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Reinforced Concrete Beams with High Tension Shear Reinforcement

Poutres en béton armé renforcées par des étriers à très haute résistance

Schubwiderstand von Stahlbetonbalken mit hochfestem Bewehrungsstahl

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SUMMARY
Reinforced concrete structures have frequently suffered heavy damage by shear failure in reinforced concrete members during strong earthquakes. This paper describes the experimental results concerning the effectiveness of the high tension shear reinforcement on the shear failure, and the analytical results concerning the shear transfer carried by the shear resistant elements across the critical inclined crack near the ultimate shear strength in beams.

RESUME
Des poutres en béton armé ont souvent souffert de grands dommages d'effort tranchant pendant les séismes. Cette contribution décrit les résultats expérimentaux concernant l'utilité d'étriers à très haute résistance et les résultats analytiques concernant le comportement de ces étriers avant la ruine.

ZUSAMMENFASSUNG
Bei starken Erdbeben wird bei Stahlbetonbauteilen oft Schubversagen beobachtet. Im Beitrag werden die experimentellen Ergebnisse über die Wirksamkeit hochfesten Bewehrungsstahls auf den Schubwiderstand vorgestellt und analytische Ergebnisse über die Schubkraftübertragung der Bewehrung im kritischen Riss präsentiert.

1. INTRODUCTION

Recent research works regarding the effectiveness of shear reinforcement have been primarily devoted to the members with the ordinary shear reinforcement whose yield stress was about 340 MPa. Although several investigations have included the members with the high tension shear reinforcement, the factors affecting the ultimate shear strength of members with the high tension shear reinforcement have not been systematically studied. Then, the experimental study was carried out in order to seize the real phenomenon concerning the effectiveness of the high tension shear reinforcement in beams. The analytical study was carried out in order to examine the mechanism of shear transfer carried by the shear resistant elements across the inclined crack near the ultimate shear strength. The analytical method was the FEM linear analysis using the models with some inclined cracks as many as the experimental results.

2. EXPERIMENRAL STUDY

2.1 Outline of the experimental study

Nine specimens designed to investigate the ultimate shear strength were tested as shown in Table 1. The primary factors were the shear span ratio a/D, the yield stress of the shear reinforcement ${}_w\sigma_y$ (MPa), and the shear reinforcement ratio p_w (%) as shown in Table 1. All specimens had the same cross section (b x D = 18cm x 40cm) as shown in Fig.1. The compressive strength ${}_c\sigma_B$ were 27.6 MPa in case of a/D =1.0, and the 31.8 MPa in case of a/D =1.5 , and the yield stress of or 0.2% proof stress of the shear reinforcement ${}_w\sigma_y$ were the range from 250 to 1370 MPa as shown in Table 1. The high tension shear reinforcement was the heat treated steel called ULUBON. Loading was carried out in an anti-symmetrical method as shown in Fig.2. The shear force P (N) was measured by the load cells between the oil jacks and the stubs of specimen, and the relative deformation δ(mm) was measured by the electric gages as shown in Fig.2.

No.	${}_c\sigma_B$	a/D	p_w	${}_w\sigma_y$	${}_s\tau_c$	${}_s\tau_u$	mode
1	27.6	1.0	0.0		1.10	1.87	S
2	27.6	1.0	0.34	345	1.82	4.87	S
3	27.6	1.0	0.34	1361	1.46	6.47	S
4	31.8	1.5	0.0		1.29	2.01	S
5	31.8	1.5	0.28	250	0.93	3.53	S
6	31.8	1.5	0.28	674	1.10	5.13	S
7	31.8	1.5	0.28	1322	0.96	6.04	S
8	31.8	1.5	0.56	250	1.27	4.58	S
9	31.8	1.5	0.56	1370	1.65	6.92	F

${}_c\sigma_B$: Compressive strength of concrete (MPa)
a/D: Shear span ratio
p_w :Amount of shear reinforcement (%)
${}_w\sigma_y$: Yield stress of shear reinforcement (MPa)
${}_s\tau_c$: = Q_c/bj (MPa) Q_c: First inclined crack
${}_s\tau_u$: = Q_u/bj (MPa) Q_u: Ultimate shear strength
S : Shear failure mode
F : Flexural failure mode

Table 1 Specimens and Experimental Value

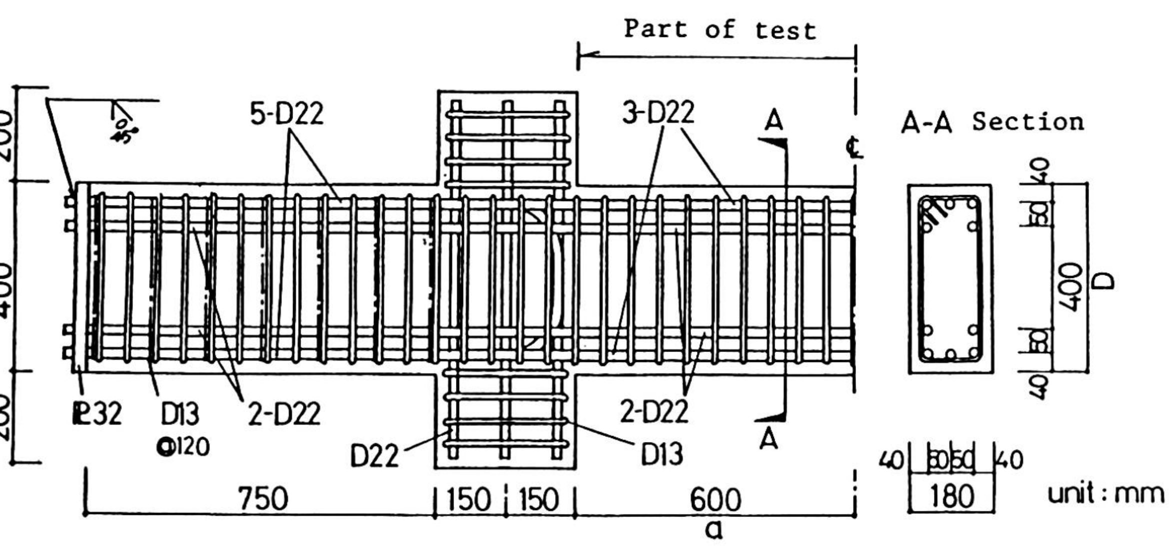

Fig.1 Specimen (a/D = 1.5)

2.2 Experimental results and discussion

2.2.1 Failure mode

The failure mode of specimens expect the No.9 was the shear failure type as shown in photo.1, and the failure mode of No.9 was the flexural failure type after the flexural tensile yielding of longitudinal reinforcement.

2.2.2 Effect of $_w\sigma_y$

Fig.3, 4 and 5 were the p(Mpa) - δ(mm) curves in case of a/D = 1.5 under the same value of p_w(= 0.28%) which the yield stress of shear reinforcement $_w\sigma_y$ in Fig.3, 4 and 5 was 354, 674 and 1323 Mpa.
The effectiveness of $_w\sigma_y$ on the shear strength and deformation capacity could be remarkably observed from those figures, so that it was found that the seismic ability of RC members colud be improved by using the high tension shear reinforcement instead of the ordinary strength.

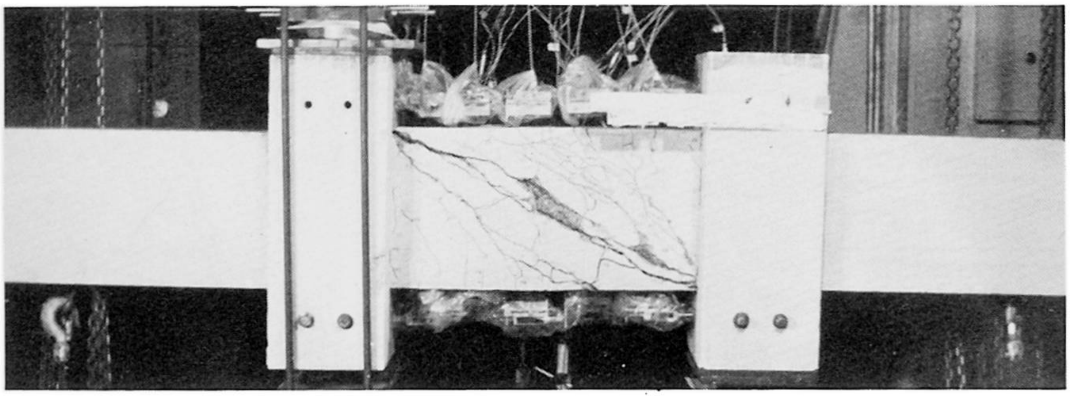

Photo.1 Behaviour of cracks after the shear failure (a/D=1.0)

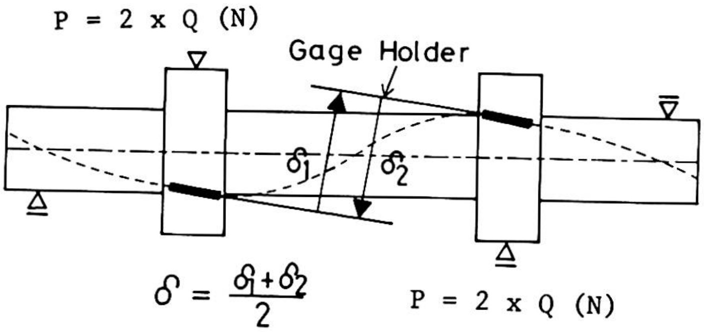

Fig.2 Loading and measuring method

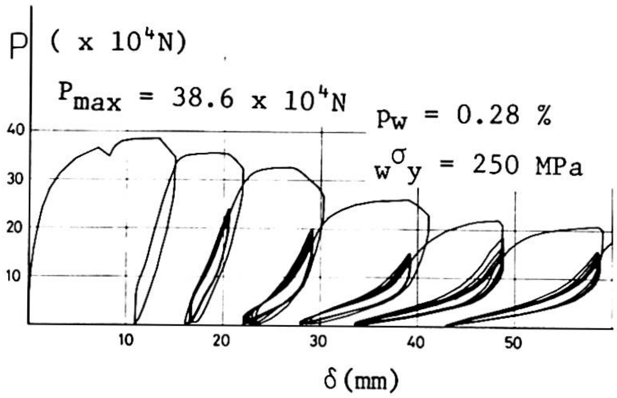

Fig.3 P - δcurve (No.5)

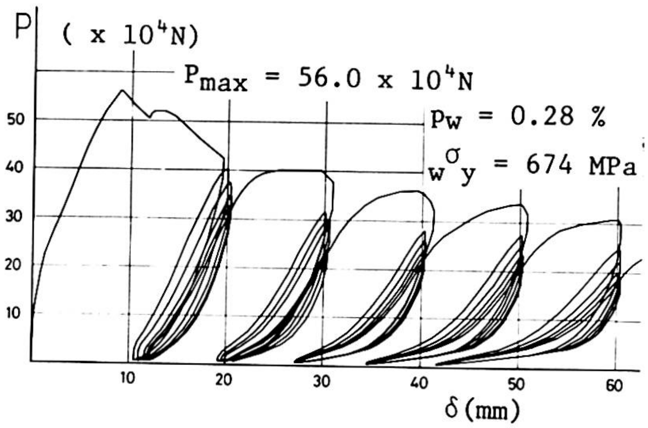

Fig.4 P - δ curve (No.6)

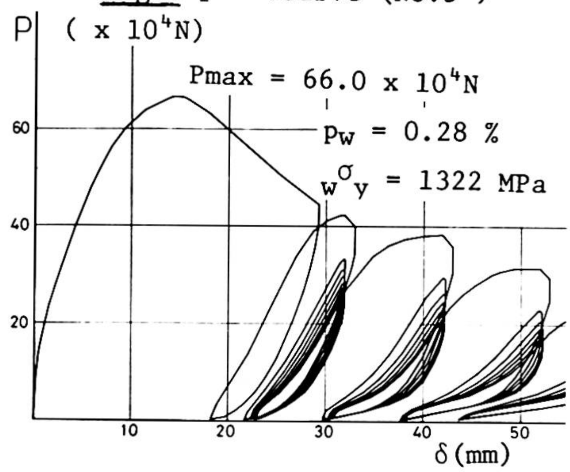

Fig.5 Q - δ curve (No.7)

2.2.3 Consideration for the effect of ${}_{w}\sigma_{y}$

Fig.6 and 7 show the P(Mpa) - δ(mm) curves under the same value of p_w(= 0.56%). Fig.6 was with ${}_{w}\sigma_{y}$ =250 Mpa, and the Fig.7 was with ${}_{w}\sigma_{y}$ =1323 Mpa. As shown in Fig.6 and 7, the effectiveness of high tension could be remarkably observed more than ordinary strength too.

Fig.8 and 9 show the relation between the shear force and the strain of shear reinforcement measured by the wire strain gages in above specimens. Those figures indicated the essential cause for the large effectiveness of the high tension shear reinforcement on P(Mpa) - δ(mm) curves. After all, the strain of shear reinforcement increased remarkably after the first inclined crack in both specimens. But as soon as the ordinary shear reinforcement had reached near the yield strain (ε_y = 1214 μ), the specimens with ordinary strength failured. On the other hand, the high tension shear reinforcement not reached the yield strain (ε_y = 6424 μ) yet, so that the specimen with the high tension could keep the more shear strength than the specimen with ordinary strength.

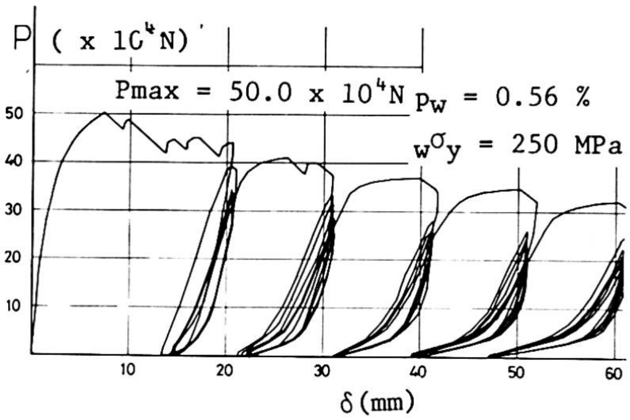

Fig.6 P - δ curve (No.8)

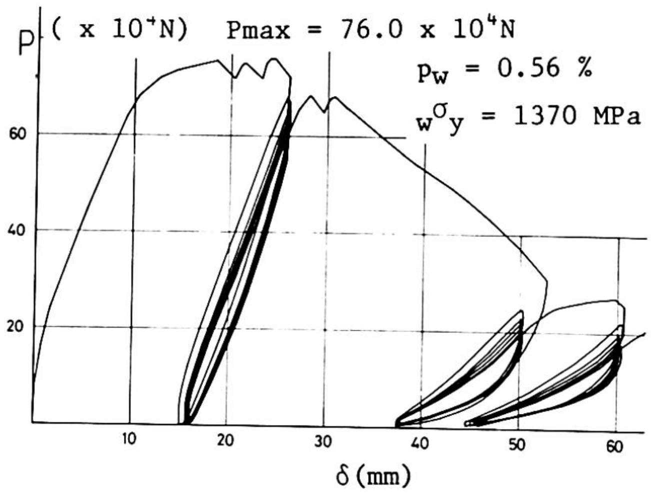

Fig.7 P - δ curve (No.9)

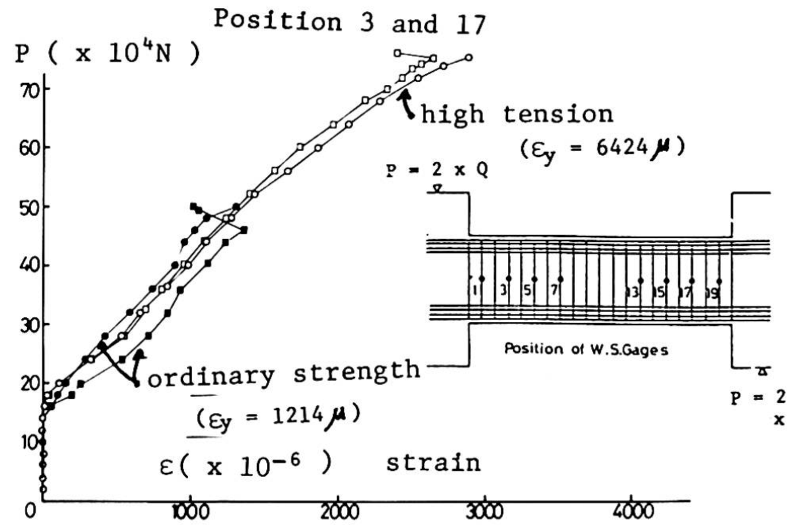

Fig.8 Relation between p and strain (3-17)

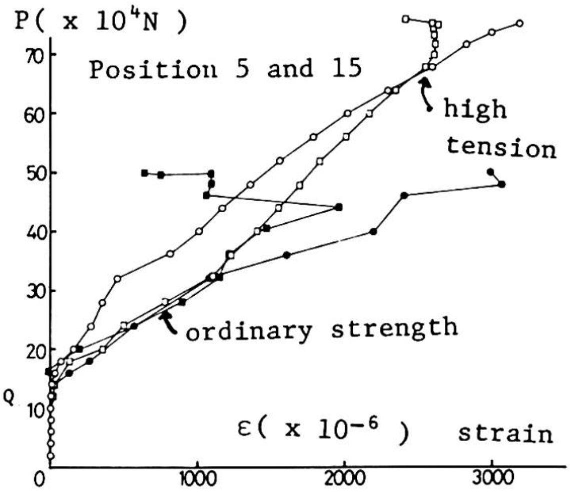

Fig.9 Relation between P and strain (5-

3. ANALYTICAL STUDY

3.1 Outline

The purpose in this analytical study is to investigate the shear transfer carried by the shear resistant elements across the critical inclined crack near ultimate shear strength. At first in this study, the analytical model having some inclined cracks as many as the experimental results on the shear failure was produced, and the reasonable propriety of the model was inspected. And then the shear transfer carried by the shear resistant elements across the inclined crack was examined by the results of the parameter analysis used this model subjected to the unit shear force Q_{unit}(= 98. x10^2 N = 1.0 tonf)

3.2 Analytical model

Fig.10 (a/D= 1.0) and 11 (a/D= 1.5) show the analytical models. FEM models was produced by refering to the shear behavior on the status that some inclined cracks occurred as shown in Photo.1. Fig.12 shows the relation between the shear force $_sQ_u$ and each shear transfer Q_w, Q_c, Q_d carried by the shear resistant elements across the inclined crack. The parameters in this model in case of a/D= 1.5 were the amount of the shear reinforcement ratio p_w(%), the yield stress of reinforcement $_w\sigma_y$ (Mpa) and the amount of the longitudinal reinforcement p_t, p_c(%). Elements properties (young's modulus E_c and E_s, poisson's ratio and bond links $_{x,y}K_b$) in this FEM model were used as shown in Table 2.

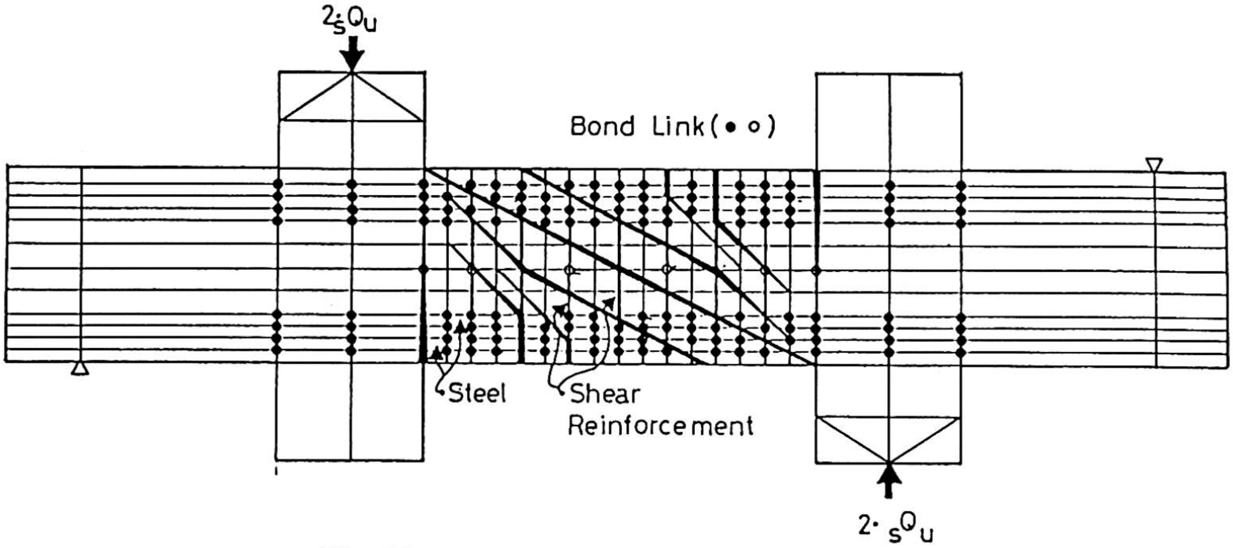

Fig.10 Analytical model (a/D = 1.0)

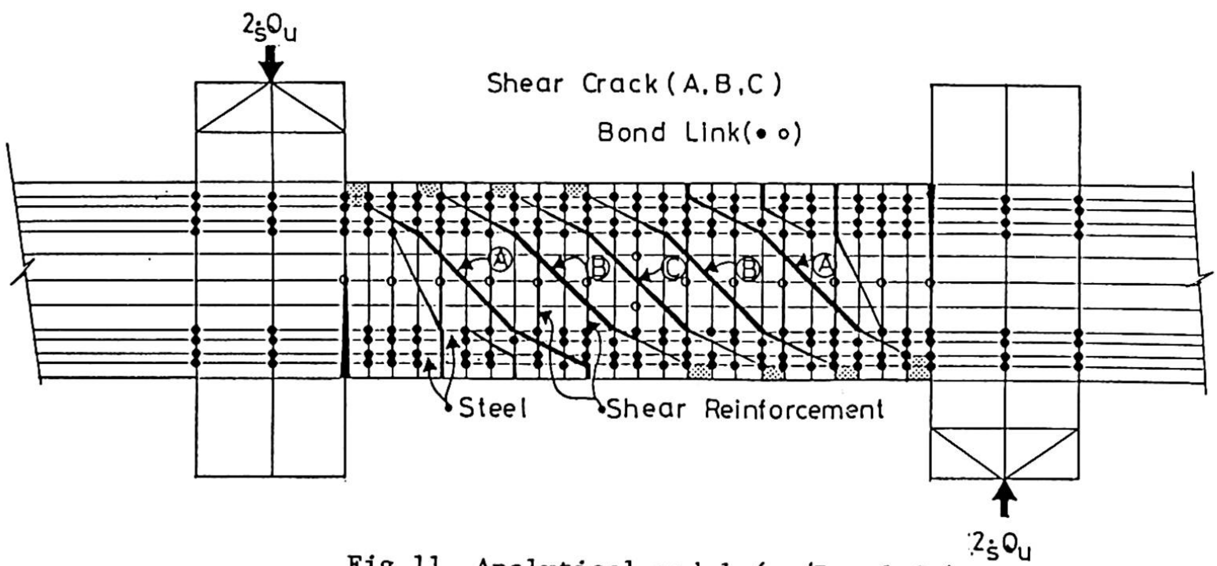

Fig.11 Analytical model (a/D = 1.5)

3.3 Discussion of analytical results

3.3.1 Analytical method

The comparison between the analytical and experimental results at the ultimate shear strength ${}_sQ_u$(=37.24 x 10^4N =38.0 tonf) were shown in following Fig.13. Fig.13 showed the strain distribution of shear reinforcement. It could be comfirmed that those analytical result nearly coincided with the experimental results in above figures, so that the analytical method was one of the effective methods in order to investigate the ultimate shear behavior in RC beams.

	Concrete element	Steel element
Young's modulus	2.0 x 10^4 MPa	2.0 x 10^5 MPa
Poisson's ratio	0.167	2.333
Bond link	${}_xK_B = {}_yK_B$ = 2.0 tonf/cm^3	

Table 2 Elements Properties

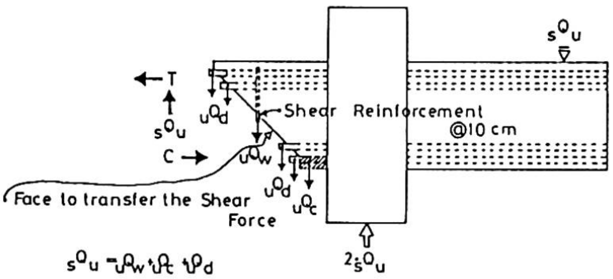

Fig.12 Equilibrium equation of shear force at inclined crack

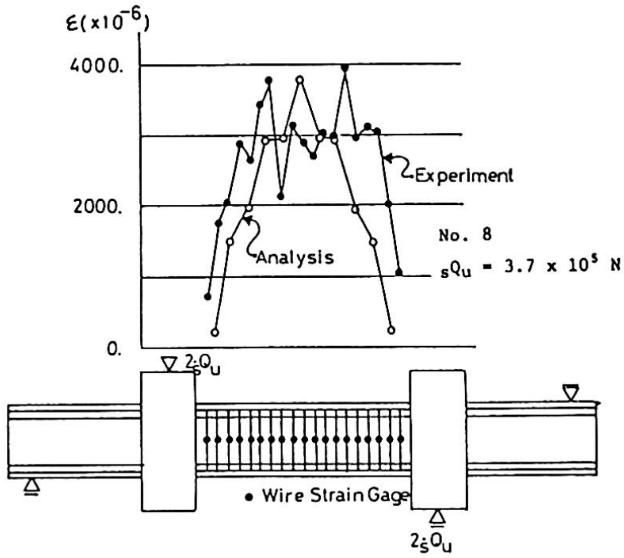

Fig.13 Strain distribution of shear reinforcemen

3.3.2 Effect of a/D

Fig.14 and 15 showed the distribution of compressive principal stress under the unit shear force Q_{unit}(= 98 x 10^2N = 1.0 tonf). Fig.14 was in case of a/D=1.0 and Fig.15 was in case of a/D=1.5. It was found that the compressive principal stress in a/D= 1.0 followed along the diagonal shear crack, on the other hand, that in a/D=1.5 distributed amoung the whole of specimen as shown in Fig.14 and 15.

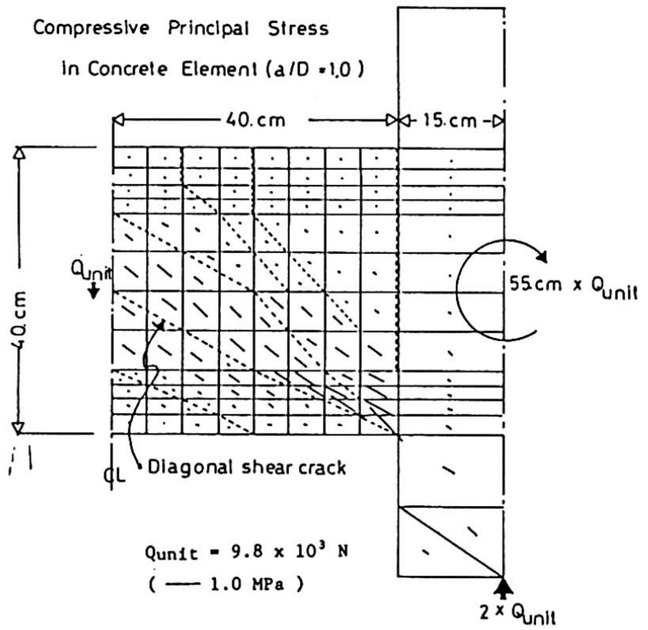

Fig.14 Compressive principal stress (a/D=1.0)

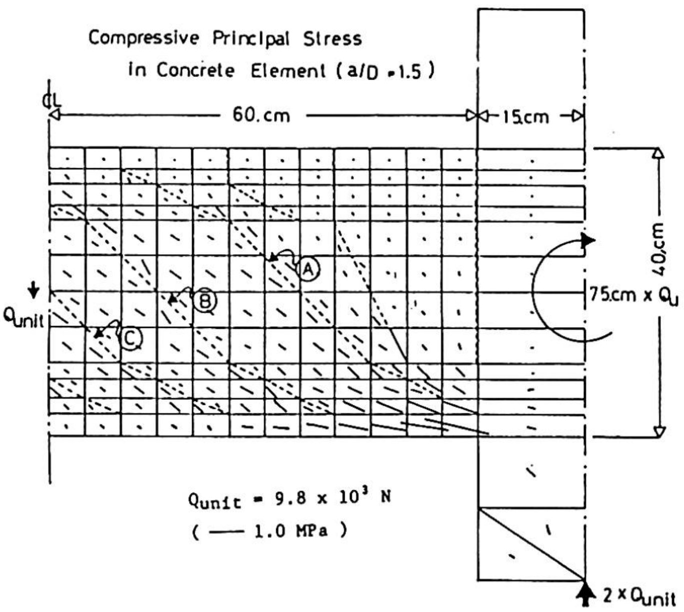

Fig.15 Compressive principal stress (a/D=1.5)

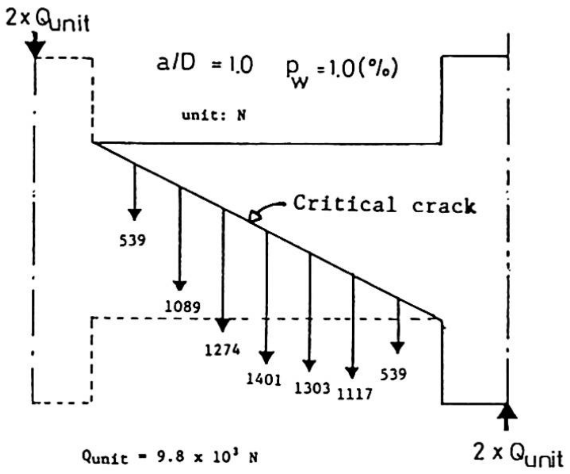

Fig 16 Shear stress of shear reinforcement (a/D = 1.0)

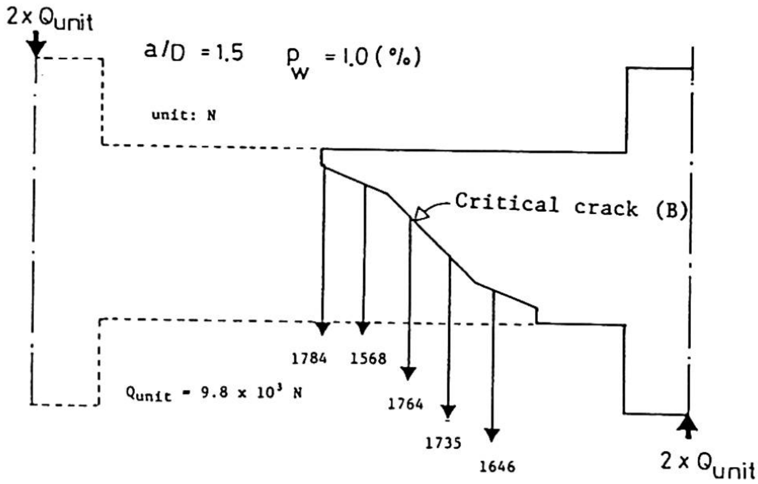

Fig.17 Shear stress of shear reinforcement (a/D=1.5)

3.3.3 Relation between p_w and $_wQunit$

Fig.18 shows the relation between p_w(%) and $_wQunit$. Here, $_wQunit$ is amount of the shear transfer carried by the shear reinforcement across the critical inclined crack. It was observed that the $_wQunit$ increased in propotion to p_w and the rate of increase on $_wQunit$ over about p_w = 1.0% came down as shown in Fig.18.

3.3.4 Relation between p_t, p_c and $_c\bar{\sigma}unit$

Fig.19 shows the relation between p_t, p_c(%) and $_c\bar{\sigma}unit$. Here, p_t,p_c(%) is the amount of longitudinal reinforcement and $_c\bar{\sigma}_{unit}$ is the average value of compressive stress appeared to the concrete element in compressive zone at the end of specimen as shown in Fig.19. It was clearly recognized that the shear behavior of concrete elements in compression zone was influenced by amount of the longitudinal reinforcement as shown in Fig.19.

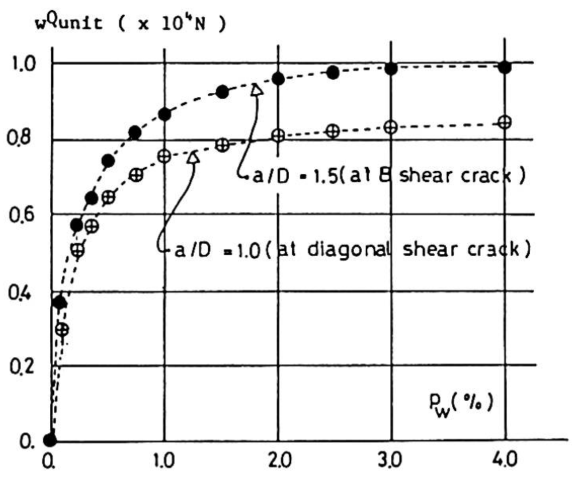

Fig.18 Relation between $_wQunit$ and p_w

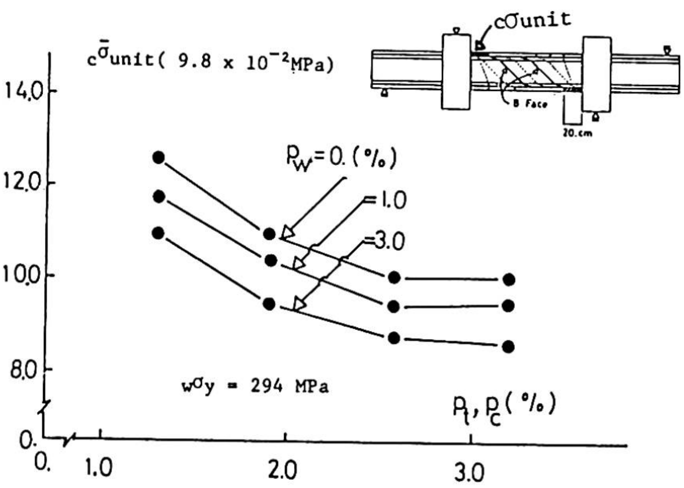

Fig.19 Relation between $_c\bar{\sigma}unit$ and p_t, p_c

3.3.5 Relation between p_t, p_c and $_dQ_{unit}$

Fig.20 shows the relation between p_t, p_c(%) and $_dQ_{unit}$. Here, $_dQ_{unit}$ was the dowel shear carried by the longitudinal reinforcement across the critical inclined crack. It was observed that $_dQ_{unit}$ increased proportionally to p_t, p_c(%) and such tendency was indicated more remarkably in case of little p_w than in case of much p_w.

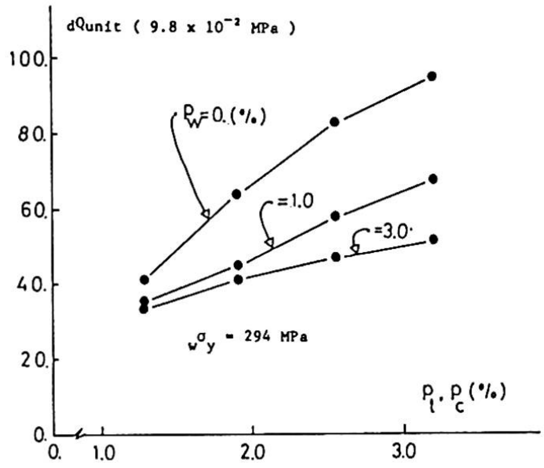

Fig.20 Relation between $_dQ_{unit}$ and p_t, p_c

4. CONCLUSIONS

Based on the experiment and analysis reported herein, the following conclusions can be drawn.

1) Effect of yield stress ($_w\sigma_y$)

It was found that the effect of $_w\sigma_y$ on the ultimate shear strength was remarkable in this experimental study, and the specimens with high tension shear reinforcement could possess more the ultimate shear strength than that with ordinary shear reinforcement for the same value of p_w(%).

2) Analytical model

It could be comfirmed that the FEM linear analysis using the analtyical model with some inclined cracks as many as experimental results was one of the effective method in order to investigate the shear transfer carried by the shear resistant elements across the critical inclined crack near the ultimate shear strength in reinforced concrete beams.

3) Shear transfer

The analytical results using the analytical model subjected to the unit shear force provided the information about the mechanism of the shear transfer carried by the shear resistant elements across the critical inclined crack.

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