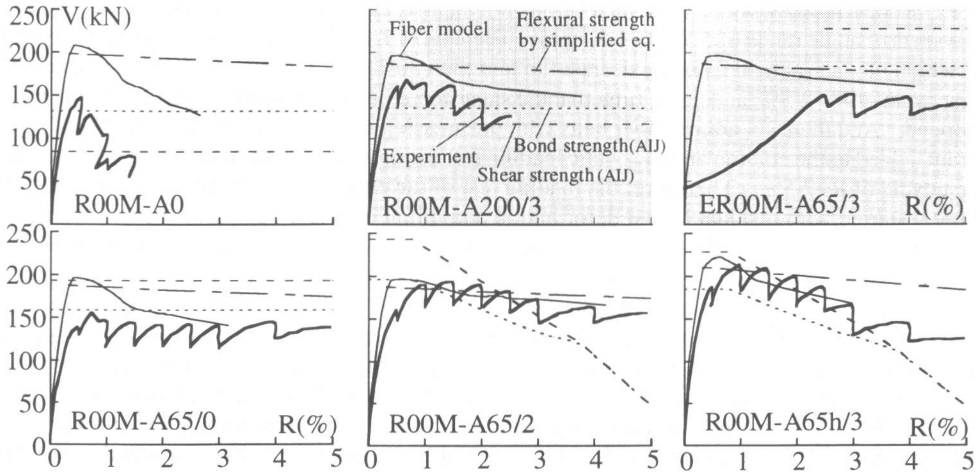


Fig. 5 Comparison between the experimental and analytical results

results for R00M-A200/3 show that the experimental capacity exceeds the calculated shear strength (AIJ) but does not reach to flexural strength, endorsing shear failure mode. The calculated strength for ER00M-A65/3 does not take into account the initial damage, which are accompanied with this column. The skeleton curve of R00M-A65/0 reaches neither flexural nor shear strength, as expected. Especially, AIJ bond equation well predicts the bond strength of the column. The V-R curves of both R00M-A65/2 and R00M-A65h/3 reach flexural strength, showing flexural failure type. Because of high axial force, bond slip does not occur in R00M-A65h/3, but due to buckling of rebars, which observed during the test, the column behavior is governed by flexural compression failure.

6. CONCLUSIONS

1) The test results indicated that the proposed method can be a highly effective retrofit technique for RC columns. Moreover, the prestressing is a beneficial procedure and by appropriately selecting the reinforcement quantity and prestressing level, the failure mode can be changed to flexural one.
2) The suitable level for prestressing seems to be one-third of broken strength of AFRP material. Higher prestressing can accelerate the cover concrete damage during the test, and lower prestressing level may waste the beneficial effects of the high strength of new materials.
3) Emergency retrofit procedure can be an effective method in order to maintain the lateral capacity of damaged columns and develop ductile behavior.

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