KCI CONCRETE JOURNAL
Vol.14 No.3, Sep. 2002, pp.130-137

Seismic Performance and Retrofit of Circular Bridge Piers with Spliced Longitudinal Steel

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(Received January 28, 2002; Accepted May 28, 2002)

Abstract

It is known that lap splice in the longitudinal reinforcement of reinforced concrete(RC) bridge columns is not desirable for seismic performance, but it is sometimes unavoidable. Lap splices were practically located in the potential plastic hinge region of most bridge columns that were constructed before the adoption of the seismic design provision of Korea Bridge Design Specification on 1992. The objective of this research is to evaluate the seismic performance of reinforced concrete(RC) bridge piers with lap splicing of longitudinal reinforcement in the plastic hinge region, to develop the enhancement scheme of their seismic capacity by retrofitting with glassfiber sheets, and to develop appropriate limited ductility design concept in low or moderate seismicity region. Nine test specimens in the aspect ratio of 4 were made with three confinement ratios and three types of lap splice. Quasi-static test was conducted in a displacement-controlled way under three different axial load levels. A significant reduction of displacement ductility ratios was observed for test columns with lap splices of longitudinal steels.

Keywords: Lap splice, column, Korea Roadway Bridge, retrofit, design concept, Quasi-static test, axial load

1. Introduction

Even though earthquakes have several economic, social, psychological, and even political effects in the areas and the countries where they take place, Korea is considered to be immune from the earthquake hazards since it is distant from active fault areas. However, it has been observed in the Korean Peninsula that the number of minor or low earthquake motions have increased year by year. The collapse or near collapse of bridge superstructures during the 1995 Kobe earthquake and the 1996 Northridge earthquake stimulated the establishment of seismic design provisions for various infrastructures in Korea. Furthermore, lap splices of longitudinal steels were sometimes practically located in the lower plastic hinge region of most RC bridge columns that were designed and constructed before the 1992 new seismic design code of Korea bridge design specification, even though longitudinal lap splicing of bridge columns was not desirable for their seismic performance. Therefore, there is a need to investigate the effect of lap splice and retrofit scheme for the lap spliced piers.

Many researchers have reported on the effects of confinement on the compressive strength and ductility of reinforced concrete bridge piers. They investigated the effect of lap splice lengths of the longitudinal reinforcement. Aboutaha et al.(1999) investigated the seismic repair of lap splice failures in damaged concrete columns. A total of six specimens were fabricated and tested under axial load and cyclic lateral displacement. The column size was 17.5×17.5mm in cross section In order to investigate the effect of confinement steel type, two confinement steel types were studied. And to investigate the effect of retrofit method, different lengths of steel jacket with anchor bolt or through rods were adopted. Tests were conducted to evaluate the methods and technique retrofitting reinforced concrete columns. From this research, existing columns with inadequate lap splice were first tested until splice failure occurred. Panahshahi et al.(1992) indicated that compression lap splices can be designed to sustain a minimum of a dozen cycles of high intensity loads into the inelastic range, where the maximum bar strain reached at least three times the yield strain. Jaradat et al.(1998) investigated the perform-

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ance of older reinforced concrete bridge columns under seismic loading, particularly with regard to assessing the residual strengths present in degraded hinge regions. For the experimental research, eight reduced scale specimens were fabricated and tested. Through comparisons of specimen behavior, the effects of varying shear-span-to-depth ratio, longitudinal steel ratio, lap splice length, and retrofitting detail on column performance were evaluated. Through this research, plastic hinge regions with poor confinement and lap splices experienced a rapid flexural strength degradation as a result of concrete cracking and splice slippage. In the plastic hinge regions that contained no splices but with poor confinement, the columns exhibited moderate ductility with eventual degradation due to longitudinal bar buckling.

In this research, the effect of lap splice, axial force, retrofit, and transverse confinement was investigated. Transverse confinement could be provided by transverse reinforcement steels and a retrofit material such as a fiber jacket. To provide different levels of transverse confinement, test specimens were designed in accordance with the nonseismic design code, the seismic design code for strong ground motion, and the limited ductility design concept from Eurocode 8. Since placement of longitudinal lap splices in bridge piers are sometimes practically unavoidable, three and one test specimens were made with lap splice of 50% and 100% longitudinal reinforcement steels, respectively. Three levels of axial load were also included so that the effect of axial load was investigated. The objective of this quasi-static test is to evaluate the seismic performance of practical RC bridge piers with lap splicing of longitudinal reinforcement steels in the plastic hinge region, to investigate the enhancement of their seismic capacity by retrofitting with glassfiber sheets, and to develop appropriate transverse confinement ratios for limited ductile bridge columns in low or moderate seismicity region, like Korea. Nine test specimens with an aspect ratio of 4.0 were made using three confinement ratios and three levels of lap splicing.

2. Material properties of test specimen

D10 deformed steel was used as longitudinal steel in RC test specimens, of which confinement steels had been laterally used with D6 deformed steel. Yield strength from the tensile coupon test is 450.8MPa for D10 deformed steel and 352.8MPa for D6 deformed steel. The achieved compressive strength, f_c', of concrete was 23.5MPa. Table 1 shows the mix proportions of the test specimens. Two nonseismic test specimens with 50% lap splicing were wrapped with one layer of glassfiber sheet around their potential plastic hinge region, of which physical properties are shown in Table 2.

Table 1 Mix proportions of test specimens

Max. size of coarse agg. (mm)		13
W/C (%)		50.8
Air content (%)		6.5
Slump (cm)		21
Unit weight (kg/cm^3)	Water	208
	Cement	409
	Agg.	762
	A.E.	1.37
Achieved compressive strength (MPa)		23.5

Table 2 Physical properties of glassfiber sheets

Classification	TYFO SEH 51	CAF GL-1000
Tensile strength (MPa)	548.8	490
Tensile modulus (MPa)	24,696	24,500
Elongation (%)	2.0	2.3
Thickness (mm)	1.3	1.0

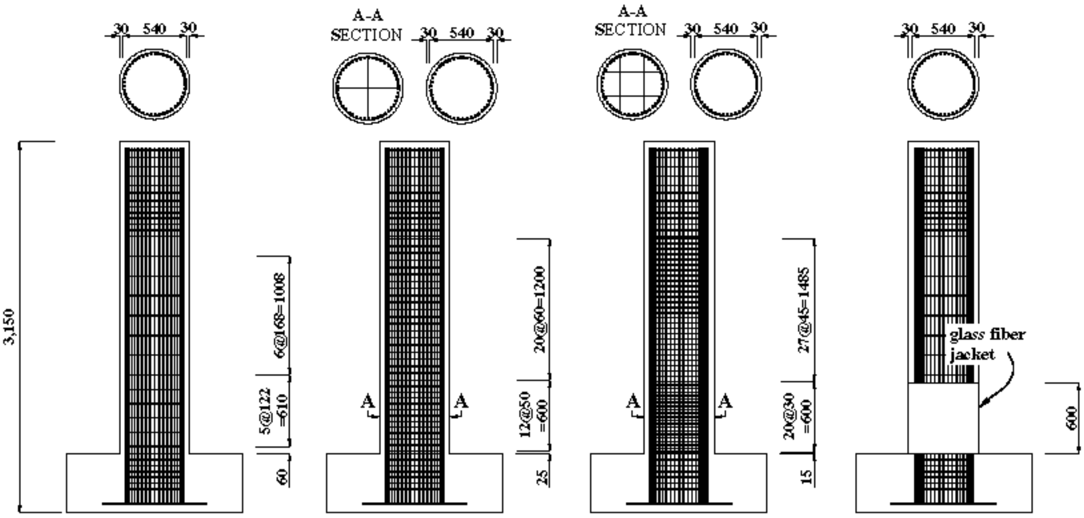
Thickness of the glassfiber sheet was computed using Eq. (1), which was proposed by Paulay and Priestley(1991).

$$t_g = \frac{0.1(\varepsilon_{cu} - 0.004)Df'_{cc}}{f_{ul}\varepsilon_{ul}} \tag{1}$$

where t_g is the thickness of the glassfiber sheet, ε_{cu} and ε_{ul} are the ultimate strain of confined concrete and glassfiber sheet, respectively, D is the diameter of the test specimen, and f'_{cc} and f_{ul} are the yield strength of confined concrete and galssfiber sheets, respectively.

3. Test program

Circular solid RC piers of the Hagal bridge in Korea were adopted as a prototype of this test. The bridge had been seismically designed in accordance with the provisions of the Korea bridge Design Specification. Fig. 1 shows the detailed dimensions of all test columns. As shown in Table 3, nine test specimens were prepared for the quasi-static test to investigate their seismic performance. Seven test columns were nonseismically designed and made without lap splicing, or with lap splicing of longitudinal steels in the lower plastic hinge region. Among them, three specimens are nonseismic test specimens without lap splicing of longitudinal steels, three specimens were nonseismic test specimens with lap splicing of 50% longitudinal reinforcement steels, and another specimen was a nonseismic test specimen with lap splicing of 100% in the longitudinal steels. Three levels of axial load of $0.1f_c'A_g$, $0.15f_c'A_g$, $0.2f_c'A_g$ were applied to investigate the effect of axial load. Other two specimens were designed in accordance with the 1996 seismic design code of the Korean bridge design specification, and with the limited ductile design concept of

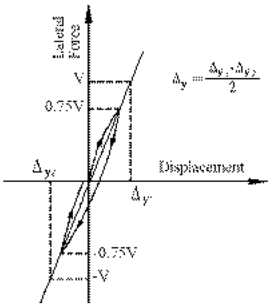


(a) Nonseismic (b) Moderate (c) Seismic (d) Retrofit

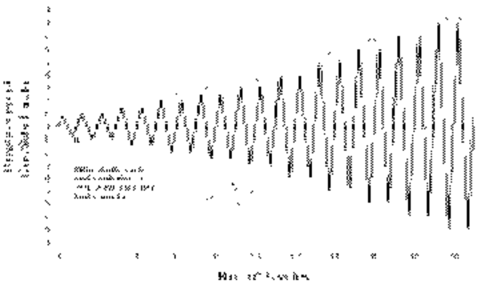
Fig. 1 Details of test specimens (mm)

Eurocode 8, as shown in Table 3. In Table 3, PHR and NPHR denote the plastic hinge region and the nonplastic hinge region, respectively.

Quasi-static cyclic load tests have been carried out in a displacement-controlled way. Cyclic loads have been applied to the top of the test columns using 1,000kN hydraulic actuator. As shown in Fig. 2(a), the yield displacement, Δ_y , has been computed by extrapolation on the basis of the yield strain of 0.002 and the measured strain of longitudinal steel from the first load cycle, of which peak load was approximately 75% of the theoretical yield load. Fig. 2(b) shows cyclic load history, which was based on the lateral displacement pattern of increasing magnitude of yield displacement.



(a) Yield displacement



(b) Load pattern

Fig. 2 Cyclic load pattern

4. Test results

4.1 Lateral force-displacement behavior

Lateral force-displacement hysteresis loops for all test

Table 3 Characteristics of test specimens and experimental ductility ratio

Classification		Nomenclature*	Cross tie	Confinement steel space(cm)	$\frac{P}{f_c' A_g}$	Ductility ratio	
			PHR	PHR / NPHR		Displacement	Energy
Non seismic design	0% lap-splice	N-SP00-P1-R0	None	12.2 / 16.8	0.1	4.0	6.1
		N-SP00-P2-R0			0.15	3.4	5.0
		N-SP00-P3-R0			0.2	3.3	4.9
	50% lap-splice	N-SP05-P1-R0			0.1	2.5	4.6
		N-SP05-P1-R1				4.0	6.0
		N-SP05-P1-R2				4.3	6.4
	100% lap-splice	N-SP10-P1-R0				1.6	2.1
Limited ductile design		L-SP00-P1-R0	2EA	5 / 6		4.4	6.8
Seismic design		S-SP00-P1-R0	4EA	3 / 4.5		5.8	9.3

*Abbreviations : N = nonseismic ; L = limit ductile ; S = seismic ; SP = splicing ; P = axial force ; R = retrofit columns are shown in Fig. 5. Figs. 5(a), 5(b), and 5(c) show that nonseismic test specimen (N-SP00-P1-R0) without lap splices developed more ductile hysteresis loops than the other nonseismic test specimens (N-SP05-P1-R0,N-SP10-P1-R0) with lap splicing of longitudinal steels. It was also observed from Figs. 5(a), 5(f), and 5(i) that the increase of axial force induced the slight reduction of the ductility factor. As shown in Figs. 5(b), 5(e), and 5(h), it was found that the glassfiber sheets remarkably increased the displacement ductility factor. In addition, Figs. 5(a), 5(d), and 5(g) showed that test specimens with more transverse reinforcement steels could have greater displacement ductility. Fig. 6 shows the comparative lateral force-displacement envelope curve for all test specimens in accordance with the four test parameters ; transverse confinement, lap splice, axial force, and retrofit. Fig. 6(a) shows that greater transverse confinement in the plastic hinge region of the RC bridge columns increases envelope curve. It was also observed that significant reduction of the displacement ductility ratio resulted for test specimens with lap splices in longitudinal steels from Fig. 6(b). Figures 6(c) and 6(d) show the effect of axial force and retrofit, respectively.

4.2 Displacement and strain energy ductility

Seismic performance of RC bridge piers can be evaluated as a displacement ductility. The yield displacement, Δ_y, was computed by extrapolation from the yield strain of 0.002 in the longitudinal steel in the plastic hinge region, and the experimental strain of corresponding longitudinal steel at 75% of theoretical yield load, as shown in Fig. 2(a). The ultimate displacement, Δ_u, was defined as the smaller displacement between Δ_{u1} and Δ_{u2}; Δ_{u1} is the displacement at when the longitudinal or confinement steel has exceeded its fracture state but the strength on the descending branch of the force-displacement envelope curve is above $0.85V_{\max}$. Δ_{u2} is the displacement at when the strength on the descending branch of the force-displacement envelope curve has dropped below $0.85V_{\max}$ but the longitudinal or confinement steel has not reached the failure state. The displacement ductility, $\mu_\Delta = \Delta_u / \Delta_y$, was computed in Table 3. It was found in Table 3 that the use of glassfiber sheets for retrofitted test specimens (N-SP05-P1-R1, N-SP05-P1-R2) increased the displacement ductility ratio by about 62% with respect to the displacement ductility factor of the corresponding reference test specimen(N-SP05-P1-R0). The displacement ductility ratio of 100% for the lap spliced test specimen(N-SP10-P1-R0) was significantly reduced to approximate 40% of those for the non-spliced test specimen(N-SP00-P1-R0).

Strain Energy ductility, $\mu_E = E_u / E_y$, has been also analyzed in Table 4. As shown in Fig. 3, the areas ΔOAC and ⌂OABD indicate the yield strain energy until the specimen yielded, and the ultimate strain energy until the specimen reached the ultimate state, respectively. Similar trends were observed for the strain energy ductility of all test specimens depending on test parameters, such as lap splice of longitudinal steel, axial force, transverse confinement, and retrofit. Significant reduction in strain energy ductility ratio was observed for test specimens(N-SP05-P1-R0, N-SP10-P1-R0) because of lap splicing of the longitudinal steels in the plastic hinge region, compared with the strain energy ductility ratio of the corresponding nonspliced test specimen(N-SP00-P1-R0).

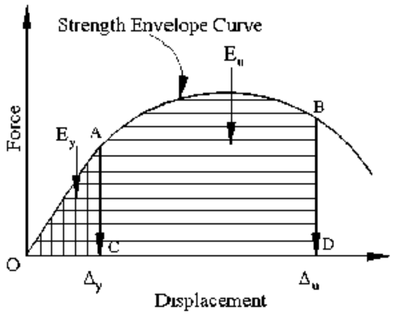


Fig. 3 Definition of yield and ultimate strain energy

Table 4 Experimental ductility ratio

Specimen	Displacement				Strain energy			
	Yield	Ultimate	Ductility	Normal*	Yield	Ultimate	Ductility	Normal*
N-SP00-P1-R0	19.973	79.81	4	1	268	1640	6.1	1
N-SP00-P2-R0	21.905	73.764	3.37	0.84	323	1619	5.0	0.82
N-SP00-P3-R0	22.812	75.89	3.33	0.83	399	1945	4.9	0.8
N-SP05-P1-R0	18.719	46.928	2.5	0.625	232	1079	4.6	0.75
N-SP05-P1-R1	24.527	98.751	4	1	350	2096	6.0	0.98
N-SP05-P1-R2	22.217	94.834	4.27	1.08	318	2053	6.4	1.05
N-SP10-P1-R0	15.7	25.753	1.64	0.41	160	339	2.1	0.34
L-SP00-P1-R0	22.339	97.902	4.38	1.1	304	2069	6.8	1.11
S-SP00-P1-R0	21.339	123.724	5.8	1.45	283	2635	9.3	1.52

* Normalized ductility was computed with respect to the ductility of specimen. (N-SP00-P1-R0)

4.3 Energy absorption capacity

Fig. 4 shows the Definition of Absorption energy Capacity and Fig. 7 shows comparative curve of the cumulative energy absorption capacity of all test specimens depending on four test parameters. The amount of absorption energy in one cycle of load has been calculated from the hysteresis loop between two consecutive displacement peaks. As shown in Fig. 7(a), limited ductile test specimen(L-SP00-P1-R0) and seismic test specimens(S-SP00-P1-R0) showed greater energy absorption capacity by about 65% and 71%, respectively as against the nonseismic test specimen(N-SP00-P1-R0) without lap splicing of longitudinal steels. It is seen from Fig. 7(c) that the increase of axial load also increased the energy absorption capacity. It was also found from Fig. 7(b) that the energy absorption capacity of test specimen(N-SP05-P1-R0) with lap splicing on 50% of the longitudinal reinforcement steels decreased by about 63% as against the energy absorption capacity of the nonspliced test specimen(N-SP00-P1-R0). Fig. 7(d) shows that retrofitted specimens(N-SP05-P1-R1, N-SP05-P1-R 2) by glassfiber sheets has increased the energy absorption capacity by about 92% as against non-retrofitted test specimen(N-SP05-P1-R0).

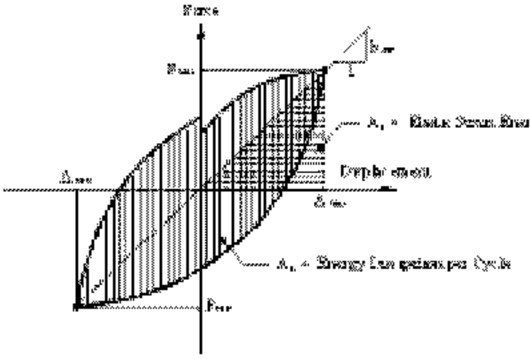


Fig. 4 Definition of absorption energy capacity

4.4 Strength degradation

Strength degradation of test columns can be obtained by normalizing the lateral test loads with respect to the lateral yield load as shown in Fig. 8. A steeper slope in the figure corresponds to a greater strength drop. It has been clearly shown that the specimens designed according to the seismic design code and the limited ductile design concept showed a flatter curve than the nonseismic specimens. As shown in Fig. 8(b), the specimens with lap splices of longitudinal steels showed a significant strength drop compared with the specimens without lap splicing of longitudinal steels. It is seen in Fig. 8(d) that the use of glassfiber sheets can remarkably decrease the magnitude of the strength drop.

4.5 Capacity spectrum analysis

The seismic performance of the test specimens was evaluated using the capacity spectrum analysis of ATC40 for the function maintenance level and the failure prevention level, which was specified in the Korean bridge design specification. Equivalent viscous damping ratio, ξ_{eq}, for the capacity spectrum was calculated from the Takeda model of Eq. (2).

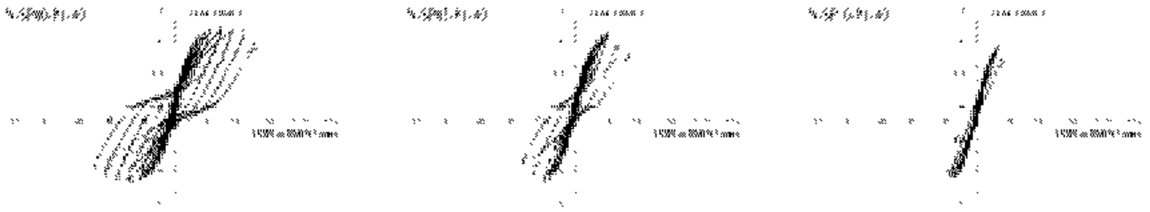
$$\xi_{eq}=0.05+(1\quad(1\quad\gamma)/\sqrt{\mu_\Delta}\quad\gamma\sqrt{\mu_\Delta})/\pi \qquad (2)$$

where $\gamma=0.05$ is the second stiffness ratio after yielding, and μ_Δ is the displacement ductility. Figure 9 shows the analyzed result for the capacity spectrum for all test specimens of 2 span continuous bridge (weight:1583.78 ton), which satisfied both the function maintenance level and the failure prevention level, except for both spliced specimens(N-SP05-P1-R0, N-SP10-P1-R0). Particularly, it is can be seen from Fig. 9 that 100% the spliced test specimens(N-SP10-P1-R0) could be far below the demand spectrum.

5. Conclusions

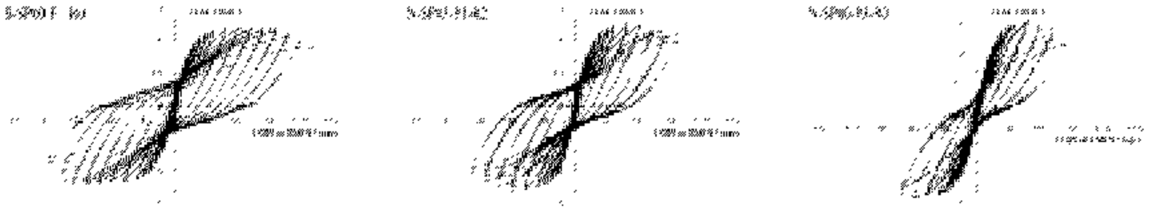
The experimental program indicated that retrofitting RC bridge columns by wrapping glassfiber sheets in the potential plastic hinge region was an effective retrofitting measure to enhance flexural ductility. The following conclusions can be made.

1) Nonseismically designed RC bridge piers, with lap splicing of longitudinal reinforcement steels in the plastic hinge region, appeared to fail at low ductility levels. This was due to the debonding of the lap splice, which resulted from insufficient development length of the longitudinal bars It is desirable to prohibit the lap splice of longitudinal steels in the potential plastic hinge region, or to increase the transverse confinement.
2) The limited ductile design specimen showed a considerably large displacement ductility capacity, which should be sufficient for low or moderate seismic regions like Korea.
3) Increase in axial load caused a decrease in the displacement ductility and the strength degradation.
4) Test columns(N-SP05-P1-R1, N-SP05-P1-R2) externally wrapped with glassfiber sheets in the plastic hinge region showed a significant improvement in displacement ductility. Therefore, glassfiber sheets could be an



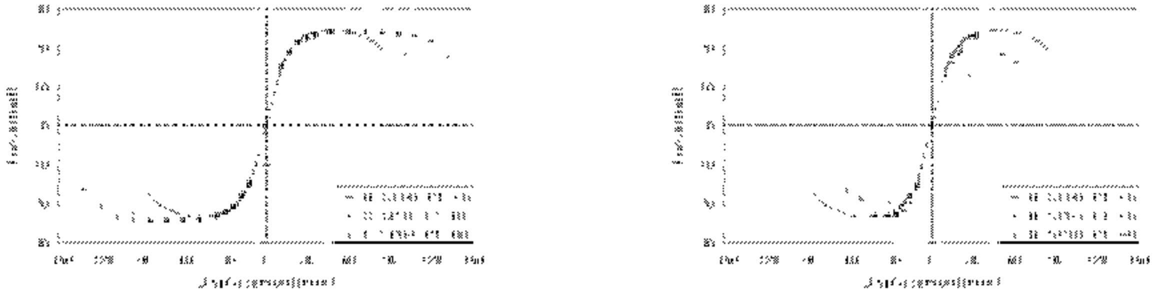
(a) N-SP00-P1-R0 (b) N-SP05-P1-R0 (c) N-SP10-P1-R0

(d) L-SP00-P1-R0 (e) N-SP05-P1-R1 (f) N-SP00-P2-R0

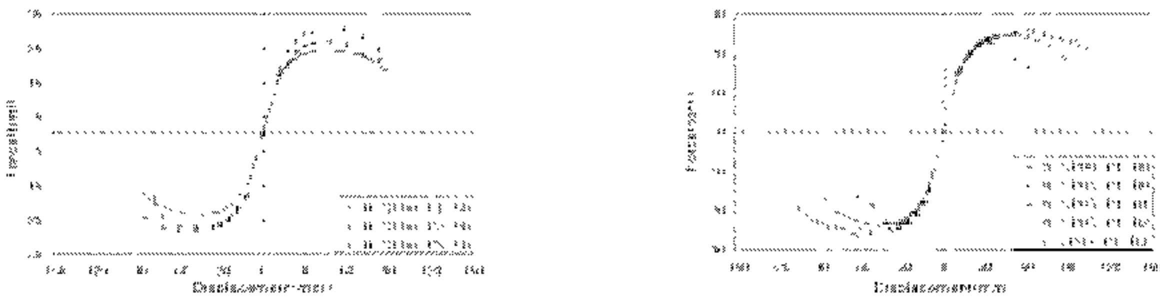


(g) S-SP00-P1-R0 (h) N-SP05-P1-R2 (i) N-SP00-P3-R0

Fig. 5 Lateral force-displacement hysteresis loop

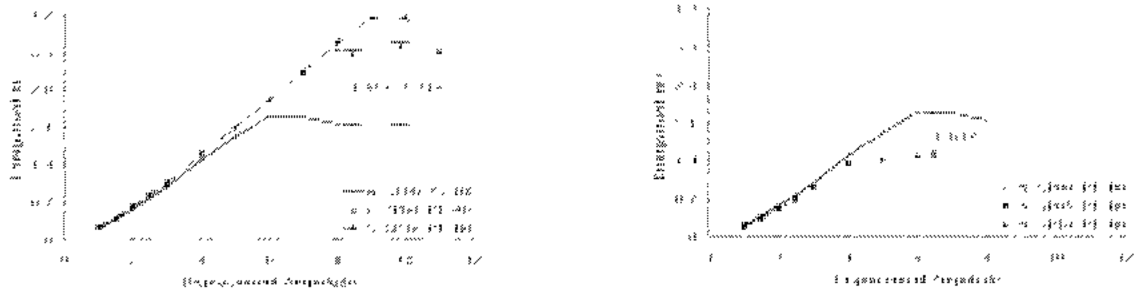


(a) Transverse confinement (b) Lab splice

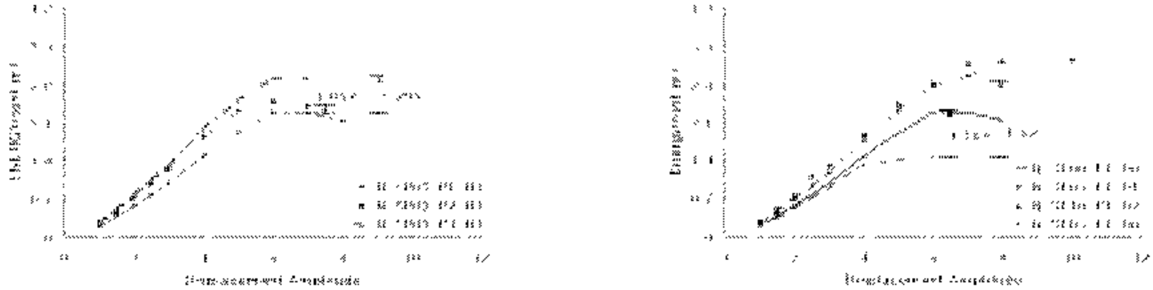


(c) Axial load (d) Retrofit

Fig. 6 Lateral force-displacement envelope curve

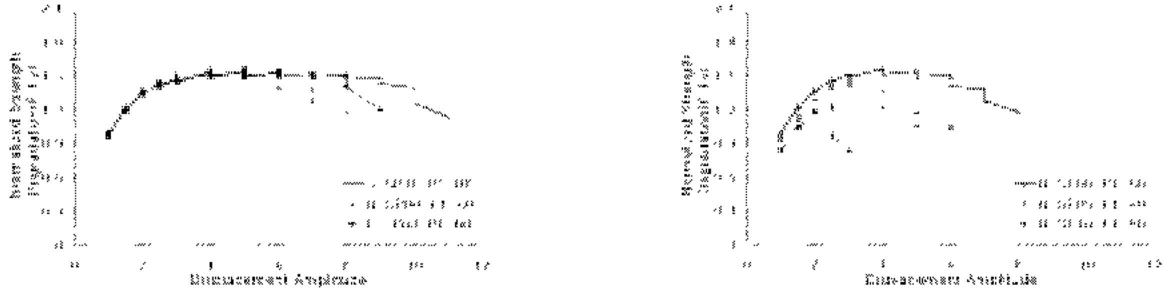


(a) Transverse confinement (b) Lab splice

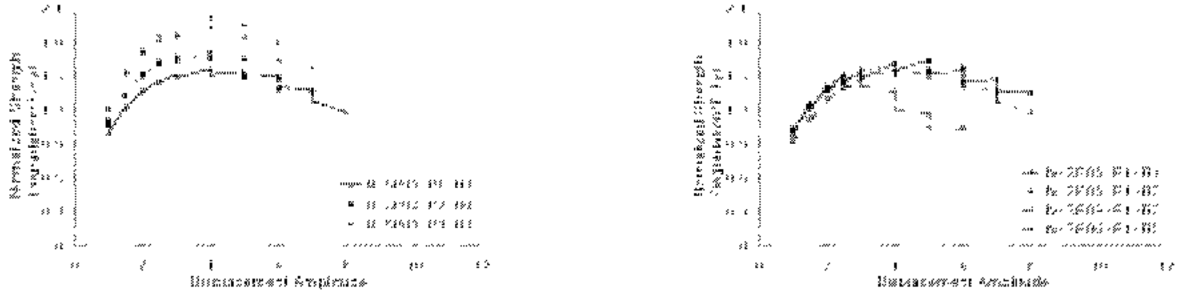


(c) Axial load (d) Retrofit

Fig. 7 Comparative energy absorption capacity

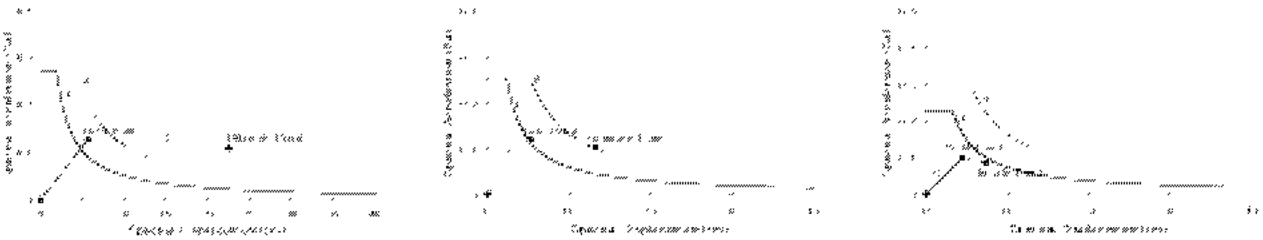


(a) Transverse confinement (b) Lab splice



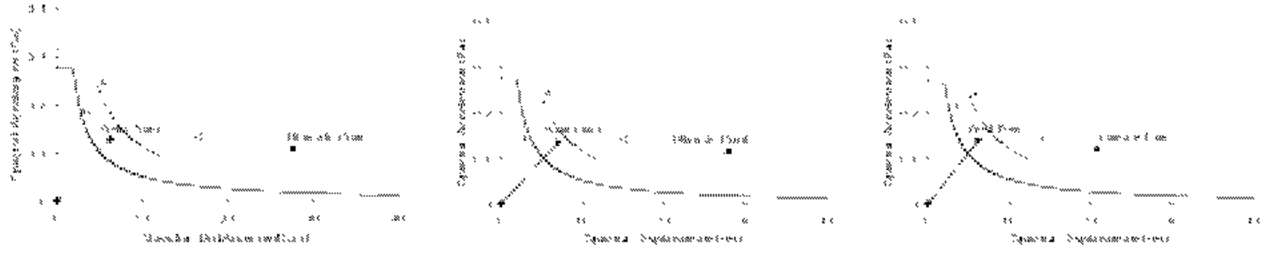
(c) Axial load (d) Retrofit

Fig. 8 Normalized strength degradation

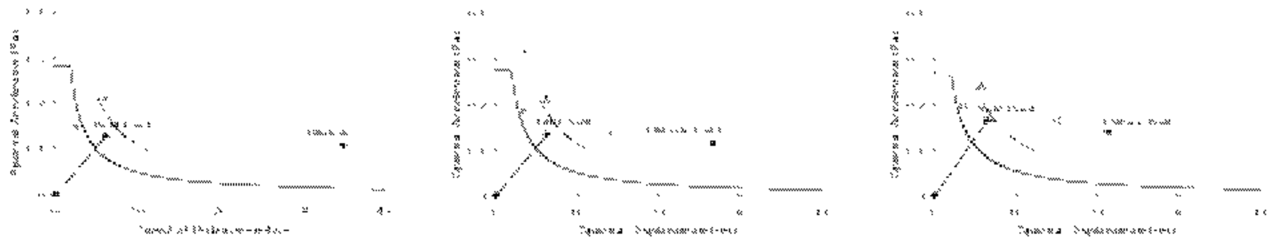


(a) N-SP00-P1-R0 (b) N-SP05-P1-R0 (c) N-SP10-P1-R0

Fig. 9 Capacity spectrum(continue)



(d) L-SP00-P1-R0 (e) N-SP05-P1-R1 (f) N-SP00-P2-R0



(g) S-SP00-P1-R0 (h) N-SP05-P1-R2 (i) N-SP00-P3-R0

A: Demand spectrum for failure prevention level, B: Demand spectrum for function maintenance level,
C: Capacity spectrum of 2 span continuous bridge

Fig. 9 Capacity spectrum

effective retrofitting measure to enhance flexural ductility in the potential plastic hinge region of RC bridge columns.

Acknowledgements

The authors gratefully acknowledge the support from the Korea Earthquake Engineering Research Center(Contract No. 2000G0302). The author also thank Conclnic Co. for providing experimental specimens.

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