EFFECT OF SHEAR SPAN RATIO ON THE FRACTURE OF DEEP BEAMS

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ABSTRACT

Shear resistance of deep beams with a small shear span ratio and containing shear reinforcement was studied by conducting vertical loading tests on simple beam specimens. Parameters used were the shear span ratio (a/d), shear reinforcement ratio, and effective height. It was found that the fracture mode of beams with a/d=1.5 is different from that of beams with a/d=0.5 and a/d=1.0, and that shear reinforcement can provide sufficient shear resistance by controlling the crack width effectively.

1. INTRODUCTION

It has been pointed out that the shear strength of deep beam structures with a/d$\leqq$2.5 (by Japanese Bridge Specifications) is unable to be evaluated in the same way as the evaluation of ordinary reinforced concrete members.

Kotsovos et al.[1] presented that the fracture mode of deep beams with a/d$\fallingdotseq$1.5 greatly differs from that of deep beams with a/d<1.0, because an increase in the shear strength of concrete is low and diagonal cracking becomes predominant in the former beams. But, research on the difference of fracture mechanism due to the effect of a/d is very little. In the present study, the fracture mode of deep beams was investigated by conducting vertical loading tests on simple beam specimens.

2. OUTLINE OF EXPERIMENT

2.1 Specimens

Attributes of specimens and their compressive strength are shown in Table 1. The configuration of a specimen is shown in Fig. 1. Parameters adopted were the shear span ratio (a/d: 0.5, 1.0, 1.5), shear reinforcement ratio (P_w: 0.0, 0.4, 0.8%), and effective height (d: 300, 400, 500, 600 mm). A total of 14 specimens were tested as shown in Table 1. "R" attached to the specimen name means it is the second specimen of the same configuration. The reinforcing bars arranged were all SD345. Deformed bars of D19, D22, and D25 were used as the main reinforcement. Deformed bars of D10 and D6 were used as the compressive reinforcement. Deformed bars of closed type were used as the shear reinforcement and anchored to the concrete.

The spacing of D6 reinforcing bars in the specimens of P_w = 0.4% was 65 mm, and that of D10 reinforcing bars in the specimens of P_w = 0.8% was 75 mm. In the case of specimens

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Table 1 Attributes of specimens

Specimen No.	shear span ratio a/d	Effecctive height d[mm]	Member width b[mm]	shear reinforce ratio Pw[%]	main reinforce ratio Pt[%]	compressive strengh σck [Mpa]
B-2	0.5	400	240	0.0	2.02	36.2
B-3	0.5	400	240	0.4		36.2
B-4	0.5	400	240	0.8		31.3
B-6R	1.0	400	240	0.0		31.3
B-7R	1.0	400	240	0.4		31.3
B-8	1.0	400	240	0.8		37.8
B-10	1.5	400	240	0.0		29.2
B-10R	1.5	400	240	0.0		37.0
B-11	1.5	400	240	0.4		29.2
B-12	1.5	400	240	0.8		31.3
B-10.1	1.5	300	180	0.0		37.0
B-10.1R	1.5	300	180	0.0		42.3
B-10.2	1.5	500	300	0.0		37.0
B-10.2R	1.5	500	300	0.0		42.3
B-10.3	1.5	600	360	0.0		37.8
B-10.3R	1.5	600	360	0.0		37.0

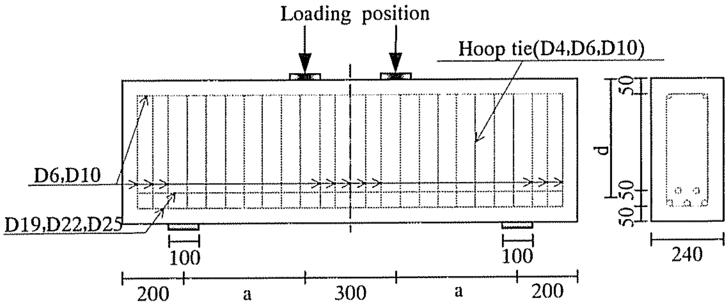


Fig.1 Configuration of Specimen

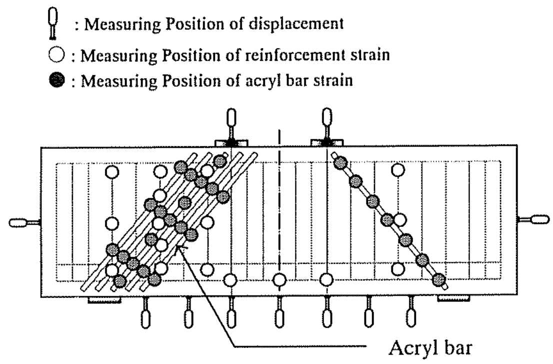


Fig.2 Typical arrangement of strain gauges and displacement meters

without the arrangement of shear reinforcement, dummy reinforcement was arranged to measure the strain in the vertical direction, just like the measurement of the strain of shear reinforcement. As the dummy reinforcement, round bar D4 were arranged between the loading plate and bearing plate. The ratio of dummy reinforcement was about 0.05%so as not to have an effect on the shear strength. The cover concrete was 50 mm thick in all specimens. Loading tests were performed after specimens were cured in the wet condition for 28 days.

2.2 Loading method and measuring method

Loading was applied to each specimen at two symmetrical positions as seen in Fig. 1. To measure cracking, the load applied was unloaded until reaching 0 kN in every loading step. To eliminate the effect of the loading plate width (r) vs. effective height (d) ratio, the width of the loading plate and that of the bearing plate of specimens were determined to be r/d=0.25.

Primary measurement items were five: the displacement of a specimen, strain of reinforcement (main reinforcement, dummy reinforcement, shear reinforcement), propagation of cracking, strain of acryl bar in the strut direction, and shear deformation. Figure 2 shows a typical measuring positions of shear reinforcement strain and dummy reinforcement strain, measuring positions of acryl bar strain, and the measuring positions of vertical and horizontal displacements. The strain gauges placed on the main reinforcement were intended to measure the tensile strain in the horizontal direction caused by flexural deformation. The strain gauges installed on the shear reinforcement and dummy reinforcement were intended to measure the tensile strain in the vertical direction around the strut. The compressive strain in the strut area was measured by burying acryl-made square bars (acryl bars) fitted with a strain gauge into the strut area between the loading plate and the bearing plate. Acryl bars were provided with indents to increase bonding and they were arranged on the entire cross section at a ratio of less than 0.5% so as not to affect the strength. Also, to measure the shear displacement, two displacement meters were placed in the diagonal form on the specimen's surface within the shear span, as shown in Photo 1.

2.3 Measuring method of diagonal cracks

As shown in Fig. 3, the width of diagonal cracks within the shear span was measured using a digital camera (Pixel: six million). To measure the crack width as small as 0.02 mm, the measuring range of one camera was made to 300 x 400 mm by dividing the strut area into three parts.

The image analysis software was used for the processing of the measured images. The crack width was obtained by comparing it with the 50 mm mesh inscribed on the specimens in advance. The crack width was measured at five positions at an interval of 10 mm, and then the average crack width was derived.

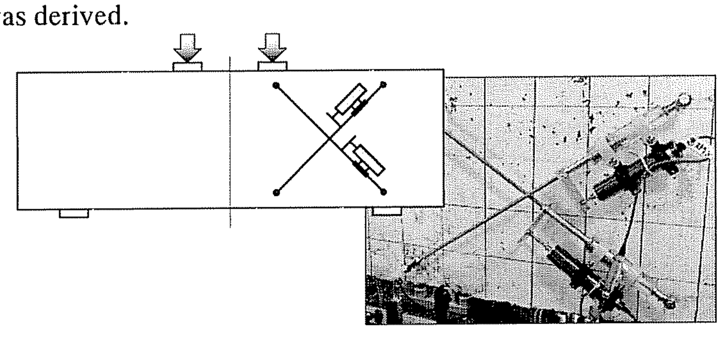


Photo.1 Placement of shear displacement meter

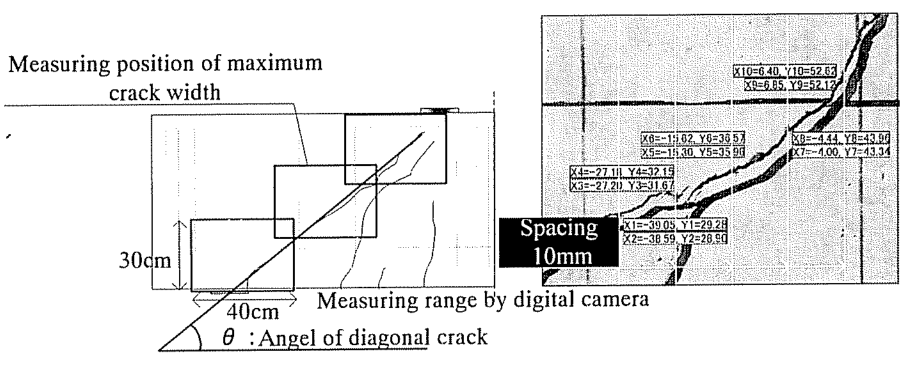


Fig.3 Measuring method of diagonal cracks

3. EXPERIMENTAL RESULTS

3.1 Fracture mode

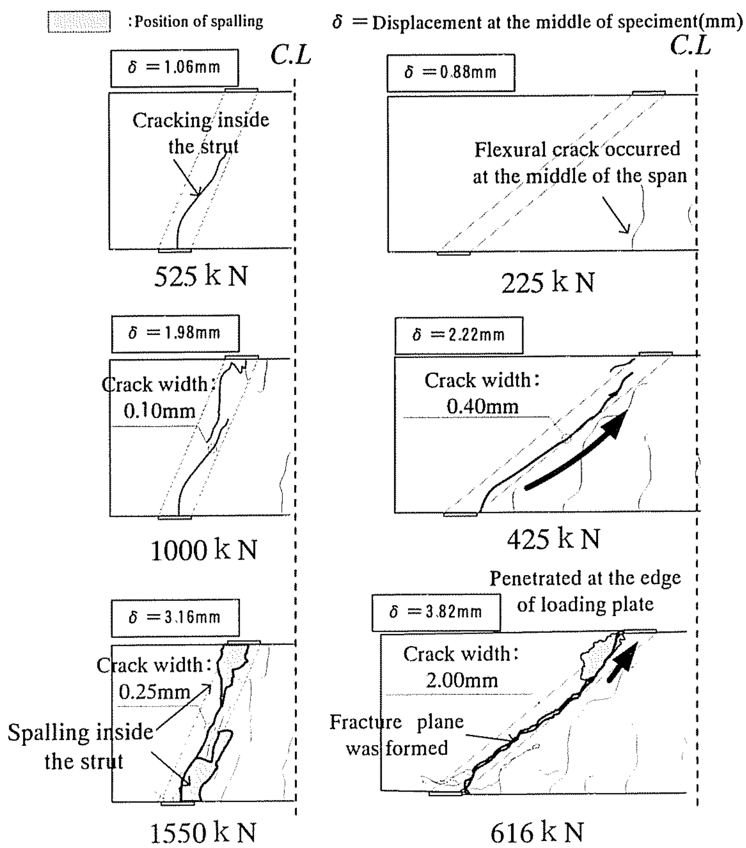
Specimens with a/d≦1.0 and specimens with a/d=1.5 can be grouped because their fracture mode and strain propagation were different, as mentioned below. As the typical examples of the a/d≦1.0 group and the a/d=1.5 group, the fracture mode of Specimen B-2 (P_w = 0.0%) and Specimen B-10 (P_w=0.0%) are introduced below, respectively.

(1) Specimen B-2 (a/d≦1.0)

Damage to Specimen B-2 is shown in Fig. 4(a). In this specimen, diagonal cracking started from the upper part of the bearing plate and ran within the strut under a load of 525kN. Diagonal cracking from the bottom and that from the top met within the strut under a load of 1,000kN. Diagonal cracking within the strut further propagated under a load of 1,550kN, caused spalling of concrete, and finally resulted in a fracture at two positions, around the loading plate and around the bearing plate. When fractured, the deflection (δ) in the middle of the specimen was 3.16 mm. The shear displacement was slightly smaller than this value but basically similar to it. The width of a diagonal crack at the time of fracture was as small as 0.25 mm.

(2) Specimen B-10 (a/d=1.5)

Damage to Specimen B-10 is shown in Fig. 4(b). In this specimen, flexural cracking started in the center of the span under a load of 225 kN. When the load increased to 425kN, diagonal cracking that started beside the bearing plate propagated along the lower face of the strut up to



(a) Specimen B-2 (b) Specimen B-10

Fig.4 Propagation of cracks

the compressive range below the loading plate, then stopped, and caused the yielding of dummy reinforcement around the center of the diagonal crack. Under a load of 616kN, the diagonal crack that reached below the loading plate penetrated through the specimen, resulting in a fracture. When fractured, the deflection (δ) at the center of the specimen was 3.82 mm. The shear displacement was slightly smaller than this value but basically similar to it. With the crack width as large as 2.0mm, a shear fracture was observed.

3.2 Strain-fracture relationship

As the fracture examples of the specimen group of a/d≦1.0 and the specimen group of a/d=1.5, specimens without shear reinforcement (P_w=0.0%) are presented here. Figure 5 shows the positions where the largest tensile strain of dummy reinforcement was obtained, and the positions where the largest compressive strain of acryl bar was obtained, as well as the state of their propagation.

In the case of specimens with a/d≦1.0, it is known from the figure that the strain of dummy reinforcement did not reach its yield strain (1,800 μ), but that the compressive strain of acryl bars reached close to the ultimate strain of concrete (-3,500 μ). In the case of specimens with a/d=1.5, the strain of dummy reinforcement was largely in excess of its yield strain, but strain of concrete did not reach close to its ultimate strain. Because such differences were seen in the propagation of acryl bar strain and in the propagation of dummy reinforcement strain, it is considered that grouping of specimens into the group of a/d≦1.0 and the group of a/d=1.5 is possible.

4. DISCUSSIONS

4.1 Evaluation of fracture type

From the experimental results, it is considered that specimens with a/d≦1.0 fractured by shear compression with resistance provided by a tied arch.

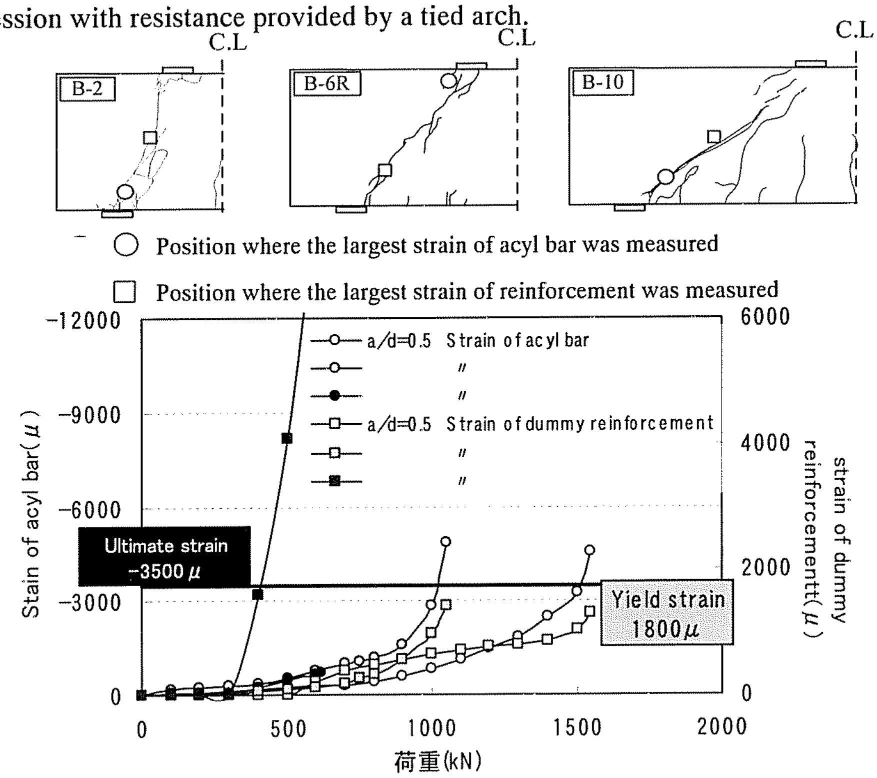


Fig.5 Propagation of compressive and tensile strains

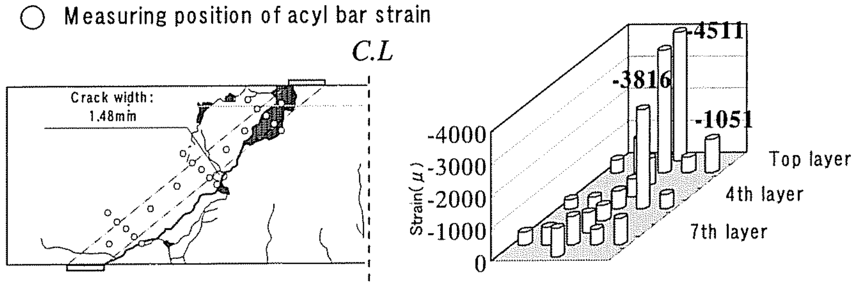


Fig.6 Type1 fracture and distribution of acryl bar strain
(Specimen B-10R)

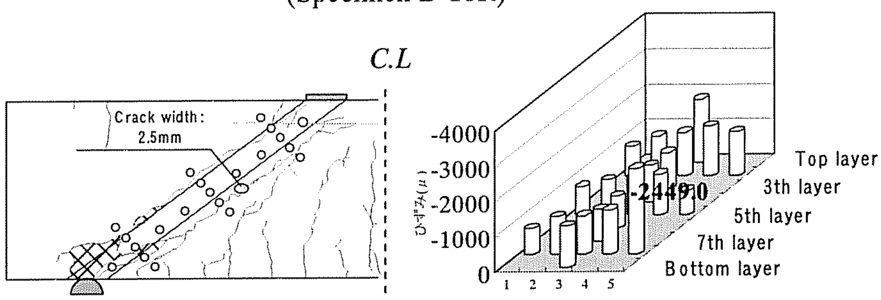


Fig.7 Type2 fracture and distribution of acryl bar strain
(Specimen B-10.3)

Whereas, in the case of specimens with a/d=1.5, the crack width widened after the stop of diagonal crack propagation and resulted in the yielding of dummy reinforcement. Up to immediately before fracture, no clear difference was seen in the propagation of cracks in any specimen of this group (a/d=1.5). However, as shown in Figs. 6 and 7, these specimens can be grouped into two types by the state of final fracture: a) a diagonal crack which propagated along the strut penetrated through the specimen beside the loading plate and resulted in fracture; b) another cracks different from the propagated diagonal crack appeared in the strut and resulted in fracture. The former is called Fracture Type 1 and the latter Fracture Type 2 for ease of identification. According to the experimental results, specimens of Fracture Type 1 are B-10.1, 10, 10R, 10.2, 10.3, 11, 12, and specimens of Fracture Type 2 are B-10.1.R, 10.2R, and 10.3R.

Figures 6 and 7 show a comparison of those two fracture types and the distribution of acryl bar strains. It is known from the figures that, when the maximum load was applied, the acryl bar strain propagated locally in Fracture Type 1 but it distributed on the entire range in Fracture Type 2. Figure 8 shows the comparison of shear strengths obtained by experiment and by calculation. For the calculation, the equation (1) proposed by the authors was used.[2)]

$$S = Cdc \cdot 0.82 pt^{1/3} \cdot (1/d)^{1/3} \cdot \sigma ck^{1/3} \cdot b \cdot d + \phi Ss$$

$$Cdc = \frac{10.3}{1+(a/d)_2} \qquad (1)$$

S: shear strength of member

Ss: effect of reinforcement calculated from the truss theory

ϕ: $-0.17 + 0.30\,(a/d) + 0.33/P_w$

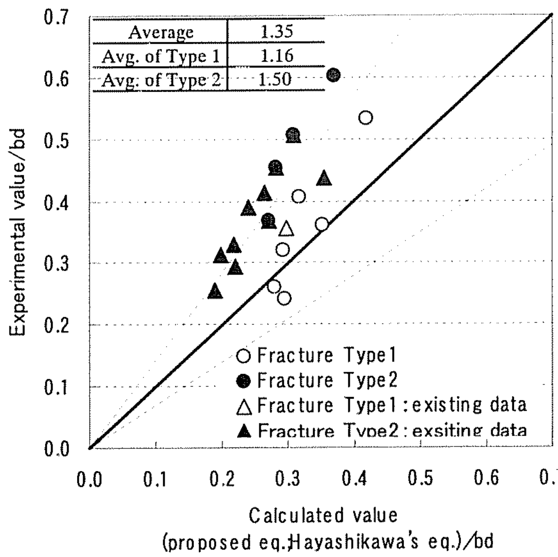
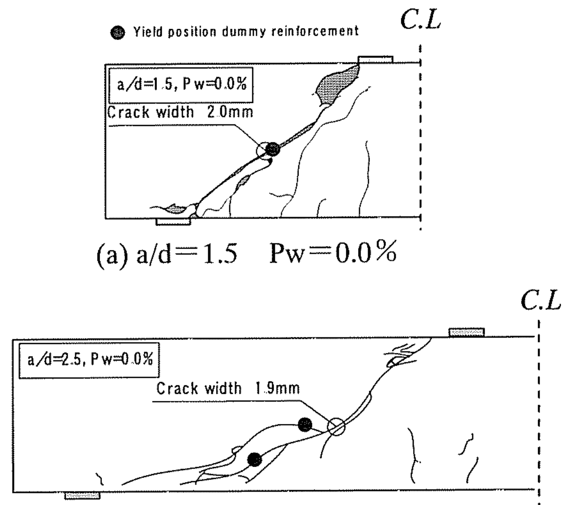


Fig.8 Comparison of experimental and calculated values



(a) a/d=1.5 Pw=0.0%

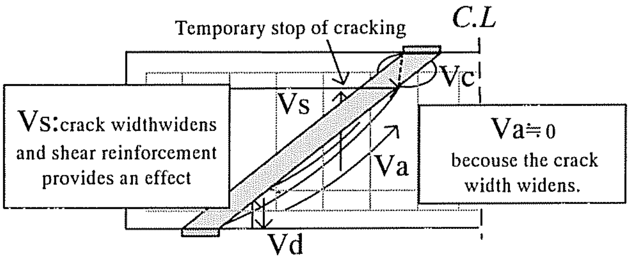
(b) a/d=2.5 Pw=0.0%

Fig.9 Comparison of fractures between shear span ratios of 1.5 and 2.5

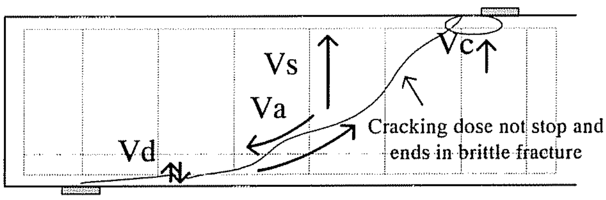
To increase the number of data, the results of nine specimens (a/d = 1.5, d = 400~1,400mm) which were tested at the Public Works Research Institute (PWRI) in 2002 were also included in the evaluation. They were represented as the existing data in Fig. 8. As seen from the figure, the shear strength of Fracture Type 2 in which load did not act locally but distributed uniformly was larger compared with the shear strength of Fracture Type 1. The ratio of experimental load to calculated load of specimens at the time of fracture is also shown in the figure. Although the average ratio of all the specimens was 1.35, the average ratio of Fracture Type 2 specimens was 1.50 exceeding that of Fracture Type 1 specimens which was 1.16. Concerning the reason for this, Type 1 fracture was caused when the concrete strength around the loading plate had a small defect or when the force acted locally because of unevenness of the loading plate. In that case, the strength becomes lower than that of Fracture Type 2, resulting in a smaller average value under maximum loading.

4.2 Evaluation of shear strength

It is considered that the strength of specimens with a/d≦1.0 can be evaluated using an ordinary strut model because the fracture of this type of specimens is an ordinary shear compressive fracture. But, a different evaluation method may be necessary for the specimens with a/d=1.5 because their fracture type appears different. Then, the fracture of specimens with a/d=1.5 was compared with specimens with a/d=2.5 which fractured by diagonal tensile fracture. The results of this comparison are shown in Fig. 9. The data of specimens with a/d=2.5 were taken from a separate test conducted at our university before.[3)] In the specimens with a/d=1.5, the dummy reinforcement yielded at the position to which a diagonal crack propagated, like the case of specimens with a/d=2.5, which is a similarity in fracture between the two types of specimens. The dissimilarity in fracture is seen in Fig. 10 which shows the state of fracture and the shear resistance model. In the case of specimens with a/d=1.5, the propagation of diagonal cracking stopped temporarily around the concrete in the compressive range, whereas specimens

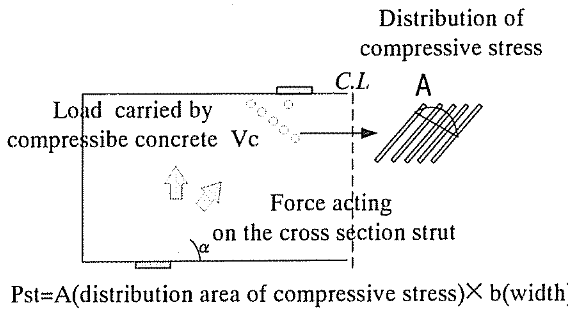


(a) a/d=1.5

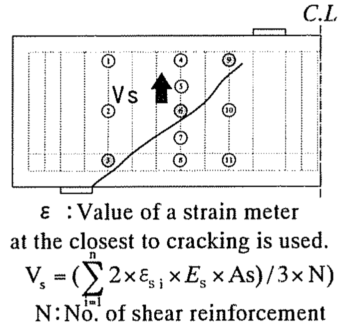


(b) a/d=2.5

Fig.10 Schematic of fracture and shear resistance model



(a) Load carried by Vc
(concrete in the compression range)



(b) Load carried by Vs(shear reinforcement)

Fig.11 schematic of calculation methods for Vc and Vs

with a/d=2.5 fractured brittlely by diagonal tension without such a stop of crack propagation. The temporal stop of crack propagation in the specimens with a/d=1.5 was caused by the tied arch formed, as seen in Fig. 10.

Assuming that specimens with a/d=1.5 fractured as shown in the figure, their fracturing process was investigated. As shown in Fig. 10 (a), interlocking of aggregates (Va) was considered providing virtually no resistance to fracture because the crack width enlarges in any specimen at the time of fracture. The contribution of the dowel action (Vd) to shear strength was not taken into account because past investigation results show that it carries as little as about 10% of the total shear strength. The calculation method of the shear strength carried by concrete in the compressive range (Vc) and the shear strength carried by shear reinforcement (Vs) is shown in Fig. 11. The width of the strut and the number of shear reinforcement were determined based on the past investigations.[4), 5)] 0.95Pmax which is close to the fracture load was adopted for the current investigation.

The shear strengths carried by the concrete and shear reinforcement that are derived by the above calculation and the load applied were compared in Fig. 12. Past investigation data [3)] were also included in this comparison. From this figure, it is known that the strength of the specimens without shear reinforcement is balanced with the load applied because the concrete in the compression range carries the load. The strength of the specimens with shear reinforcement is balanced with the load applied because the shear reinforcement carries the load.

Figure 13 compares the crack width of specimens with a/d=0.5 which fractured by shear compression and the crack width of specimens with a/d=1.5. In the case of specimens with

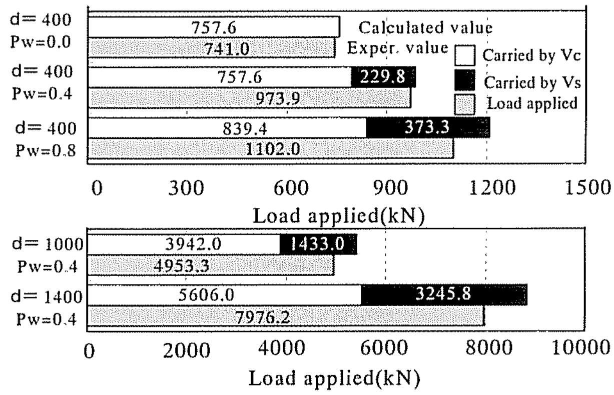


Fig.12 Shear strength carried by calculation and the load applied

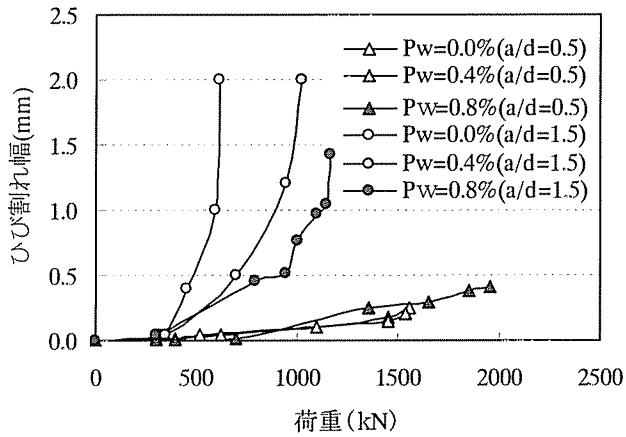


Fig.13 comparison of control of crack width by reinforcement

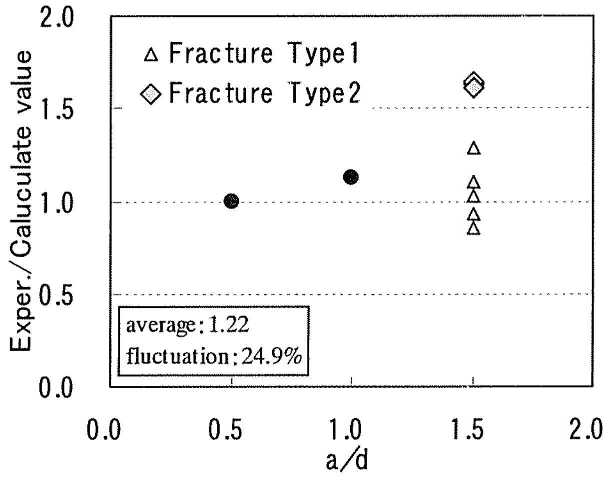


Fig.14 Adaptability of the proposed equation

a/d=0.5, no control effect on the crack width is seen. But, in the specimens with a/d=1.5, the control effect on the crack width is seen and it can be said that reinforcement provides such an effect.

4.3 Applicability of the proposed equation

Figure 14 shows the applicability of the proposed equation to the experimental results. From the figure, the average value is 1.22 and the fluctuation factor is 0.24. In the case of specimens with a/d=1.5, the fluctuation is large as seen in the figure. However, as mentioned earlier, there are two fracture types for the specimens of a/d=1.5. As to the specimens of Fracture Type 2, the shear strength derived by experiment is 1.5 times larger than that obtained by calculation using the proposed Equation. But, for the specimens of Fracture Type 1, both the experimental and calculated shear strengths are almost similar. Therefore, it can be said that the proposed equation can estimate the lower values adequately.

5. CONCLUSIONS

(1) It was found that specimens with a/d≦1.0 fractured by shear compression, but specimens with a/d=1.5 fractured after the diagonal crack propagated.
(2) There are two fracture types for the specimens with a/d=1.5. The shear strength is larger in Fracture Type 2 than in Fracture Type 1.
(3) In the case of specimens with a/d=1.5, the crack width is controlled by the tensile force. Therefore, the shear reinforcement can provide shear resistance in combination with the concrete in the compressive range.
(4) Concerning the fracture of specimens with a/d=1.5 whose shear strength varies largely, the proposed equation can estimate its lower values with relatively good accuracy.

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