- Technical Paper -

EXPERIMENTAL INVESTIGATION ON SHEAR-DAMAGED RC COLUMNS RETROFITTED BY PRESTRESSED FIBER BELTS

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ABSTRACT

The purpose of this study is to evaluate the effect of active lateral confinement pressure and epoxy resin on the strength and stiffness recovery of shear-damaged RC columns retrofitted by fiber belts. Fiber belts and couplers are the key confining elements in this emergency retrofit technique. Active lateral confinement pressure clamps the damaged RC columns. As a result, the damaged RC columns behave uniformly. It was observed that the strength and stiffness recovery of damaged RC columns is proportional to the applied level of active lateral confinement pressure and use of epoxy resin.
Keywords: Emergency retrofit, lateral confinement, fiber belt, epoxy resin, shear-damage

1. INTRODUCTION

In the emergency retrofit of a shear-damaged RC column, a rapid recovery of its load carrying capacity is essential. In this investigation, fiber belts are used to laterally confine the damaged RC columns for a quick recovery of their load carrying capacity. Because they apply active lateral confinement pressure on damaged RC columns and clamp them immediately. The lateral confinement pressure performs an active effect if the fiber belts are prestressed and a passive effect otherwise. Fiber belts induce active lateral confinement pressure on the column's surfaces perpendicular to its axial direction. Therefore, an active confinement effect is expected while the belts are tightened. On the other hand, lateral confinement pressure caused by transverse hoops has a passive effect on the RC columns.

Several investigations conducted by Yamakawa and Nakada *et al.* [1 to 4] demonstrate that PC bars and fiber belts enhance seismic performance of RC columns due to their active lateral confinement effect. In another study by Nakada *et al*. [5], it was shown that the active lateral confinement pressure of fiber belts closes the columns' cracks. As a result, the damaged RC columns partially regain their axial capacity (depend on their damage level). In the same study, it was observed that the shear strength of damaged RC columns improves due to the compressive strength recovery of concrete. And the active lateral confinement pressure unifies separate parts of damaged RC columns. Another study [6] indicates that the retrofitted RC columns perform flexural behavior due to the active lateral confinement effect of the fiber belts.

In an emergency retrofit, the expected primary effect of applying active lateral confinement pressure is to restore the load carrying capacity of shear-damaged RC columns immediately. Because lateral confinement pressure leads the concrete to demonstrate confined behavior (where the descending zone in the stress-strain curve is flatter). Therefore, an immediate formation of sturdy axial, flexure, and shear resistance mechanisms are expected in the shear-damaged RC columns when they are retrofitted by fiber belts.

In this investigation, the applied level of active lateral confinement pressure on the shear-damaged RC columns and the effect of using epoxy resin are the key research parameters. In addition, unlike the requirement of epoxy resin standards, which demands an adequate hardening period (at least 24 hours after injection of epoxy resin), the lateral confinement pressure was applied immediately to evaluate the epoxy's emergency effect on the strength and stiffness recovery of shear damaged RC columns.

It is indicated in the previous studies that the active lateral confinement pressure restores the shear strength and enhances the ductility of shear-damaged RC columns, but further understanding of their relation is essential. And the effect of epoxy resin on the strength and stiffness recovery of shear-damaged RC columns need to be clearly recognized. Therefore, in this study, a cyclic loading test was conducted to evaluate the effect of active lateral confinement pressure caused by fiber belts. And the effectiveness of epoxy resin on the strength and stiffness recovery of shear-damaged RC columns was discussed. A series of test specimens were constructed according to the requirements of this investigation. Then the experiment was carried out to evaluate the effectiveness of research parameters. The research parameters related to this study is explained in detail in the next section.

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2. TEST PLAN

The details of test specimens are shown in Table 1. To induce a certain damage level, the specimens were subjected to initial test (hereafter, referred as shear failure test) prior applying emergency retrofit. Then the second test (hereafter, referred as emergency loading test) was carried out on the retrofitted specimens. From Table 1, the specimens were constructed considering three research variables. The first and second variables were the level of active lateral confinement pressure and the bond performance of longitudinal rebars, respectively. The third variable was use of epoxy resin in an emergency manner. The active lateral confinement pressure (σ_r) was calculated by equation (1).

$$\sigma_r = 2\,{}_A a/\left(b \cdot {}_A s\right) \cdot {}_A E \cdot \varepsilon_{pt} \qquad (1)$$

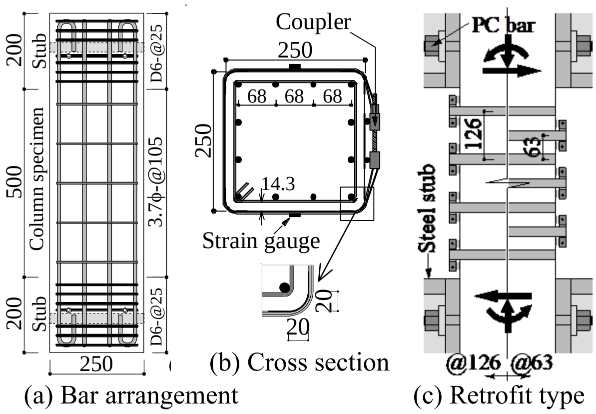
Here, ${}_A a$: cross-sectional area of fiber belt, b: width of RC column, ${}_A s$, ${}_A E$ and ε_{pt}: are belt's spacing, Young's modulus and applied initial tension strain, respectively. Fiber belts were used as external hoops' rings. Each ring was formed of two pairing layers of a belt. From equation 1, when the applied tensile strain is 1800μ, the value $\sigma_r = 2 \times 2 \times 28.6mm^2/(250mm \times 126mm) \times 118000\,N/mm^2 \times 1800 \times 10^{-6} = 0.77\,N/mm^2$.

The structural detail of test specimens is shown in Fig. 1. From this Fig., the specimens had a square cross sectional dimensions $b \times D$ = 250×250 mm, and they were constructed at a scale of 1/2.4. The total height of bond specimens was 1500 mm and that of unbond specimens was 900 mm. As shown in Fig. 1 (a), the test section of bond and unbond specimens were set as 500 mm. Therefore, the overall shear span-to-depth ratio of bond and unbond specimens was $M/(VD)$ = 1 regardless of their total height. The test specimens were longitudinally reinforced by 12 D10 rebars, and their reinforcement ratio p_g was 1.36%. Hoops ϕ3.7 were used as transverse reinforcements along the height of specimens within their test section. They were spaced at 105 mm distances and the reinforcement ratio was p_w = 0.08%. The top and bottom of test specimens (beyond their test section) were transversely reinforced by D6 hoops to concentrate the cracks within their test section.

Table 1 Details of test specimens

Specimen (ER21S-)	12MD2se	6LD4e	6MD3e	12MD4Ue	6MD4Ue
Damage level	II	IV	III	IV	IV
Max. crack width (mm)	0.65	3.5	1.5	3.0	3.5
Initial strain of belt. (μ)	1800	600	1800	1800	1800
Initial force (kN)	6.1	2.0	6.1	6.1	6.1
Interval of fiber belts (mm)	126	63	63	126	63
σ_r (MPa)	0.77	0.51	1.54	0.77	1.54
Bar's performance	Bond			Unbond	
Common details	Column cross section: 250×250mm, $M/(VD)$ = 1.0, $\eta = N/(bD\sigma_B)$ = 0.2, Bar: 12-D10, (p_g = 1.36%), Hoop: 3.7ϕ-@105 (p_w = 0.08%), σ_B = 18.7 MPa				

Notes: σ_B = compressive strength of concrete, σ_r = lateral confining pressure, $M/(VD)$ = shear span-to-depth ratio, η = axial force ratio, N = applied axial force, the numbers 6 and 12 = number of fiber belt's rings, L and M = pretension strain level, D2, 3 and 4 = damage level, U= unbond force between rebar and concrete, e = use of epoxy resin.



Note: the unbond specimen's height is shown in (a)

Fig. 1 Column specimens [unit: mm]

In this investigation, five specimens were tested to evaluate the effectiveness of applying active lateral confinement pressure and use of epoxy resin on the strength and stiffness recovery of shear-damaged RC columns. As shown in Table 1, the specimen's series was named as ER21S-(12MD2se, 6LD4e, 6MD3e, 12MD4Ue and 6MD4Ue). Hereafter, ER21S- is omitted from the name of specimens.

Longitudinal rebars were detached from concrete to prevent truss action in unbond specimens 12MD4Ue and 6MD4Ue. Thus, the surface of their longitudinal rebars were covered with a vinyl tube to eliminate their adhesion with concrete. As shown in Fig. 1 (b), corners of specimens had chamfered with a 20 mm radius, and a teflon sheet (0.8 mm thickness) was installed at each corner to prevent belt's friction. Unbond specimens were tested to evaluate shear (arch) strength recovery of shear-damaged RC columns retrofitted by fiber belts.

The total width of fiber belt was 50 mm and was crouched into two equal layers (each layer's width = 25 mm). Both ends of the belts were wrapped up to a 100 mm and bonded with epoxy resin to form belts' rings. The couplers were used to connect both ends of fiber belts. A release film was placed beneath fiber belts (within couplers where they are bent) to reduce friction risk. As shown in Fig. 1 (b), two strain gauges were attached to each belt. And they were placed on the surfaces of specimens parallel to lateral load direction. Fiber belts were simultaneously tightened to reduce variation of initial strain due to closer of the cracks.

The mechanical properties of material are shown in Table 2. Fig. 2 shows loading apparatus used in this investigation. The shear failure test was conducted to induce shear cracks under a constant axial force ratio η = 0.2. Similar as shown in Fig.1 (c), only three seats of fiber belts were loosely fastened around specimens during shear failure test to control their damage level. The residual displacement was returned to zero, and the axial force was released at the end of shear failure test. After applying emergency retrofit, the emergency loading test was carried out under a constant axial force ratio (η = 0.2). From Fig. 2, the emergency loading test was carried once at drift angles ±0.125% and ±0.25%. And it was carried twice at drift angles ±0.5, ±0.75, ±1.0,±1.5, ±2.0, ±2.5 and ±3.0 %, respectively.

Table 2 Mechanical properties of material

Reinforcement		a (mm^2)	σ_y , σ_u* (MPa)	E (GPa)
Bar for bond specimens	D10	71	393	193
Bar for unbond specimens	D10	71	912	177
Hoop	3.7ϕ	11	215	201
Hoop	D6	32	479	180
Aramid fiber belt	t = 0.572mm	28.6	2060*	118

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

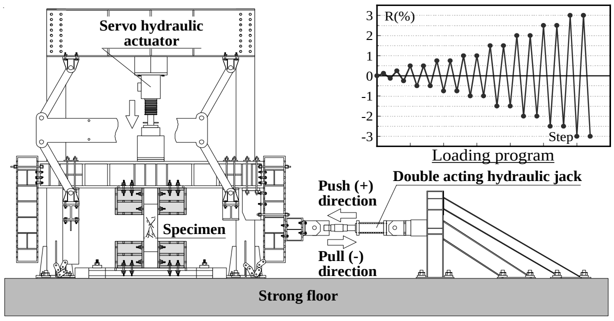


Fig. 2 Test setup and loading procedure

3. EXPERIMENTAL RESULTS

3.1 Shear failure test of specimens

The relation between lateral load V and drift angle R of the specimens after shear failure test is illustrated in Fig. 3. Table 3 indicates crack patterns of specimens drawn at the end of shear failure test. During shear failure test, three seats of fiber belts were loosely fastened around the specimens to control their damage within a designated level. The specimens' maximum residual crack width (RCW) and their level of damages were determined in according to the criteria of ref.[7]. The damage levels are II, III and IV if the RCW is 0.2 to 1.0, 1.0 to 2.0 and beyond 2.0 mm, respectively. In Fig. 3, the flexural strength Q_{mu} [8] was calculated based on concrete cylinder strength (σ_B). And shear strength Q_{su} was calculated by Arakawa's equation [9].

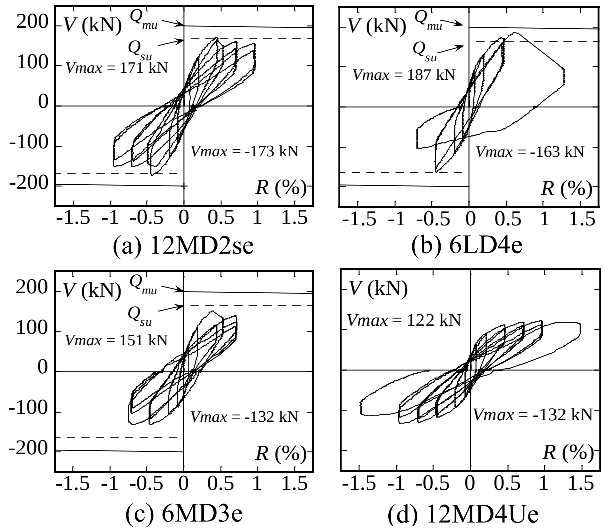
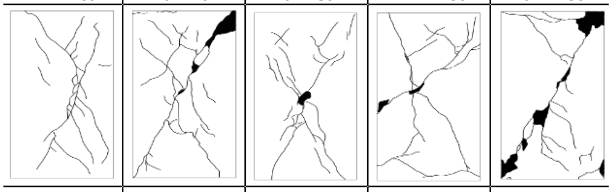


Fig. 3 V-R relations (shear failure test)

Table 3 Crack patterns after shear failure test

12MD2se	6LD4e	6MD3e	12MD4Ue	6MD4Ue
				
II (0.65 mm)	IV (3.5 mm)	III (1.5 mm)	IV (3.0 mm)	IV (3.5 mm)

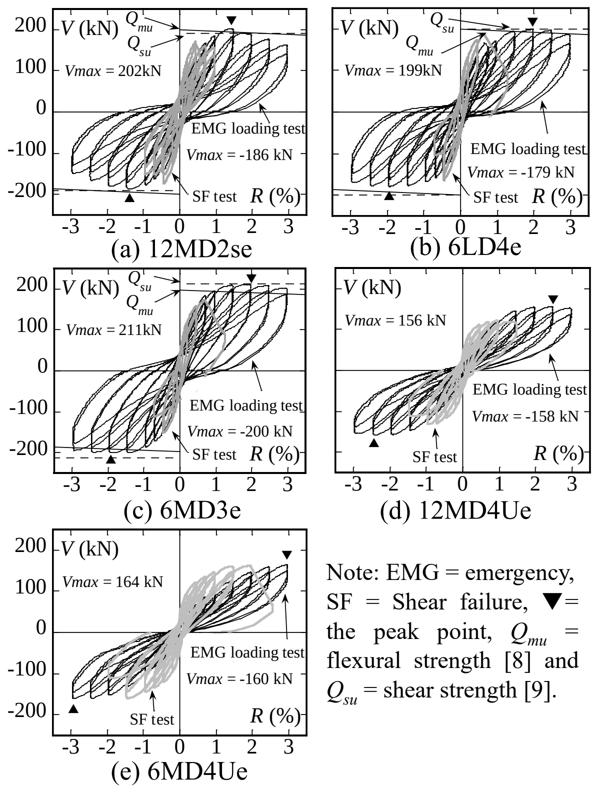
Note: II, III and IV = damage level[7], () = residual crack width after shear failure test (depth side).

As illustrated in Table 3, all the specimens had diagonally cracked under shear failure test. And as a result, the specimens' damage levels were determined based on the RCW measurement. In this investigation, none of the longitudinal rebars had buckled under shear failure test. The values of RCW were measured as 0.65, 3.5 and 1.5 mm in bond specimens 12MD2se, 6LD4e and 6MD3e, respectively. In unbond specimens 12MD4Ue and 6MD4Ue, they were measured as 3.0 and 3.5 mm, respectively.

3.2 Emergency loading test of specimens

In Fig. 4, the relation between lateral load V and drift angle R of specimens at the end of emergency loading test is shown. The gray color in this Fig. indicates the results of shear damage test. In Fig. 4, the lines Q_{mu} indicate the calculated flexural strength [8] based on the result of concrete cylinder strength σ_B. And the lines Q_{su} indicate the calculated shear strength by Arakawa's modified equation [9].

As shown in Fig. 4 (a), specimen 12MD2se reached its maximum experimental lateral strength V_{max}



Note: EMG = emergency, SF = Shear failure, ▼= the peak point, Q_{mu} = flexural strength [8] and Q_{su} = shear strength [9].

Fig. 4 V-R relations (emergency loading test)

= 202 kN at drift angle R = 1.5%. In this specimen, the RCW declined from 0.65 to 0.24 mm as a result of applying active lateral confinement pressure. From Fig. 4 (b), 6LD4e performed its maximum lateral strength V_{max} = 199 kN at drift angle R = 2.0%. Cracks appeared in 6LD4e in the beginning of loading test, and spalling of concrete cover was observed at R =2.0%. In 6LD4e, the RCW declined from 3.5 to 3.0 mm. From Fig. 4 (c), 6MD3e performed its maximum lateral strength V_{max} = 211 kN at drift angle R = 2.0%. Some small cracks appeared in this specimen at the initial stage of loading test. And RCW (1.5 mm) declined to 0.2 mm as a result of active lateral confinement pressure.

From Fig. 4 (d), unbond specimen 12MD4Ue performed its maximum lateral strength V_{max} = 158 kN at drift angle R = 2.5% in the pull direction. In this specimen, a crack (width = 0.95 mm) existed on its depth side in the push direction prior shear failure test. Therefore, 12MD4Ue showed its V_{max} in pull direction. And the RCW declined from 3.0 to 1.9 mm in this specimen. From Fig. 4 (e), unbond specimen 6MD4Ue reached its maximum lateral strength V_{max} = 164 kN at drift angle R =3.0%. Some small cracks appeared at the top and bottom of this specimen during the loading test. And the RCW declined from 3.5 to 2.0 mm in 6MD4Ue due to applying lateral confinement pressure.

From Fig. 4, the maximum lateral strength in unbond specimens is less than bond specimens. It is due to the removal of bond force between longitudinal rebars and concrete in unbond specimen. Because it prevents formation of truss mechanism. Thus, the shear strength in unbond specimens indicate the arch strength. Unbond specimens 12MD4Ue and 6MD4Ue failed in shear mode when concrete reached its ultimate strength.

In Fig. 5, the stress distribution in a corner rebar of the specimens is shown in the push direction. Table 4 indicates the crack patterns drawn after emergency loading test. Fig. 6 shows belts' strain distribution along the height of RC column specimens. As shown in Fig. 5 (a), a rebar has yielded in 12MD2se at drift angle R = 1.5%. In addition, it is shown in Table 4 that the diagonal cracks have widened in this specimen under emergency test. From Fig 6 (a), the initial strain of belts in 12MD2se has increased at drift angle R =1.5% (when this specimen performed its maximum lateral strength V_{max}). In this specimen, the calculated shear strength Q_{su} was lower than the calculated flexural strength Q_{mu}. Therefore, it can be said that specimen 12MD2se was faild in a shear mode after flexural failure. As shown in Fig. 5 (b), the longitudinal rebar yielded when 6LD4e performed its maximum lateral strength. The maximum lateral strength V_{max} of this specimen was almost the same as the calculated flexural strength Q_{mu}. As shown in Table 4, the diagonal cracks widened in 6LD4e. From Fig. 6 (b), the tensile strain has significantly increased at drift angle R = 2.0% in 6LD4e. Therefore, specimen 6LD4e performed a shear failure mode after flexural failure. From Fig. 4 (c), in specimen 6MD3e, the calculated shear strength Q_{su} was slightly higher compared to that of 6LD4e. The reason of this slight increment in the shear strength of 6MD3e compared to 6LD4e is the

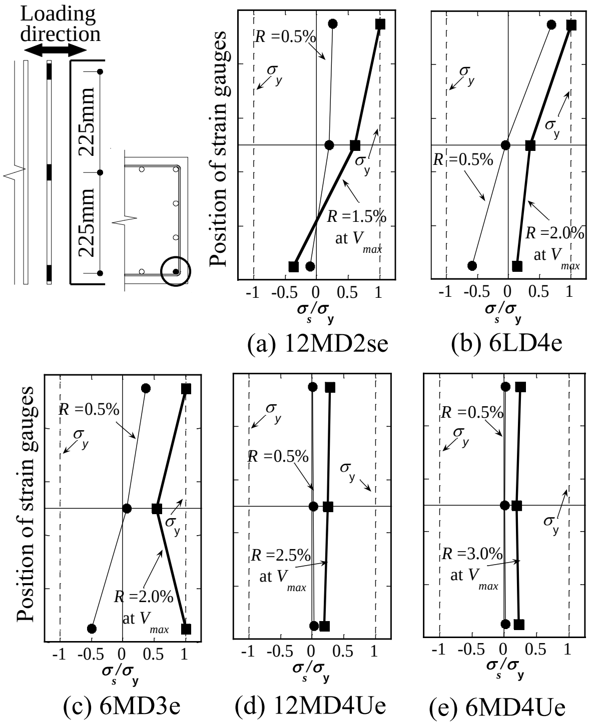
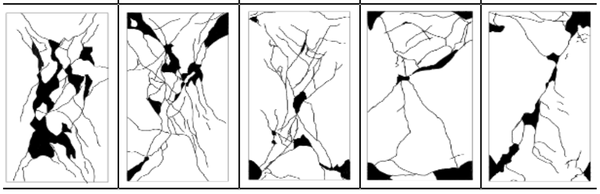


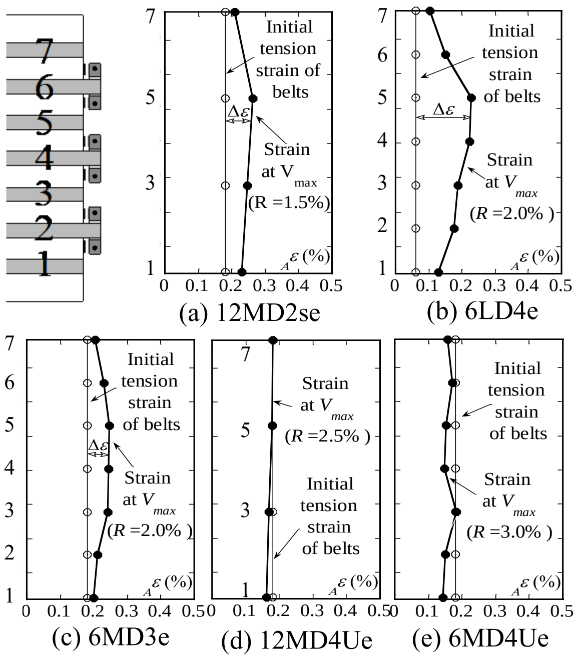
Fig. 5 Stress distribution of rebars

Table 4 Crack pattern after emergency loading test

12MD2se	6LD4e	6MD3e	12MD4Ue	6MD4Ue



Note: The crack pattern was drawn after removal of belts at the end of emergency loading test (depth side)



Note: Δε = variation in initial tensile strain at V_{max}

Fig. 6 Distribution of fiber belt strain applied level of active lateral confinement pressure. Furthermore, the damage level of specimen 6MD3e was III. As shown in Fig. 5 (c), a corner rebar has yielded in specimen 6MD3e. As shown in Table 4, diagonal cracks have appeared in 6MD3e. From Fig. 6 (c), the initial tensile strain of belts in 6MD3e has increased at V_{max}. This specimen performed a flexural behavior due to applying active lateral confinement pressure.

As illustrated in Fig. 5 (d), longitudinal rebars did not yield in unbond specimen 12MD4Ue (due to rebars' high yield strength). Spalling of concrete cover was observed during the emergency loading test of specimen 12MD4Ue. As shown in Fig. 6 (d), the tensile strain of fiber belts at V_{max} remained almost the same as applied initial tensile strain in 12MD4Ue. This specimen performed a shear failure mode when concrete reached its compressive strength. In specimen 6MD4Ue, some tensile cracks appeared at its top and bottom in the initial stages of loading test. The cracking continued until the end of the loading test and spalling of concrete cover was observed during emergency loading test. As shown in Table 4, shear failure has occurred in specimen 6MD4Ue. From Fig. 6 (e), It is evident that the initial tensile strain of fiber belts has not changed significantly in this specimen.

4. SKELETON CURVE

In Fig. 7, the test results of specimen's series ER21S is compared with that of ER16S [10] and ER20S [5] series. The compressive strength of ER16S and ER20S series were σ_B = 17.2 MPa and σ_B = 14.7 MPa, respectively. In Fig. 7 (a), the test results of bond specimens 12MD2se and 12MD3s [5] are compared. The active lateral confinement pressure in 12MD2se was the same as that of 12MD3s (0.77N/mm^2). From Fig. 7 (a), the maximum lateral strength and stiffness of 12MD2se is larger than that of 12MD3s. In 12MD2se, the damage level was II and the RCW was 0.65mm. In addition, the cracks of 12MD2se were filled by epoxy resin. In specimen 12MD3s, the damage level was III (RCW = 1.95 mm) and without use of epoxy resin. Therefore, it is evident that epoxy resin has enhanced the experimental lateral strength V_{max} and stiffness in 12MD2se. The strength and stiffness of 12MD2se may be partially dependent on its damage level (II) as well.

As shown in Fig. 7 (b), the maximum lateral strength of 6LD4e is higher than that of 6LD4 [10]. Both specimens were constructed with bond force of rebars, and their damage levels were the same (IV). Thus, the main reason for strength and stiffness enhancement in 6LD4e can be the effect of using epoxy resin in this specimen.

From Fig. 7 (c), the maximum lateral strength of 6MD3e is higher compared to that of 6MD4 [10]. The applied active lateral confinement pressure on these specimens were the same. Thus, the RCW of both specimens may have closed equally by tightening fiber belts. The reason of higher lateral strength and stiffness in 6MD3e is the effect of epoxy resin that has partially recovered the concrete's compressive strength.

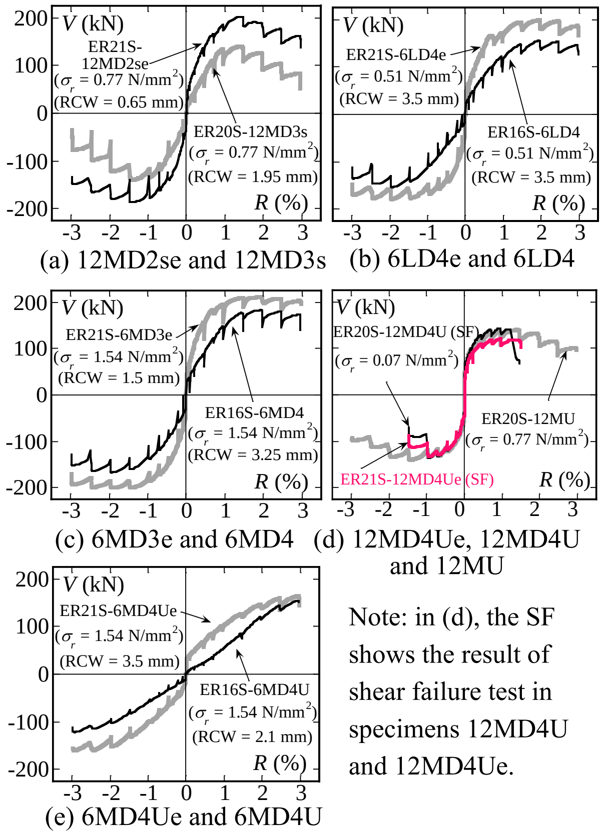


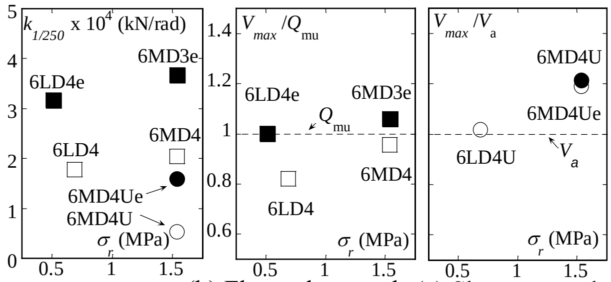
Fig. 7 Skeleton curves of specimens

In Fig. 7 (d), the results of shear failure test of unbond and undamaged specimens 12MD4Ue and 12MD4U [5] are compared with emergency loading test result of unbond and undamaged specimen 12MU [5]. The applied level of active lateral confinement pressure on 12MD4Ue and 12MD4U was σ_r = 0.07 MPa, and it was σ_r = 0.77 MPa on specimen 12MU [5]. As shown in Fig. 7 (d), the effect of active lateral confinement pressure is not so significant on the lateral strength and stiffness of unbond and undamaged specimens.

In Fig 7 (e), the results of 6MD4Ue and 6MD4U [10] are compared. Their active lateral confinement pressure level was the same. From Fig.7 (e), 6MD4Ue performed higher lateral stiffness due to the use of epoxy resin. Thus, it can be understood that epoxy resin improves the lateral stiffness in unbond specimens.

5. COMPARATIVE EVALUATION OF RESULTS

In Fig. 8, a comparative evaluation of the test results of specimens' series ER21S and ER16S-(6LD4, 6MD4, 6LD4U and 6MD4U) [10] is shown. As shown in this Fig., low to medium level of active lateral confinement pressure (σ_r = 0.51 to 1.54 MPa) was applied on the specimen series ER16S and ER21S. Epoxy resin was injected within the cracks of specimen series ER21S, and specimens' series ER16S were tested without use of epoxy resin. The concrete compressive strength σ_B of specimen series ER21S and ER16S were 18.7 MPa and 17.2 MPa, respectively. As illustrated in Fig. 8 (a), the lateral stiffness $k_{1/250}$ [11] of bond specimens has improved by applying active lateral confinement pressure. In addition, the epoxy resin has enhanced their lateral stiffness significantly. From the same Fig., epoxy resin has significantly increased the stiffness of unbond specimens as well. In Fig. 8 (b), the line Q_{mu} [8] indicates the calculated flexural strength based on the compressive strength of concrete σ_B. From Fig. 8 (b), the flexural strength in bond specimens has reached the ultimate flexural strength Q_{mu} as result of applying active lateral confinement pressure and use of epoxy resin. As shown in Fig. 8 (c), the lateral strength in unbond specimens has enhanced by the active lateral confinement pressure but not by using epoxy resin.



(a) Stiffness (b) Flexural strength (c) Shear strength

Note: V_a indicates shear strength of arch mechanism [12], and σ_B was used as compressive strength of diagonal strut σ_a in the calculation of V_a.

Fig. 8 Analytical evaluation of test results

6. CONCLUSIONS

This research was carried out to verify the effect of active lateral confinement pressure and epoxy resin on the strength and stiffness recovery of shear-damaged RC columns retrofitted by fiber belts. Epoxy resin was used after shear failure test. Then an emergency loading test was conducted immediately to evaluate emergency effect of epoxy resin. The results are concluded below:

(1) Applying active lateral confinement pressure and use of epoxy resin had a significant impact on the stiffness recovery of bond and unbond specimens.
(2) The flexural strength of bond specimens 6LD4e and 6MD3e enhanced by both epoxy resin and active lateral confinement pressure.
(3) The lateral strength in unbond specimens was improved by active lateral confinement pressure, but epoxy resin did not show a significant impact on the lateral strength of unbond specimens.
(4) It was observed that an emergency use of epoxy resin can have a significant impact on the strength and stiffness improvement of shear-damaged RC columns retrofitted by fiber belts.

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