

Assessing the Seismic Performance of Threaded Rebar Coupler System

Do-Kyu, Hwang, Ho-Young Kim, Ho-Hyeong Choi, Gi-Beom Park, Jae-Hoon Lee

Abstract—Currently there are many use of threaded reinforcing bars in construction fields because those do not need additional screw processing when connecting reinforcing bar by threaded coupler. In this study, reinforced concrete bridge piers using threaded rebar coupler system at the plastic hinge area were tested to evaluate seismic performance. The test results showed that threads of the threaded rebar coupler system could be loosened while under tension-compression cyclic loading because tolerance and rib face angle of a threaded rebar coupler system are greater than that of a conventional ribbed rebar coupler system. As a result, cracks were concentrated just outside of the mechanical coupler and stiffness of reinforced concrete bridge pier decreased. Therefore, it is recommended that connection ratio of mechanical couplers in one section shall be below 50% in order that cracks are not concentrated just outside of the mechanical coupler. Also, reduced stiffness of the specimen should be considered when using the threaded rebar coupler system.

Keywords—Reinforced concrete column, seismic performance, threaded rebar coupler, threaded reinforcing bar.

I. INTRODUCTION

SINCE ACI 318-11 [1] and KCI-2012 [2] prohibit the use of lap splice, mechanical splice should be used to connect the reinforcement in plastic hinge area of reinforced concrete bridge pier designed in seismicity regions. However, conventional ribbed reinforcing bar need additional screw processing when connecting reinforcement by threaded coupler.

Alternatively, threaded reinforcing bar do not need additional screw processing because transverse ribs of the threaded reinforcing bar play a role as a screw thread for fastening a coupler. For this reason, currently there are many uses of threaded reinforcing bars in construction fields in USA, Australia, Switzerland, Germany, and Poland [3].

Performance requirements for mechanical splice of ACI 318-11 [1] and KCI-2012 [2] are only focused on a strength capacity. However, for threaded rebar coupler system, strain could be more concentrated at the region just outside of the coupler and slip of threaded reinforcing bar within the coupler could be larger than that of conventional ribbed reinforcing bar. The reasons for this are as follows. Firstly, spacing of transverse ribs of threaded reinforcing bar is generally greater than those of artificially processed screw thread. Therefore,

length of mechanical coupler used in threaded reinforcing bar could be greater than that used in conventional ribbed reinforcing bar. As a result, strain of threaded reinforcing bar could be more concentrated at the region just outside of the coupler because stiffness of mechanical coupler is generally greater than that of the steel reinforcement. Secondly, tolerance of a threaded rebar coupler is generally greater than that of a conventional ribbed rebar coupler. This is because transverse ribs of threaded reinforcing bar are more likely to be damaged than that of artificially processed screw thread of conventional ribbed reinforcement. As a result, tolerance of a threaded rebar coupler could lead to loose threaded reinforcing bar and mechanical coupler. Thirdly, rib face angle (angle between the face of the rib and the longitudinal axis of the bar) of the threaded reinforcing bar is greater than that of artificially processed screw thread of conventional ribbed reinforcing bar. This could lead to loose threaded reinforcing bar and mechanical coupler.

Generally, length of the mechanical coupler increase by increasing diameter and strength of reinforcement. On the other hands, seismic design code has set limits on spacing of transverse reinforcement of the reinforced concrete bridge pier designed in seismicity regions. Therefore, when using staggered mechanical couplers to connect large diameter high strength reinforcements, there is a gap between the transverse reinforcement and the longitudinal reinforcement without mechanical coupler. This gap could lead to influence failure behavior of the reinforced concrete bridge pier designed in seismicity regions because longitudinal reinforcement without mechanical coupler is unbraced over a much greater length than with mechanical coupler.

Current design codes do not consider as follows: the strain concentration at the region just outside of the mechanical coupler; slip of reinforcement within the mechanical coupler; and reinforcement specification such as gap between the transverse reinforcement and the longitudinal reinforcement. In this study, the specimens of reinforced concrete bridge pier using threaded rebar coupler system at the plastic hinge area were tested under cyclic loading to evaluate seismic performance of threaded rebar coupler system. Threaded reinforcing bars and threaded rebar couplers used in this study are shown in Fig. 1.



Fig. 1 Threaded rebar coupler system

Do-Kyu Hwang is with the Civil Engineering Department, Yeungnam University, Gyeongsan, Korea (Phone: +82-53-810-3662; Fax: +82-53-810-4622, e-mail: likeability@paran.com).

Ho-Young Kim, Ho-Hyeong Choi, Gi-Beom Park and Jae-Hoon Lee are with the Civil Engineering Department, Yeungnam University, Gyeongsan, Korea (e-mail: hpm00700@hanmail.net, chh2385@naver.com, clanoz@naver.com, JHL79@ynu.ac.kr).

II. EXPERIMENT

A. Test Specimens

Fig. 2 shows the details of the specimens, and Table I summarizes the variable of the specimens. The test variable was ratio of the mechanical splices in one section at the plastic hinge area. The M0-S80 specimen had no splice of longitudinal reinforcements. The M50-S80 and M100-S80 specimens had mechanical splices used to connect the longitudinal reinforcement at a distance of 135 mm from top surface of a footing. Transverse reinforcements of all specimens were with the spacing of 80 mm and provided a transverse reinforcement ratio of 0.0106, which satisfied requirement of ACI 318-11[1] section 21.6.4.4.

All specimens had section diameter of 1,000 mm and aspect ratio of 4.5. Threaded reinforcing bars of 38.1 mm diameter with nominal yield strength of 600 MPa were used as the longitudinal reinforcements. Nominal diameter of the

transverse reinforcements was 15.9 mm and nominal yield strength of that was 500 MPa.

TABLE I
PROPERTIES OF TEST SPECIMENS

Specimens	M0-S80	M100-S80	M50-S80
cross section diameter(mm)	1000	1000	1000
cylinder concrete strength(MPa)	53.2	53.2	53.2
diameter(mm)	38.1	38.1	38.1
longitudinal rebar yield strength(MPa)	690	690	690
Reinforcement ratio (%)	1.7	1.7	1.7
Ratio of mechanical splice (%)	-	100	50
diameter(mm)	15.9	15.9	15.9
transverse rebar yield strength(MPa)	577	577	577
spacing(mm)	80	80	80
axial force axial load(kN)	2510	2510	2510
Axial force ratio (%)	6	6	6
aspect ratio	4.5	4.5	4.5

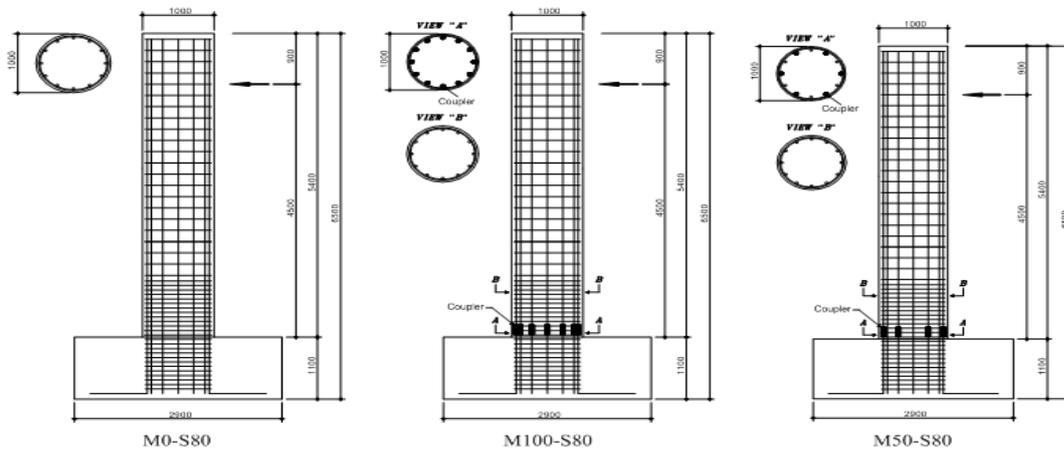


Fig. 2 Dimensions and reinforcing bar details of test

B. Material Properties

Geometrical characteristics of the threaded reinforcing bar used in longitudinal reinforcements of the specimens were measured and shown in Table II. Height and spacing of transverse rib and rib face angle were 2.93 mm ($0.077d_b$), 17.1 mm ($0.45d_b$), and 82° , respectively.

TABLE II
GEOMETRICAL CHARACTERISTICS OF THREADED REINFORCING BAR

Bar designation	Height of transverse rib	Spacing of transverse rib	Rib face angle	Gap
D38	2.93mm ($0.077d_b$)	17.1mm ($0.45d_b$)	82°	13.5mm ($0.354d_b$)

Length and external diameter of the threaded rebar couplers to connect the longitudinal reinforcement were 170 mm and 65 mm, respectively (refer to Fig. 1).

Tension test pieces used in longitudinal and transverse reinforcement of the specimens were tested. The stress-strain diagrams of both reinforcing bars are shown in Fig. 3. The longitudinal and transverse reinforcements exhibited a well-defined yield point and yield plateau. The yield strength

and the tensile strength of the longitudinal reinforcement were 690 MPa and 874 MPa, respectively. The yield strength and the tensile strength of the transverse reinforcement were 577 MPa and 714 MPa, respectively. The elongation of the longitudinal and transverse reinforcements was 13.5% and 17.0%, respectively, and satisfy the requirements of ASTM A706 [4] in Grade 80 bar. The concrete compressive strength was 53.2 MPa.

In order to use the mechanical splices for the reinforced concrete columns designed in seismicity regions, performance of the mechanical splices should satisfy the seismic design provisions for mechanical splices specified in the design criteria. ACI 318-11[1] and KCI-2012[2] require that mechanical splices shall develop the 125% of the specified yield strength and the specified tensile strength of the spliced bar to be used at any location of the structure designed in seismicity regions. In order to verify the performance of the threaded rebar couplers used in this study, tension tests were conducted. Test results showed that the average tensile strength was 937 MPa, which is over 125% of the nominal yield strength and over nominal tensile strength. Therefore, threaded rebar

couplers used in this study can be used to connect the longitudinal reinforcements of the earthquake resistant reinforced concrete columns. Also, high stress cyclic test was conducted, as specified by KS D 0249[5]. The criteria of this test is that total slip of the bar within the splice after 30 cycles of tensile stress variation from 2% to 95% of the nominal yield strength shall not exceed 0.3 mm. Test results showed that slip of the bar within the splice after 30 cycles is 0.026 mm, which is under 0.3 mm of the allowable slip.

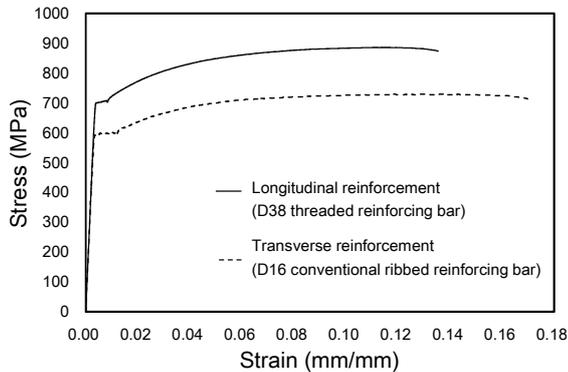


Fig. 3 Stress-strain relationship for reinforcements



Fig. 4 Test setup

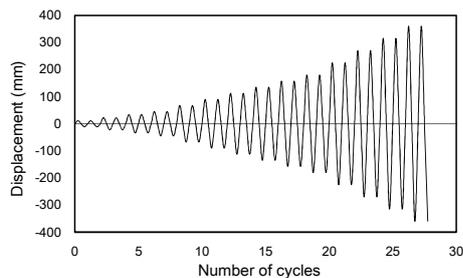


Fig. 5 Lateral loading history

C. Test Procedure

Fig. 4 shows the quasi-static test setup. The footing of the specimen was fixed by connecting it to the strong floor of the laboratory using high strength post-tensioning bars. A cyclic lateral load under a constant axial load was applied at the column top by 3,500 kN capacity hydraulic actuator. The lateral load was applied under displacement control by increasing lateral drift ratios of $\pm 0.25\%$, $\pm 0.50\%$, $\pm 0.75\%$, $\pm 1.00\%$,

$\pm 1.50\%$, $\pm 2.00\%$, $\pm 2.50\%$, $\pm 3.00\%$, $\pm 3.50\%$, $\pm 4.00\%$, $\pm 5.00\%$, and so on. Two cycles of each drift ratio were repeated as shown in Fig. 5. All specimens were tested under the $0.06f_{cu}A_g$ constant compressive axial load of 2,510 kN by 4,000 kN capacity hydraulic actuator.

During the test, the lateral loads and displacements were measured using a built-in load cell and a linear variable differential transducer (LVDT) of the hydraulic actuator, respectively. The strains in the longitudinal reinforcements were measured by electrical strain gauges.

III. EXPERIMENTAL RESULTS

The general behavior of each specimen is described as follows:

Specimens M0-S80—during the lateral drift ratio of 0.5%, the first flexural crack occurred near the bottom of the column. During the lateral drift ratio of 1.5%, flexural-shear cracks took place. During the lateral drift ratio of 2.5%, longitudinal reinforcements yielded, and the concrete crushed at the plastic hinge area. During the lateral drift ratio of 7.0%, longitudinal reinforcements buckled, and then transverse reinforcement ruptured due to the buckling of the longitudinal reinforcements. After the transverse reinforcement ruptured, buckling of the longitudinal reinforcements was severe and longitudinal reinforcement ruptured due to the low-cycle fatigue.

Specimens M100-S80—during the lateral drift ratio of 0.5%, the first flexural crack occurred near the bottom of the column. As lateral drift ratio increase, the number of the flexural cracks increased and flexural crack width near the ends of the coupler increased more rapidly than other area (refer to Fig. 6). During the lateral drift ratio of 1.5%, flexural-shear cracks took place. During the lateral drift ratio of 2.5%, longitudinal reinforcements yielded, and the concrete crushed at the plastic hinge area. During the lateral drift ratio of 8.0%, longitudinal reinforcements buckled, and then transverse reinforcement ruptured due to the buckling of the longitudinal reinforcements. After the transverse reinforcement ruptured, buckling of the longitudinal reinforcements was severe and longitudinal reinforcement ruptured due to low-cycle fatigue.

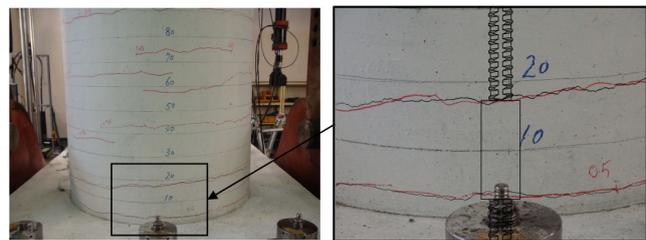


Fig. 6 Flexural cracks near the end of the coupler for M100-S80

Specimens M50-S80—during the lateral drift ratio of 0.5%, the first flexural crack occurred near the bottom of the column. As lateral drift ratio increase, the number of the flexural cracks increased and flexural crack width near the ends of the coupler increased more rapidly than other area (refer to Fig. 7). However, flexural crack width near the ends of the coupler of

M50-S80 specimen tend to be lesser concentrated than that of M100-S80 specimen. During the lateral drift ratio of 1.5%, flexural-shear cracks took place. During the lateral drift ratio of 2.5%, longitudinal reinforcements yielded, and the concrete crushed at the plastic hinge area. During the lateral drift ratio of 7.0%, longitudinal reinforcements without coupler buckled on the level at which mechanical couplers were installed. Longitudinal reinforcements with coupler buckled on the level above the coupler, which is similar to that of the other specimens. This is because there is the gap between the transverse reinforcement and the longitudinal reinforcement without mechanical coupler; on the contrary, longitudinal reinforcements with mechanical coupler were laterally confined by transverse reinforcements. Dividing buckling location of the longitudinal reinforcements into two levels caused to reduce the stress applied to the transverse reinforcements. Because of this, transverse reinforcements did not rupture and there was no severe buckling of longitudinal reinforcements. During the lateral drift ratio of 8.0%, longitudinal reinforcements ruptured.

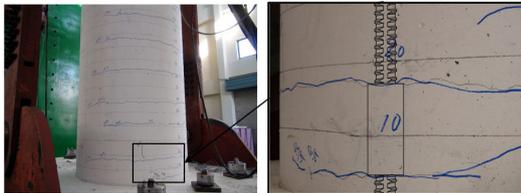


Fig. 7 Flexural cracks near the end of the coupler for M50-S80

The hysteretic response of lateral load-displacement of the specimens and failure modes of test specimens at end of test are presented in Fig. 8. The predicted strength F_n and maximum strength F_u , yield displacement Δ_y , ultimate displacement Δ_u , displacement ductility μ_Δ , yield stiffness k_y were summarized in Table III.

TABLE III
SUMMARY OF TEST RESULTS

Specimen	Load-carrying capacity		Deformation capacity			Yield stiffness (kN/mm)	
	Calc. (kN)	Test (kN)	Calc./Test	Yield (mm)	Ultimate (mm)		Ductility
M0-S80	854	1110	1.30	95	315	3.31	10.56
M100-S80	854	1064	1.25	109	360	3.31	8.40
M50-S80	854	1064	1.25	98	360	3.67	9.52

IV. ANALYSIS OF EXPERIMENTAL RESULTS

Ductility of the reinforced concrete columns can be quantitatively evaluated by displacement ductility factor μ_Δ as follows (Δ_y is the yield displacement, Δ_u is the ultimate displacement).

$$\mu_\Delta = \Delta_u / \Delta_y \tag{1}$$

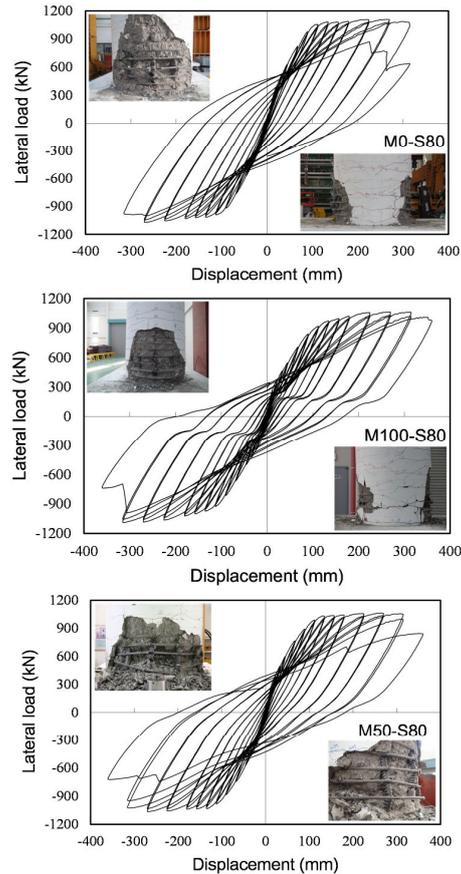


Fig. 8 Hysteretic response of lateral load-displacement

Fig. 9 shows how the yield displacement and the ultimate displacement are determined from the envelope of the load–displacement curve. The yield displacement is determined as the displacement corresponding to the intersection of the maximum lateral load and secant stiffness at 75% of maximum lateral load, which consider the reduction in stiffness due to cracking near the end of the elastic range. In case of the fracture of longitudinal reinforcements, the ultimate displacement is determined as the displacement corresponding to the drift ratio at the previous cycle just before the fracture of the reinforcements. When fracture does not occur in the reinforcements, the ultimate displacement is determined as the displacement corresponding to undergoing a 15% reduction in lateral load [6].

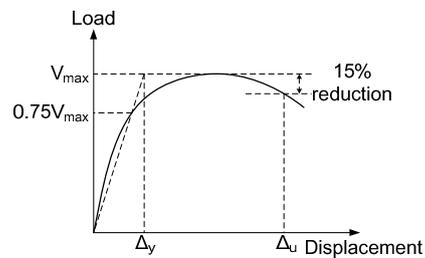


Fig. 9 Definitions for yield displacement and ultimate displacement

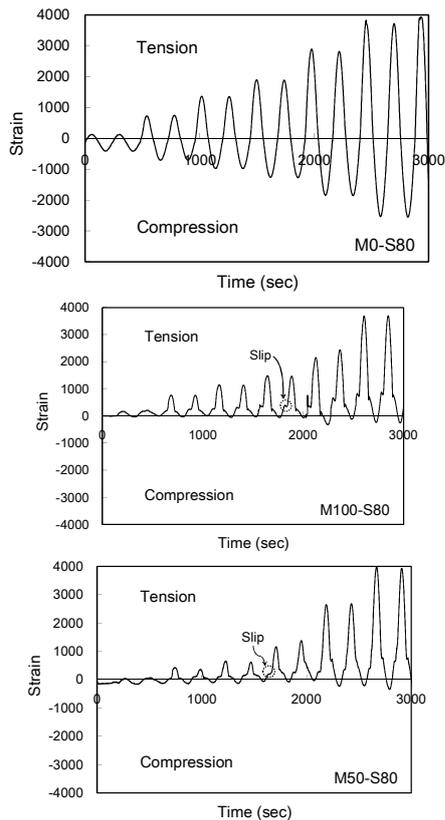


Fig. 10 Strains of longitudinal reinforcements

Fig. 10 shows the strain gage data just outside of the mechanical coupler of M50-S80 and M100-S80 specimens and on the same level of M0-S80 specimen. For M0-S80 specimen without mechanical couplers, strains of longitudinal reinforcement increased as drift ratio increase and were symmetrical in compression and tension. For M50-S80 with staggered mechanical couplers and M100-S80 of which entire longitudinal reinforcement were connected by mechanical couplers in one section, strains of longitudinal reinforcements tend to decrease in compression and increase in tension as drift ratio increase. Also, even though drift ratio increase, lateral load and longitudinal strains were temporarily constant at certain strain. This might be due to the slip between the longitudinal reinforcement and the mechanical coupler by loosening threads of mechanical couplers. Although, the mechanical couplers used in this study met the requirements of allowable slip in the high stress cyclic test as specified by KS D 0249 [5], this test specimens were under tension-tension state during high stress cyclic test. The longitudinal reinforcements of quasi-static test specimens, on the other hand, were under tension-compression state during the test. The mechanical couplers could be loosened while under tension-compression cyclic loading and this is the main cause of the slip between the longitudinal reinforcement and the mechanical coupler. Particularly, threaded rebar coupler was easily loosened than conventional ribbed rebar coupler because tolerance and rib face angle of the threaded rebar coupler system are greater than

that of a conventional ribbed rebar coupler system.

Fig. 11 compares the envelope of lateral load-displacement curve of the M0-S80, M50-S80, and M100-S80 specimens. These specimens showed the similar behavior until the lateral loads were 200 kN. However, above the lateral loads of 200 kN, stiffness of specimens decreased as connection ratio of mechanical couplers increase due to slip between longitudinal reinforcement and mechanical coupler (refer to Table III).

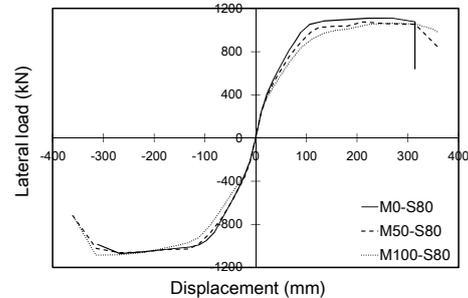


Fig. 11 Envelope of load-displacement curve

While yield displacement of M0-S80 specimen was 95 mm, yield displacements of M50-S80 and M100-S80 specimens were 98 mm and 109 mm, respectively. This is because slip between longitudinal reinforcement and mechanical coupler increased as connection ratio of mechanical couplers increase. While ultimate displacement of M0-S80 specimen was 315 mm, ultimate displacement of M100-S80 specimen was 360 mm due to the effect of slip between longitudinal reinforcement and mechanical coupler. Ultimate displacement of M50-S80 specimen was 360 mm, though slip of M50-S80 specimen is less than M100-S80 specimen. The reasons are as follows. The gap between the transverse reinforcement and the longitudinal reinforcement led to dispersing buckling location of longitudinal reinforcements. Transverse reinforcements did not rupture because dispersing buckling location of longitudinal reinforcements caused decreasing stress of transverse reinforcements. Transverse reinforcements delayed the low-cycle fatigue of longitudinal reinforcements. As a result, displacement ductility of M100-S80 specimen is 3.31, which is equal to that of M0-S80 specimen. Displacement ductility of M50-S80 specimen is 3.67, which is 11 % greater than that of M0-S80 and M100-S80 specimens.

V. CONCLUSIONS

In this study, the earthquake resistance of the reinforced concrete columns with threaded rebar coupler system was investigated. On the basis of the test results, the following conclusions can be drawn:

Threads of mechanical coupler used to connect the threaded reinforcing bar could be loosened while under tension-compression cyclic loading. This is because the longitudinal reinforcements of the reinforced concrete column specimens were under tension-compression cyclic loading state during the quasi-static test, even though the mechanical couplers used in this study met the requirements of allowable

slip in the high stress cyclic test as specified by KS D 0249. Particularly, threaded rebar coupler was easily loosened than conventional ribbed rebar coupler because tolerance and rib face angle of the threaded rebar coupler system are greater than that of a conventional ribbed rebar coupler system. Consequently, when using the threaded rebar coupler system under tension-compression cyclic loading state, cracks were concentrated just outside of the mechanical coupler and stiffness of the specimen decreased. Therefore, when using the threaded rebar coupler system, it is recommended that connection ratio of mechanical coupler in one section shall be below 50% in order that cracks are not concentrated just outside of the threaded rebar coupler. Also, reduced stiffness of the specimen should be considered in design.

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Do-Kyu Hwang is Ph.D. student in Yeungnam University, Korea. He received BS and MS in civil engineering from Yeungnam University. His research interests include seismic design of bridge pier, bond, and development of reinforcement.

Ho-Young Kim is Ph.D. student in Yeungnam University, Korea. He received BS in civil engineering from Yeungnam University. His research interests include seismic design of bridge pier and lateral confinement of concrete.

Ho-Hyeoung Choi is MS student in Yeungnam University, Korea. He received BS in civil engineering from Yeungnam University. His research interests include seismic design of bridge pier and shear friction.

Gi-Beom Park is MS student in Yeungnam University, Korea. He received BS in civil engineering from Yeungnam University. His research interests include seismic design of bridge pier and size effect of shear.

Jae-Hoon Lee is professor of civil engineering at the Yeungnam University, Korea. He received his BS and MS in civil engineering from Seoul National University, and his Ph.D. in civil engineering from University of Wisconsin-Madison. His research interests include seismic design of bridge pier and design method of reinforced concrete structures.