Structural Performance of Reinforced Concrete Roof Exterior Beam Column Joint with Headed Bars

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SUMMARY:
Effective reinforcing method for knee joint to develop good seismic performance is discussed based on current experimental study, in case of no elongation of column and straight anchorage of beam main rebar in a joint using mechanical headed bars. The main objective of the test was to investigate the anchorage performance of beam main rebar. Reinforcing the end of beam main rebar by enclosed reinforcement or stick type reinforcement is effective to inhibit expanding of the diagonal crack in joint. Bond reinforcement by U-shaped bars is effective to prevent the anchorage failure of beam main rebar and to prevent deterioration of story shear until large story drift. Sufficient confining reinforcement for end of beam main rebar is important to develop the effect of by U-shaped bars. Reinforcing for bond along beam main rebar and confining end of beam rebar are significantly effective to inhibit the damage of concrete around anchorage plates and to keep the bearing capacity of concrete.

Keywords: Reinforced Concrete, Knee Joint, Mechanical Anchorage, U-shaped reinforcing Bar, Stick Type Bar

1. INTRODUCTION

Headed deformed reinforcing bars are becoming widely used for reinforced concrete high rise or relatively large buildings which are exposed earthquake or strong wind loads. Good anchorage performance is developed by bearing reaction of concrete around mechanical head of bars. Longitudinal bars in beams or columns are usually anchored within exterior beam column joints using headed bars for construction convenience. In a roof exterior (knee) beam column joint, longitudinal bars both in beam and column are anchored all together in the joint. However, in many researches, structural tests demonstrated brittle behaviour of the knee joint in case that headed bars are used as top bars of a beam straight in the joint due to the immediate deterioration of their anchorage capacity. Earthquake resistant performance and improvement method of the structural performance of knee joints using longitudinal headed bars both in beam and column are investigated by authors in a series of tests.

Based on the consideration for anchorage performance of headed bars and stress transfer mechanism by the formation of compressive strut in the joint, the following terms were chosen and combined as the test parameters, i.e., the elongation length of column from the roof level, quantity and shape of confined reinforcement for longitudinal headed bars at the top of column, anchorage method of beam top rebar, the ratio of shear strength of the joint to yield strength of the story and the ratio of yield strength between beam and column. Among above parameters, both elongation of column and confinement for column longitudinal headed bars are important to prevent brittle anchorage failure along top longitudinal headed bars of beam.

In this paper, effective reinforcing method for knee joint to develop good seismic performance is discussed based on current experimental study by authors, in case of no elongation of column and straight anchorage of beam main rebar in a joint using mechanical headed bars. In order to prevent brittle anchorage failure of beam main rebar, increasing of resistance for bond along main rebar and confining for the ends of main rebar were considered. U-shaped reinforcing bars and spiral reinforcement were chosen to improve bond resistance along anchored rebar. Enclosed reinforcement and stick type headed bar were chosen as effective confining reinforcement.

2. OUTLINE OF TEST

2.1. Specimens

Outline of specimens and reinforcement details are shown in Table 1 and Figure 1, respectively. Reinforcement in a column and a beam were common in all specimens. Confinement for main rebar at the top of column were also common using a set of □–D13 deformed bar of SD785, whose nominal diameter and nominal yield point was 13 mm and 785 N/mm^2, respectively. Ratio of flexural yield strength of column for that of beam was designed to be 1.0. All main rebar in column and beam were anchored straight within the joint using cap’s type anchorage metals at each end of rebar.

Table 1. Outline of Specimens

Specimen No.	Confinement for top main rebar of beam: 1)At the end of beam main rebar	Confinement for top main rebar of beam: 2)Vertical reinforcement along main rebar of beam	Common subject matter
AL2	None	None	Beam: b×D=360×430(mm), Main rebar 4-D19(SD390), Stirrup 2-D10,4-D10(SD295) alternate @100(mm) Column:b×D=480×480(mm), Main rebar8-D22(SD345), Hoop 3-D10(SD295)@100(mm) Joint: Hoop 3×2-D10(SD295A) Confinement for main rebar at the top of column □-13(SD785),3sets
BL1	a)Confined by enclosed reinforcement*1	None	
BL2		c)Confined by U-shaped rainforcing bars*3	
BL3	b)Confined by stick type reinforcement*2		
BL4		d)Confined by spiral reinforcement	
BL5		c)Confined by U-shaped rainforcing bars*3	

*1;4-D13(SD785), *2;BL3,BL4:4-D13(SD390), BL5:8-D13(SD390), *3;4-D13(SD295) 3sets

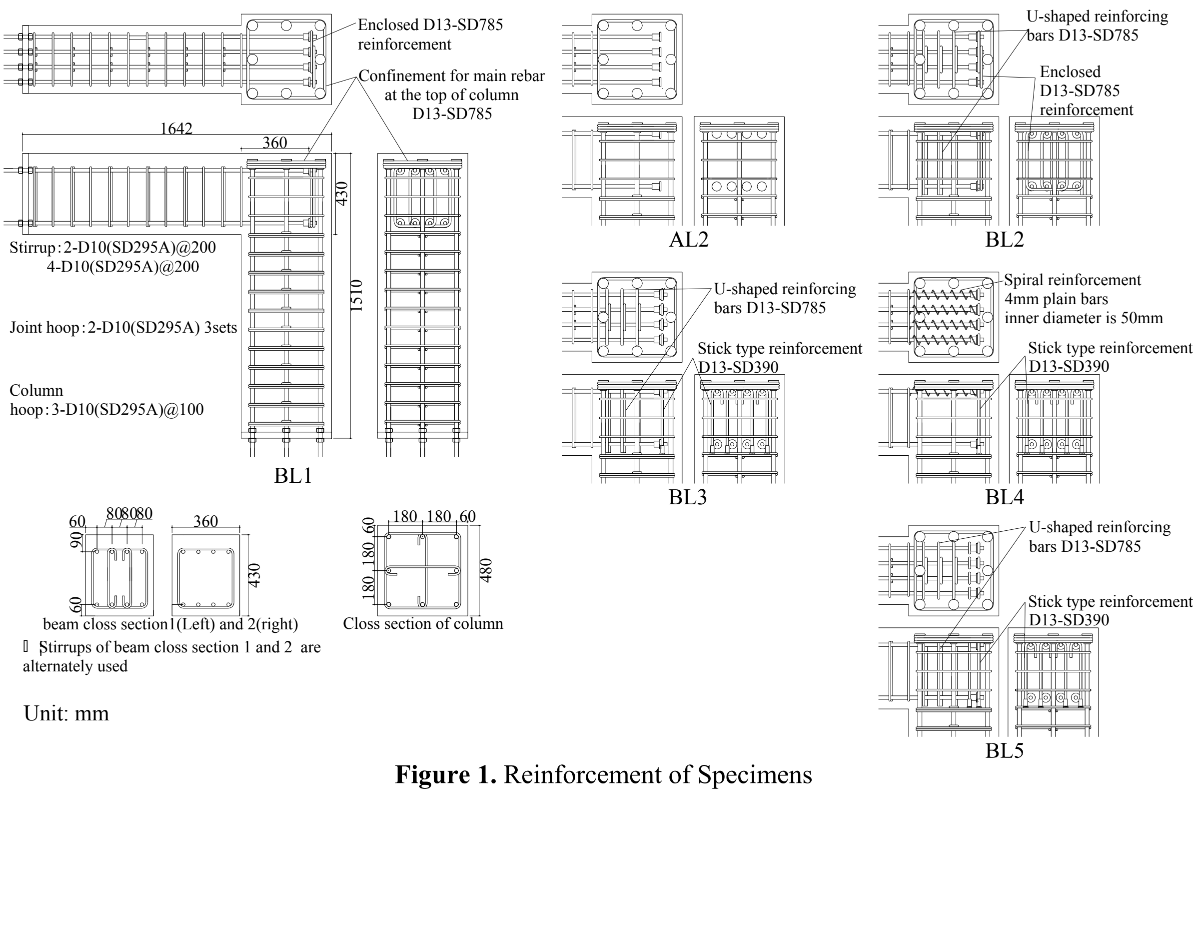


Figure 1. Reinforcement of Specimens

The main objective of the test was to investigate the anchorage performance of beam main rebar. Specimen AL2 with no reinforcement along beam main rebar and no confinement at the end of the rebar was predicted to collapse in brittle failure mode.

2.1.1. Confinement at the end of main rebar of beam

Typical stress condition around anchorage part of beam main rebar is illustrated in Figure 2. Rotation of beam at its hinged zone generates bond stress along rebar and tensile stress of cover concrete due to bending of the rebar. In specimen BL1～BL5, reinforcement vertical to the main rebar was arranged in order to reduce the stress in cover concrete and prevent the brittle concrete failure along the rebar. All ends of beam main rebar in specimens BL1 and BL2 were confined by two sets of enclosed D13-SD785 reinforcement whose yield tensile force was equivalent to the vertical tensile strength of cover concrete in the anchorage zone. Stick type reinforcement with steel plate at its end for anchorage is easier to arrange than enclosed type reinforcement. This type reinforcement 4-D13-SD390 with the same cross section area to two sets of enclosed D13-SD785 reinforcement was used as confinement at the end of beam main rebar in specimens BL3 and BL4. Stick type reinforcement 8-D13-SD390 was used in specimen BL5. The yielding force of the reinforcement at the end of main rebar in specimen BL1 and BL2 was almost twice to that in specimen BL3 and BL4, and almost equal to that in specimen BL5.

2.1.2. Bond reinforcement along main rebar of beam

In order to improve bond resistance between concrete and beam main rebar, U-shaped reinforcing bars of three sets of 4-D13-SD295 were arranged over the rebar in specimens BL2, BL3 and BL5. In specimen BL4, spiral reinforcement of 4 mm diameter with 50 mm in the collar inside diameter and 50 mm in the spiral pitch. In specimen BL1, no reinforcement was arranged for bond improvement.

2.1.3. Materials

Properties of concrete and reinforcement obtained from material tests are summarized in Table 2 and Table 3, respectively. Maximum diameter of coarse aggregate of concrete was 13 mm. Compressive strength of concrete σ_B was measured at the same age as the loading of each specimen.

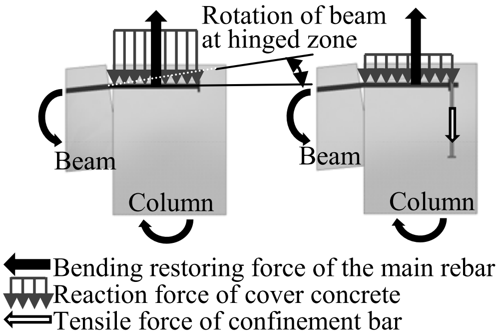


Figure 2. Resisting Mechanism of Beam Main Rebar Anchored in Joint

Table 2. Material Properties of Concrete

Specimen No.	σ_B N/mm^2	E_c ×10^{4}N/mm^2	σ_t N/mm^2
AL2	30.8	2.79	2.43
BL1	33.2	2.42	2.58
BL2	33.5	2.58	3.09
BL3	33.9	2.69	2.55
BL4	33.6	2.57	2.28
BL5	33.9	2.69	2.76

σ_B:Compressive strength, E_c:Secant modulus at 1/3, σ_t:Spilt tensile strength

Table 3. Material Properties of Reinforcement

Bar		normal diameter,mm /Type	Used specimen no.	f_y N/mm^2	f_u N/mm^2	ε_y %	E_s $\times 10^4$N/mm^2
D22	SD345	22/Deformed	AL2	377	553	0.207	18.3
			BL1-5	392	569	0.211	19.3
D19	SD390	19/Deformed	AL1	435	604	0.237	18.4
			BL1-5	458	635	0.246	19.9
D13	SD785	13/Deformed	AL2	846	1040	0.426	19.9
			BL1-5	821	1059	0.455	19.5
			BL1,2	806	1053	0.473	19.3
D13	SD290		BL2,3,5	368	532	0.187	19.7
D13	SD390		BL3,4,5	420	600	0.254	18.9
D10	SD290	10/Deformed	AL2	363	508	0.181	20.3
			BL1-5	368	517	0.194	19.7
φ4	SR295	4/Plain	BL4	347	514	0.197	18.6

f_y:Yield strength, f_u:Tensile strength, ε_y:Yield strain, E_s:Young's modulus

2.2. Loading Procedure

Loading apparatus in the test is shown in Figure 3. Knee joint specimens were supported at the assumed pin location after rotated 90 degrees. Cyclic loading simulating seismic loads was carried by a lateral 1000 kN hydraulic lack at the pin support of the column, maintaining a constant vertical level controlled by a vertical 1000 kN hydraulic jack. Loading direction was defined that closing of L-shape was positive and opening was negative. No long term axial force was applied to the column. However, varying axial force equivalent to shear force of the other member was acted on column and beam at any time during loading. Cyclic loading was controlled by increasing story drift R=±1/800rad, ±1/200rad, ±1/100rad, ±1/50rad, ±1/33rad, ±1/25rad, and finally up to +1/15rad in one way. The loading was duplicated twice at every amplitude, except for final one way loading.

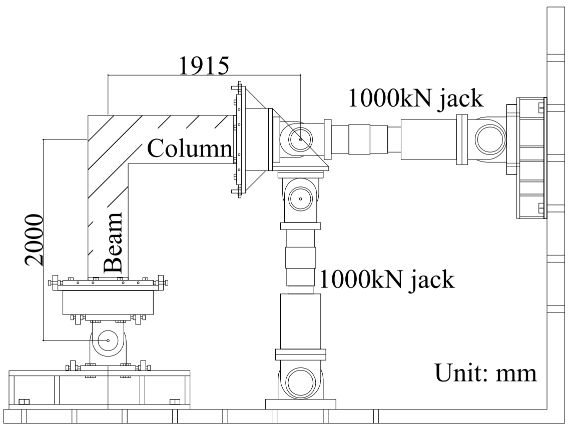


Figure 3. Loading Apparatus

3. TEST RESULTS AND DISCUSSIONS

3.1. Failure Process

Damages of every specimen by the loading are shown in Photo 1, Photo 2 and Photo 3. In all specimens, flexural cracks occurred at critical sections column and beam in the loading cycle of R=±1/800rad. Shear cracks occurred in the beam column joint in the first loading cycle of R=±1/100rad in specimens AL2, BL1, BL2 and BL3, and in the first loading cycle of R=＋1/100rad or R=－1/100rad in specimens BL4 and BL5.

In specimen AL2, no flexural yielding occurred in the positive loading direction due to anchorage failure of beam top main rebar. In specimens BL1～BL5, flexural yielding in beam was observed in both positive and negative loading cycles of R=±1/50rad. However, among these specimens, only in specimen BL1, anchorage failure of beam top main rebar was observed.

In specimens BL2 and BL5, flexural crack width opened in proportion as the story drift increased, but another damage has not been significant up to large deformation. Failure process in specimens BL3 and BL4 was almost same as that in specimens BL2 and BL5. However, final predominant damage was different as shown in Photo 1, where observed cracks (b) or (c) opened significantly. No distinguished damage of cover concrete in anchorage layer of beam top main rebar was observed in case that U-shaped reinforcing bars or spiral reinforcement were used with confining reinforcement for the ends of main rebar concurrently.

In all specimens, a diagonal crack occurred in the negative loading direction as shown as (d) in Photo 2. The width of diagonal crack was significantly large only in specimen AL2.

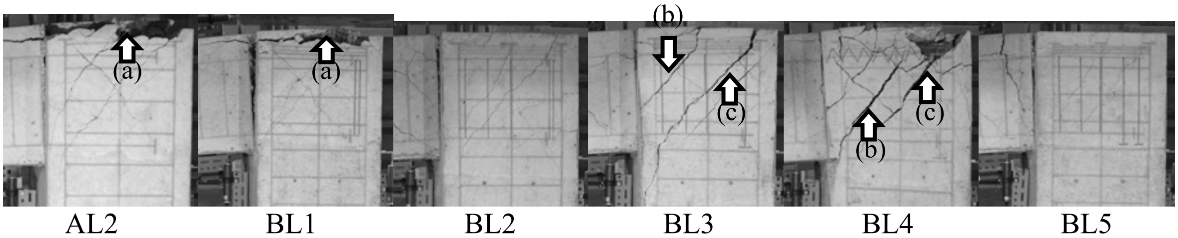


Photo 1. Damage View at Amplitude Peak, AL2: R=＋1/25rad, Others: R=＋1/15rad

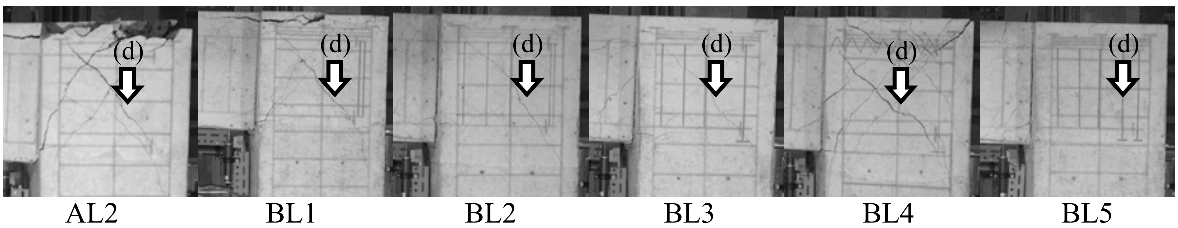


Photo 2. Damage View at Amplitude Peak, R=－1/25rad

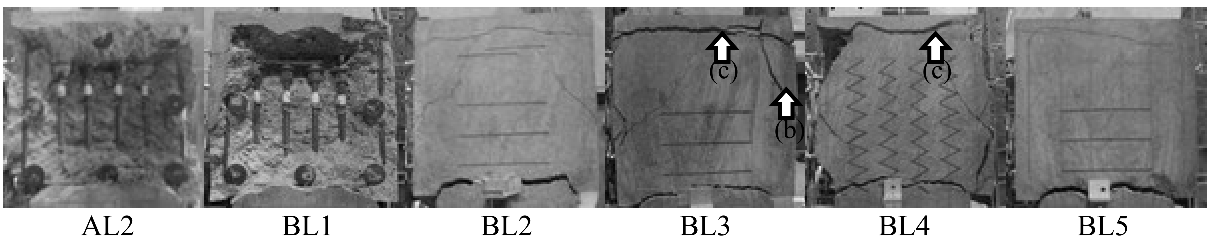


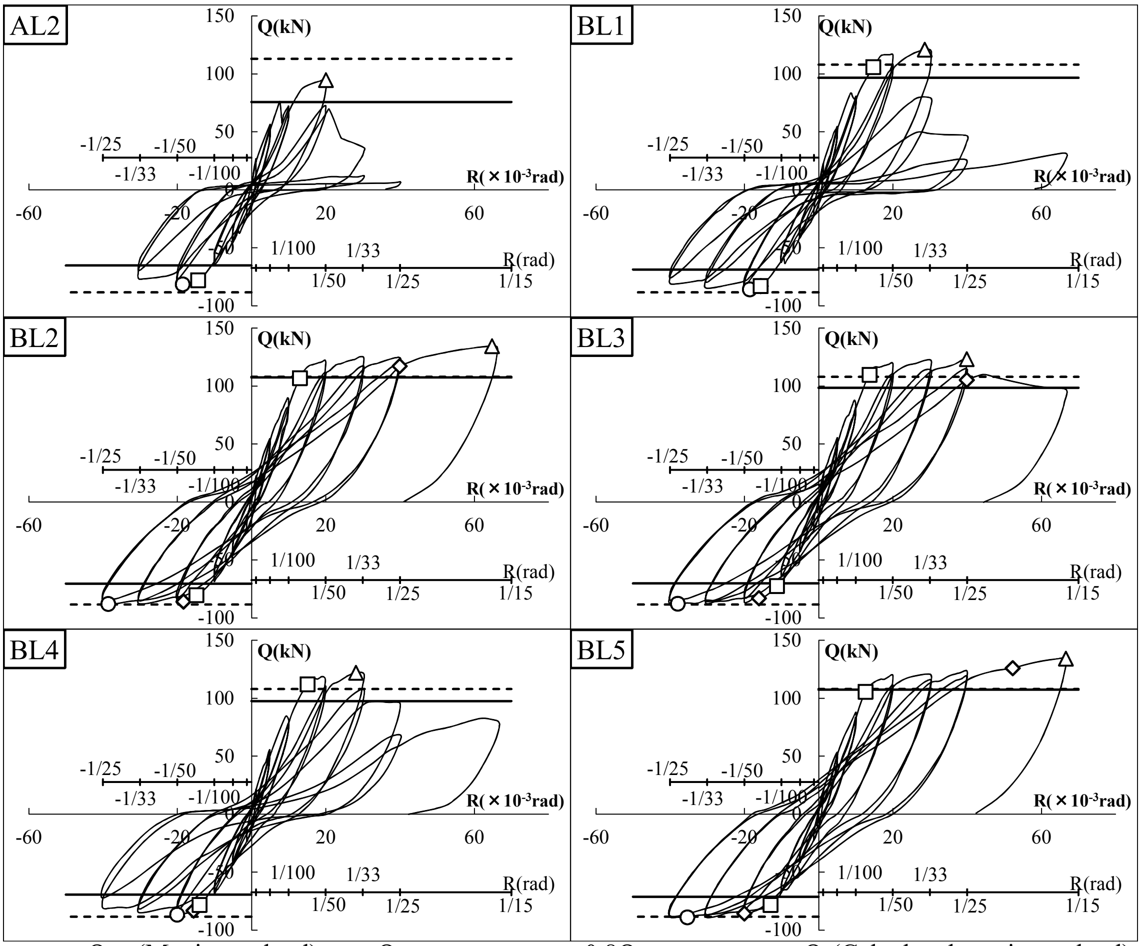
Photo 3. Damage View of Column Top after Loading

3.2. Restoring Force Characteristics

The relationships between story shear Q vs. story drift R of each specimen are shown in Figure 4. Test results are summarized in Table 4.

The Q-R relationships of specimens AL2 and BL1 demonstrated deteriorating characteristics and poor energy dissipating ability probably because of anchorage failure of beam main rebar. On the other hand, expected good energy dissipation ability was developed in specimens BL2, BL3 and BL5, which were strengthened bond resistance of beam main rebar by U-shaped reinforcing bars.

In the loading to positive direction, specimen AL2 has not reached to flexural yielding and deteriorated in the lateral capacity suddenly at R=＋1/50rad. Story shear of specimen BL1 deteriorated significantly in the second reversal during the loading of R=＋1/33rad. On the contrary, lateral resistance of specimens BL2 and BL5 well maintained to the drift of R=＋1/15rad without deterioration. In specimen BL3, the story shear started to deteriorate around the drift of R=＋1/25rad, and decreased to about 80 % of the maximum story shear in the positive direction. In specimen BL4, the story shear deteriorated to 80 % of the maximum story shear in the first loading cycle of R=＋1/25rad. Therefore, strengthening beam main rebar using U-shaped reinforcing bars or spiral reinforcement is much effective to improve the restoring force characteristics of knee joint frame, in case of straight anchorage of beam main rebar by mechanical anchorage method.



△:+Q_{max}(Maximum load), ○:-Q_{max}, ——— : ±0.8Q_{max}, - - - - - - : Q_u(Calculated maximum load)
□:Beam yielding, ◇:Column yielding

Figure 4. Story Shear Q vs. Story Drift R Relationship

Table 4. Test Results

	Specimen No.	AL2	BL1	BL2	BL3	BL4	BL5
Positive loading	Failure mode*1	A	B	C	D	D	C
	Maximum load Qmax(kN)*2	94.5	120.7	134.2	123.1	121.8	134
	Calculated maximum load Qu(kN)	111.5	117.2	117.2	117.2	117.2	117.2
	Story drift angle at maximum load ($\times 10^{-3}$rad.)	20.1	28.6	64.8	40	28.2	66.7
	R80*3($\times 10^{-3}$rad.)	20.1	30.3	≧70	61.7	36.7	≧70
Negative loading	Failure mode*1	C	C	C	C	C	C
	Maximum load Qmax(kN)*2	81.8	86	88.1	87.9	86.9	89.3
	Calculated maximum load Qu(kN)	88.6	93.1	93.1	93.1	93.1	93.1
	Story drift angle at maximum load ($\times 10^{-3}$rad.)	20	19.9	40	40.1	20	40
	R80*3($\times 10^{-3}$rad.)	≧30	≧40	≧40	≧40	≧40	≧40

*1
A:Anchorage failure
B:Anchoage failure after flexural yielding
C:Flexural yielding of Beam
D:Opening of diagonal crack in joint after flexural yielding

*2:Calculated story shear at beam flexural yielding based on measured material strength.Bending strength of beam wascalculated by the following formuras, considering varying axial force.

$M_u=0.8a_t \sigma_y D+0.5ND(1-N/(bDF_c))$ (N≧0) , $M_u=0.8a_t \sigma_y D+0.4ND$ $(N<0)$

M_u is ultimate moment; a_t is section area of tensile reinforcement; σ_y is tensile yield point of main rebar; D is full depth of the member; N is axial force; b is breadth of the member; Fc is compressive strength of concrete

*3:Story drift angle when story shear decrease to 80% of ultimate load.

In the negative loading direction, the observed strength was slightly lower than the calculated one in all specimens, probably because the compressive resultant at critical section of beam located lower than the assumed location in the calculation, influenced by the formation of compressive strut in the joint. However, the calculated strength was almost equivalent to the observed one in specimens reinforced by U-shaped reinforcing bars.

3.3. Effect of Confining Reinforcement for Beam Main Rebar

Locations of strain gauges on reinforcement in the joint are illustrated in Figure 5. Changes of strain at each location on the confining enclosed reinforcement or the stick type reinforcement are represented in Figure 6.

In all specimens, the strain of confining reinforcement increased after the drift of R=+1/100rad, when the diagonal cracks occurred in the joint. In specimens BL3 and BL4, immediately after the tensile yielding of confining reinforcement occurred, the diagonal cracks suddenly opened and the story shear deteriorated. This fact means that reinforcement for confining the end of anchorage portion is effective to prevent the development of diagonal crack in the joint. Behaviour of specimen BL5 was comparable well to that of specimen BL2, stick type reinforcement was effective to improve the seismic performance same as the enclosed reinforcement.

In specimen BL2, whose beam main rebar was confined by U-shaped reinforcing bars, no deterioration in the capacity was observed until large deformation, while in specimen BL1 without no U-shaped reinforcement, immediate deterioration occurred. The strain of the enclosed confining reinforcement in specimen BL2 was smaller than that in specimen BL1. The total yielding force of stick type confining reinforcement in specimen BL3 was almost half of that in specimen BL2. The performance of specimen BL3 was not so good as specimen BL2, as shown in Figure 4. However, the performance of specimen BL5 with equivalent yield tensile force of confining reinforcement as specimen BL2 developed well performance as specimen BL2. Therefore, in order to obtain good performance of knee joint with straight anchorage of beam top rebar, it is necessary not only to arrange the confining reinforcement along the main rebar, but to confine the end of the main rebar by enough reinforcement not to yield.

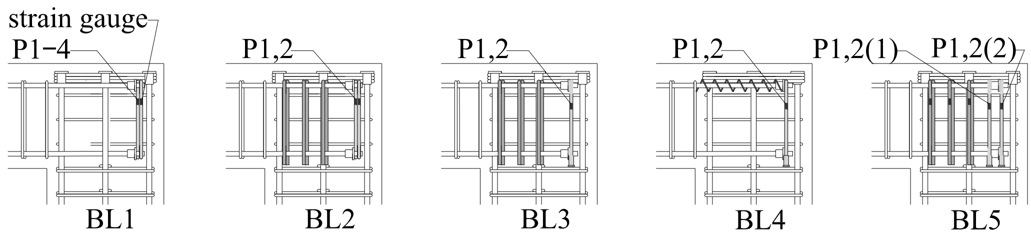


Figure 5. Location of Strain Gauges of Reinforcement

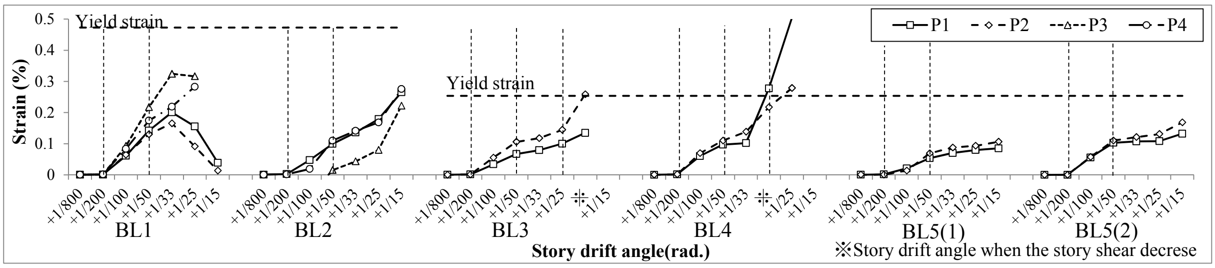


Figure6. Change of Strain in Enclosed Reinforcement (BL1, 2) and Stick Type Reinforcement (BL3, 4, 5)

3.4. Resistance of Beam Main Rebar in the Joint

Change of bearing force T1 of anchorage plate at the end of beam main rebar and tensile force T2 of beam main rebar at the critical section in the positive loading direction is represented in Figure 7. These forces were derived from measured strain at each location.

In all specimens, both T1 and T2 increased until R=＋1/50rad at which T1 reached tensile yielding, except for specimen AL2. Bond force derived by (T2－T1) were around 200 kN regardless of specimens parameter. Bearing force T1 increased after T2 reached tensile yielding in specimens BL2 and BL5, and finally reached almost tensile yielding at R=＋1/15rad. Bearing forces have not deteriorated until R=＋1/50rad even in specimens BL3 and BL4. Reinforcing for bond along beam main rebar and confining end of beam rebar are judged to be significantly effective to inhibit the damage of concrete around anchorage plates and to keep the bearing capacity of concrete.

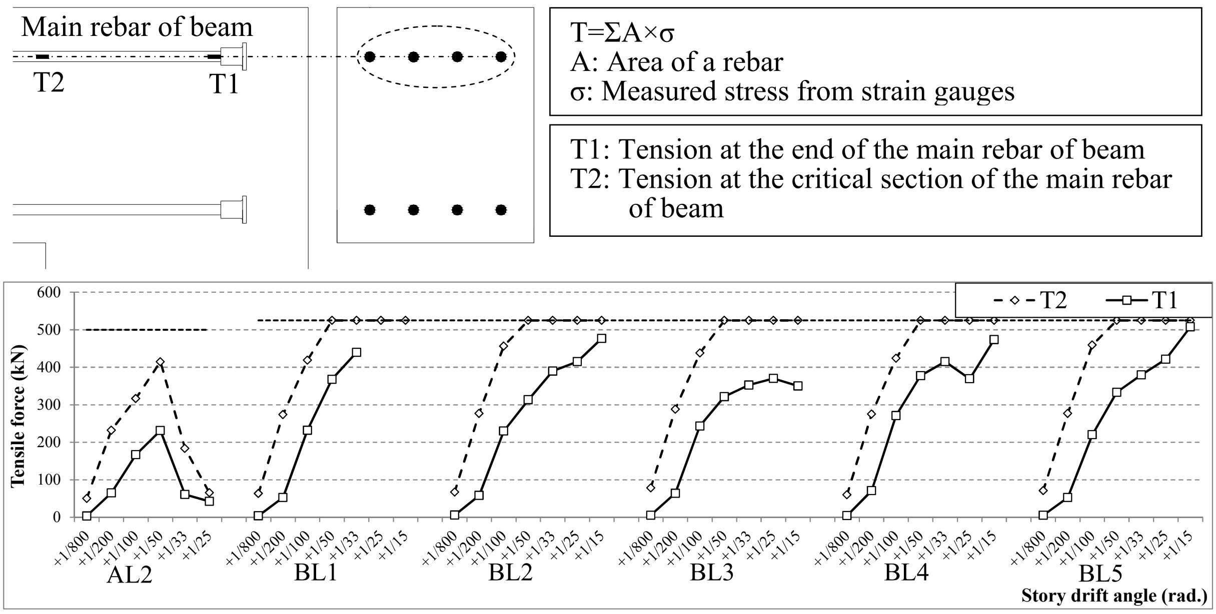


Figure7. Change of Bearing Force T1 and Tensile Force T2 of Beam Main Rebar

4. CONCLUSIONS

Seismic performance of reinforced concrete roof exterior beam column joint was studied experimentally, in case of mechanical anchorage of main rebar straight in the joint. The effectiveness of reinforcing method for bond along anchorage rebar and confinement for the end of the rebar was investigated. The main findings are summarised as follows.

(1) Reinforcing the end of beam main rebar by enclosed reinforcement or stick type reinforcement is effective to inhibit expanding of the diagonal crack in joint.
(2) It is difficult to obtain good structural performance under no bond reinforcement for beam main rebar. Bond reinforcement by U-shaped reinforcement bars is effective to prevent the anchorage failure of beam main rebar and to prevent deterioration of story shear until large story drift.
(3) Sufficient confining reinforcement for end of beam main rebar is important to develop the effect of by U-shaped reinforcing bars.
(4) Reinforcing for bond along beam main rebar and confining end of beam rebar are significantly effective to inhibit the damage of concrete around anchorage plates and to keep the bearing capacity of concrete.

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