NEW REINFORCING METHOD FOR REINFORCED CONCRETE BEAM WITH WEB OPENING INTRODUCED PRESTRESSING FORCE

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Abstract: The authors originated new reinforcing methods for reinforced concrete beams with web opening. Those new methods consist of using unbonded prestress tendons, which are arranged near web opening. Prestressed force is introduced to each tendon. The authors made two arranging ways of unbonded tendons near web opening. The authors aim that both new methods will be suitable not only for seismic retrofit of existing reinforced concrete buildings having beam with web opening, but also new buildings.
In this study the authors performed shear-bending experiments of reinforced concrete beams with those new reinforcing methods for web opening, and tried to confirm effectives of those methods and make clear shear characteristics of those beams.
From specimens the following facts were taken;
1. Shear strength of specimens could be calculated by well-known formula by regarding prestress tendons near web opening as reinforcing bars for web opening.
2. When sufficient prestressed force was introduced to each tendons, crack width under allowable shear force for sustained loading could be controlled to lower than 0.2mm.

1. INTRODUCTION

Reinforced concrete (R/C) beams with web opening have some loss in their section caused by web opening, so their section loss may cause large crack width around web opening. Sometimes their large crack width may exceed beyond design assumption. To improve that situation the authors has proposed new reinforcing method, named “the IC reinforcing method; the IC reinforcing method is made up of unbonded-type prestress tendons arranged around web opening and introducing prestressed tensile force to prestress tendons. The authors intend that the IC reinforcing method may be adopted for new construction buildings for restraint of crack width being small.

In this research the authors intended to investigate effects of amount of prestressed tensile force to prestress tendons, ratio of web opening reinforcement by prestress tendons and compressive strength of concrete, for ability of restraint of crack width and shear ultimate strength of reinforced concrete beams having the IC reinforcing method.

The authors, furthermore, have proposed new reinforcing method, named “the OC reinforcing method”, for beams with web openings in existing building; the OC reinforcing method is made up of prestress tendons placed on the surface of beam roundly, and introducing prestressed tensile force to the tendons. In this study the authors also intended to investigate effect of the OC reinforcing method.

2. EXPERIMENTAL PROGRAM

2.1 Specimens

Specimen's details are shown in ***Fig. 1***, and ***Table 1***. Twelve specimens were tested in this study. Eleven of specimens were made as specimens of the IC reinforcing method, and one of specimen was as the OC reinforcing method. All specimens had 300mm in width $\boldsymbol{b}$ and 450mm in depth $\boldsymbol{D}$ of section, 150mm in diameter of web opening (equal to $\boldsymbol{D}/3$) and 1.54 of shear span ratio $\boldsymbol{M/Qd}$.

Three pieces of D22 high strength bar having screw-type knot were used as longitudinal reinforcement. Three pieces of U8, which were arranged as stirrup and unbonded-type prestress tendons of φ7.1, φ9.2 and φ11 were all approved in JIS (Japan Industrial Standard) as "C-1 class".

On the IC reinforcing method, four pieces of unbonded-type prestress tendons were arranged symmetrically having 40 degree of inclined angle against longitudinal direction. On specimen of the OC reinforcing method (No.3), a pair of prestress tendons was placed round on the surface of specimen near web opening. Those round tendons were connected each other by steel corner blocks, and same amount of prestressed tensile force was loaded to those tendons, not only tendons placed to beam-depth direction but also beam-width direction. On all specimens, prestressed tensile force for tendons, not only the IC reinforcing method but also the OC reinforcing method, were loaded by the post tension-style loading. To normalize the effects of prestressed tensile force, which may be varied by reinforcing method, the authors defined $\boldsymbol{\sigma_D}$ as an average prestress suffer to crack occurred near web opening which were assumed that crack angle against longitudinal direction was equal to 45 degree, which is shown in ***Fig. 2***.

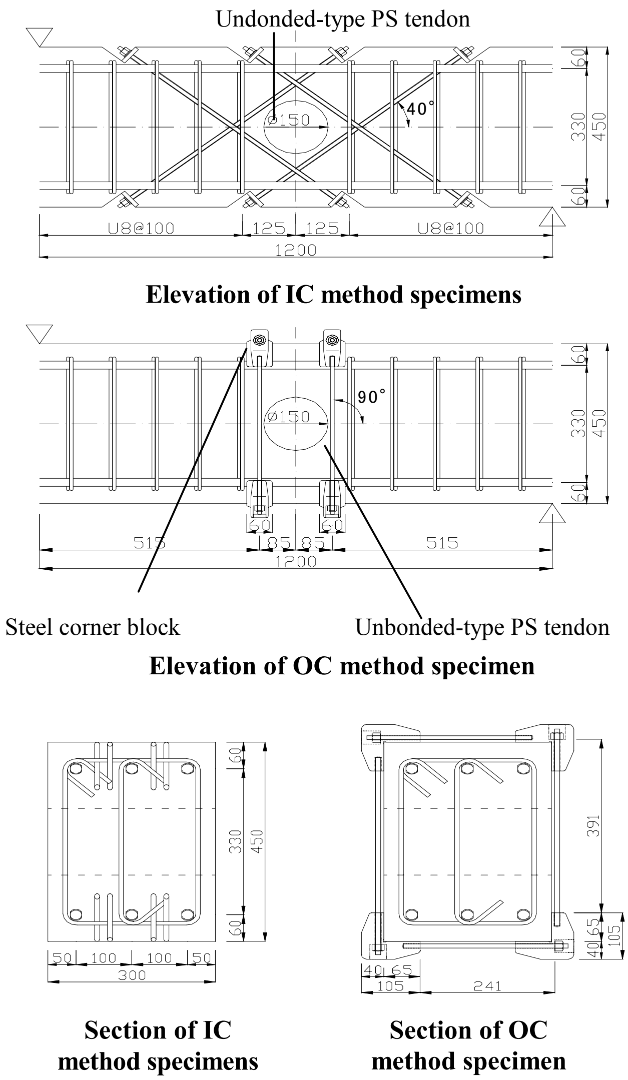


Fig. 1: Details of specimens

On the specimens of the IC reinforcing method, specimens had 0.23%, 0.38% and 0.54% of ratio of reinforcement for web opening $\boldsymbol{p_p}$ calculated by diameter of prestress tendons arranged near web opening.

2.2 Shear-Bending Loading System

Fig. 3 shows loading setup. Specimens were suffered from multi-cyclic shear-bending force. So-called "Kenken-style shear-bending loading system" was adopted. By using that loading system, specimens were suffered from reversal bending moment against mid-point of specimens on longitudinal axis. Peak point of each loading cycle were decided by deformed angle of specimen $\boldsymbol{R}$; $\boldsymbol{R}$ were decided to ±1/500rad., ±1/200rad., ±1/100rad., ±1/67rad. and ±1/50rad..

Table 1: List of specimens

Spec. No.	Tendons' diameter, mm	Reinf. method	F_c, MPa	p_p, %	P_1, kN	P_1/P_y	σ_D, N/mm^2
No.1	7.1	IC	30	0.23	---	---	---
No.2					31	0.7	0.8
No.3	9.2	OC		0.27	40	0.5	
No.4		IC		0.38	15	0.2	0.4
No.5					31	0.4	0.8
No.6					61	0.8	1.7
No.7	11			0.54	---	---	---
No.8					31	0.3	0.8
No.9					61	0.6	1.7
No.10			60		---	---	---
No.11					31	0.3	0.8
No.12					61	0.6	1.7

IC: IC reinforcing method OC: OC reinforcing method

F_c: Specified concrete strength

p_p: Ratio of reinforcement for web opening by prestress tendons arranged near web opening;

$$p_p = \sum \left(a_s \cdot \left(\sin\theta_p + \cos\theta_p\right)\right) / b \cdot c$$

P_1: Prestressed tensile force per one piece of prestress tendon

P_y: Yield tesile force of prestress tendon (= σ_y/A)

σ_D: average prestress suffer to crack occurred near web opening which are assumed that crack angle against longitudinal direction is equal to 45 ° ; $\sigma_D = n \cdot P_1 \cdot \cos(\theta_p \cdot - \pi/4) / (b \cdot (\sqrt{2} \cdot D - H))$

n: Number of prestress tendons which cross section having 45 degree of inclined angle

θ_p: Inclined angle of prestress tendons against longitudinal axis of specimens

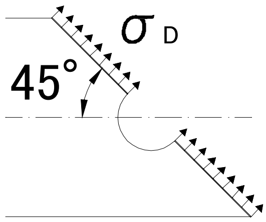


Fig. 2: Definition of σ_D

Table 2: Mechanical properties of steel bars and concrete

Steel bar	$_s\sigma_y$, $_p\sigma_y$ (N/mm^2)	$_s\sigma_t$ (N/mm^2)	E_s (GPa)	A (mm^2)
Longitudinal, D22	1152	1279	190	387
Stirrup, U8	874	943	195	50
PS Tendon for the IC method, 7.1φ	1182	1192	185	40
PS Tendon for the IC method, 9.2φ	1244	1282	193	66
PS Tendon for the OC method, 9.2φ	1273	1312	196	66
PS Tendon for the IC method, 11φ	1220	1292	195	95
Concrete	**F_c (MPa)**	**σ_B (MPa)**	**$_c\sigma_t$ (MPa)**	**E_c (GPa)**
Spec. No.1-3	30	42	3.0	25
Spec. No.4-6		39	2.8	24
Spec. No.7-9		35	2.6	24
Spec. No.10-12	60	66	3.8	29

$_s\sigma_y$, $_p\sigma_y$: Yield strength $_s\sigma t$, $_c\sigma_t$: Tensile strength
E_s, E_c: Elastic modulus A: Section area
F_c: Designed strength σ_B: Compressive strength

2.3 Crack Observation

To observe crack near web opening, the authors decided the area of 330mm × 330mm near web opening, shown in ***Fig. 3***, and width of crack occurred in that area were measured frequently. Crack width ***W*** was defined as width perpendicular to longitudinal direction of crack which occurred diagonally.

3. RESULT AND DISCUSSION

3.1 General Behavior

Experimental results are shown in ***Table 3***, and relations between shear force ***Q*** and deformation angle ***R*** and crack pattern are shown in ***Fig. 4.*** On specimens of the IC reinforcing method width of

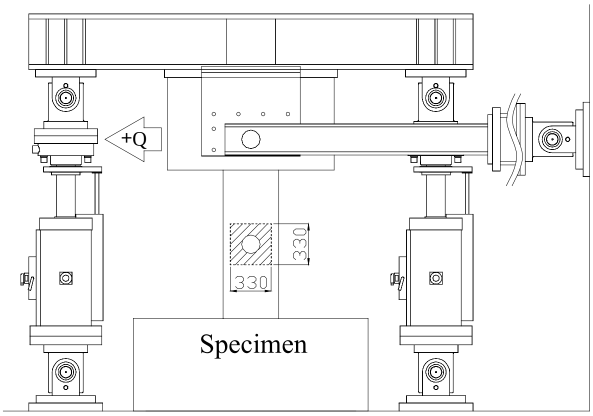


Fig. 3: Loading setup
(Hatched area shows crack-observing area)

crack occurred near web opening became wide and specimens became failure.

On spec. No.1 and No.2, unbonded-type tendons yielded and reached to maximum shear force just before ***R*** was equal to +1/67 rad.. But on other specimens of the IC reinforcing method, shear force became the maximum at the point that ***R*** was equal to +1/67 rad.. On spec. No.3 of the OC reinforcing method, shear failure were occurred on upper and lower area of web opening when ***R*** was equal to -1/50 rad., then ***Q*** had fallen.

Relations between shear crack strength near web opening τ_{sco} and average prestress σ_D are shown in ***Fig. 5***. As figure shows, generally τ_{sco} increased according to growth of σ_D, that is growth of prestressed tensile force. And figure shows that τ_{sco} may not be influenced by p_p and concrete compressive strength σ_B.

After shear crack occurred, number of shear crack near web opening became smaller according to growth of σ_D, and other shear cracks were occurred outside of web opening area.

Table 3: Experimental result

Spec. No.	$_cQ_{bu}$ (kN)	$_cQ_{AL}$ (kN)	$_cQ_{AS}$ (kN)	$_cQ_{suo}$ (kN)	$_eQ_{sco}$ (kN)	$_eQ_{max}$ (kN)	$_eQ_{max}/_cQ_{suo}$
No.1	783	179	346	294	66	343	1.17
No.2					101	356	1.21
No.3				308	122	475	1.54
No.4		175	339	325	55	387	1.19
No.5					106	401	1.23
No.6					129	449	1.38
No.7		168	329	347	58	408	1.18
No.8					113	422	1.22
No.9					141	424	1.22
No.10		218	403	395	63	478	1.21
No.11					98	515	1.31
No.12					138	507	1.29

$_cQ_{bu}$: Calculated maximum bending strength $_cQ_{AL}$: Allowable shear strength for sustained loading by AIJ approved formula for reinforced concrete beam not having web opening $_cQ_{AS}$: Allowable shear strength for temporary loading by AIJ approved formula for reinforced concrete beam not having web opening $_cQ_{suo}$: Shear strength calculated by the Hirosawa's formula[1]:

$$_cQ_{suo} = \left\{ \frac{0.092 \cdot k_u \cdot k_p \cdot (F_c + 18)}{M/Q \cdot d + 0.12} \cdot \left(1 - \frac{1.61 \cdot H}{D}\right) + 0.85 \cdot \sqrt{p_s \cdot {}_s\sigma_y + p_p \cdot {}_p\sigma_y} \right\} \cdot b \cdot j \quad \cdots (1)$$

a_s: Sectional area of prestress tendons θ_p: Inclined angle of prestress tendons against longitudinal axis of specimens $_p\sigma_y$: Yield strength of prestress tendon $_eQ_{sco}$: Shear cracking load near web opening taken in experiments $_eQ_{max}$: Maximum shear strength taken in experiments

3.2 Crack Width near Web Opening

Relations between average shear stress τ and maximum crack width W_{max} are shown in ***Fig. 6*, 7, and *8***. On those figures range of τ were positive. As figure shows, crack width, both width when shear loading and unloading, became small according to growth of σ_D and p_p. For example, if σ_D is equal to 1.7MPa, that is to say that σ_D is a small value, crack width became about 1/20 as small as that if σ_D is equal to zero, when specimen is under situation of allowable shear stress for long sustained loading. As compared between spec. No.2 and No.3, strength when shear crack occurred were approximately equal, but crack width of spec. No.3 was smaller than that of spec. No.2. Reason why that may be that stiffness for axial direction of prestress tendon used for spec. No.3 was larger

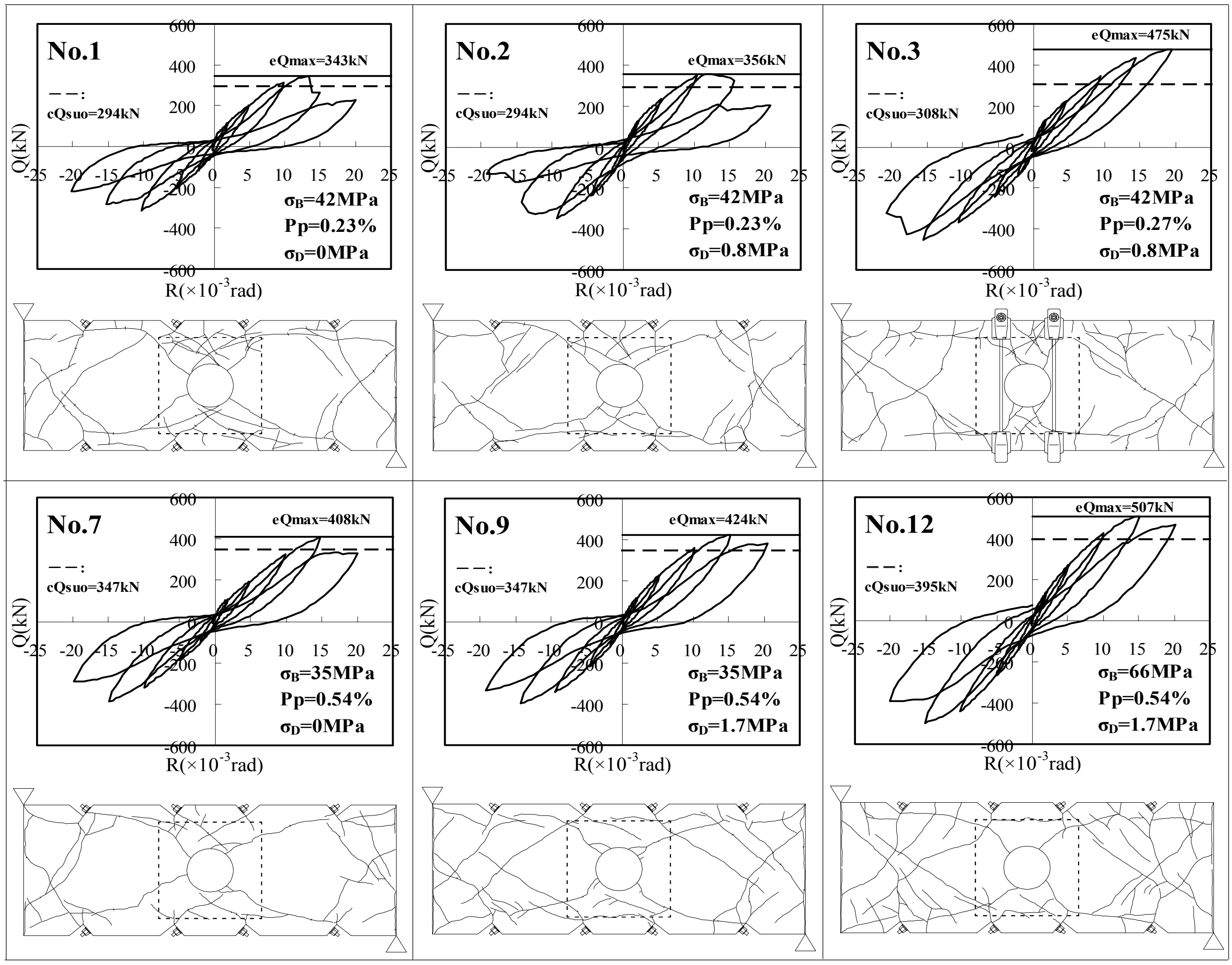
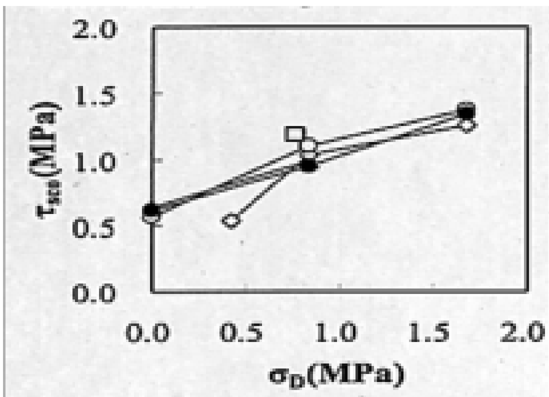


Fig. 4: Q-R relations and crack patterns

than that of spec. No.2, because tendon for spec. No.3 had larger area of section and shorter length than those of spec. No.2.



△: No.1,2 (p_p=0.23%, σ_B=42MPa, IC method)
□: No.3 (p_p=0.27%, σ_B=42MPa, OC method)
◇: No.4-6 (p_p=0.38%, σ_B=39MPa, IC method)
○: No.7-9 (p_p=0.54%, σ_B=35MPa, IC method)
●: No.10-12 (p_p=0.54%, σ_B=66MPa, IC method)
$\tau_{sco}={}_eQ_{sco}/(b\cdot j)$

Fig. 5: τ_{sco} -σ_D relation

Relations between σ_D and crack width when specimens were under situation of allowable shear stress for long sustained loading ${}_{AL}W_{max}$ are shown in ***Fig. 9***. Generally in Japan, maximum crack width when prestressed concrete structures are under situation of allowable shear stress for long sustained loading may be recommended to 0.2mm or below. But as shown in figure, crack width ${}_{AL}W_{max}$ of specimens which had no prestressed tensile force for prestress tendons reached between 1.10mm and 1.31mm. Those values are approximately six times as largeas 0.2mm. So those facts show that it is estimated that maximum crack width of normal reinforced concrete beam with web opening, not having the IC or OC reinforcing method, may be exceed to 0.2mm, when beam is under situation of allowable shear stress for long sustained loading.

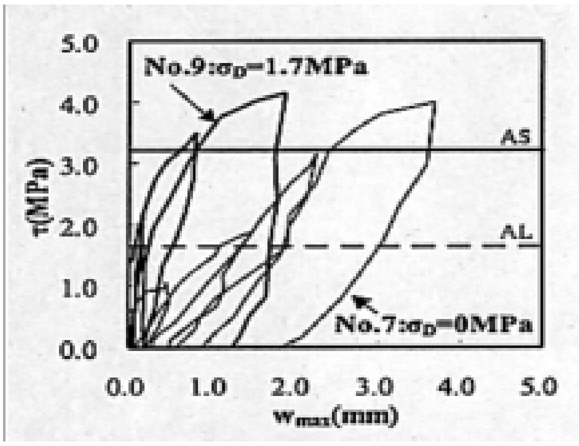


Fig. 6: τ-W_{max} relation
(Spec. selected by the scope of variable of σ_D)

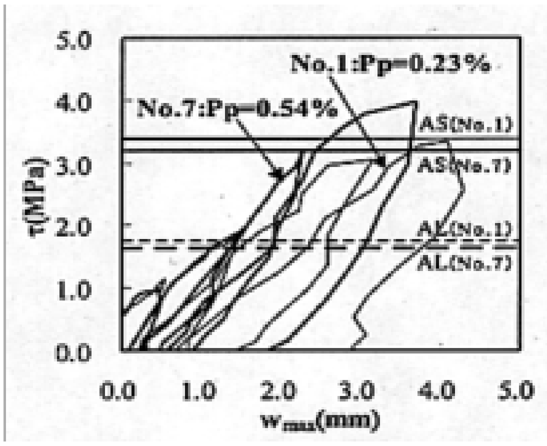


Fig. 7: τ-W_{max} relation
(Spec. selected by the scope of variable of p_p)

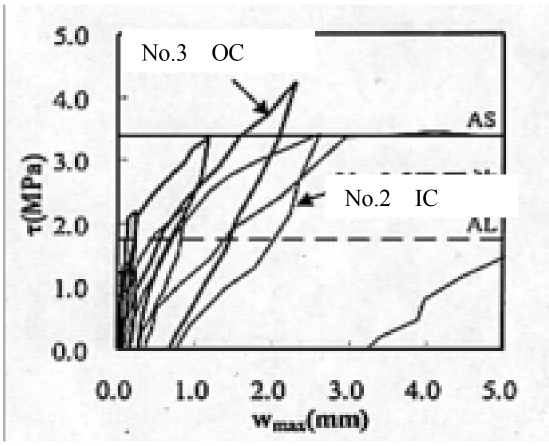


Fig. 8: τ-W_{max} relation
(Spec. selected by the scope of reinforcing method)

In Fig. 6-8;

$\tau = Q/(b \cdot j)$

AL: Allowable shear stress for long sustained loading;

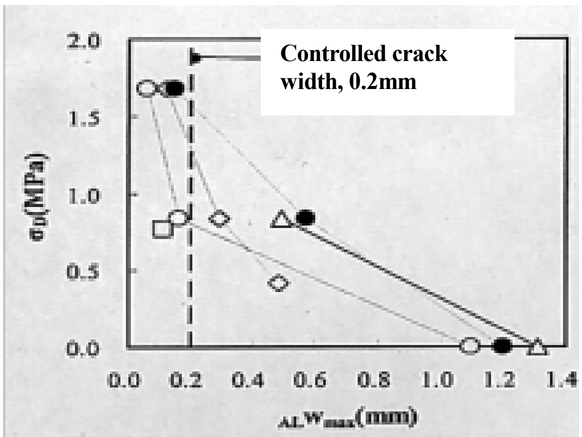
$AL = {}_cQ_{AL}/(b \cdot j)$

AS: Allowable shear stress for temporary loading;

$AS = {}_cQ_{AS}/(b \cdot j)$

j: Distance between centers of tension and compression;

j=341.25mm



△: No.1,2 (p_p=0.23%, σ_B=42MPa, IC)
□ : No.3 (p_p=0.27%, σ_B=42MPa, OC)
◇: No.4-6 (p_p=0.38%, σ_B=39MPa, IC)
○: No.7-9 (p_p=0.54%, σ_B=35MPa, IC)
●: No.10-12 (p_p=0.54%, σ_B=66MPa, IC)

Fig. 9: σ_D-${}_{AL}W_{max}$ relation

3.3 Behavior of Reinforcing Bar near Web Opening

Relations between shear force $\boldsymbol{Q}$ and vertical shear force loaded by prestress tendons $\boldsymbol{V_p}$, vertical shear force loaded by stirrup arranged near web opening $\boldsymbol{V_s}$, which are defined on ***Fig. 10***, are shown in between ***Fig. 11*** to ***14***. As figure shows, point that shear force loaded by stirrup arranged near web opening became to grow may appear later according to growth of prestressed tensile force. That is because large prestressed tensile force prevents to become width of shear crack near web opening wide.

Among specimens not having prestressed tensile force, characteristics between σ_D and V_p, V_s are similar to each other even if concrete compressive strength may vary. But on specimen having σ_B is equal to 66MPa and having prestressed tensile force, shear force not only loaded by prestress tendon but also loaded by stirrup arranged near web opening tend to

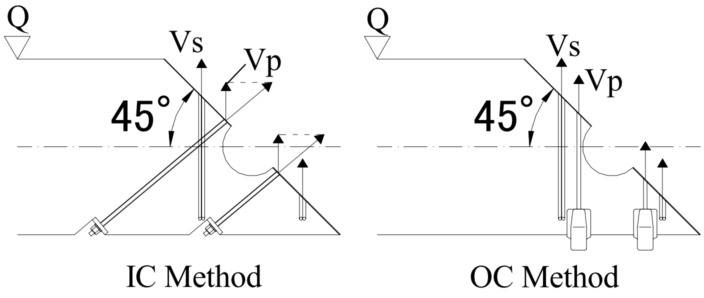


Fig. 10: Shear force at PS tendons and stirrup

grow. So it became clear that prestressed tensile force makes prestress tendon and stirrup arranged near web opening act effectively.

3.4 Shear Strength between Experiment and Calculation

In Japan the formula suggested by Dr. Hirosawa (eq.1)[1)] is well-known for calculation of shear strength of reinforced concrete beam with web opening. Exactly that formula is not following to beam with the OC and IC reinforcing method, but in this section the authors tried to apply that formula to each specimen. Relation between shear strength calculated by the Hirosawa's formula $_cQ_{suo}$ and that taken in experiments $_eQ_{max}$ are shown in ***Fig. 15***. In this figure, it is assumed that prestress tendons were considered as reinforcement for web opening like stirrup. As figure shows, $_eQ_{max}$ exceeded $_cQ_{suo}$. Value of $_eQ_{max}/_cQ_{suo}$, that is safety factor, became between 1.14 and 1.38 on specimens with the IC reinforcing method, and became 1.54 on specimen with the OC reinforcing method. Safety factor for

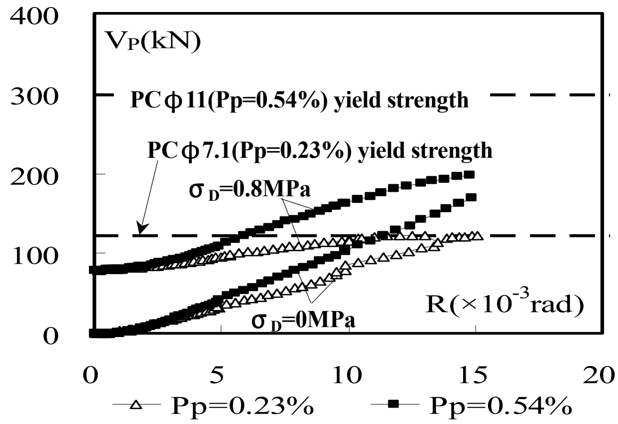


Fig. 11: V_p-R relation
(Spec. selected by the scope of variable of p_p and σ_D)

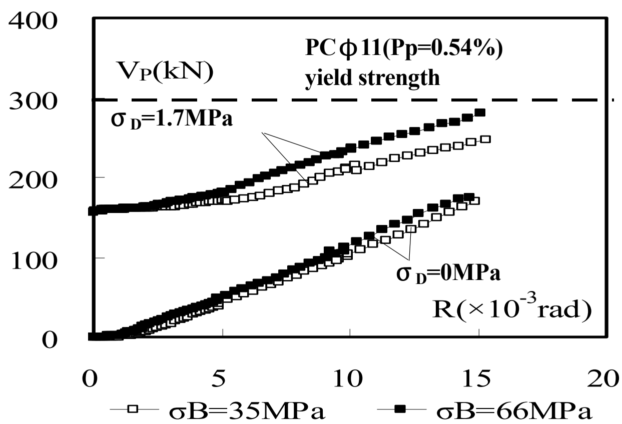


Fig. 12: V_p-R relation
(Spec. selected by the scope of variable of σ_B and σ_D)

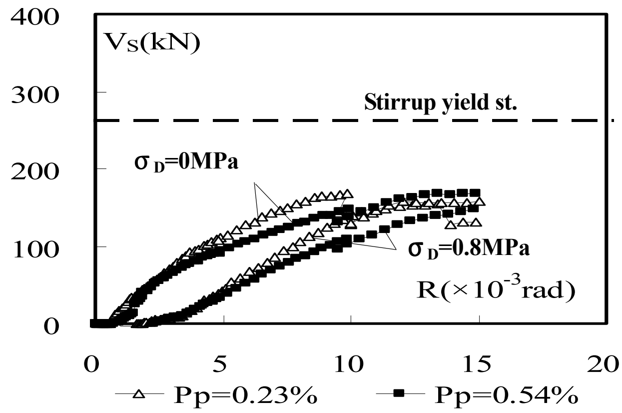


Fig. 13: V_s-R relation
(Spec. selected by the scope of variable of p_p and σ_D)

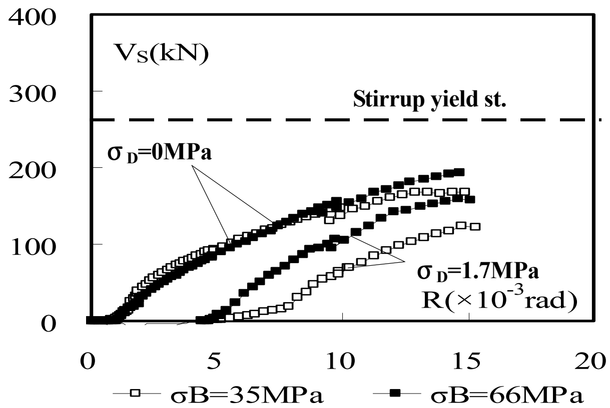


Fig. 14: V_s -R relation
(Spec. selected by the scope of variable of σ_B and σ_D)

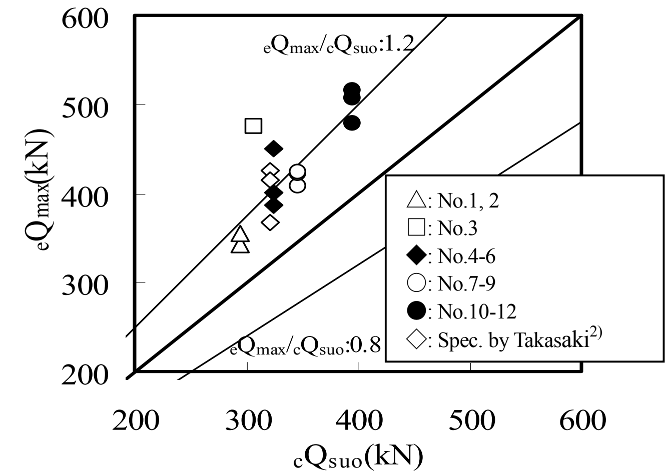


Fig. 15: ${}_{e}Q_{max}$-${}_{c}Q_{suo}$ relation

specimen with the OC reinforcing method was larger than that for specimens with the IC reinforcing method. It may be thought that the reason above is that prestress tendon for the OC reinforcing method has larger effects for shear strength than that of the IC reinforcing method.

4. CONCLUSION

This study examined the effects of new reinforcing method of reinforced concrete beam with web opening. The following conclusion can be made:

1. Shear crack strength near web opening increases according to growth of prestressed tensile force for prestress tendons arranged or placed near web opening.
2. Crack width become small according to growth of prestressed tensile force for prestress tendons arranged or placed near web opening. Moderate prestressed tensile force for prestress tendons and amount of reinforcement for web opening may lead crack width under controlled width value.
3. If specimens are made of high strength concrete, prestressed tensile force may make prestress tendon and stirrup arranged near web opening act effectively.
4. The Hirosawa' s formula, which is famous in Japan to estimate shear strength of reinforced concrete beam with web opening, is applicable to specimens having the IC and OC reinforcing methods.

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