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論文 Shear Transfer Mechanism of Reinforced Concrete Beams with a Slot at the Beam-end

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ABSTRACT: Reinforced concrete beams with a narrow vertical slot at the beam-end were tested to examine the shear transfer mechanism at the beam-end region. The narrow slot was installed in the bottom 3/4 of the beam immediately adjacent to the column. The bottom longitudinal reinforcement was continuous through the slot. In this special beam when the bottom is in compression the shear must be transferred through the small section of concrete at the top of the beam which is in tension. Five specimens with the different arrangements of shear reinforcement were designed and tested. The results show which arrangement of reinforcement gives good shear transfer.
KEYWORDS: Reinforced concrete slotted beam, shear transfer mechanism, cyclic load tests, alternate yielding of bottom beam reinforcement.

1. INTRODUCTION

Earthquake resistant design for reinforced concrete moment resisting frames plans for yield hinges to form at the end of the floor beams, in a technique called the total yield mechanism[1]. In such a design, if the frames are subjected to severe earthquake motions, both the top and bottom reinforcement at the beam ends yield. Consequently a number of large cracks develop in the yield-hinge regions, which should subsequently be repaired. However, in the Kobe Earthquake, 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 [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, termed 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.

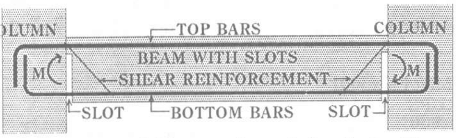

Fig.1 Conceptual illustration of the slotted beam

In the slotted beam concept, a vertical narrow slot is formed between the beam and the column, running from the bottom of the beam for about 3/4 of the beam depth, or 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. To reduce concrete cracking in the

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bottom part of the beam and to reduce the strains in the bottom reinforcement it is unbonded over a length about equal to half the beam depth at the beam end. This unbonding is achieved by placing the reinforcement in a short length of steel tube, which also aids in preventing or delaying buckling of the bottom reinforcement.

Ohkubo and Zhang had tested some earlier models designed by the slotted beam concept[3]. The hysteretic load displacement results were almost as good as for the normal moment resisting design. However, it was concluded that the shear transfer mechanism in the beam-end region needed improvement. This paper presents the result of the two series of experiments which were conducted to examine and improve the shear transfer mechanism through the reduced concrete area in the end region.

2. PHASE ONE EXPERIMENTS

2.1 TEST SPECIMENS

In Phase 1, two slotted beams with different end reinforcement details were tested to observe the fundamental shear transfer mechanism of the slotted beams. One ordinary beam was also included in this Phase to provide a comparison to the slotted beams. All the specimens are cantilever beams connected to a column at the slotted end and loaded through the free end which corresponds to the inflection point of the frame structure. See Fig. 2. The beams are all 300 mm wide, 400 mm deep and 1350 mm long, while the columns are 400 mm wide by 500 mm deep.

Fig.2 shows the reinforcement for specimen RCB, which is the companion ordinary beam to provide comparison with the slotted beams. In this beam equal amounts of longitudinal reinforcement (4-D19) are placed at the top and bottom. Rectangular two legged stirrups(2-D6) were spaced at 60 mm over the entire length of the beam.

In the slotted specimens, denoted RCSB-1 and RCSB-2, the top longitudinal reinforcement area (4-D22) was increased to prevent flexural yielding of the top reinforcement and thus minimize the concrete cracking in the top portion of the beam-end. Fig.3(a) shows the detail of the beam-end region of the slotted beams. A 20 mm wide slot along the column face over the bottom 3/4 depth of the beam is formed in the concrete. Each bottom reinforcement bar is inserted through a close fitting 180 mm long steel tube (23.5 mm and 27.3 mm interior and exterior diameters). The tubes serve to break the bond over the 180 mm length and so spread the plastic elongation over a longer length, and they also prevent or delay buckling when the bottom reinforcement is in compression. Since the area of the top reinforcement is larger than the bottom reinforcement area, the bottom reinforcement will govern the flexural strength in both the positive and negative directions

Fig.3(b) shows the shear reinforcement for the specimens RCSB-1 and RCSB-2, respectively. In the 180 mm length section at the beam-end region, the stirrup spacing was decreased providing roughly 50% more shear reinforcement than provided by the 2-D6 stirrups at 60mm in the remainder of the beam. In specimen RCSB-2, one inclined U-type stirrup (high strength steel, 2-U7.4) was added to carry the shear through the

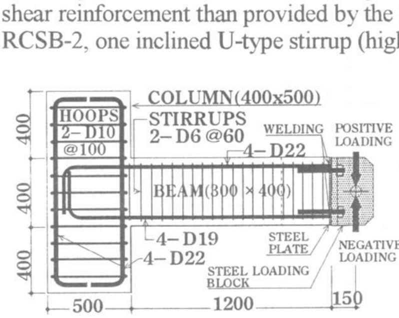
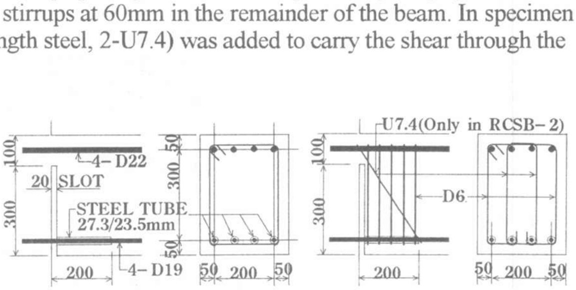


Fig.2 Dimension and reinforcement of RCB



(a) DETAILS OF BEAM END (b) RCSB-1 & RCSB-2

Fig.3 Details of the Slotted Beams

Table 1 Concrete

Compressive strength, σ_B	22.0 MPa
Compressive strain, ε_c	0.0022
Tangent modulus, Ec	19.9 GPa

Table 2 Reinforcing steels

	D22	D19	D6	U7.4
Yield strength, σ_y(MPa)	379	393	405	1431
Yield strain, ε_y	0.0022	0.0022	0.0024	0.0072
Young's modulus, Es(GPa)	173	179	167	200

reduced concrete area.

2.2 MATERIALS

The results of material tests, for the concrete(normal weight concrete) and the steel reinforcement, are shown in Tables 1 and 2.

2.3 LOADING AND INSTRUMENTATION

The load, which is equivalent to the shear force in the beam, was applied at the free end of the cantilever beam and had a moment arm of 135 cm to the face of the column. The planned pattern of load reversals was as follows; one full cycle at a deflection angle R=0.0025 radians, followed by one cycle at R=0.050 radians, and then three cycles at R=0.01 and 0.02, and two cycles at R=0.03 and 0.04 radians. Here, the deflection angle, R is that the free end deflection was devided by the distance to the beam end, 1350 mm. The positive direction of loading is defined as producing compression in the bottom reinforcement.

Instrumentation consisted of measuring the applied load with a load cell at the load point, beam displacement at the load point and longitudinal displacement at points along the beam, measured with displacement transducers, and reinforcement strains at various points, measured using strain gages.

2.4 LOAD DEFLECTION CURVES AND FAILURE BEHAVIOR

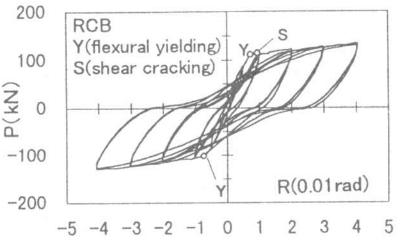
The load vs. deflection ratio history for all three specimens are plotted in Figs. 4(a)-4(c). Fig. 4(a) shows the results for specimen RCB. First yielding occurred in the top reinforcement at the beam-end at a deflection R=0.0065 radians. This is indicated on the plot with the letter Y in the positive loading region. Shear cracks appeared shortly after yield as indicated by the letter S in the figure. As shown in the figure the beam went through the cyclic load pattern with essentially no degradation in strength up to the end of testing at R=0.04 radians. The load at flexural yielding matched well with the predicted load. Fig. 5(a) shows the crack pattern in specimen RCB at the end of the test. Although the diagonal shear cracks in the beam-end region are large, shear failure did not occur. The shear strength predicted by Arakawa's Minimum Equation was about 1.8 times the flexural yield load.

Figure 4(b) shows the hysteresis plots for specimen RCSB-1, and it is apparent that its performance is not as good as the ordinary beam RCB. Yielding of the bottom reinforcement occurred at a deflection R=0.0095 radians in the first positive loading cycle to R=0.01, and at a load close to what was predicted for flexural yielding. The large inclined shear crack shown in Fig.5(b) appeared during positive loading of the first cycle to R=0.02. This crack was unexpected because the bottom of the beam is in compression for positive loading, and the crack was wider at the bottom surface of the beam than that at the mid depth. This type of crack is not usually observed in ordinary beams, and will be termed the "S-crack" in this paper.

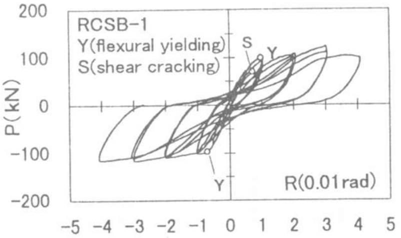
The following reasons are put forth as to why the S-crack formed where it did, and why it was wider at the bottom of the beam. Before cracking the diagonal compression struts in the concrete would have attempted to create tension in the short tubes surrounding the bottom reinforcement. Since the tubes end at the point B shown in Fig. 5(b) the tension would have been transferred to horizontal tension in the bottom concrete around point B, resulting in the start of the S-crack. Once the crack forms the segment ABCD of the beam is loaded with the downward shear force applied along BC and an upward shear force at D. The resulting couple tends to rotate the segment ABCD around point D, which causes an increase in the S-crack width at the bottom of the beam, and eventually resulting in the bottom of the beam at A contacting the face of the column. The rotation of segment ABCD added to the displacement, and the size of the S-crack was of major concern. The cracking behavior put forward above is supported from observation of the stress distribution shown in Fig.6, which was obtained from an elastic finite element analysis. Fig.6 shows the vector of the maximum principal stress (usually tension). In the analysis there is no bond between the bottom reinforcement and the concrete between the points A and B. The high tensile stresses shown in Fig. 6 perpendicular to the observed S-crack confirms why the crack would form in that position.

Specimen RCSB-2 had inclined U-type shear reinforcement added in the beam end region as shown in Fig.3(b). The S-crack appeared at an earlier deflection, R=0.005, than it did in RCSB-1, and before flexural yielding of the bottom reinforcement. The diagonal U-type reinforcement may have originally acted in tension but as it was neither bent at the beam bottom nor extended along the longitudinal reinforcement, it may have contributed to the tension in the concrete and given rise to the early cracking. Once the crack had formed the diagonal U-type reinforcement had little effect.

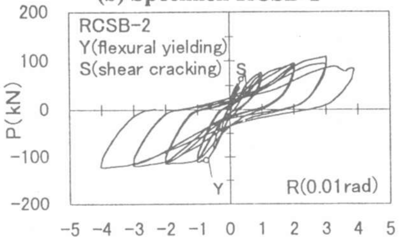
Considering the rather poor test results of the slotted beams, and based on the stress distribution shown in Fig.6, three additional specimens were designed and tested in Phase 2 of the program as described below.



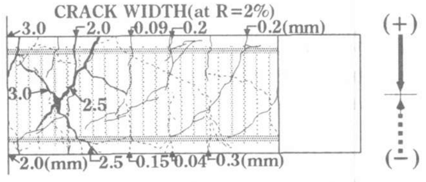
(a) Specimen RCB



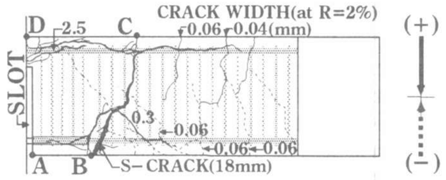
(b) Specimen RCSB-1



(c) Specimen RCSB-3
Fig. 4 Load/deflection curves



(a)Specimen RCB



(b)Specimen RCSB-1
Fig.5 Final crack patterns

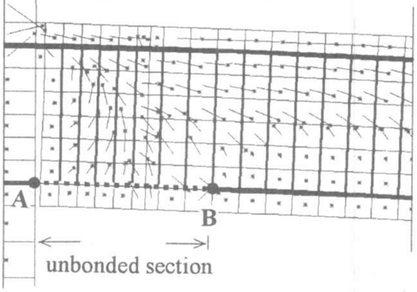


Fig.6 Stress distribution of the slotted beam analyzed by FEM
(Vector of principal maximum stress)

3. PHASE TWO EXPERIMENTS

3.1 TEST SPECIMENS

In the Phase 2 program, three slotted beams(RCSB-3, RCSB-4 and RCSB-5) were planned. The overall shape of the specimens, the amount of longitudinal reinforcement, stirrups, and the short steel tubes for debonding of the bottom reinforcement were the same as those in Phase 1. Fig.7 shows the arrangement of shear reinforcement in the Specimen RCSB-3, in which two bent bars(2-U7.4) were placed to aid in the shear transfer in the beam-end region. The bottom end of the bent reinforcement extended along the beam and was intended to prevent development of the S-crack that developed in the Phase 1 tests. The bent reinforcement were high tension steel, and the capacity of the vertical component of the bent reinforcement was close to the shear force that would occur with flexural yielding.

Fig.8 shows the Specimen RCSB-4, in which one short inclined U-type shear reinforcement (2-U7.4) was arranged in the upper left part of the beam end, and additional short lengths of reinforcement (2-D19, and termed ‘cut-off reinforcement’ in the text and figures) were placed along the bottom reinforcement. It was expected that the additional reinforcement would transmit the horizontal component of the diagonal compression struts in the beam-end region to the bottom reinforcement, and would also prevent the development of the S-crack. The short inclined U-type reinforcement (2-U7.4) was expected to resist the diagonal tension stresses in the upper left part of the beam-end as shown in Fig.6.

The reinforcement of specimen RCSB-5 was the same as RCSB-4, except that the additional short lengths of longitudinal reinforcement were not placed.

3.2 MATERIALS

The reinforcement properties were the same as those used in the Phase 1 experiments. However, the

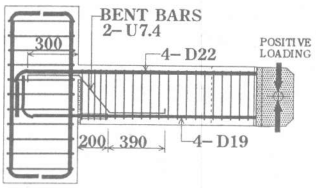


Fig.7 Reinforcement in RCSB-3

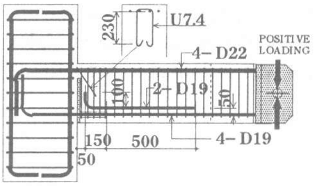


Fig.8 Reinforcement in RCSB-4

compressive strength of the concrete used in the Phase 2 experiments was 38.7 MPa, higher than in Phase 1. The strain at the compressive strength was 0.0024, and the tangent modulus at one third of the compressive strength was 29.7 GPa.

3.3 LOAD DEFLECTION RELATIONSHIPS AND FAILURE BEHAVIOR

The loading pattern and instrumentation was almost the same as that used in the Phase 1 experiments.

Fig.9 shows the load deflection relationships of specimen RCSB-3 which has the long bent shear reinforcement. The bottom reinforcement yielded at a deflection ratio R=0.0096 radians in positive loading, almost exactly the same as in RCSB-1. The yield load was 1.07 times that predicted by using the measured yield strength of the reinforcement. The S-crack discussed in the Phase 1 experiments appeared during positive loading, but not until the second cycle of loading to R=0.04, and did not widen in the following load cycles. The bottom reinforcement alternately yielded in tension and compression during the load reversals up to the deflection ratio R=0.02. However, during loading to R=0.04 the two interior bottom reinforcement bars buckled, leading to a deterioration in the positive load capacity.

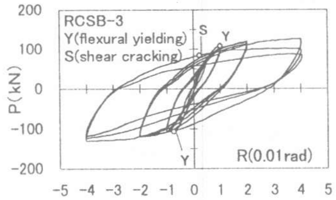


Fig.9 Load/deflection curves of RCSB-3

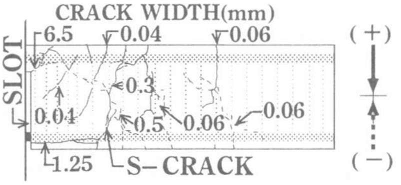


Fig.10 Final crack pattern of RCSB-3

Fig.10 shows the crack pattern of specimen RCSB-3, at the completion of the test. All the crack widths were small and would not have to be repaired except for the diagonal crack which appeared just at the top of the slot, and the horizontal crack along the bottom reinforcement which developed when the two interior bottom reinforcement bars buckled.

The other two specimens, RCSB-4 and RCSB-5, had load deflection relationships up to R=0.04 that were almost identical to RCSB-3, with alternate flexural yielding in tension and compression of the bottom reinforcement during the load reversals. The crack pattern of RCSB-4 was almost the same as that of RCSB-3. However, in specimen RCSB-5, which did not have additional longitudinal reinforcement, the S-crack suddenly appeared at a deflection R=0.038 radians, and became extremely wide during the following load reversals. In this respect RCSB-5 performed more like the slotted Phase 1 specimens.

3.4 SHEAR FORCE SHARING OF THE SHEAR REINFORCEMENT

All the Phase 2 specimens had strain gages installed on the high strength inclined U-type shear reinforcement. Fig.11 shows the relationship between the tensile stress of the inclined reinforcement and the beam deflection angle. The stress increased almost linearly as the deflection increased to R=0.01, where flexural yielding occurred. The share of the shear force carried by the inclined reinforcement was 17% to 22% of the total shear force at R=0.01. The inclined reinforcement of specimen RCSB-3, with the longer bent reinforcement, carried more of the shear than did the other two specimens with only partial length U-type reinforcement. If the remainder of the shear is assumed transmitted across the small concrete section above the slot, which ignores shear carried by dowel action of the top reinforcement, the average shear stress would be approximately 2.6 MPa (6.8% of the compressive strength of the concrete). The stress in the inclined reinforcement continued to increase as the deflection increased and at R=0.04 the inclined reinforcement was carrying between 23% and 33%. The width of the diagonal shear crack originating at the top of the slot was approximately 6 mm at a deflection of R=0.02 radians. However, this did not lead to load deterioration and the combination of high tension in the inclined reinforcement and dowel action of the top reinforcement was sufficient to carry the shear into the column,.

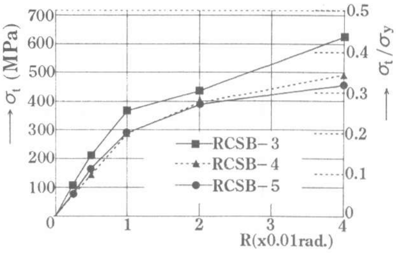


Fig. 11 Stress of the inclined shear reinforcement

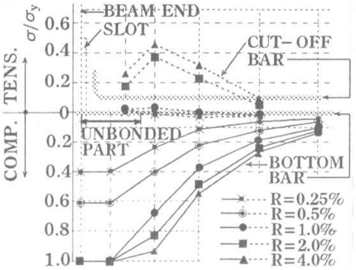


Fig.12 Stress distribution of the cut-off bar

3.5 STRESS DISTRIBUTION OF THE CUT-OFF REINFORCEMENT

In pecimen RCSB-4, the cut-off reinforcement was arranged at the bottom side of the beam in order to prevent the S-crack from widening. Fig.12 shows the stress distribution in the cut-off reinforcement and in the beam-bottom longitudinal reinforcement. The cut-off reinforcement is always in tension, even though the reinforcement is placed in the compression side of the beam for positive loading, but the stresses are very small until the deflection ratio exceeds R=0.01. The significant tensile stress in the cut-off reinforcement at the higher displacement ratios confirms that this reinforcement picks up the horizontal component of force from the concrete compression struts in the beam-end region, and transfers this through bond to the beam-bottom-reinforcement in the region to the right of the "unbonded section".

4. DISCUSSION AND CONCLUSIONS

The tests of the slotted beams in general show good flexural characteristics, but the shear transfer at the slotted end requires special detailing of the reinforcement. The tests revealed the following information concerning the shear transfer in the slotted beam end region:

(1)The characteristic shear crack (S-crack) probably arises from the tensile stresses created in the concrete in the beam-bottom, even when the bottom reinforcement is in compression, that is required to equilibrate the compressive strut forces in the concrete carrying the shear to the end region of the beam where the longitudinal reinforcement is unbonded.

(2)To prevent the S-crack from developing, there must be reinforcement crossing the potential S-crack that is well anchored into the portion of the beam away from the end of the unbonded section. This reinforcement can be in the form of bent diagonal reinforcement that is well anchored in the beam away from the slotted end region, or it can consist of well anchored longitudinal reinforcement that is additional to the regular longitudinal reinforcement.

(3)In the slotted beams, a diagonal crack running from the top corner of the slot to the top of the beam arises at a comparatively early deflection. The inclined U-type shear reinforcement crossing this crack, plus dowel action of the top longitudinal reinforcement is effective in transferring the shear across the slot. The location and size of the crack were of concern but it was not fatal to the performance of the beam.

Slotted beams, which have special shear transfer reinforcement as described in (2) and (3) above, can produce a stable flexural–yield mechanism in which only the bottom beam reinforcement undergoes alternate yielding in tension and compression . The amount of cracking in the concrete of the slotted beams is much reduced when compared to comparable normally detailed beams.

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