Effects of Haunch on the Beam-Column Joint of Soft First-Story in RC Building

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SUMMARY
There are many damage reports about the soft-story construction against earthquakes. Therefore, four specimens consisting of members only around the beam-column joint of soft first-story are constructed and loaded to failure by statically cyclic load simulating earthquake to obtain fundamental data. In opening direction loading, all the specimens showed flexural failure of first-story column. In closing direction loading, the specimens in which the first-story column is extended toward inside show flexural failure of first-story column, whereas the specimens in which the first-story column is extended toward outside showed joint failure. The stiffness and the strength of the specimens with haunches are larger than those of the specimens without haunches. A set of new design equations to estimate the flexural and joint strength are proposed based on the observed failure modes, considering the effect of haunch and position of critical section.

Keywords: soft first-story, Beam-column joints, anchorage, haunch

1. INTRODUCTION

There are many damage reports about the soft-story construction against earthquakes. The first story in a multi-story apartment building is expected to use for parking lot or commercial space. In these buildings, shear walls with boundary columns are used as partition wall in the upper stories whereas the first-story is single-bay moment resisting frame. Once an earthquake would occur, deformation of the structure is concentrated to the soft first-story. Therefore, the building is in danger of causing story collapse.

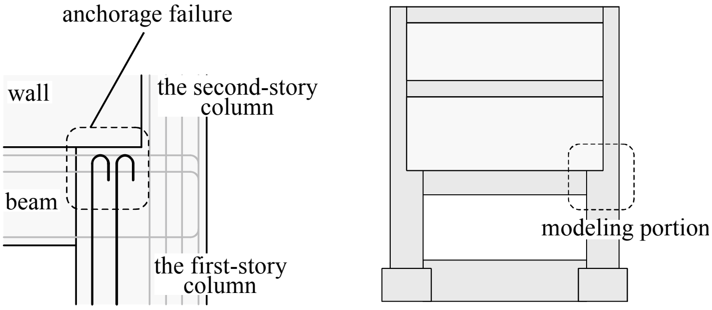
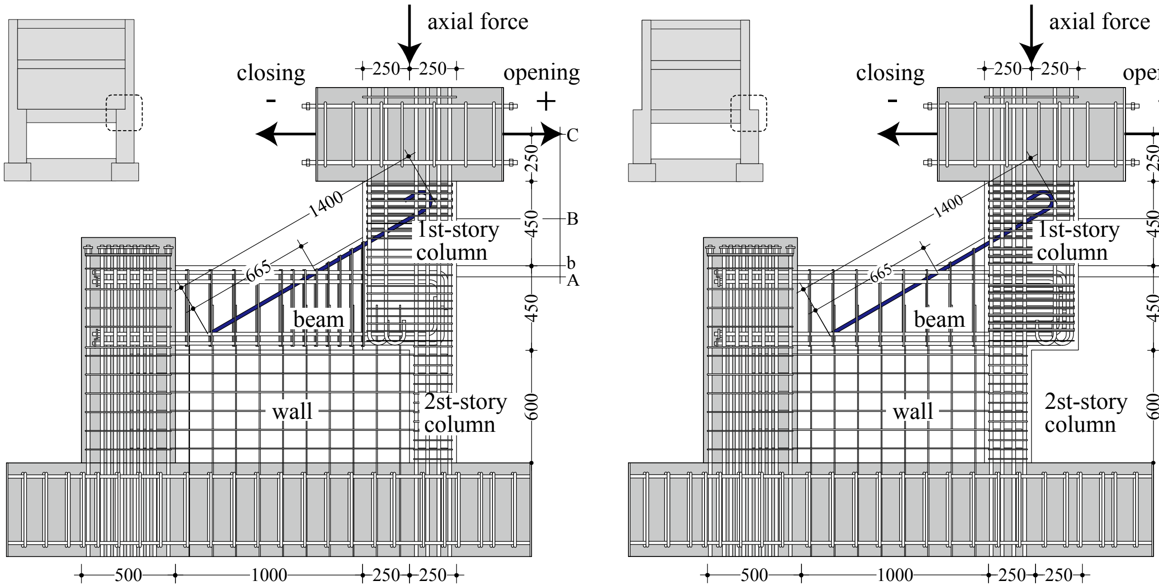


Figure 1.1. The typical beam-column joint at the soft first-story

In order to present from the soft first-story collapse, the stiffness and the strength of the first-story are increased by making the depths of the first-story columns much larger than those of upper stories (See Fig 1.1). But it is hard to transfer the moment of the top of the first-story column to the beam and the second-story column well due to the discontinuous of column. In addition, unexpected failure mode might cause, for example, shear failure on a beam-column joint and anchorage failure (G. Kotani., et al, 2011). In this study, tests are conducted to clear the force transfer mechanism and to avoid such failures.

2. TEST SPECIMEN AND MATERIAL

Four specimens I-1t, I-ht, O-1t and O-ht consisting of members only around the joint illustrated in Fig. 1.1 are tested. Scale of the specimens is one half. The specimens are upside-down for the convenience of the loading. The general shape and re-bars arrangement of I-ht and O-ht is shown in Fig. 2.1. The test parameters are as follows: (1) extension direction of the first-story column, outside (O-1t, O-ht) or inside (I-1t, I-ht), and (2) with/ without haunch at the corner of the joint.



(a) specimen I-ht

(b) specimen O-ht

Figure 2.1. The general shape and re-bars arrangement of Test specimens, I-ht and O-ht

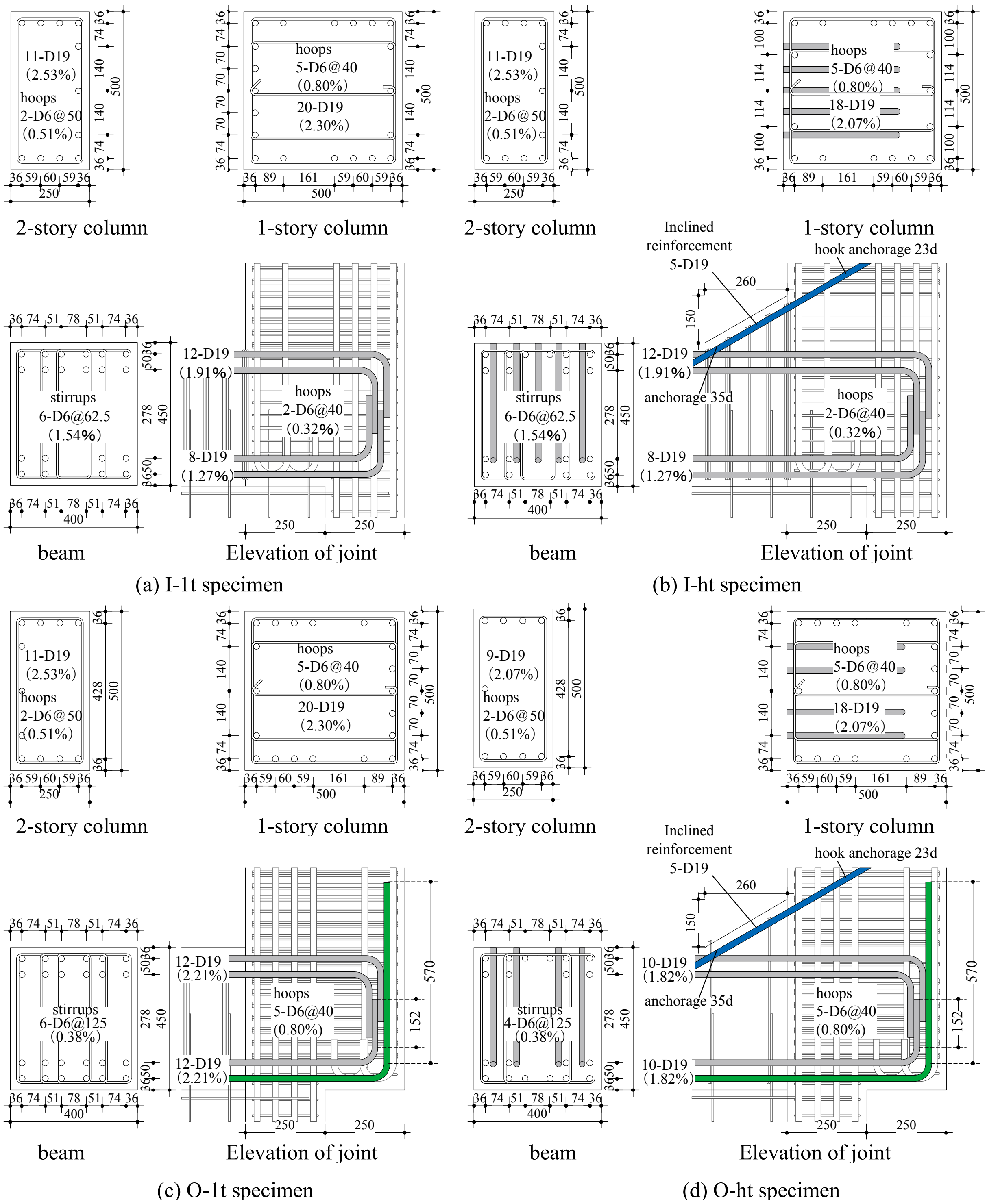
2.1. Detail of I-1t, I-ht specimens

The specimens I-1t and I-ht are constructed with the reinforcing arrangement shown in Figure 2.2 (a), (b). The discontinuous first-story column re-bars are anchored into beam-column joint with 180 degrees hook. The anchorage length from the face of the column joint is satisfied with the AIJ Guideline [1]. The beam re-bars are anchored into beam-column joint with 90 degrees hook. The anchorage length from the face of the beam joint is also satisfied with the AIJ Guideline [1]. The specimen I-ht is provided with haunch in which five reinforcement (blue reinforcement in Fig. 2.2 (b)) inclined 30 degrees are set at the corner of the joint. The inclined reinforcements are anchored into column with 180 degrees hook and into beam on straight anchorage.

2.2. Detail of O-1t, O-ht specimens

The specimen O-1t and O-ht was constructed with the reinforcing arrangement shown in Figure 2.2 (c), (d). The discontinuous first-story column re-bars are anchored into beam-column joint with 180 degrees hook. The anchorage length from the face of the column joint is satisfied with the AIJ

Guideline [1]. The beam re-bars are anchored into beam-column joint with 90 degrees hook. The anchorage length from the face of the beam joint is also satisfied with the AIJ Guideline [1]. The anchorage length of the top first layer reinforcement (green reinforcement in Fig. 2.2 (c), (d)) from the tail length is also satisfied with the AIJ Guideline [1]. The specimen O-ht is provided with haunch and four reinforcements (blue reinforcement in Fig. 2.2 (d)) inclined 30 degrees at the corner of the joint. The inclined reinforcements are anchored into column with a 180 degree hook and into beam on straight anchorage.



* d : diameter of the reinforcement

Figure 2.2. Test specimen details of I-1t, I-ht, O-1t, O-ht

2.3. Material

Normal Portland cement concrete is used. Mechanical properties of concrete are shown in Table 2.1. Deformed bar (JIS G3112) is used for longitudinal bars in columns, hoops and stirrups in the specimen. The mechanical properties of deformed bars are listed in Table 2.2.

Table 2.1. Mechanical properties of concrete

specimen	Compressive Strength (MPa)	Young's modulus (GPa)	Tensile Strength (MPa)
I-1t, O-1t	25.5	24.8	2.31
I-ht, O-ht	28.9	31.0	2.51

Table 2.2. Mechanical properties of steel

Reinforcing Bars	Sectional Area (mm^2)	Yield Point (MPa)	Tensile Strength (MPa)	Young's modulus (GPa)
D6	32	373*	553	185
D19	287	389	561	190

* 0.2% offset strength

3. TEST SETUP

The loading setup is shown in Figure 3.1. The specimens are restrained the deformation out-of-plane. Statically cyclic lateral load was applied at the top of the column. The distance between the loading point and the face of the first-story column is 700mm. Actuator was used to apply the horizontal load. Axial load was applied at the center of the first-story column by hydraulic lifter with capacity of -450kN to 2000kN. The drift angle is defined to be divided the deformation at the point of the lateral load by the height from the face of the first-story column to the point of the lateral load.

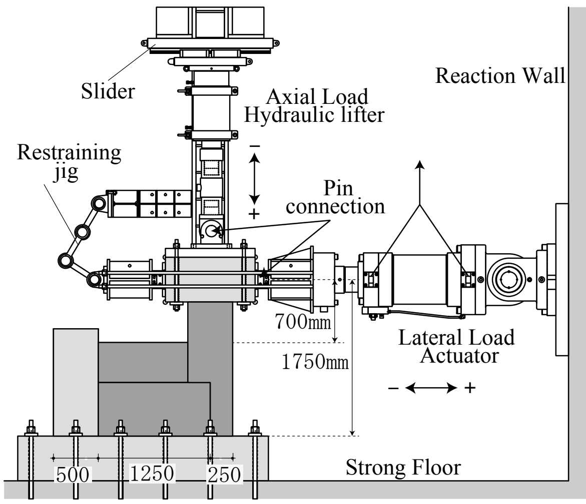


Figure 3.1. Test setup

The horizontal loading cycles are shown in Figure 3.2. Before the cycles of 0.5% story drift, applied axial load was 500kN in constant considering the sustained load of the building. After that, the axial force is applied -450kN in pull cycle and 2000kN in push cycle considering the effects of overturning moment under severe earthquake. Displacements, loads, strains and deformations around beam-column joint are measured.

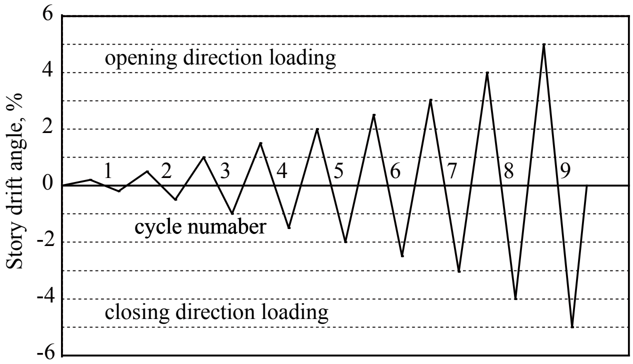


Figure 3.2. Loading history

4. TEST RESULTS

Relation of story drift and story shear of each specimen is shown in Fig. 4.1. Relation of story drift and story shear before the story drift angle 0.5% are enlarged and also shown in Fig. 4.1. The position of the strain gauges and the yield points of re-bars are also shown in Fig. 4.1. The cracking pattern on the beam-column joint of the each specimen at story drift of 4% is shown in Fig 4.2. The solid lines show the crack of opening direction loading, the dashed lines show the crack of closing direction loading and the bold lines show remarkable cracks. The gray part shows the detachment of concrete.

4.1. I-1t specimen

In opening direction loading, flexural crack *A* of the first-story column and crack *B* of beam occurred during the story drift of 0.2%. Shear crack *C* of beam and crack *D* of the first-column occurred during the story drift of 0.5%. Flexural crack *A* extended to 1.2mm in width and maximum story shear force 519kN was attained at the story drift of 2%. Cracking *E* extended to 3.0mm in width during the story drift of 3%. Totally, the cracks progressed with arcs pattern around a corner of beam-column joint. Failure mode of I-1t is considered to be flexural failure of the first-story column judging from the strains of the first-story column and crack appearance.

In closing direction loading, flexural crack *a* of the first-story column occurred during the story drift of 0.2%. Flexural crack *b* and shear crack *c* of the beam occurred during the story drift of 0.5%. Concrete crushing *d* occurred at the corner of the joint during the story drift of 1.5%. Flexural crack *a* extended to 1.4mm in width and maximum story shear force 899kN was attained at the story drift of 2%. Failure mode of I-1t is considered to be flexural failure of the first-story column at the face of beam.

4.2. I-ht specimen

In both opening and closing direction loading, the outline of crack process resembled I-1t. In opening direction loading, flexural crack *A* extended to 3.0mm in width and maximum story shear force 686kN was attained at the story drift of 4%. Failure mode of I-ht is considered to be flexural failure of the first-story column.

In closing direction loading, Flexural crack *a* extended to 1.4mm in width and maximum story shear force 1049kN was attained at the story drift of 2.5%. Shear crack *b* extended to 4.0mm in width during the story drift of 4%. Failure mode of I-ht is considered to be flexural failure of the first-story column.

4.3. O-1t specimen

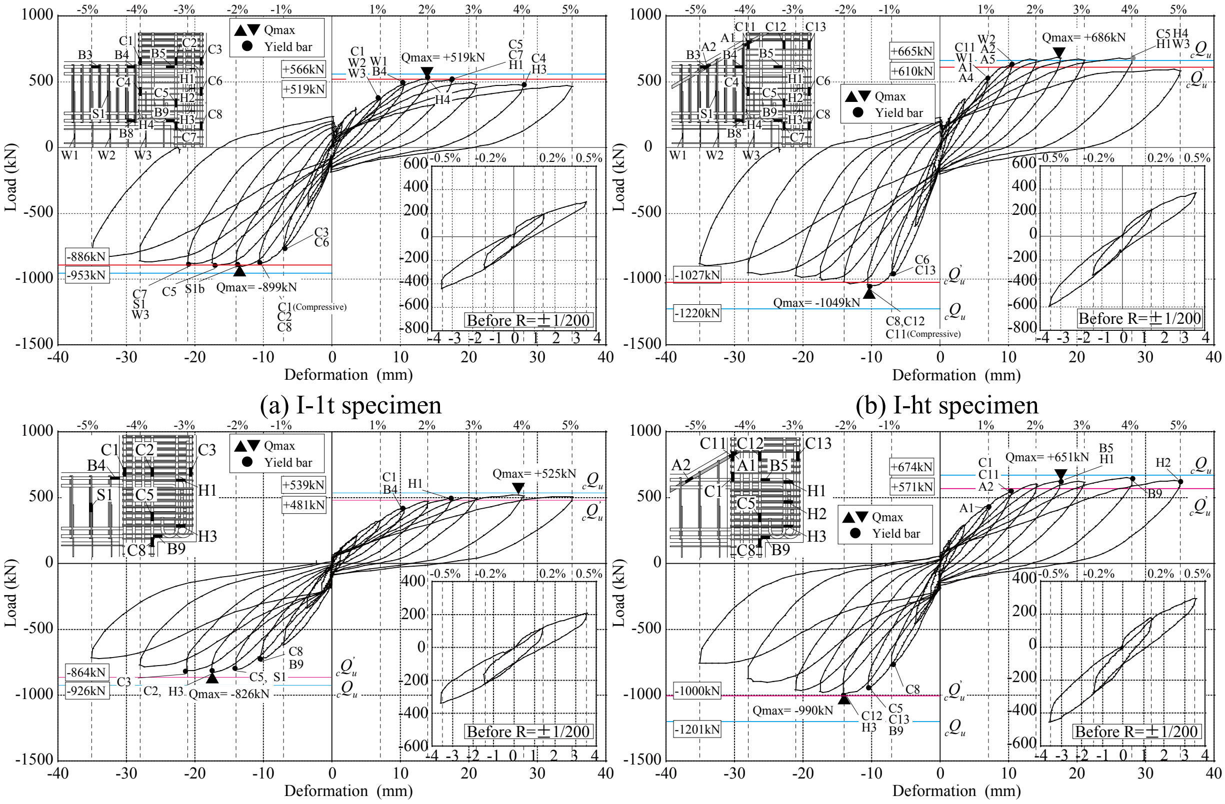
In opening direction loading, flexural crack *A* of the beam and crack *B* of the first-story column occurred during the story drift of 0.2%. Shear crack of beam and diagonal crack *C* in beam-column joint occurred during the story drift of 0.5%. Concrete crushing of the second-story column base occurred during the story drift of 3%. Flexural crack *B* extended to 2.2mm in width and maximum story shear force 525kN was attained at the story drift of 4%. Totally, the cracks progressed with arcs pattern around a corner of beam-column joint. Failure mode of O-1t is considered to be flexural failure of the first-story column.

In closing direction loading, diagonal crack *a* in beam-column joint, flexural crack *b* of the first-story column and crack *c* of the beam occurred during the story drift of 0.2%. Shear crack of the first-story column and the beam occurred during the story drift of 0.5%. Concrete crushing at the corner of the joint occurred during the story drift of 1.5%. Flexural crack *a* extended to 0.15mm in width and maximum story shear force 826kN was attained at the story drift of 2.5%. Failure mode of O-1t is considered to be flexural failure of joint failure.

4.4. O-ht specimen

In both opening and closing direction loading, the outline of crack process resembled O-1t. In opening direction loading, flexural crack *A* at the haunch occurred during the story drift of 0.2%. Flexural crack *B* extended to 4.0mm in width and maximum story shear force 686kN was attained at the story drift of 4%. Failure mode of O-ht is considered to be flexural failure of the first-story column.

In closing direction loading, Concrete crushing *d* of the haunch occurred and diagonal crack *a* extended to 1.4mm in width and maximum story shear force 990kN was attained at the story drift of 2%. After that, Concrete crushing *d* of the haunch progressed and diagonal crack from around extended joint increased and extended. Failure mode of O-ht is considered to be flexural failure of joint failure.



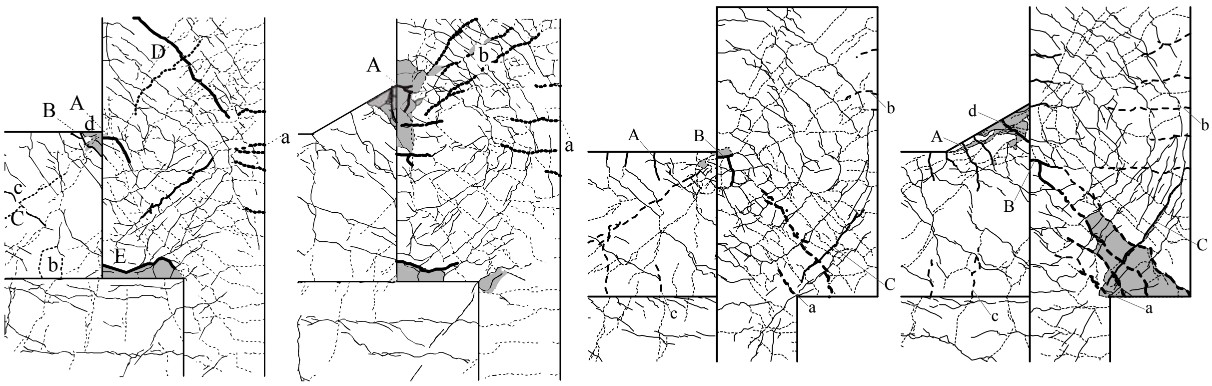
(a) I-1t specimen

(b) I-ht specimen

(c) O-1t specimen

(d) O-ht specimen

Figure 4.1. Relation of story drift and story shear



(a) I-1t specimen (b) I-ht specimen (c) O-1t specimen (d) O-ht specimen

Figure 4.2. Observed crack pattern

5. EQUATION OF ULTIMATE STRENGTH

In opening direction loading, failure mode of all specimens is considered to be flexural failure of the first-story column at the face of beam judging from the strains in the beam-column joint and crack appearance. In closing direction loading, failure mode of I-1t, I-ht is also considered to be flexural failure of the first-story column at the face of beam. Failure mode of O-1t, O-ht is considered to be joint failure but the reinforcement of the first-story column is yielded. Each flexural strengths of the first-story column ${}_cQ_u$, which is divided ultimate flexural moment M_u calculated based on Navier hypothesis by the height from critical section (I-1t, O-1t : at the face of the first-story column (A) in Fig 2.1, I-ht, O-ht : at the face of haunch (B) in Fig 2.1) to the point of the lateral load, is shown in Fig 4.1. However, the test results do not match with each flexural strength. To judge from the prominent flexural crack, the critical section is considered to move into the joint. Therefore the critical section is reset according to 5.1.

5.1. Critical section of the first-story column in opening direction loading

In opening direction loading, the compressive strut of the specimens is assumed as shown in Fig 5.1. It is considered that the first-story column is yielded because shear force of first-story column is pulled by tensile force of reinforcement arranged at the bottom in the beam. Therefore the critical section of the flexural failure of the first-story column is set to be at the center of gravity position of bottom reinforcement.

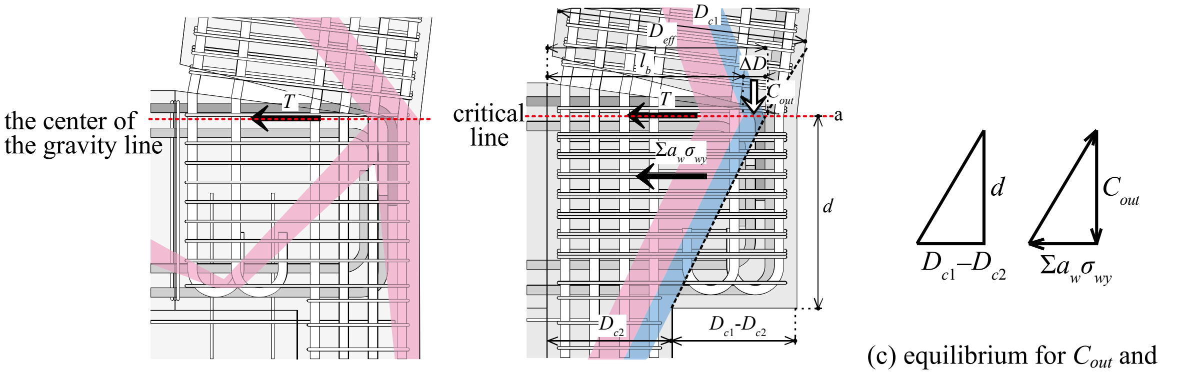
The specimen O-1t, O-ht is observed to be prominent crack C in Fig 4.2 (c), (d). The effective depth is smaller than normal depth due to that prominent crack. Therefore the effective depth is recalculated based on the assumption shown below. The equilibrium condition for effective section shown in Fig. 5.1 (c) is given by Eq. (1). The compression C_{out} of the concrete section resisted by equilibrium for C_{out} and tensile of the joint hoops $\Sigma a_w \sigma_{wy}$ shown in the blue tie width ΔD in Fig 5.1 (b) is given by Eq. (2). The effective depth D_{eff} is given by Eq. (3).

$$\frac{C_{out}}{\sum a_w \sigma_{wy}} = \frac{d}{D_{c1} - D_{c2}} \tag{1}$$

$$C_{out} = \Delta D \cdot b_c \cdot F_c \tag{2}$$

$$D_{eff} = l_b + \Delta D = l_b + \frac{\sum a_w \sigma_{wy}}{b_b F_c} \times \frac{d}{D_{c1} - D_{c2}} \leq D_{c1} \tag{3}$$

where, d : effective depth of beam, D_{c1} : depth of first-story column, D_{c2} : depth of second-story column, b_c : width of first-story column, F_c : compressive strength of concrete, a_w : cross sectional area of joint hoops, σ_{wy} : tensile yield point of joint hoops, l_b : the length from the face of the beam to the starting point of the 90 degrees hooked shown in Fig 5.1.



(a) I-1t, I-ht specimen (b) O-1t, O-ht specimen (c) equilibrium for C_{out} and tensile of the joint hoops $\Sigma a_w \sigma_{wy}$

Figure 5.1. Critical section of the first-story column in opening direction

5.2. Critical section of the first-story column in closing direction loading

In closing direction loading, flexural failure of first-story column is considered as shown in Fig 5.2. It is considered that the first-story column is yielded because shear force of first-story column is resisted by compression range x_n of the beam. The equilibrium condition for that compression range x_n is given by Eq. (4). The average stress of concrete is assumed as 85% of the compressive strength of the concrete.

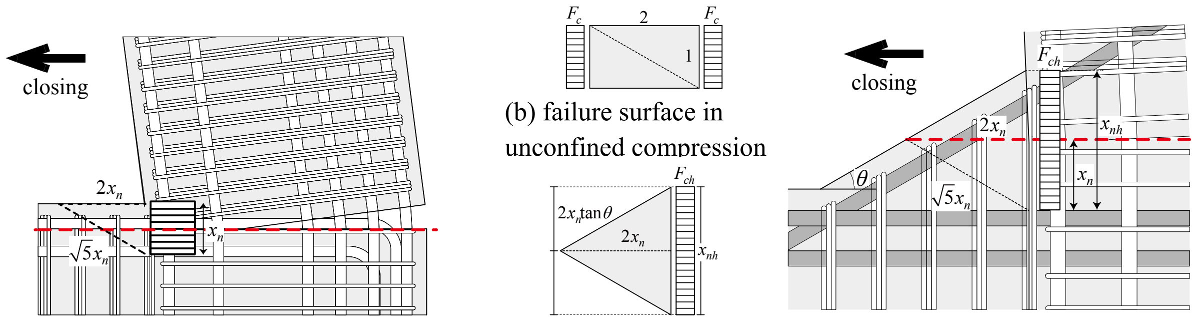
$$x_n = \frac{{}_cQ_u}{0.85 \cdot b_b \cdot F_c} \tag{4}$$

where, b_b : depth of beam, F_c : compressive strength of the concrete

Therefore, the critical section of the flexural failure of the first-story column is set to be at the center of compression range of beam $x_n/2$. However the critical section of the flexural failure of the first-story column of the specimen I-ht, O-ht with haunch is reset to be the section based on the assumption shown below.

The failure plane of the concrete by unconfined compression is considered to be plane inclined around 1:2 (Carpinteri A. et al., 2001) shown Fig 5.2 (b). The concrete block shown in Fig 5.2 (a) is also assumed to be failure plane of the concrete inclined 1:2 with the length $\sqrt{5}\,x_n$. Besides, the specimens with haunch shown in Fig 5.2 (c), (d) are also assumed to be failure plane of the concrete inclined 1:2 with the length $\sqrt{5}\,x_n$. The compression range x_{nh} of the specimens with haunch is given by Eq. (5). Therefore the critical section of the flexural failure of the first-story column is reset to be at the center of compression range of beam $x_{nh}/2$.

$$x_{nh} = x_n(1 + 2\tan\theta) \tag{5}$$



(a) specimen without haunch (c) failure surface of haunch (d) specimen with haunch

Figure 5.2. Critical section of the first-story column in closing direction loading

5.3. Modelling of the joint failure in closing direction loading (O-1t, O-ht)

In closing direction loading, the prominent crack *a* of the specimen O-1t, O-ht shown in Fig 4.2 (c), (d) progress at about 45 degrees. The failure mode of specimens O-1t and O-ht is considered to be joint failure mode shown in Fig 5.3 (a). The point at intersection of failure line of 45 degrees from outside of second-story column and the compression range x_{2c} of the second-story column is reflected to the beam. The compression range x_{2c} and ultimate flexural moment of the second-story column ${}_{2c}M_u$ is calculated by the way based on Navier hypothesis. The range from that point to extreme compression fiber is assumed to be the compression range x_{nb} of the beam.

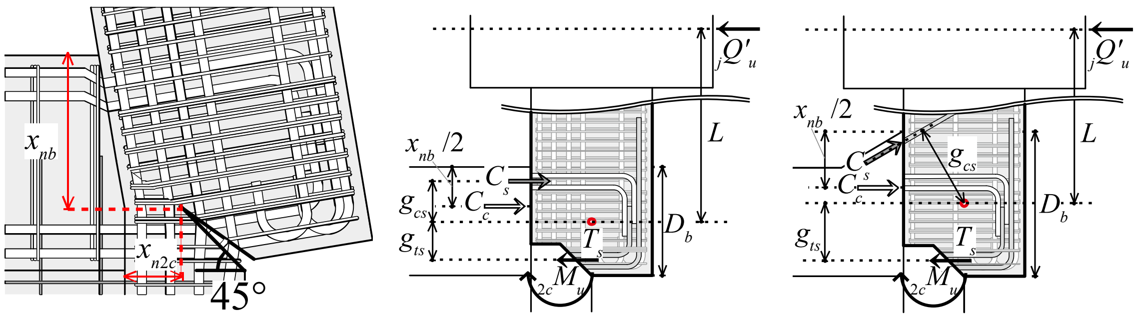
The joint failure strength ${}_{j}Q_u$ is considered by the equilibrium shown in Fig 5.3 (b). All the tensile and compression reinforcement of the beam are assumed to be yielded. Tensile force and compression force represent T_s and C_s. The compression C_c of the concrete of the beam is given by Eq. (6). The beam moment is calculated at the center of the beam. The compression C_c is assumed to be acted at $x_{nb}/2$. The moment ${}_{b}M_u$ of the beam is given by Eq. (7). The joint failure strength ${}_{j}Q_u$ is calculated by Eq. (8). The moment ${}_{j}M_u$ of the ultimate joint strength is calculated as a total of the moment ${}_{2c}M_u$ and ${}_{b}M_u$. The length L is from the center of the depth of the beam to the lateral load.

$$C_c = {}_{j}Q_u + T_s - C_s \tag{6}$$

$${}_{b}M_u = T_s \cdot g_{ts} + C_s \cdot g_{cs} + C_c \cdot \frac{D_b - x_{nb}}{2} \tag{7}$$

$${}_{j}Q'_u = \frac{{}_{j}M_u}{L} = \frac{{}_{2c}M_u + {}_{b}M'_u}{L} \tag{8}$$

However, The joint failure strength ${}_{j}Q_u$ of the specimen O-ht with haunch is considered by the equilibrium shown in Fig 5.3 (c). Compression reinforcements of the beam are assumed to be not yielded. Instead, inclined reinforcements are assumed to be yielded. The moment ${}_{j}M_u$ of the ultimate joint strength is calculated in the same way. The depth of the beam is included in the part of haunch.



(a) O-1t, O-ht specimen (b) O-1t specimen (c) O-ht specimen

Figure 5.3. Modelling of the joint failure in closing direction loading (O-1t, O-ht)

5.4. Comparison the calculated and observed story shear

Comparison the calculated and observed story shear is shown in Fig 5.4. The dashed lines show ±10% error lines. Approximately, in both opening and closing direction loading, the strength of the observed failure mode is evaluated as shown in Fig 5.4. On the other hand, in closing direction loading, the observed failure mode of the specimens O-1t, O-ht is considered to be joint failure. However, Modified flexural strengths of the first-story column ${}_cQ'_u$ are lower than joint failure strengths ${}_jQ_u$ and the observed failure mode does not correspond to the calculated failure mode.

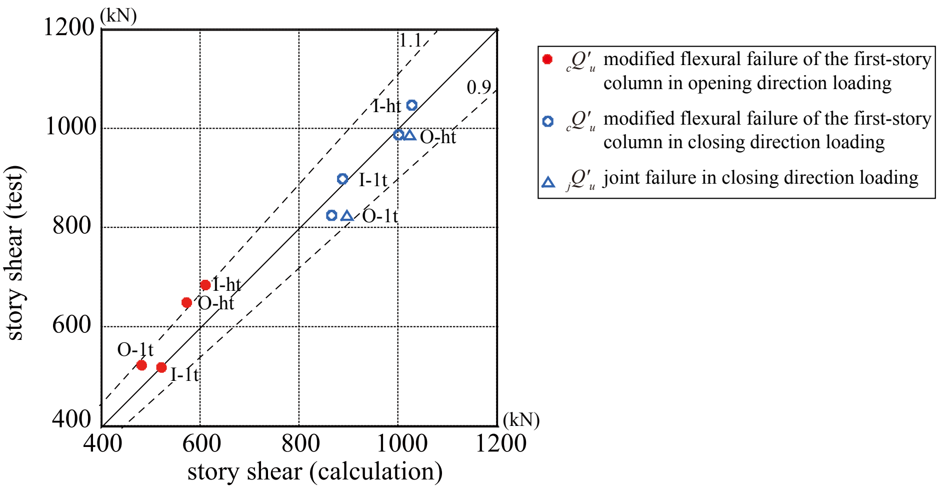


Figure 5.4. Comparison the calculated and observed story shear

6. CONCLUSIONS

The followings are concluded:

1) In the opening direction loading, all the specimens showed flexural failure of first-story column.
2) In the closing direction loading, the specimens in which the first-story column are extended toward inside show flexural failure of first-story column, whereas the specimens in which the first-story column are extended toward outside showed joint failure.
3) Haunch at the corner of the joint is effective on improving strength and stiffness.
4) The proposed equations of the flexural strength of the first-story column and the joint failure can estimate the strength obtained by experiments.

ACKNOWLEDGEMENT

The authors acknowledge the supports by the Grant-in-aid for researches on the building codes improvement by Ministry of Land, Infrastructure, Transport and Tourism, Japan.

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