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STRUCTURAL PERFORMANCE OF DAMAGED OPEN-WEB TYPE SRC BEAM-COLUMNS WITH BOLT-CONNECTED BATTEN STEEL PLATES AFTER RETROFITTING

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In this paper, structural performance of damaged SRC beam-columns with open-web type of batten steel plate after retrofitting was investigated. Three open-web type SRC beam-columns with bolt-connected batten steel plates were fabricated and tested under combined constant axial load and cyclic lateral load. At first, each beam-column was cyclically loaded to the targeted displacement. After the first loading, the test columns were retrofitted and reloaded till large deformation or failure. The damaged portion of each column was retrofitted with the polymer cement mortar and epoxy resin was injected into the cracks. The measured stiffness of retrofitted columns varied between 71.4% and 85.5% of the initial one. And, test results also indicated that the column which experienced the larger displacement and higher axial load showed lower load carrying capacity, but the others showed approximately the same capacities as the initial columns. Numerical analysis was also conducted to explain the retrofitted columns. Analytical results predicted the experimental behavior fairly well, which verifies the validity of the analytical models in low axial load.

Keywords: Cracks, Stiffness, Load carrying capacity, epoxy resin, polymer cement mortar.

1 INTRODUCTION

After a great earthquake, many damaged buildings were demolished and reconstructed instead of being seismically retrofitted and reused, even though many of them were only moderately damaged. This was done because the structural performance of the damaged buildings after retrofitting was not clear, which made it difficult to accurately evaluate the recovery degree of structural performance.

Recently, we obtained basic data of the seismic recovery of damaged reinforced concrete (RC) beam-columns and damaged open-web type of steel encased reinforced concrete (SRC) beam-columns with weld-connected batten and lattice steel plates after retrofitting (Fujinaga and Sun 2010). However, it was open-web type SRC beam-columns with bolt-connected batten steel plate that had suffered significant damages in Kobe earthquake. In this paper, open-web type SRC beam-column specimens with bolt-connected batten steel plates encasement were fabricated and tested under combined constant axial load and cyclic lateral loads. The objectives of this paper are

1) to investigate the structural performance of damaged open-web type SRC beam-columns and 2) to evaluate the structural performance of the retrofitted beam-columns both experimentally and analytically.

2 EXPERIMENT OF OPEN-WEB TYPE SRC BEAM-COLUMNS

2.1 Outline of experiment

The test specimens were open-web type SRC beam-columns with bolt-connected batten steel plates. Specimens were tested under combined constant axial load and cyclic lateral load, with loading apparatus shown in Figure 1. First, each beam-column was cyclically loaded to a targeted displacement. After the first loading, the specimens were retrofitted and reloaded. The damaged portions of each column were retrofitted with polymer cement mortar, and epoxy resin was injected into the cracks.

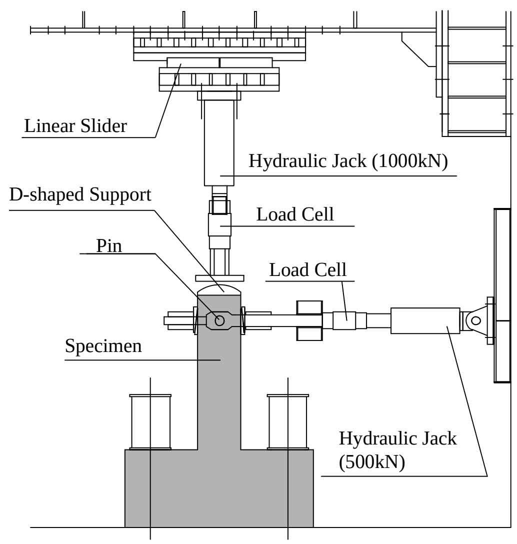


Figure 1. Loading apparatus

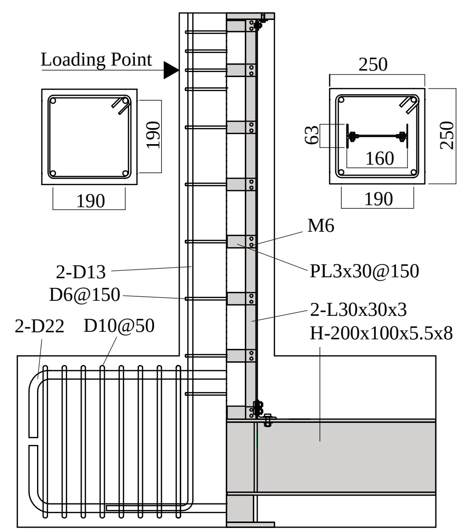


Figure 2. Test specimen

2.2 Specimen

Three specimens were fabricated and tested (see Figure 2). Test conditions of specimens are shown in Table 1. The experimental parameters were the axial load ratio and the tip displacement of the columns in the initial loading. Two ranges were set as the tip displacement: 1) the displacement corresponding to the peak strength, and 2) the displacement where the lateral load drops to the yield strength after the peak.

2.3 Material properties

The standard tensile or compressive test was conducted for the steels, concrete, mortar, and epoxy resin that would be injected into cracks of the damaged portions, to gain the mechanical proportion of the materials used. The measured results are presented in Tables 1 and 2. Examples of the compressive stress-strain relations of epoxy resin are plotted in Figure 3. It is apparent that the epoxy resin remains elastic until its compressive strength that was twice the strength of concrete and its strain is about 0.015.

Table 1. Test conditions

Specimens		Axial load ratio $n'=N/N_0{}^{*}$	Maximum rotation angle (rad.)	Young's modulus of concrete ${}_cE$ ($\times 10^3$N/mm^2)	Comp. strength of concrete F_c ($\times$N/mm^2)	Tensile strength of concrete F_t ($\times$N/mm^2)
1st. loading	B3-B2	0.2	0.03	21.6	24.5	2.50
	B3-M4	0.4	0.015	22.7	24.3	2.46
	B3-B4		0.02	23.8	24.1	2.43
2nd. loading	B3-B2-R	0.2	-	23.8 10.2**	26.3 20.1**	2.11 2.67**
	B3-M4-R	0.4		21.8 8.83**	24.5 20.6**	2.00 1.93**
	B3-B4-R			22.8 10.1**	25.0 21.2**	2.36 2.53**

$^{*}N_0={}_cA\cdot F_c+{}_sA\cdot {}_s\sigma_y$, **Polymer cement mortar

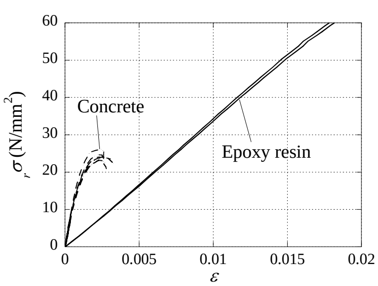


Figure 3. Stress-strain relation of epoxy resin

(a) Rebuilding of damage cross section with PCM (b) Injection of epoxy resin

Picture 1. Method of retrofitting

Table 2.Material properties of the steels used.

		Young's Modulus ${}_sE$($\times 10^3$N/mm^2)	Yield strength σ_Y(N/mm^2)	Yield strain ε_Y	Tensile strength σ_U(N/mm^2)	Yield Ratio σ_Y/σ_U	Elongation (%)
Steel	Cord angle	201	354	0.00180	354	0.748	31.5
	Batten plate	212	382	0.00176	382	0.735	26.4
Reinforcement	Main reber D13	183	355	0.00194	355	0.715	23.6
	Hoop D6	189	391	0.00206	390	0.758	25.7

3 METHOD OF RETROFITTING

The main retrofitting method is the injection of epoxy resin into the observed cracks, and the cross sections were rebuilt using polymer cement mortar (see Picture 1) before injecting the epoxy resin because the damage was heavy and the cover concrete was partially exfoliated. After removing the fragile portion of concrete, primary resin was coated onto the surface to improve adhesiveness with the existing concrete. Then the section was rebuilt with polymer cement mortar.

The injection of the epoxy resin into cracks was conducted using the internal pressure of the rubber tube swollen by resin for injection. After removing surface dust, rubber tube attachments were put on the cracks whose width was large or the point where two cracks were crossed. The other cracked portions were caulked; then rubber tubes were set and epoxy resin was injected. The surface was grinded after the resin hardened.

4 EXPERIMENTAL RESULTS

Figure 4 shows the measured lateral load-drift ratio relations. The measured behavior is shown in solid line. The circle and square show the point at which the reinforcement and steel began yielding. The broken lines express the plastic collapse mechanism line. These figures show that the stiffness of the retrofitted columns became lower than that of the original ones. The column which experienced the larger displacement and higher axial load showed lower load carrying capacity, but the others showed approximately the same load carrying capacity. The lower stiffness might be attributed to the deterioration of the concrete rigidity, low rigidity of the resin and imperfect injection of the resin. The lower load carrying capacity might be attributed to the buckling of longitudinal reinforcement in that first loading.

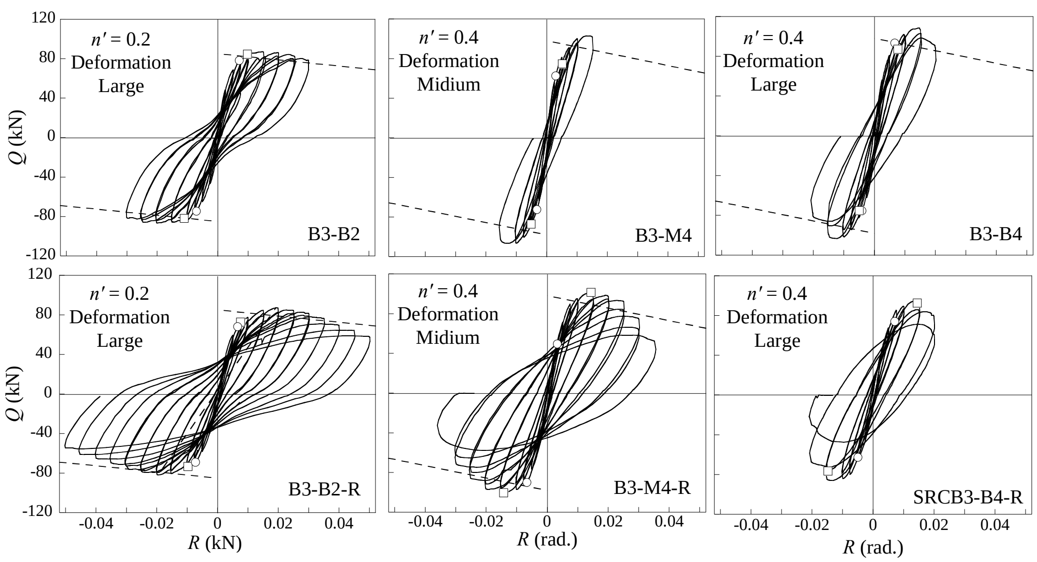


Figure 4. Experimental relations between the lateral load and drift ratio.

5 EVALUATION OF THE STRUCTURAL PERFORMANCE

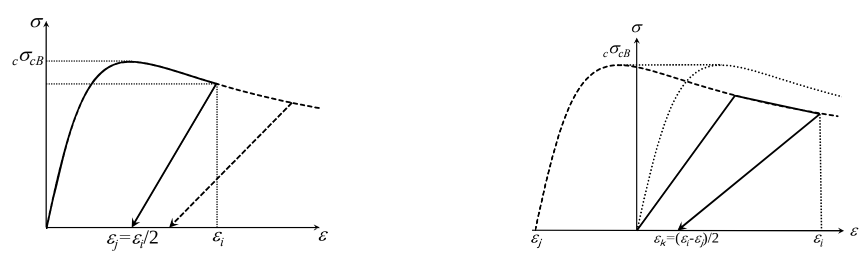
5.1 Analysis method

Numerical analysis was conducted to explain the lower stiffness and same load carrying capacity of the retrofitted columns. The bending moment versus curvature relation was calculated using the so-called finite fiber method. The following assumptions were adopted: 1) the plane section remains plane after bending, 2) tensile strength of concrete is negligible, 3) shear deformation is negligible, and 4) the rotation angle of the beam-column is concentrated within the plastic hinge region. The Sakino-Sun stress-strain relation was used for concrete (Sakino and Sun 1994). The bilinear model and Kato's cyclic stress-strain curve were used for the steel and reinforcing bar (Kato *et al.* 1973). The plastic hinge length was determined using Sakai's model (Sakai and Matsui 2000).

Figure 5 shows the stress-strain relation of the concrete in the second loading. It is a hysteresis after the last hysteresis during the first loading. The last unloaded point in the first loading is taken as the origin for the hysteresis curve of concrete under the second loading. The hysteresis rule is moved to the new origin. Also, the stress during the second loading is assumed to be less than the skeleton curve of the first loading.

Table 3. Primary experimental results.

Specimens	Initial stiffness (kN/mm)	Stiffness reduction ratio(%)	Maximum Strength (kN)				Deformation angle at max. strength(rad.)	
			+		-		+	-
B3-B2	32.9	-	87.1	-	-86.7	-	0.015	-0.020
B3-M4	37.2	-	103.0	-	-106.6	-	0.014	-0.013
B3-B4	34.4	-	108.5	-	-103.3	-	0.015	-0.012
B3-B2-R	24.4	74.2	87.0	1.00	-81.9	0.94	0.020	-0.020
B3-M4-R	31.8	85.5	101.4	0.98	-100.4	0.94	0.014	-0.014
B3-B4-R	24.6	71.4	94.4	0.87	-86.0	0.83	0.013	-0.013



(a) 1st. loading (b) 2st. loading

Figure 5. Stress-strain relation of concrete.

5.2 Comparison with the experimental results

Figure 6 presents comparisons of analytical and experimental behaviors. The dotted lines represent the experimental results and the solid lines show the analytical results. Analytical results predicted the experimental behavior well, which implies the validity of the analytical results except for specimen B3-M4-R. In low axial load, analytical results predicted the experimental behavior fairly well, which verifies the validity of the analytical models. However, in high axial load, the analytical model underestimates the experimental behavior. It is supposed that it caused by handling of buckled reinforcing bar and stress-strain relation of polymer cement mortar.

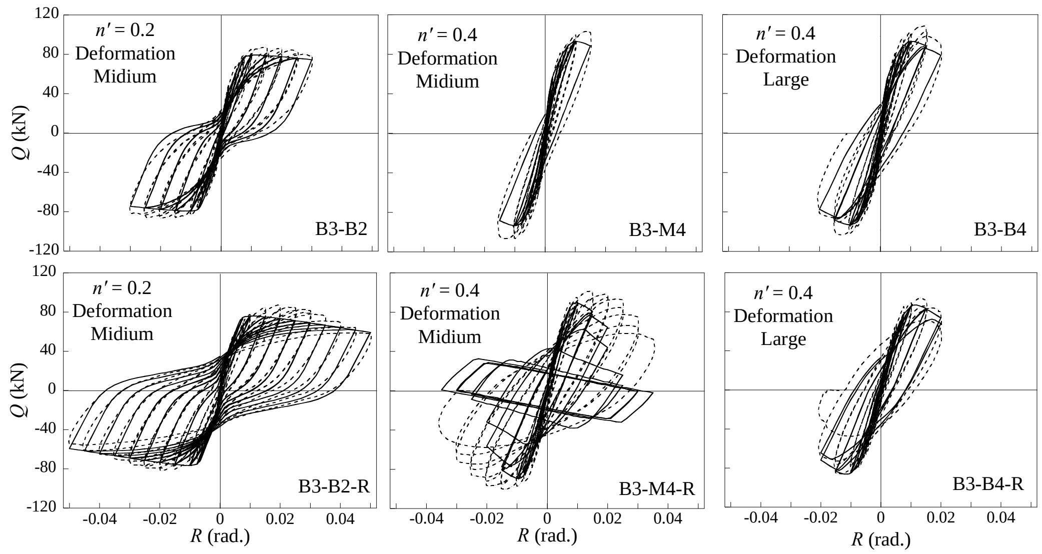


Figure 6. Comparison of analytical and experimental results.

6 CONCLUSIONS

From experimental and analytical results obtained for three open-web type SRC beam-columns with bolt-connected batten steel plates described in this paper, the following conclusions can be drawn:

1) The retrofitted SRC columns showed lower stiffness and the column which experienced the larger displacement and higher axial load showed lower load carrying capacity.
2) The lower stiffness might be attributed mainly to deterioration of concrete rigidity.
3) The lower load carrying capacity might be attributed to the buckling of main reinforcement in first loading.
4) The analytical method proposed in this paper predicted the experimental behavior well in low axial load.

Acknowledgments

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