SEISMIC RETROFIT OF RETANGULAR RC COLUMNS AT NCREE

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Abstract: One of the major collapse modes of RC structures during the 1999 Taiwan Chi-Chi earthquake is the failure of columns due to lap-splicing at the plastic hinge zone. It has been shown that directly apply the CFRP or steel jacket to large rectangular RC column is ineffective in providing confinement to concrete except at the corners of the cross-section. This paper summarizes experimental results of two effective methods using steel jacketing and FRP wrapping to retrofit the existing RC columns with the above mentioned problems. For steel jacketing methods, the octagonal steel jacketing scheme for seismic retrofitting the rectangular RC bridge columns is presented in this paper. For applying the CFRP, a new retrofit method -"CS retrofit method" is proposed. Experimental results show that both the octagonal steel jacketing and the CS retrofit methods can great improve the lateral strength, displacement ductility, and energy dissipation of the columns lap spliced at the plastic hinge zone.

Key word：Rectangular RC column, Lap-spliced, Octagonal steel jacketing, CS Retrofit

1. INTRODUCTION

Significant amount of retrofit research and actual implementations to enhance the seismic performance of existing bridges have been made in the United States (Gates 1988), Japan (Kawashima 1990) and New Zealand (Priestley and Park 1987). Recent studies indicate that under a severe earthquake some existing bridges in Taiwan can be severely damaged in bridge columns due to a number of factors (Chang et al. 1999). Among many others, (1) inadequate design strength, (2) inadequate confinement at potential plastic hinge region, and (3) inadequate shear strength due to the change of lateral steel spacing, have been identified as the most possible sources for seismic hazard. Therefore, a coordinated research effort on seismic retrofit of reinforced concrete bridge columns has been lunched in the National Center for Research on Earthquake Engineering (NCREE). This coordinated research program aims at reviewing and developing effective measures in seismic retrofit of the existing rectangular and circular RC bridge piers. The joint research effort has applied several retrofit techniques in the tests, including the steel jacketing, reinforced concrete jacketing, and the advanced composite material wrapping using the FRP jackets. The purposes of the program are to gather additional data for seismic bridge engineering applications and accelerate retrofit programs to be implemented for seismically deficient bridges in Taiwan. As part of the aforementioned join research program, this paper focuses on the flexural and shear retrofit techniques for rectangular RC bridge columns using steel and CFRP jackets.

The objectives of this study, in the context of a joint research with other researchers, include: (1) collecting additional data on seismic retrofit of rectangular RC columns using the elliptical steel jacket, and (2) seeking other cost-effective steel or FRP jacketing schemes for rectangular RC columns. In this paper, the experimental results of the rectangular RC columns retrofitted with the octagonal steel jackets and the combined CFRP wrapping and steel plates (CS) are critically compared with other schemes.

2. STEEL JACKETING RETROFIT

2.1 Experimental Program

A total of eleven 0.4 scale specimens were tested. All the test specimens were subjected to constant axial load and cyclic lateral displacements. The test setup is shown in Figure 1 and Photo 1. All test specimens were loaded in the strong bending direction and subjected to the same displacement pattern of increasing magnitude as shown in Figure 2. Displacement control method was used in the test. The vertical stress was kept approximately at 0.15f ´c during the tests.

In order to gain insight into the three most possible seismic failure modes of RC bridge column in Taiwan, three as-built specimens were tested. All the test specimens have the same cross-sectional dimensions. The rectangular cross section of the specimens is 600 by 750 mm, a 2/5 scale of the prototype column using the pre-1987 details. A double U-shaped, alternation arrangement of the transverse reinforcements was adopted in all specimens. This type of transverse reinforcing details is rather common in the construction of bridge columns in Taiwan, therefore, is one of the key items studied in this research. Table 1 shows the details and design parameters of the specimens. The steel jacketing details for the retrofitted specimens were shown in Table 2. To ensure that the jacket does not bear against the footing when in compression, a nominal gap of 30 mm is provided between the toe of the jacket and the footing.

Photo 1. Test setup

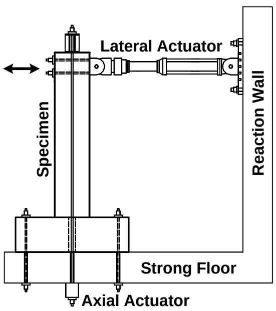


Figure 1. Test setup

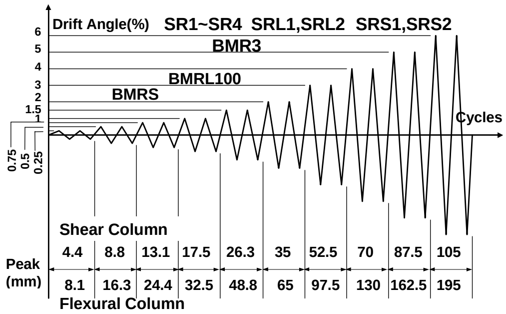


Figure 2. Lateral loading history

Table 1. Design parameters of test specimen

Parameter	BMR3	BMRL100	BMRS
Dimensions (mm)	600x750	600x750	600x750
Column Height (mm)	3250	3250	1750
Concrete Stress (MPa)	21	21	21
Longitudinal Steel	32#5	32#6	32#6
Longitudinal Stress (MPa)	280	420	420
Transverse Steel	#3@130mm #3@240mm	#3@130mm #3@240mm	#3@300mm
Transverse Stress (MPa)	420	280	280

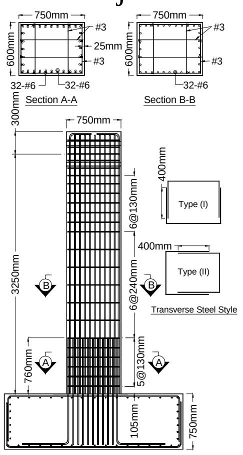
Table 2. Steel jacketing details and experimental results

Specimen	Steel Jacketing Details (A36 Steel)			Ductility		Failure Mode
	Scheme	Thickness	Height	Push	Pull	
BMR3	NA	NA	NA	4	4	Confinement
SR1	Octagonal	3 mm	2800 mm	10.7	11	Low Cycle Fatigue
SR2	Elliptical	3	2800	13.1	9.4	Low Cycle Fatigue

SR3	Octagonal	6	2800	11.8	10.1	Low Cycle Fatigue
SR4	Elliptical	3	2800	11.7	13.9	Low Cycle Fatigue
BMRL100	NA	NA	NA	NA	NA	Lap-Splice
SRL1	Octagonal	6	2800	6.6	6.7	Low Cycle Fatigue
SRL2	Elliptical	3	2800	10.6	7.3	Low Cycle Fatigue
BMRS	NA	NA	NA	1.3	1.9	Shear
SRS1	Octagonal	3	1400	8.2	6.9	Low Cycle Fatigue
SRS2	Rectangular	3	1400	6.6	5.5	Low Cycle Fatigue

2.2 Test Results of Lap-Spliced Deficient Specimens

According to a rather common reinforcing detail found in Taiwan, as-built Specimen BMRL100 shown in Fig. 3 adopted a 76cm (equal to 40 times of the longitudinal bar diameter) lap-splice length for the longitudinal reinforcing bars in the plastic hinge region. For the retrofitted specimens (Fig. 4), SRL1 was retrofitted with a 6mm thick octagonal steel jacket while SR2 was retrofitted with a 3mm thick elliptical steel jacket.



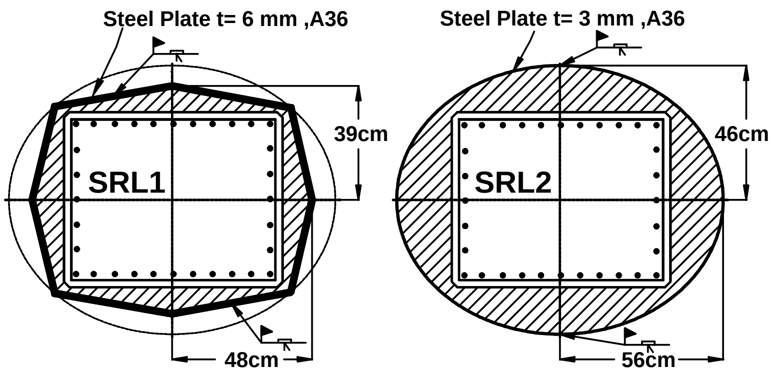
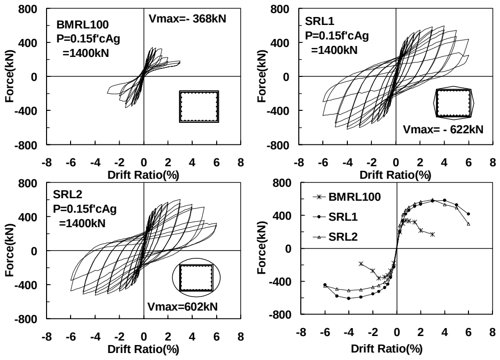


Figure 3. Details of Lap-splice specimen   Figure 4. Details of the steel jackets for Lap-splice specimens

All specimens were subjected to the same cyclically increasing lateral displacement history until significant strength degradation was observed. The cyclic lateral load-deformation relationships for all specimens are shown in Figure 5. The energy dissipation histories are given in Figure 6. For the BMRL100, this lap-splice deficient bridge column can not develop full flexural strength to the nominal design level, and the strength degradation resulted from bond slip occurred prematurely and severely in the small displacement range.

Test results given in Figures 5 and 6 confirm that the seismic performance of rectangular RC bridge columns can be significantly and equally enhanced by properly designed elliptical or octagonal steel jacket following the procedures noted above. Bridge columns retrofitted with the octagonal or the elliptical steel jacket exhibit stable lateral force-displacement hysteretic response, possess excellent displacement ductility and energy dissipation capacities.



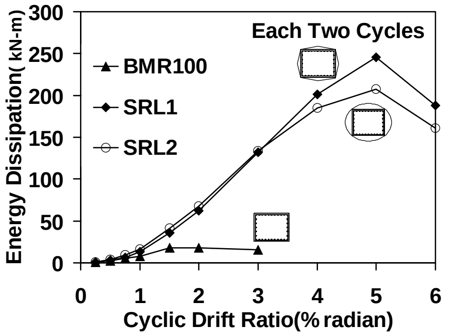
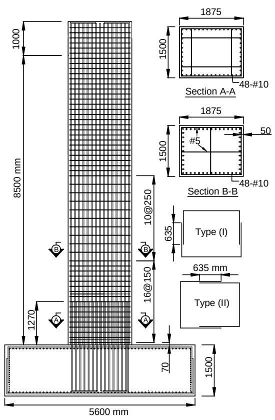
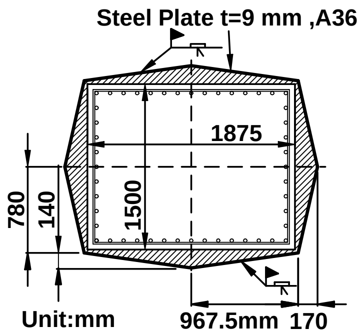


Figure 5. Cyclic lateral load vs. deflection relationships Figure 6. Energy dissipation curves

2.3 Full Scale Testing

One full-scale specimen with lap splice retrofit using the octagonal steel jacket was testing in order to verify the seismic performance of the octagonal steel jacketing. The details and design parameters of the full-scale specimen was shown in Fig. 7. The rectangular cross section of the columns is 1500 by 1875 mm, a full scale of the prototype column using the pre-1987 details. The column height is 8500 mm from the top of footing to the center of horizontal actuator. The footing is 1500-mm thick. A 1270-mm (equal to 40 times of the longitudinal bar diameter) lap splice length for all longitudinal reinforcement bars right above the top of the footing in the potential plastic hinge region was detailed and constructed. Ready mixed concrete providing a target compressive strength of 17.5 MPa at 28 days was adopted. This was to consider the effects of possible insufficient strength of concrete commonly observed in the existing old bridge columns constructed with a design strength of 21 MPa. Octagonal steel jacket (9 mm thick) was applied as shown in Fig. 8. The lap splice failure was completely prevented in LSRL-R. Fig. 9 shows the hysteretic responses.





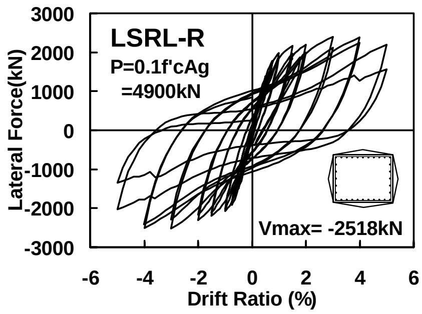


Figure 7 Reinforcing details of a full scale specimen	Figure 8 Retrofit design	Figure 9 Hysteretic response

3. THE “CS” RETROFIT

The reinforce concrete is composed of steel and concrete material. While using lap-spliced design, it’s very important that the interface strength between concrete and the lap splicing reinforcements is sufficient. Because the lap-spiced steels strongly affect the column ductility, the ACI 318-95 (1995) specifies the construction detail in section 21.4.3.2 that no lap-spliced should be used in the joint and probable places of plastic hinge zone. However, it has been a common practice for the existing RC columns in Taiwan to lap-spliced the main steel bars at the plastic hinge zone. Fig.10 and 11 show the failure mode lap-spliced column in two collapsed buildings during the 1999 Chi-Chi earthquake.

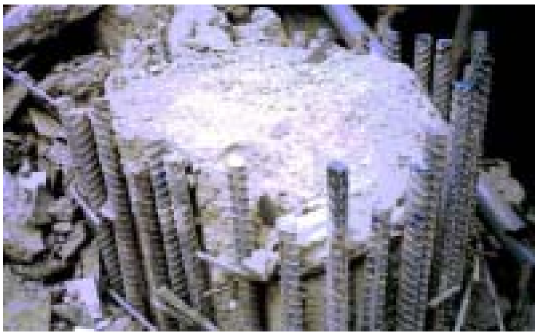


Fig.10 Lap splices failure of rectangular Column　　　Fig.11 Lap splices failure in a collapsed building

In 1977, Orangun et. al (1997) proposed the well known O.J.B model based on 254 development length tests. This model considers concrete strength, clear cover, reinforcement spacing, reinforcement dimension, and confinement effect of lateral reinforcement. Besides, Orangun found that the O.J.B model can be applied to estimate the lap splices strength based on 286 test specimens. Another model was proposed by Paulay (1982) in 1982. The best way to improve columns ductility is to increase confinement stress by lateral reinforcements. Both the peak stress and ultimate strain of concrete will increase. This paper provides a new retrofit method, named "CS method" to improve the behavior of rectangular RC columns lap spliced at the plastic hinge zone.

The CS method combines the advantages of steel plates and CFRP jackets to provide more efficient confinement effect. The procedure of CS method is described as follows. First, clean the column surface; then, apply suitable steel plates on the surface; finally, wrap the CFRP jacket around the column. Fig.12 shows the drawing of the proposed CS method.

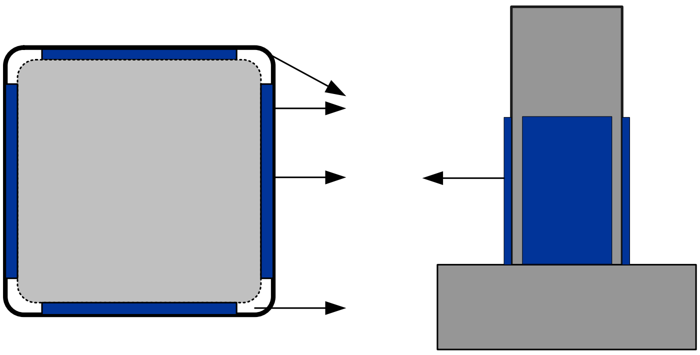


Fig12. Design drawing of CS method

3.1 Experimental Program

Table 2 shows the details and design parameters of the test specimens. These specimens represent the as-built, CFRP wrapped, and combined steel plate and CFRP.

For all the specimens, the lap spliced length is 40 times of the longitudinal bar diameter in the plastic hinge zone. This type of longitudinal reinforcing details was common in the construction of buildings in Taiwan. In addition to the lap splice steel, the double U-shaped, transverse reinforcement was used as the ties in each specimen. For retrofitted specimens, the design parameters are summarized in Table 3.

Table 2　The retrofitted Design parameter of Steel Jakets method

	Name	Failure Type	Lap Height (cm)	Section (cm^2)	Height (cm)	Concrete Strength (kg/cm^2)	Main Bar Strength (kg/cm^2)	Main Bar Ratio (%)	Axial Load (*f'cAg*)
1	**B1L17–BM**	Lap Spliced	76	60×75	325	170	4339	2.02	0.19~0.25
2	**B2L21–BM**	Lap Spliced	89	60×75	325	208	5188	2.07	0.27~0.42
3	**B3L17–C8**	Lap Spliced	76	60×75	325	170	4339	2.02	0.19~0.25
4	**B4L21–B30S6**	Lap Spliced	89	60×75	325	208	5188	2.07	0.27~0.44
5	**B5L17–C8S10**	Lap Spliced	76	60×75	325	170	4339	2.02	0.19~0.25
6	**B6L21–C12S10**	Lap Spliced	89	60×75	325	208	5188	2.07	0.28~0.43
7	**B7L21–C12S5**	Lap Spliced	89	60×75	325	208	5188	2.07	0.27~0.41
8	**W1L19–B30S6**	Lap Spliced	89	75×60	325	193	5188	2.07	0.30~0.43
9	**W2L19–C15S10**	Lap Spliced	89	75×60	325	193	5188	2.07	0.29~0.43
10	**S1L19–C5S10**	Lap Spliced	76	30×50	110	186	5273	1.90	0.41~0.47
11	**S2L19–C5S10**	Lap Spliced	76	30×50	200	186	5273	1.90	0.41~0.46
12	**M1L19–C10S10**	Lap Spliced	127	50×80	200	186	5467	1.98	0.15~0.21

Table 3-1 Design parameters of Steel Jacketing Method

Name	Section (cm^2)	Steel thickness (Height)：(mm)	Bolt diameter (mm)	Bolt　distane (cm)
B4L21–B30S6	60×75	Under 100 cm：6	22	vertical：30
W1L19–B30S6	75×60	Under 100 cm：6	22	vertical /transversely: 30/25

Table 3-2 Design parameters of the CS Method

Name	Section (cm^2)	CFRP thickness (Height)：(layer)	Steel size (cm^2)	Steel thickness (mm)
B3L17–C8	60×75	Under 100 cm：8		
B5L17–C8S10	60×75	Under 100 cm：8	50×100	10
B6L21–C12S10	60×75	Under 50 cm：12	50×100	10
B7L21–C12S5	60×75	Under 50 cm：12	50×100	5
W2L19–C15S10	75×60	Under 50 cm：15	50×100	10
S1L19–C5S10	30×50	Under 80 cm：5	14× 86	10
S2L19–C5S10	30×50	Under 100 cm：5	14× 86	10
M1L19–C10S10	50×80	Under 150 cm：10	34×138	10

3.2　Instrumentation and Testing Procedures

Fig. 13 shows the test setup in this study. Fig. 14 shows the displacement control cycles. The test began with the application of the axial load at the target value, and ended when the lateral force dropped more than 80% of the maximum experienced capacity.

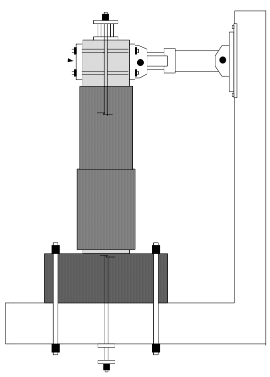


Fig.13 Test setup

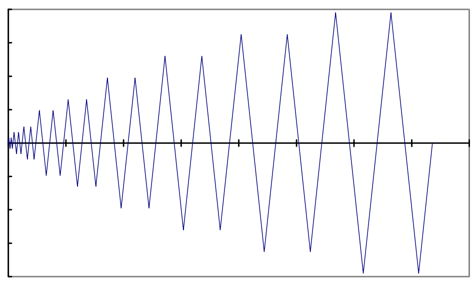


Fig.14 Lateral displacement control history

3.3 Test Results and Discussion

(1) Fig. 15 shows the different failure types at the bottom of the column before and after retrofit. For the as-built specimens B1L17-BM、B2L21-BM, the specimens failed when the cover concrete was spalled and large concrete block were crushed at the corner. The longitudinal bars experienced no buckling. For the retrofitted specimens, it can be observed that, after removing the CFRP, the internal lap spliced reinforcements bucked under combined axial and lateral force.

(a) specimen B2L21-BM

(b) specimen B7L21-C12S5

Fig15. Photographs of damaged region at plastic hinge zone

(2) The load-displacement hysteresis loops are given in Figure 16. The failure of lap spliced column (B1L17-BM、B2L21-BM) at low ductility =1.5 and 2.0 ,was caused by the bond failure at the splices of longitudinal bars. From the hysteresis loops, the strength of the as-built specimens decreased rapidly after failure. However, highly ductile behavior was observed in the retrofitted rectangular column (B6L21-C12S10、B7L21-C12S5、W2L19-C15S10,etc.).

(3) In the lap spliced models, specimens S1L19-C5S10 、S2L19-C5S10、M1L19-C5S10 are short columns. The CS method was used for enhancing the shear resistance to avoid the shear failure mode. The test results showed that such columns can be effectively retrofitted with the new retrofit technique.

(4) The efficiency of using direct steel jackets to retrofit the lap spliced column can be improved by augmented a small number of adhesive anchor bolts. Comparing with CS method, they both have excellent performance.

(4) To analyze the test result of specimens B6L21-C12S10、B7L21-C12S5, although their plate thickness are different (10 mm / 5 mm), they have similar highly ductile behavior.

4. CONCLUSIONS

1. Test results confirmed that the seismic performance of the rectangular RC bridge columns can be significantly and equally enhanced by properly constructed elliptical or octagonal steel jacket.
2. The thickness of the steel jacket can be determined from the static equilibrium assuming a spcific confinement pressure is to be developed. Using a reduced elliptical shape but a thickened steel jacket can reduce the cross-sectional area of an octagonal steel jacketed rectangular RC bridge column.
3. Octagonal steel jacketing scheme is cost-effective. It can provide lateral confinement and the shear strength to mitigate seismic failure of rectangular RC bridge columns due to a lack of lateral confinement, improper lap-splice or inadequate shear capacity.
4. A smaller cross-sectional area and better seismic performance than the elliptical steel jacketing scheme have been achieved from the octagonal steel jacketing.
5. The CS method is an effective method to improve the strength, ductility, and energy dissipation of rectangular RC columns, including those columns with main steels lap spliced at the plastic hinge zone.

6. Further analytical studies are necessary to better understand the mechanisms and critical parameters for the combined steel plate and CFRT retrofit method.

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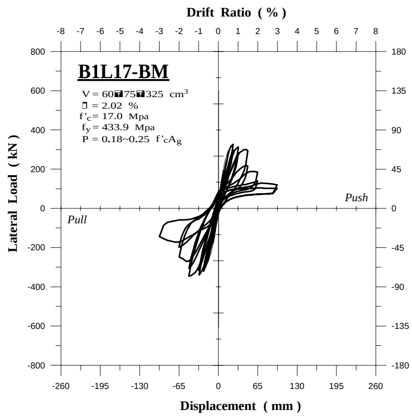
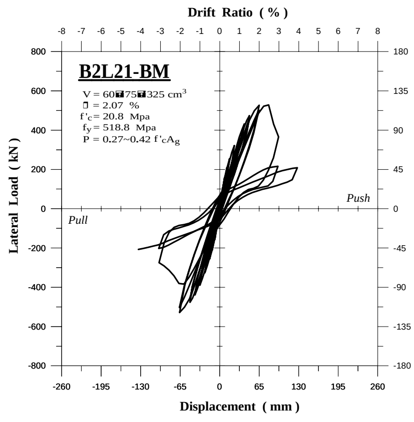
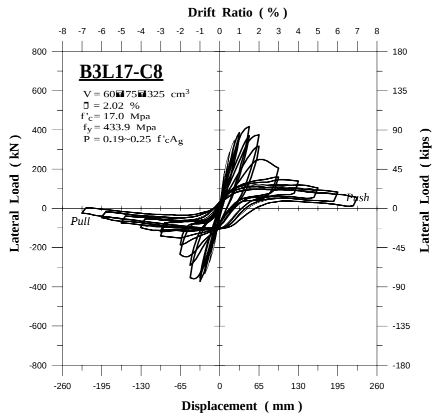


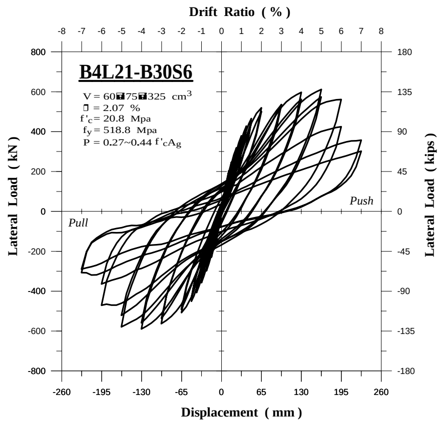
specimen B1L17–BM



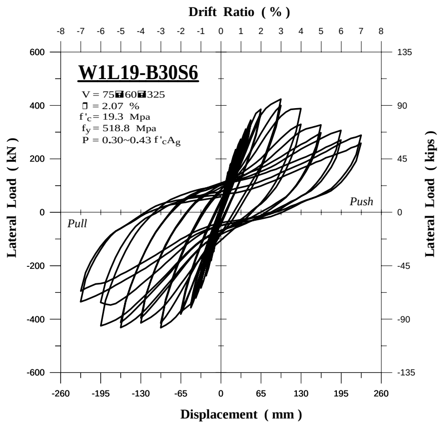
specimen B2L21–BM



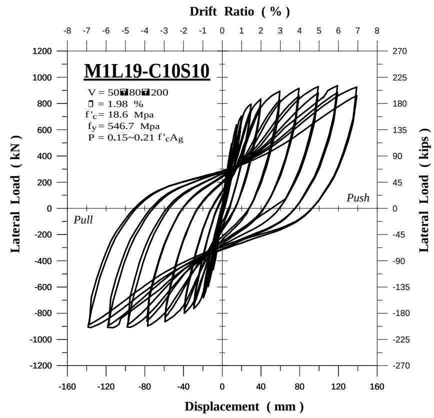
specimen B3L17–C8



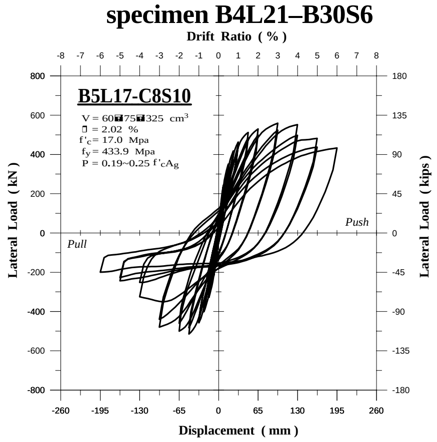
specimen B4L21–B30S6



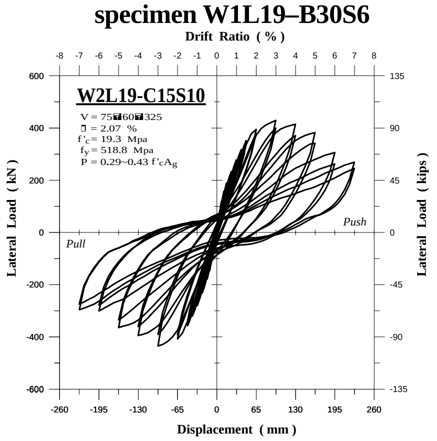
specimen W1L19–B30S6



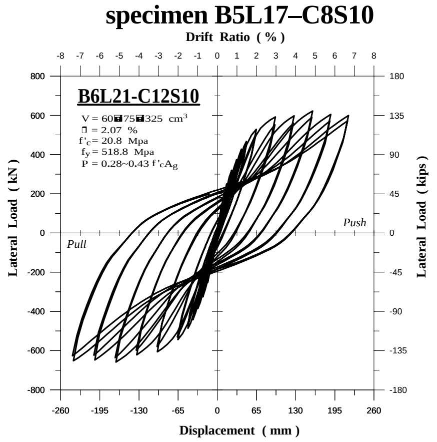
specimen M1L19–C10S10



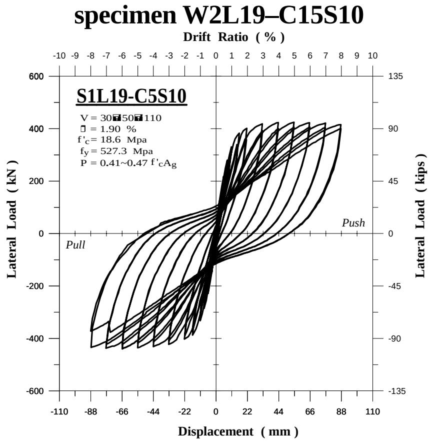
specimen B5L17–C8S10



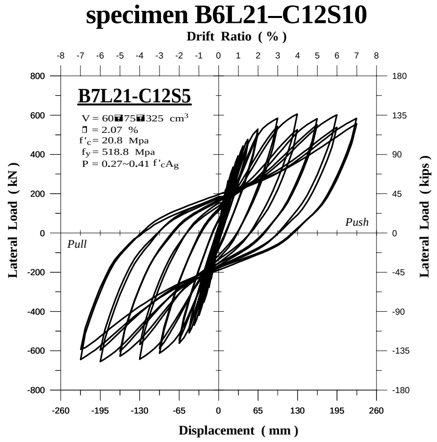
specimen W2L19–C15S10



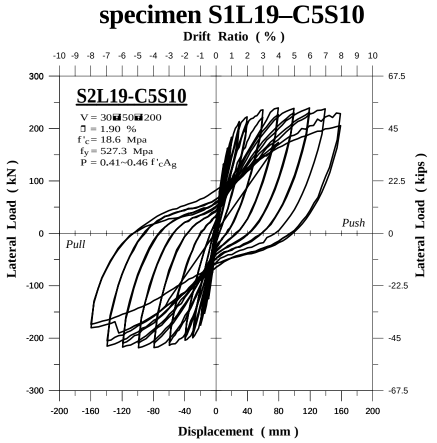
specimen B6L21–C12S10



specimen S1L19–C5S10



specimen B7L21–C12S5



specimen S2L19–C5S10

Fig.16 Load-Displacement hysteretic curve