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Strength of Beam-column Joint in Soft First Story RC Buildings Part 1: Experiment

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Abstract

This study describes the strength of reinforced concrete (RC) beam-column joints in buildings with a soft first story. In such buildings, the sections of first-story columns are usually much larger than those of second-story columns to prevent story collapse. To investigate the strength of the beam-column joints, four specimens are constructed and the test is conducted with two types of joints: 1) the first-story column is extended toward the inside of the building (I-type joint) and 2) the first-story column is extended toward the outside of the building (O-type joint). The test parameters are the hoops in the beam-column joint, beam reinforcements, stirrups in the beam, and axial force. The beam longitudinal reinforcements are effective to prevent the yielding of the beam reinforcements in both types of joint. Stirrups in beam and hoops in joint strengthen I- and O-type joints, respectively. The force-resistant mechanisms of these joints are different from those of usual beam-column joints because sign of the bending moment in the second-story column is the same as that of the first-story column. The failure modes of these joints are also different from those of the usual beam-column joints.

1. Introduction

Reinforced concrete (RC) buildings with soft first story are popular because the large space in the first story serves as a parking lot, commercial space, or other similar purposes. However, as shown in **Fig. 1**, many collapses occurred in soft first story in the 1995 Kobe earthquake. In Japan, researchers proposed to strengthen the columns in the soft first story (e.g., Yoshimura and Kihara 1997) after the 1995 Kobe earthquake. As a result of such experiences and researches, many RC buildings are being constructed in Japan with a soft first story in which the sectional area of the first-story column is larger than those of the upper stories to prevent story collapse as shown in **Fig. 2**. In this paper, the joints shown in **Figs. 2a** and **2b** are called “I-type” and “O-type” joints, respectively, where the first-story columns are extended toward the inside and outside of the frame.

In either case, the vertical reinforcements in the extended area of the first-story column are anchored in the beam-column joint. A question arises whether the joint may fail before the column exhibit its strength. In fact, the joint in **Fig. 1** is more damaged than the column.

Hanai *et al.* (2009) conducted an experimental study on I-type joint subjected to opening load (“opening” **Fig. 2a**). In this test, the flexural failure of the first-story

Fig. 1 Joint failure in the soft story.

(a) I-type joint

(b) O-type joint

Fig. 2 Two types of buildings with soft-first story.

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column was not observed and the measured strength was lower than the strength of the first-story column, while the joint had large ductility. The observed failure mode was different from that of usual exterior beam-column joint discussed by Shiohara (2004). In the case of joint in soft-first story building, the wall panel makes the stress transfer mechanism around the joint different from that of usual exterior beam-column joints.

In this study, a test is conducted to investigate the strength and failure modes of both loading directions and both type of joints. In addition, the reinforcements effective in strengthening the beam-column joint in soft first story are discussed.

2. Experimental program

Two specimens of each type of building are constructed: Specimens I-1 and I-1t for the building shown in Fig. 2a and Specimens O-1 and O-1t for the building shown in Fig. 2b. The area around the joint denoted by the dashed line in Fig. 2 is used as specimen to investigate the strength of the beam-column joint. The specimens are 1/2 scale models constructed upside down to easily apply the forces. Figure 3 shows the test setup and the dimensions of Specimen I-1, where the specimen and test setup are drawn upside down to treat the specimen as a part of an actual building. The stub column at the left end of the specimen is constructed to prevent the flexural failure of the wall panel that never occurs in real buildings. The deflections of the stub column corresponding to the strengths in the positive and negative loading were less than 10% and 20% of those at the loading point, respectively. The lower stub is prepared to fix the specimen to the floor. The loading point is assumed to be

the middle point of the clear height of the first story; therefore, 700 mm in Fig. 3 corresponds to one half of the clear height in 1/2 scale model. The displacement is controlled at the lateral loading point. The lateral drift is defined as a ratio of the lateral displacement at the loading point to 700 mm. The applied axial load is shown in Table 1 where the positive value represents compressive axial force. The axial load is constant up to the drift of 0.5%. Considering the overturning mechanism of the building due to larger displacements, the axial load is changed for opening and closing directions (Table 1). In the test, the axial load is changed when the lateral drift becomes zero. The validity of the loading setup in Fig. 3 is discussed in the Part-2 paper.

Figures 4 and 5 show the upside-down elevations of Specimens I-1 and O-1, respectively. These specimens are expected to fail at the joint or beam, not at the column. Figures 6 and 7 show the detail around the joints of Specimens I-1t and O-1t. The dimensions of the specimens and the reinforcement in the columns of Specimens I-1t and O-1t are same as those of Specimens I-1 and O-1, respectively. However, the amount of beam longitudinal and shear reinforcement and joint hoop is increased to prevent failure at the beam or the joint (Table 2). The red-, blue-, and green-colored reinforcements in Figs. 6 and 7 are provided only in I-1t and O-1t. Furthermore, the tail length of the beam-top reinforcements in the upper layer of O-1t (yellow in Fig. 7) is longer than that of O-1. This longer length is determined according to the provisions for knee joint (AIJ 2010) because the failure of O-type specimens may be similar to that of knee joint.

The end of the beam reinforcement is 90° hooked, while the first-story column reinforcement in the extended area is 180° hooked (pink-colored bars in Figs. 4 and 5).

Material properties of the steel bars are indicated in Table 3, where f_y is the yield strength, f_u is the ultimate

Fig. 3 Test set up and dimensions of specimen I-1. [mm].

Table 1 Applied axial load.

Specimen		$R \leq 0.5\%$	$R \leq 0.5\%$
I-1 O-1	Open	1125 kN ($\eta = 0.15$)	0 kN
	Close		2250 kN ($\eta = 0.30$)
I-1t O-1t	Open	500 kN ($\eta = 0.07$)	-450 kN
	Close		1450 kN ($\eta = 0.20$)

η : Ratio of the axial force to the compressive capacity of the first story column

Table 2 Differences of bar arrangement.

Specimen	Beam			Joint Hoop	Column		Wall
	Top	Bottom	Stirrup		Main bar	Hoop	
I-1	4-D19 (0.64 %)	10-D19 (1.59 %)	4-D6@125 (0.26 %)	2-D6@75 (0.17 %)	20-D19 (2.30 %)	5-D6@40 (0.80 %)	Vertical: 2-D6@125 (0.51 %) Horizontal: 2-D6@100 (0.64 %)
O-1		10-D19 (1.59 %)					
I-1t	8-D19 (1.28 %)	12-D19 (1.91 %)	6-D6@62.5 (0.77 %)	2-D6@40 (0.32 %)			
O-1t		12-D19 (1.91 %)	6-D6@125 (0.38 %)	5-D6@40 (0.80 %)

Fig. 4 Elevation of Specimen I-1. [mm].

Fig. 5 Elevation of Specimen O-1. [mm].

strength, and E_s is the elastic modulus. The properties of concrete are indicated in **Table 4**, where f'_c is the compressive strength, f_{ct} is the splitting tensile strength, and E_c is the elastic modulus.

3. Experimental results

3.1 Strengths and failure modes of specimens I-1 and I-1t

The load–drift relationship of I-1 is shown in **Fig. 8**, where the loading cycles smaller than 0.5% drift are not shown because the scope of this study is to discuss the strength and failure mode of the beam-column joints. Blue lines represent the analytical strengths based on the flexural failure of the first-story column at the beam bottom face. These strengths are computed on basis of the Bernoulli–Euler assumption using the stress–strain relationship of concrete proposed by Hognestad *et al.*

Fig. 6 Specimen I-1t. [mm].

Fig. 7 Specimen O-1t. [mm].

(1955). In the opening (positive) direction, during the cycle to +1% drift, the beam bottom reinforcements and the stirrups yielded. The maximum strength is recorded at +2% drift and corresponds to 66% of the computed strength. **Figure 9a** shows the crack pattern at +2% drift at which the maximum strength is recorded. A crack in the beam (thick line in **Fig. 9a**) is prominent. This crack proceeds to the joint above the hooks of the vertical reinforcement in the extended area of the first-story column. The vertical reinforcements in the second-story column yielded during the cycle to +2% drift (C4 in **Fig. 8**). Based on the test result, a simplified failure mode with schematic strut diagram is shown in **Fig. 9b**, where the yielded bars are shown in black color. In this failure mode, the beam bottom reinforcements and the vertical reinforcements in the second-story column are yielded.

Table 3 Properties of reinforcing bars.

Specimen	Bar	f_y [MPa]	f_u [MPa]	E_s [$\times 10^3$ MPa]
I-1, O-1	D6	369	509	199
	D19	377	585	193
I-1t, O-1t	D6	373	553	190
	D19	389	561	185

Table 4 Properties of concrete.

Specimen	f'_c [MPa]	f_{ct} [MPa]	E_c [$\times 10^3$ MPa]
I-1, O-1	26.4	2.33	24.5
I-1t, O-1t	25.5	2.31	24.8

Fig. 8 Load-drift relationship of I-1.

Fig. 9 Failure of I-1 in opening loading.

In this paper, the failure mode associated with the yielding of the beam reinforcement either in the beam or in the joint is called *beam failure*. Specimen I-1 showed large ductility: the strength remains almost constant up to +5% lateral drift. If the longitudinal reinforcements in the beam and the column were much larger than those in specimen I-1, the concrete would have failed prior to the yielding of the reinforcement; but such a failure is out of the scope of this paper. In Fig. 9b, the red arrows indicate the bending moments of the columns and the beam determined based on the crack observation and the strain measurement. Figure 9c shows a schematic bending moment diagram of the specimen, where q_b is the tensile force given by the vertical reinforcement of the wall panel, q_c is the compressive force given by the concrete of the wall panel, and N_b is the axial force of the beam. Figure 9d shows the bending moment diagram of a typical exterior beam-column subassembly. Note that the sign of the bending moment of the second story column is opposite to that in Fig. 9c.

In the closing direction, during the cycle to -2% drift,

the beam-top reinforcements yielded (B4 in Fig. 8). Figure 10a shows the crack pattern at -2% drift. The lateral strength degraded during this cycle as shown in Fig. 8. The compressive failure of the wall panel was observed. As discussed above, the force-resistant mechanism of this joint is different from that of the usual beam-column joints; the failure of the wall panel triggered the strength degradation (see the photo in Fig. 10a). An inclined crack in the beam is prominent in the closing direction. On the basis of these results, as shown in Fig. 10b, the failure mode corresponds to the *beam failure*, which is a brittle failure mode, and the lateral load decreases rapidly when the wall panel fails under compression (Fig. 8).

The load-drift relationship of I-1t is shown in Fig. 11, where the blue lines represent the analytical strengths computed assuming the critical section at the beam bottom face. In the opening direction, the vertical reinforcements in the first-story column yielded prior to the beam bottom reinforcements during the cycle to +1% drift. The maximum strength is recorded at +2% drift, which corresponds to 92% of the analytical strength based on the flexural capacity of the first-story column. Figure 12a shows the crack pattern at +2% drift, at which the maximum strength is recorded. A crack in the first-story column near the joint is prominent. On the basis of these results, the failure mode is assumed to be the flexural failure of the first-story column. However, the cracks of the column at +2% drift proceed toward the location of the hook of the beam bottom reinforcement (Fig. 12a), where CCT node is expected to anchor the reinforcement as shown in Fig. 12b. Because the flexural deformation occurs around this node, the critical section of the first story column in this experiment should be assumed 61 mm (the distance from the beam bottom face to the centroid of the beam bottom reinforcement) higher than the bottom of the beam (the assumption to obtain the blue line in Fig. 11). Figure 13 shows the relationship between the observed strain of the stirrups and the lateral drift of Specimens I-1 and I-1t, where positive strain value expresses the tensile strain. The stirrups in the beam of I-1t did not yield¹ in the opening direction of the loading, while the stirrups in I-1 yielded. The effect of the beam stirrups is discussed further in terms of the cracks width appeared on the beam. Figure 14a shows the most prominent cracks observed on the beams of both specimens. The measured crack widths are plotted against lateral drift (Fig. 14b). The crack width of I-1 increases rapidly after the yielding of the stirrups. On the other hand, the crack width of I-1t decreases after the drift exceeded +1.5%. Many stirrups provided in the beam of I-1t prevented the failure shown in Fig. 9b. As a result, the first-story column of I-1t failed in flexure

¹ In this study, the yielding of a bar is defined as the point where the tensile strain reaches 90% of the yield strain given by the coupon test; the strain at a critical crack may be larger than that observed at a strain gauge because of the bond stress between the cracks and the strain gauge.

Fig. 10 Failure of I-1 in closing loading.

Fig. 13 Strain of the stirrups.

Fig. 14 Effect of stirrups on the crack width in opening loading.

(defined as column failure).

In the closing direction (the left half of **Fig. 11**), the vertical reinforcements in the first-story column yielded during the cycle to -1% drift. The yielding of the beam-top reinforcements and the compressive failure in the wall panel are not observed in I-1t. **Figure 15a** shows the crack pattern observed up to -2% drift at which the maximum strength is recorded. A crack in the first-story column near the joint is prominent in the closing direction. The additional beam-top reinforcements and the stirrups provided in Specimen I-1t prevented the *beam failure* observed in I-1 (**Fig. 10b**). The prominent cracks appeared on the beam of I-1 and I-1t are shown in **Fig.**

Fig. 11 Load-drift relationship of I-1t.

Fig. 12 Specimen I-1t at $+2\%$ drift. Fig. 15 Specimen I-1t at -2% drift.

Fig. 16 Effect of stirrups and beam top reinforcement on the crack width in closing loading.

16a, and the measured crack widths plotted against the lateral drift are shown in **Fig. 16b**. Although the stirrups in the beam of I-1t yielded in the closing direction (**Fig.**

13), the additional stirrups and the beam top bars helped prevent opening of the crack as discussed in Part-2 paper. A small axial force compared to that of I-1 also contributed to decrease the compression force in the wall panel. The failure mode in the closing direction is again a flexural failure of the first-story column (column failure), as shown in **Fig. 15b**. However, the maximum strength is 94% of the analytical strength. In the closing direction, the observed cracks proceed to the point indicated by the white circle in **Fig. 15b**. Because the flexural deformation occurs around this point, the critical section should be defined at this point and the effective shear span length is longer than that assumed to obtain the blue line in **Fig. 11**. The specimen I-1t has large ductility in the closing direction as well as in the opening direction.

3.2 Strengths and failure modes of O-1 and O-1t

The load–drift relationship of O-1 is shown in **Fig. 17**, where the blue lines again represent the analytical strengths computed assuming the critical section at the beam bottom face. In the opening (positive) direction, during the cycle to +1.5% drift, the beam bottom reinforcements yielded while the stirrups yielded during the cycle to +2% drift. **Figure 18a** shows the crack pattern at +2.5% drift at which the maximum strength is recorded. The three cracks depicted in **Fig. 18b** are prominent. Therefore, the failure mode in the opening direction is regarded as *beam failure*. The observed strength is 72% of the computed strength. This reduction is attributable to the following three reasons. The first reason is the shortage of the beam bottom reinforcement: as shown in **Fig. 17**, the beam bottom bar (B3) yielded earlier than the column bar (C1). The second reason is the reduction of the effective depth for the moment of the first story column: as shown in **Fig. 18b**, the compressive strut of the first story column is bent at the anchorage of the beam reinforcement; the effective depth is therefore the distance between the anchorage point and the column reinforcement and is smaller than that assumed to obtain the blue line in **Fig. 17**. The third reason is the movement of the critical section as discussed for Specimen I-1t.

In the closing direction, the beam-top reinforcements yielded during the cycle to -2% drift at which the maximum strength is recorded. **Figure 19a** shows the crack pattern at the maximum strength. The crack at the reentrant corner above the joint is more prominent than those in the beam and column. **Figure 19b** shows the failure mode of the closing direction, which is again a *beam failure* and has a larger ductility than that of Specimen I-1 in the closing direction. The compressive failure of the wall panel was not observed in O-1. The maximum strength of O-1 is also larger than that of I-1 in the closing direction.

The load–drift relationship of O-1t is shown in **Fig. 20**. In the opening direction, during the cycle to +1.5% drift, the reinforcements in the first-story column and the beam yielded. The maximum strength is recorded at +4% drift, which is close to the analytical strength of the first-story

column. **Figure 21a** shows the crack pattern at +4% drift. The crack in the first-story column near the joint is prominent. The failure mode of O-1t is depicted in **Fig. 21b**. As shown in this figure, the strut can go outside of the hook of the beam bars because of the additional hoops in the joint. **Figure 22** shows the measured strain of the reinforcements in O-1 and O-1t. In both specimens, the vertical reinforcements in the first-story column and the beam bottom reinforcements yielded (**Fig. 22**). However, the measured strain of the beam bottom reinforcements in O-1t decreases after the yielding of the vertical reinforcements in the first story. On the basis of these results, it is concluded that the failure mode of O-1t is a flexural failure of the first-story column (column failure). The observed strength is 97% of the analytical strength because of the same reason as that for I-1t in the opening loading. Specimen O-1t has enough beam bot-

Fig. 17 Load-drift relationship of O-1.

Fig. 18 Failure of O-1 in opening loading.

Fig. 19 Failure of O-1 in closing loading.

Fig. 20 Load-drift relationship of O-1t.

Fig. 21 Failure of O-1t in opening loading.

Fig. 22 Measured strain versus lateral drift.

tom reinforcements and hoops in the joint that prevented the failure mode indicated in Fig. 18b. Figure 23a shows the inclined cracks in the joints of O-1 and O-1t. These cracks will be used to discuss the effect of the hoops. Figure 23b shows the comparison of the crack width between O-1 and O-1t. In the case of O-1, the crack width grew rapidly when the drift exceeded 1%. In the case of O-1t, the crack width was smaller than 0.1 mm until the drift reached 2.5%. The hoops contributed to keep the crack width small. As shown in Fig. 24, this difference affected the strains in the compressive reinforcement in the first-story column, in which the compressive strain of O-1 decreases after the drift of 2% while that of O-1t increases. It indicates that the larger amount of the hoop reinforcement in the joint of specimen O-1t helped to make the effective depth of the first story column larger than that shown in Fig. 18b, thus making the strength of the specimen to the opening load closer to the computed one (the blue line in Fig. 20).

Table 5 Failure modes of specimens.

Specimen	Open	Close
I-1	Beam	Beam
I-1t	Column	Column
O-1	Beam	Beam
O-1t	Column	Beam*

*The degree of beam failure was reduced and some symptoms of column failure were observed.

In the closing direction, during the cycle to -1.5% drift, the reinforcements near the reentrant corner above the joint yielded (B9 and C8 in Fig. 20), indicating *beam failure*. The maximum strength is recorded at -2.5% drift and the hoop reinforcements in the upper part of the joint (H3 in Fig. 20) yielded during this loading cycle. During the cycle to -3% drift, the vertical reinforcements in the first-story column (C3) yielded, indicating column failure. The observed damages of the specimen are represented in Fig. 25, where the crack at the reentrant corner above the joint is more prominent than those in the column. According to these results, the failure mode of O-1t in the closing direction is considered the same as of O-1 (Fig. 19b, *beam failure*). However, the measured strain of the vertical reinforcement in the first-story column is beyond the yield strain and larger than that of O-1 (Fig. 24). Figure 26 shows that the comparison between the prominent cracks appeared on the specimens O-1t and O-1. The crack of O-1 grew rapidly after the drift exceeded -1% , indicating that the damage concentrated at the reentrant corner above the joint. The crack width of O-1t gradually increased even though the beam-top reinforcement yielded because the hoops in the joint constrained the opening of the crack. Additional beam-top reinforcements and hoop reinforcements in O-1t contributed in increasing M_b in Fig. 19b and prevented the increase in the *beam failure*.

The failure modes of the specimens are summarized in Table 5. Because the *beam failure* of Specimen I-1t is prevented in both directions of the loading, it is concluded that the stirrups and beam reinforcements increase the strength of the *beam failure* of the I-type joints. Because the *beam failure* of Specimen O-1t is prevented in the opening loading and reduced in the closing direction, it is concluded that the hoops in the joint and beam reinforcements increase the strength of the *beam failure* of the O-type specimen.

4. Conclusions

The strength of the joints in soft first story is experimentally investigated. Two types of joints are tested: 1) first-story column is extended toward the inside of the building (I-type joint; Specimens I-1 and I-1t) and 2) first-story column is extended toward the outside of the building (O-type joint; Specimens O-1 and O-1t). On the basis of the test results, the following conclusions are obtained:

1. In Specimens I-1 and O-1, the failures associated

(a) Location of the crack (b) Measured crack width
Fig. 23 Effect of hoops on the crack width in opening loading.

Fig. 24 Strain of the vertical reinforcement in the 1st story column.

Fig. 25 Specimen O-1t at -2.5 % drift.

with the yielding of the beam reinforcements and cracks in the joint or the beam (Figs. 9b, 10b, 18b, and 19b) are observed in both directions of the loading. These failures are called *beam failure*. The strengths of these failures are much smaller than those of the flexural strength of the first-story column.

(a) Location of the crack and strain gauge (b) Measured crack width
Fig. 26 Effect of hoops and beam reinforcements on the crack width in closing loading.

2. In both types of specimens, the beam-top and bottom reinforcements are effective to prevent the joint failure in the closing and opening directions, respectively.
3. The stirrups in the beam are effective to prevent the *beam failure* of I-type joint.
4. The hoops in O-type joint are effective to prevent the *beam failure* both in the opening and closing loads.
5. The observed crack pattern (Figs. 9a, 10a, 18a, and 19a) indicate that the force-resistant mechanisms of these joints are different from those of the usual beam-column joints because, in contrast with the usual beam-column joints, the sign of the bending moment of the second-story column is the same as that of the first-story column.

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