Anchorage Failure and Shear Failure of RC Exterior Beam-Column Joint

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SUMMARY:
In the exterior column in RC building, beam longitudinal bars are generally bent into beam-column joint or an anchorage device is set at the end of bar to keep anchorage performance. In this portion, not only shear failure but also anchorage failure should be considered in structural design. The statistical analysis using the experimental data of 138 specimens showed that the equation defined in Architectural Institute of Japan (AIJ) guideline makes safety estimation for joint shear failure. If a large number of longitudinal bars in beam like as a foundation beam, the anchorage failure will occur prior to beam yielding. Experimental work was carried out using pull-out specimens and beam-column sub-assemblage specimens of exterior beam-column joint, which has multi-layered arrangement of beam bars. From both consideration, the mechanism of shear and anchorage failure of RC exterior beam-column joint is discussed and the evaluation of strength for each failure is shown.

Keywords: Reinforced concrete (RC), Exterior beam-column joint, Anchorage failure, Shear failure

1. INTRODUCTION

Moment resisting frame are generally designed as weak beam - strong column concept, to acquire large energy dissipation by beam yielding at beam ends during severe earthquake. The structural designers make appropriate margin in the strength of undesirable failure types like as column shear or brittle failure, compare to the strength of beam flexural. In the exterior column in reinforced concrete (RC) building, beam longitudinal bars are generally bent into beam-column joint or an anchorage device is set at the end of bar to keep anchorage performance. As beam-column joint generally suffers large shear force during earthquake, structural designers should make large margin for joint concrete volume to decrease joint shear stress for preventing shear failure, which means that the development length of beam bars in the joint should be made larger. But it becomes difficult because the reinforcing bar is complicated in the joint due to the existing of transverse members. In case that development length is not enough, anchorage failure is also expected to occur in addition to shear failure. Anchorage failure of hooked bar is considered as 3 types, that are side split, local compressive and raking-out failure. Among these failure types, raking-out failure tends to occur in case of lack of development length, which is focused in this study.

1.1. Shear failure of exterior beam-column joint

Fig. 1.1 shows a typical detail of exterior beam-column joint and acting horizontal forces. As acting load becomes lager, the compressive stress generates at inside of bent portion of beam bars with the deterioration of bond performance in straight portion. Joint shear is considered to be transferred by both of compressive force in concrete strut formed between bent portion and beam compressive zone and tensile force generating in joint transverse reinforcement after concrete cracking. Joint shear strength is decided by compressive fracture of concrete strut or yielding of joint reinforcement. AIJ (Architectural Institute of Japan) design guideline (AIJ 1999) defines the equation for joint shear strength as Eqn. 1.1 on the condition of minimum joint reinforcement volume of 0.3%, where joint reinforcement is not considered. This design equation intent to give the shear strength at story displacement of beam yielding and it tends to show the safety estimation.

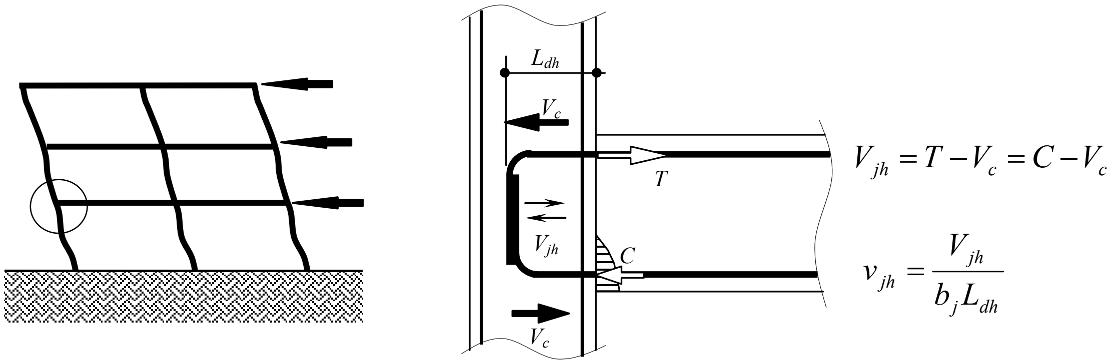


Figure 1.1. Acting Force at Exterior Beam-Column Joint

$$V_{ju} = \kappa \phi F_j b_j D_j \tag{1.1}$$

where,

κ : coefficient for joint configuration, κ=0.7 for exterior joint
ϕ : coefficient of existence of transverse beams, ϕ=1.0(both side), 0.85(others)
F_j : fundamental joint shear strength, F_j=0.8$\sigma_B^{0.7}$(N/mm^2)
σ_B : concrete compressive strength
b_j : joint effective width,
D_j : column depth (interior joint) or development length L_{dh} of hooked bar (exterior joint)

1.2. Anchorage failure of exterior beam-column joint with hooked bar

Tree types of anchorage failure of hooked bar are defined in AIJ design guideline as follows (see Fig. 1.2);

A. Side splitting failure: Concrete located adjacent side of bent portion is fractured in split, when the thickness of cover concrete is not appropriate
B. Local compressive fracture: Concrete located inside of bent portion is fractured by bearing stress, when bent radius of reinforcement is not enough large
C: Raking-out failure: Concrete located in front of bent portion is raked out as one body

All types of anchorage failure are caused by large compressive stress generated inside of bent portion. Type-A and Type-B are able to avoid by means of detailing of reinforcement or cover concrete. Joh et. al (1993) made some experimental study on raking-out type of anchorage failure and proposed the equation for estimating the strength of this failure as Eqn. 1.2 by modelling shown in Fig. 1.3, where the contributions of concrete and transverse reinforcement are considered.

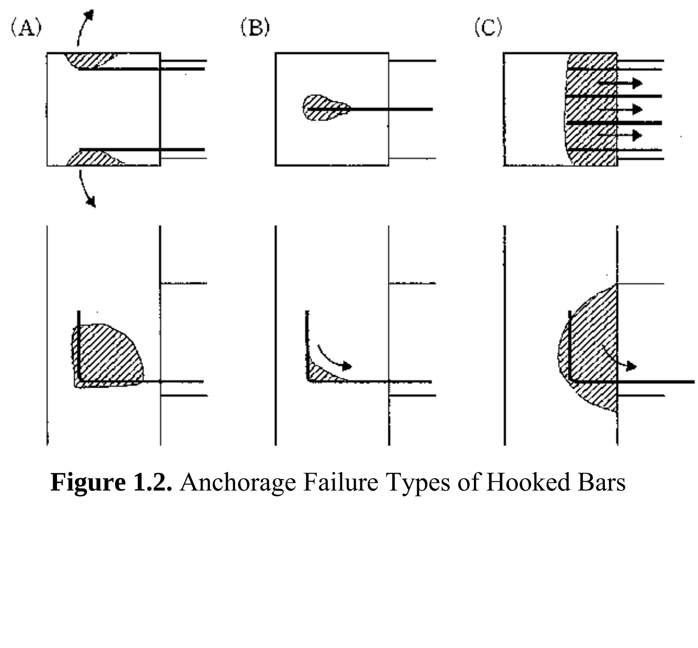


Figure 1.2. Anchorage Failure Types of Hooked Bars

$$T_{AR} = T_c + T_w \tag{1.2}$$

where,

$$T_c = 0.626 \cdot l_{dh} \cdot b_e \sqrt{\sigma_B} \cdot \left(1 + 6.32\,\sigma_0 / \sigma_B\right) / \sin\theta \tag{1.3}$$

$$T_w = k_w \cdot a_w \cdot \sigma_{wy} \tag{1.4}$$

T_c : component of concrete (N)
T_w : component of transverse reinforcement (N)
l_{dh} : length of failure area $l_{dh} = L_{dh} - d_b/2$
b_e : effective joint width
σ_B : concrete compressive strength(N/mm^2)
σ_0 : column axial stress (compression is positive)
θ : strut angle (degree)
k_w : effective coefficient of reinforcement (=0.7)
a_w : total area of transverse reinforcement located within of l_{dh} from beam bar
σ_{wy} : yielding strength of transverse reinforcement (N/mm^2)

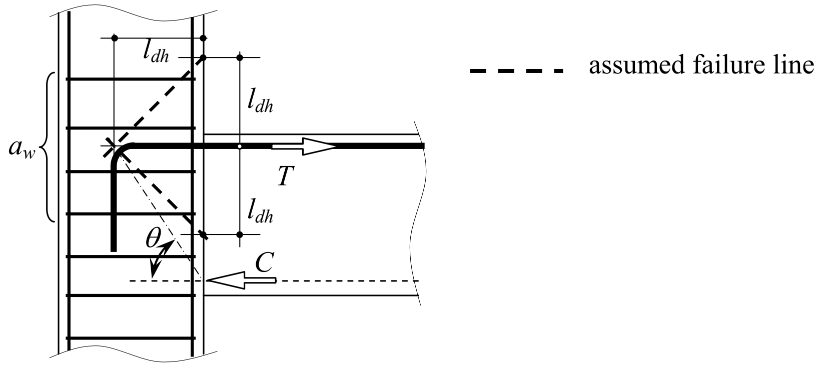


Figure 1.3. Calculate Model of Raking-out Anchorage Failure (Joh et. al)

1.3. Objective of this study

The purpose of this study is to clarify the relationship of joint shear and anchorage failure by means of both statistical analysis with previous experimental study and experimental work using exterior beam-column sub-assemblages. In particular, if a large number of longitudinal bars in beam like as a foundation beam, the anchorage failure will occur prior to joint shear failure or beam yielding.

2. STATISTICAL ANALYSIS USING PREVIOUS EXPERIMENTAL RESULTS

2.1. Experimental Database of Exterior Beam-Column joint

Statistical analysis was carried out to examine the correspondence of observed failure mode and the failure type predicted by proposed equation. Experimental data of 138 specimens were quoted from the technical papers which were presented by Japanese researchers at AIJ and JCI (Japan Concrete Institute) annual meeting from 1972 to 2010. The properties of specimens are shown in Table 2.1 and 2.2.

Table 2.1. Failure Mode of Specimens (Test Result)

Failure Mode	symbol	specimen
Joint shear	JS	50
Beam yielding →Joint shear	BY-JS	65
Column yielding →Joint shear	CY-JS	7
Raking-out	AR	10
Beam yielding →Raking-out	BY-AR	6
total		138

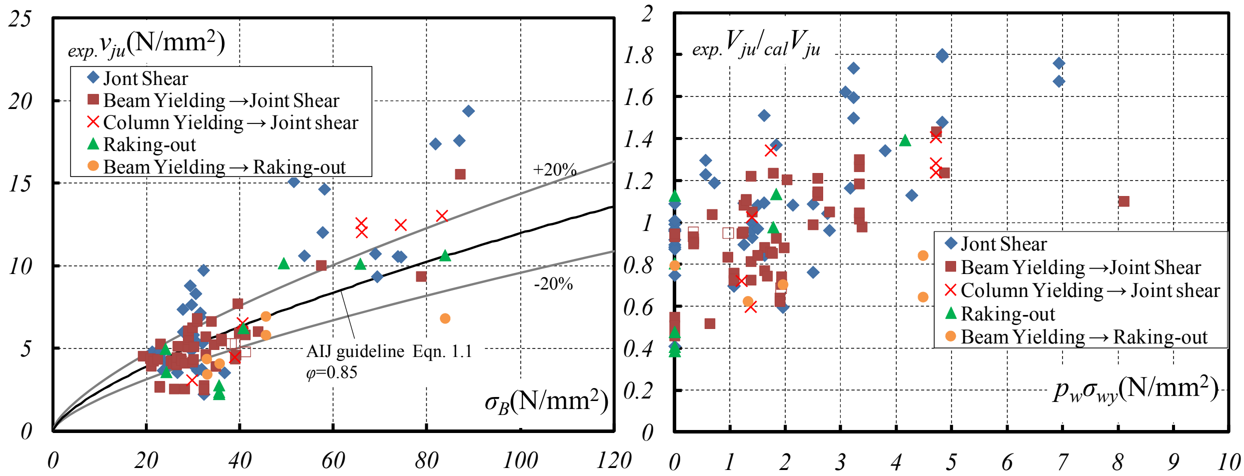
* Failure mode is decided by researchers

Table 2.2. Properties of Specimens

125×125	≦	Column section b_c(mm)×D_c(mm)	≦	540×540
90×140	≦	Beam section b_b(mm)×D_b(mm)	≦	365×560
19.2	≦	Concrete compressive strength (N/mm^2)	≦	88.8
196	≦	Yielding strength of joint reinforcement (N/mm^2)	≦	1392
0	≦	Joint reinforcement ratio (%)	≦	1.27
338	≦	Yielding strength of column main bar (N/mm^2)	≦	1122
171	≦	Yielding strength of column hoop (N/mm^2)	≦	1392
329	≦	Yielding strength of beam main bar (N/mm^2)	≦	1091
171	≦	Yielding strength of beam stirrup (N/mm^2)	≦	1392

2.2. Consideration on Statistical Analysis

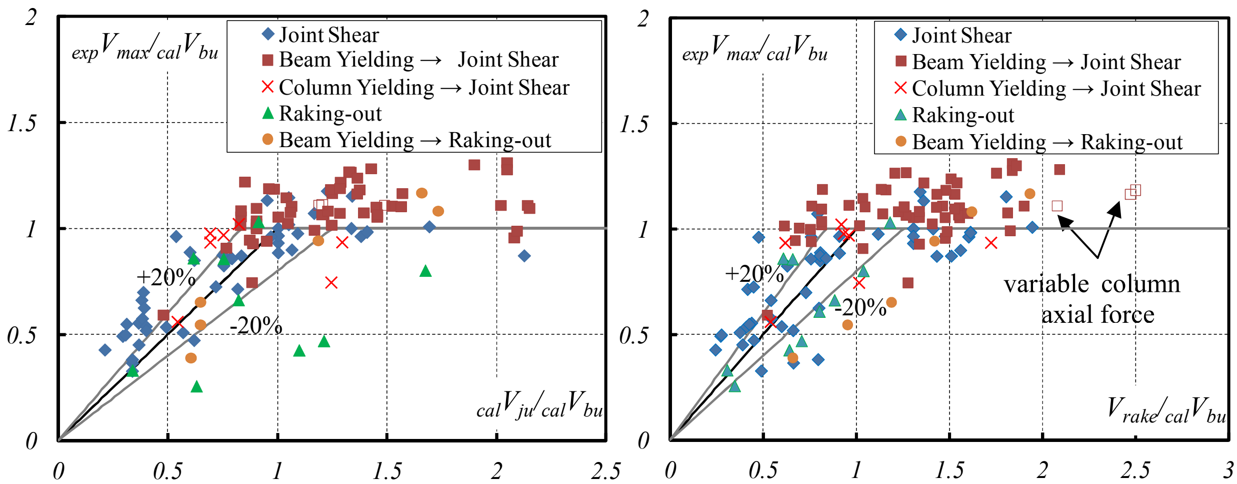
Fig. 2.1(a) shows the relationship between maximum joint shear stress v_{ju} and concrete compressive strength. AIJ design equation roughly predicts minimum strength of specimens failed in joint shear.



(a) Maximum Strength - Concrete Strength **(b)** Exp/Cal of Joint Strength- Joint Reinforcement Strength

Figure 2.1. Relationship of Shear Strength and Parameters

Some specimens show a larger strength than predicted values; this is because that shear strength becomes larger in proportion to shear reinforcement strength shown in Fig. 2.1(b). This result shows that joint reinforcement becomes effective on shear resistance at ultimate stage.



(a) Joint Shear strength **(b)** Raking-out Anchorage failure

Figure 2.2. Verification of Proposed Equation

For the verification of proposed equation for joint shear and raking-out anchorage failure, each value of experimental and calculated is divided by beam flexural strength calculated by Eqn. 2.1, which results are shown in Fig. 2.2.

$$V_{bu} = M_{bu} / l_b \tag{2.1}$$

where,

$M_{bu} = 0.9 a_t \cdot \sigma_y \cdot d$: beam flexural strength (moment)

l_b: shear span of beam

a_t : total area of beam tensile reinforcement

σ_y : yielding strength of beam longitudinal reinforcement

d : beam effective depth

The maximum strength of specimens, in which beam yielding occurred at first, was decided by beam flexural, and the equation for raking-out failure gives the mean value of test results. From Fig. 2.2(b), Eqn. 1.2 makes overestimation on the specimen with large beam flexural strength, which means the raking-out failure tends to occur in case of the large amount of beam bars are arranged.

3. EXPERIMENTAL WORK ON EXTERIOR BEAM-COLUMN JOINT

3.1. Objective of Experimental Works

The equation for raking-out anchorage failure of Eqn. 1.2 was proposed from the experimental results, where specimen has single layered arrangement in beam longitudinal reinforcement. If a large number of longitudinal bars provided in beam like as a foundation beam, multi-layered arrangement of beam bars is to be adapted and the larger flexural strength of beam leads the anchorage failure prior to beam yielding. On the other hands, structural designers should make large margin for joint concrete volume to decrease joint shear stress for preventing joint shear failure, which means that the development length of beam bars in the joint should be made larger. But it becomes difficult because the reinforcing bars are complicated in the joint due to the existing of transverse members. In case that development length is not enough, anchorage failure is also expected to occur in addition to shear failure. In this study, two experimental works were carried out to investigate the behaviour of RC exterior beam-column joint with multi-layered arrangement of beam bars, which were pull-out loading test with column shape specimens and cyclic shear loading test with sub-assemblage specimens.

3.2 Pull-out Test

3.2.1. Specimens and Loading Setup

Half scale ten specimens were prepared for pull-out test to examine the influence of anchorage details on raking-out anchorage failure shown in Fig. 3.1, which have different in development length, number of bar layer, concrete strength and so on as shown in Table 3.1. Pull-out specimen is a part of column with beam bars, where beam concrete and compressive beam bars are omitted.

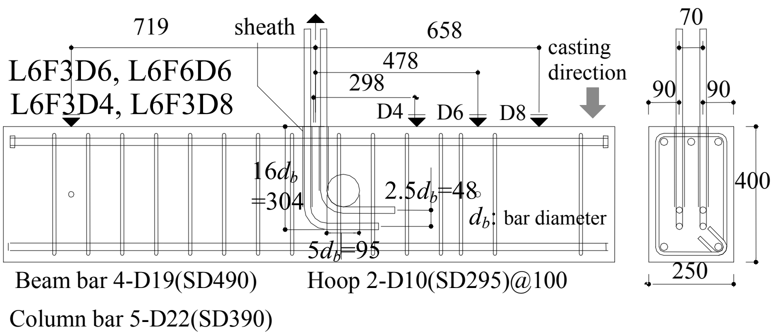


Figure 3.1. Pull-out specimen (Column Type)

Table 3.1. Properties of Specimens

specimen	development length of outer bar L_{dh1} (mm)	concrete compressive strength F_c (N/mm^2)	beam bars layer n	beam depth D_b (mm)
L6F3D6	$16d_b$=304	30	2	600
L6F3T6			3	
L2F3D6	$12d_b$=228		2	
L2F3T6			3	
L6F3D4	$16d_b$=304		2	400
L6F3D8			2	800
L6F6D6		60	2	600
L6F6T6			3	
L2F6D6	$12d_b$=228		2	
L2F6T6			3	

*Specimen name

L6 or L2: development length of 16d_b or 12d_b
F3 or F6: Concrete strength of 30N/mm^2 or 60N/mm^2
D or T: Double layer or Triple layer of beam bars
4, 6 or 8: Beam depth of 400mm, 600mm or 800mm
d_b: beam bar diameter =19mm

Sheath tube was set in straight portion of beam bar in order to remove the bond, which condition is to be expected at ultimate stage of building during severe earthquake. Loading setup and path of pull-out test is shown in Figs. 3.2 and 3.3, respectively. Loading has been controlled to keep the same displacement in every beam bars and also target tensile force is decided on the basis of calculation strength obtained by Eqn. 1.2 for outer layered beam bar. Materials properties of concrete and reinforcement are shown in Table 3.2, respectively.

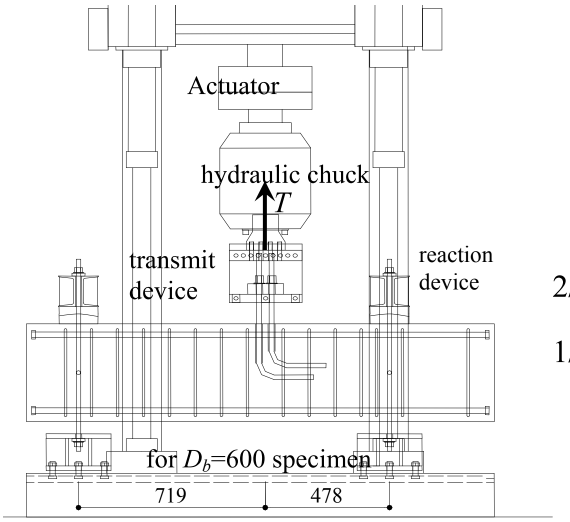


Figure 3.2. Loading Setup for Pull-out Test

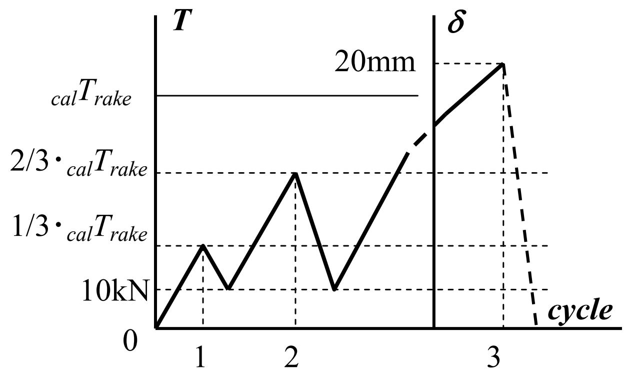


Figure 3.3. Loading Path of Pull-out Test

Table 3.2. Properties of Concrete (ϕ100x200 cylinder)

specimen	compressive strength σ_B (N/mm^2)	strain at maximum strength ε_{max} (μ)	tensile strength σ_t (N/mm^2)	Young's modulus (kN/mm^2) $E_{1/3}$	Young's modulus (kN/mm^2) $E_{2/3}$
L6F3D6	30.8	2660	2.61	27.0	21.9
L6F3T6	30.7	2580	3.02	26.7	22.3
L2F3D6	29.6	2690	2.97	25.3	21.4
L2F3T6	29.5	2790	2.73	26.0	21.3
L6F3D4	30.0	2700	2.73	25.9	21.7
L6F3D8	30.9	2770	2.69	25.8	21.5
L6F6D6	57.3	2230	3.02	34.1	31.6
L6F6T6	59.1	2320	3.21	34.1	31.3
L2F6D6	59.1	2500	3.79	34.2	31.3
L2F6T6	59.6	2300	4.32	35.3	32.6

Table 3.3. Properties of Reinforcements

reinforcement	type (spec.)	yielding		tensile strength	elongation	Young's modulus
		σ_y(N/mm^2)	ε_y(μ)	σ_{max}(N/mm^2)	(%)	E_s(kN/mm^2)
beam longitudinal	D19(SD490)	538	2820	678	18.6	198
column longitudinal	D22(SD390)	468	2390	646	19.8	203
shear reinforcement	D10(SD295)	370	1920	524	18.5	196

3.2.2. Test Results

Typical crack pattern of specimen and total load-bar displacement relationship are shown in Figs. 3.4 and 3.5, respectively. All specimens were failed in raking-out anchorage failure since the width of crack located supposed failure line (see Fig. 1.3) became lager after maximum strength. The deterioration of rigidity was observed when flexural crack appeared at the vicinity of beam bars. In all specimens, maximum strength was obtained at bar displacement of approximately 5mm, which value includes bar elongation of straight portion (no bond). Test results show the maximum strength dose not depend on number of bar layer but on development length and concrete strength.

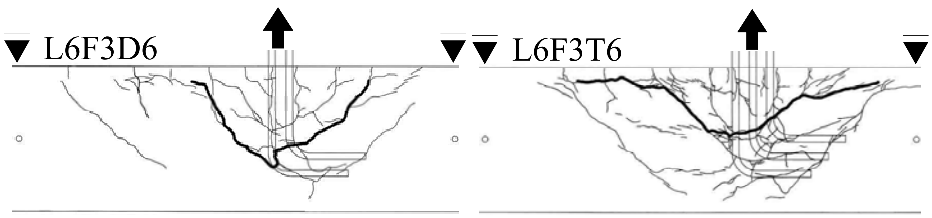


Figure 3.4. Crack Pattern of Typical Specimens (thick line shows failure line)

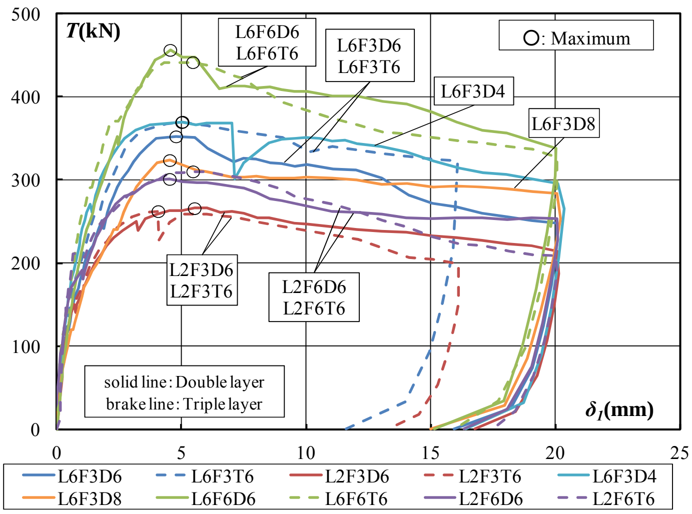


Figure 3.5. Total Bar Force - Bar Displacement Relationship

3.3 Cyclic Loading Test of Exterior Beam-Column Sub-assemblages

3.3.1. Specimens and Loading Setup

Half scale two specimens which have different in number of bar layer were built to examine the influence of cyclic loading and bar arrangement of beam on raking-out anchorage failure and joint shear strength. Both specimens were designed to have almost equal strength value of raking-out anchorage and joint shear failure, calculated by Eqns. 1.1 and 1.2, respectively. Specimen detail and the properties of materials are shown in Fig. 3.6, Tables 3.4 and 3.5, respectively. Column and beam section were 400x400 mm and 200x600 mm, respectively, and both members had enough margin in shear strength. Development length of outer beam bar was fixed as 16d_b.

Fig. 3.7 shows the loading setup of sub-assemblages specimen, where column was set horizontally and supported at reflection point. Loading was made at beam reflection point and controlled by the displacement at loading point. Fig. 3.8 shows loading path.

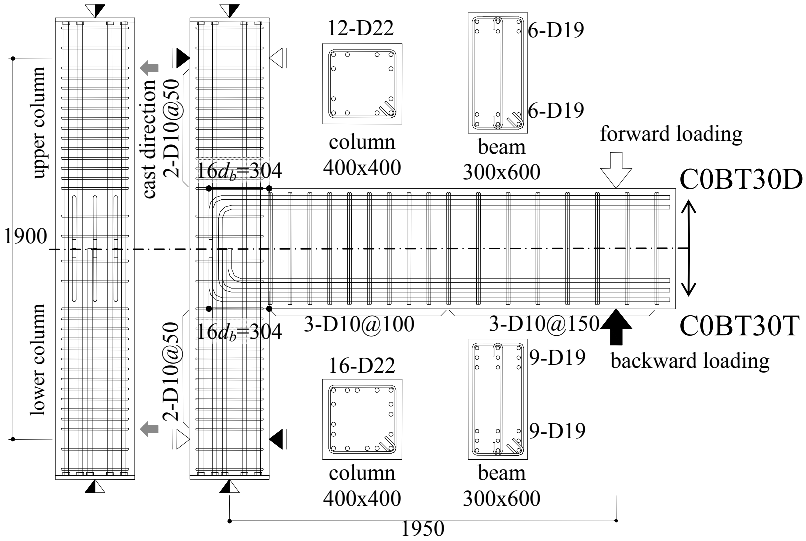


Figure 3.6. Sub-assemblage Specimen for Cyclic Loading Test

Table 3.3. Properties of Concrete (ϕ100x200 cylinder)

Specimen	Compressive		Tensile	Young's Modulus (GPa)	
	σ_B(MPa)	ε_{max}(μ)	σ_t(MPa)	$E_{1/3}$	$E_{2/3}$
C0BT30D	29.9	2860	2.55	23.9	19.8
C0BT30T	31.4	2720	2.58	24.5	21.1

Table 3.4. Properties of Reinforcements

Reinforcement	Bar type	Yielding		Tensile	Elongation	Young's modulus
		σ_y(MPa)	ε_y(μ)	σ_{max}(MPa)	(%)	E_s(GPa)
Beam	D19(SD345)	409	2410	607	20.0	178
Column	D22(SD390)	469	3530	648	16.3	161
Hoop	D10(SD294)	370	1920	524	18.5	196
Stir-rup	D10(SD295)	370	1920	524	18.5	196

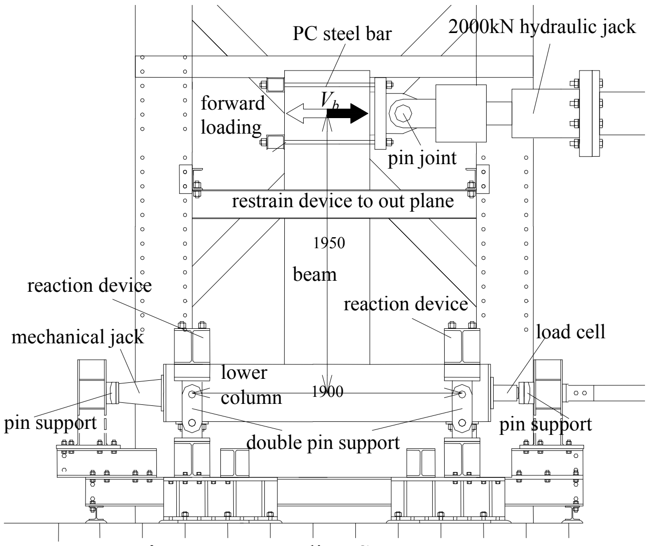


Figure 3.7. Loading Setup

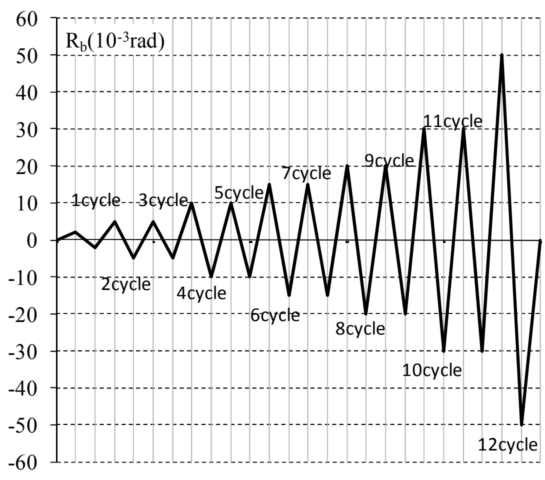


Figure 3.8. Loading Plan

3.3.2. Test Results

Fig. 3.9 shows crack pattern of specimens after loading. Both specimens were failed in joint shear, but aspect of raking-out failure appeared after maximum strength at story drift angle of 1/100. Fig. 3.10 shows relationship between beam shear and story drift angle. Maximum strength was decided due to yielding of joint reinforcement and sudden decreasing of load was observed in both specimens.

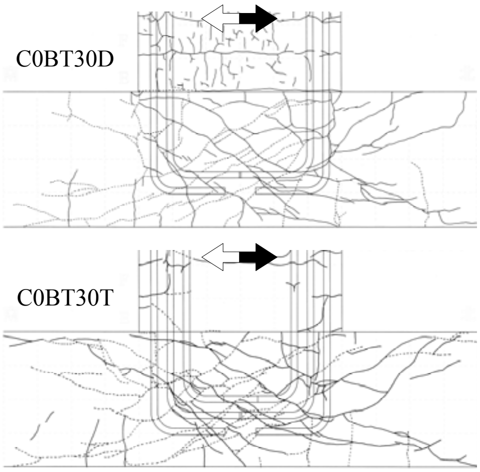


Figure 3.9. Crack Pattern after Test

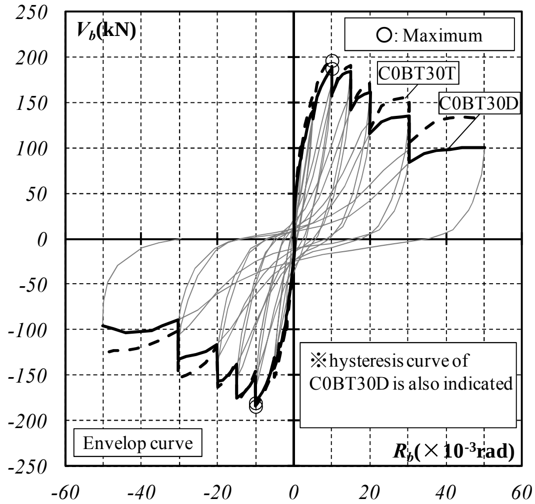


Figure 3.10. Relationship of Beam Shear-Story Drift Angle

4. CONSIDERATION

Test results of maximum strength and calculated value of raking-out failure and local compressive fracture are shown in Table 4.1. Strength is represented as total tensile force of beam, where moment arm is assumed as 0.875d (d: effective beam depth) in sub-assemblage specimens. Failure line for calculation of raking-out failure strength for each bar in multi layered arrangement is assumed as Fig. 4.1. Bearing stress acting on concrete located inside of bent portion is calculated using bar tensile force measured by strain gage at start and end point of bent portion, and maximum value is shown in Table 4.1. Fig. 4.2 shows the calculation method of bearing stress for inside bar, where bearing stress from outside bar is added. Kaneko et al. (2006) reported that bearing stress acting at concrete located inside of bent portion increased to 8 times of concrete compressive strength at fracture.

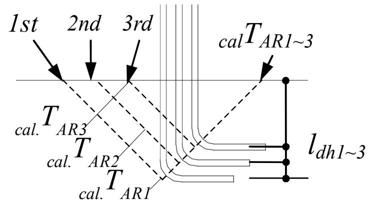


Figure 4.1. Failure Line for Each Layer

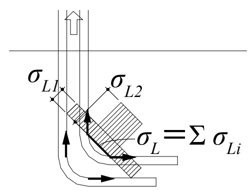


Figure 4.2. Superposition of Bearing Stress

Table 4.1. Test Results of Strength (marked square is the best agreement)

sereies	specimen	Experiment: Total tensile force ${}_{exp.}T_{max}$ [kN]	Experiment: Bearing stress (each bar) ${}_{exp.}\sigma_L$ [N/mm^2]	Experiment: Displacement /Angle δ_1・R_b	Calculation, Equation 1.2, 1st layer l_{dh}: ${}_{cal.}T_{AR1}$ [kN]	exp/cal	2nd layer l_{dh}: ${}_{cal.}T_{AR2}$ [kN]	exp/cal	3rd layer l_{dh}: ${}_{cal.}T_{AR3}$ [kN]	exp/cal	Local compressive fracture Kaneko (2006): 8.0・σ_B [N/mm^2]	exp/cal
pull-out	L6F3D6	352	140	4.80 mm	437	0.81	354	$\boxed{0.99}$	—	—	246	0.57
	L6F3T6	370	115	5.05 mm	436	0.85	354	$\boxed{1.04}$	273	1.35	246	0.47
	L2F3D6	266	111	5.54 mm	283	$\boxed{0.94}$	205	1.29	—	—	237	0.47
	L2F3T6	262	79	4.08 mm	283	$\boxed{0.93}$	205	1.28	129	2.03	236	0.33
	L6F3D4	369	148	5.03 mm	476	0.78	388	$\boxed{0.95}$	—	—	240	0.62
	L6F3D8	324	129	4.54 mm	422	0.77	343	$\boxed{0.94}$	—	—	247	0.52
	L6F6D6	456	169	4.56 mm	528	0.86	429	$\boxed{1.06}$	—	—	458	0.37
	L6F6T6	441	137	5.47 mm	534	0.83	434	$\boxed{1.02}$	336	1.31	473	0.29
	L2F6D6	301	127	4.54 mm	354	$\boxed{0.85}$	260	1.16	—	—	473	0.27
	L2F6T6	310	111	5.48 mm	355	$\boxed{0.87}$	260	1.19	168	1.85	477	0.23
joint	C0BT30D	686	168	1/100 rad	660	$\boxed{1.04}$	514	1.33	—	—	239	0.70
	C0BT30T	718	123	1/100 rad	670	$\boxed{1.07}$	522	1.38	376	1.91	251	0.49

Calculated value by Eqn. 1.2 of raking-out failure shows good coincidence with test results, when 1st layer failure line is adapted for development length of $12d_b$, and the 2nd layer line for development length of $16d_b$ in the pull-out test. But it might make overestimation with other assumed line.

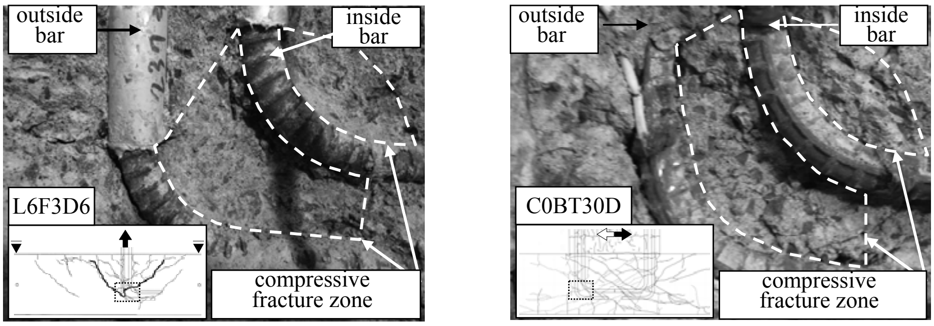


Photo 4.1. Local Compressive Fracture of Concrete Located Inside of Bent Bars

After test, cover concrete was removed to check the condition of concrete located inside of bent bar shown as Photo 4.1. Concrete in that area was crashed as splitting fracture. Such fracture occurred even though the bearing stress is not larger than bearing strength, which is needed to be discussed.

5. CONCLUSIONS

The results of analysis using experimental database and experimental works of pull-out and cyclic test show the following:

1) Joint shear strength equation of AIJ design guideline gives safety value, but the strength would increase at large displacement because joint reinforcement becomes effective on shear resistance.
2) Proposed equation for raking-out anchorage failure tends to make overestimation in case that beam flexural strength is large, where a large number of beam bars are provided.
3) Pull-out test shows that raking-out failure strength is influenced by development length strongly comparing with other parameters.
4) In case of multi layered arrangement of beam bars, the calculated strength of raking-out failure by proposed equation shows good agreement with test results, but it would make overestimation with incorrect assumption on failure line.
5) Local fracture of concrete located inside of bent bar occurred even though the bearing stress did not reach bearing strength.

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