SHEAR REINFORCEMENT OF RC MEMBERS USING POST-REINFORCING BARS

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Abstract: This paper reports on the results of basic tests intended for the development of a method of shear reinforcement of reinforced concrete structures from one side using post-reinforcing bars, while preventing shear sliding failure along joints between new and old concretes. Loading tests were conducted by using three types of beam specimens. The following were the main findings about shear reinforcement effects:
(1) Post-reinforcement using straight bars with no hook or bars having hooks at one side is an effective method of shear reinforcement. It is necessary to allow for loss of their load-bearing capacity when compared with standard stirrups because of insufficient anchorage at the ends of the bars.
(2) The load-bearing capacity of post-shear-reinforcement tends to be affected by the bending stress state at construction joints. The shear strength of post-reinforcement was stronger when the stress state at construction joints was tensile than when it was compressive.
(3) The use of a SHCC (strain-hardening cement composites) for an added layer with post-reinforcing bars is an effective method for strengthening when compared with the use of normal concrete, as SHCCs not only increase the durability of members but also increase their toughness by 2 to 3 times.

1 INTRODUCTION

Many of reinforced concrete structures built before 1980 suffer insufficient shear capacity due to the low shear reinforcement ratio in Japan. Various methods have been adopted for shear strengthening of reinforced concrete members since 1996 in line with the revised seismic design code. Steel panel lining, reinforced concrete lining, continuous fiber sheet lining, and other methods are available for reinforced concrete columns, which can be strengthened from all directions. Shear strengthening using reinforcing bars having an enlarged end ('post-head-bars') or bars with no end enlargement has been adopted for reinforced concrete structures that can be reinforced from only one direction, such as box culverts having wall elements. For reinforced concrete slabs of highway bridges, the overlay method using steel fiber-reinforced concrete has been employed instead of shear reinforcement to improve the punching shear capacity.

However, research has been insufficient regarding post-reinforcing techniques whereby concrete members are shear-strengthened while surface concrete damaged by frost attack, etc., is simultaneously replaced with new concrete.

This paper reports on the results of basic tests intended for the development of a method of shear-strengthening of slab-shaped reinforced concrete structures from one side using post-reinforcing bars, while preventing shear sliding failure along joints between new and old concretes. [1-2]

2 EXPERIMENTAL PROGRAM

Three types of beam specimens were fabricated for loading tests. Series A specimens are used to examine the shear-strengthening effect of post-reinforcing bars. Series B specimens are used for examining their effect in members having construction joints. Series C specimens are used for examining the difference in their effect depending on the stress condition of construction joints.

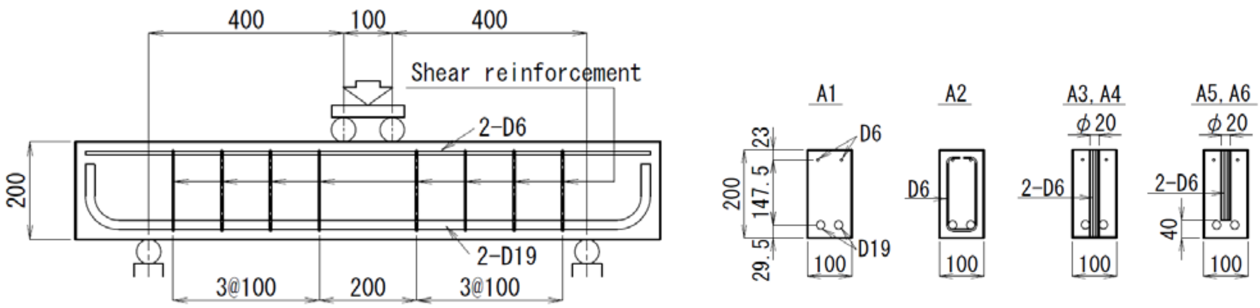
2.1 Specimens

(1) Series A regarding shear-strengthening by post-reinforcing bar

Series A specimens are used to investigate the difference between the shear-strengthening effects of standard shear reinforcement and post-shear-reinforcement. These are fabricated in six types as shown in Fig. 1 and Table 1 with a size that leads to shear failure (shear span-depth ratio: 2.35).

Specimens A1 and A2 are reference specimens for comparing the shear-strengthening effects with specimens strengthened by post-reinforcing bars (Specimens A3 to A6). Whereas Specimens A3 and A4 had post-reinforcing bars to the full depth, the bars were inserted to the depth of the upper level of the longitudinal bars at the bottom (80% of the beam depth) of Specimens A5 and A6 with the holes drilled for insertion.

To investigate the effect of grout for anchoring post-reinforcing bars, general non-shrinkage mortar was used for A3 and A5, whereas the slightly expansive fiber reinforced mortar was used for A4 and A6. Note that the diameter of holes for inserting post-reinforcing bar was 20 mm and that two straight D6 bars



(a) Side view **(b)** Cross section

Figure 1: Dimension and configuration of Series A specimens

Table 1: Series A specimens

Specimen	Shear strengthening	Grout for anchoring	Depth of anchoring
A1	No shear reinforcement		
A2	Shear strengthening with standard stirrups		
A3	Post-reinforcement	Non-shrinkage mortar	200mm(Full of beam depth)
A4		Fiber reinforced mortar	
A5		Non-shrinkage mortar	160mm(80% of beam depth)
A6		Fiber reinforced mortar	

were inserted side by side in each hole so that the cross-sectional area of the bars would be the same as the stirrups used for A2.

(2) Series B regarding the effect in specimens having construction joints

Series B specimens are intended to investigate the effect of post-reinforcing bars in members having construction joints. Four kinds of specimens were fabricated as shown in Fig. 2 and Table 2, with the size being determined so that flexural failure would predominate (shear span-depth ratio: 3.17).

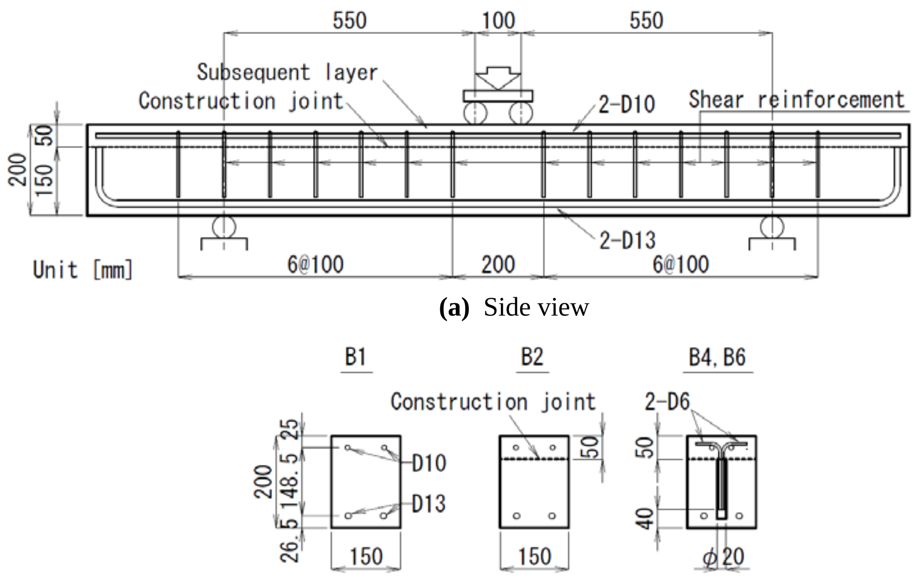
Specimen B1 was a reference specimen with no construction joint or shear reinforcement. Specimen B2 was used for investigating the effect of a construction joint on the load-bearing capacity of the member in comparison with B1. Specimens B4 and B6 were shear-strengthened using post-reinforcing bars. In these specimens, each pair of post-reinforcing bars having hooks at the upper ends were allowed to hang down from the upper longitudinal bars and grouted with fiber reinforced mortar. The subsequent layer was then placed after removing laitance on the joint surface with high-pressure water.

The concrete for the upper layers of B2 and B4 specimens was proportioned equally to the previously placed concrete. On the other hand, a SHCC (strain-hardening cement composites) with high durability was used for the upper layer of B6 from the standpoint of replacing concrete surfaces deteriorated by chloride attack or frost damage.

(3) Series C regarding stress condition at construction joints

Series C specimens are intended to investigate the effect of shear strengthening in members having construction joints with different stress conditions. Eight kinds of specimens were fabricated as shown in Fig. 3 and Table 3 so that shear failure would predominate (shear span-depth ratio: 2.64).

Specimen C1 had no construction joint or



(a) Side view

(b) Cross section

Figure 2: Dimension and configuration of Series B specimens

Table 2: Series B specimens

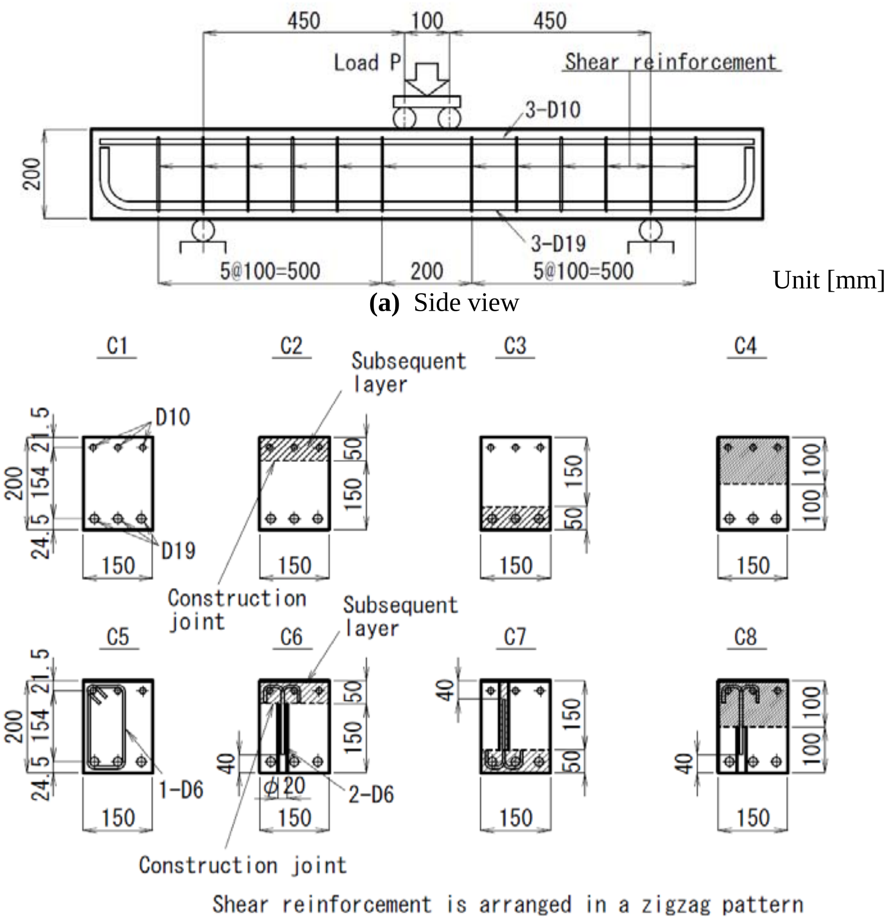
Specimen	Shear strengthening	Material of subsequent layer
B1	–	–
B2	–	Normal concrete
B4	Post-reinforcement	Normal concrete
B6	Post-reinforcement	SHCC

shear reinforcement. Specimens C2, C3, and C4, which were not shear-strengthened, were placed with a construction joint on the compression side, on the tension side, and at mid-depth, respectively. Specimen C5 with no construction joint was shear-strengthened. Specimens C6, C7, and C8, which were shear-strengthened, were placed with a construction joint on the compression side, on the tension side, and at mid-depth, respectively.

In these specimens, each pair of D6 post-reinforcing bars having a hook at one end were hung down from the longitudinal bars to be embedded in the subsequent layer and grouted with fiber reinforced mortar. The subsequent layer was then placed after removing laitance on the joint surface with high-pressure water.

2.2 Properties of materials

Table 4 gives the mix proportions of concrete used for specimens, grouts (non-shrinkage mortar and slightly expansive fiber



(a) Side view

(b) Cross section

Figure 3: Dimension and configuration of Series C specimens

Table3: Series C specimens

Specimen	Shear strengthening	Construction joint
C1	–	–
C2		Compression side
C3		Tension side
C4		mid-depth
C5	With stirrups	–
C6	Post-reinforcement	Compression side
C7		Tension side
C8		mid-depth

reinforced mortar), and a SHCC used for the subsequent layer of B6. The slightly expansive fiber reinforced mortar was developed with increased viscosity in view of upward grouting for repair using post-reinforcing bar. Table 5 gives the strength properties of materials for specimens used in the tests.

2.3 Loading test procedure

As shown in Figs. 1 (a) to 3 (a), loading tests were conducted by four point loading while measuring the load and the displacement. The displacement was measured at the two loading points.

3 EXPERIMENTAL RESULTS

3.1 Shear-strengthening effect

Figure 4 and Table 6 show the results of tests on Series A specimens for the shear-strengthening effect. Figure 4 (a) shows the load-displacement relationships of Specimens A3 and A4 having post-reinforcing bars to the full depth in comparison with those of A1 with no shear reinforcement and A2 shear-strengthened with standard stirrups. Similarly, Fig. 4 (b) shows the load-displacement relationships of Specimens A5 and A6 having post-reinforcing bars to a level of 80% of the

Table 4: Mix proportions of concrete and SHCC

Materials	W／C (%)	Unit weight [kg/m^3]								
		Water	Cement	Fine aggregate	Coarse aggregate	Lime stone powder	Expansive agent	Fiber	Water-reducing agent	Viscosity enhancer
Normal concrete	55	180	327	810	920	—	—	—	1.02※2	—
Non-shrinkage mortar	44	380	858	345※1	—	379	27	—	1.896※3	1.074
Fiber reinforced mortar	46	380	832	345※1	—	379	53	9.7	3.79※3	1.074
SHCC	30	380	1264	395※1	—	—	—	14.7	37.9※4	0.900

Fine aggregate : ※1 Quartz sand
Water reducing agent : ※2 Air-entraining and water-reducing agent
※3 Air-entraining and high-range water-reducing agent（powder）
※4 Air-entraining and high-range water-reducing agent（liquid）
Cement : Early-strength type　Expansive agent : Mixed type with ettringite and lime
Fiber: High-strength Polyethylene Fiber (Diameter:12μm, Length:12mm, Tensile strength:2.6GPa, Young's modulus: 88GPa),

Table 5: Mechanical properties of materials
(a) Concrete, mortar and SHCC

Material	Compressive strength (MPa)	Flexual strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Test age (days)	Application site
Normal concrete	40	4.1	—	31.0	21	Series A and B
	49	—	—		21	Series C（Base material）
	44	—	—		20	Series C (Subsequent layer)
Non-shrinkage mortar	72	—	—	—	11	Series A (Grout)
Fiber reinforced mortar	61	—	6.4	—	11	Series A, B, C (Grout)
SHCC	83	—	6.2	20.0	21	Series B (Subsequent layer)

(b) Reinforcing bars

Applicationsite	Diameter	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
Tension bar	D19	396	601	200
	D13	390	582	
Compression bar	D10	356	521	
Compression bar Retro-reinforcing bar	D6	502	614	
Stirrups	D6	481	600	

full beam depth in comparison with those of A1 and A2.

Table 6 compares the calculatted values and test results of the shear capacity of members and its components, that is, the load-bearing capacities of concrete and shear-reinforcement.

The calculated load-bearing capacity of concrete, V_{cd}, was calculated using an equation for diagonal-cracking load[1] in consideration of the effect of shear span-depth ratio.

$$V_{cd} = 0.2 f_c^{1/3} (100 p_w)^{1/3} \left(\frac{10^3}{d} \right)^{1/4} \left(0.75 + \frac{1.4d}{a} \right) b_w d \quad (1)$$

V_{cd} : shear capacity of diagonal -cracking (N)

f_c : compressive strength of concrete (MPa)

$p_w = A_s / b_w d$

d : effective depth (mm)

a : shear span (mm)

b_w : width of member (mm)

A_s : cross-sectional area of tension reinforcement (mm^2)

Also, the calculated capacity of shear reinforcement, V_{sd}, was calculated based on truss model [3-4].

$$V_{sd} = \frac{A_w f_{wyd}}{s_s} z \quad (2)$$

V_{sd}: capacity of shear reinforcement (N)

A_w: total cross-sectional area of the shear reinforcing bars at spacing s_s(mm^2)

f_{wyd}: yield strength if the shear reinforcing bar (MPa)

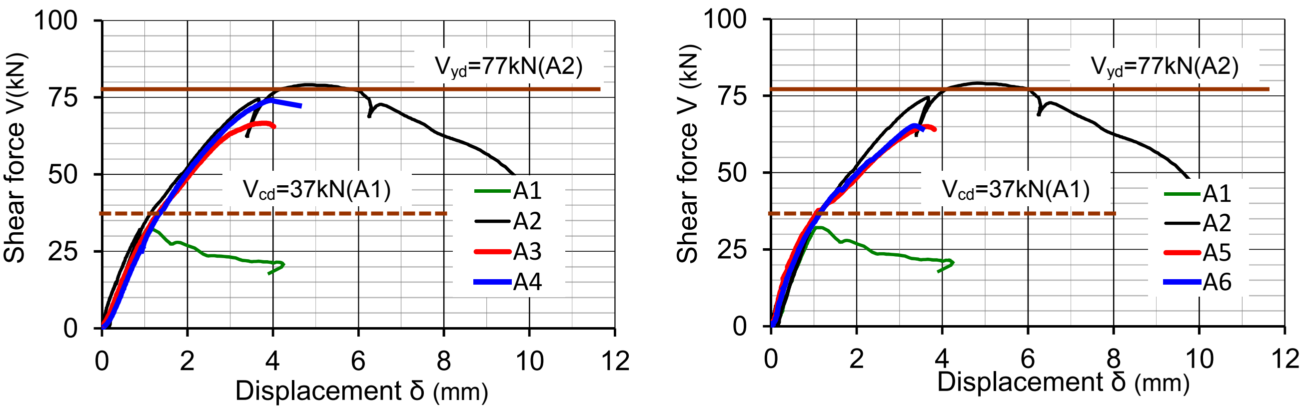
s_s:spacing of shear reinforcing bars (mm)

z: internal lever arm (mm)

The shear capacity of member, V_{yd}, was calculated by Equation (3).

$$V_{yd} = V_{cd} + V_{sd} \quad (3)$$

All of Specimens A1 to A6 failed in shear. Within the range of this study, the load-bearing capacity of post-reinforcing bars with no hooks was around 70% of standard stirrups and the shear capacity of a member as a whole was around 80% of a reference specimen with stirrups, suggesting a slight adverse effect of insufficient anchoring at the ends of reinforcement. Comparison between A3 and



(a) Depth of anchoring 100%　　**(b)** Depth of anchoring 80%

Figure 4: Relationship between shearing force and displacement of Series A specimens

Table 6: Test results of Series A specimens

Specimen	Calculated values			Test results						
	Vyd (kN)	Vcd (kN)	Vsd (kN)	Vye (kN)	Vce (kN)	Vse (kN)	Comparison with specimen A2		Comparison with calculated value	
							Vye	Vse	Vye/Vyd	Vse/Vsd
A1	36.6	36.6	–	32.1	32.1	–	–	–	0.88	–
A2	77.0	36.6	40.4	78.9	32.1	46.8	1.00	1.00	1.03	1.16
A3	78.7	36.6	42.1	66.6	32.1	34.5	0.84	0.74	0.85	0.82
A4				74.0	32.1	41.9	0.94	0.90	0.94	1.00
A5				65.0	32.1	32.8	0.82	0.70	0.83	0.78
A6				65.3	32.1	33.1	0.83	0.71	0.83	0.79

Vyd, Vye : Calculated and test values of maximum shear capacity
Vcd, Vce : Calculated and test values of shear capacity of concrete
Vsd, Vse : Calculated and test values of shear capacity of shear reinforcement

A5 revealed that the 80% depth of post-reinforcing bar led to a shear capacity approximately 3% lower than full depth post-reinforcing bar.

Note that slightly expancive fiber reinforced mortar (A4, A6) demonstrated a reinforcement-anchoring performance equal to or higher than non-shrinkage mortar as a grout for shear-strengthening using post-reinforcing bars.

3.2 Strengthening effect on a construction joint

Tables 7, 8 and Fig. 5 show the results of tests for strengthening effects on construction joints using Series B specimens. Table 7 also includes the calculated values and test results of the yield capacity, flexural failure capacity, shear failure capacity, and shear sliding stress at the construction joint. The yield capacity and flexural failure capacity were calculated based on the Standard Specifications for Road Bridges in Japan [5]. Also, the shear capacity was calculated by the same way that of Series A specimens.

Table 8 shows the failure modes of specimens after the yielding of tension bars. In

Table 7: Test results for Series B specimens

Specimen	Calculated values				Test results					
	Flexual yield capacity	Flexual failure capacity	Shear failure capacity	τ_{csu}	Flexual yield capacity		Flexual failure capacity		Maximum displacement (mm)	τ_{cs}
	Vmyd(kN)	Vmud(kN)	Vyd(kN)	(MPa)	Vmye(kN)	Vmye/Vmyd	Vmue(kN)	Vmue/Vmud		(MPa)
B1	27.9	29.5	32.6	—	30.8	1.11	32.0	1.08	11.7	—
B2				1.14	30.9	1.11	32.4	1.10	8.1	1.22
B4			75.4	2.00	30.6	1.10	33.6	1.14	19.6	1.26
B6	28.8	31.5	75.4		31.2	1.09	37.8	1.20	48.9	1.42

τ_{csu} : Ultimate sliding shear stress at the construction joint

τ_{cs} : Slinding stress at the construction joint for failure load

Table 8: Failure modes of Series B specimens after yielding of tension bars

Specimen	Failure mode
B1	Upper edge crashed
B2	Shear failure
B4	Subsequent layer crashed
B6	Previous layer crashed

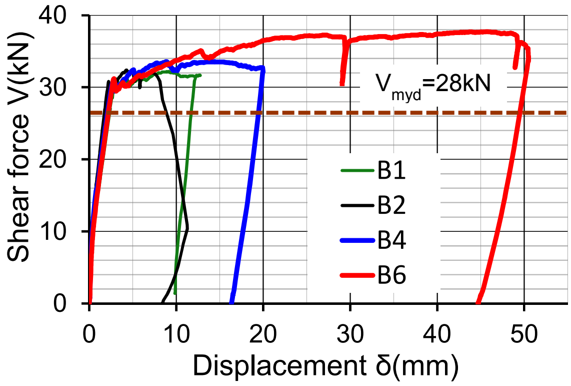


Figure 5: Relationship between shearing force and displacement of Series B specimens

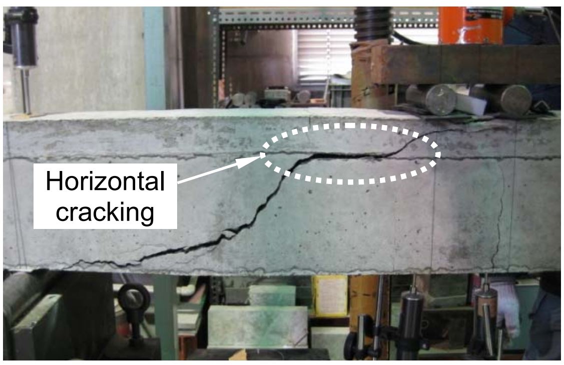


Photo 1: Shear failure of Specimen B2

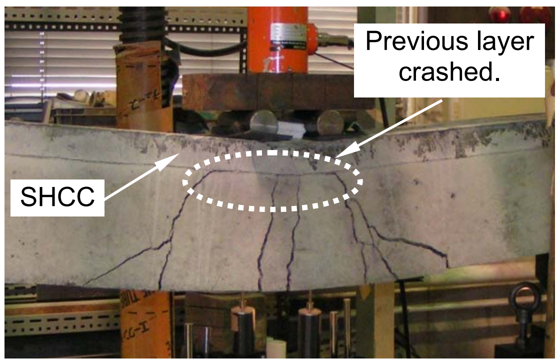


Photo 2: Ultimate state of Specimen B6

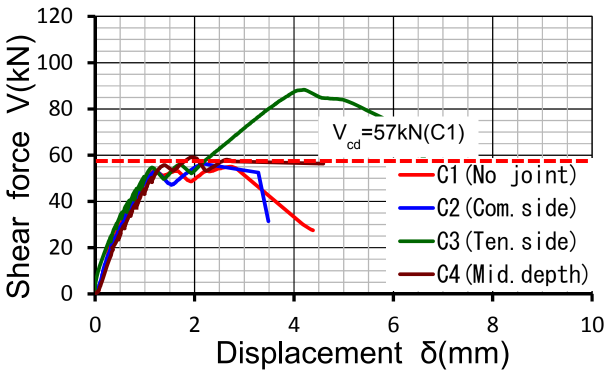
regard to Specimen B1 with no construction joint or shear reinforcement, concrete of the upper edge crushed to the ultimate state. The failure mode of Specimen B2 with a construction joint without shear reinforcement shifted to shear failure after the yielding of tension bars, reaching the ultimate state. Photo 1 shows the shear failure mode of Specimen B2. Diagonal shear cracking that occurred in the middle of section height gradually propagated upward, with horizontal cracking due to shear sliding rapidly progressing along the construction joint as shown in the Photo 1. The shear sliding stress at the construction joint, τ_{cs}, of specimen B2 that failed in shear sliding exceeded the ultimate shear sliding stress at the construction joint, τ_{csu}, as given in Table 7.

No shear sliding failure occurred either in Specimen B4 or B6 having post-reinforcing bars. In Specimen B4 in which normal concrete is used as the subsequent layer reached the ultimate state when the upper edge of the subsequent layer crushed. In contrast, in Specimen B6 with the subsequent layer made of a SHCC, the high-strength SHCC did not crush. Instead, it reached the ultimate state when the previous layer below the construction joint was fractured. Photo 2 shows the failure state of Specimen B6. As shown in Fig. 5, the displacement at the ultimate state of B6 (displacement to the maximum load after rebar yielding) is 2 to 3 times greater than that of B4 using normal concrete.

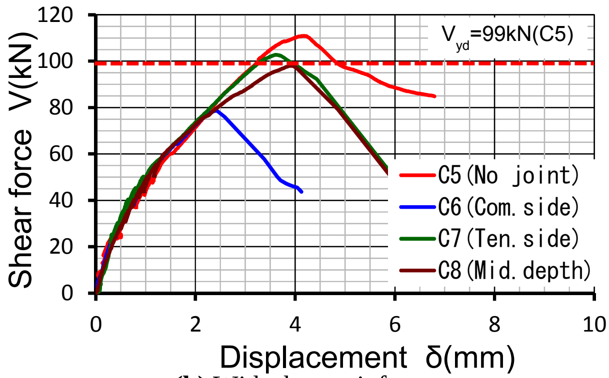
3.3 Effect of stress state at joint surface

Figure 6, Tables 9 and 10, and Photo 3 show the results of tests on Series C specimens for shear-strengthening effects with different flexural stress conditions at construction joints.

Figure 6 shows the load-displacement relationships of Specimens C1 to C4 with no shear reinforcement and Specimens C5 to C8 with shear reinforcement. Note that the load-bearing capacity of Specimen C3 increased after shear cracking. This is explained as follows: Shear sliding along the construction

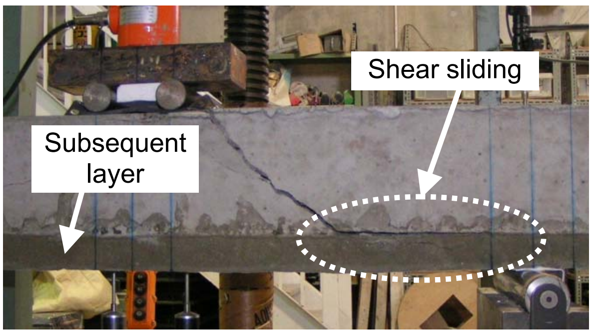


(a) Without shear reinforcement

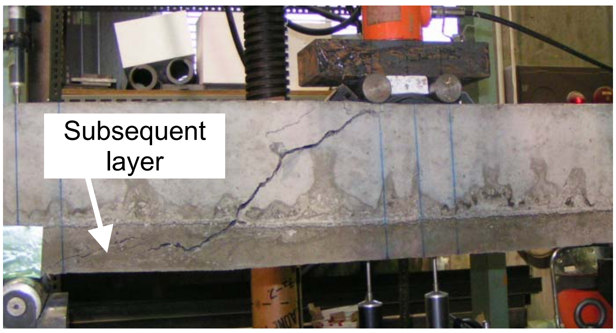


(b) With shear reinforcement

Figure 6: Relationship between shearing force and displacement of Series C specimens



(a) C3 (Tension side, without shear reinforcement)



(b) C7 (Compression side, with shear reinforcement)

Photo 3: Ultimate state of Series C specimens joint on the tension side caused delamination of the subsequent layer, including longitudinal bars on the tension side, from the previously placed concrete as shown in Photo 3. The added layer therefore acted like a tie element to bear the load.

Table 9 compares the calculated values and test results of maximum shear capacity, as a member, of each Series C specimen, as well as its components, the capacities of concrete and shear reinforcement. The shear capacity of concrete was calculated by the same way that of Series A specimens.

Figure 6 and Table 9 reveal that different flexural stress state at construction joints lead to different shear capacities. Within the range of these tests, the shear-strengthening effect is stronger when the stress state is tensile at the construction joint (C7) than when it is compressive (C6). The shear-strengthening effect of post-reinforcement as a member is found to be around 90% and 70% of that of C5 reinforced with standard stirrups when the construction joint is on the tension side (C7) and compression side (C6), respectively. As to the capacity of shear reinforcement, those of Specimen C7 with a construction joint on the tension side and C6 on the compression side are around 80% and 60%, respectively, of that of C5 with standard stirrup reinforcement, suggesting the adverse effect of insufficient anchorage at the ends of post-reinforcing bars.

Table 10 shows the shear sliding stress at construction joints calculated by the same way that of Series B specimens and whether or not shear sliding occurred along the construction joints. No distinct relationship was recognized between the occurrence of shear sliding and shear sliding stress as found in Series B specimens. This is presumably explained as follows: The shear-span-depth ratio of Series C specimens is as small as 2.64 when compared with 3.17 of Series B specimens. The load therefore affects the normal stress, which is perpendicular to the shear sliding plane, increasing the capacity against shear sliding.

Table 9: Test results of Series C specimens

Specimen	Calculated values			Test results								
	Maximum shear capacity Vyd(kN)	Shear capacity of concrete Vcd(kN)	Shear capacity of shear reinforcement Vsd(kN)	Cracking		Shear capacity			Comparison with calculated value		Comparison with Non-construction joint	
				Bending crack (kN)	Shear crack (kN)	Total capacity Vye(kN)	Concrete capacity Vce(kN)	Shear reinforcement Vse(kN)	Vye/Vyd	Vse/Vsd	Vye/Vye(1) & Vye/Vye(5)	Vse/Vse(5)
C1	57	57	–	40	45	53	53	-	0.93	-	1.00	-
C2	57	57	–	40	45	53	53	-	0.93	-	1.00	-
C3				40	50	55	55	-	0.96	-	1.03	-
C4	56	56	–	45	50	50	50	-	0.89	-	0.94	-
C5	99	57	42	40	45	111	53	58	1.12	1.39	1.00	1.00
C6	100	57	43	40	35	79	41	37	0.79	0.86	0.71	0.65
C7				40	50	103	55	48	1.02	1.11	0.93	0.83
C8	100	56	43	40	50	98	50	48	0.98	1.10	0.88	0.83

Table 10: Shear sliding stress at construction joints

Specimen	Caluculated values	Test results		
	τ_{csu} (MPa)	τ_{cs} (MPa)	τ_{cs}/τ_{csu}	Shear sliding
C1	-	-	-	-
C2	1.14	1.99	1.75	No
C3		2.05	1.80	Occurred
C4		2.51	2.20	No
C5	-	-	-	-
C6	2.04	2.95	1.45	No
C7		3.85	1.89	
C8		4.90	2.40	

τ_{csu} : Ultimate shear sliding stress at the construction joint
τ_{cs} : Shear slinding stress at the construction joint for failure load

4 CONCLUSIONS

4.1 Shear-strengthening effect of post-reinforcement

Post-reinforcement was found to have the following shear-strengthening effects:

- Post-reinforcement using straight bars with no hook is an effective method of shear-strengthening.
- When designing post-reinforcement using straight bars, it is necessary to allow for a 20% to 30% loss of their load-bearing capacity when compared with standard stirrups because of insufficient anchorage at the ends of the bars.
- The load-bearing capacity of post-shear-reinforcement tends to be affected by the flexural stress state at construction joints. Within the range of the present tests, the shear-strengthening effect of post-reinforcement was stronger when the stress at construction joints was tensile than when it was compressive.

4.2 Effect of post-reinforcement at construction joints

The following effects of post-reinforcement across the joint between old and new concretes were found:

- When a flexural member without shear reinforcement is partially replaced with new concrete, its failure mode can shift to shear failure after the yielding of tensile reinforcement, resulting in low toughness. It is therefore necessary, when repairing members where toughness is required, to add shear reinforcement to retain the toughness.
- When a reinforced concrete member that has a construction joint but has no shear reinforcement undergoes shear failure, such failure can abruptly progress involving shear sliding along the construction joint. The occurrence of shear sliding failure can be predicted by assessing the shear sliding stress at the construction joint. Note that shear sliding failure tends to occur in the ultimate state of flexural failure of a member with a shear-span-depth ratio exceeding 3.
- Arrangement of anti-sliding reinforcement is necessary for preventing shear failure involving abrupt shear sliding. Shear strengthening using post-reinforcing bars is also found effective in strengthening against shear sliding.
- The use of a SHCC for an added layer is an effective method of post-reinforcing when compared with the use of normal concrete, as SHCC not only increase the durability of members but also increase their toughness by 2 to 3 times.

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