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SHEAR RESISTANT PERFORMANCE OF VINYL-FIBER REINFORCED CONCRETE COLUMN

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ABSTRACT

It is known that vinyl-fiber contained in concrete is effective to enhance the ductility of concrete subjected to tensile force (generally called tension stiffening) and prevent explosion of concrete suffering from fire because numerous vapor paths are formed within concrete by melting of vinyl-fibers. In the paper, shear resistant performance of reinforced concrete columns mixed with vinyl-fibers was studied from the view of shear strength, deformation capacity and shear transfer mechanism. Vinyl-fiber contributed to restrain crack opening, confine core concrete in columns and ensure ductile behavior after shear strength, however hardly enhanced shear strength. Vinyl-fiber had no influence on truss mechanism, but was useful to maintain arch mechanism after shear strength because of its confining action to core concrete.

1. INTRODUCTION

Plain concrete cannot carry tensile force after occurrence of cracks because of its brittle characteristics. However, ductile deformation capacity will be provided for concrete by the mixture with steel- or vinyl-fibers. In the study, the availability of this improved concrete by mixing short vinyl-fibers, which seems to be useful for future reinforced concrete (RC) structures, was researched through column tests providing anti-symmetric bending moment at the top and bottom of a column. Shear resistant performance of vinyl-fiber reinforced concrete (called FRC) columns was studied by investigating shear strength, deformation capacity and shear resisting mechanism through tests. Vinyl-fiber concrete proves to be able to keep tensile strength up to large tensile deformation even after cracking. Light-weight vinyl-fiber reinforced concrete (called LFRC) column was also tested, which is beneficial to save resources and energy on the earth, to ascertain the applicability of LFRC to structural members of buildings in high seismicity zones.

2. OUTLINE OF TEST

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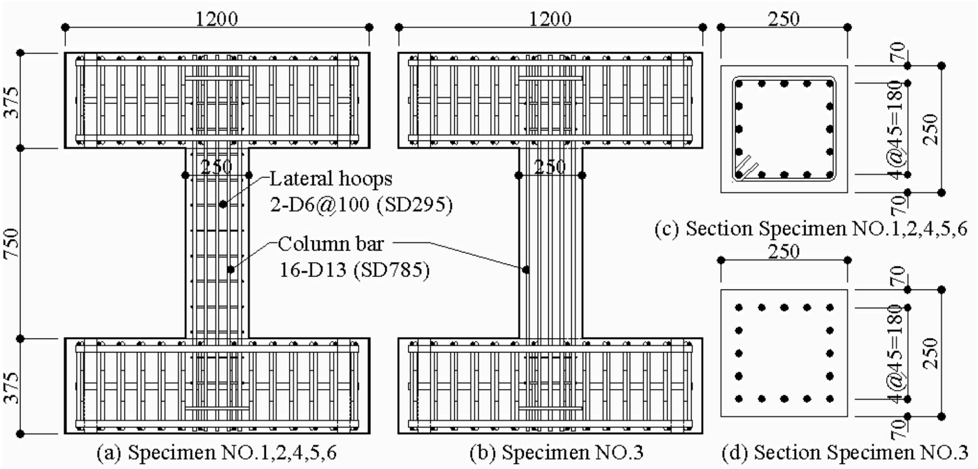
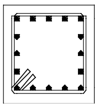
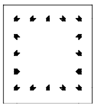
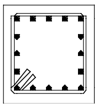


(a) Specimen NO.1,2,4,5,6 (b) Specimen NO.3 (c) Section Specimen NO.1,2,4,5,6 (d) Section Specimen NO.3

Fig. 1 Configurations and reinforcement details

Table 1 Properties of specimens, material properties and predicted strength

Specimen Number			1	2	3	4	5	6
Column section								
Concrete		Types	FRC	FRC	FRC	FRC	RC	LFRC
		Compressive strength [MPa]	39.7	76.8	40.5	40.5	37.1	42.1
		Splitting tensile streng [MPa]	3.4	5.0	3.4	3.4	2.8	2.7
		Young’s modulus [GPa]	30.0	33.5	29.0	29.0	27.6	16.1
Longitudinal bar		Arrangement	16-D13					
		Yield strength [MPa]	885					
		Gross ratio [%]	1.02					
Shear reinforcement		Arrangement	2-D6@100		none	2-D6@100		
		Yield strength [MPa]	343.4		none	343.4		
		ratio [%]	0.26		none	0.26		
Axial load (Comp. : positive)		N [kN]	784	735	784	-392	735	833
		Axial stress ratio	0.32	0.15	0.31	-0.15	0.32	0.32
Flexural strength		Q_{mu} [kN]	596.7	675.4	598.6	337.3	586.2	596.7
Shear strength	AIJ *1	Vu [kN]	209.3	251.6	153.7	199.1	153.0	202.1
	Arakawa *2	$Q_{su,min}$ [kN]	211.0	294.9	200.1	151.9	177.2	214.0
	Arakawa *3	$Q_{su,mean}$ [kN]	237.7	340.8	227.2	178.6	202.7	241.9

*1 AIJ provision (Ref.2), *2 Modified Arakawa minimum formula, *3 Modified Arakawa mean formula

2.1 SPECIMENS

Specimen configuration and reinforcing details are shown in Fig. 1. Properties of specimens and material properties of concrete and steel are summarized in Table 1. Six column specimens with one-third scale to actual frames were tested. Square column section (250 mm x 250 mm), shear span ratio of 1.5, the amount of longitudinal bars (16 deformed bars with 13 mm diameter) were common for all specimens. High-strength column longitudinal bars were arranged to cause shear failure prior to flexural yielding. Kind of concrete (plain, FRC and LFRC), nominal concrete compressive strength (35 MPa and 80 MPa), column

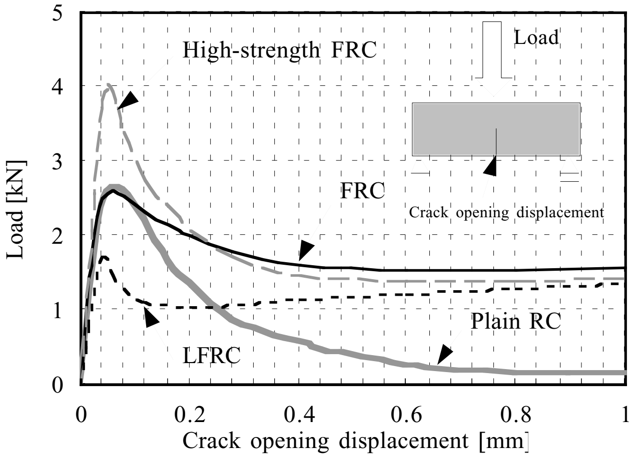


Fig. 2 Load- crack opening displacement relations tested by Kitsutaka

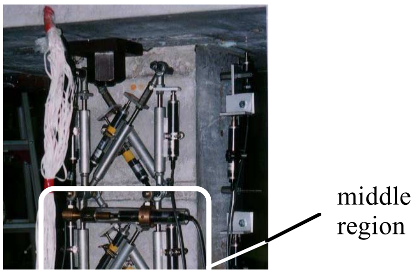


Fig. 3 Instrumentation for column

axial load (compression and tension) and the amount of shear reinforcement (none and 0.26 percent) were selected as test parameters. Control specimen No.1 was made of FRC with nominal concrete compressive strength of 35 MPa, had shear reinforcement ratio of 0.26 percent and was subjected to constant compressive axial stress of which ratio to concrete compressive strength was 0.32.

Short vinyl-fiber with 30 mm length and 0.66 mm diameter, whose fracture strength and Young's modulus was 900 MPa and 290GPa respectively, were used. The ratio of volume of vinyl-fibers to concrete was 1 percent taking account of workability of concrete mixing and casting. Compressive strength of FRC was 1.1 times greater than that of plain RC, while tensile strength by splitting test using cylinders with 100 mm diameter and 200 mm height was enhanced by vinyl-fiber mixture to 1.2 times that of plain RC. Weight of unit volume was 2.3 g/cm^3 for normal vinyl-fiber concrete and plain concrete, and 1.5 g/cm^3 for light-weight vinyl-fiber concrete. Artificial coarse aggregates with the diameter of 5 mm were used for LFRC. All kind of concrete was cast in horizontal position using wood form.

Load-crack opening displacement (COD) relations are shown in Fig. 2 for vinyl-fiber and plain concrete, which were obtained from simple beam tests conducted by Kamiyama and Kitsutaka [1] using 100mm-square and 400mm-length prisms with the notch of 50 mm depth at the center. Vinyl-fiber concrete and plain concrete was mixed by the same batch as FRC and RC column specimens. Vinyl-fiber concrete exhibited significant tension stiffening and ductile behavior due to fiber bridging across a crack while plain concrete showed brittle behavior after cracking.

2.2 LOADING METHOD AND INSTRUMENTATION

Reversed cyclic lateral shear force was applied to column specimens by an actuator so as to keep both stubs at the top and bottom of a column parallel through a pantograph. Constant compressive axial load except for Specimen No.4 was applied. Specimens were controlled by lateral drift angle for one cycle of 0.25 %, two cycles of 0.5 %, 1 %, 1. 5% and 2 % respectively, one cycle of 3 % and 4 %. However, monotonic lateral drift was forced up to the drift angle of 10% if shear resistant capacity degraded to less than half of shear strength.

Lateral drift of a column, and horizontal, vertical and diagonal local displacements of each region divided into three parts with equal height along a column were measured by displacement transducers as illustrated in Fig. 3. Strains of longitudinal bars and lateral hoops were measured by strain gauges.

2.3 PREDICTION OF STRENGTH

Flexural ultimate strength and shear strength were predicted before tests as listed in Table 1. Shear strength was computed according to provision of Architectural Institute of Japan (AIJ) [2]and modified Arakawa formulae. For the use of AIJ provision, judging from Fig. 2, the half of splitting tensile strength of vinyl-fiber concrete was taken into account to compute the contribution of truss action as expressed by Equation (3) mentioned later, where the term of σ_{ct} was replaced by $\frac{1}{2}\sigma_{cr}$ (σ_{cr} : splitting tensile strength of vinyl-fiber concrete). For modified Arakawa formulae, the contribution of shear reinforcement, i.e., $0.845\sqrt{p_w \sigma_{wy}}\, b \cdot j_t$ in unit of N (p_w : shear reinforcement ratio, σ_{wy} : yield strength of hoops in unit of MPa and $b \cdot j_t$: sectional area to resist shear effectively) was replaced by $0.845\sqrt{p_w \sigma_{wy} + \frac{1}{2}\sigma_{cr}}\, b \cdot j_t$.

3. TEST RESULTS

All specimens failed in shear without yielding of longitudinal bars. Crack patterns and shear

Table 2 Test results

Specimen Number			1	2	3	4	5	6
Flexural crack	Qmc	[kN]	159.6	107.5	158.7	-	134.3	143.2
Shear crack	Qsc	[kN]	246.3	264.4	232.9	-	206.2	143.2
Shear at hoop yielding	Qy	[kN]	247.2	294.5	-	141.3	223.0	185.7
	δy	[%]	0.77	0.80	-	1.00	0.65	0.50
Shear strength	Qmax	[kN]	247.5	299.7	238.9	166.8	225.3	185.7
	δmax	[%]	0.50	0.85	0.45	1.50	0.50	0.50
Limit state *1	Qu	[kN]	198.0	239.7	191.1	133.4	180.2	148.6
	δu	[%]	1.30	1.00	0.60	3.00	1.10	1.20

*1 Shear capacity and deformation at 20% degradation from shear strength in load-deformation envelope curve force-drift angle relations are shown in Fig. 4 and 5 respectively. Column shear force was corrected by taking P-delta effect due to column axial load into account. Test results are summarized in Table 2.

3.1 CRACK PATTERNS

Spall-off of shell concrete was prevented in FRC columns. At first, fine and short diagonal cracks occurred along the center of the column, then diagonal shear cracks were observed at both end regions for Specimen No.1 made of FRC. Bond splitting cracks along column longitudinal bars also developed under large drift loading. More diagonal cracks were observed in Specimen No.1 than Specimen No.5 made of plain concrete. In specimen No.3 made of FRC without shear reinforcement, primary diagonal shear crack occurred suddenly linking the top and the bottom of compressive zone at critical sections, and opened widely accompanying shear resistance decay. Number of cracks for Specimen No.3 was least among specimens. Crack patterns for Specimen No.6 made of LFRC were almost similar to those for Specimen No.1, however many fine cracks occurred over entire column surface.

3.2 SHEAR STRENGTH AND DUCTILITY

Shear strength was attained between drift angle of 0.5 % and 1 % immediately after development of primary diagonal shear crack except for Specimen No.4 subjected to tensile axial load at drift angle of 1.5 %.

Shear strength for Specimen No.1 made of FRC was enhanced to 1.10 times that for Specimen No.5 made of plain RC by the effect of vinyl-fibers. Shear resistant capacity for FRC Specimen No.1 decreased moderately after shear strength comparing with plain RC Specimen No.5.

Shear strength for Specimen No.3 made of FRC without shear reinforcement was almost same as that for FRC Specimen No.1 with lateral hoops, however shear resistant degradation was remarkable under cyclic loading after shear strength. This indicates that only use of vinyl-fiber of 1 percent content, without shear reinforcement, for RC columns failed in shear cannot contribute to maintain ductile behavior under earthquake loading.

Shear strength for Specimen No.2 made of high-strength FRC was only 1.21 times greater than that for Specimen No.1 although concrete compressive strength for former specimen was as high as 1.9 times that for later specimen.

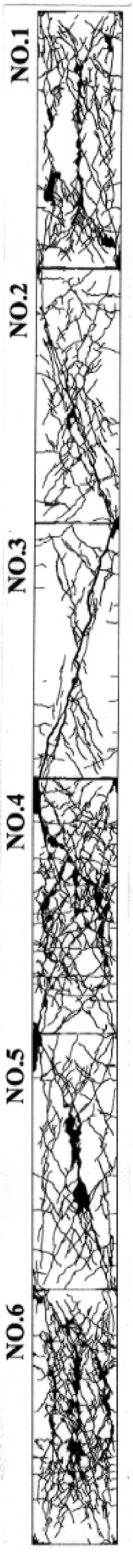


Fig.4 Crack patterns

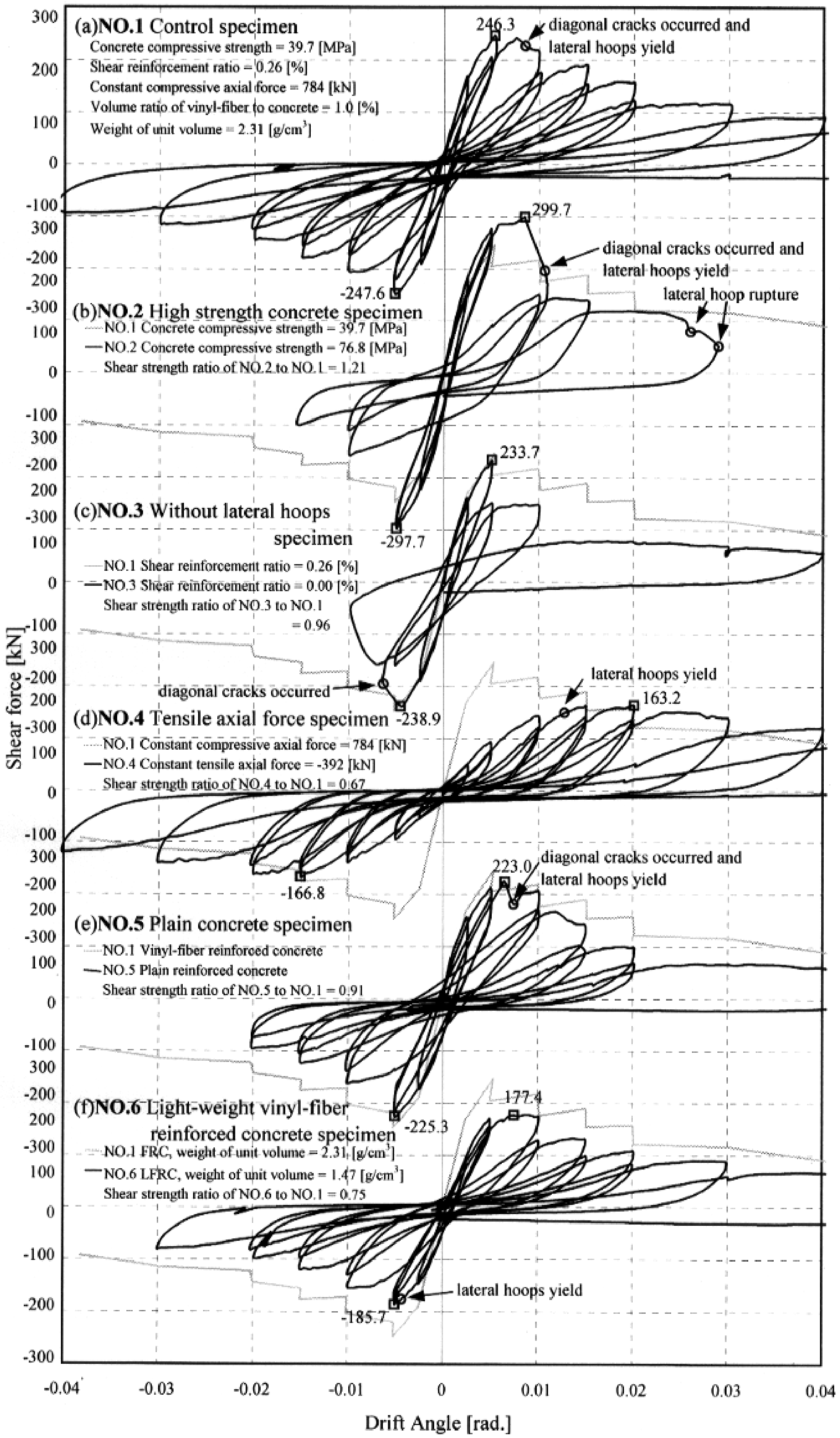


Fig. 5 Shear force - drift angle relations

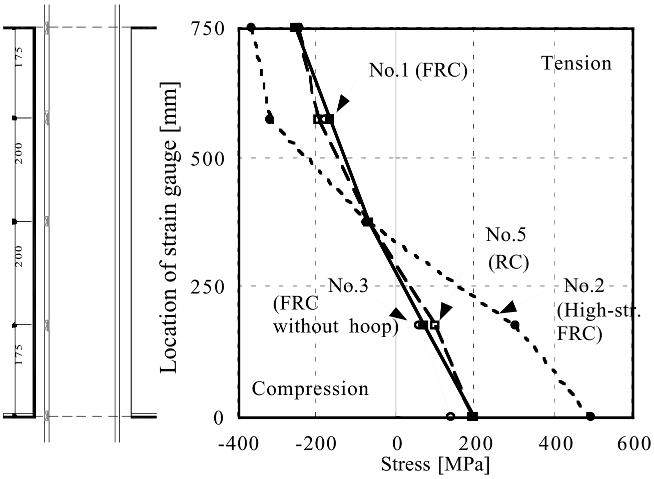


Fig. 6 Stress distribution along column bar

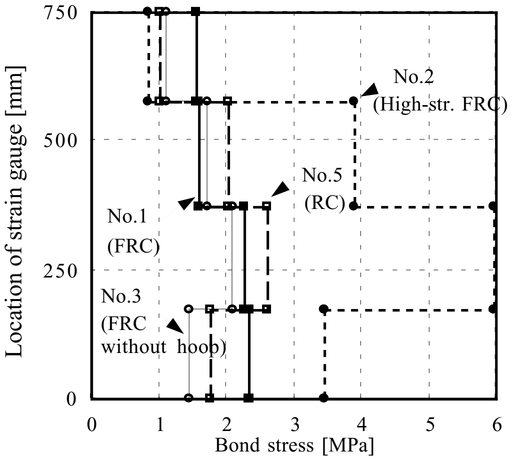


Fig. 7 Bond stress distribution along column bar

*0.86

For Specimen No.4 made of FRC subjected to axial tensile load, initial stiffness was very small comparing with FRC Specimen No.1 subjected to axial compressive load, and shear strength, which was attained at drift angle of 1.5 %, reduced to two-thirds that for Specimen No.1.

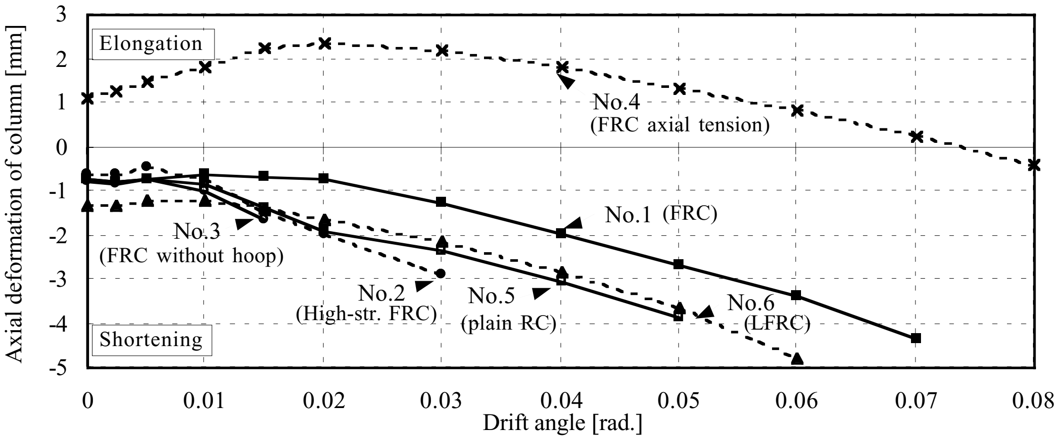
Initial stiffness for Specimen No.6 made of LFRC was only the half of FRC Specimen No.1 since the elastic modulus of light-weight vinyl-fiber concrete was approximately half of normal vinyl-fiber concrete. Shear strength for LFRC Specimen No.6 reached only three-quarters that for Specimen No.1.

3.3 STRAIN AND BOND STRESS DISTRIBUTION ALONG COLUMN BAR

Strain and bond stress distributions along column longitudinal bars are shown in Fig. 6 and 7 respectively. Bond stress was computed from strain difference between two adjacent strain-gauges. Column bars did not yield under cyclic loading. Maximum bond stress reached 2 to 3 MPa at drift angle of 1 % for normal-strength concrete specimens. It is supposed that columns failed in shear before bond stress reached the bond strength of 5.6 MPa computed according to AIJ provision [2].

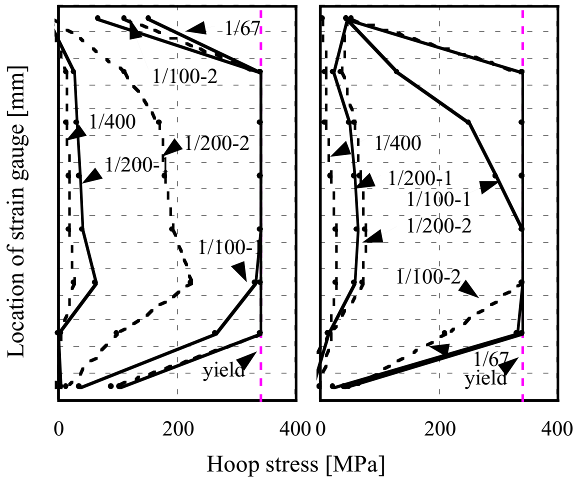
On the other hand, for Specimen No.2 made of high-strength FRC, maximum bond stress was approximately two times that for other specimens, reaching 4 to 7 MPa at drift angle of 1 % which is almost equal to bond strength of 6.5 MPa computed from AIJ provision.

3.4 AXIAL DEFORMATION OF COLUMN



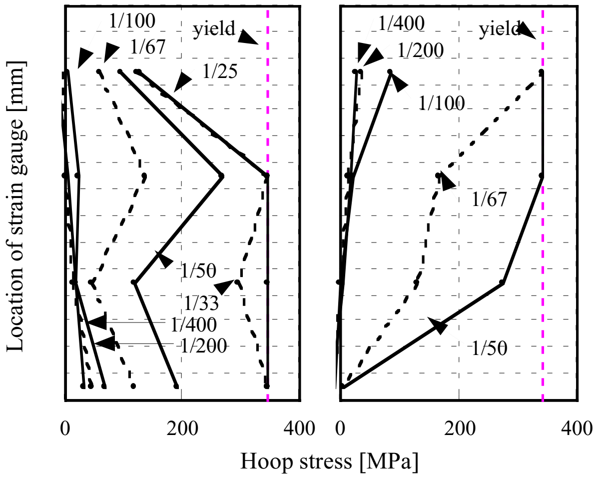
*0.90

Fig. 8 Axial deformation in column



(a) Specimen No.1 (FRC) (b) Specimen No.5 (RC)

Fig. 9 Stress distribution of hoops parallel to loading direction



(a) Specimen No.1 (FRC) (b) Specimen No.5 (RC)

Fig. 10 Stress distribution of hoops perpendicular to loading direction

Column axial deformation is shown in Fig. 8. For FRC Specimen No.1, almost constant compressive deformation was held up to drift angle of 2 %, then axial deformation went to considerable shortening. On the contrary, column axial deformation for plain RC Specimen No.5 showed tendency of remarkable shortening after drift angle of 1 %. Vinyl-fibers contained in plain concrete was effective to prevent severe collapse of a column.

4. DISCUSSIONS

4.1 EFFECT OF VINYL-FIBER

1) Stress in lateral hoops

Stress distributions of lateral hoops parallel to loading direction are shown in Fig. 9 for

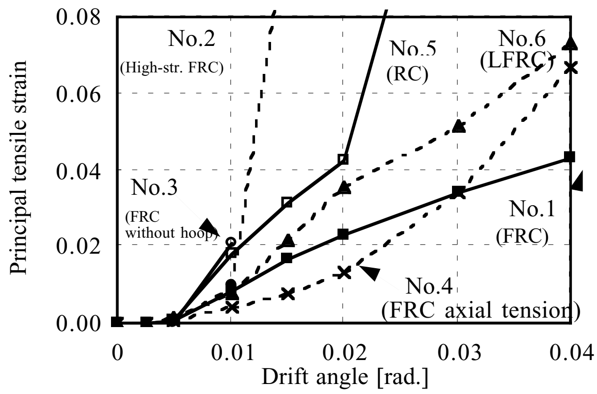


Fig. 11 Principal tensile strain in web concrete

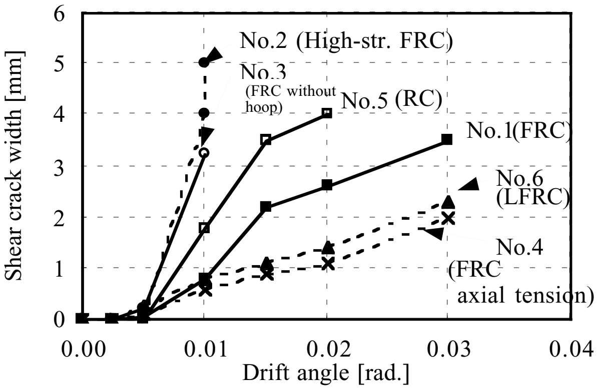


Fig 12 Shear crack width

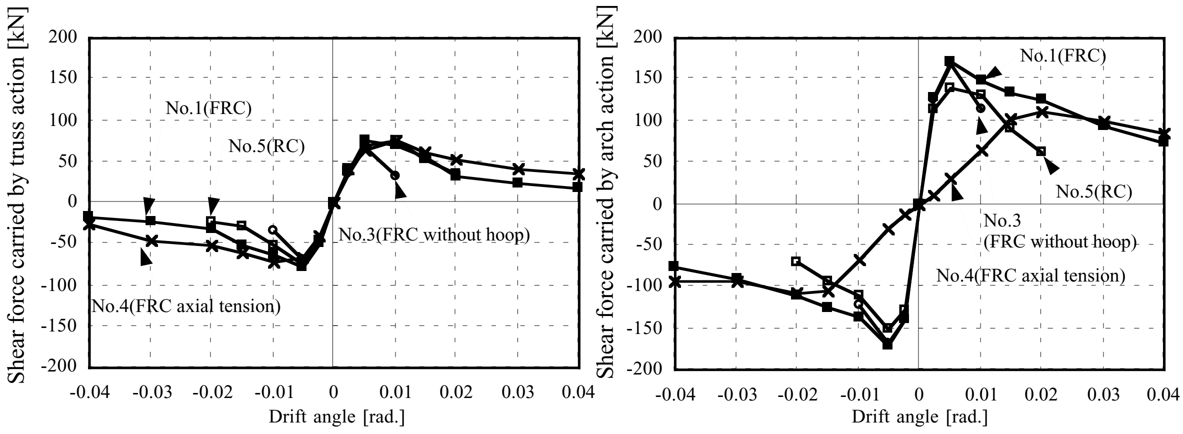
FRC Specimen No.1 and plain RC Specimen No.5. Hoops except for those close to top and bottom RC stubs yielded at drift angle of 1 % for all specimens.

Stress distributions of lateral hoops perpendicular to loading direction are shown in Fig. 10. Hoop stress was approximately 50 MPa for both specimens at drift angle of 1 % just after column shear strength. At drift angle of 1.5 % exhibiting shear strength degradation, hoop stress was 100 MPa for FRC Specimen No.1 whereas ranged between 120 MPa and yield stress (343 MPa) for Specimen No.5. Vinyl-fibers contributed to restrain concrete lateral expansion caused by progress of shear failure.

2) Principal tensile strain of concrete

Principal tensile strains of web concrete within middle region of a column are shown in Fig. 11. Principal strain was computed from horizontal, vertical and diagonal displacement measured by displacement transducers set as illustrated in Fig. 3. Principal strains are picked at drift angle of 1 % among Specimens No.1, No.3 and No.5. Principal tensile strain for FRC Specimen No.1 was approximately half of that for FRC Specimen No.3 without shear reinforcement and plain RC Specimen No.5. This indicates that vinyl-fiber contained in plain concrete was efficient to reduce the increase in tensile strain. The strains were almost same for Specimens No.3 (no hoops) and No.5 (no fibers). The effect of vinyl-fibers of 1 percent content on restricting principal tensile strain in web concrete seemed to be equivalent with confining effect by steel hoops of 0.26 percent content. From above comparison, vinyl-fibers cooperated with steel hoops in shear resistant performance under descending branch of shear capacity.

3) Shear crack width



(a) Truss contribution

(b) Arch contribution

Fig. 13 Truss and arch contributions to shear resistance

Maximum width of diagonal shear cracks is shown in Fig. 12 measured at peak displacement in each loading cycle. Crack widths for specimens made of normal concrete increased suddenly at drift angle of 1 %. The width for FRC Specimen No.1 was more restrained by vinyl-fibers than for plain RC Specimen No.5. Shear crack width for FRC Specimen No.4 subjected to tensile axial load was the smallest among specimens. The width for LFRC Specimen No.6 increased gradually and was smaller than for other specimens subjected to compressive axial load since many fine diagonal cracks occurred uniformly.

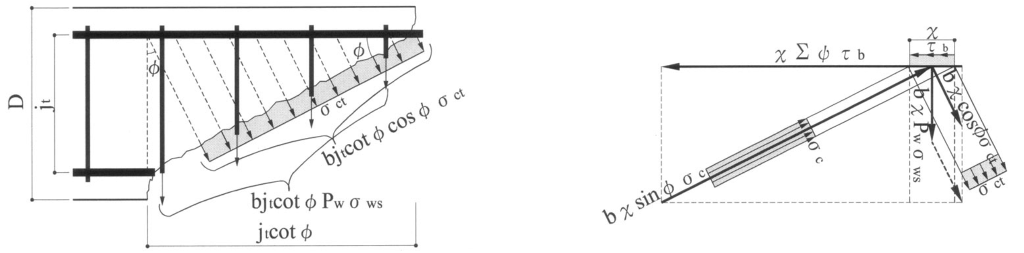
4.2 SHEAR RESISTING MECHANISM

Effect of vinyl-fibers mixed with plain concrete on shear resistant performance is discussed from studying on the contribution of truss and arch mechanism to shear resistance. Contribution of truss mechanism denoted as Q_{truss} was computed from Equation (1) by using measured bond stress along column longitudinal bars ;

$$Q_{truss} = n \cdot \psi \cdot \tau_b \cdot j_t \tag{1}$$

where n : number of column longitudinal bars in most outer layer, ψ : perimeter length of a column bar, j_t : distance between tensile and compressive column bars in opposite most outer layer and τ_b : bond stress along column bars which was obtained from tests as described at section 3.3. Contribution of arch mechanism denoted as Q_{arch} was taken by subtracting truss contribution from total shear capacity that was measured in the test as follows ;

$$Q_{arch} = Q_s - Q_{truss} \tag{2}$$



(a) Truss mechanism accounting for concrete tensile force across crack

(b) Force polygon for equilibrium at node

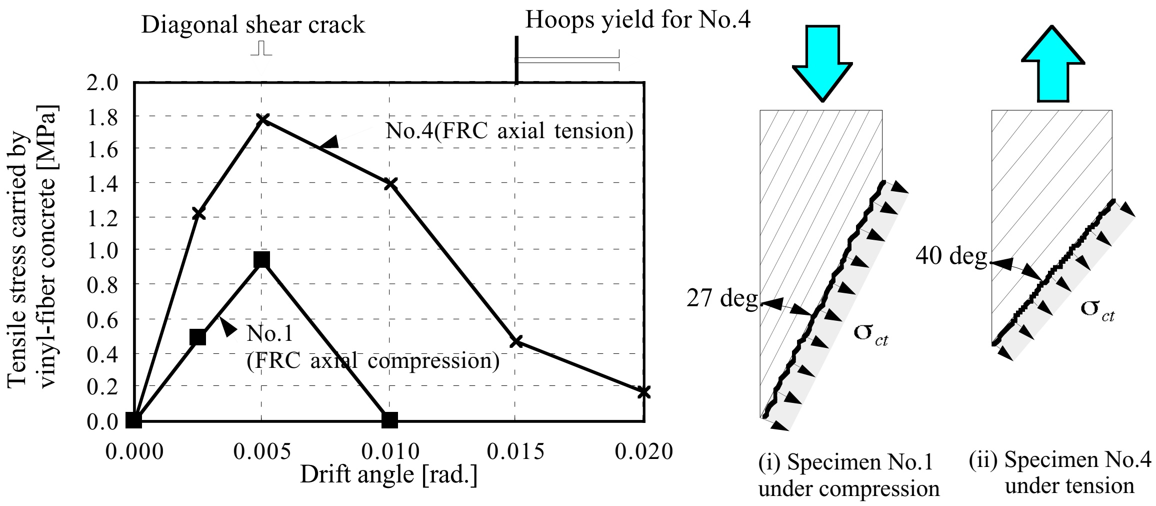
Fig. 14 Shear resisting mechanism of truss action in FRC

where Q_s is measured column shear capacity. Both contributions are shown in Fig. 13. Comparing with Specimens No.1 and No.5, truss contribution was almost same even after shear strength at drift angle of 1 %. This caused the difference of arch contribution between two specimens after shear strength, exhibiting that arch contribution for FRC Specimen No.1 decreased more moderately than for plain RC Specimen No.5. Vinyl-fibers did not enhance the resistance carried by truss mechanism in this test, however appeared to be efficient to maintain arch mechanism since reduction of concrete compressive strength due to tensile strain orthogonal to diagonal compressive strut may be prevented.

On the assumption that uniform compression field is formed in web concrete with the inclination of ϕ as shown in Fig. 14, shear resistance carried by truss mechanism is computed taking account of tensile stress of vinyl-fiber concrete as Equation (3) ;

$$Q_{truss} = b \cdot j_t \cot\phi \cdot \left(p_w \sigma_{ws} + \cos^2\phi \cdot \sigma_{ct} \right) \tag{3}$$

where b : column width, p_w : shear reinforcement ratio by lateral hoops, σ_{ws} : stress in lateral hoops, which was obtained from measured strains and σ_{ct} : tensile stress developed by vinyl-fiber concrete. Quantity of Q_{truss} in left-hand side of Equation (3) could be taken alternatively by Equation (1). Hence σ_{ct} can be computed from Equation (3) even after occurrence of diagonal shear cracks. Tensile stress carried by vinyl-fiber concrete across diagonal cracks is shown in Fig. 15 for FRC Specimen No.1 under axial compression and FRC Specimen No.4 under axial tension. In calculation of right-hand side of Equation (3), the inclination of diagonal uniform struts in web concrete was chosen from primary crack inclination observed in tests as $\phi = 26.6\text{ deg.} \left(\cot\phi = 2.0 \right)$ for Specimen No.1 and $\phi = 39.8\text{ deg.} \left(\cot\phi = 1.2 \right)$ for Specimen No.4.



(i) Specimen No.1 under compression

(ii) Specimen No.4 under tension

Fig. 15 Tensile stress carried by vinyl-fiber concrete across crack

Tensile stress carried by vinyl-fiber concrete reached the maximum value of 0.9 MPa for Specimen No.1 and 1.8 MPa for Specimen No.4 at drift angle of 0.5 % corresponding to occurrence of primary diagonal shear crack. Tendency of tensile stress after drift angle of 0.5 % was quite different between two specimens. Tensile stress in Specimen No.1 decreased considerably and contribution of vinyl-fibers disappeared after drift angle of 1 %, whereas tensile stress in Specimen No.4 diminished moderately and reached approximately zero stress at drift angle of 1.5 % when lateral hoops began to yield. This indicates that vinyl-fibers contained in plain concrete contributed to truss action in the column subjected to tensile axial load. However the point that vinyl-fibers developed the full effectiveness to transfer of tensile stress was not coincident with the point that lateral shear reinforcement developed full capacity, i.e., yielding.

5. CONCLUSIONS

Shear resistant performance of vinyl-fiber reinforced concrete columns was studied in the paper. Following concluding remarks were drawn.

(1) Vinyl-fiber contributed to restrain crack opening, confine core concrete in columns and ensure ductile behavior after shear strength, however hardly enhanced shear strength.

(2) Vinyl-fiber contained in a column subjected to axial compressive load had no influence on truss mechanism, but was useful to maintain arch mechanism after shear strength because of its confining action to core concrete.

(3) On the other hand, vinyl-fiber contributed to truss mechanism up to the onset of hoop yielding in a column subjected to axial tensile load.

(4) Both initial stiffness and shear strength in light-weight vinyl-fiber concrete column was inferior to those in normal-weight vinyl-fiber concrete column. In order to judge the applicability of LFRC to actual buildings, however, it is necessary to investigate the influence of reducing dead load, which is significant advantage of the use of light-weight vinyl-fiber concrete, on earthquake response of LFRC buildings.

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