SHEAR CRACK CONTROL ON REINFORCED CONCRETE COLUMN BY LATELAL PRESTRESSING

H. Watanabe[1)], K. Katori[2)], Y. Shinohara[3)], and S. Hayashi[4)]

1) Research Student, Structural Engineering Research Center, Tokyo Institute of Technology, Japan
2) Research Associate, Structural Engineering Research Center, Tokyo Institute of Technology, Japan
3) Associate Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan
4) Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan
hwatanab@serc.titech.ac.jp, katori@serc.titech.ac.jp, yshinoha@serc.titech.ac.jp, hayashi@serc.titech.ac.jp

Abstract: This paper describes the investigation of the influence of lateral prestress on the crack opening within reinforced concrete column by experiments. From the experiments, it is found that either shear crack strength and allowable shear force which makes residual shear crack opening into target value increased with lateral prestressing.

1. INTRODUCTION

According to building design based on structural performance, damage on reinforced concrete building such as crack must be controlled to implement required performance. On the reinforced concrete column, from views of durability, waterproof and appearance, shear crack should be prevent or its residual opening should be controlled. Shear crack opening also should be controlled to keep residual strength of the column, since its transverse reinforcements stresses and residual deformation become larger due to increasing of the crack width.

When design was performed to control residual shear crack opening within reinforced concrete column, it is seem that allowable shear force for temporary loading formula in Architectural Institute of Japan Standard of Reinforced Concrete Structures (1999) might be available. However, AIJ Standard does not describe clearly on residual crack width control. Based on experimental results in beam, residual shear crack width was predicted by using allowable shear force formula above as index of damage by Fukuyama et al. (2000). Crack widths could not be controlled in some member, and verification based on other index was required. An axial load could not be neglect, although the effect of the axial load was not considered in the formula, when shear crack strength was examined. Thus, it might be needed:

(a) Method of restricting residual shear crack opening.
(b) To control residual crack opening, evaluation index at design.

This paper develops effect of lateral prestressing into column (Watanabe et al. 2002 and 2003) on shear design for minor earthquake, as preventing method on shear crack occur, or as control method on the residual shear crack width, based on experimental results. An evaluation method of allowable shear force which makes residual shear crack width within the column as control target value, as control index, was also considered.

Table 1 List of Test Specimens

No.	b, D (mm)	d_w (mm)	σ_0 $/f_c$	s (mm)	p_w (%)	p_{wp}* (%)	Longitudinal bars	f_c (N/mm^2)	f_{ct} (N/mm^2)	f_{wp} (N/mm^2)	σ_L (N/mm^2)
1	340	6.4*, and D16**	0.30	60	2.54	0.29*	8-D22	40.1	2.09	859	2.5
2								45.0	2.21	528	1.6
3								48.0	2.29	0	0.0
4		6.4*, and D13**			0.29			35.4	1.96	876	2.6
5								35.3	1.96	0	0.0

*pretensioned hoop, **sub hoop, b is breadth of column, D is depth of column, d_w is nominal diameter of transverse hoop, σ_0 is axial stress of column, f_c is compressive strength of concrete, s is spacing of transverse hoops in longitudinal direction, p_w is ratio of transverse hoop(=$(A_{wn}+A_{wp})/(b\cdot s)$), p_{wp} is ratio of transverse hoop used in prestressing(=$(A_{wp})/(b\cdot s)$), f_{ct} is tensile strength of concrete, A_{wn} is cross area of one pair of transverse reinforcement without prestressing, A_{wp} is cross area of one pair of transverse reinforcement with prestressing and σ_L is lateral prestress($=p_{wp}\cdot f_{wp}$)

2. TEST PROGRAM

2.1 Test Specimens

Table 1 lists test specimen, and Fig. 1 shows details of the specimens. The test specimens were total five specimens which have square shaped section 340mm×340mm, height 900mm. Five specimens were designed as which occur shear failure in ultimate condition, before longitudinal reinforcement had been yielded, without bond splitting failure, based on AIJ Guidelines for Reinforced Concrete Buildings (1999). Principal variables were effective tensile stress into a piece of transverse

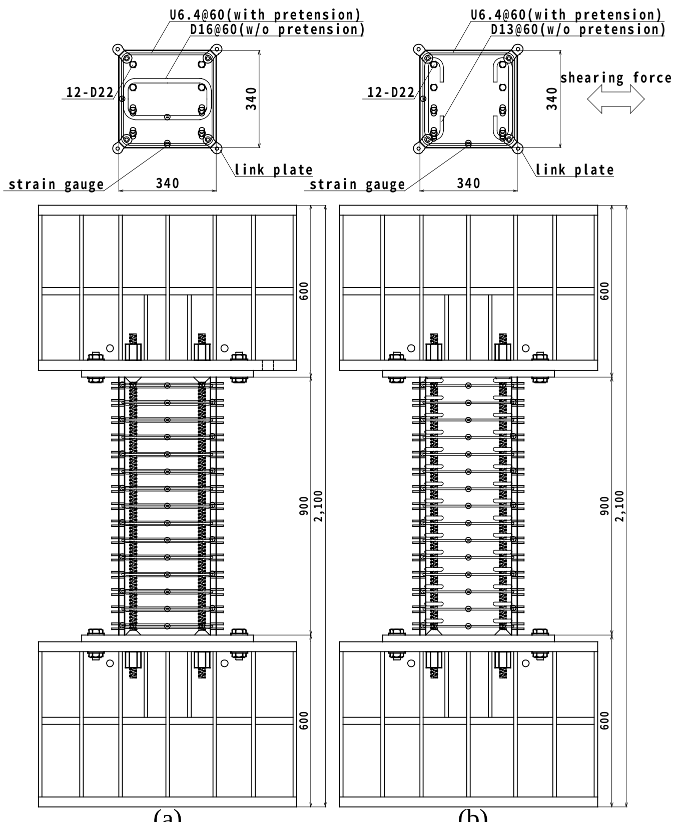
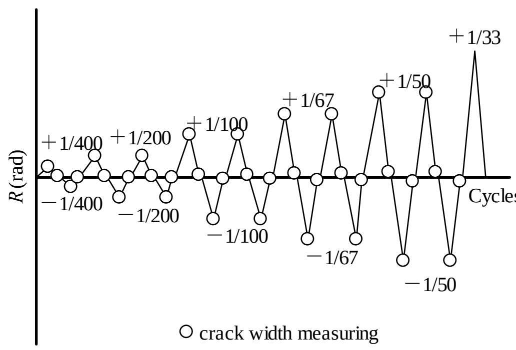


Fig. 1 Details of Test Specimens: (a) No.1-3, and (b) No.4 and



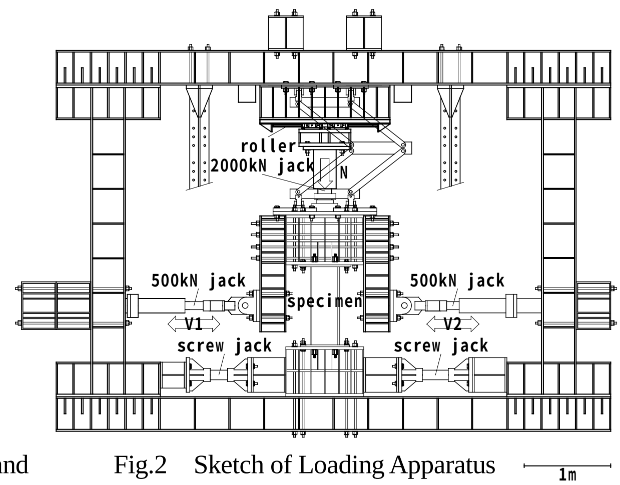


Fig.2 Sketch of Loading Apparatus

Table 2 Mechanical Properties of Steel used in the Experiments

Type	Material	f_{sy}, f_{wy} (N/mm^2)	f_{st} (N/mm^2)	E_s (kN/mm^2)
D22	—	1016*	1162	206
U6.4	—	1441	1465	197
D13	SD345	378	535	198
D16	SD295A	344	513	202

*0.2% offset, f_{sy} and f_{wy} are yield strength of steel, f_{st} is tensile strength of steel, and E_s is steel Young's modulus

reinforcement f_{wp} (60, 37 and 0% of its yield). Two types of sub reinforcements were used (see Figs. 1(a) and (b)). In this experiment, the transverse hoop used for prestressing was only outer one. Cover to transverse reinforcements was 12mm. Maximum particle size of coarse aggregate was 25mm. Cement was high early strength Portland cement. Mechanical properties of steel used in the experiments were shown in Table 2.

2.2 Loading and Measuring Method

The loading apparatus is shown as Fig. 2. Vertical force on the test specimen was supplied by one hydraulic jack capacity 2MN, and axial load ratio (on assumption that this axial load equal to dead load without consideration of steel) was kept constant as 0.30 controlled in the load during test. To comparison among shear crack strength of columns with different prestress, so that absolute value of difference among specimens become larger, higher axial force ratio was adopted. Horizontal forces on test specimen was supplied by two hydraulic jacks capacity 500kN, and controlled in displacement during test. Horizontal forces were applied in cyclic, and made an unsymmetrical moment. Tests repeated, once at deformation angle of member R=±400, two times, at R=±1/200, ±1/100, ±1/67 and ±1/50, once at R=±1/33, and finished at +1/25. R is horizontal relative displacement between top and bottom of the column divided by its height. Shear crack openings were measured by using digital micro scope (which had minimum divisions of a scale, 0.01mm) at deformation peak and horizontal force unloaded (added shear force due to dead load was still residual) of each cycle until ±1/50, after cracks occurring. Shear cracks upon transverse reinforcement and the middle point between two transverse reinforcements were measured.

2.3 Lateral Prestressing Method

Lateral prestress is applied into the concrete with high strength transverse hoops pretensioned mechanically. Reacting forces of pretension is taken with steel cast, and the cast is removed after concrete hardening. Lateral prestress is introduced just before axial force due to dead load of assumed upper structure loaded into the column, such as Precast column. Lateral prestress σ_L was defined as value which was product of ratio of transverse reinforcement used in prestressing and transverse reinforcement stress before column had been loaded axially.

3. EXPERIMENTAL RESULTS

3.1 *V*—*R* Curves

Each hysteresis of specimens were shown in Fig. 3. For typical damage process observed on the specimens, after flexural crack, flexural shear crack, and shear crack occurred, reached maximum strength with increasing of the input shear force.

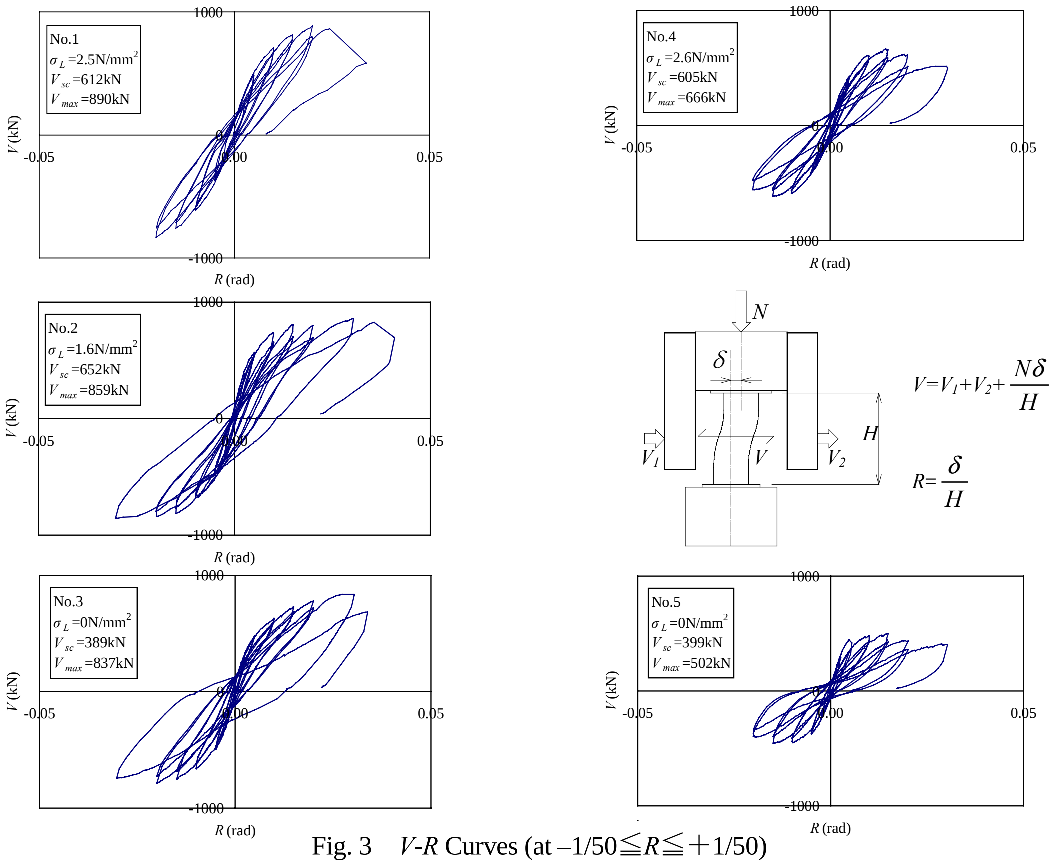


Fig. 3 *V*-*R* Curves (at –1/50≦*R*≦+1/50)

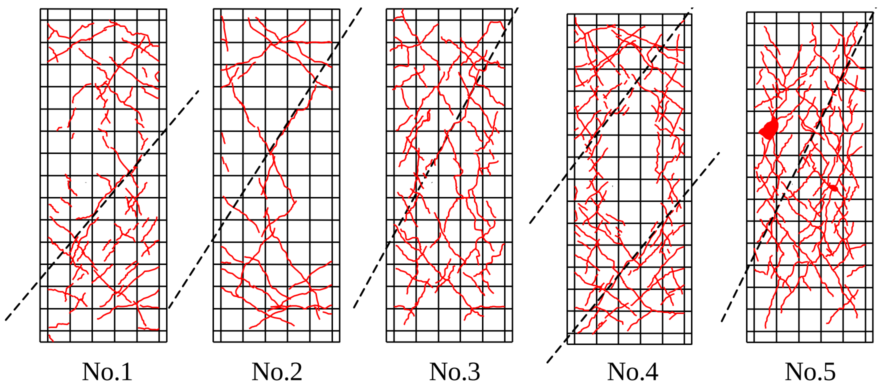


Fig. 4 Observed Crack Patterns at *R*=1/50

3.2 Failure Mode

Observed crack patterns at *R*=1/50 were shown in Fig. 4. Here, an angle of crack which reached severe opening was indicated in a broken line. According to increase of lateral prestress, these angles at crack relative to axis of the column approximated 45 degrees from axial direction of the column. Finally, all specimen represented shear compression failure without flexural yield.

3.3 Effects of Lateral Prestress on Shear Crack Strength

Relations between shear crack strength ${}_{exp}V_{sc}$ and lateral prestress was considered. Relations between shear crack stress ${}_{exp}\tau_{sc}$ (=${}_{exp}V_{sc}/bD$) and lateral prestress were plotted in Fig. 5, together with data from literature (Watanabe et al. 2002). Shear crack strength improved with increasing of prestress.

3.4 Evaluation of Shear Crack Strength

Verification of precision was estimated by evaluation equation of shear crack strength based on

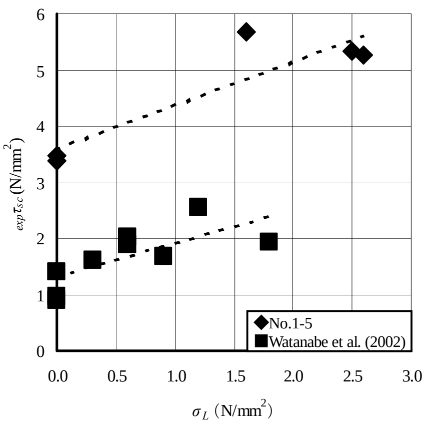


Fig.5 Relations Between Shear Crack Stress and Lateral Prestress

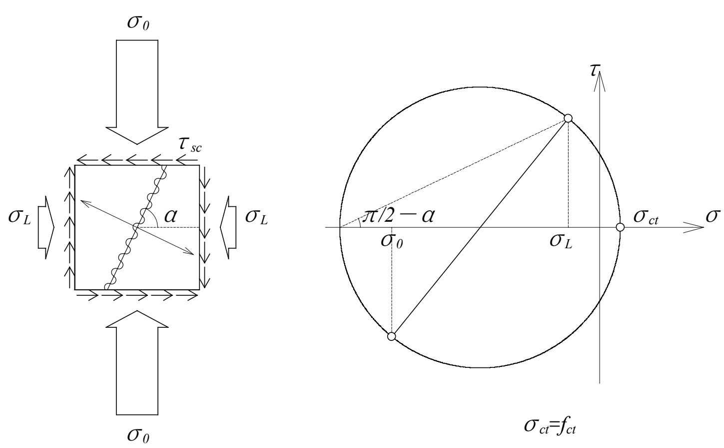


Fig.6 Assumption of Mohr's Circle due to Lateral Prestressing

maximum principal stress theory which proposed in literature (Watanabe et al. 2003). Equation was not derived empirically from statistics of experimental results, based on the hypothesis which could be explained theoretically. Eq. (1) adopted in AIJ Design Guidelines for Reinforced Concrete Buildings (1999) and AIJ Standard of Prestressed Concrete Structures (1998). Actually, lateral prestressed reinforced concrete column was seated under three dimensional stresses condition with combination of lateral prestress and axial load added column, but here, projected into two dimensions like Fig. 6. Comparison estimated precisions of calculated values between usual evaluation Eq. (1) of shear crack strength without consideration of lateral prestress and evaluation Eq. (2) with consideration of prestress, was examined, adding 10 columns from literature (Watanabe et al. 2002).

$$\tau_{sc} = \sqrt{(f_{ct})(\sigma_0 + f_{ct})} \Big/ \kappa \quad (1)$$

$$\tau_{sc} = \sqrt{(\sigma_L + f_{ct})(\sigma_0 + f_{ct})} \Big/ \kappa \quad (2)$$

where f_{ct} is concrete tensile strength, σ_0 is axial stress of the column and κ is constant (κ= 1.5). f_{ct} was calculated by Eq. (3) which was adopted from literature (Collins and Mitchell 1991) same as AIJ Design Guidelines (1999). Unit of f_c is in N/mm^2.

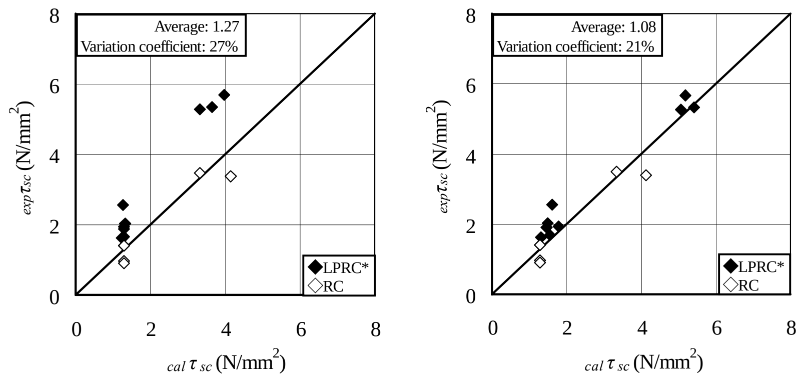
$$f_{ct} = 0.33\sqrt{f_c} \quad (3)$$

Fig.7 shows estimated precision on shear crack stress both calculated by original Eq. (1) and proposal Eq. (2). Proposed Eq. (2) takes accounts of lateral prestress, which had coefficient of variation 21%, estimate in safely with smaller dispersion than original Eq. (1), which had coefficient of variation 27%. Thus, prediction accuracy was given by using Eq. (2), more than using present design formula.

3.5 Effect on Damage

Fig. 8 shows envelopes of hysteresis of shear force V - shear crack width W. Here crack width W is maximum shear crack width, which had been measured on surface of the specimens. Starting from shear crack strength, and W at shear force reaching almost zero (added shearing force due to dead load was still residual) represents residual shear crack width W_r. For lateral prestressed reinforced concrete column, W_r is prevented in smaller value, even if the column had experienced larger shear force or crack opening than usual reinforced concrete column had experienced.

Relations between residual shear crack widths and shear stresses which apply the widths are shown in Fig. 9. The shear stress applied residual shear crack width as 0.2mm, which increased with



(a) (b) *LPRC (Lateral Prestressed Reinforced Concrete)

Fig. 7 Comparisons of Shear Crack Stress Between Experimental Results and Calculations: (a) by Eq.(1), and (b) by Eq.(2)

lateral prestress. For column with larger quantity of transverse reinforcements, shear stress increased with prestress from occurring of shear crack to residual shear crack width reaching 0.2mm, for column with smaller quantity of transverse reinforcements, shear stress at residual shear crack width reaching 0.2mm within lateral prestressed reinforced column was equal to shear cracking stress of non-prestressed column. For columns had smaller quantity of transverse reinforcement, when shear crack occurred, then residual crack opening reached 0.2mm.

3.6 Definition of Shear Damage Strength

The shear stress is defined as "*shear damage stress*" τ_{sd} which applies control target value on residual shear crack width. Here, control target value on crack width was indicated by AIJ Recommendations for Design of Partially Prestressed Concrete (2003), as 0.2mm. From a viewpoint of durability, the absolute value of crack width is adopted as 0.2mm without its reduction in scale-downed specimen used in this experiment. However, when total depth of a member becomes two times, also residual crack width becomes about two times, even if the member had been experienced coordinate shear stress, experimental results were reported (Honjou et al. 2001). The control target value of crack width should be given attention in actual design. Relations between shear crack stress τ_{sc} and lateral prestress σ_L, and relations between *shear damage stress* τ_{sd} and lateral prestress σ_L were shown in Fig. 10. Both shear crack strength and *shear damage strength* increased with lateral prestress. Residual crack width is defined under the following condition, as inputted horizontal load into column is unloaded and added shear force due to dead load is still residual.

In particular, for specimen with large quantity of transverse reinforcement, under same shear stress, residual shear crack width on reinforced concrete column with no prestress reached 0.2mm, while lateral prestressed reinforced concrete column (σ_L=2.5N/mm^2) had no shear crack. *Shear damage stress* increased in lateral prestressed column one and a half times than reinforced concrete column.

3.7 Evaluation of Shear Damage Strength

To control damage on reinforced concrete column, estimate method of shear damage strength V_{sd} which makes residual shear crack width into control target value, is expressed in this paper. It is always after cracking that residual shear crack occurs. Since the tensile force due to horizontal load becomes impossible to be subjected by concrete after cracking occur, therefore, be supported by transverse reinforcements instead. Transverse reinforcement subjected tensile force was required tensile strain. When transverse reinforcement is in elastic condition, tensile stress in a single piece of the reinforcement is taken as

$$f_w = W_r \cdot E_s / (j \cdot \sin\alpha) \tag{4}$$

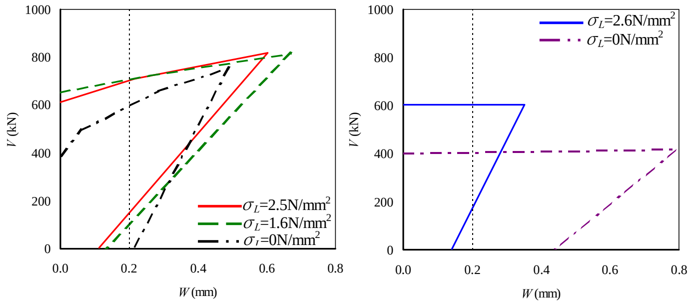
where, j is distance between corner longitudinal reinforcement bars, and α is an angle at diagonal crack plane relative to horizontal plane. The crack width used in Eq. (4) is crack width at *shear damage strength*. Correctly, residual crack width differs from crack width in Eq. (4). Here, crack width in Eq. (4) is assumed that equal to residual crack width, since crack width in Eq. (4) equal to sum total of crack width and strain distribution in transverse reinforcements is un-uniform.

By assuming *shear damage strength* equals to total subjected load by all transverse reinforcement across shear crack surface, *shear damage strength* ${}_{cal}V_{sd1}$ given by

$${}_{cal}V_{sd1} = (f_w + f_{wp}) A_{wp} \cdot n + f_w \cdot A_{wn} \cdot n \tag{5}$$

where, A_{wp} is cross area of one pair of transverse reinforcement with prestressing, A_{wn} is cross area of one pair of transverse reinforcement without prestressing, and n is the number of pieces of transverse reinforcement which crossing shear crack surface. Eq. (5) takes account of lateral prestress by including transverse reinforcement effective tensile stress f_{wp}.

Eq. (5) required number of transverse reinforcement crossing crack surface. Judging from crack patterns, the number of transverse reinforcement was defined. Since residual crack width do not



(a) (b)

Fig. 8 Relations Between Shearing Force and Shear Crack Width: (a) p_w=2.54%, and (b) p_w=0.29%

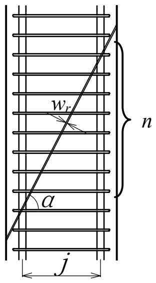
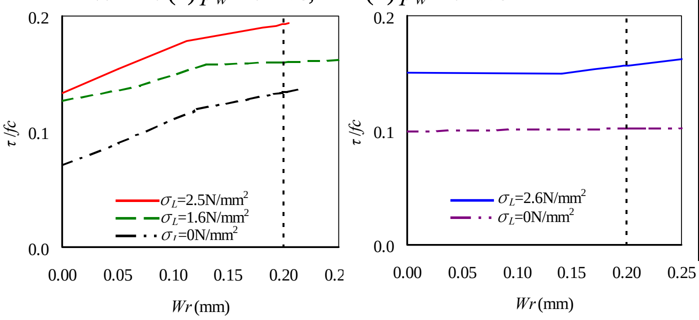


Table 3 Calculated Results of Shear Damage Strength

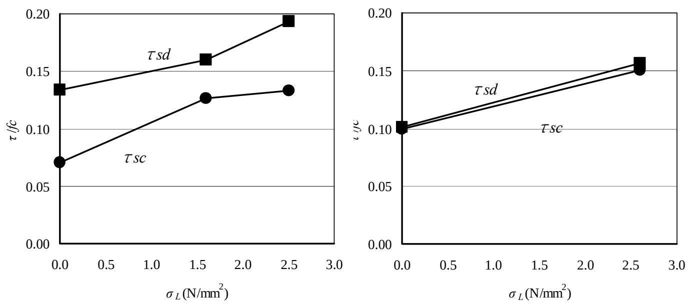
No.	n	${}_{cal}V_{sd1}$ (kN)	${}_{cal}V_{sc}$ (kN)	${}_{exp}V_{sc}$ (kN)	${}_{cal}V_{sd}$ (kN)	${}_{exp}V_{sd}$ (kN)	${}_{exp}V_{sd}$ / ${}_{cal}V_{sd}$
1	6	**850**	622	612	**850**	886	1.04
2	7	**819**	595	652	**819**	827	1.01
3	9	**738**	476	389	**738**	738	1.00
4	6	384	**582**	605	**582***	629	1.08
5	10	106	**382**	399	**382***	407	1.07

Bold number shows the bigger value. (*${}_{cal}V_{sd1} < {}_{cal}V_{sc}$)



(a) (b)

Fig. 9 Relations Between Shearing Stress and Residual Shear Crack Width: (a) p_w=2.54%, and (b) p_w=0.29%



(a) (b)

Fig.10 Relations Between *Shear Damage Strength* and Lateral Prestress: (a) p_w=2.54%, and (b) p_w=0.29%

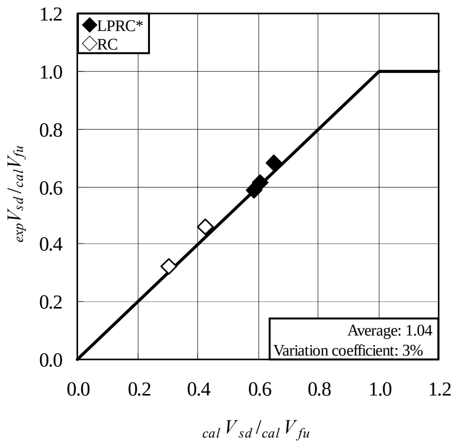


Fig.11 Comparisons of *Shear Damage Strength* Between Experimental Results and Calculations

occur before crack occur, V_{sd} is calculated as the larger one, ${}_{cal}V_{sd1}$ or ${}_{cal}V_{sc}$ (which calculated by Eq. (2)).

Calculating *shear damage strength* of specimens of this experiment, Fig. 11 and Table 3 were obtained. Both axes are normalized by ${}_{cal}V_{fu}$, the shear force when the bending moment at column end section reaches the theoretical flexural capacity. V_{sd} was defined as ${}_{cal}V_{sd1}$ for No.1-3, while V_{sd} was defined as ${}_{cal}V_{sc}$ for No.4 and 5. This phenomenon corresponded to results of Fig. 9.

Average of experimental value/calculated value was 1.04 and coefficient of variation was 3%. Above is evaluated with sufficient accuracy and safely.

4. CONCLUSIONS

From the behavior observed during the flexure-shear experiment on lateral prestressed reinforced concrete column and results presented above, the following conclusions can be drawn:

Shear crack strength on column able to be improved by introduction of lateral prestress. Moreover, based on a consistent theory, evaluation method of shear crack strength of usual Reinforced Concrete column and Lateral Prestressed Reinforced Concrete column was shown.

By introducing of lateral prestress, improvement of the *shear damage strength* could be recognized, which makes residual shear crack width to control target value is newly defined. By taking account of lateral prestress as transverse reinforcements stresses which crossing shear crack surface, *shear damage strength* was evaluated. The design could allow larger shear force into the columns by lateral prestressing, when occurrence of shear crack is prevented or residual shear crack width is controlled.

By using evaluation method of *shear damage strength* which takes accounts of only load subjected by transverse reinforcements, input shear force into column makes residual crack width to control target value was calculated safely with sufficient accuracy.

Acknowledgements:

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