

Emergency retrofitting of shear-damaged RC columns using fiber-belt prestressing

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ABSTRACT: This study proposes a rehabilitation method (emergency retrofitting) to restore the axial compression capacity and shear resistance mechanism of shear-damaged reinforced concrete (RC) columns. For the emergency retrofitting of shear-damaged RC columns, lashing belts comprising a ratchet buckle and aramid fiber belts are used. Initial prestressing of the damaged RC columns is supplied by using lashing belts; therefore, this technique offers both active and passive confinement as well as shear strengthening. The key concept of this approach is to provide active confinement to firmly confine the damaged RC column, thereby uniting these blocks as a confined concrete unit with its vertical and lateral load-carrying capacities restored. To determine the rehabilitation capacity achieved using fiber-belt prestressing, axial compression and cyclic loading tests were conducted.

1 INTRODUCTION

The vertical and lateral load-carrying capacities of reinforced concrete (RC) columns decrease when an earthquake damages RC buildings. This study proposes a rehabilitation method (emergency retrofitting) to restore the axial compression capacity and shear resistance mechanism of shear-damaged RC columns. To retrofit shear-damaged RC columns, high-strength fiber belts applying initial prestressing are used as emergency retrofitting tools in this study. Thus, this technique provides both active and passive confinement as well as shear strengthening. Regarding the active and passive confinement, the results from axial compression tests (cylinder strength of concrete = 22.2–25.3 MPa) reveal that the lateral confinement technique using high-strength steel-bar (PC-bar) prestressing enhances the compressive strength of the confined concrete up to 1.28 times that of non-retrofitted specimens and that the descending branch of the stress–strain curve gradually decreases owing to the passive confinement of the PC bars (Nakada et al. 2002). Furthermore, a shear-critical RC column that undergoes shear strengthening by PC-bar prestressing exhibits flexural behavior with high ductility (Yamakawa et al. 1999).

The key concept of this approach is to provide active confinement to firmly confine damaged RC columns externally. The active confinement is used to close cracks in damaged RC columns and to recover their vertical and lateral load-carrying capacities and ductility. To investigate the rehabilitation capacity using fiber-belt prestressing, the damage level of the RC columns, the use of epoxy resin repair, and lateral retrofitting with high-strength materials are considered in axial compression and cyclic loading tests, and their results are discussed.

2 TEST PLAN

Tables 1 and 2 list the test parameters of the cyclic loading (ER series) and axial compression (AC series) test specimens, respectively, and Fig. 1 shows the retrofitting details of these specimens. The RC column specimens were square with a cross-sectional area of 250×250 mm² and a height of 900 mm. The height of the RC column test section was 500 mm with a shear span-to-depth ratio (M/VD) of 1.0. The longitudinal reinforcement ratio (p_g) of the specimens was 1.36% (diameter = 10 mm; number of rebars = 12) and the shear reinforcement ratio (p_w) of the specimens within the height of the test section was 0.08%. Closely spaced hoops were arranged at the top and bottom of each specimen within a length of 200 mm to ensure that the damage occurred at the central part of the column. These specimens were designed to have shear failure before flexural failure. To avoid bleeding, these concrete specimens were casted horizontally. Figure 2 shows the test setup and loading procedures. Concrete blocks, each with a cross-sectional area of 250×250 mm² and height of 300 mm, were connected to the top and bottom of the column specimens and the united specimens with the steel stubs were placed on the loading apparatus. The contact surface of the RC columns and the concrete blocks of the stubs were firmly connected with epoxy resin and PC bars with a

Table 1 Specimen details (ER series)

Specimen	ER15S-6LD4e	ER15S-6MD4	ER14S-6LD3e
Damage level (Max. crack width)	IV (2.6 mm)	IV (2.7 mm)	III (1.4 mm)
Initial strain of fiber reinf. (Initial force)	800 μ (2.7 kN)	1800 μ (6.1 kN)	800 μ (2.7 kN)
σ_B	20MPa		17.7MPa
σ_r	0.69MPa	1.54MPa	0.69MPa
With or without of epoxy resin	With epoxy resin	Without epoxy resin	With epoxy resin
Common details	Cross section: 250×250 mm, $M/(VD) = 1.0$, $\eta = 0.2$, Rebar: 12-D10 ($p_g = 1.36\%$), Hoop: $3.7\phi@105$ ($p_w = 0.08\%$), $A_s = 63$ mm.		

Notes: σ_B = compressive strength of concrete cylinder, σ_r = lateral confining pressure, $M/(VD)$ = shear span-to-depth ratio, η = axial force ratio, A_s = interval of lashing belt, ER14S = previous test result (Nakada et al. 2016).

Table 2 Specimen details (AC series)

Specimen	AC15-					AC13-	AC14-		
	N1	N2	D4	D4e	6LD4e	D3e	D4e	6LD3e	6MD4
Damage level (Max. crack width)	-	-	IV (2.2 mm)	IV (3.0 mm)	IV (2.6 mm)	III (1.4 mm)	IV (2.4 mm)	IV (1.3 mm)	IV (2.1 mm)
With or without of epoxy resin	-	-	Without epoxy resin	With epoxy resin	Without epoxy resin				
σ_B	20 MPa					21.2	17.7MPa		
σ_r	-	-	-	-	0.69MPa	-	-	0.69MPa	1.54MPa
N_{max} (kN)	1381	1326	878	1254	1227	1435	1329	1363	1404
N_{max}/N_0	1.00	1.00	0.64	0.91	0.89	0.95	0.99	1.01	1.04
Common details	Cross section: 250×250 mm, $M/(VD) = 1.0$, Rebar: 12-D10 ($p_g = 1.36\%$), Hoop: $3.7\phi@105$ ($p_w = 0.08\%$).								

Notes: N_{max} = max. axial load, N_0 = max. axial load of non-damaged RC column, AC13 and AC14 series = previous test results (Nakada et al. 2015 and Nakada et al. 2016).

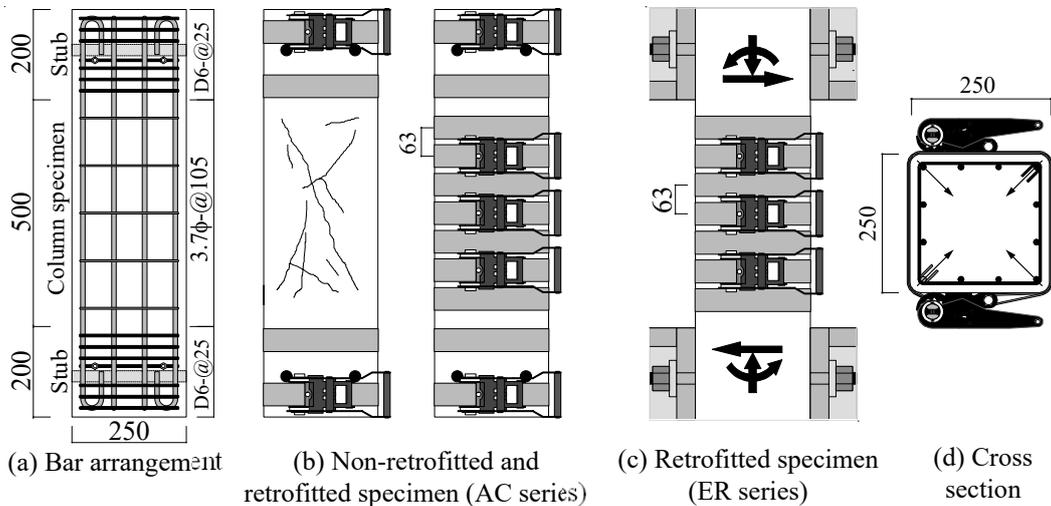


Fig. 1 Column specimen [Unit: mm]

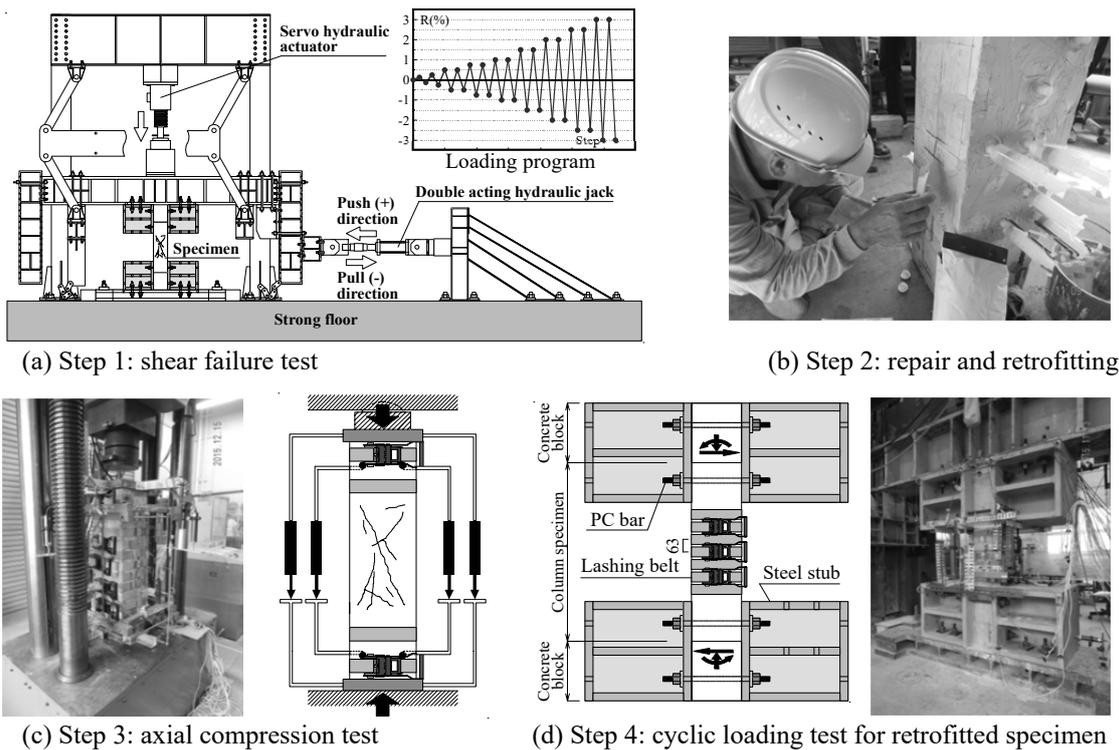


Fig. 2 Test setup and loading procedure.

diameter of 23 mm (Fig. 2). The shear critical RC columns were then damaged by cyclic lateral loading under a constant axial force ratio of 0.2 (shear failure test), based on the assumption that earthquakes cause shear damage to RC columns. The cyclic loading test was carried out with drift angles of $\pm 0.125\%$, $\pm 0.25\%$ in one cycle, and $\pm 0.5\%$, $\pm 0.75\%$, $\pm 1.0\%$, $\pm 1.5\%$, $\pm 2.0\%$, $\pm 2.5\%$, and $\pm 3.0\%$ in two successive cycles. Here, during the loading test, to control the level of shear damage, the column specimens were retrofitted using widely spaced aramid fiber belts at intervals of 150 mm. According to the classifications of the Japan Building Disaster Prevention

Table 3 Damage level criteria (JBDPA 2002)

Damage level	Damage state
I	Crack width is under 0.2 mm.
II	Crack width is about 0.2–1.0 mm.
III	Crack width is about 1.0 – 2.0 mm and cover concrete peels off small.
IV	A lot of cacks beyond 2.0 mm generate and cover concrete peels off, and steel reinforcement appears.
V	Cover concrete ruptures and buckling of the rebars generate. It is impossible to sustain live and dead loads.

Table 4 Mechanical properties of materials

Reinforcement		a (mm ²)	σ_y, σ_u^* (MPa)	E (GPa)
Rebar	D10	71	393	193
Hoop	3.7 ϕ	11	339	195
Hoop	D6	32	479	180
Aramid fiber belt	Thickness = 0.572mm	28.6	2060*	118

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

Association (JBDPA. 2002) (Table 3), the damage status of each RC column in the shear failure tests was classified as being between III and IV (Tables 1 and 2). After the shear failure test, the residual lateral displacement and axial force were recovered to zero for the safe application of the emergency retrofit. In the ER series (Table 1), the shear-damaged RC column was retrofitted by lashing-belt prestressing with a ratchet buckle and aramid fiber belts (ER15S-6MD4), and epoxy resin repair and lashing-belt prestressing were applied in the ER15S-6LD4e and ER14S-6LD3e specimens. After repair and retrofitting, a constant vertical load and cyclic lateral forces were applied again. In the AC series, the column specimens, the four steel stubs, and the two concrete blocks were separated to perform axial compression testing using a universal testing machine.

To avoid any stress concentration on the aramid fiber belts, the four corners of the RC columns were chamfered with a radius of 20 mm. After applying grease, the RC columns were retrofitted with the lashing belts. Prestressing was easy to apply using the ratchet buckle. To control and measure the tension strain, strain gauges were attached onto the belt surface, which was locally impregnated with the epoxy resin. Table 4 lists the mechanical properties of the steel and fiber reinforcements.

The ER and AC series test parameters were as follows: 1) damage level (III–IV), 2) initial tension strain of the lashing belts of either 800 μ or 1800 μ , which it is designated as L and M in the specimen name, and 3) the conditions in which the epoxy resin repair was and was not applied. The lateral confining pressure (σ_r) is expressed as follows:

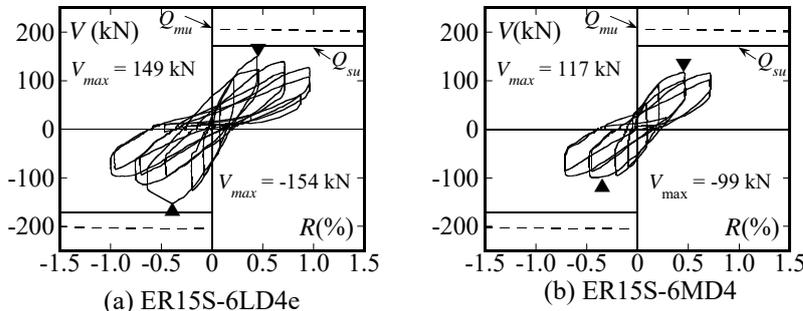
$$\sigma_r = 2 \frac{a}{b \cdot s} \frac{A}{A} E \cdot \varepsilon_{pt} \quad (1)$$

where a is the cross section of the aramid fiber belt (57.2 mm²), b is the column width, s is the lashing belt interval, A is the Young's modulus of elasticity of the aramid fiber belt, and ε_{pt} is the initial tension strain.

3 TEST RESULTS

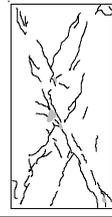
3.1 Shear failure test

Figure 3 shows the experimental shear force (V) vs. drift angle (R) relation of typical specimens, and Table 5 shows the observed cracking patterns, residual crack widths, and damage levels



Notes: Q_{mu} and Q_{su} = Flexural and shear strength (AIJ 1990), \blacktriangledown = peak point.
Fig. 3 Shear force (V)–drift angle (R) relationship (shear failure test).

Table 5 Cracking patterns after shear failure testing (ER15S and AC 15 series)

	6LD4e	6MD4		D4	D4e	6LD4e
ER15S series			AC15 series			
	IV (2.6 mm)	IV (2.7 mm)		IV (2.2 mm)	IV (3.0 mm)	IV (2.6 mm)



Notes: IV = damage level, () = max crack width (depth side).

following the shear failure tests. Each specimen failed in shear, as shown in Fig. 3, and cyclic loading was continued until reaching the target damage level. There was no buckling of the longitudinal reinforcement in any specimen.

3.2 Axial compression test

3.2.1 Axial load vs. axial strain

Figure 4 shows the test results for the damaged RC columns, epoxy resin-repaired RC columns, and retrofitted shear-damaged RC columns. The axial loads of these specimens are divided by the average value (N_0) of the maximum axial load of non-damaged RC columns N1 and N2. Figure 4 also shows the previous test results of AC13-D3e ($W_{cr} = 1.4$ mm), AC14-6LD3e ($W_{cr} = 1.3$ mm), AC14-D4e ($W_{cr} = 2.4$ mm), and AC14-6MD4 ($W_{cr} = 2.1$ mm) (Table 2). In Fig. 4(a), the recovered maximum axial load of specimen D4e (damage level: IV, epoxy resin repair) was greater than that of the damaged specimen D4 with damage level IV. Conversely, the maximum axial loads are approximately the same in specimens D4e and 6LD4e (damage level: IV, low prestressing and epoxy resin repair), D3e (damage level: III, epoxy resin repair) and 6LD3e (damage level: III, low prestressing and epoxy resin repair). It can be seen that the active confinement from the lashing belts with low prestressing in specimens 6LD4e and 6LD3e may yield low crack closure; therefore, the restored maximum axial load of these specimens was achieved by injecting epoxy resin into the shear cracks. In Fig. 4(b), the maximum axial load of specimen 6MD4 (damage level: IV, high prestressing) was the same as that of specimen D4e (damage level: IV). It is also understood that the ability to close cracks by lashing-belt prestressing at high lateral confining pressure is equivalent to or higher than the obtained by epoxy resin repair. In addition, the compressive ductility of the axial load-axial

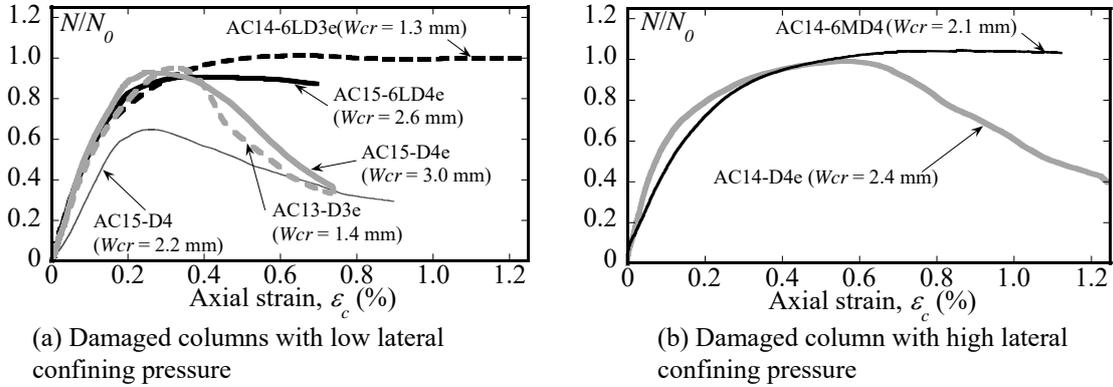
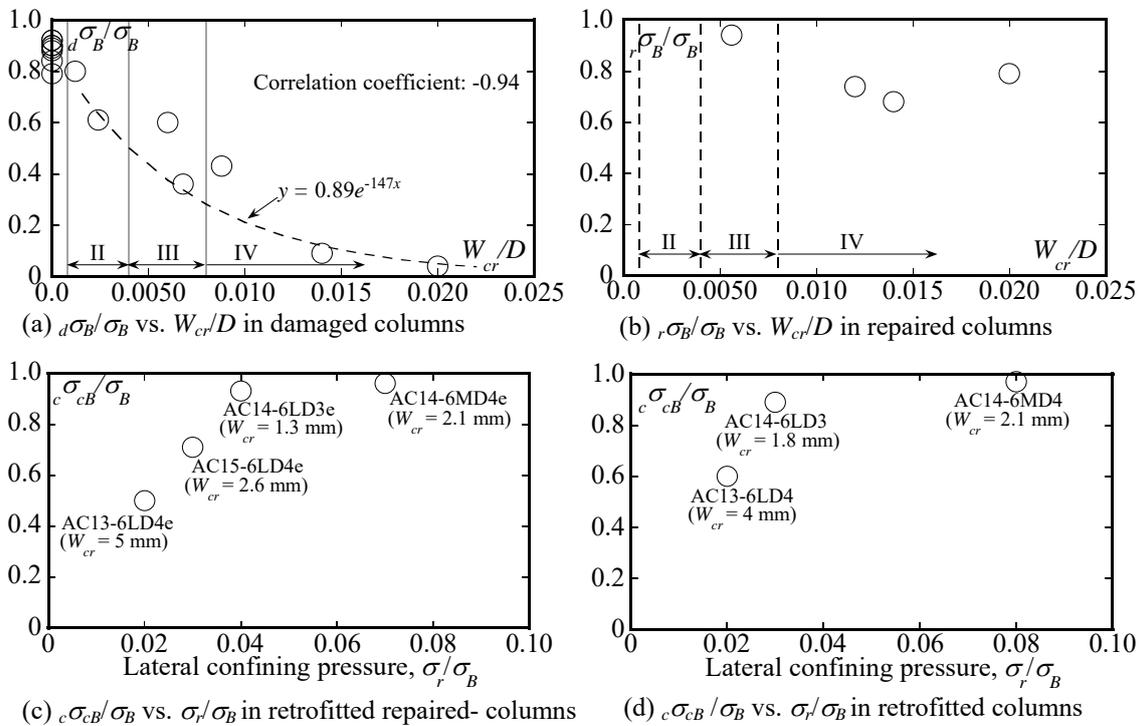


Fig.4 Axial load vs. axial strain relationship (W_{cr} = residual crack width after shear failure test).



Notes: $d\sigma_B$, $r\sigma_B$, and $c\sigma_{cB}$ represent compressive strength of damaged columns, repaired columns, and retrofitted columns, respectively.

Fig. 5 Compressive strengths of damaged RC columns.

strain relation was greatly improved due to the passive confinement provided by the lashing belts.

3.2.2 Compressive strength of concrete

Figure 5 shows the compressive strengths of the damaged RC columns ($d\sigma_B$), repaired RC columns ($r\sigma_B$) and retrofitted RC columns ($c\sigma_{cB}$) including those measured by the authors in previous testing research (Nakada et al. 2015 and Nakada et al. 2016). In Fig. 5, the axial load of the longitudinal reinforcements is subtracted from that of the RC columns and the vertical axis of Fig. 5 is divided by the compressive strength of the concrete cylinder (σ_B). The

horizontal axis of Figs. 5(a) and 5(b) is the residual crack width (W_{cr}) following the shear failure test, divided by the depth of column (D). In Fig. 5(a), the residual compressive strength of the shear-damaged RC columns decreases with increasing residual crack width. The specimens with severe damaged concrete and large crack widths show diminished load-carrying capacity; hence, it is understood that the longitudinal reinforcements sustain the greater part of the residual axial load. In Fig. 5(b), compressive strengths $r\sigma_B/\sigma_B$ ranging from 0.68–0.94 were obtained by the repair with epoxy resin and that the three specimens exhibited mostly the same compressive strength at damage level IV. Therefore, it can be seen that epoxy resin was successful in being injected into the wide cracks. In Figs. 5(c) and 5(d), the compressive strengths of confined concrete $c\sigma_{cB}/\sigma_B$ range from 0.5–0.97 was confirmed in the retrofitted and retrofitted-repaired RC columns, which also increased with increasing lateral confining pressure. It is important note in Figs. 5(c) and 5(d) that active confinement by lashing-belt prestressing provide firmly and effective confinement to damaged RC columns to quickly restore the vertical load-carrying capacity of damaged RC columns after earthquake events.

3.3 Test results of cyclic loading test

Figure 6 shows the experimental shear force (V) vs. drift angle (R) relation, which also includes previous test results for specimen ER14S-6LD3e (Nakada et al. 2016). In the figure, the dashed and solid lines indicate flexural strength based on the compressive strength of the concrete cylinder (σ_B), which can be calculated by a simplified equation provided by the Architectural Institute of Japan (AIJ 1990), in which the lateral load V is divided by $bD\sigma_B$. In Fig. 6, the flexural behavior involved tension yielding of the longitudinal reinforcements was confirmed in all specimens. However, the maximum lateral force did not reach the calculated flexural strength in specimens ER15S-6LD4e and ER15S-6MD4. It is understood that the residual compressive strength of damaged concrete did not recover to the level of the compressive strength of the concrete cylinder despite the applied repair and retrofitting. In Fig. 6(a), approximately similar hysteretic behaviors were observed between specimens ER15S-6LD4e and ER15S-6MD4 with almost the same residual crack width. For the case in which low lateral confining pressure was applied, the results for specimen ER15S-6LD4e indicate that both epoxy resin repair and lashing-belt prestressing generated a seismic strengthening effect equivalent to that of lashing-belt prestressing at a high lateral confining pressure. In Fig. 6(b), which shows the retrofitted-repaired specimens with different damage levels (III and IV) and low lateral confining pressure, it is understood that the maximum lateral force due to the large residual crack width of specimen ER15S-6LD4e having a residual crack width of 2.6 mm is less than that of specimen ER15S-6LD3e having a residual crack width of 1.4 mm.

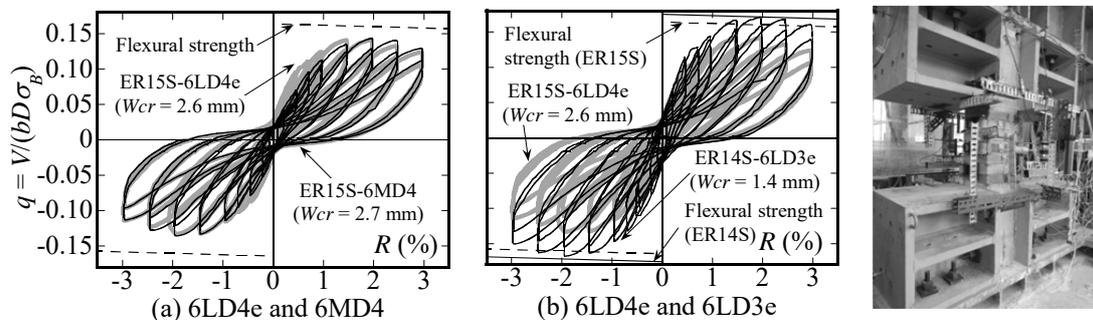


Fig. 6 Shear force (V) vs. drift angle (R) relation following emergency retrofit.

4 CONCLUSIONS

- (1) In axial compression tests of the damaged specimens repaired with epoxy resin as well as retrofitted by lashing-belt prestressing at low lateral confining pressure, the epoxy resin repair restored the maximum axial load of the damaged specimens and the descending branch gradually decreased due to the passive confinement of the lashing belts.
- (2) In axial compression tests of damaged specimens to which lashing-belt prestressing had been applied at high lateral confining pressure only, the axial compression capacity was almost the same as that of the damaged specimen repaired with epoxy resin. In addition, the descending branch after maximum axial load gradually decreased due to the passive confinement of the lashing belts.
- (3) For the same residual crack width, the hysteretic behavior of the specimen retrofitted by lashing belts with low lateral confining pressure as well as repaired with epoxy resin was approximately the same as that of the specimen retrofitted using lashing-belt prestressing at high lateral confining pressure only.
- (4) In a comparison of specimens with different damage levels, when the same lateral confining pressure and epoxy resin repair is applied, the less lateral force capacity and lateral stiffness was confirmed in the damaged specimen with a large crack width.

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