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DEVELOPING REINFORCED CONCRETE SLOTTED BEAM STRUCTURES TO REDUCE EARTHQUAKE DAMAGE AND TO ENHANCE SEISMIC STRUCTURAL PERFORMANCE

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SUMMARY

This paper presents the test results of the reinforced concrete slotted-beam structure, which is newly developed to minimize the damage of concrete and to produce the sufficient structural performance during an earthquake. The slotted-beam structure is a reinforced concrete moment resisting frame, which is constructed by the beams with a narrow vertical slot at the beam-ends and the strong columns. The slot that runs from the beam bottom to the bottom of floor slab isolates the direct transmission of stresses in concrete generating by the bending moment at the beam-end. However, the bottom longitudinal reinforcement of the beam is continuous through the slot, and the area of the top longitudinal reinforcement is made larger than the bottom area so that yielding of top reinforcement is avoided. Consequently cracking and crushing of concrete is minimized. This is the first feature of the slotted beam structure. The yielding of the bottom reinforcement governs the flexural strength of the beam in both positive and negative moment directions, so that an uncertain procedure how to define the effective width of floor slabs for calculating ultimate flexural strength in the structural design is avoided. This is the second feature of this structure. In this beam, when the bottom is in compression, the shear must be transferred through the cross section of the floor slab at the beam end, which is in tension. However, the bent steel bars are placed to aid in the shear transfer in the beam-end region, so that the stable and ductile structural behavior is possible. In the moment resisting reinforced concrete beam-frame-structure that resists against earthquake forces by the cyclic yield strength of both the top and bottom longitudinal reinforcement for the positive and negative lateral load reversals during an earthquake, the longitudinal elongation in the beam always generates. Such the beam elongation generates for each column of the frame to make the different lateral deformation. Although this behavior is one of the difficult issues in the seismic structural analysis, it is not resolved in the present structural design procedure yet. No significant beam elongation generates in the slotted beam structure, because the top reinforcement of the slotted beam does not yield and behaves in the elastic condition under the cyclic loadings. This is the third feature of this structure. Two slotted-beam column sub-assemblages and one ordinary beam column sub-assemblage were tested. This paper presents the result for the three features mentioned above. The slotted-

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beam structures reduced big cracks of concrete and performed well without any structural degradation during the loading test, in comparison with the ordinary beam column sub-assemblage without the slot.

INTRODUCTION

Earthquake resistant design for reinforced concrete moment resisting frame plans for yield hinges to form at the floor beams, in a technique called the total yield mechanism, AIJ [1]. In such the design, if the frames are subjected to severe earthquake motions, both the top and bottom longitudinal reinforcement at the beam ends yield. Consequently a number of large cracks develop in the yield-hinge regions, which should subsequently be repaired. In the Kobe Earthquake in 1995, a building, which performed with an ideal crack pattern, was demolished after the earthquake, and one of the reasons given for the demolition was the excessive cost to repair the cracks, Araigumi Engineering Report [2].
To avoid the excessive repair cost after an earthquake it is desirable to limit the cracking in the planned beam-end yield sections. The authors have examined a new resisting mechanism, called a slotted-beam, as shown in Fig.1, where the yielding is restricted to only the lower reinforcement and cracking and crushing of the concrete is minimized.

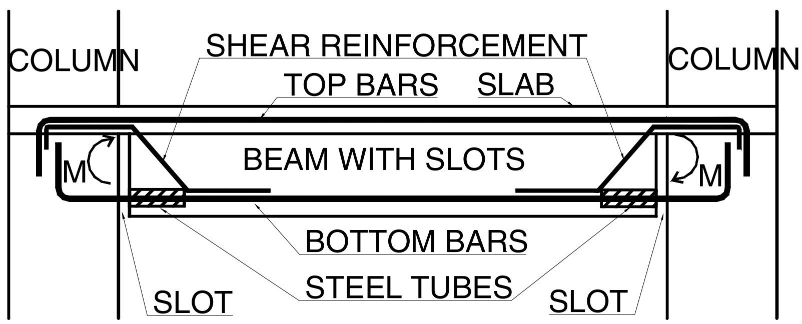


Fig.1 Conceptual illustration of the Slotted Beam

In the slotted beam concept, a vertical narrow slot is formed between the beam and the column, running from the bottom of the beam to the bottom of floor slab. The width of the slot is made large enough so that the concrete at the bottom of the beam never contacts the column and so never goes into compression. The bottom reinforcement is continuous through the slot and transmits beam moments to the column. The area of the top reinforcement is made larger than the bottom area so that yielding of top reinforcement is avoided. The yielding of the bottom reinforcement governs the flexural strength of the beam in both positive and negative moment directions during an earthquake. To reduce concrete cracking in the bottom part of the beam and to reduce the strains in the bottom reinforcement it is not bonded over a length about equal to half the beam depth at the beam-end region. This breaking bond is achieved by placing the reinforcement in a short length of steel tube, which also aids preventing buckling of the bottom reinforcement.
Ohkubo et al. [3] had tested some models designed by the slotted beam concept. The load vs. displacement histories were almost as good as the normal moment resisting design. However, the effect of the reducing cracks in the slotted-beam models was not discussed, because the models did not have floor slabs and the width of the concrete above the slot was the same as the web of the beam.
This paper presents the result of the experiments, which were conducted to examine the cracking behavior of the slotted-beams with floor slabs.

TEST MODELS

The names and the characteristics of test models

The models tested are the cross type of sub-assemblages consisted of beams with floor slabs and columns. Two slotted-beam column sub-assemblages SB1 and SB2 and one conventional beam column sub-assemblage RCB were tested. Fig.2 and Fig.3 show the model of SB1 and SB2, respectively.

The width and the depth of the beam are the same of 400mm. The thickness of the floor slabs is 100 mm, and the total width of the floor slab is 1200mm. The width and the depth of the column are 400mm and 600mm, respectively. The narrow slot of 20mm wide at the beam end, running from the bottom of the beam to the bottom of floor slab, isolates for the concrete jointing between the beam-end and the column in the models of SB1 and SB2 as shown in Figs.2 and 3.

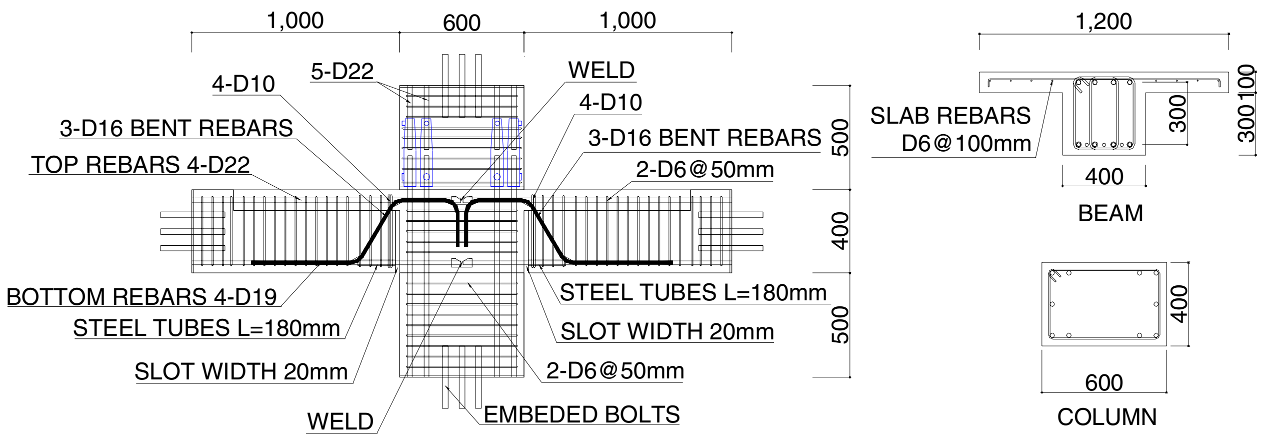


Fig. 2 The details of the model SB1

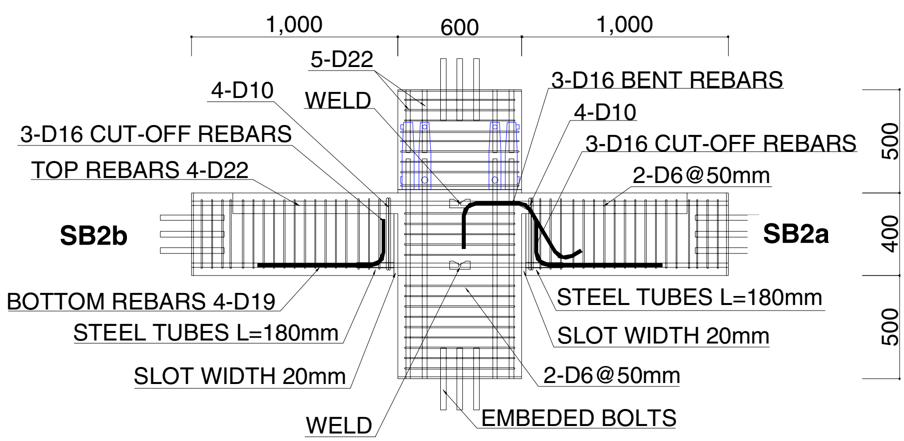


Fig.3 The details of the model SB2a (right) and SB2b (left)

In the beams of SB1 and SB2, four deformed steel bars of D22 and D19 whose diameter 22mm and 19mm are placed in the top and the bottom of the beam, respectively.

The SB2a beam has three bent reinforcement with the short anchorage length to transmit the beam shear force at the narrow section above the slot and has three L-shape cut-off reinforcement in the beam bottom to prevent widening of the shear crack in the beam, as shown in right side of Fig.3. The SB2b beam does not have the short length bent reinforcement but has the L-shape cut-off reinforcement as shown in the left side of Fig.3.

In the slotted beam, two rectangular stirrups with 4 legs using the bar size of D10 are placed to prevent widening the crack width between the beam and the floor slabs immediately beside the slot.

Fig.4 shows the details of the conventional frame model RCB. The same amount of longitudinal reinforcement 4-D19 is placed at the top and bottom of the beam in the RCB model. The thickness, width, and the reinforcement of the floor slab are the same as the model SB1.

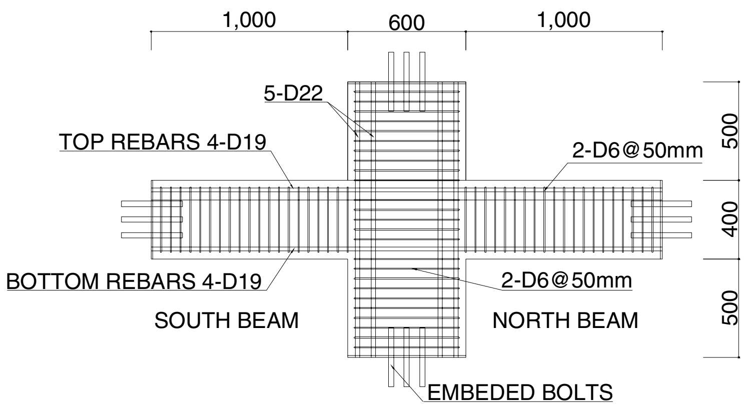


Fig.4 The details of the model RCB

Test set-up and the loading procedures

Fig.5 shows the test set-up diagram. The bottom end of the column is supported by the pin-joint, and at the top end of the column under the pin-roller condition the lateral forces which is equivalent to the story shear force of the test model *Vs* (kN) is applied using the actuator. The length between the centers of the top and bottom pin-joints is 1700 mm.

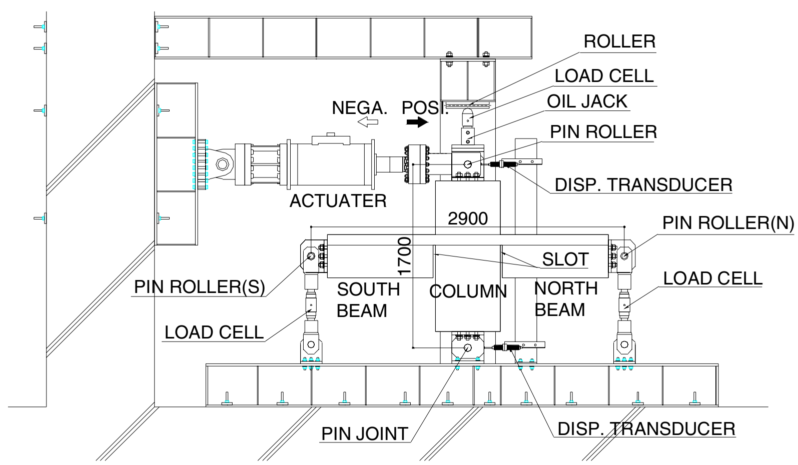


Fig.5 Test set-up and loading diagram

Both the cantilever beam ends are supported by the pin-rollers with the load cells for measuring the shear forces of beams. The length between the centers of both sides of pin-joints is 2900 mm.

The planned pattern of load reversals was as follows; one full cycle at a story drift angle *Rs*=0.0025 radians, followed by one cycle at *Rs*=0.050 radians, and then two cycles at *Rs*=0.01, 0.02 and 0.03 radians. Here, the story drift angle *Rs* is that the lateral displacement at the pin-roller end of the top column was divided by the length between the centers of both the pin-joints at the top and bottom columns.

Material strength of concrete and reinforcing steels

The compressive strength of precast concrete which were used for the beams and columns of SB1 and SB2 was 60.6 MPa, and the compressive strength of cast-in-place concrete which were used for the beam-column joints, floor slabs of SB1 and SB2 and the members lower than the top column of RCB was 47.2 MPa. The compressive strength for the top column of RCB was 53.8 MPa.

The yielding strength of the longitudinal reinforcement for beams and columns were 374 MPa for D22 (A_s = 3.87 cm^2) and 383 MPa for D19 (A_s = 2.87 cm^2), and those for the shear reinforcement and floor slabs were 345 MPa for D16 (A_s = 1.99 cm^2), 337 MPa for D10 (A_s = 0.71 cm^2) and 384 MPa for F6 (A_s = 0.32 cm^2), respectively.

TEST RESULT

Load displacement relationships and flexural yielding behavior

Fig.6 and Fig.7 show the relations between the story shear force *Vs* (kN) and story drift angle *Rs* (%) for the test model SB1 and SB2, respectively.

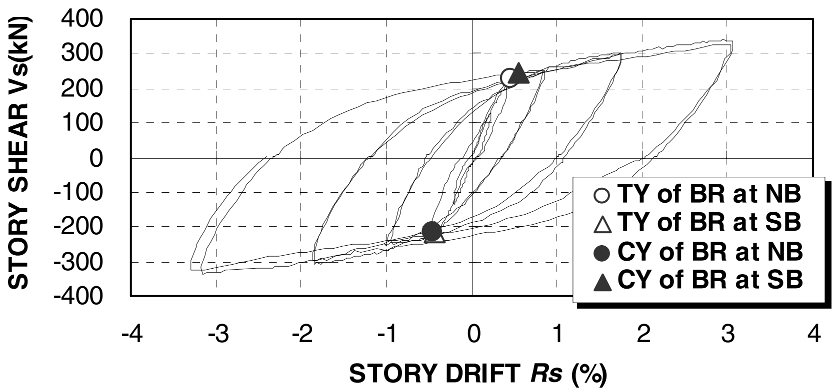


Fig.6 Relations between story shear *Vs* and story *Rs* drift of the model SB1

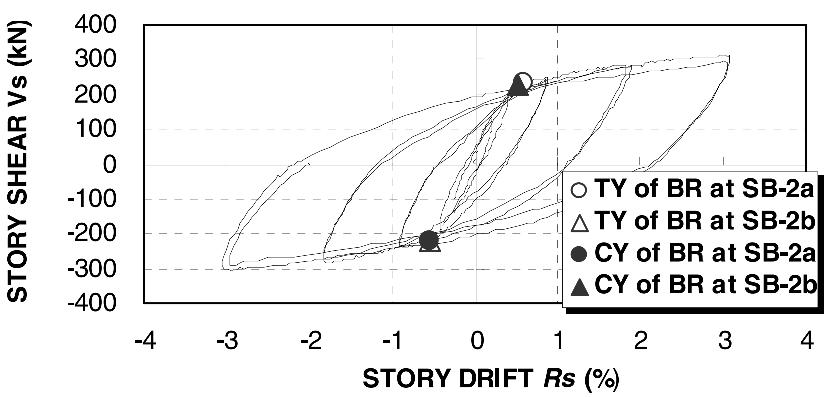


Fig.7 Relations between story shear *Vs* and story *Rs* drift of the model SB2

The notations in the figures are defined as follows in this paper; TY and CY mean the tensile and the compressive yielding, respectively. BR means the bottom longitudinal reinforcement in the beams. NB and SB mean the north and the south beams. The differences between SB-2a and SB-2b in Fig.7 are defined in Fig.3.

In the slotted beams, as shown in Both of Fig.6 and Fig.7, only the tension or compression yielding of the bottom reinforcement repeated by the load reversals as planned, and the top reinforcement in beams did not yield. Therefore, the shape of the hysteresis loops showed likely to be observed in the experiments of steel structures. The structural performance of the model SB2 was somewhat poor than SB1 due to the increasing of shear deformation in SB2b in which the bent reinforcement for shear transferring was not placed at the beam-end region. However, the strength at the flexural yield was almost the same as SB1, as that the yield of the bottom reinforcement governed the flexural strength in both of SB1 and SB2.
Fig.8 shows the relations between the story shear force *Vs* (kN) and story drift angle *Rs* (%) for the conventional model RCB.

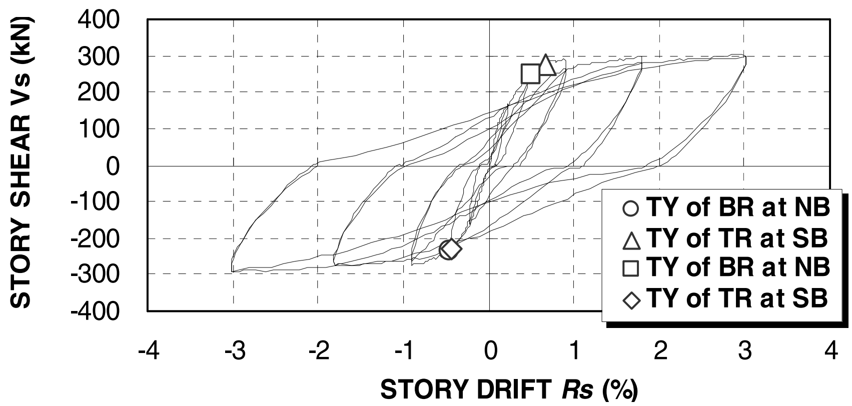


Fig.8 Relations between story shear *Vs* and story *Rs* drift of the model RCB

In this conventional mode RCB, the tension yielding alternately appeared at the top and bottom beam ends during the load reversals. The flexural yielding strength was a little higher than those of SB1 and SB2, because the longitudinal reinforcement in the floor slabs contributed to the increase of yield strength of the beam when the top of the beam was in tension. The difference is recognized by the comparison of the *Vs* vs. *Rs* envelope curves in Fig.9.

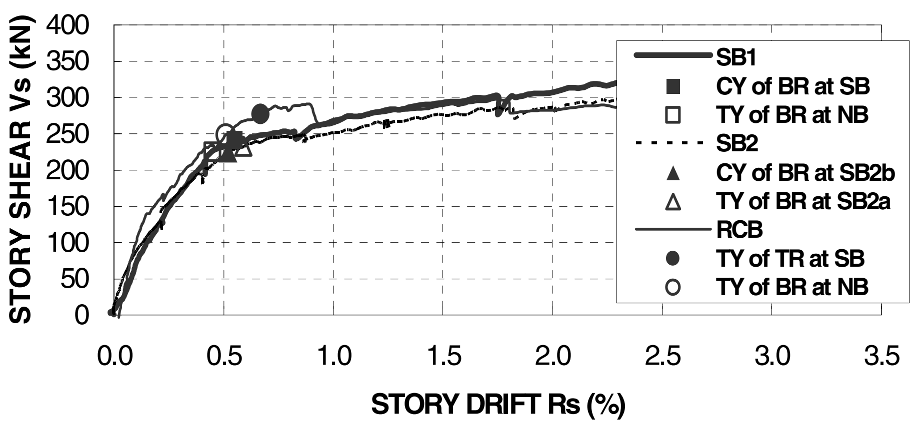


Fig.9 Envelope curves of *Vs* and story *Rs* for SB1, SB2 and RCB

As the result, it is recognized that the concept of effective width of floor slabs does not concern to calculate the flexural moment capacity of the beams in the slotted beam structures.

Energy dissipation behavior during load reversals

Fig.10 shows the comparisons of the energy dissipation among three models during the load reversals. The vertical axis presents the equivalent viscous damping ratios *he* (%), which was defined as the area of the load displacement loop was divided by the product of 3.14 times the potential energy at the peak point in each loop.

The performance of energy dissipation in the model of slotted beam structures is better than that of the conventional model RCB in the larger deformation range after one percent of the story drift angle *Rs*. This will be observed by comparing the load displacement histories among three models shown in Fig.6 through Fig.8.

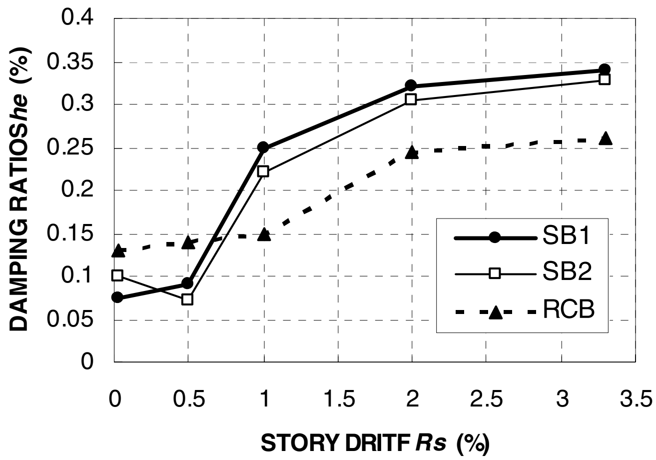
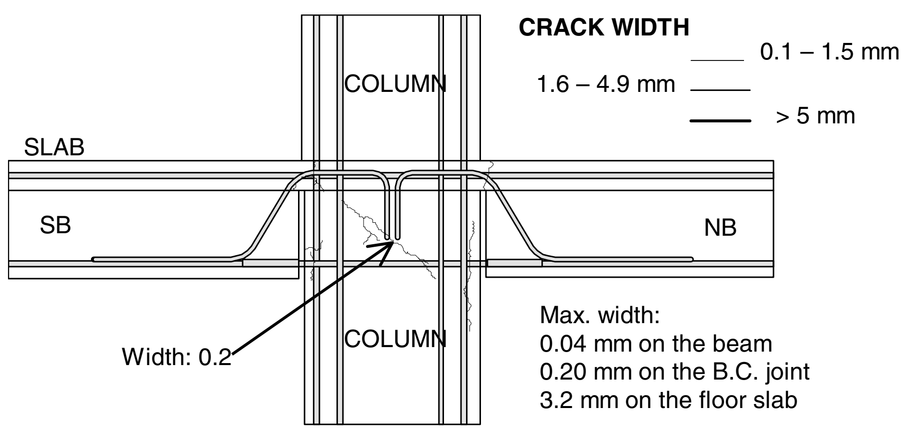


Fig.10 Comparisons of energy dissipation behavior among three models

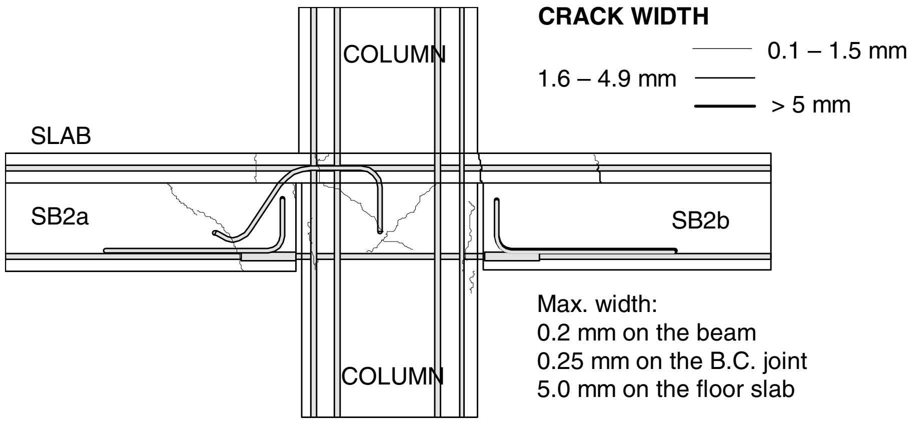
Cracking behavior

Fig.11 (a), (b), and (c) show the crack patterns of beams and columns in the model SB1, SB2, and RCB, respectively. Fig.12 (a), (b), and (c) also show the crack patterns of the top surface of floor slabs. The cracks shown in the figures are those wider than 0.15 mm. They will be repaired, if the continuous service is required for the structures after the earthquake damage.

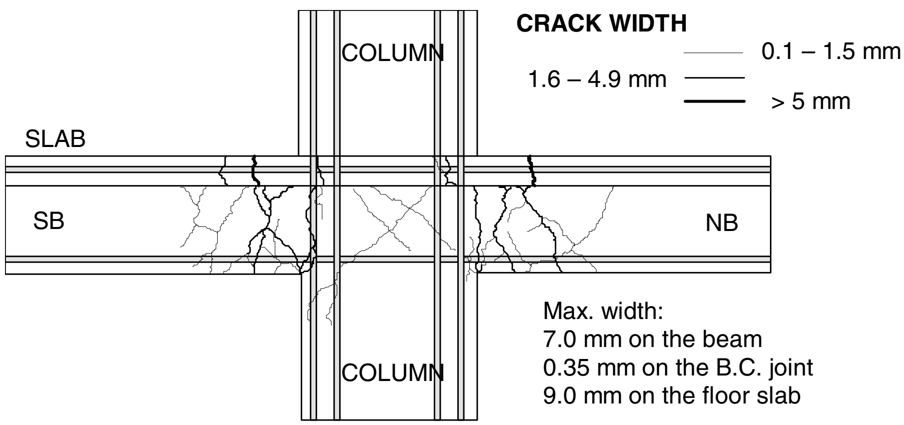


(a) Crack pattern of SB1

Fig.11 Crack patterns of the beams and columns after the load reversals at *Rs* = 3%

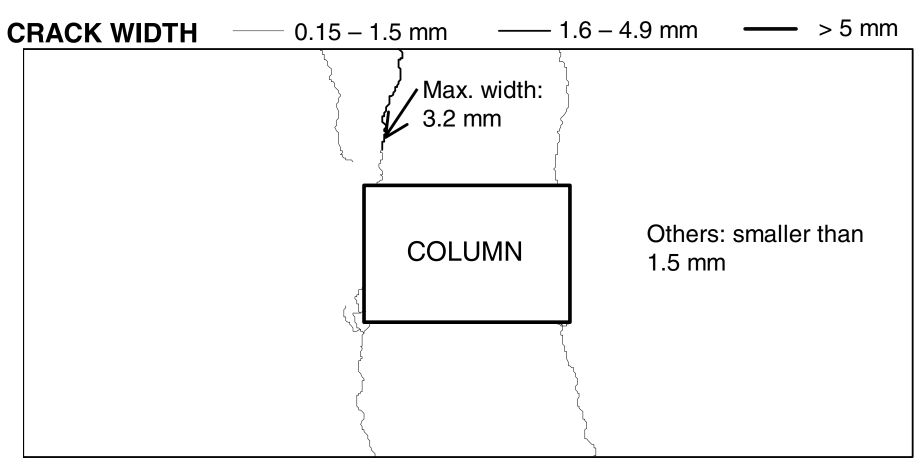


(b) Crack pattern of SB2a and SB2b



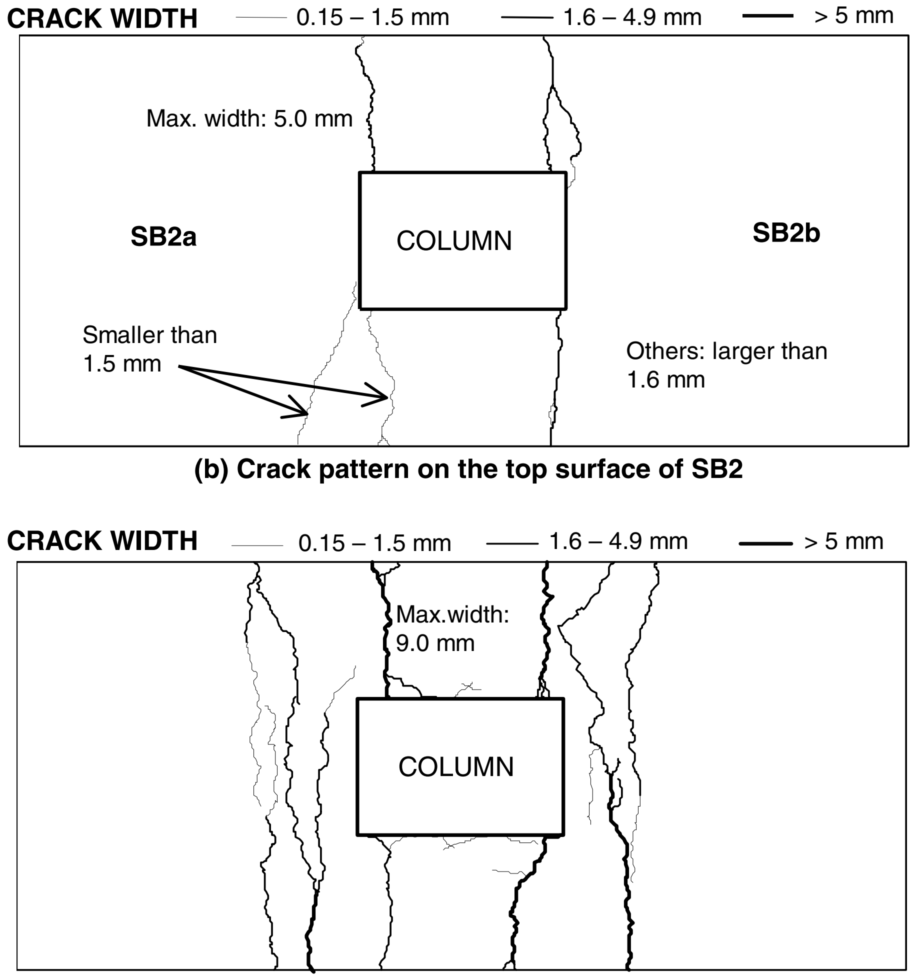
(c) Crack pattern of RCB

Fig.11 Crack patterns on the top surface of slabs after the load reversals at *Rs* = 3%



(a) Crack pattern on the top surface of slabs of SB1

Fig.12 Crack patterns on the top surface of slabs after the load reversals at *Rs* = 3%



(b) Crack pattern on the top surface of SB2

(c) Crack pattern on the top surface of RCB

Fig.12 Crack patterns on the top surface of slabs after the load reversals at Rs = 3%

As we can observe on Fig.11 and Fig.12, the number of cracks in the models SB1 and SB2, which should be repaired, reduces comparing with that of the model RCB. The result of the model SB1 was the best among three models for the purpose to minimize the cracking damage.

Behavior on longitudinal elongation of beams during load reversals

Fig.13 shows the behavior on longitudinal elongation of beams during load reversals comparing with the model SB1 and RCB.

In the conventional model RCB, the elongation of the beam increases in accordance with the increasing load reversals and the story drift angle, because that the longitudinal reinforcement of the top and bottom at the beam-end alternately yielded during load reversals and the plastic strains of the reinforcing bars accumulated. Such the behavior always observes in the experiments in which the flexural yielding governs the post-yield deformation of reinforced concrete beams. The elongation of beams makes increase of the lateral deformation in columns. The resolving this problem in the structural design has been one of the issues in the reinforced concrete structures.

However, the beam elongation is almost not accumulated during the load reversals in the model SB1, as we can observe it in Fig.13. This is one of the significant features in the slotted beam structures.

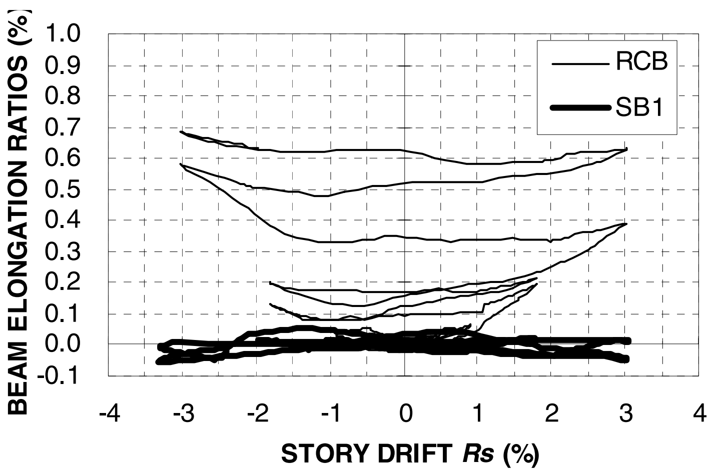


Fig.13 Relations between beam elongation and story drift in the model SB1 and RCB

CONCLUSIONS

This paper showed the experimental data of the slotted beam structures and the conventional reinforced concrete frame structure, and the slotted beam structure presented the following significant resolutions for the seismic design techniques of reinforced concrete moment resisting frame structures in future.

(1) The cracking and crushing of concrete are minimized against earthquake load reversals.
(2) The yielding of bottom reinforcement at the beam-end governs the flexural moment capacity in both positive and negative loading, so that the effective width of floor slabs does not concern in the calculation of the moment capacity.
(3) The beam elongation during load reversals after flexural yield is minimized in the slotted beam structures.

The techniques how to predict the flexural and shearing strength and the member stiffness in elastic range for the slotted beams were discussed in the paper No.4 shown in **REFERENCES** (Ohkubo et al. [4]). In the slotted beams, the special shear crack that is not usually observed in ordinary beam and that starts diagonally from the end of steel tubes at the beam bottom may occur in the slotted beams. The behavior of the special shear crack and the reinforcing techniques how to minimize the crack width was discussed in the paper No.3 shown in **REFERENCES** (Ohkubo et al. [3]).

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