COMPREHENSIVE SERIES OF TESTS ON SEISMIC PERFORMANCE OF REINFORCED CONCRETE BEAM-COLUMN JOINTS

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ABSTRACT

Preliminary results of seismic test on one third scale, twenty reinforced concrete interior beam-column joint subassemblages are reported. The effects of the combination of design parameters of joints on lateral capacity and post yielding behavior are investigated. Three major parameters selected in the test are (1) amount of longitudinal reinforcement, (2) ratio of the flexural strength of the beams to the flexural strength of the columns framing into a joint, and (3) ratio of the depth of the beam to the depth of the column. Maximum story shear of some specimens fell 5% to 30% short of the story shear calculated by the flexural strength of the beam or the column, although the joints have enough margin of the nominal joint shear strength by 0% to 50% compared to the calculated value by a current seismic provision. The extent of insufficiency in the story shear is larger if the flexural strength of the column is equal or nearer to the flexural strength of the beam, and if the depth of the column is larger than that of the beam. This kind of combination of design parameters is not a rare feature but is rather seen frequently in existing reinforced concrete buildings. This means that current seismic provisions for RC beam-column joints are deficient and can not secure the lateral strength of moment resisting frames predicted by the flexural theory of RC sections. Hence a large number of existing moment resisting frame reinforced concrete structures may be more vulnerable than we expect. Immediate actions by engineers, researchers and code writers are necessary.

INTRODUCTION

The current building codes in high seismic zone have provisions for design of reinforced concrete beam-column joints to preclude joint shear failure. It is based on an idea that the joint shear failure occurs before yielding of the beams or columns, if excessive tensile force in longitudinal reinforcing bars passing through a joint need to be developed in a column with too small section. So the joint capacity equations have been adopted in the seismic provisions. The equations of joint shear strength have been empirically derived based on sets of tests of beam-column joint subassemblages which have relatively heavily reinforced in the beams as well as in the columns to assess a potential of joint shear resistance. The effects of design parameters on the joint shear resistance have been regarded as very complicated and no study has not been successful to get a good correlation of joint shear strength to particular design parameters (Bonacci et al. 1993), but only for (a) dimension of column and (b) concrete compressive strength. Hence the most of the current provisions for beam-column joint admit consideration only these two parameters for design. Unfortunately, this has been producing a side effect that little attention has been paid to the actual strength and post-yielding behavior of more realistically reinforced beam-column joints in practice, which are usually moderately longitudinally reinforced. On the contrary, it has been believed by engineers that if the joint shear demand is smaller than nominal joint capacity, the frame with the joint could achieve a

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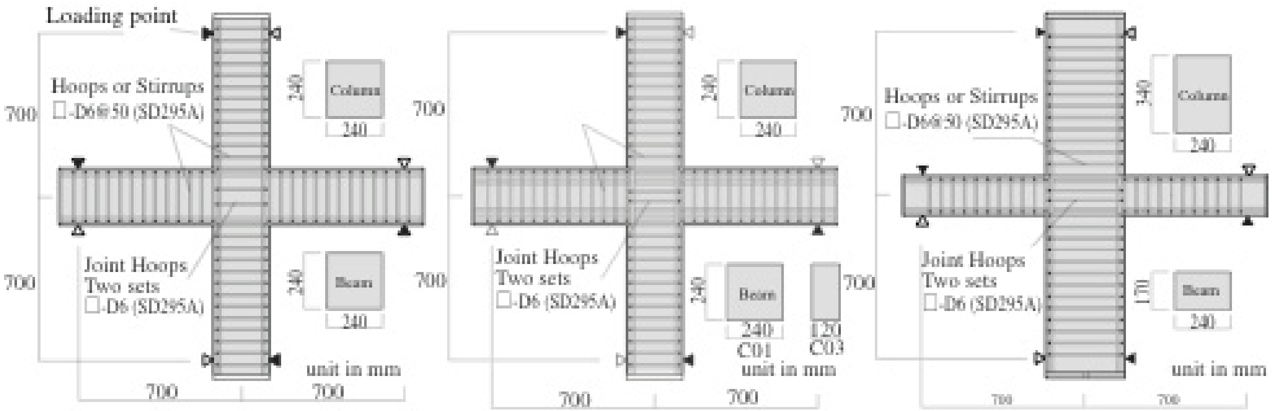
story shear calculated by flexural strength of the beam or columns and they have rich post-yielding behavior with fat hysteresis loops.



(a) Series B (b) Series C (c) Series D

Fig. 1. Geometry of Specimens

However, it is revealed recently by a research (Shiohara 2008) that the flexural strength of beam nor column could not be achieved in a crucial beam-column joint subassemblage if the flexural strength of beam and flexural strength of column framing into a joint are identical or close to each other by a series of algebraic equations derived theoretically using a model for a failure of beam-column joint (Shiohara 2001). Hence, an experimental study have been carried out to get validated the theory and to get test data for the development of performance based seismic design used for evaluation of post-yielding behavior of beam-column joints for next generation. This is a preliminary report on the experimental study, which investigates the effects of the three major design parameters, including (1) longitudinal reinforcement ratio in beams, (2) ratio of the flexural strength of the beams to the flexural strength of the columns framing into a joint, and (3) ratio of the depth of the beam to the depth of the column. The effects of the combination of three parameters on the maximum story shear and the post-yielding behavior are discussed.

TEST PROGRAM

Test result of twenty specimens are selected and reported here out of thirty one specimen of planar reinforced concrete beam-column joints in an experimental project carried out at the University of Tokyo. The specimens are 1/3 scale beam-column joint subassemblages of crucial form. Table. 1 summarizes the arrangement of the reinforcements and other properties of the specimens. The depth of the columns and the beams are 240 mm in common for Series B and Series C, whereas the depths of column and beam are 340 mm and 170 mm for Series D. The width of all the beams and the columns is 240 mm in common. Figure 1 shows the geometry and dimensions of the specimens. The hoops and the stirrups of all the specimen are of rectangular shape of D6 deformed bars at spacing of 50 mm. Two sets of rectangular hoops of D6 deformed bars are provided in horizontal direction in a joint of all the specimen. The joint shear reinforcement ratio is approximately 0.3% and satisfies the minimum requirement of the AIJ Guidelines (1999).

Test Parameters

Four test parameters are included in the selected specimens in this report. They are (1) ratio of joint shear demand to joint shear capacity; 0.55-1.50, where joint shear capacity is calculated by the AIJ Guidelines (1999), (2) ratio of flexural strength of beam and column evaluated at the center of a joint; 0.72-2.24, (3) ratio of column depth to beam depth; 1.0 or 2.0, and (4) longitudinal reinforcing bar distant ratio; 0.5-0.8, which is the ratio of distance of tensile and compressive reinforcements to the full depth of a cross section.

Table 1. Properties of Specimens
(a) Series B

Specimens		B01	B02	B03	B04	B05	B06	B07	B08	B09	B10
concrete compressive strength in MPa		29.0									
longitudinal reinforcing bar distant ratio		0.8						0.65	0.5	0.65	0.5
beam	section in mm	240 × 240									
	longitudinal reinforcing bars	4-D13	5-D13	5-D16	4-D13	5-D13		4-D13		5-D16	
		SD345	SD345	SD390	SD345	SD345		SD345		SD390	
	tensile reinforcement ratio %	0.98	1.22	1.92	0.98	1.22	1.22	1.07	1.18	2.09	2.30
column	section in mm	240 × 240									
	longitudinal reinforcing bars	4-D13	5-D13	5-D16	6-D13	5-D13 2-D13	5-D13 5-D13	4-D13		5-D16	
		SD345	SD345	SD390	SD345	SD345		SD345		SD390	
	tensile reinforcement ratio %	0.98	1.22	1.92	1.47	1.80	2.67	1.07	1.18	2.09	2.30
joint	joint hoops	□-D6(SD295) 2 sets									
joint shear capacity margin		1.29	1.03	0.57	1.29	1.03	1.03	1.26	1.24	0.56	0.55
ΣMuc / ΣMub		1.00	1.00	1.00	1.48	1.35	1.78	1.00	1.00	1.00	1.00

(b) Series C & D

Specimens		C01	C03	D01	D02	D03	D04	D05	D06	D07	D08
concrete compressive strength in MPa		31.0		32.4							
beam	width in mm	120	240	240							
	depth in mm	240	240	170							
	longitudinal reinforcing bar distant ratio	0.5 & 0.8		0.72							
	longitudinal reinforcing bars	3-D13+2-D13		5-D13			7-D13				7-D16
		SD345		SD345							
	tensile reinforcement ratio %	1.31	2.62	1.81			2.54				3.98
column	width in mm	240		240							
	depth in mm	240		340							
	longitudinal reinforcing bar distant ratio	0.8	0.8	0.86							
	longitudinal reinforcing bars	5-D13		2-D13	3-D13	5-D13	2-D13	3-D13	4-D13	6-D13	3-D16
		SD345		SD345							
	tensile reinforcement ratio %	1.22		0.33	0.50	0.84	0.33	0.50	0.67	1.04	0.79
joint	joint hoops	□-D6(SD295) 2 sets									
joint shear capacity margin		1.10	0.80	1.50			1.06				0.68
ΣMuc / ΣMub		1.03	1.10	0.99	1.42	2.24	0.72	1.03	1.34	1.72	1.01

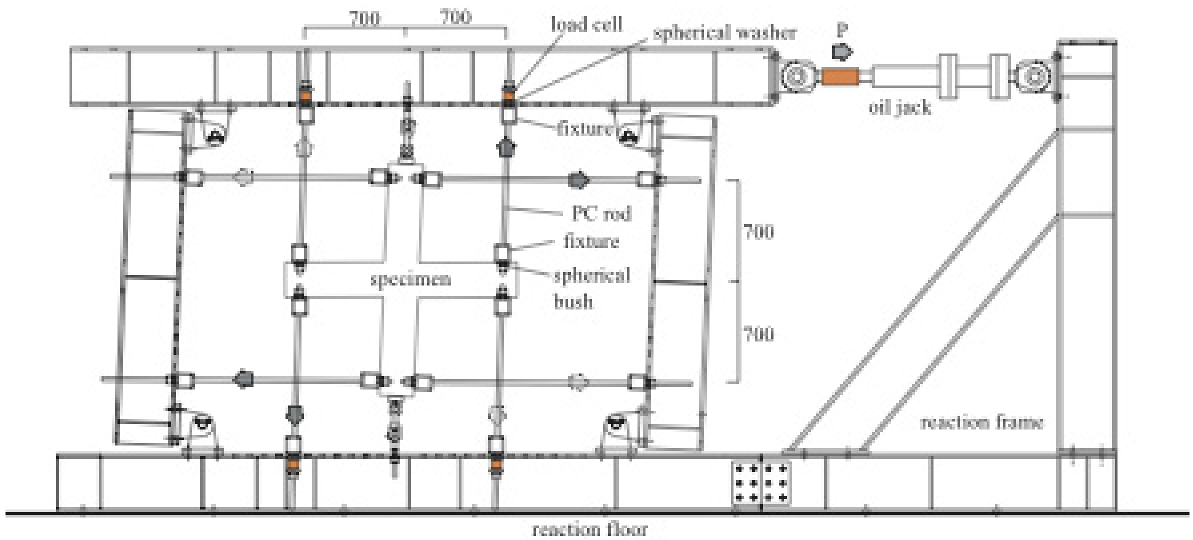


Fig. 2. Loading Setup

Material Properties

The specimens are made of normal concrete and normal strength deformed steel bars. Concrete compressive strengths were tested by a 100 mm by 200 mm cylinder. They are 29.0 MPa, 31.0 MPa and 32.4 MPa for Series A, B and C respectively. The yield points by tensile tests of reinforcing steel are 399 MPa, 378 MPa, and 425 MPa for D6, D13 and D16 deformed bars respectively.

Loading Setups

The loading setup are shown in Fig. 2. A specimen is connected to a loading steel frame with a set of horizontal and vertical PC bars. The distance of the loading points at the end of the beams and the columns is 1400 mm. The upper horizontal loading beam is supported with two vertical loading columns with a pinned joint at the both ends. The vertical loading columns are connected to a lower horizontal loading beam with a pinned joint. The lower loading beam is fixed to a testing floor. By applying a horizontal displacement by a oil jack to the upper loading beam, a beam-column joint specimen is forced to deform like in a moment resisting frame.

Loading Cycles and Measurements

Statically cyclic lateral load reversals with an increasing amplitude were applied to the specimen to get load-deformation relationships. The first cycle is load controlled before cracking. Then two reversals with displacement control are applied at each story drift ratio of 0.25%, 0.5%, 1.0%, 1.5%, 2.0% and 3.0%. In Series D, a loading cycle with 4.0% story drift ratio is added. Zero axial force in the columns and beams are kept during the test in all specimens. Shear story is measured from the force reading by load cells which are installed at the end of vertical PC bars. Story drift ratio is measured as the difference of lateral displacement at the two inflection points in the column divided by the distance of the inflection points (=1400 mm). The strain on the longitudinal reinforcing bars in beams and columns as well as in joints are measured by strain gauges. The strain at the column face as well as in the joint on the point of diagonal of the joint are measured.

TEST RESULTS

Overall Behavior

Photo 1 shows typical appearance at story drift ratio of 3%. In all the specimen, diagonal cracks at the corner started at story shear around 5 kN in loading cycles to both directions. Diagonal cracks at the center of the joint appeared at story shear around 30 kN. As the number of loading cycles increases, the number of cracks increased and the width of the diagonal cracks increased. At the load cycles with story drift ratio of 2.0%, concrete crush at the center of the joint initiated and cover concrete spalled off at the load cycle with story drift ratio of 3.0% or more. In all the specimens, significant cracks are observed on the beam-column joints but on beams nor columns. While the flexural cracks in the beam or column ends are observed, their crack width remained small compared to the cracks in the beam-column joints.

Yielding of Reinforcement

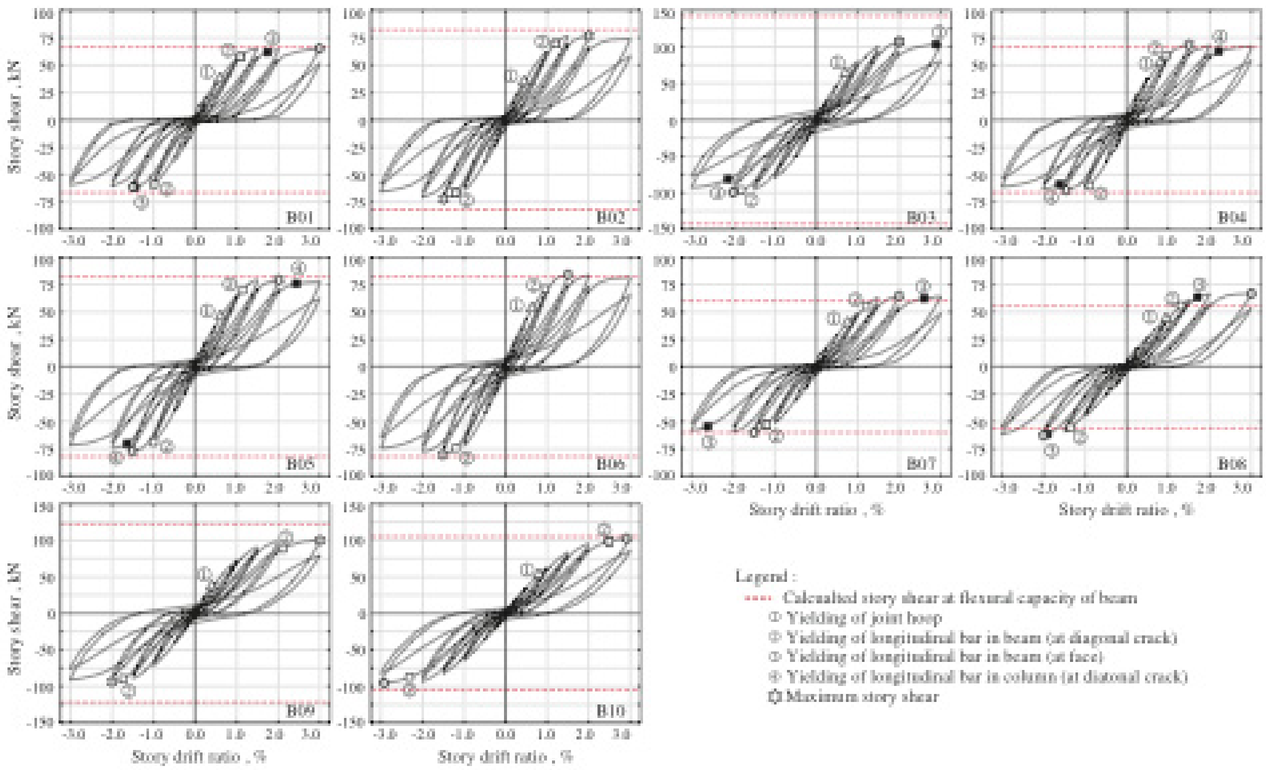
The story shear-story drift ratio relation of each specimen is shown in Fig. 3. The marks are put in the figures to show the sequence of the yielding of reinforcing bars. Table 2 lists the location of strain gauges and the story shear at which yielding of the reinforcing bars are observed. In all specimens except specimen D08, yielding of longitudinal bars in beams occurred before the specimens attained its maximum story shears. In all specimens except specimens B06, yielding of longitudinal bars in columns occurred. The story shear at first yielding and attained maximum story shear and the story drift ratio are also listed in Table 2. It should be noted that yielding of beam bars was observed in most of the specimen with joint shear demand higher than code specified and the yielding of column bars was observed in most of the specimen with stronger column than beams framing into a joint with margin less than 2.0. The joint hoops yielded before the first yielding of longitudinal reinforcement in all the specimen in Series B and C. On the contrary, the yielding of joint hoops in Series D is not necessary observed in all the specimens.

Maximum Story Shear

Calculated story shear by the flexural theory is shown as horizontal dotted line in Fig. 3. The values are also listed in Table 3. Results of material test are used for the calculation. The maximum story shear are not be attained in the tests except a few specimens. In some specimens, the calculated maximum story shear overestimate 5% to 30% the test results. The exceptions in Series B are specimen B04, B05, and B06, which have columns the flexural strength of which are larger than that of beam by 48%, 35% and 78%, and specimen B07 and B08, in which the distance ratio of reinforcement of beams is 0.65 and 0.5 which is smaller than ordinary reinforced concrete beams in practice. The exception in Series D are Specimens D03 and D07, the flexural strength of the column of which are larger than that of the beams by 124% and 72%. So it is concluded that for ordinary beam-column joint, the story shear calculated based of flexural theory of the section overestimate, if the flexural strength of beams and columns are identical or near.

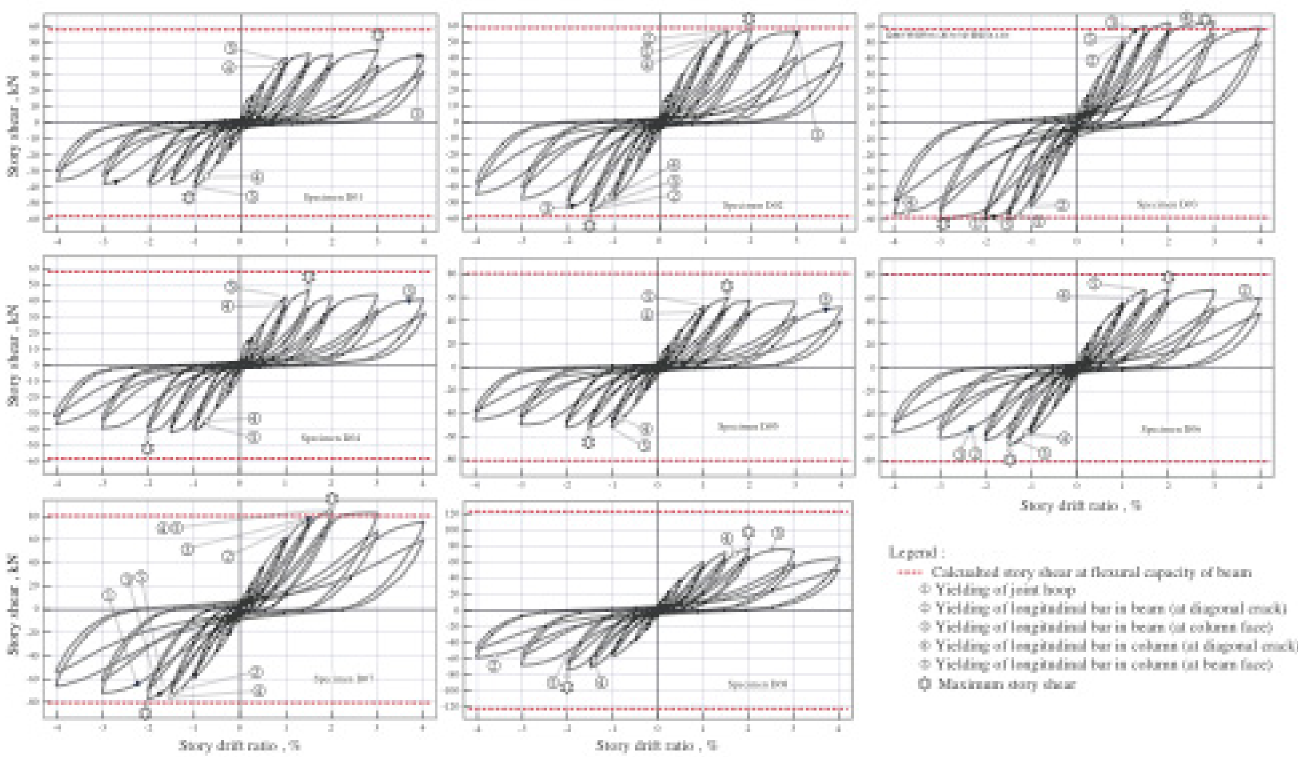
Post-Yielding Behavior

Post-yielding hysteresis relation of beam-column joint subassemblages are compared in Fig. 3. All the specimens show poor hysteresis curves with little energy dissipation and severe slip shape. No significant strength degradation are observed within the range of displacement reversals. No sudden strength degradation are observed instead the some of the specimen are judged to joint shear failure type by current seismic design codes. Strength degradation ratio due to cyclic loading of same amplitude are estimated 20-30% in most of the specimens within the story drift ratio less than 3.0%.



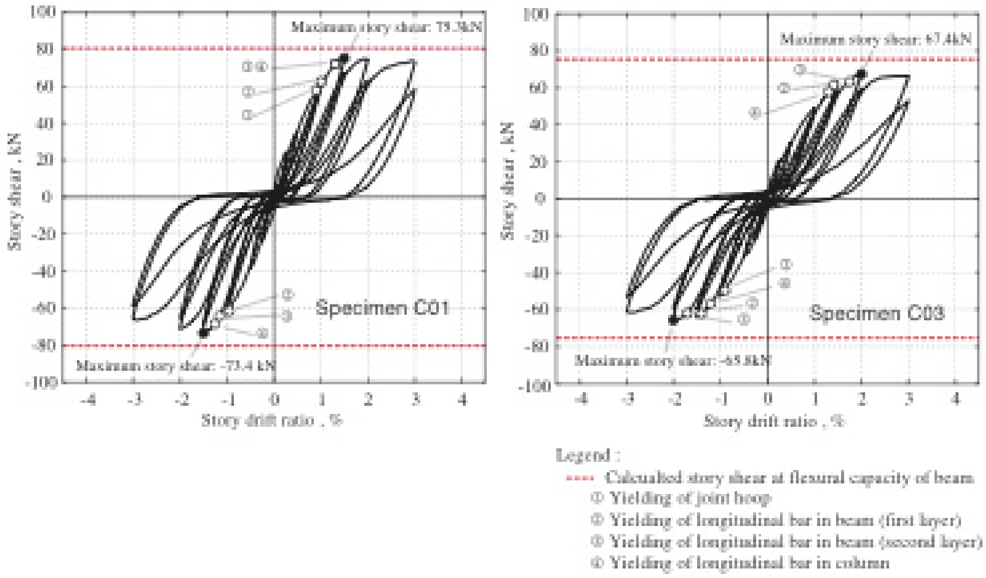
(a) Series A

Fig. 3. Story shear-story drift relations



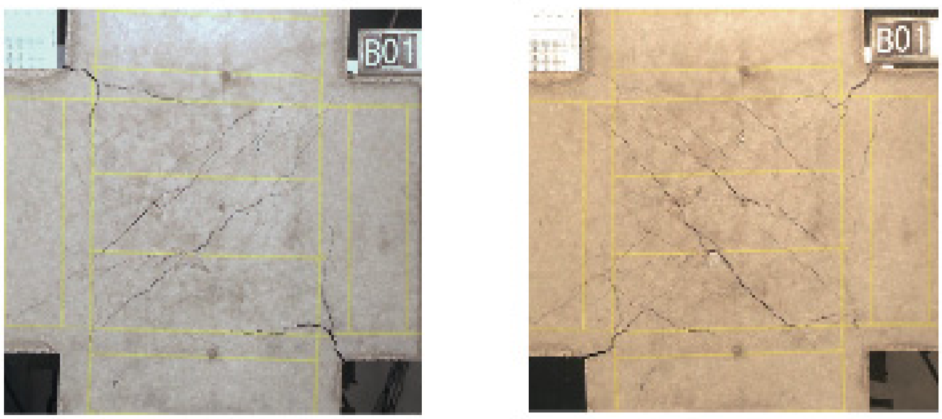
(b) Series D

Fig. 3. Story shear-story drift relations (Continued)



(c) Series B

Fig. 3. Story shear-story drift relations



(a) Specimen B01 at story drift ratio of 3.0%

(b) Specimen D02 at story drift ratio of 3.0%

Photo 1. Typical damage of beam-column joints

Table 2. Strengths at yielding and maximum strength

(a) Series B

Specimen		B01	B02	B03	B04	B05	B06	B07	B08	B09	B10
Yielding of longitudinal bars in beams	at diagonal cracks in joint	57.6 1.09	69.5 1.20	107.1 2.20	58.8 0.95	69.9 1.14	70.9 0.95	57.0 1.25	55.7 1.31	88.8 2.11	98.5 2.50
	at column face	61.8 1.74	–	NY	–	–	–	63.1 2.80	66.4 2.80	NY	NY
Yielding of longitudinal bars in columns	at diagonal cracks in joint	57.6 1.09	69.5 1.20	101.5 2.62	62.6 2.21	75.8 2.44	NY	55.2 1.20	59.5 1.45	93.6 2.32	98.5 2.50
	at beam face	63.0 1.88	–	103.3 2.89	–	–	–	62.3 2.60	63.3 1.70	NY	NY
Yielding of horizontal joint hoops		37.3 0.59	34.2 0.44	63.1 0.70	52.0 0.80	45.2 0.61	52.5 0.63	40.0 0.76	43.5 0.95	36.1 0.40	52.1 0.80
At attained maximum story shear	+	65.2	76.7	107.1	68.6	79.3	84.0	64.6	66.7	99.8	102.6
	–	-61.5	-72.3	-99.4	-64.2	-77.7	-80.5	-60.4	-63.0	-94.2	-95.8

Upper low : story shear in , Lower low : story drift ratio in %, N/A : data not available, NY : no yielding

(b) Series C & D

Specimen		C01	C03	D01	D02	D03	D04	D05	D06	D07	D08
Yielding of longitudinal bars in beams	at diagonal cracks in joint	62.5 1.00	61.4 1.41	NY	55.5 1.38	52.1 1.11	NY	NY	59.6 3.83	73.7 1.32	NY
	at column face	–	–	41.6 3.89	55.3 3.00	57.4 1.26	40.1 3.70	49.6 3.67	NY	77.8 1.51	NY
Yielding of longitudinal bars in columns	at diagonal cracks in joint	72.0 1.30	57.7 1.30	35.2 0.78	48.0 1.00	61.3 2.54	37.4 0.82	47.2 0.87	59.4 1.17	83.7 1.96	70.3 1.70
	at beam face	–	–	38.6 0.88	53.4 1.25	55.2 3.01	42.2 1.00	51.8 1.01	65.9 1.41	83.7 1.96	74.9 2.52
Yielding of horizontal joint hoops		57.8 0.90	-49.4 -0.90	NY	NY	-59.0 -2.00	NY	NY	–	-63.5 -2.21	NY
At attained maximum story shear	+	75.3	67.4	45.4	57.1	63.1	46.3	59.3	67.4	83.8	76.4
	–	-73.4	-65.8	-39.4	-55.1	-59.8	-41.9	-52.8	-66.3	-77.3	-74.4

Upper low : story shear in , Lower low : story drift ratio in % , N/A : data not available, NY : no yielding

DISCUSSION

Effect of Design Parameters on Story Shear Strength

Mechanical reinforcement ratio in beam. The maximum moment at the center of the joint normalized by the width of the beam section *b*, square of beam depth D^2 and concrete compressive strength f'_c are plotted against the mechanical reinforcement ration of beam for the specimens at which the flexural strength of beams are identical to that of the columns in Fig. 4. Lines drawn in the figure are the prediction by the current design equations for comparison. They correspond to the calculated moment at flexural strength of beams and calculated moment at joint shear nominal strength based on the equations adopted in the AIJ Guidelines (1999). In Series B, the both current design equations for flexural failure and joint shear failure overestimate the test results of specimen B01 and B02, while the joint shear strength of specimen B03 is underestimated. In series D, the current design equations both for flexural strength and joint shear strength overestimate the test results. Therefore, it is concluded that the current design equations underestimate lateral capacity of beam-column joint subassemblages with moderately reinforced beam-column joint. In particular, the deficiency of strength of beam-column joints is significant if the depth of beam is smaller than that of column. An approximate line fitting is shown for each series in Fig. 4. The approximate lines for Series B and D seems to coincide.

Ratio of flexural strength of column to flexural strength of beam. The attained maximum moment normalized by the beam width *b*, square of beam depth D^2 and concrete compressive strength f'_c are plotted against the ratio of the flexural strength of the column to the flexural strength of the beam in Fig. 5. The lines representing flexural strength of the columns and the beams are also shown in the same figure. The plot of test results are not on the calculated lines but locates beneath the lines. In Series B, the test valued is smaller when the ratio of the flexural strength the column is equal to the flexural strength of the beam framing into the joint. The strength of the specimens the flexural strength of the column of which is much larger than the flexural strength of the beam is well predicted by the flexural theory. In Series D, the deficiency in strength is more evident than Series B. In all these specimen in Series B and D, the line fitting to the test results seems to be on the straight line which has the slope equal to the average slope of the flexural strength of beam and the strength of the column.

CONCLUSION

Results of seismic test on twenty interior reinforced concrete beam-column joint were reported. Story shear capacity of some specimens fell 5% to 30% short of the story shear predicted by the flexural strength of the beam or the column, although the joints have enough margin for nominal joint shear capacity by 0% to 50% based on current seismic provisions. In such specimens, the calculated flexural strength of the column are found to be fallen in the range of 70% to 140% of the flexural strength of the beam. The extent of insufficiency in the story shear is larger if the flexural strength of the column is equal or nearer to the flexural strength of the beam, and if the depth of the column is larger than that of the column. This kind of combination of design parameters is not a rare feature but is rather seen frequently in existing reinforced concrete buildings. This means that current seismic provisions for RC beam-column joints are deficient and can not secure the lateral strength of moment resisting frames predicted by the flexural theory of RC sections. Hence a large number of existing moment resisting frame reinforced concrete structures may be more vulnerable than we expect. Immediate actions by engineers, researchers and code writers are necessary. Development of mathematical models suitable for codes are important. The results of the investigation should be reflected to the seismic design of building codes, and seismic vulnerability assessment method for existing reinforced concrete buildings.

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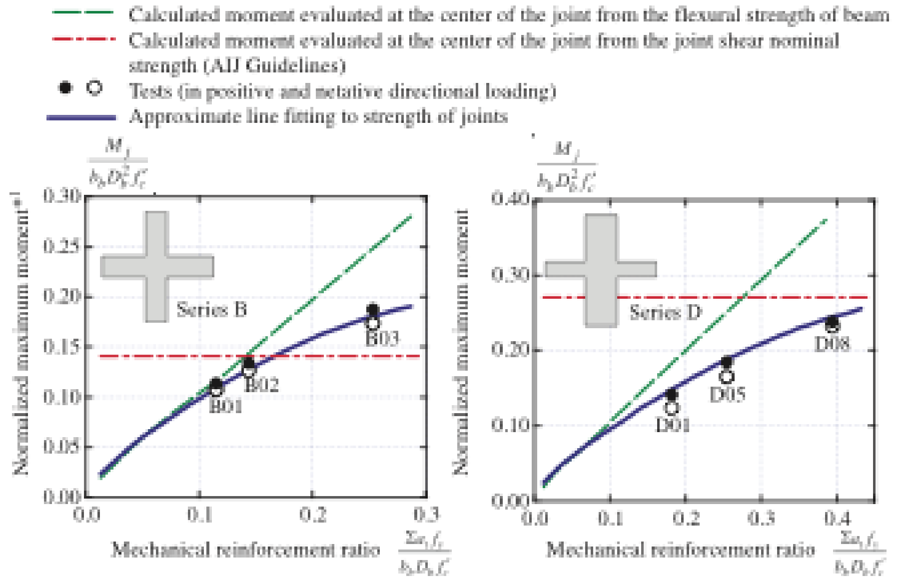
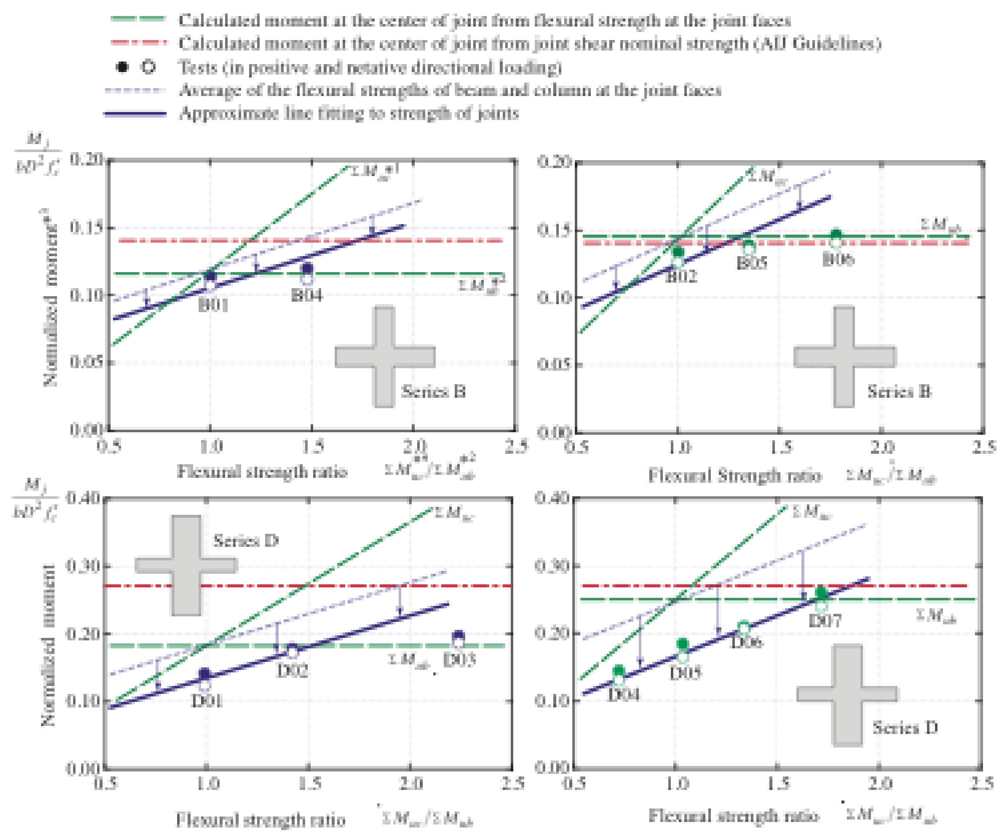


*1 Moment evaluated at the center of joint normalized with respect to the beam width b_b, square of the beam depth $D_b{}^2$ and concrete compressive strength f_c'

Fig. 4. Effect of mechanical reinforcement ratio on strength



*1 Sum of ultimate flexural strength of columns framing into the joint evaluated at the center of joint
*2 Sum of ultimate flexural strength of beams framing into the joint evaluated at the center of joint
*3 Moment evaluated at the center of joint normalized with respect to the beam width b, square of the beam depth D^2 and concrete compressive strength f_c'

Fig. 5. Effect of ratio of flexural capacity of column to flexural capacity of beam

Table 3. Comparison of test and calculation

(a) Series B

Specimen		B01	B02	B03	B04	B05	B06	B07	B08	B09	B10
Ratio of the distance of tens. and comp. reinforcement to the full depth of the section		0.8						0.65	0.5	0.65	0.50
Joint shear capacity / Joint shear demand		1.29	1.03	0.57	1.29	1.03	1.03	1.26	1.24	0.56	0.55
Ratio of flexural strength of column to flexural strength of beam section evaluated at joint center		1.0			1.48	1.35	1.78	1.0			
Attained maximum story shear	+	65.2	76.7	107.1	68.6	79.3	84.0	64.6	66.7	99.8	102.6
	−	-61.5	-72.3	-99.4	-64.2	-77.7	-80.5	-60.4	-63.0	-94.2	-95.8
Calculated story shear at flexural strength of beam		66.3	82.1	142.1	66.3	82.1	82.1	60.1	56.2	122.1	105.2
Test / Calculation	+	0.98	0.93	0.75	1.03	0.97	1.02	1.07	1.19	0.82	0.98
	−	0.93	0.88	0.70	0.97	0.95	0.98	1.00	1.12	0.77	0.91
Calculated story shear at nominal joint shear strength by AIJ Guidelines (1999)		85.5	84.5	80.9	85.5	84.5	84.5	75.7	85.5	68.4	57.8

(b) Series C and D

Specimen		C01	C03	D01	D02	D03	D04	D05	D06	D07	D08
Ratio of the distance of tens. and comp. reinforcement to the full depth of the section		0.5 and 0.8 for beam 0.8 for column		0.72 for beam 0.86 for column							
Ratio of flexural strength of column to flexural strength of beam section evaluated at joint center		1.03	1.10	0.99	1.42	2.24	0.72	1.03	1.34	1.72	1.01
Attained maximum story shear	+	75.3	67.4	45.4	57.1	63.1	46.3	59.3	67.4	83.8	76.4
	−	-73.4	-65.8	-39.4	-55.1	-59.8	-41.9	-52.8	-66.3	-77.3	-74.4
Calculated story shear at flexural strength of beam		80.5	75.4	58	58.6	58.6	58	80.5	80.5	80.5	122.6
Test / Calculation	+	0.94	0.89	0.78	0.97	1.08	0.8	0.74	0.84	1.04	0.62
	−	0.91	0.87	0.68	0.94	1.02	0.72	0.66	0.82	0.96	0.61
Calculated story shear at nominal joint shear strength by AIJ Guidelines (1999)		82.2	61.6	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8

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