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EVALUATION OF MECHANICAL ANCHORAGE OF REINFORCEMENT BY EXTERIOR BEAM-COLUMN JOINT EXPERIMENTS

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SUMMARY

Generally, a conventional 90 degree standard hook is used for the reinforcement's anchorage. However, this results in steel congestion, and it makes fabrication and construction difficult. Using a mechanical anchor offers a potential solution for these problems and may also ease fabrication, construction and concrete placement. To evaluate the performance of the mechanical anchor compared with that of the conventional standard hook, 2 sets of exterior beam-column joints were tested. One set was designed so that flexural failure of the beam would occur, and the other set was designed so that shear failure of the joint would occur.

The behavior of the specimens, where the mechanical anchor was applied, was very similar to that of the specimens where the standard hook was applied. The tests results show that the mechanical anchor has enough anchorage capacity in the exterior beam-column joints.

INTRODUCTION

The standard hook is used to anchor longitudinal re-bars that terminates within an exterior beam-column joint and shear re-bars, where straight development length cannot be achieved (Chun [1], Chun [2]). However, the use of a standard hook results in steel congestion, making the fabrication and construction difficult (Wallace [3]). In addition, the poor concrete placement due to congestion sometimes degrades the quality of structures. In the future, the anchorage of re-bars is expected to be more difficult as the strength of materials becomes higher.

Using a mechanical anchor offers a potential solution for these problems and may also ease fabrication, construction and concrete placement (Wallace [3], HRC [4], ERICO [5], KOBE STELL [6], and TOKYOTEKKO [7]). But, because of the complex stress flow in joints, there has not been a general model or design provision for the mechanical anchor. To develop the mechanical anchor for the longitudinal re-bar within the exterior beam-column joint, especially from the constructability and cost's viewpoints, the new mechanical anchor (Figure 1), with the minimum head plate, was proposed. The

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objective of this research was to conduct tests on large-scale connections to show the mechanical anchor's possibility to replace 90 degree standard hooks within exterior beam-column joints.

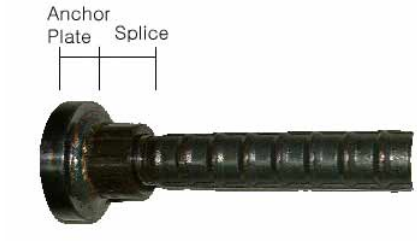
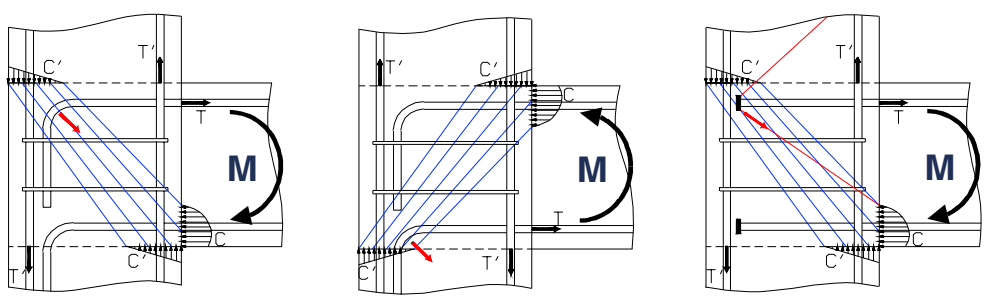


Figure 1 Mechanical Anchor

MECHANICAL ANCHORAGE

Figure 2 shows the state of the stresses in the exterior beam-column joints according to the anchorage methods of the longitudinal re-bars. In the design code (ACI [8] and KCI [9]), the anchorage capacity of the 90 degree standard hook is the same regardless of the hook direction. However, when the hook extension is placed inward toward the joint (Figure 2 (a)), the shear strength and the resistance to the cyclic load are better than the other case (Figure 2 (b)) (Paulay [10]). For the mechanical anchorage (Figure 2 (c)), the stress flow is favorable in any situation. Because the concrete strut (hatched area in Figure 2 (c)) and the local bearing stress at the anchor plate (2 inclined lines in Figure 2 (C)) coincide, the capacity of mechanical anchorage sufficiently increases only if the anchor plate is located within the concrete strut area.



(a) 90° Standard Hook (-) (b) 90° Standard Hook (+) (c) Mechanical Anchorage

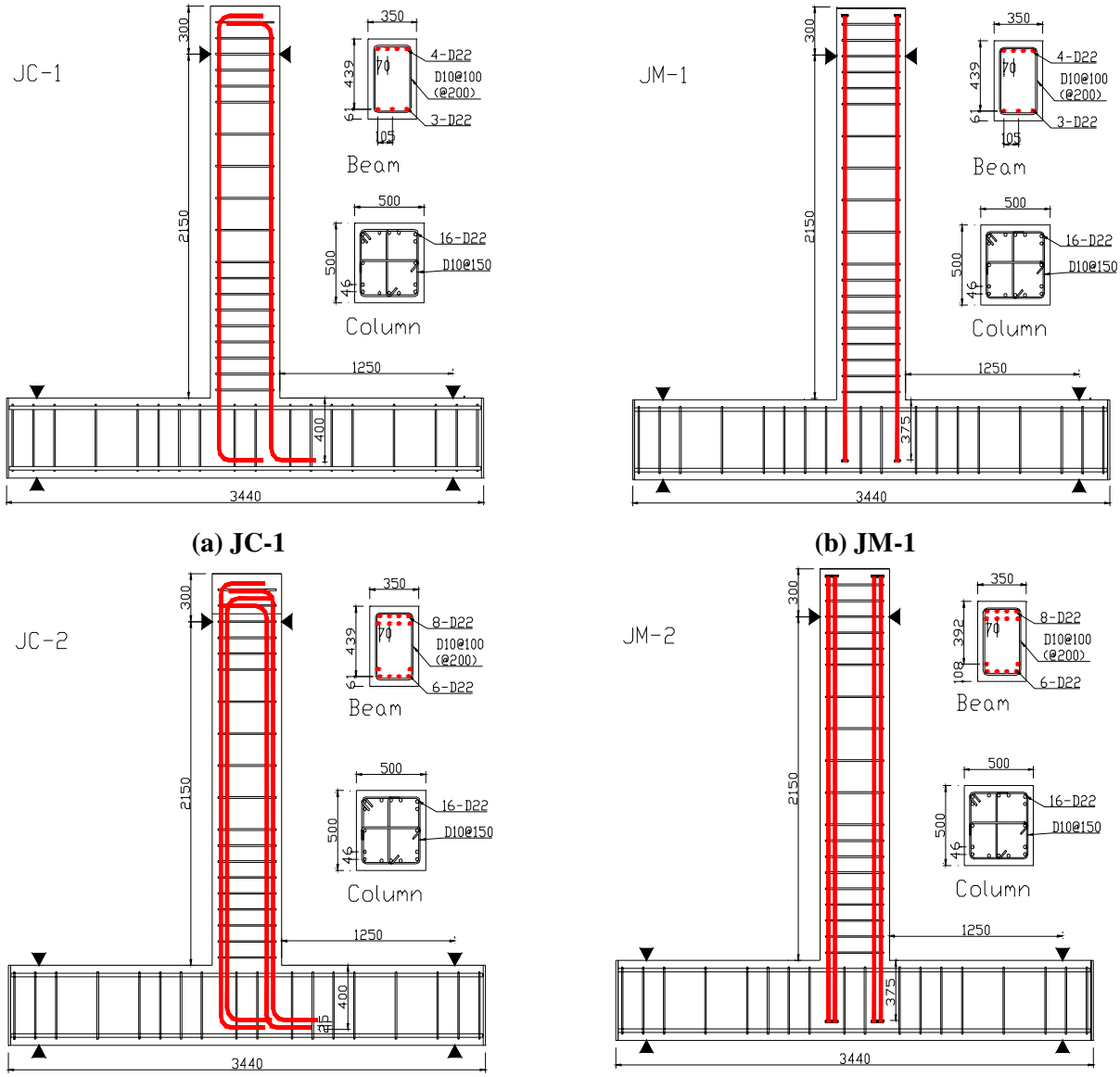
Figure 2 Mechanisms of Exterior Joint

EXPERIMENTAL RESEARCH PROGRAM

Geometry of Specimen

The prototype for the experiments was the exterior beam-column joint of upper stories in RC structure (Figure 4 (b)). The specimens represent sub-assemblies of a building subjected to lateral loads. Two sets of exterior beam-column joints were tested. One set (JC-1, JM-1) was designed so that flexural failure of beam would occur, and the other set (JC-2, JM-2) was designed so that shear failure of joint would occur, where C denotes 90 degree standard hook and M denotes mechanical anchorage.

The specimens of each set have the same geometry and the same material properties. The cyclic lateral loads were applied to the beam. The structural performance, such as strength, stiffness, ductility, slip of re-bars, the extent of joint damage and the energy dissipation were assessed.



(a) JC-1 **(b) JM-1**

(c) JC-2 **(d) JM-2**

Figure 3 Details of Specimens

Table 1 Test Matrix

Specimen	Expected Failure Mode	Anchorage	Beam			Column		
			B × H [mm]	Re-bars [upper/lower]	Stirrup	B × D [mm]	Re-bars	Hoop
JC-1	Beam Flexure Failure	90 degree hook	350 × 500	4-D22 3-D22	D10@200 (D10@100 in the vicinities of loading point and joint)	500 × 500	16-D22	D10@300-3 legs (D10@150 in the vicinities of reaction points and joint)
JM-1		Mechanical anchor						
JC-2	Joint Shear Failure	90 degree hook		8-D22 6-D22				
JM-2		Mechanical anchor						

The concrete compressive strength (f_c') of 40.8 MPa and the reinforcement yield strength (f_y) of 392 MPa were used for design purposes. D22 and D10 reinforcement were used for longitudinal and shear steel, respectively. The test matrix is shown in Table 1 and the overall dimensions for the specimens and the reinforcement details are presented in Figure 3.

Design of Specimen

The 90 degree standard hook was designed according to ACI [8], and the development length of mechanical anchor was three quarters of the column depth as Flat Nut (TOKYOTEKKO [7]). To prevent premature push-out failure, the compression anchorage was also checked according to KCI-99. To ensure the beam bars would be subjected to inelastic strain levels, the ratio of the beam flexural strength to the column flexural strength was over 1.4 as required by ACI-ASCE 352 [11]. The joint shear strengths (Q_{ju}) of JC-1 and JC-2 were calculated using ACI-ASCE 352 [11], and those of JM-1 and JM-2 were calculated as follows (TOKYOTEKKO [7]).

$$Q_{ju} \geq V_{ju} \quad (1)$$

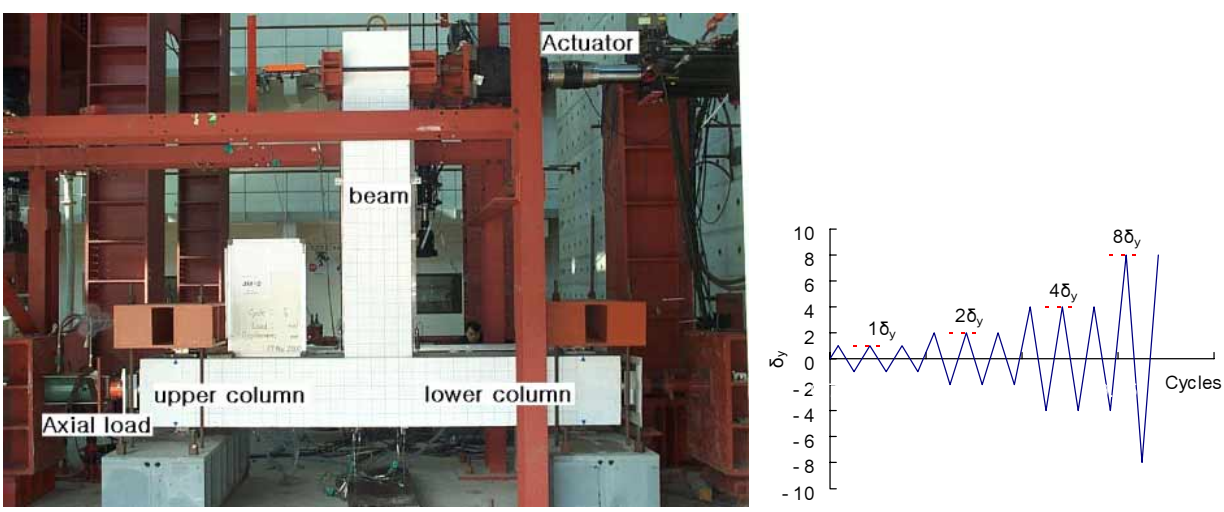
$$Q_{ju} = \kappa \phi F_j b_j D_j \quad (2)$$

$$V_{ju} = T_u - V_{col} \quad (3)$$

$$T_u = \alpha A_s f_y \quad (4)$$

$$V_{col} = 2\frac{M_b^{'} L_b}{L(H_c + H_c^{'})} \quad (5)$$

Where: V_{ju} is applied joint shear force; κ (= 0.7) is joint shape factor; ϕ (= 0.85) is coefficient depending on the existence of transverse beam; F_j = 0.8 $f_c'^{0.7}$ is concrete shear strength of joint in MPa; b_j is the effective joint width equal to the average of the beam width and the column width; D_j is the development length of re-bars; T_u is the ultimate tensile force of longitudinal beam re-bars; V_{col} is the column shear force; α (= 1.25) is the coefficient for the overstrength and strain hardening of re-bars; A_s is the area of re-bars; M'_b is the ultimate beam flexural strength considering α; L_b and L are the span and the clear span of beam, respectively; H_c and H'_c are the upper and lower story height, respectively.



(a) Test Setup **(b) Loading Schedule**

Figure 4 Test Setup and Loading Schedule

Testing Method and Data Acquisition

For a simple test setup, a cyclic lateral load was simulated by means of applying a load to the beam instead of the column as shown Figure 4 (a). Load was applied under displacement control as indicated in Figure 4 (c). To evaluate exact resistance to the cyclic load and ductility, 3 complete cycles were performed at each drift level. When obvious failure occurred, such as rupture and buckling of re-bars, or when the load was reduced to the 85% of peak load, the test was stopped. A 490kN (= $0.05A_gf_{ck}$) of axial load was imposed before applying cyclic load. The special device was attached to keep the axial load constant during the test. Instrumentation was used to measure the beam load, column axial load and beam displacement. To measure the beam displacement and the joint deformations without any slips of reaction points, the isolated reference frame was installed. Besides, the slips of re-bars at the end of the anchor were measured.

TEST RESULTS

The average concrete compressive strengths at the test date were 61.7 MPa (JC-1, JM-1) and 60.1 MPa (JC-2, JM-2). The measured yield strengths of re-bars were 383.9 MPa (D10) and 402.9 MPa (D22), respectively. The test results are summarized in Table 2, where the design strengths are calculated using the measured material properties.

Test Results of Beam Flexural Failing Specimens (JC-1, JM-1)

Overall Behavior

A typical flexural behavior, such as [tensile re-bars yield] -> [compressive concrete crushing] -> [compressive re-bars buckling] -> [strength reduction], was observed at both JC-1 and JM-1 (Figure 5). The measured yield strengths were very close to the designed values, and the measured flexural strengths sufficiently exceeded the designed values by 26~36%. The compressive concrete strength (61.7 MPa) at the test date was far higher than the design strength (39.2 MPa). The depth of the compressive concrete became shallow and the tensile re-bars underwent strain hardening. Consequently, the flexural strengths increased.

Specimen JC-1: At the first positive (+) cycle of $4\delta_y$ drift, even though the concrete crushing was initiated, the capacity didn't decrease. At the third positive (+) cycle of $8\delta_y$ drift, the compressive re-bars buckled and the load decreased (Figure 5 (a)).

Specimen JM-1: The overall behavior was so similar to that of JC-1. The concrete crushing occurred at the third + cycle of $8\delta_y$ drift, and the re-bars' buckling happened at the first + cycle of $12\delta_y$ drift. After that the load slowly decreased. However, at the negative (–) loading, even $12\delta_y$ drift the load was not reduced (Figure 5 (b)).

TABLE 2 Test Results

Expected Failure Mode	Specimen	Design Strength				Measured Strength		Ductility Ratio	Energy Dissipation
		Beam		Joint					
		M_y	M_n	$\phi_j V_{jn}$	V_{ju}	M_y	M_n		
Beam Flexure Failure	JC-1(+)	248	265	1,413	659	254	361	8	92
	JC-1(–)	188	204		492	187	257		
	JM-1(+)	248	265	1,359	659	233	335	12	137
	JM-1(–)	188	204		492	193	260		
Joint Shear Failure	JC-2(+)	419	478	1,394	1,341	450	563	8	126
	JC-2(–)	334	383		951	294	379		
	JM-2(+)	419	478	1,334	1,341	428	568	7	122
	JM-2(–)	334	383		951	355	407		

Where M_y, M_n, $\phi_j V_{jn}$ and V_{ju} mean yield strength, flexural strength, shear strength and applied shear force,

respectively. (+) or (−) means that upper or lower re-bars were subjected to tensile stress, respectively. Unit: kN, m

Damage of Joint

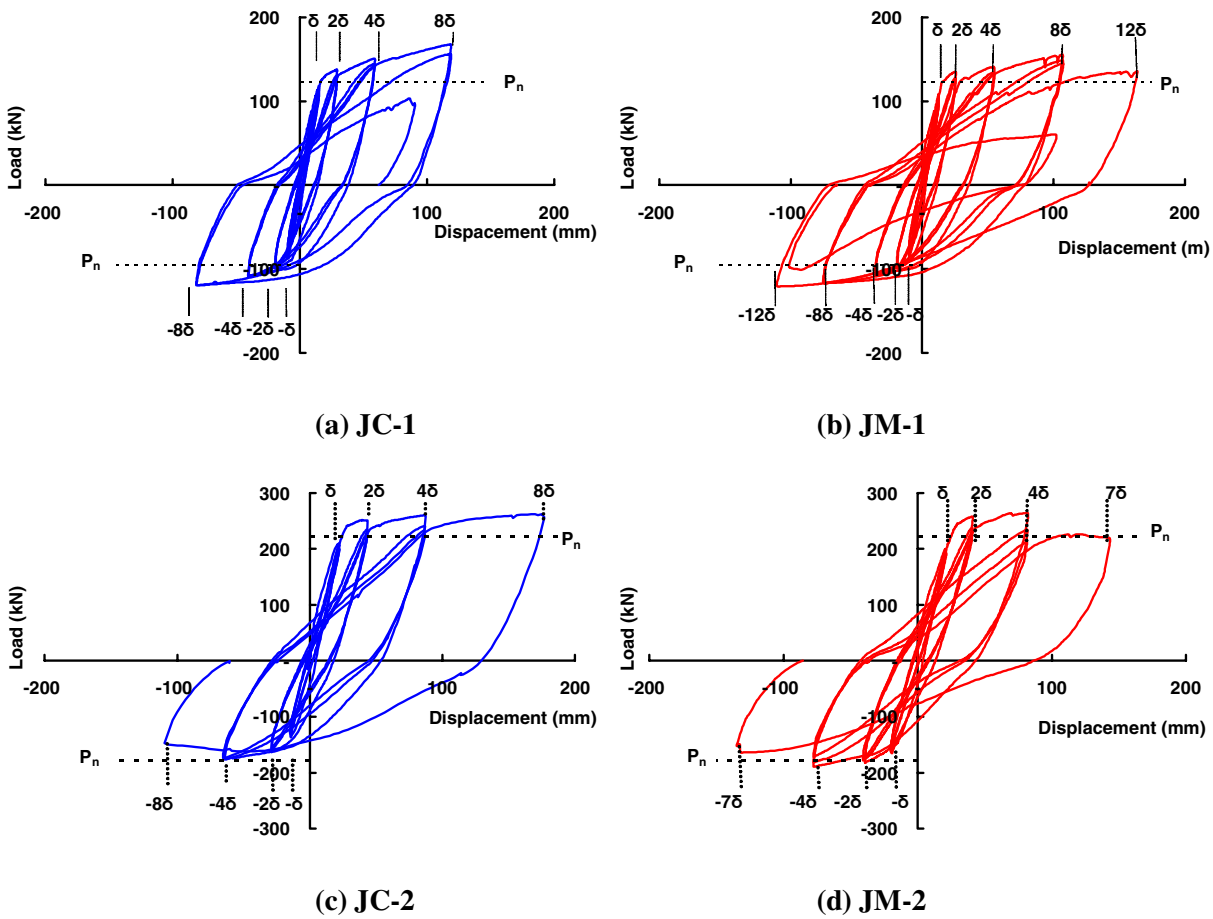
The first crack of joint for JC-1 occurred at the first + cycle of $1\delta_y$ drift, and for JM-1 did at the second + cycle of $1\delta_y$ drift. The crack of opposite direction occurred at − cycle and there were some flexural cracks at the columns. Compared with the beam end region, the joint and columns were very intact. Figure 6 (a) and (b) show that the joints of both specimens were very sound. Figure 5 (a) and (b) show that there was no reduction of load at the same drift cycles and the hysteresis loops are so stable that there is no pinching effect in both specimens.

Ductility

Since the shear re-bars were placed according to the seismic design provision (ACI [8]), the required ductility ratio of 4 for general RC frame could be achieved. The ductility ratio (μ) of JM-1 was 12 and was higher than μ of JC-1 (= 8).

Capability of Dissipating Energy

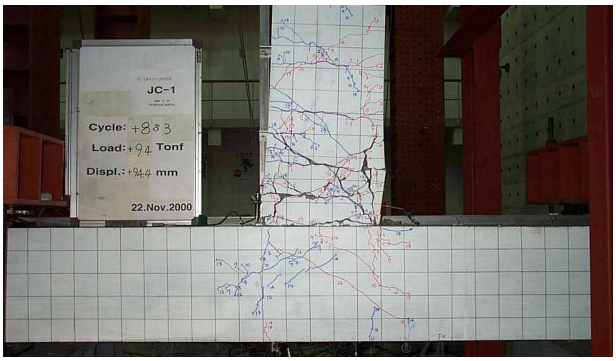
Figure 7 was plotted to evaluate the energy dissipation capability and shows the cumulative external work of each specimen. Until $8\delta_y$, the dissipated energies of both specimens were the same. However, JC-1 failed earlier than JM-1 thus JM-1 absorbed more energy.



(a) JC-1 **(b) JM-1**

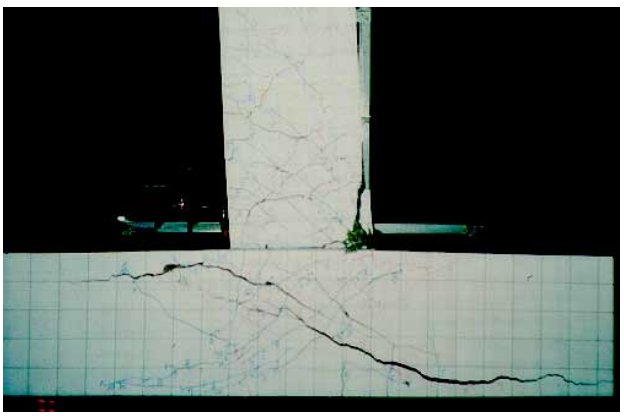
(c) JC-2 **(d) JM-2**

Figure 5 Load versus Displacement

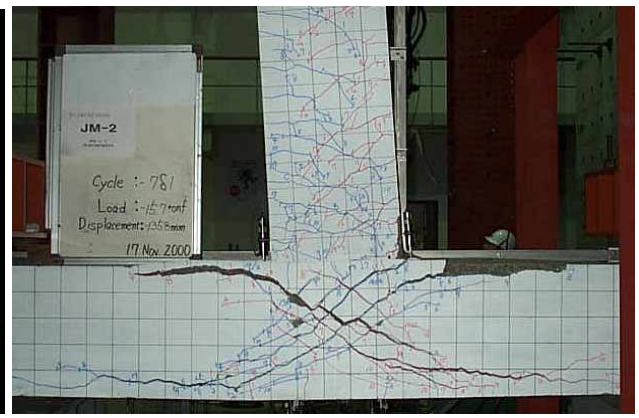


(a) JC-1

(b) JM-1

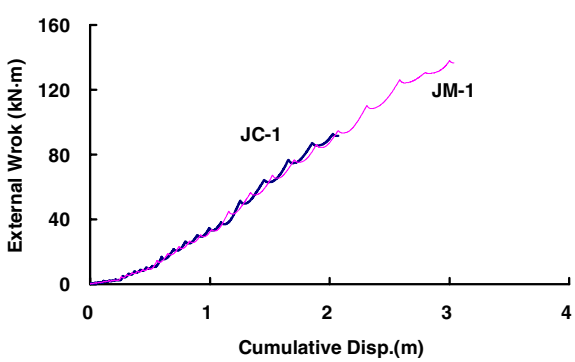


(c) JC-2

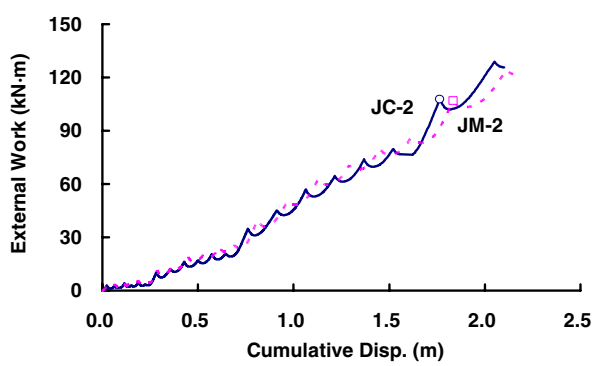


(d) JM-2

Figure 6 End of Test



(a) JC-1, JM-1



(b) JC-2, JM-2

Figure 7 Cumulative External Work

Test Results of Joint Shear Failing Specimens (JC-2, JM-2)

Overall Behavior

The compressive concrete strength at the test date was much higher than the value used in the design. Therefore, the joint shear failure took place after beam flexural yield (after yielding of tensile re-bars, compressive concrete crushed without compressive re-bars buckling).

Figure 5 (c) and (d) presents the load-displacement relationships, and they show that the overall behaviors were similar.

Specimen JC-2: Stable behavior was observed until + cycle of $8\delta_y$ drift, but at the − cycle the load was reduced because of the severe joint shear damage.
Specimen JM-2: Until $4\delta_y$ drift the conduct of JM-2 was similar to the JC-2, but the joint shear failure occurred at + cycle of $7\delta_y$ drift. Even though the joint was damaged severely at − cycle, the strength and deformation of negative (−) direction were better than those of JC-2.

Damage of Joint
From Figure 6, the damage of joints of J-2 specimens was more severe than that of J-1. The first crack of joint for JC-2 occurred at the first − cycle of $1\delta_y$ drift, and for JM-2 did at the first + cycle of $1\delta_y$ drift. Because of the severe damage of joints, the loads were reduced at the second cycle of $4\delta_y$ and pinching effects were severe, too.

Ductility
Despite the joint shear failure, the ductility ratios of JC-2 and JM-2 were 7 and 8 respectively, which were sufficiently high.

Capability of Dissipating Energy
Although the ductility ratio of JM-2 was lower than that of JC-2, with the excellent deformability JM-2 had the same energy dissipation as JC-2.

CONCLUSION

The standard hook is used to anchor longitudinal re-bars that terminates within an exterior beam-column joint. However, this may result in steel congestion, and it makes fabrication and construction difficult. The mechanical anchor can be an alternative to the 90 degree standard hook. In this research, the performance of the mechanical anchor was evaluated by exterior beam-column joint tests. Based on this study, the following conclusions were reached:

1) From the beam flexural failing experiments, the specimen (JM-1), where the mechanical anchor was applied, had similar yield strength, yield displacement and member capacity to those of the specimen (JC-1) where the hook was applied. In addition, the ductility ratio and the energy dissipation of JM-1 were better than those of JC-1.

2) From the joint shear failing experiments, the specimen (JM-2), where the mechanical anchor was applied, had similar yield strength, yield displacement and energy dissipation to those of the specimen (JC-2) where the hook was applied. Besides, the behavior of JM-2 at negative direction was better than JC-2, where the hook extension was placed outward from the joint.

From this study, it was validated that the mechanical anchor, in place of the standard hook, has enough anchorage capacity within the exterior beam-column joints. Especially, the mechanical anchor has better capacity than the standard hook of which the extension is placed outward from the joint.

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