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EXPERIMENTAL STUDY ON THE FAILURE BEHAVIOR OF RC EXTERIOR BEAM-COLUMN JOINT AT TOP FLOOR

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SUMMARY

RC exterior beam-column joint at top floor which is called L-joint has different ultimate strength in both inside-corner-opening state (joint-opening action) and inside-corner-closing state (joint-closing action), previous tests of L-joint were reexamined in the point of both actions. Test data indicated that the shear strength of joint-closing is higher than that of the joint-opening. The calculated values of shear strength of joint-opening and joint-closing were less than observed values from experiment. Moreover, in order to discuss the failure mode of L-joint, two reinforced concrete L-joints which have different tail anchoring length of beam bent bar were tested under statically cyclic lateral loadings. The specimens were designed such that joint failure would initiate before beam's flexural yielding failure and anchorage failure of beam bent bar in joint. From test results, the decrease of story shear is attributable to the deterioration of anchorage capacities of beam main bars in joint, which occurs due to the decrease of the tensile force of main bars at beam end and the distance between stress resultants. Therefore, the possibility was indicated that failure of L-joint is caused by deterioration of anchorage capacities of beam main bars in joint.

INTRODUCTION

RC exterior beam-column joint at top floor which is called L-joint has suffered joint shear failure. In the current Japanese design code [1], the calculation equation for joint shear strength V_{ju} is proposed based on the experimental results as Eq.(1).

$$V_{ju} = \kappa \cdot \phi \cdot F_j \cdot b_j \cdot D_j \tag{1}$$

where, κ: configuration factor of joint

(κ =1.0 for +-type joint, κ =0.7 for - ㅏ or T-type joint, κ =0.4 for L-type joint)

φ: joint restraint condition coefficient

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(φ=1.0 for joint with two transverse beams, φ=0.85 for others)

F_j : fundamental value for joint shear strength

F_j=0.8・σ_B (σ_B is concrete compressive strength)

D_j : column depth or embedded length of beam main bar.

(D_{jopen} and D_{jclose} are used as D_j in Eq.(1). D_{jopen} is embedded length of beam bottom bar in joint-opening. D_{jclose} is that of beam top bar in joint-closing.)

b_j : effective width of joint (Eq.(2))

where, b_b is beam width, b_{a1} is min (b_i/2,D/4), b_i is distance from outer side of column to outer side of beam (see Fig.1)

$$b_j = b_b + b_{a1} + b_{a2} \tag{2}$$

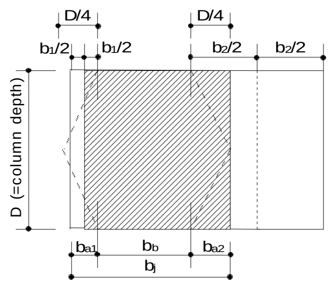


Fig.1 effective width of joint

The shear failure in beam-column joint occurs when joint shear exceeds the shear strength of beam-column joint. From the previous tests it is said that reinforcing details of L-joint influences on joint shear strength and L-joint has different ultimate strength in each inside-corner-opening state (joint-opening action) and inside-corner-closing state (joint-closing action). Then, the previous tests of L-joint shear failure were reexamined in the point of both states [2], and the results are shown in Fig.2, where V_c(exp) and V_c(cal) represent the observed maximum story shear and calculated one from V_{ju} , respectively. Some value of V_c(exp) were not found in the reference papers. In joint-opening, the average value of V_c(exp)/V_c(cal) is 1.31 and in joint-closing, it is 1.85 and each value scatters more compared with the case of joint-opening. It is said that AIJ's Eq.(1) does not evaluate the difference of both actions and the influence of joint reinforcing details appropriately, and the equation to calculate properly strength is needed.

From these facts, The objective of this paper is to obtain basic knowledges for the failure of L-joint and discuss the failure mode and process of L-joint specimens which have different tail anchoring length of beam bent bar in both actions.

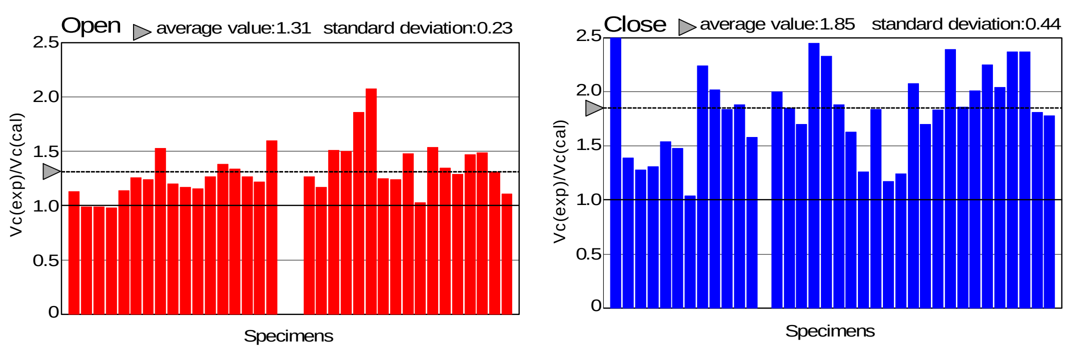


Fig.2 Comparison of observed values (V_c (exp)) and calculated values (V_c (cal))

TEST PROGRAM

Specimens and Test Parameters

Two reinforced concrete beam-column L-joints which have different tail anchoring length of beam bent bar (L-180-S and L-180-L) were tested. They were designed such that joint shear failure would initiate before beam's flexural yielding failure and anchorage failure of beam bent bar in joint. The reinforcing details of specimens is shown in Fig.3, and tail anchoring length of beam bent bars were $10d_b$ (d_b:diameter of beam bars, for L-180-S) and $47d_b$(for L-180-L) respectively. All the other properties are common for L-180-S and L-180-L [3]. The material properties of the concrete and the high strength steels are listed in Table.1, and story shear calculated in each failure mechanism are listed in Table.2. From the table, it is said that these specimens were designed to initiate joint shear failure.

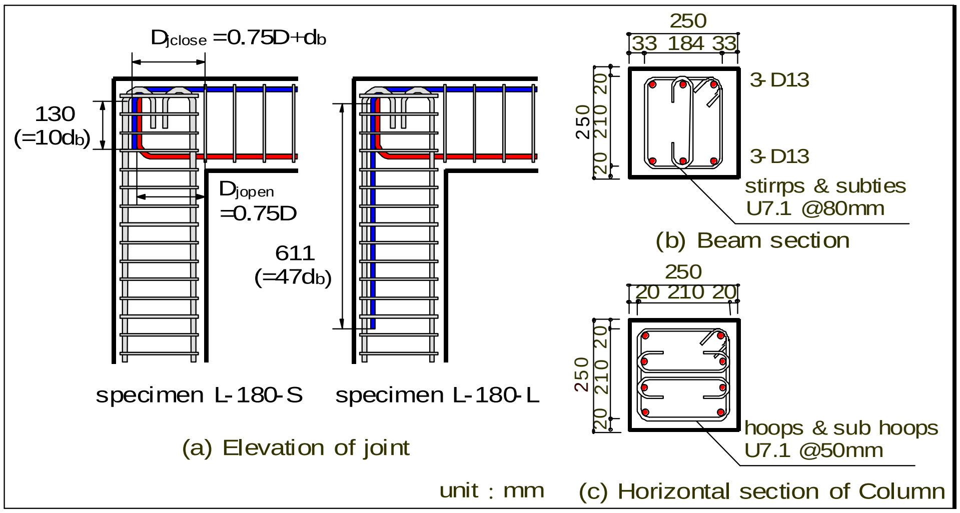


Fig.3 Reinforcing details of L-joint

Table.1 Material properties

concrete

	compressive strength (MPa)	tensile strength (MPa)	young modulus (MPa)
L-180-S	24.2	2.9	1.92×10^4
L-180-L	23.9	2.9	1.92×10^4

steel

Reinforcing bars	yield strength (MPa)	yield strain (μ)	young modulus (MPa)
D13	721	4026	1.87×10^5
U7.1	1481	6891	2.2×10^5

Table.2 Story shear calculated in each failure mechanism

specimens	L-180-S		L-180-L	
joint-cornor state	Open	Close	Open	Close
story shear at joint shear failure specified in AIJ 1999	27.5	28.5	27.3	28.3
story shear at joint ancorage failure specified in AIJ 1999	40.4	41.5	40.2	41.2
story shear at flexual yield of beam	66.1		66.1	

Test setup and loading Sequence and Measurement

The loading set up is shown in Fig.4. To generate a stress state of L-joint in frame structure, specimens were supported by three pins (at bottom of base, end of load cell and loading point). Load cell was set up at beam end to measure vertical load. Statically horizontal cyclic loading was applied by the horizontal actuator with displacement control.

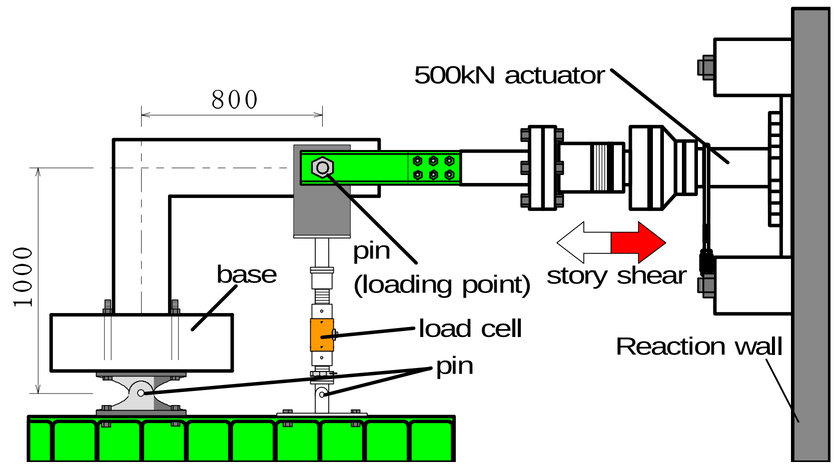


Fig.4 Test setup and loading rig

TEST RESULT

Development of Cracks

The cracking patterns of specimen L-180-S are shown in Fig.5. The diagonal cracks were observed at the inside-corner in joint-opening action. The cracks at the top face of joint widely opened in joint-closing action. Finally, the cover concrete at the top face of joint spalled off. In the specimen L-180-L, these similar cracking patterns were observed.

(a) inside-corner-opening (story drift 6%)

(b) joint-corner-closing (story drift 6%)

(c) failure property after test

Fig.5 Cracking patterns (L-180-S)

Story shear - Story drift relation

Fig.6 shows the relation between story shear and story drift, and the dotted lines the show story shear at joint shear failure defined in AIJ 1999. From the test result it is observed specimen L-180-S has different maximum story shears in both joint-opening action (29.7kN) and joint-closing action (32.9kN), and the maximum value obtained in joint-closing action was larger than that in joint-opening action. The maximum story shear in joint-closing action was attained at first cycle of 2% story drift, and the secant stiffness at maximum story shear in joint-closing action was larger than that in joint-opening action.

In the specimen L-180-L, the relation between story shear and story drift in joint-opening action is similar to that of L-180-S. However, the maximum story shear (45.5kN) in joint-closing action is larger than that of L-180-S (32.9kN), and the story shear of L-180-L moderately increased up to the end of the loading cycle in joint-closing action. This means the important of the reinforcing anchoring details of joint.

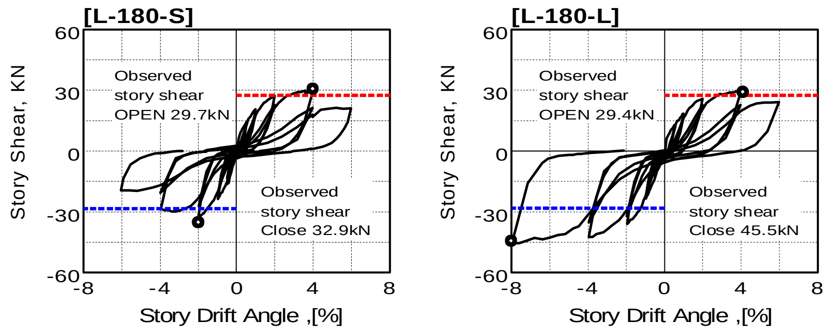
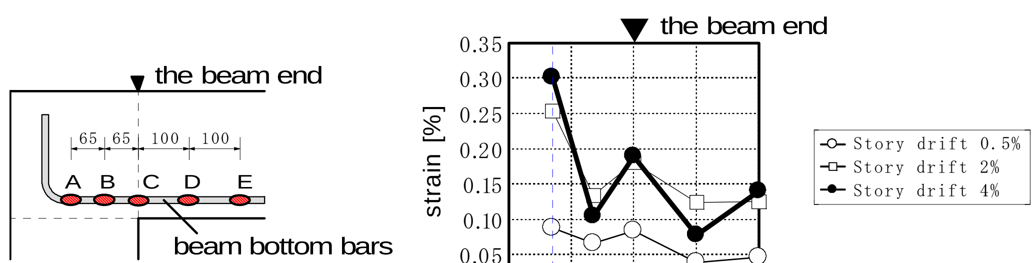


Fig.6 Story shear - Story drift

INVESTIGATION OF FAILURE PROCESS (L-180-S)

Joint-opening action

Strains of beam bent bars were monitored by strain gauges. The points of attached strain gauges on beam bottom bars are shown in Fig.7(a), and the strain distribution is shown in Fig.7(b). At story drift of 0.5%, the each strain at point A and C increased slightly. The strain at point A increased remarkably at story drift of 2%. But, this strain did not reach the yield point at story drift of 4% yet.



(a) The points of attached strain gauges

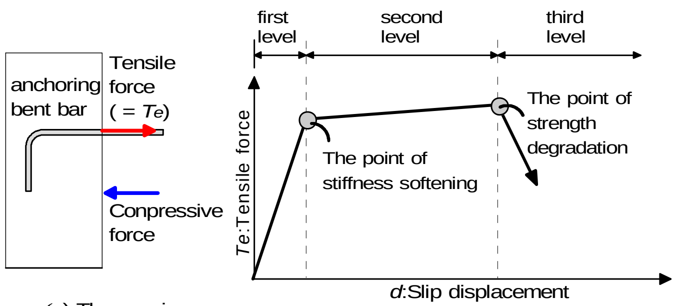
(b) Strain distribution of beam bottom bars

Fig.7 The behavior of beam bottom bars in joint-opening action (L-180-S)

Some specimens as shown in Fig.8(a) were tested by Fujii et. al.[4], where beam bent bar in concrete was pulled out to quantify the anchorage capacities in joint. The relation between tensile force T_e of beam bent bars and slip displacement d obtained from the tests is briefly shown in Fig.8(b), where failure process is divided into three levels. At the first level, T_e increased in proportion to d. At the second level, T_e moderately increased as d increased. At the third level, the decrease of T_e occurred and the beam bent bars began slipping out.

The envelope curve of the relation between tensile force T of main bars at beam end and story drift in this study is plotted in Fig.9. Up to story drift of 2%, T increased in proportion to story drift, T moderately increased when story drift exceeded 2%. Large bond stress occurred at the joint part of the beam bottom bars (see Fig.7(b)), T would decrease when story drift exceeded 4%. Fig.9 is similar to Fig.8(b), where shows that tensile force of main bars at beam end decreases due to the deterioration of anchorage capacities.

It is said that the failure process in joint-opening action is affected by the deterioration of anchorage capacities of beam bottom bars in joint.



(a) The specimen

(b) Tensile force - Silp displacement

Fig.8 Tensile force - Slip displacement
(Fujii et al.)

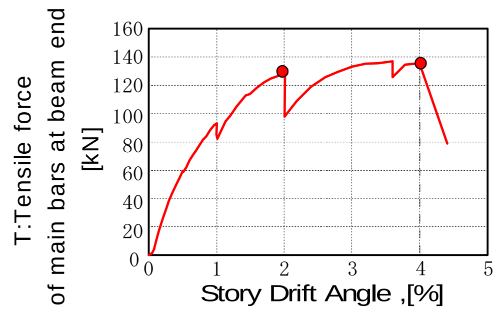
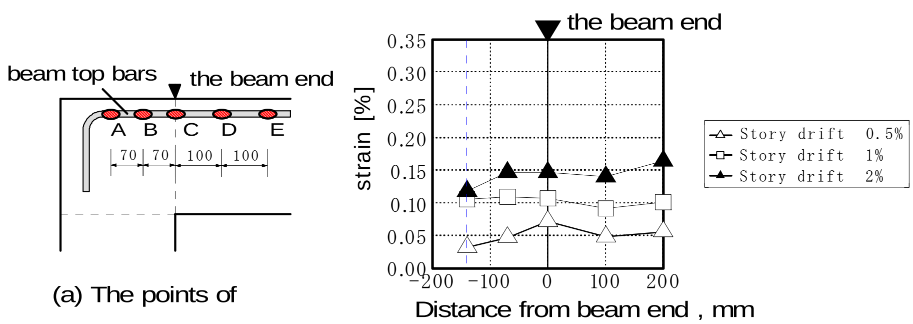


Fig.9
Tensile force of main bars at beam end - Story drift

Joint-closing action

The points of attached strain gauges on beam top bars is shown in Fig.10(a), and the strain distribution is shown in Fig.10(b). The strain at point C increased slightly more than those at other points at story drift of 0.5%. When story drift exceeded 1%, the each strain at point A and B was almost same as the one at point C. It is thought that the beam top bars began slipping out at lower range of story drift than joint-opening action.



(a) The points of attached strain gauges

(b) Strain distribution of beam top bars

Fig.10 The behavior of beam top bars in joint-corner-closing action (L-180-S)

The envelope curve of the relation between tensile force T of main bars at beam end and story drift is plotted in Fig.11. T increased in proportion to story drift up to story drift of 1%. When story drift exceeded 1%, T moderately increased, and the cracks at the top face of joint widely opened (see Fig.5(b)). When the slip displacement of beam top bars rapidly increased, the beam top bars easily slip out from joint. The tensile force T of main bars at beam end decreased when story drift exceeded 2% as shown in Fig.11 which is similar to Fig.8(b). It is thought that tensile force of main bars at beam end decreases by deterioration of the anchorage capacity due to poor confinement of top concrete.

However, the story drift at maximum story shear is less than that in case of joint-opening action. It

implies joint-closing action may have some unique phenomena. Fig.12 shows the relation between strain at beam bottom end and story drift, where the strain in compressive reinforcement changed from compression to tension at story drift of 2%. Then, the distance between stress resultants *j* decreased as shown in Fig.13. It is said that the influence of many cracks due to cyclic loading.
Shiohara[5] indicated from the previous experimental results for RC interior beam-column connection that the distance between stress resultants *j* decreases as the story drift increases.
The decrease of bending moment M_b at beam end or consequently the decrease of story shear is attributed to the decrease of both the tensile force *T* of main bars at beam end and the distance between stress resultants *j*.

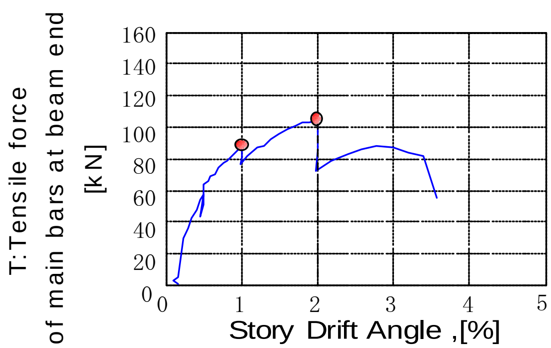


Fig.11
Tensile force of main bars at beam end- Story drift

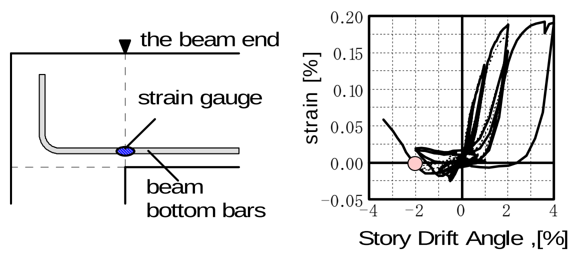
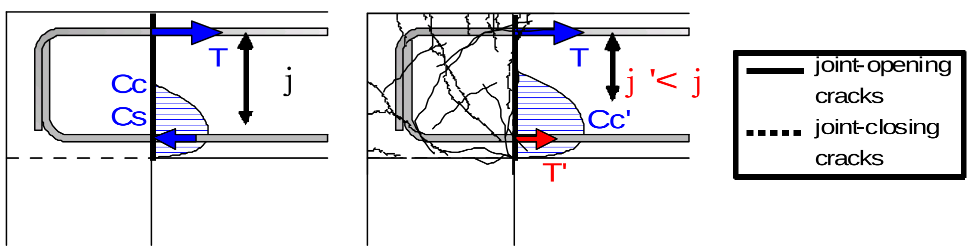


Fig.12 Strain - Story drift



(a)good anchorage state
T=Cs＋Cc

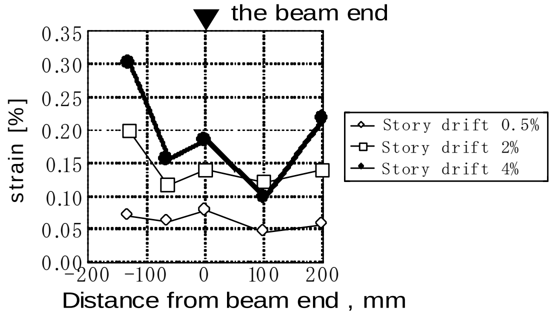
(b)poor anchorage state
T＋T'=Cc'

Fig.13 Anchorage capacity in L-joint

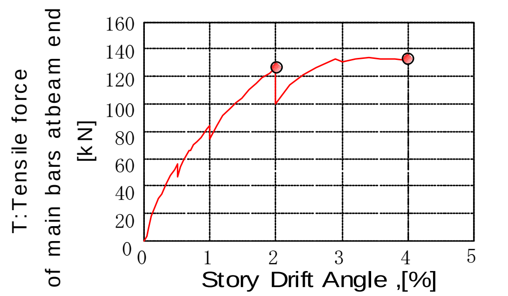
INVESTIGATION OF FAILURE PROCESS (L-180-L)

Joint-opening action

Strain distribution of beam bottom bars is shown in Fig.14(a) (The points of attached strain gauges are shown in Fig.7(a)), the envelope curve of the relation between tensile force *T* of main bars at beam end and story drift is plotted in Fig.14(b). These figures are almost similar to those of L-180-S up to story drift of 4% (see Fig.7(b) and Fig.9).
When story drift exceeded 4%, strain at beam bottom end should be much larger than monitored one by strain gauge, since large bond stress would occur at the joint part of beam bottom bars (see Fig.14(a)), which would raise the decrease of the story shear (see Fig.6).
Then, it is thought that *T* began decreasing at story drift of 4%. These results are very similar to those results to L-180-S. It is also said that the failure process of L-180-L in joint-opening action is affected by the deterioration of anchorage capacities of beam bottom bars in joint.



(a) Strain distribution of beam bottom bars



(b) Tensile force of main bars at beam end - Story drift

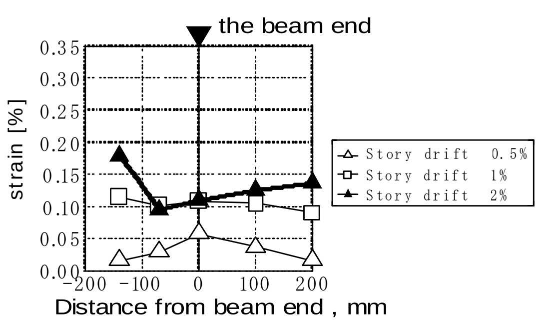
Fig.14 The behavior of beam bottom bars in joint-opening action (L-180-L)

Joint-closing action

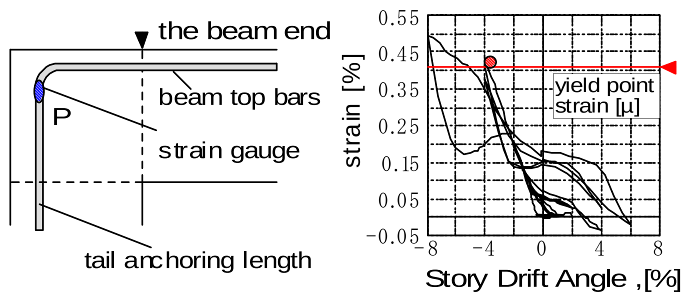
Strain distribution of beam top bars is shown in Fig.15(a) (The points of attached strain gauges shown in Fig.10(a)). These figures are almost similar to those results of L-180-S up to story drift of 1%, and the strain at point A increased at story drift of 2%. This behavior of L-180-L differs from that of L-180-S. The relation between the strain at point P (see Fig.15 (b)) and story drift is shown in Fig.15 (b), the strain at point P reached at the yield point (0.403%) at story drift of 4%.

The envelope curve of the relation between tensile force *T* of main bars at beam end and story drift is plotted in Fig.16. At story drift of 2%, *T* decreased as observed in L-180-S. However, *T* moderately increased when story drift exceeded 2%. It is said that the tail anchoring length of beam bent bars which are arranged longer than L-180-S (see Fig.3) prevented the tensile force of main bars at beam end from decreasing.

The tail anchoring length of beam bent bars is one of factors which can develop the anchorage capacities in joint. From these results, the anchorage capacities in joint is greatly affected by tail anchoring length of beam bent bars.



(a) Strain distribution of beam top bars



(b) Strain-Story drift

Fig.15 The behavior of beam top bars in joint-corner-closing action (L-180-L)

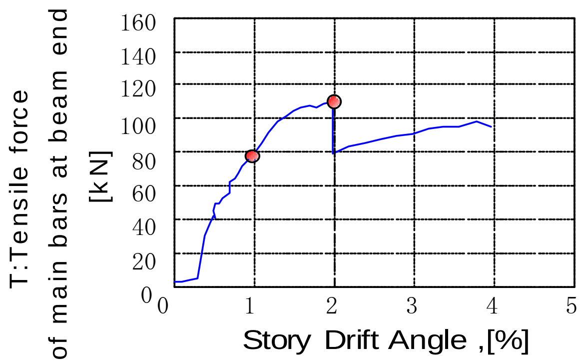


Fig.16 Tensile force of main bars at beam end - Story drift

PROCESS ON THE DECREASE OF STORY SHEAR

This paper deals with the L-joint failure mode caused by deterioration of anchorage capacities in both joint-opening and joint-closing actions. The failure process caused by deterioration of anchorage capacities for each action is shown in Fig.17. The characteristic of joint-opening action is the decrease of tensile force of main bars at beam bottom end, and that of joint-closing action is the decrease of both tensile force of main bars at beam top end and the change of distance between stress resultants.

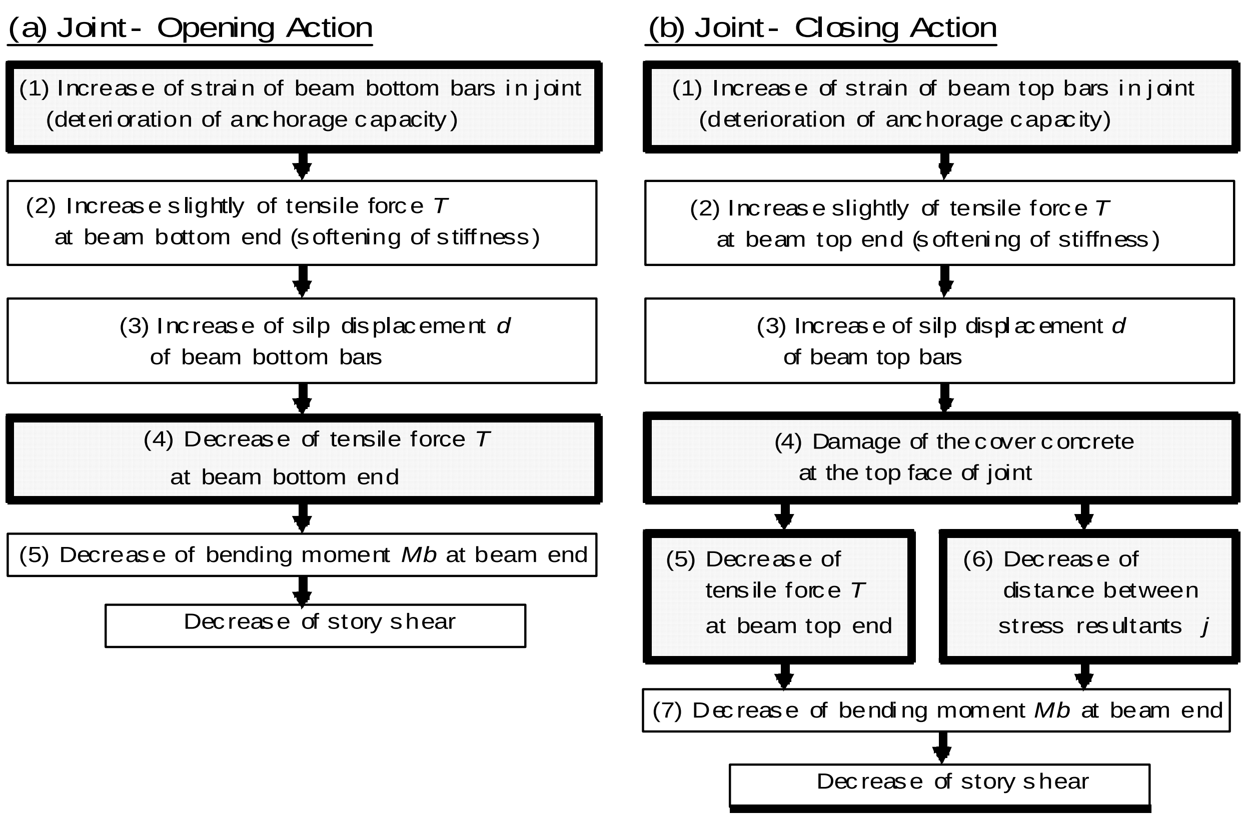


Fig.17 The failure process caused by deterioration of anchorage capacities

CONCLUSIONS

In this study, previous tests of L-joint shear failure were reexamined in the point of accuracy of joint shear strength defined in AIJ 1999. And the failure behavior of L-joint was investigated with respect to inside-corner-opening state and inside-corner-closing state and tail anchoring length of beam bent bar. From these investigations, the followings are concluded:

1) L-joint has different ultimate strength in both joint-opening and joint-closing actions. And AIJ's Eq.(1) does not evaluate the difference of both actions.

2) In the specimen L-180-S, the joint failure caused by the deterioration of anchorage capacities of beam main bars in joint occurred in both joint-opening and joint-closing actions.

3) In the specimen L-180-L, the maximum story shear in joint-closing action is larger than that of L-180-S. The story shear moderately increased up to the end of the loading cycle in joint-closing action. The tail anchoring length of beam bent bars is one of factors which can develop the anchorage capacities in joint.

4) The failure process on the decrease of story shear caused by deterioration of anchorage capacities in both joint-opening and joint-closing actions was shown. The characteristic of joint-opening action is the decrease of tensile force of main bars at beam bottom end, and that of joint-closing action is the decrease of both tensile force of main bars at beam top end and the change of distance between stress resultants.

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