Experimental Study on Influence of Arrangement of Main Bars on Stress Transmission in Reinforced Concrete Beam-column Knee Joints

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SUMMARY:
In seismic design guidelines for earthquake resistant R/C buildings (AIJ guideline 1997) in Japan, shear strength of R/C beam-column joint panel is determined by only strength and volume of concrete in the panel. The objective of this study is empirically to show influence of arrangement of reinforcing bars as for R/C knee joint subject to closing loads. Two series of specimens were made and tested. One is with continuous tensile bars and the other is with lapped ones within the joint. The variables were inside radius of corner bars and the breadth of the joints. It is concluded that main reasons of instability of the joints are early splitting crack between lapped tensile bars and bearing failure due to small bending radius of corner bars.

Keywords: Reinforced concrete, Beam-Column knee joints, Stress transmission, shear strength

1. INTRODUCTION

In seismic design guidelines for earthquake resistant R/C buildings (AIJ guideline 1997) in Japan, shear strength of R/C beam-column joint panel is determined by only strength and volume of concrete in the panel regardless of arrangement of reinforcing bars. As for knee joints, the strength is expected to 40% of that for interior beam-column joints. This limitation may be mainly caused by severe stress transmission between reinforcing bars and concrete at an anchorage and it may be influenced by detail and arrangement of reinforcing bars. Moreover knee joints, where confinement due to axial load is very small, may show more slipping behavior than interior joints show, because bond between reinforcing bars and concrete cannot be expected in general, however, the difference in restoring force characteristics between interior and knee joints is not considered in the present structural design. Bond characteristics may be also influenced by arrangement of reinforcing bars.

From those backgrounds, several experiments, objective of which is to know the influence of detail and arrangement of reinforcing bars on shear strength and restoring behavior of panels, were planned and carried out as a basic research for R/C knee joints subject to closing load.

2. OUTLINE OF TESTS

2.1 Specimens

As shown in Table 1, 8 specimens were made and tested. In the table, test results which are failure reasons and shear strength are also indicated. The specimens were categorized to 2 series, LA and LB.

In LA series specimens, tensile reinforcing bars were arranged continuously in a joint panel and columns' and beams' section had the same dimension. As illustrated in Fig. 1, bent radius of tensile reinforcing bars at the corner of the joint panel (3 kinds of inside radius of 20mm, 26mm and 80mm) and breadth of members (2 kinds of the breadth of 50mm and 80mm) were varied. D10 deformed bars were used for tensile reinforcement and D6, for compressive one. The columns and the beams were

Table 1. List of test specimens and their main test results

Speci-men		Beam/Column member			Joint		Test results			
								Shear strength		
		Section b×D [mm×mm]	Tensile main bars (p_t)	Hoop (p_w)	Inside radius of beam bars in 90 degree bent [mm]	Anchor of column bars	Failure mode	Experimental value V_{exp}	Caluculated value V_{cal}	V_{exp}/V_{cal}
LA	LA-50-20	50×200	2-D10 (1.43%)	3φ@30 (0.943%)	20		bearing failure	48.2	39.0	1.24
	LA-50-80				80		yield of menbers	65.2	39.0	1.67
	LA-80-20	80×200	2-D10 (0.89%)	3φ@30 (0.589%)	20		bearing failure	65.3	54.4	1.18
	LA-80-26				26		yield of menbers	65.2	50.1	1.30
	LA-80-80				80		yield of menbers	65.2	54.4	1.20
LB	LB-26	column: 100×200 beam: 80×200	column: 3-D10 (1.07%) beam: 2-D10 (0.89%)	column: 3φ@30 (0.471%) beam: 3φ@30 (0.589%)	26	180° hook	bearing failure + compressive failure	50.0	47.2	1.06
	LB-80				80	180° hook	bond failure	54.3	47.2	1.15
	LB-26C				26	180° hook + 90° hook (center)	bearing failure + compressive failure	61.2	47.2	1.30

laterally strengthened by sufficient hoop reinforcement which were round bars with diameter of 3mm, however, no lateral reinforcement were arranged in the panel.

LB series specimens were more practical. In LB series specimens, columns had bigger section than beams had and the tensile bars were lapped within the panel as detailed in Fig. 2. The empirical variable was also inside radius of bent tensile bars of the beam. The specimen LB-26C in which one of 3 tensile bars of the column was extended in the panel with 90 degree bend until the critical section of the beam in addition. The bars used were same as LA series specimens' ones, and there were also no lateral reinforcement in the panel.

The shear strength of the panel indicated in Table 1 is coincident with tensile force of the tensile reinforcing bar at the critical section of the beam by definition, and test values were calculated from shear and axial force of the beam by section analysis in which nonlinearity of materials were considered. The calculated values are given by the following equation (AIJ guideline 1997).

$$V_{js} = \kappa \times 0.85 \times 0.8 \times {\sigma_B}^{0.7} \times b_j \times l_{dh} \qquad (2.1)$$

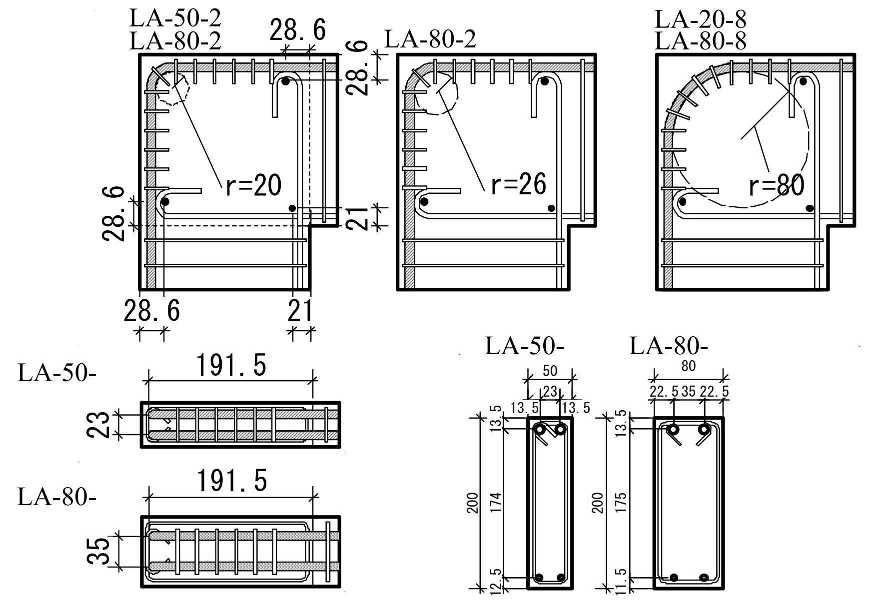

Figure 1. Dimension and detail of bar arrangement for LA series specimens

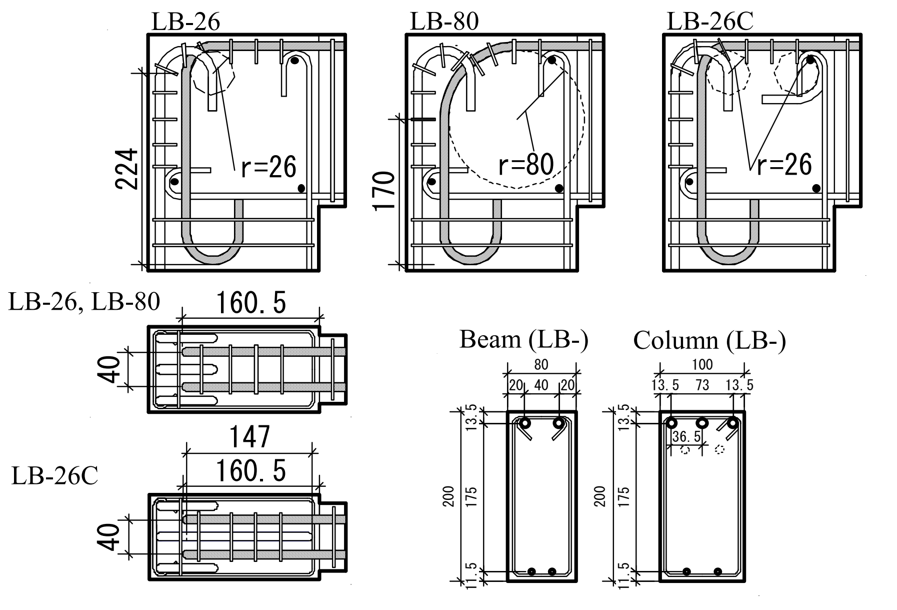

Figure 2. Dimension and detail of bar arrangement for LB series specimens

Where κ is coefficient dependent on joint type and is equal to 0.4 for knee joints, σ_B is compressive strength of concrete, b_j is effective breadth of joint panel and is equal to the breadth of members for LA series specimens and 90mm for LB series ones, and l_{dh} is distance between critical section of the beam and the end of tensile reinforcing bars anchored to the panel and is 191.5mm for LA series specimens and 160.5mm for LB series ones.

Mechanical properties of used concrete and reinforcing bars are described in Table 2. High strength steel was used for tensile reinforcement in order that the specimens fail due to failure at the joint panel as possible.

2.2 Loading method and measuring method of deflection

The whole dimension of the specimens and a way of loading are outlined in Fig. 3. The specimens were set to the pin and pin-roller blocks of a loading apparatus at both the end plates by PC bars and

Table 2. Mechanical properties of materials

Concrete

Specimen	Comp. strength [N/mm^2]	Splitting tensile strength [N/mm^2]	Young's modulus $\times 10^4$[N/mm^2]
LA-50-20,80 LA-80-20,80	39.3	2.97	2.99
LA-80-26 LB-26,80,26C	34.9	2.68	3.05

Steel

Bar	Yield strength [N/mm^2]	Tensile strength [N/mm^2]	Young's modulus $\times 10^5$ [N/mm^2]
D10	457	633	1.83
D6	381	537	1.86
3φ	541	627	1.89

external load was horizontally applied from the roller block in closing direction. The elevation of all specimens was symmetrical, therefore the axial force of the members N are always equal to the shear force V. In order to measure deformation of elements, which were the column, the beam and the joint panel, terminals were embedded in the panel at the position as shown in Fig. 3, and the measuring apparatuses were set to both sides of the specimen as illustrated in Fig. 4. The measured deformations were elongation of the beam and the columns, both end rotations of the beam and the columns, and shear deformation of the panel. By the location of the terminals, deformation due to cracks outside the terminals is regarded as the deformation of the beam or the column in this measuring system. Strain of reinforcing bars was not measured at all in the test, because putting strain gauges unignorably influences bond characteristics of the bars.

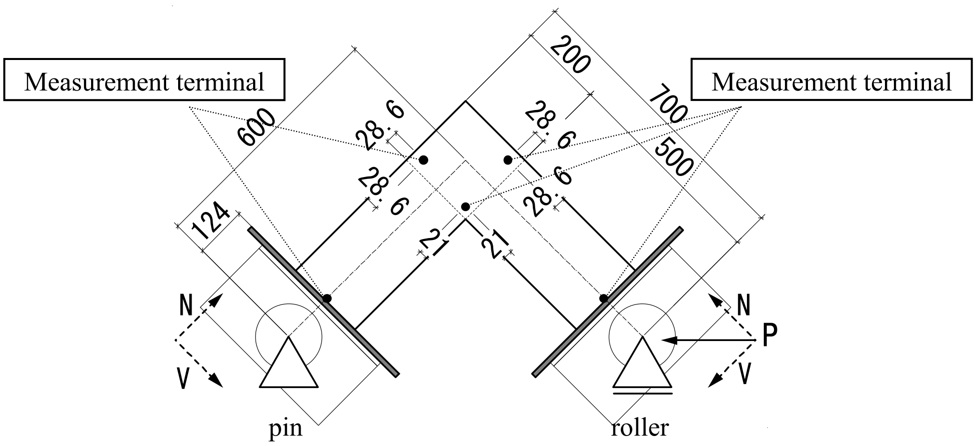

Figure 3. Method of loading

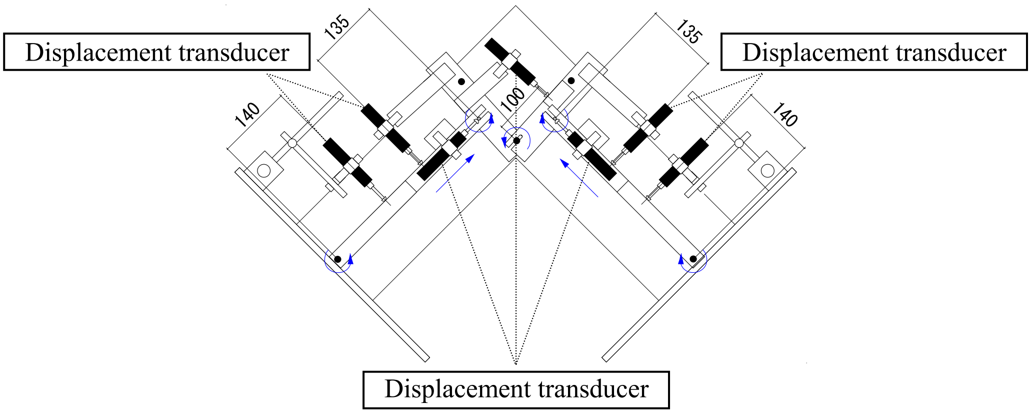

Figure 4. Apparatus for measuring deformation

3. TEST RESULTS

3.1 Load deflection curves

Figure 5 gives load versus deflection curves for LA series specimens. Vertical axes of the figure stand for horizontal force introduced to the roller end and horizontal axes give horizontal displacement of the one. 4 curves are described for each specimen in the figures. One expressed by a solid line is a load-total displacement curve of the specimen, and the others expressed by dashed, dotted and chained lines are the ones shared by the beam, the column and the panel respectively. More horizontal axes which stand for member angle of the beam and the column and shear strain of the panel corresponding to the shared horizontal displacement are added to the figures. 'Yield load' which is the one when the tensile stress of reinforcing bars reaches to the yield strength at the critical section of the members and calculated by inelastic section analysis and 'diagonal crack load' calculated by the following equation are also given in the figures.

$$V_{cr} = f_t b_j l_{dh} \tag{3.1}$$

Where f_t is tensile strength of concrete of which value is indicated in Table 2 as splitting strength.

In the case the tensile bars were bent with large radius of 80mm, the maximum load exceeded the 'yield load' even when the breadth of the panel was considerably thin, however, in the case the breadth of the panel was 80mm, the flexural yielding of the member was recognized in the specimens with bent bars having the radius more than 26mm. The specimens LA-50-80 and LA-80-80, both of which have the corner bars with large radius seem to have sufficient margin against bearing failure because the deformation is almost uniformly shared by the members and the panel, however, as for the specimen LA-80-26, the margin seems tight because only shear deformation of the panel is enlarged after yielding. As for the other specimens with the bars having small radius, the maximum load did not reach to 'yield load', and the load descended gradually after showing the maximum strength. No diagonal cracks due to splitting failure occurred in LA series specimens.

Figure 6 gives load versus deflection curves for LB series specimens. Diagonal cracks due to splitting failure of concrete occurred near the calculated crack load in all specimens, and every maximum load did not reach to 'yield load'. Shear deformation of the panel became major while the load was descending in the specimens.

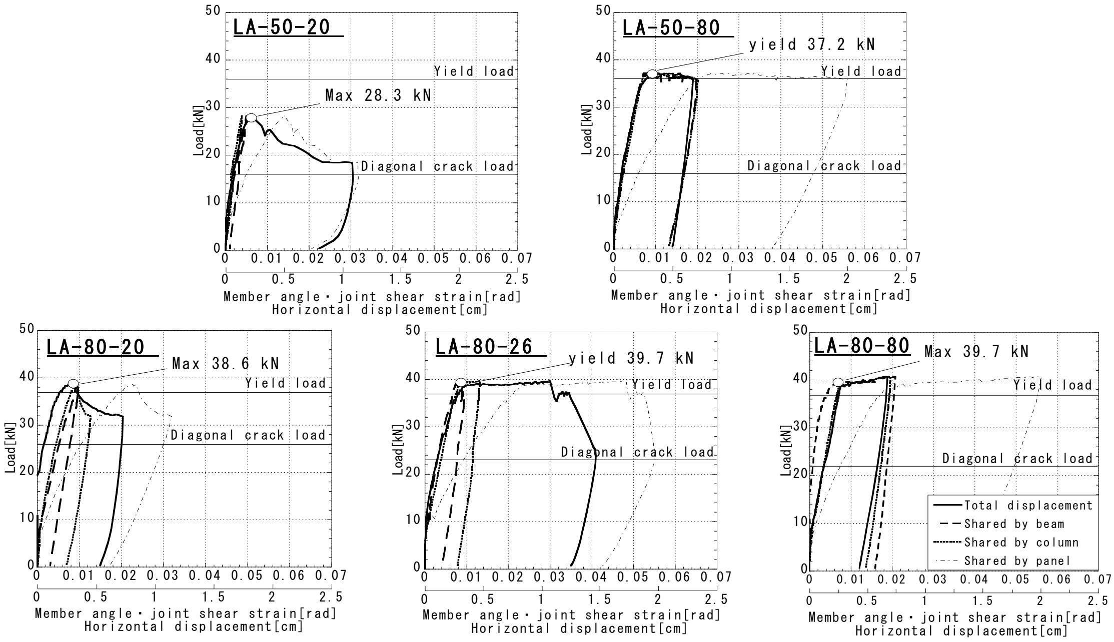

Figure 5. Load-deflection curves for LA series specimens

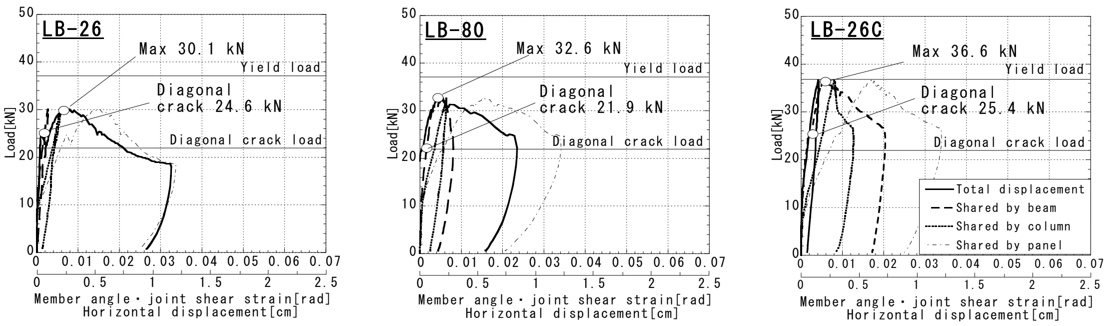

Figure 6. Load-deflection curves for LB series specimens

3.2 Cracks and failing procedure

Crack pattern and stress distribution around the panel at the maximum strength or yielding are given in Fig. 7 for LA series specimens. There were no cracks due to splitting failure of concrete in the panel as for all LA series specimens. As for the specimens LA-50-80, LA-80-26 and LA-80-80 of which the maximum strength was decided by flexural yielding of the members, concrete was sound around the corner, however, cracks occurred along the corner bars in the specimens LA-50-20 and LA-80-20 which showed less maximum strength than that due to members' flexural yielding and the concrete was gradually peeled out near the corner.

Figure 8 gives crack pattern for LB series specimens. Characteristic cracks recognized in LB series specimens are the ones occurred from compressive corner to tensile corner along the diagonal. Many cracks around the corner where tensile bars of the beam and the column were lapped could be observed in the specimen LB-26. Cracks which might be probably caused due to crushing of concrete were also observed in the specimens LB-26 and LB-26C. On the contrary, many cracks occurred near the parallel lap and the crack located just at the anchoring end of the beam's tensile bars widened eventually in the specimen LB-80.

From those cracks' extending procedure, the reason of strength degradation is considered bearing failure at the corner for the specimens LA-50-20 and LA-80-20, failure due to insufficient anchorage for the specimen LB-80 and bearing failure or compressive failure of diagonal strut for the specimens LB-26 and LB-26C. Moving eyes again to the shear strength obtained through the test and the one calculated indicated in Table 1, empirically obtained shear strength was about 1.2-1.67 times as high as the calculated one for LA series specimens with continuous bars in the case tensile bars were yielded, however, both strengths were almost equal for the specimen LB-26 with bars lapping which seems to have practical and ordinal bars' arrangement. The specimen LB-26C showed the strength 1.3 times as high as the calculated one. It is shown that widening the lapping region in the panel can improve the strength of the panel. The specimen LB-80 showed intermediate strength, however, there is some probability that sufficient anchorage improves the strength.

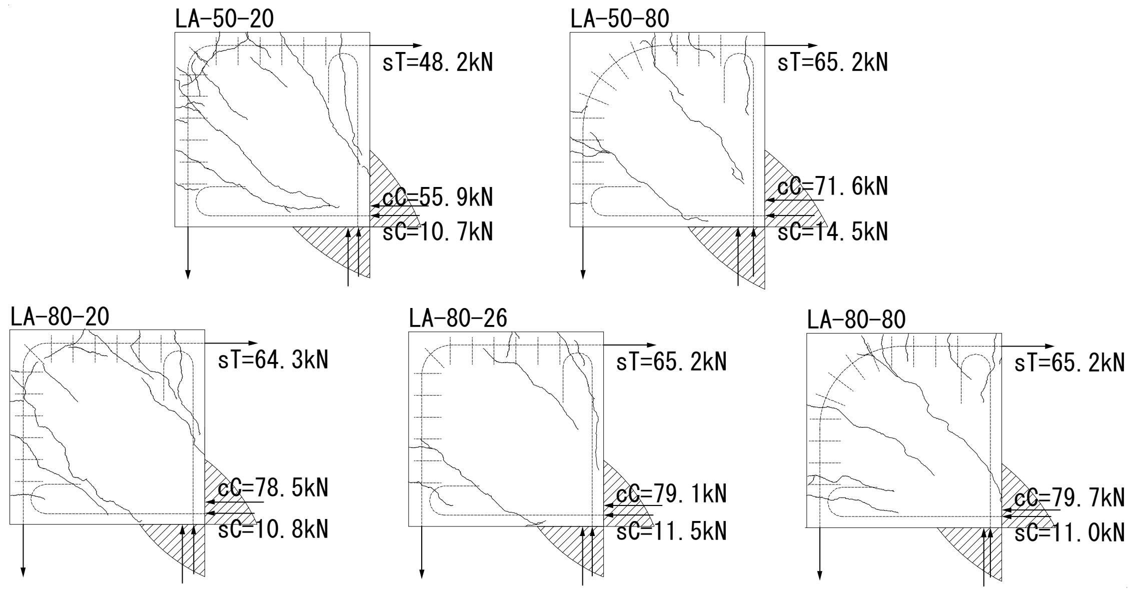

Figure 7. Crack pattern and stress distribution at the max or yield strength (LA series)

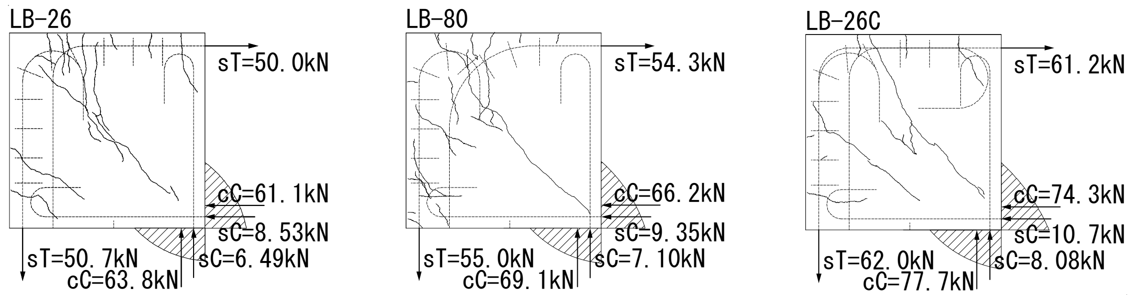

Figure 8. Crack pattern and stress distribution at the max or yield strength (LB series)

4. FAILURE MECHANISM OF EACH SPECIMEN

4.1 Failure mechanism of LA-series specimens

As for LA series specimens, bearing strengths at the 90 degree bend obtained from the test are compared with the ones calculated using the following equations (Fujii et al.1991) in Table 3.

$$P_u = k_0 k_1 k_2 k_3 k_4 k_5 f_{b0} d_b r \tag{4.1}$$

Where k_0 is coefficient on concrete strength σ_B and is given by $k_0 = (\sigma_B/40)^{0.5}$, k_1 is coefficient on radius of the bend and is given by $k_1 = (r/d_b)^{-0.72}$, k_2 is coefficient on side cover thickness C_0

Table 3. Bearing strength of beam bar at the tensile side 90° bend

Specimen	Failure mode	Experimental value P_{exp}[kN]	Calculated value P_{cal}[kN]	P_{exp}/P_{cal}
LA-50-20	Bearing	24.1	21.2	1.14
LA-50-80	Yield	32.6	31.3	1.04
LA-80-20	Bearing	32.1	25.6	1.25
LA-80-26	Yield	32.6	26.4	1.25
LA-80-80	Yield	32.6	37.7	0.86

and spacing of bars S_0 and is given by $k_2 = (0.7 + 0.11S_0)(0.38 + 0.1C_0)$, k_3 is coefficient on geometrical location of the bend and is equal to 1.0, k_4 is coefficient on l_{dh} and is equal to 1.15 and k_5 is coefficients on transverse reinforcement and is equal to 1.0 in this test. Also where f_{b0} is standard bearing strength and is 187MPa, d_b is a nominal diameter of a reinforcing bar, and *r* is inside radius of bend.

Except for the specimen LA-80-80, the experimental values exceed the calculated one, so it can be said that those bends are under severe condition against bearing failure, including the specimen LA-80-26 which failed due to yielding of the members.

4.2 Failure mechanism of specimen LB-80

The length of the anchorage was calculated based on AIJ standard 2010 during design procedure of the specimens, however, practical length did not satisfy required one slightly because the actual concrete strength became less than designed one. The following equation can be given on bond stress around the anchorage.

$$\left(l_j\tau_j + l_c\tau_c\right)n\phi = {}_sT_{80} \tag{4.2}$$

Where l_j is length of anchorage in the panel (101.5mm), τ_j is bond strength when $p_w = 0$, l_c is length of anchorage in the column (68.5mm), τ_c is bond strength when $p_w = 0.471\%$ which is hoop ratio for the column, *n* is number of the bars, ϕ is length of a bar in circumference, and ${}_sT_{80}$ is tensile load of tensile reinforcing bars of the column at the critical section when the specimen LB-80 showed the maximum strength and is 54.3kN.
Assuming $\tau_c = 4.05\mathrm{N/mm^2}$ from AIJ guideline 1997 and bond strength is linear function of lateral reinforcement, the following relationship between bond strength τ and p_w can be given.

$$\tau = 6.773p_w + 4.05 \tag{4.3}$$

Equation 4.3 is compared with several previous research works in Fig. 9 and it corresponds well with the proposal by Otani et al.(1994), therefore it is adequate that the failure of the specimen LB-80 is caused by bond failure around the anchorage.

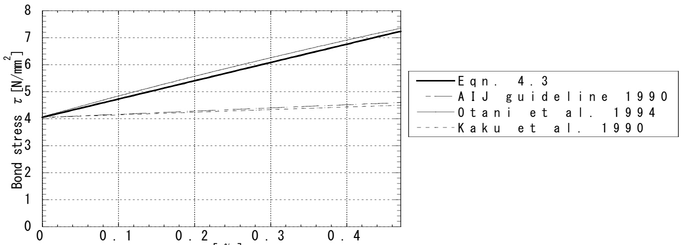

Figure 9. Bond stress-hoop ratio(p_w) relationship

4.3 Failure mechanism of specimens LB-26 and LB-26C

Two causes can be considered as failing reason of the specimens LB-26 and LB-26C. One is bearing failure around the corner lapping and the other is compressive failure of diagonal strut of concrete.

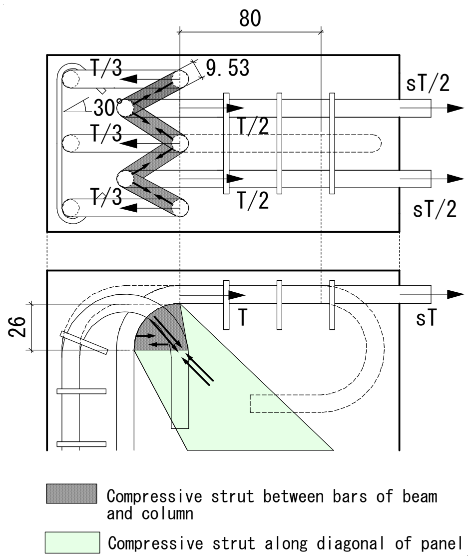

Figure 10. Bearing condition around corner lapping

Figure 10 gives bearing condition around the corner lapping for the specimens LB-26 and LB-26C. In addition to the ordinary diagonal transferring of stress indicated in the lower figure, stress transmission among the lapped bars are required in the case the bars are lapped in the panel, as shown in the upper figure. As for the specimen LB-26, it is assumed that tensile force of bars at the end of straight part T is equal to $_{s}T = 50.0\text{kN}$ which is tensile force of the bars at the critical section, because the bond stress cannot be expected, however, some stress transmission due to bond between the beam's bars and extended column's bar can be expected as for the specimen LB-26C. Assuming that bond strength is 5.65N/mm^2 which is correspondent with $p_w = 0.236\%$ in Eqn. 4.3 that is expected lateral confinement by ties between 2 beam's bars, tensile force of bars at the end of the straight become 47.6kN, which is almost coincident with the one for the specimen LB-26. Using those tensile forces, bearing stress due to the stress transmission among the lapping f_{b1} and the one due to the ordinary stress transmission through the strut f_{b2} can be calculated as indicated in Table 4. The bearing stress calculated using Fujii's proposal (Fujii et al. 1991) is also indicated in the table. We are not sure the simple addition of f_{b1} and f_{b2} is adequate for evaluating the bearing stress at the bend, however those extremely exceed the calculated bearing strength.

Table 4. Bearing strength

Specimen	f_{b1} [N/mm^2]	f_{b2} [N/mm^2]	f_{b1}+f_{b2}	Calculated strength [N/mm^2]
LB-26	77.6	100.9	178.5	123.5
LB-26C	73.6	96.1	169.7	123.5

Crack patterns and adequate concrete struts limited by diagonal crack when the specimen showed the maximum strength are illustrated in Fig. 11. The breadth of compressive strut is assumed shortened by diagonal cracks as illustrated in the figure. The breadth of the strut measured from the figure and resulting compressive stress of the strut is listed in Table 5. The ratio of the compressive strut to concrete strength is ranged from 0.84 to 0.99 as a result. That shows the probability of compressive failure of the strut.

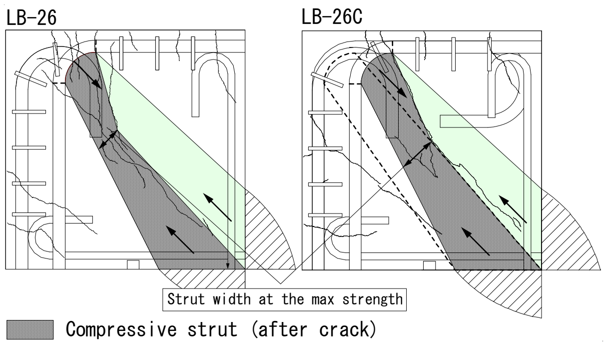

Figure 11. Compressive strut along diagonal of panel

Table 5. Strut width and compressive stress

Specimen	Strut width s[mm]	Tensile force of bars $_{s}T$[kN]	Compressive stress of strut $_{st}\sigma[\mathrm{N/mm^2}]$	$_{st}\sigma/\sigma_B$
LB-26	22.7	50.0	34.6	0.99
LB-26C	33	61.1	29.9	0.84

5. CONCLUSIONS

Monotonic closing loading tests were carried out for several R/C knee joints and the following results were obtained.

In the case tensile bars were continuously arranged in the panel and bend of bars had radius about 3 times as large as standard one, knee joints showed much higher shear strength than that indicated in AIJ design guideline.

In the case the bars were lapped in the panel and the bend had standard radius, there becomes severe bearing condition around lapped bends and diagonal splitting cracks may prevent sound stress transmission of concrete strut. Those are considered main reasons of weakening shear strength in knee joints with the ordinal arrangement of reinforcing bars.

In the case the bend has sufficient radius for bearing, there is some probability that the strength can be improved.

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