Joint Shear? or Column-to-Beam Strength Ratio? Which is a key parameter for seismic design of RC Beam-column joints - Test Series on Exterior Joints

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SUMMARY:
Tests on reinforced concrete exterior beam-column joint sub-assemblages with low column-to-beam strength ratio in the range commonly constructed in practice are reported following the part 1 about interior joints. Story shear capacity of some specimens were 30% lower of the story shear predicted by the flexural strength of the beam or the column at the maximum, although the joints have enough margins for nominal joint shear capacity by 10% to 50%. The decrease of story shear is larger in case of the column-to-beam flexural strength ratio is equal or near to unit. Column-to-beam strength ratio required to secure lateral strength predicted by the flexural theory of R/C sections is so small that amount of transverse reinforcement in the joint is large, the column depth is large relatively to the beam depth or bent bar anchorage is used instead of mechanical anchor with headed bars.

Keywords: reinforced concrete, beam-column joint, joint failure, joint shear, column-to-beam strength ratio

1. INTRODUCTION

In recent seismic design code, some provisions with joint shear capacity equations are provided to prevent failure of beam-column joints in R/C moment resistant frames. These equations of joint strength are experimental and taking only the influence of dimension of column and concrete compressive strength into consideration. In some codes, effects of development length of beam bars are added in case of exterior and knee joints.

Some experimental and theoretical studies including by the authors pointed out effects of column-to-beam flexural strength ratio on joint strength. However there is very limited number of specimens with low column-to-beam strength ratio in the range commonly constructed in practice. In this study, this type of reinforced concrete beam-column joint sub-assemblages are constructed and loaded to failure by lateral loading. The part 2 investigates the effect of design parameters including column-to-beam flexural strength ratio on lateral capacity of exterior beam-column joints following the part 1 about interior joints.

2. TEST PROGRAM

2.1. Specimens and test parameters

The test program consists of five series of tests. Twenty eight one-third reinforced concrete exterior beam-column joint sub-assemblages were constructed. The specimens were virtually isolated in moment resisting frame at inflection point. Table 1 lists the specimens and their test parameters. Figure 1 shows the geometry and the reinforcing details of the specimens.

The depth of the columns and the beams were 240 mm in common for Series L, M and O, while the depths of column and beam were 340 mm and 170 mm for Series N and 170 mm and 340 mm for Series P. The width of all the beams and the columns was 240 mm in common. The joint shear reinforcement ratio was approximately 0.3%, which is the minimum requirement of the AIJ Guidelines (1999), expect in the specimens in Series M and specimen P04. Basically the beam bars were headed with steel plate welded at the ends of bars to be anchored in the joints, whereas the U-shaped continuous anchorage of top and bottom beam bars was adopted for Series O.

The test parameters were (1) amount of longitudinal reinforcement in beams; ratios of joint shear demand to joint shear capacity were 0.76 to 1.48, (2) development length of beam bars in the joints; ratios of anchor length to column depth were 0.8, 0.65 and 0.5, (3) column-to-beam flexural strength ratio; ratios of sum of flexural strengths of columns to flexural strength of beam section evaluated at the joint center were 1.03 to 3.54, (4) amount of transverse hoop reinforcement in a joint; joint lateral

Table 1. Properties of Specimens

(a) Series L and M

<table>
<tr><td colspan="2">Specimen</td><td>L01</td><td>L02</td><td>L03</td><td>L04</td><td>L05</td><td>L06</td><td>L07</td><td>L08</td><td>L09</td><td>L10</td><td>L11</td><td>M01</td><td>M02</td><td>M03</td><td>M04</td></tr>
<tr><td colspan="2">concrete compressive strength, MPa</td><td colspan="11">27.7</td><td colspan="4">29.0</td></tr>
<tr><td rowspan="3">beam</td><td>cross section, mm</td><td colspan="15">240 x 240</td></tr>
<tr><td>number of longitudinal reinforcing bars (D13)</td><td colspan="9">4</td><td colspan="2">6</td><td colspan="4">4</td></tr>
<tr><td>tensile reinforcement ratio, %</td><td colspan="9">0.98</td><td colspan="2">1.47</td><td colspan="4">0.98</td></tr>
<tr><td rowspan="4">column</td><td>cross section ,mm</td><td colspan="15">240 x 240</td></tr>
<tr><td>number of longitudinal reinforcing bars (D13)</td><td>2</td><td>3</td><td>4</td><td>2</td><td>3</td><td>4</td><td>2</td><td>4</td><td>6</td><td>4</td><td>6</td><td colspan="4">3</td></tr>
<tr><td>tensile reinforcement ratio, %</td><td>0.49</td><td>0.73</td><td>0.98</td><td>0.49</td><td>0.73</td><td>0.98</td><td>0.49</td><td>0.98</td><td>1.47</td><td>0.98</td><td>1.47</td><td colspan="4">0.73</td></tr>
<tr><td>lateral reinforcement ratio, %</td><td colspan="11">0.22</td><td>0.33</td><td>0.67</td><td>0.33</td><td>0.67</td></tr>
<tr><td rowspan="2">joint</td><td>number of joint hoops (D6)</td><td colspan="11">2</td><td>3</td><td>6</td><td>3</td><td>6</td></tr>
<tr><td>lateral reinforcement ratio, %</td><td colspan="11">0.28</td><td>0.42</td><td>0.83</td><td>0.42</td><td>0.83</td></tr>
<tr><td rowspan="3">beam bar anchorage</td><td>type</td><td colspan="15">anchor plate</td></tr>
<tr><td>anchorage length, mm</td><td colspan="3">192</td><td colspan="3">156</td><td colspan="3">120</td><td colspan="2">156</td><td colspan="2">192</td><td colspan="2">156</td></tr>
<tr><td>ratio of anchor length to depth of column</td><td colspan="3">0.8</td><td colspan="3">0.65</td><td colspan="3">0.5</td><td colspan="2">0.65</td><td colspan="2">0.8</td><td colspan="2">0.65</td></tr>
<tr><td colspan="2">column-to-beam strength ratio $\Sigma M_{cu}/M_{bu}$</td><td>1.07</td><td>1.56</td><td>2.05</td><td>1.07</td><td>1.56</td><td>2.05</td><td>1.07</td><td>2.05</td><td>3.03</td><td>1.39</td><td>2.05</td><td colspan="4">1.56</td></tr>
<tr><td colspan="2">joint shear margin</td><td colspan="3">1.40</td><td colspan="3">1.13</td><td colspan="3">0.87</td><td colspan="2">0.76</td><td colspan="2">1.45</td><td colspan="2">1.18</td></tr>
</table>

M_{bu}, M_{cu}: calculated moment at the center of the joint from beam and column flexural strength at the joint faces

(b) Series N, O and P

<table>
<tr><td colspan="2">Specimen</td><td>N01</td><td>N02</td><td>N03</td><td>N04</td><td>N05</td><td>O01</td><td>O02</td><td>O03</td><td>O04</td><td>P01</td><td>P02</td><td>P03</td><td>P04</td></tr>
<tr><td colspan="2">concrete compressive strength, MPa</td><td colspan="5">29.0</td><td colspan="4">29.8</td><td colspan="4">26.2</td></tr>
<tr><td rowspan="3">beam</td><td>cross section, mm</td><td colspan="5">240 x 170</td><td colspan="4">240 x 240</td><td colspan="4">240 x 340</td></tr>
<tr><td>number of longitudinal reinforcing bars (D13)</td><td colspan="5">6</td><td colspan="3">4</td><td>6</td><td colspan="4">3</td></tr>
<tr><td>tensile reinforcement ratio, %</td><td colspan="5">2.17</td><td colspan="3">0.98</td><td>1.47</td><td colspan="4">0.50</td></tr>
<tr><td rowspan="4">column</td><td>cross section ,mm</td><td colspan="5">240 x 340</td><td colspan="4">240 x 240</td><td colspan="4">240 x 170</td></tr>
<tr><td>number of longitudinal reinforcing bars (D13)</td><td>2</td><td>2</td><td>3</td><td>5</td><td>3</td><td>3</td><td>2</td><td>3</td><td>6</td><td>3</td><td>5</td><td>7</td><td>5</td></tr>
<tr><td>tensile reinforcement ratio, %</td><td>0.33</td><td>0.33</td><td>0.50</td><td>0.84</td><td>0.50</td><td>0.73</td><td>0.49</td><td>0.73</td><td>1.47</td><td>1.09</td><td>1.81</td><td>2.54</td><td>1.81</td></tr>
<tr><td>lateral reinforcement ratio, %</td><td colspan="9">0.22</td><td colspan="4">0.33</td></tr>
<tr><td rowspan="2">joint</td><td>number of joint hoops (D6)</td><td colspan="9">2</td><td colspan="3">3</td><td>6</td></tr>
<tr><td>lateral reinforcement ratio, %</td><td colspan="5">0.44</td><td colspan="4">0.28</td><td colspan="3">0.27</td><td>0.55</td></tr>
<tr><td rowspan="3">beam bar anchorage</td><td>type</td><td colspan="5">anchor plate</td><td colspan="4">bent bar anchorage (U-shape)</td><td colspan="4">anchor plate</td></tr>
<tr><td>anchorage length, mm</td><td>272</td><td colspan="3">221</td><td>170</td><td>192</td><td colspan="3">156</td><td colspan="4">111</td></tr>
<tr><td>ratio of anchor length to depth of column</td><td>0.8</td><td colspan="3">0.65</td><td>0.5</td><td>0.8</td><td colspan="3">0.65</td><td colspan="4">0.65</td></tr>
<tr><td colspan="2">column-to-beam strength ratio $\Sigma M_{cu}/M_{bu}$</td><td colspan="2">1.47</td><td>2.17</td><td>3.54</td><td>2.17</td><td>1.56</td><td>1.07</td><td>1.56</td><td>2.05</td><td>1.03</td><td>1.66</td><td>2.28</td><td>1.66</td></tr>
<tr><td colspan="2">joint shear margin</td><td>1.28</td><td colspan="3">1.04</td><td>0.80</td><td>1.48</td><td colspan="2">1.20</td><td>0.79</td><td colspan="4">1.14</td></tr>
</table>

M_{bu}, M_{cu}: calculated moment at the center of the joint from beam and column flexural strength at the joint faces reinforcement ratios were 0.27% to 0.83%, (5) aspect ratio of a joint; ratios of the depth of beam to the depth of column were 0.5, 1.0 and 2.0, and (6) anchorage type of beam bars; bent bar anchorage or mechanical anchorage.

2.2. Materials

The specimens were made of normal strength concrete and normal strength deformed mild steel bars. The average compressive strength of the concrete by cylinder test were 27.7 MPa, 29.0 MPa, 29.0 MPa, 29.8 MPa and 26.2 MPa for Series L, M, N, O and P respectively as shown in Table 1. The D13 of SD345 grade deformed bars were used for longitudinal bars in beams and columns while the D6 deformed bars of SD295 grade were used for transverse reinforcement in joints, beams and columns. The yield stresses by tensile tests of reinforcing bars were 380 MPa and 334 MPa for D13 bar and D6 bar respectively.

2.3. Loading set up and measurements

The loading setup is shown in Figure 2. A specimen was rotated 90 degrees; the columns were in horizontal position and the beam was in vertical position, and connected to a loading steel frame with a set of PC rods. One end of the columns was connected to the column of the loading frame by an equipment to keep the distance constant and the other was connected to the other column by an oil jack. The distance from the joint center to the loading points at the ends of beam and columns was 700 mm in common. By applying a horizontal displacement by an oil jack to the upper loading beam supported by two loading columns with pin joints at the both ends, a beam-column joint specimen was forced to deform like in a moment resisting frame.

Statically cyclic lateral load reversals with increasing amplitude were applied to the specimens. The loading history is shown in Figure 2. The first cycle was load controlled before cracking. Then reversals with displacement control were applied at each story drift ratio of up to 4.0%. No initial axial force in columns was applied and the oil jack connected to the end of the column were controlled to keep the absolute value of axial force in columns being half of the value of shear force in a beam during the test.

Shear forces in abeam and columns were measured from the forces reading by load cells which were

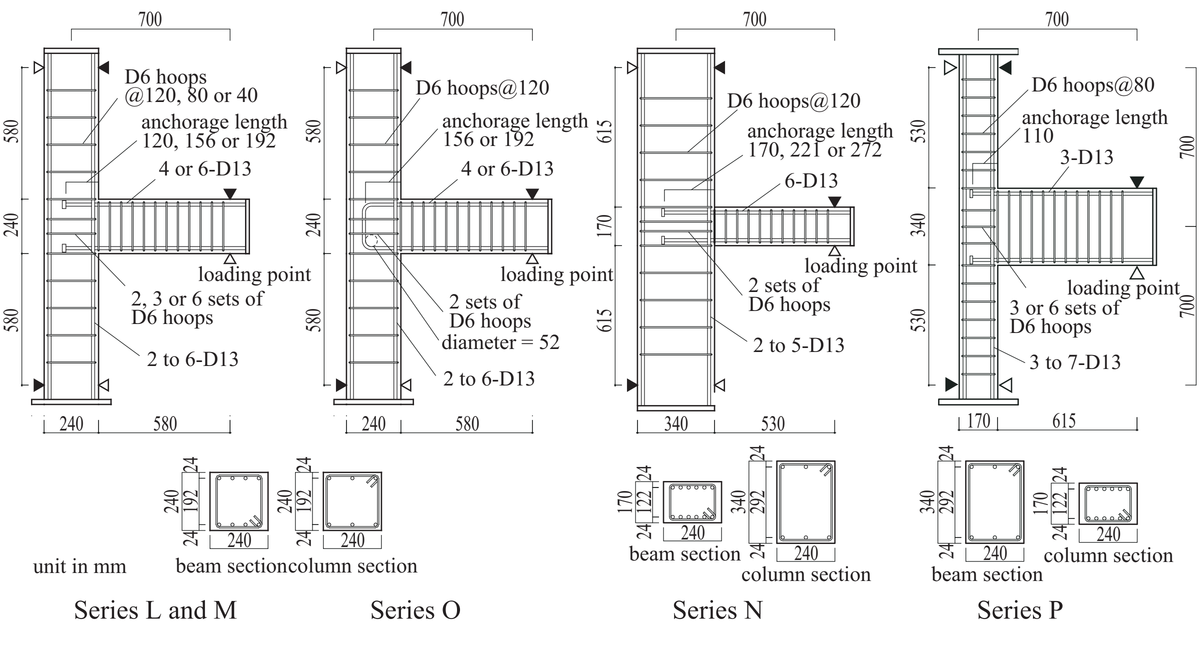


Figure 1. Geometry of Specimens

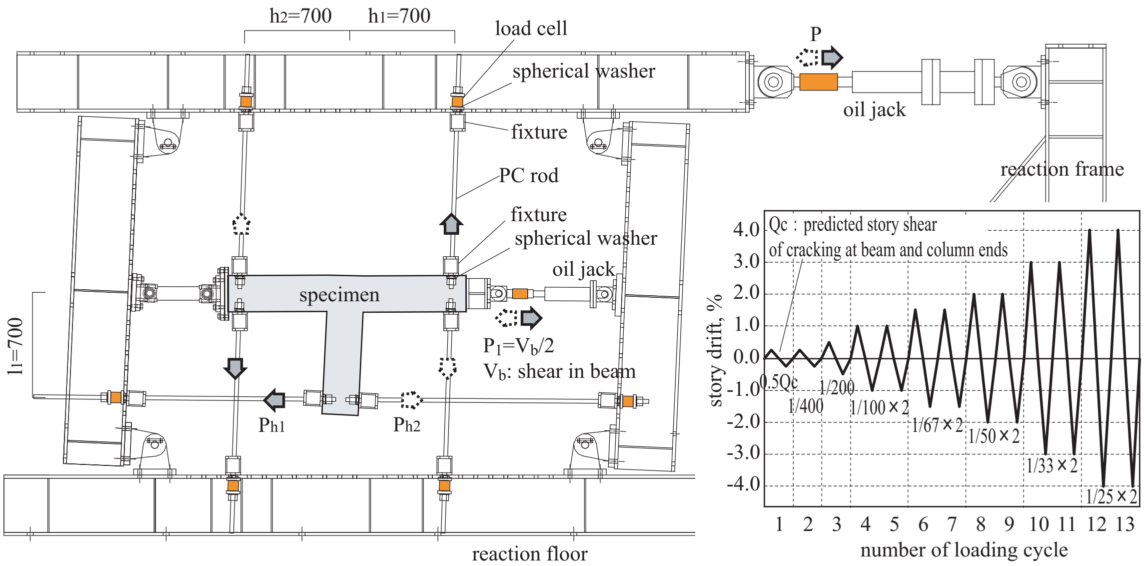
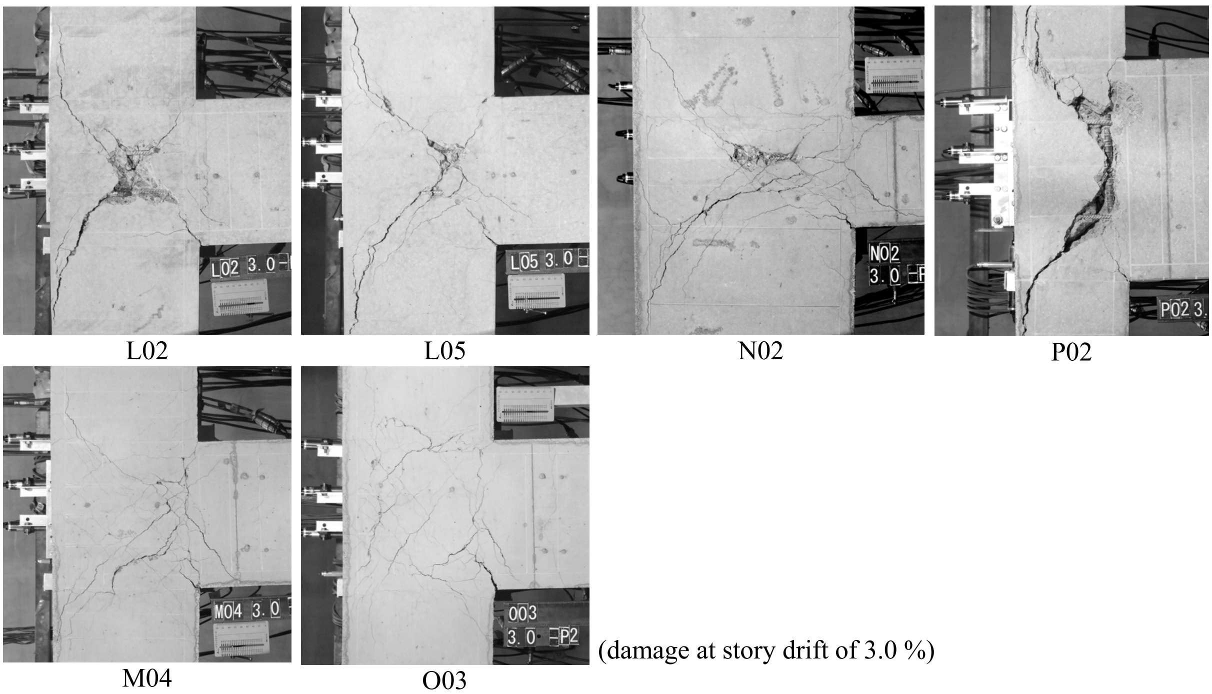


Figure 2. Loading Setup and Loading History



(damage at story drift of 3.0 %)

Photo 1. Typical damage of beam-column joints

installed at the end of PC rods. Story drift ratio was measured as the angle defined by dividing the relative horizontal displacement of the inflection point of a beam to that of columns by the distance of the inflection point of a beam and the joint center (=700 mm). The strains on the longitudinal reinforcing bars in beams and columns at the faces of the joint and on the point of the beam bars and the column bars intersected.

3. TEST RESULTS

3.1. Development of cracks

Photo 1 shows typical appearance at story drift ratio of 3%. In all the specimens, the cracks at the beam ends started at the corner of the joint and propagated to the direction of the center of the beam-column joint diagonally. Diagonal cracks at the center of the joint were observed at story shear around 10 to 20 kN. These cracks started at the ends of beam bars and toward to the corner of the joint in the specimens in Series L, M and O, of which the column and beam depth were identical, while the angles of the crack were closer to 45 degrees in Series N and P. The story shear at cracking at the center of the joint was large in the specimen of which anchor length of beam bars was long or the specimen of which column-to-beam strength ratio was large.

As the number of loading cycles repeated, the number of cracks increased and the width of the diagonal cracks increased. At the load cycles with story drift of 1.5%, concrete crush at the center of the joint initiated. Except specimen M02, of which the lateral reinforcement ratio was 0.83%, significant cracks were observed on the beam-column joints but on beam nor columns. While the flexural cracks on the beam or column ends were observed, their crack width remained small compared to the cracks on the beam-column joints. Although the ratio of joint shear capacity to demand was larger than 1.0 in most of the specimens, failure of joint after yielding of beam and/or column longitudinal bars occurred in all the specimens except the specimens with high joint lateral reinforcement ratio.

Table 2. Summary of Test Results

(a) Series L and M

Specimen		L01	L02	L03	L04	L05	L06	L07	L08	L09	L10	L11	M01	M02	M03	M04
yielding of longitudinal bars in beam	+	NY	32.1	31.2	NY	26.1	28.3	NY	26.3	NY	NY	36.3	32.1	31.2	28.9	32.2
			1.21	1.00		1.11	1.11		1.25			1.34	0.91	0.76	0.89	0.95
	−	NY	-29.4	-29.9	NY	-24.9	-29.3	NY	NY	NY	-29.6	-35.8	-30.8	-32.3	-27.8	-30.7
			-1.20	-0.92		-1.20	-1.20				-3.51	-1.34	-1.05	-0.88	-0.90	-0.80
yielding of longitudinal bars in columns (beam side)	+	23.0	30.8	33.0	20.5	28.2	30.7	17.3	26.2	-25.2	33.6	33.2	32.5	32.1	30.0	30.4
		0.87	1.00	2.28	0.93	1.32	2.62	0.77	3.40	-1.16	1.18	3.26	1.58	0.80	0.96	0.83
	−	-24.1	-30.3	-33.9	-20.6	-26.3	-26.7	-18.2	NY	NY	-33.8	-36.0	-33.3	-33.9	-27.8	-31.2
		-1.40	-1.70	-2.42	-1.00	-1.31	-3.21	-0.95			-1.35	-2.32	-2.01	-1.42	-0.90	-0.84
yielding of lateral joint hoops		21.5	22.1	24.1	13.1	-15.3	16.5	-18.8	-15.2	16.7	15.4	17.7	21.5	33.6	18.3	29.8
		0.75	0.60	0.70	0.45	-0.45	0.43	-1.00	-0.42	0.42	0.36	0.37	0.53	1.05	0.39	0.79
attained maximum story shear	+	26.5	33.0	34.8	23.9	29.3	31.7	19.7	29.1	25.9	36.6	40.1	35.3	37.1	32.6	34.5
		3.01	1.50	3.00	4.00	2.00	1.50	4.00	3.00	1.00	1.50	2.00	3.00	4.01	3.01	3.02
	−	-24.1	-32.6	-34.3	-21.3	-28.1	-31.6	-20.3	-23.7	-28.0	-35.5	-39.6	-33.7	-37.3	-30.3	-32.9
		-1.40	-3.01	-2.00	-4.00	-1.50	-1.50	-4.01	-1.50	-3.00	-1.51	-2.00	-2.87	-4.01	-1.51	-1.54

upper low: story shear in kN, lowe low story drift angle in %, NY: no yielding

(b) Series N, O and P

Specimen		N01	N02	N03	N04	N05	O01	O02	O03	O04	P01	P02	P03	P04
yielding of longitudinal bars in beam	+	NY	NY	36.4	32.0	25.4	32.9	NY	30.6	45.7	NY	25.5	27.2	32.0
				1.41	0.93	3.44	0.86		0.91	1.24		0.79	0.75	0.80
	−	NY	NY	-30.1	-31.7	-28.9	-33.2	NY	-29.1	-45.4	-24.1	-26.6	-27.7	-31.1
				-1.13	-0.98	-1.39	-0.90		-1.31	-1.36	-1.21	-0.86	-0.84	-0.80
yielding of longitudinal bars in columns (beam side)	+	28.5	23.6	33.2	35.4	26.6	35.1	23.8	32.9	48.5	23.3	NY	NY	34.6
		0.92	0.83	1.15	3.17	0.97	1.84	0.92	1.34	1.50	0.75			1.29
	−	-28.7	-24.7	-35.4	-35.6	-28.5	-30.7	-22.1	-24.9	-45.2	-25.2	NY	NY	-24.3
		-1.45	-0.96	-1.46	-3.75	-1.34	-2.21	-1.51	-2.52	-1.86	-0.95			-3.21
yielding of lateral joint hoops		-25.8	23.1	29.0	-24.4	19.6	-33.4	23.8	29.6	30.3	17.7	21.1	20.3	23.6
		-1.51	0.81	0.90	-0.66	0.61	-1.11	0.92	0.86	0.55	0.44	0.45	0.37	0.51
attained maximum story shear	+	33.5	26.5	36.6	38.3	29.0	35.8	24.1	32.9	49.3	25.5	28.4	31.3	35.5
		1.86	1.50	1.51	3.01	1.48	1.51	0.85	1.34	2.02	1.51	1.51	1.51	1.51
	−	-29.1	-25.2	-35.6	-36.7	-29.9	-34.9	-23.4	-30.7	-47.2	-25.7	-28.5	-28.9	-33.9
		-1.51	-1.49	-1.50	-3.01	-1.51	-1.02	-1.01	-1.51	-1.50	-1.86	-1.51	-1.01	-1.50

upper low: story shear in kN, lowe low story drift angle in %, NY: no yielding

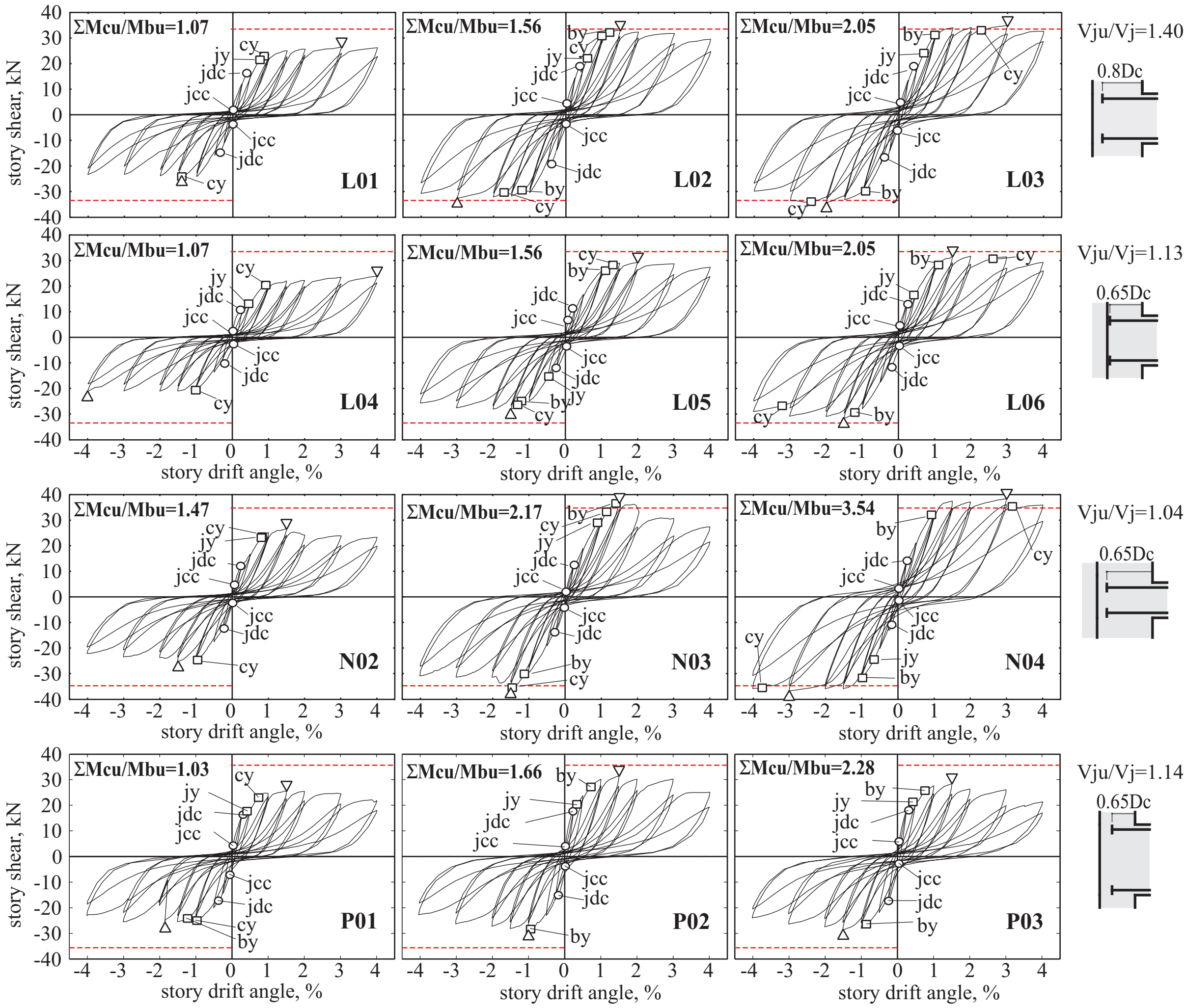
3.2. Story shear-story drift relation

The story shear-story drift ratio relations for some specimens are plotted in Fig. 3. In all the specimens, stiffness degradations were observed after cracking at the corner of the joint and at the center of the joint. In Series L, story shear fell off temporarily after the diagonal cracking at the center of the joint. Stiffness degradation after cracking was mitigated in Series M, with high amount of joint hoops, and in Series O, bent bar anchorage was used.

In all the specimens, the shape of the hysteresis loop was thin and slipping with little energy dissipating capability. No significant strength degradation was observed except Series N, the depth of columns is twice the depth of beam.

3.3. Yielding of reinforcement

Table 2 lists the story shear and story drift at which yielding of the reinforcing bars were observed. The marks of squares in Fig. 3 are also show the sequence of the yielding of reinforcing bars.



jcc diagonal cracking at corner of joint
jdc diagonal cracking at center of joint
by yielding of longitudinal bar in beam
cy yielding of longitudinal bar in column
jy yielding of joint hoop

▽ maximum story shear
--ealcurated story shear at flexural strength of beam

Dc depth of column
Vju joint shear capacity
Vj joint shear demand

Figure 3. Story shear - story drift relations (continued)

In case of the depths of column and beam were in common, Series L, M and O, only the column bars yielded in the specimens of which the values of column-to-beam strength ratios were approximately 1.1. In the specimens of which the column-to-beam strength ratios were larger than 1.5, yielding of beam bars was observed first. Though the values of column-to-beam strength ratios were larger than 1.0, yielding of column bars on the side of beam connected was observed in all the specimens except in specimen L08 and L09. The story shear at beam bar yielding was large in the specimens of which anchor length of beam bars was long, the specimens of which amount of joint hoops was large, and the specimens using bent bar anchorage. The value of column-to-beam strength ratio did not affected strength of beam bar yielding. The story shear at column bar yielding was also large in the specimens of which anchor length of beam bars was long.

In case of the column depth is twice of the beam depth, Series N, yielding of beam longitudinal bars was not observed even in specimen N01 and N02, of which column-to-beam strength ratio was 1.7. In the case of the beam depth was twice of the column depth, Series P, yielding of column bar was not observed in the specimens of which the ratio of column-to-beam strength was larger than 1.5.

The joint hoops yielded before the specimens attained its maximum story shear in all the specimens.

3.4. Maximum story shear

The attained maximum story shear of each specimen is listed in Table 2 and compared to the calculated strength. The calculated story shear is also plotted in Fig. 3. The calculations are by the flexural theory using mechanical properties of materials.

In case of the depths of column and beam were in common, Series L, M and O, the maximum story shear did not attained to calculated flexural strength in the tests except a few specimens. In some specimens, the calculated maximum story shear overestimate 5% to 35% the test results though the joint shear capacity had margin of 13% to 48% to the joint shear demand. One of the exception is specimen L03, which had columns the sum of flexural strengths of which was approximately twice of strength of beam and in which the beam bar anchorage length was 0.8 times of the column depth. The other exceptions are specimen M01 and M02, of which the joint lateral reinforcement ratios were larger than minimum requirement in the design provision, and specimen O01, in which the bent bar anchorage was used instead of mechanical anchor with headed bar. In specimen M01, M02 and O01, the column-to-beam strength ratios was approximately 1.5 and the ratios of the beam bar anchorage length of beam bars to the column were also 0.8.

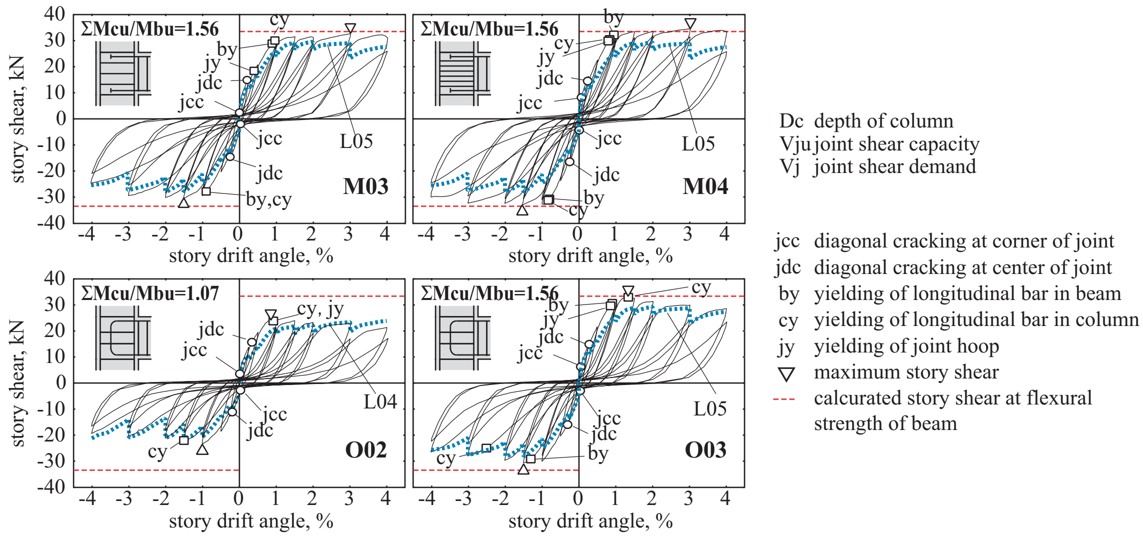


Figure 3. Story shear - story drift relations

In series N, in which the column depth was twice of the beam depth, the maximum story shear attained the calculated flexural strength only in specimen N03 and N04, in which the column-to-beam strength ratios were larger than 1.5 and the ratios of the anchor length of beam bars to the column depth were 0.65. In series P, in which the beam depth was twice of the column depth, the maximum story shear did not attained the calculated flexural strength in all the specimens, even in specimen P03, in which the column-to-beam strength ratio was larger than 2.0.

4. DISCUTIONS

4.1. Effect of column-to-beam strength ratio on strength

The attained maximum story shear are plotted against the column-to-beam strength ratio in Fig. 4. The calculated strengths including story shear at flexural strength of beam, at flexural strength of column

Table 3. Comparison of test and calculation

(a) Series L and M

Specimen		L01	L02	L03	L04	L05	L06	L07	L08	L09	L10	L11	M01	M02	M03	M04
ratio of beam depth to column depth		1.0														
column-to-beam flexural strength ratio		1.07	1.56	2.05	1.07	1.56	2.05	1.07	2.05	3.03	1.39	2.05	1.56			
joint shear margin		1.40			1.13			0.87			0.76		1.45		1.18	
joint lateral reinforcement ratio, %		0.28											0.42	0.83	0.42	0.83
beam bar anchorage		M														
ratio of beam bar anchor length to column depth		0.8			0.65			0.5			0.65		0.8		0.65	
attained maximum story shear, kN	+	26.5	33.0	34.8	23.9	29.3	31.7	19.7	29.1	25.9	36.6	40.1	35.3	37.1	32.6	34.5
	–	-24.1	-32.6	-34.3	-21.3	-28.1	-31.6	-20.3	-23.7	-28.0	-35.5	-39.6	-33.7	-37.3	-30.3	-32.9
calculated story shear at flexural strength of beam (A) , kN		33.2	33.2	33.2	33.2	33.2	33.2	33.2	33.2	33.2	49.1	49.1	33.3	33.3	33.3	33.3
calculated story shear at flexural strength of column (B) , kN		33.5	47.4	60.5	33.5	47.4	60.5	33.5	60.5	84.5	60.5	84.5	47.7	47.7	47.7	47.7
Test / Calculation (min(A,B))	+	**0.80**	**0.99**	1.05	**0.72**	**0.88**	**0.95**	**0.59**	**0.87**	**0.78**	**0.74**	**0.82**	1.06	1.11	**0.98**	1.04
	–	**0.73**	**0.98**	1.03	**0.64**	**0.85**	**0.95**	**0.61**	**0.71**	**0.84**	**0.72**	**0.81**	1.01	1.12	**0.91**	**0.99**
calculated story shear at nominal joint shear strength by AIJ Guidelines(1999)		45.2	45.2	45.2	36.7	36.7	36.7	28.2	28.2	28.2	36.7	36.7	46.6	46.6	37.9	37.9

M: mechanical anchor (anchor plate)

(b) Series N, O and P

Specimen		N01	N02	N03	N04	N05	O01	O02	O03	O04	P01	P02	P03	P04
ratio of beam depth to column depth		0.5					1.0				2.0			
column-to-beam flexural strength ratio		1.47		2.17	3.54	2.17	1.56	1.07	1.56	2.05	1.03	1.66	2.28	1.66
joint shear margin		1.28	1.04			0.80	1.48	1.20		0.79	1.17			
joint lateral reinforcement ratio, %		0.44					0.28				0.27			0.55
beam bar anchorage		M					B				M			
ratio of beam bar anchor length to column depth		0.8	0.65			0.5	0.8	0.65			0.65			
attained maximum story shear, kN	+	33.5	26.5	36.6	38.3	29.0	35.8	24.1	32.9	49.3	25.5	28.4	31.3	35.5
	–	-29.1	-25.2	-35.6	-36.7	-29.9	-34.9	-23.4	-30.7	-47.2	-25.7	-28.5	-28.9	-33.9
calculated story shear at flexural strength of beam (A) , kN		34.8	34.8	34.8	34.8	34.8	33.4	33.4	33.4	49.2	35.5	35.5	35.5	35.5
calculated story shear at flexural strength of column (B) , kN		47.6	47.6	69.0	110.7	69.0	47.8	33.8	47.8	85.6	32.4	52.3	72.2	52.3
Test / Calculation (min(A,B))	+	**0.96**	**0.76**	1.05	1.10	**0.83**	1.07	**0.72**	**0.98**	1.00	**0.79**	**0.80**	**0.88**	**1.00**
	–	**0.84**	**0.73**	1.02	1.06	**0.86**	1.05	**0.70**	**0.92**	**0.96**	**0.79**	**0.80**	**0.81**	**0.95**
calculated story shear at nominal joint shear strength by AIJ Guidelines(1999)		46.4	37.7	37.7	37.7	29.0	47.5	47.5	47.5	38.6	37.3	37.3	37.3	37.3

M: mechanical anchor (anchor plate) , B: bent bar anchorage (U-shape)

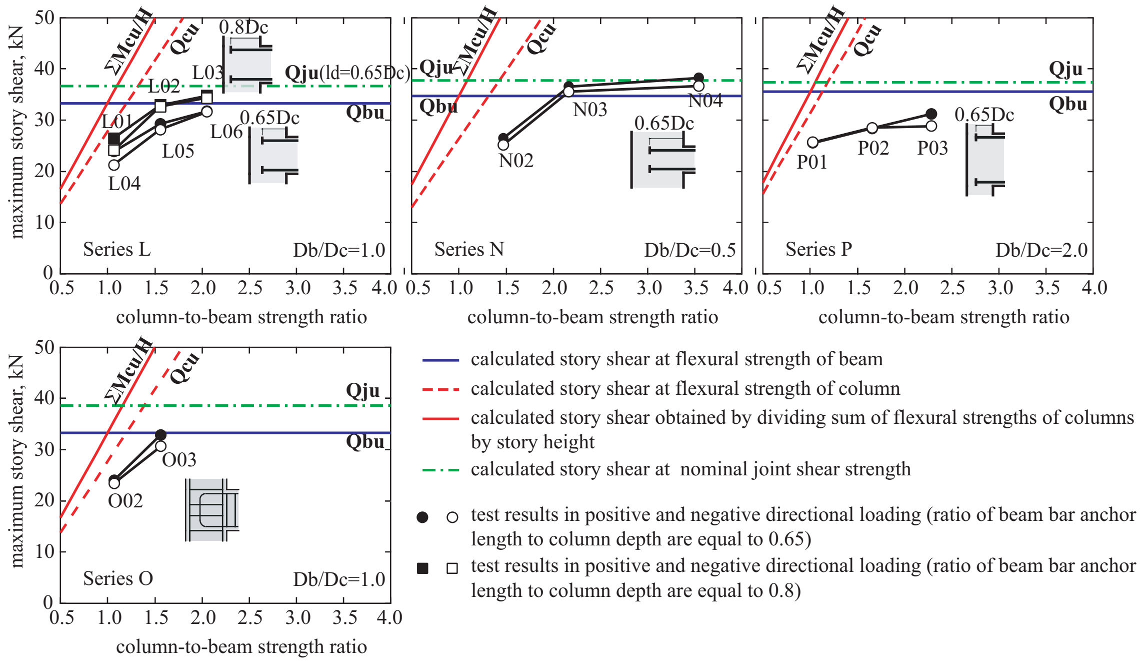


Figure 4. Effect of column-to-beam strength ratio on strength

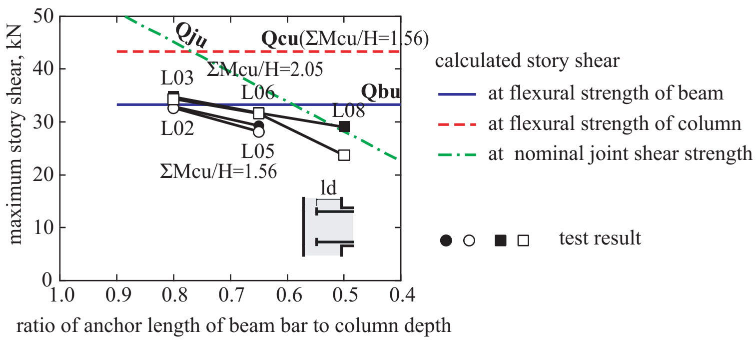


Figure 5. Effect of anchor length of beam bars

and at nominal joint shear strength are plotted in the figures in conjunction with the test results. The story shear at the column strength is calculated from the smaller one of the strengths of the two columns connected to the joint, i.e. it is based on the flexural strength of the column in which tensional axial force is acted.

As the figures show, the maximum story shear is affected by the ratio of column flexural strength to beam flexural strength. The test results were smaller when the column-to-beam strength ratio is near 1.0. In cases of the ratio of the anchor length to the column depth was 0.65, column-to-beam strength ratio required to secure lateral strength predicted by the flexural theory of beam sections was approximately 2.0 except the case of the beam depth much larger than the column depth, in which no specimen reached the calculated strength. The test results of the specimens using bent bar anchorage, Series O, were 10 to 20% larger than the specimens which have the common bar arrangement and adopted mechanical anchorage.

4.2. Effect of anchorage length of beam bars

The attained maximum story shear of Series L are plotted against the ratio of anchorage length of beam bars to column depth in Fig. 5. Even in the cases of the ratios of joint shear capacity to joint shear demand were larger than 1.0, i.e. in the cases of the ratios of anchor length to column depth were 0.65 or larger, the maximums story shear were larger in the specimens in which the anchor length was

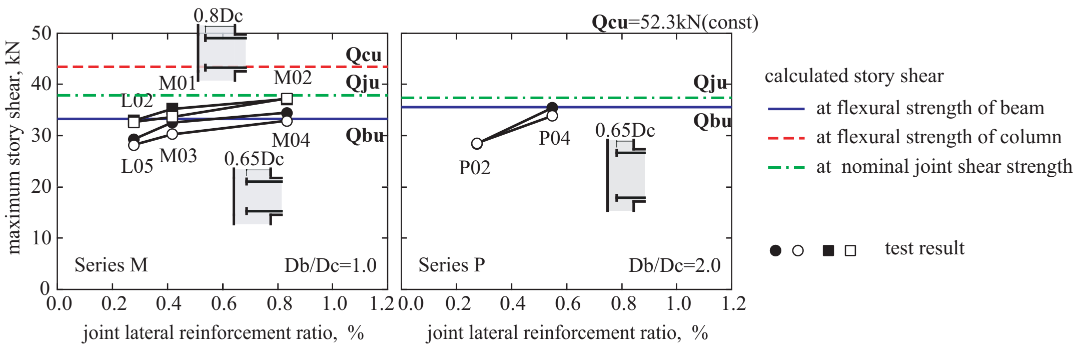


Figure 6. Effect of joint lateral reinforcement

long. The effect of anchor length was more significant in the specimens in which the column-to-beam strength ratio was small.

4.3. Effect of lateral reinforcement in joints on strength

The attained maximum story shear of Series M and P are plotted against the joint lateral reinforcement ratio in Fig. 6. As the figure shows, adding lateral reinforcement in joint made maximum story shear larger. In other words, column-to-beam strength ratio required to secure lateral strength predicted by the flexural theory of beam sections is so small that amount of lateral reinforcement in the joint is large.

5. CONCLUDING REMARKS

Story shear capacity of some specimens were 30% lower of the story shear predicted by the flexural strength of the beam or the column at the maximum, although the joints have enough margins for nominal joint shear demand by 10% to 50% based on current design provisions. Joint failure occurred after yielding of longitudinal bars of beam and/or columns regardless of joint shear margins. The decrease of story shear is larger in case of the ratio of sum of the flexural strengths of columns to the flexural strength of the beam is equal or near to unit. Column-to-beam strength ratio required to secure lateral strength predicted by the flexural theory of R/C sections is so small that amount of lateral reinforcement in the joint is large or the depth of columns is large relatively to that of the beam. In addition to that, the test results show that the joint using mechanical anchorage with headed bars has lower strength and poor energy dissipation compared with the case of bent bar anchorage.

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