EXPERIMENTAL AND ANALYTICAL STUDY ON REINFORCING METHOD OF REINFORCED CONCRETE BEAMS WITH WEB OPENING

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SUMMARY

This paper presents the effectiveness of reinforcing method by the newly developed ring metals for circular web opening of reinforced concrete beams. The experiments to investigate the ultimate shear strength and deformability of beams with web opening reinforced by the ring metals were carried out, and further, in order to confirm the test results, two-dimensional analyses were carried out elastically and elasto-plastically by finite element method.

As the results, the experimental formula of ultimate shear strength of reinforced concrete beams with circular web opening reinforced by ring metals and stirrups was obtained.

INTRODUCTION

The beams with web opening are often designed, because of the piping for air-conditioning, water supply, electric power supply and so on. And the web opening is set everywhere of beams. Therefore, the shear strength of beam is reduced due to the web opening. In Japan, the ultimate shear strength of beams with web opening was experimentally investigated by many researcheres (Ref. 1,2,3 and 4) and it has been usually estimated by Eq.(1) (Ref. 1). That of beams without web opening has been calculated by Eq.(2) (Ref. 1).

Recently, that of beams with web opening has been computed by Eq.(3) which was obtained from modifing Eq.(1) and Eq.(2) (Ref. 5 and 6).

$$Q_u = \tau_u \cdot b \cdot j = \{0.143F_c(1-1.61H/D)+0.22\sqrt{p_s \cdot {}_s\sigma_y/F_c}\}b \cdot j \quad (1)$$

$$Q_u = \tau_u \cdot b \cdot j = \{0.12k_u \cdot k_p(180+F_c)/(M/Q \cdot d+0.12)+0.27\sqrt{p_w \cdot {}_s\sigma_y}\}b \cdot j \quad (2)$$

$$Q_{hu} = \tau_u \cdot b \cdot j = \{0.12k_u \cdot k_p(180+F_c)(1-1.61H/D)/(M/Q \cdot d+0.12)+0.27\sqrt{p_s \cdot {}_s\sigma_y}\}b \cdot j \quad (3)$$

k_u : coefficient due to the size of cross section (where $d \geq 40$cm, $k_u=0.72$)
F_c : compressive concrete strength (kg/cm^2)
Q : maximum shear force (kg)
M : maximum bending moment (kg·cm)
${}_s\sigma_y$: yield stress of reinforcement (kg/cm^2)
p_s : $=a_s(\sin\theta+\cos\theta)/b \cdot C$ $\quad p_w$: $=a_s/b \cdot x$
k_p : $=0.82 \cdot p_t^{0.23}$ $\quad p_t$: $=a_t/b \cdot d$ $\quad j$: $=7/8d$

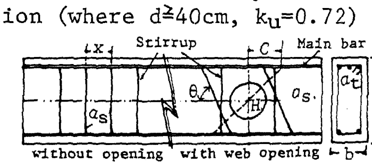

Fig.1 Notations

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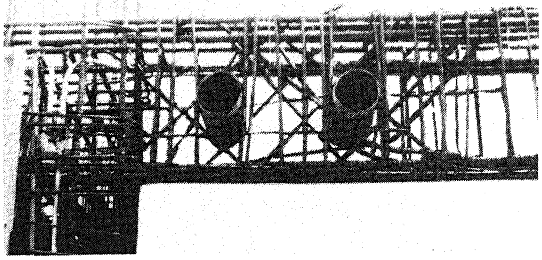


Photo 1 Conventional reinforcing method

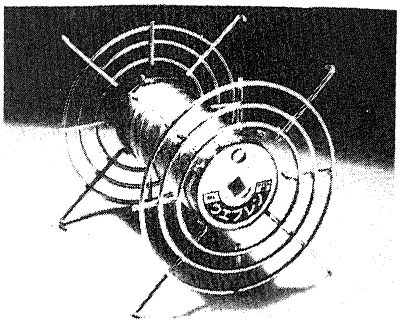


Photo 2 Newly developed ring metals

In ordinary case, the web opening was conventionally reinforced using the diagonal bars and stirrups as shown in Photo 1. This procedure is, however, complicated and difficult for construction works in site, and spends a lot of time. The mistakes often occur because of complicated arrangements of bars. Then authors tried to propose an alternative method whose procedure is easy. The ring metals as shown in Photo 2 was newly developed. In order to establish the reasonable design method of beam with web opening reinforced by ring metals , the effectiveness of reinforcing method by ring metals was investigated by experiments and analytical studies. The construction work was remarkably simplified by using the ring metals together with the steel tube which mechanically expanded and fitted on the inside of formwork. This procedure is easy to use. Term of work could be shortened and labor cost could be saved. Furthermore, it is easy to check the work results by visual inspection. The ring metals have been producted since 1980. The reinforcing method proposed in this paper has been used very often in the practical construction works as shown in Photo 3.

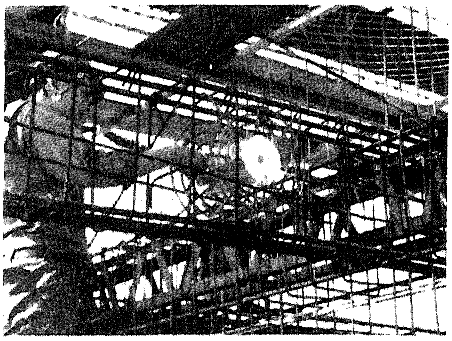


Photo 3 Practical construction work

EXPERIMENTS TO INVESTIGATE THE ULTIMATE SHEAR STRENGTH

Test Procedure

The list of specimens is shown in Table 1. The details of specimens are shown in Fig.2,3 and 4. Mechanical properties of reinforcing bars are shown in Table 2. Types of ring metals are shown in Fig.5. Specimens consist of three series. Series 1 was tested to study the effectiveness of reinforcing method of beams with web opening by ring metals, and compared with the beams without opening and with conventionally reinforced beams. Series 2 and 3 were tested to study the effect of the amount of ring metals and stirrups on the ultinate shear strength. In Series 3, the beams with large depth and with large web opening were tested. The loading and measuring arrangements are illustrated in Fig.6. The relative deflection was measured by dial gages attached on the holders which was fixed on the stubs. The alternatively repeated load was applied by a rule of incremental deformation amplitude with each one cycle at the rotation angle of member R=1/1000, 1/400, 1/200 and 1/100.

Table 1 List of specimens

Series	No. of Specimen	Reinforcement Ring metal	Reinforcement Stirrup	Web opening Diameter(mm) (H/D)	a/d	Reinforcement ratio(%) P_t	P_s (P_w) Stirrup	P_s Ring	Concrete strength Fc(kg/cm2)
1	1-No.1	without opening							306
	1-No.2	2-Ring(b')	2-D10	150 (1/3)	2.0	1.69	(0.48)		
	1-No.3	2-Ring(b')	2-D10	150 (1/3)*1	2.0	1.69	0.27	1.01	
	1-No.4	(2-D13)*2	2-D10	150 (1/3)	2.0	1.69	0.27	1.16	
2	2-No.1	without opening			1.5	1.69	(0.48)		299
	2-No.2	none	2-D10	150 (1/3)	1.5	1.69	0.54	—	
	2-No.3	1-Ring(b)	2-D10	150 (1/3)	1.5	1.69	0.54	0.51	
	2-No.4	2-Ring(b)	2-D10	150 (1/3)	1.5	1.69	0.54	1.02	
	2-No.5	2-Ring(b)	4-D10	150 (1/3)	1.5	1.69	1.08	1.02	
	2-No.6	3-Ring(b)	2-D10	150 (1/3)	1.5	1.69	0.54	1.53	
	2-No.7	2-Ring(a)	2-D10	100 (2/9)	1.5	1.69	0.54	0.68	
3	3-No.1	without opening			1.5	1.93	(0.42)		262
	3-No.2	none	4-D13	300 (1/3)	1.5	1.93	0.64	—	
	3-No.3	2-Ring(c)	4-D13	300 (1/3)	1.5	1.93	0.64	1.17	
	3-No.4	3-Ring(c)	4-D13	300 (1/3)	1.5	1.93	0.64	1.76	
	3-No.5	2-Ring(b)	4-D13	150 (1/6)	1.5	1.93	0.64	0.38	

*1 : The web opening (s) locates 225mm far from the end of beam, and in the other specimens, it locates at the center of beam span.
*2 : ( ) indicates the amount of diagonal bars.

Table 2 Mechanical properties of reinforcing bars

Reinforcing bars	Main bar D 25		Stirrups D 10	Stirrups D 13	Ring metals (a) *1	(b) *1	(b') *1	(c) *1
$_s\sigma_y$(ton/cm2)	4.47	4.06	4.17	3.56	4.24 *2	4.24 *2	3.41	3.50 *2
Series	1 and 2	3	1 and 2	3	2	2 and 3	1	3

*1 : Types of ring metals (cf. Fig.5) *2 : 0.2% proof stress

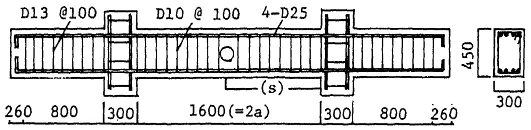


Fig.2 Details of specimen (Series 1)

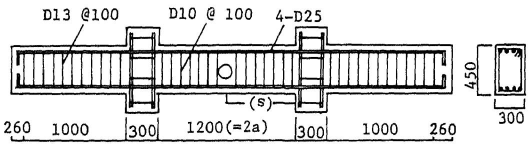


Fig.3 Details of specimen (Series 2)

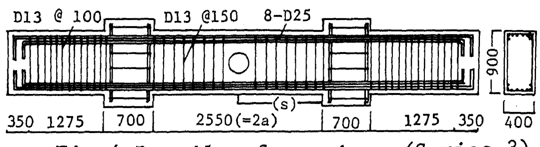


Fig.4 Details of specimen (Series 3)

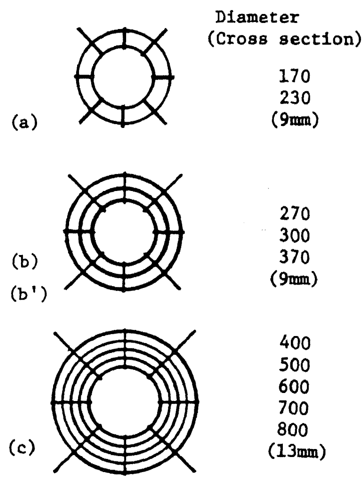


Fig.5 Types of ring metals

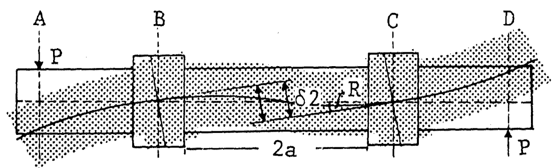


Fig.6 Loading and measuring arrangements

A and D : Loading points
B and C : Supporting points
$\delta = (\delta 1+\delta 2)/2$
$R = \delta/2a$: Rotation angle of member

Test Results

The test results are summarized in Table 3. Left side suffix C or T means the calculated values or test results, respectively. The ultimate shear force($_TQ_{max}$) was exceeded the shear force at yielding of member($_CQ_y$) in case of only two specimens(3-No.3 and 3-No.4), but the ultimate failure mode of them was also shear failure around the web opening.

Table 3 Test results and calculated results

Series	No. of Specimen	Shear force (ton) Diagonal crack $_TQ_{sc}$	$_CQ_{sc}$ *1	Yielding $_CQ_y$ *2	Maximum $_CQ_{mu}$ *3	Ultimate $_TQ_{max}$	$_CQ_{hu}$*4	Ratio $_TQ_{max}/_CQ_{hu}$
1	1-No.1	12.5	19.0	36.1	41.7	32.0	31.9	1.03
	1-No.2	11.7				30.3	28.1	1.08
	1-No.3	11.7				32.9	28.1	1.27
	1-No.4	11.7				36.0	29.6	1.21
2	2-No.1	15.5	18.9	52.8	55.6	40.8	36.8	1.17
	2-No.2	17.4				21.7	20.6	1.05
	2-No.3	19.5				29.9	27.5	1.09
	2-No.4	15.2				33.8	32.3	1.05
	2-No.5	15.2				36.2	34.2	1.06
	2-No.6	17.4				40.7	36.1	1.13
	2-No.7	17.4				34.7	32.7	1.06
3	3-No.1	40.0	44.6	99.8	104.2	98.0	92.4	1.06
	3-No.2	23.0	43.0			61.4	52.6	1.17
	3-No.3	39.0	43.2			104.7	87.7	1.19
	3-No.4	39.0	42.9			105.5	98.5	1.07
	3-No.5	40.0	42.8			93.0	82.7	1.12

*1 : $_CQ_{sc}= \{0.085k_c(500+F_c)/(M/Q\cdot d+0.17\}b\cdot j$ (4)
k_c : coefficient due to the size of cross section,(where d≧ 40cm, k_c=0.72)
*2 and *3 : by Umemura's e-function method
*4 : by Eq.(3) and Eq.(5), {where without opening, by Eq.(2)}

Envelopes of load-deflection relations are shown in Fig.7,8 and 9. A typical example of load-deflection relation is shown in Fig.10. The ultimate shear force in experiments($_TQ_{max}$) was enough exceeded the shear force by Eq.(3)($_CQ_{hu}$) in all specimens. Load-deflection relations were almost same in all specimens up to R=1/400, regardless of beams with web opening or without opening, except for the beams with web opening reinforced only by stirrups. The beams enough reinforced by ring metals showed almost same load-deflection relations as the beams without opening up to the final deflection. Beams with web opening reinforced by the new proposed method had almost same ultimate shear strength as the beam with web opening reinforced by conventional method and as the beam without opening shown in Fig.7. The ultimate shear strength of beams with web opening was gradually getting close to that of beams without opening according to the increase of shear reinforcement, when the ring metals and stirrups were effectively combined.

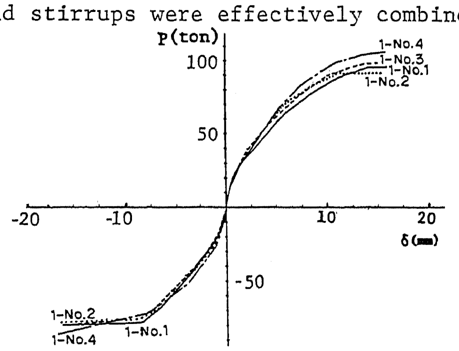


Fig.7 Envelopes of Series 1

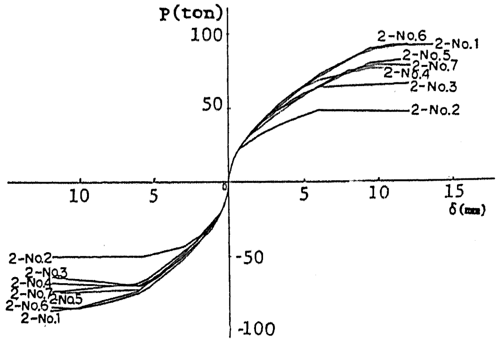


Fig.8 Envelopes of Series 2

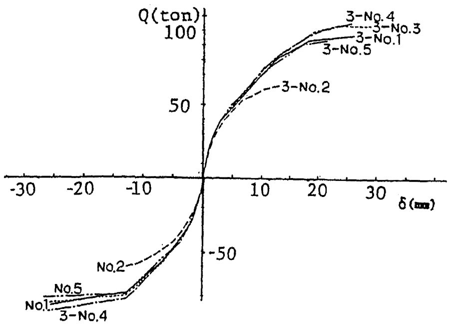


Fig.9 Envelopes of Series 3

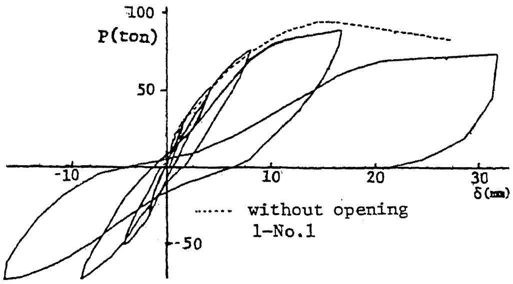


Fig.10 An example of load-deflection relation of specimen(1-No.2)

Analytical Study

The first crack occured around web opening was crack-1 as shown in Fig.11 -a. That inclined 45 degrees to the longitudinal direction. Crack-1 of beams reinforced only by stirrups rapidly developed to the top and bottom of beam. That of beams reinforced by ring metals and stirrups, however, less developed, and after crack-1, crack-2,3 and 4 were occured through not simultaneously. The failure in beams reinforced only by stirrups was caused by crack-1. On the other hand, that in beams reinforced by ring metals and stirrups was caused by crack-2 whose one end reached the crossing point B between crack-1 and main bar. And furthermore, the tensile stress was always caused all over the ring bars to the alternatively repeated load. In order to study that phenomena, two-dimensional analyses were carried out by finite element method introducing crack and bond links. Analytical model was decided as shown in Fig.12, based on the specimen of Series 2-No.4. Loading and supporting condition are set as same as experiments. Cracks were made in advance, whose position and angle of inclination were decided with reference to test results. The values of bond link stiffnesses along each reinforcing bars were given as shown in Fig.13.

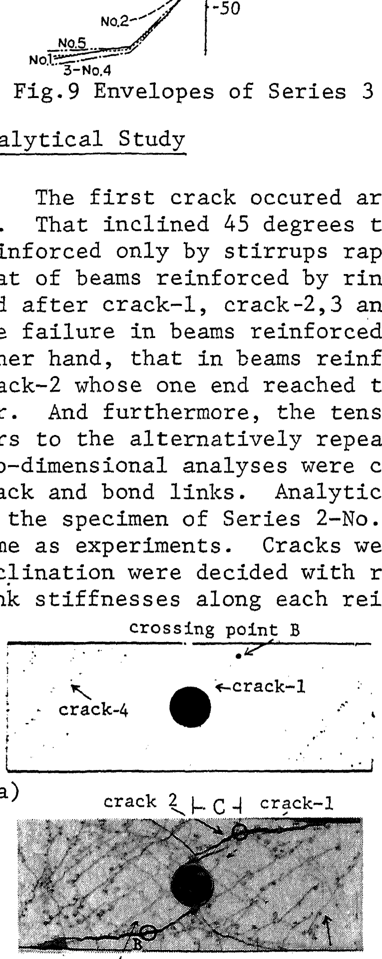


Fig.11 Cracks around web opening of specimens(2-No.4)

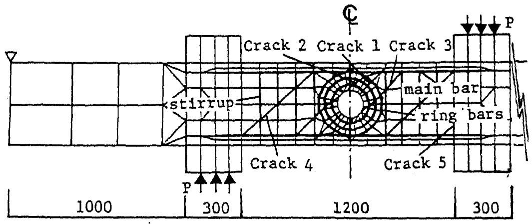


Fig.12 Analytical model

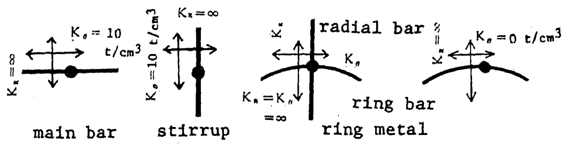
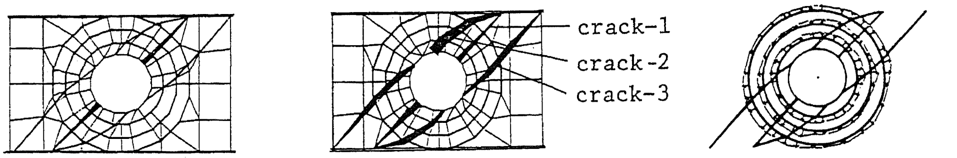


Fig.13 Bond link stiffnesses

As the results, crack-1 in specimen 2-No.4 was opened by shear force(Q= 6.8^t), in succession, crack-3 was opened by shear force(Q=25.5^t), and then, crack-2 was opened. When the load was increased more, crack-2 developed large compared with crack-1 and 3. This tendency agreed with test results.

The stress of all over the ring bars was tensile as shown in Fig.14-c. This tendency also agreed with test results.



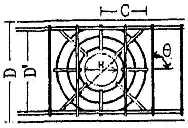
(a) : cracking (Q=66.2t) (b) : cracking (Q=82.1t) (c) : stress distribution of ring bars

Fig.14 Analytical results of specimen 2-No.4

Experimental Formula

When the computation for circular web opening of reinforced concrete beams using ring metals is conformed to Eq.(3), the calculation for reinforcement ratio around web opening(P_s) can be clalified by test and analytical study as shown in Fig.15.

$$P_s = {}_w a_s(\sin 45 + \cos 45)/b \cdot C + {}_s a_s(\sin\theta + \cos\theta)/b \cdot C \quad (5)$$



${}_w a_s$: sectional area of a group of ring bars

${}_s a_s$: sectional area of a group of stirrups

C :=D'/2 a half distance of top and bottom of main bars

Fig.15 Effective zone of reinforcement around web opening

EXPERIMENTS TO INVESTIGATE THE DEFORMABILITY

Test Procedure

The list of specimens is shown in Table 4. The details of specimens are shown in Fig.16 and 17. Mechanical properties of reinforcing bars are shown in Table 5. Specimens consist of two series. Series 4 and 5 were tested to study the effect of the number and the position of circular web opening on the deformability of beams. The loading and measuring arrangements are illustrated in Fig.18. The relative deflection was measured by a dial gage attached on the holder which was fixed on the stub. The alternatively repeated load was applied by a rule of incremental deformation amplitude with each one cycle at the rotation angle of member R=1/1000, 1/400, 1/200, each three cycles at R=1/100, 2/100 and two cycles at R=3/100.

Table 4 List of specimens

Series	No. of Specimen	Reinforcement Ring metal	Stirrup	Web opening (mm) Diameter (H/D)	Position (s)	a/d	Reinforcement ratio(%) P_t	Ps (Pw) Stirrup	Ring	Concrete strength Fc(kg/cm²)
4	4-No.1	without opening				2.0	1.44	(0.48)		236
	4-No.2	2-Ring(b')	2-D10	150 (1/3)	225	2.0	1.44	0.27	1.01	
	4-No.3	2-Ring(b')	2-D10	150 (1/3)	400	2.0	1.44	0.27	1.01	
5	5-No.1	without opening				3.0	1.69	(0.84)		262
	5-No.2	2-Ring(b)	2-D13	150 (1/3)	225	3.0	1.69	0.96	1.01	
	5-No.3	2-Ring(b)	2-D13	150 (1/3)	400	3.0	1.69	0.96	1.01	
	5-No.4	2-Ring(b)	2-D13	150 (1/3)	675	3.0	1.69	0.96	1.01	
	5-No.5	none	4-D13	150 (1/3)	225	3.0	1.69	1.93	—	
	5-No.6	2-Ring(b)	2-D13	150 (1/3)	225,675	3.0	1.69	0.96	1.01	

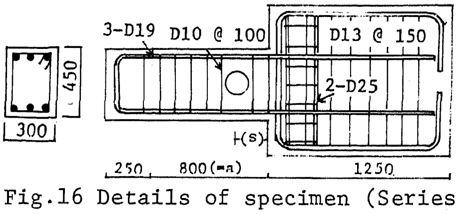


Fig.16 Details of specimen (Series 4)

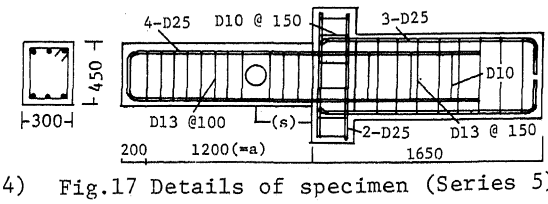


Fig.17 Details of specimen (Series 5)

Table 5 Mechanical properties of reinforcing bars

Series	Bars	$_s\sigma_y$ (ton/cm^2)
4	D 19 D 10 Ring(b')	3.75 4.17 3.41
5	D 25 D 13 Ring(b)	3.64 3.50 4.24

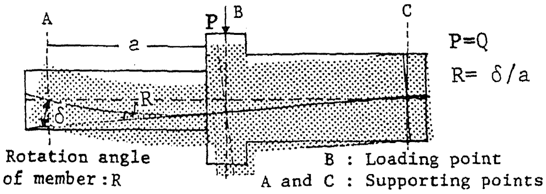


Fig.18 Loading and measuring arrangements

Test Results

The test results are summarized in Table 6. Left side suffix C or T means the calculated values or test results, respectively. The maximum shear force was caused by the yielding of main bars in all specimens.

Table 6 Test results and calculated results

Series	No. of Specimen	Shear force (ton)									Rotation angle at maximum shear force
		Bending crack	Diagonal crack		Ultimate	Yielding		Ratio	Maximum		
		$_TQ_{bc}$	$_TQ_{sc}$	$_CQ_{sc}$*1	$_CQ_{hu}$*2	$_TQ_y$	$_CQ_y$*3	$_TQ_y/_CQ_y$	$_TQ_{max}$	$_CQ_{mu}$*4	Rmax
4	4-No.1	3.5	10.5	12.8	26.2	14.5	14.7	0.99	17.4	15.5	>3/100
	4-No.2	4.0	12.5	12.8	22.2	14.5	14.7	0.99	17.7	15.5	>3/100
	4-No.3	4.0	13.9	12.8	22.2	14.8	14.7	1.01	17.7	15.5	>3/100
5	5-No.1	3.8	10.0	10.5	26.8	21.3	20.7	1.03	23.6	22.7	>3/100
	5-No.2	3.0	10.0	10.5	27.5	21.1	20.7	1.02	22.2	22.7	3/100
	5-No.3	2.8	9.8	10.5	27.5	20.1	20.7	0.97	23.0	22.7	3/100
	5-No.4	3.1	12.0	10.5	27.5	20.7	20.7	1.00	24.7	22.7	>3/100
	5-No.5	3.4	10.2	10.5	21.8	21.1	20.7	1.02	21.1	22.7	1/140
	5-No.6	2.8	11.8	10.5	27.5	21.3	20.7	1.03	23.0	22.7	3/100

*1 : by Eq.(4), *2 : by Eq.(3) and Eq.(5), where without opening, by Eq.(2)
*3 and *4 : by Umemura's e-function method

Envelopes of load-deflection relations are shown in Fig.19 and 20. Load-deflection relations before yielding were almost same regardless of beams with web opening or without opening. The deformability at the maximum load was influenced by the position of web opening. The deformability of the specimen whose position of web opening(s) was larger(675mm) was better comparing with the smaller one. The almost same deformability as the beams without opening was obtained, when the circular web opening was kept far from the end of beam by an effective beam depth or more.

The deformability of beam with two web openings was large influenced by the circular web opening which was near the end of beam.

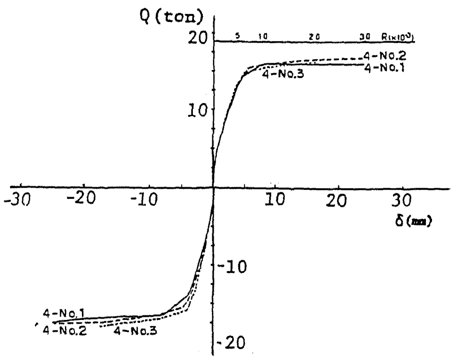


Fig.19 Envelopes of Series 4

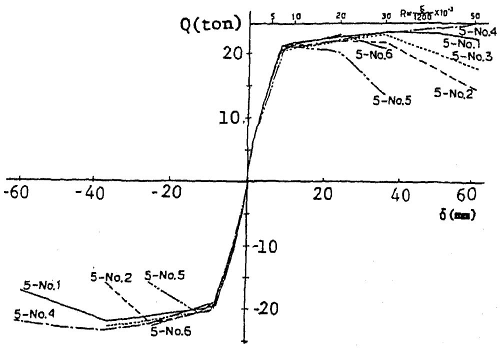


Fig.20 Envelopes of Series 5

The deformability was little influenced, however, by the circular web opening whose center was kept by three times of that diameter from the center of the circular web opening near the end of beams

CONCLUSIONS

(1) An effectiveness of reinforcing method by the newly developed the ring metals for circular web opening of reinforced concrete beams was remarkably recognized by test and analytical results.

(2) The computation for shear reinforcement ratio around the web opening (p_s) can be clalified, and the experimental formula of ultimate shear strength of beams with circular web opening using the ring metals was obtained.

(3) None of the shear strength of test results was less than the calculated values according to the experimental formula obtained by these experiments.

(4) The beams with circular web opening which were enough reinforced by the ring metals can be confirmed to have the same deformability as the beams without web opening.

(5) Analytical results based on the cracking pattern of test results can be considered to estimate a similar tendency of test results very well.

(6) The newly proposed reinforcing method for circular web opening of reinforced concrete beams using the ring metals have much effectiveness regarding the ultimate shear strength and the deformability.

This method is not only easy, accurate and convenient for practical use, but also saving term of work and labor cost. In Japan, the ring metals have been already used in many construction works.

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