BEHAVIOR OF PRETENSIONED CONCRETE BEAMS USING STEEL-FIBER REINFORCED CONCRETE

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SUMMARY
Steel-fiber reinforced concrete (SFRC) shows pseudo-strain-hardening behavior caused by uniform distribution of multiple cracks under tensile stress. SFRC is expected to enhance the tensile properties such as strength and stiffness of the resulting composite material. Pretensioned members have been used to control crack width and deflection under service load. Prestressing force applied on them is generally smaller than the one on post-tensioned members. However, the construction cost of pretensioned members is lower than the one of post-tensioned members because they do not need anchorage devices. Prestressed concrete members are considered less ductile than ordinary reinforced concrete members. In this study flexural performance to be enhanced by pretension technology and SFRC is discussed. Cyclic loading tests were conducted on pretensioned beams using steel-fiber reinforced concrete, where the main parameter was the volumetric ratios of fibers: 0.0, 0.3 and 0.5%. The tests showed that the maximum flexural strength and the initial cracking load of the beams with steel-fiber increased at most 16.4% over the beams without steel-fiber.

Keywords: steel-fiber reinforced concrete, prestressed concrete, pretension, flexural strength, crack

1. INTRODUCTION

In recent years, Fiber Reinforced Concrete (hereafter referred to FRC) material has been developed and studied for application to structural members. A property of this material is Pseudo-Strain-Hardening behavior (hereafter referred to PSH behavior) caused by the distribution of multiple fine cracks under tensile stress (Kunieda et al. 2006, Suwada et al. 2006, 2007, Fisher et al. 2003). Fibers have been used to enhance tensile characteristics of concrete by surpressing crack growth and improving mechanical behavior (Bilal S. 2001). Concrete with fibers is characterized by its fiber content. The fiber content is the weight of fibers per unit volume in concrete; it is the product of the volume fraction V_f (volume of fibers per unit volume of concrete) and the specific gravity of the fibers. It is still uncertain how the tensile characteristics of FRC affect the flexural resistance mechanism of structural elements (Suwada 2006). Various analytical and empirical methods have been proposed to predict the flexural strength of the composite material reinforced with fibers (Swamy 1982, Henager 1976). Of all the fibers currently in use to reinforce cement matrices, steel-fibers are the only fibers that can be used for carrying long-term load (Swamy et al. 1982, Padmarajaiah et al. 2001).

Prestressed concrete requires the concrete to attain high compressive strength at an early age. In addition to its higher compressive strength, high-strength concrete possesses an increased tensile strength, and reduced shrinkage and creep strains than normal-strength concrete. High-strength concrete has been found, however, to be more brittle when compared to normal-strength concrete. Inclusion of fibers is one way to alleviate the problem of brittleness in high-strength concrete. Pretensioned members have been used to control crack width and deflection under service load. Prestressing force applied on them is generally smaller than the one of post-tensioned members. However, construction cost of pretensioned members is lower than the one of post-tensioned members

Table 1.1. The advantages and disadvantages of SFRC and pretensioned member

	Advantages	Disadvantages
SFRC	Smaller crack width enhancing durability more ductile	Constructability Cost
Pretensioning	Smaller residual deformation Smaller crack width	Brittle failure in compressed concrete

because they do not need anchorage devices. SFRC are expected to improve the toughness and the failure mode of pretensioned members.

Table 1.1 summarizes the advantages and disadvantages of SFRC and pretensioned members. In order to overcome each disadvantage the synergy between SFRC and pretensioning is expected to be one of the solutions. The present paper reports the influence of steel-fibers on the ultimate flexural strength, first cracking load and maximum crack width in flexure of pretensioned beams containing steel-fiber of 0.0, 0.3 and 0.5% in volumetric ratio.

2. EXPERIMENTAL PROGRAM

The main objective of the test program was to examine the enhancement in flexural strength and ductility of pretensioned beams in the presence of fibers.

2.1 Details of Test Beams

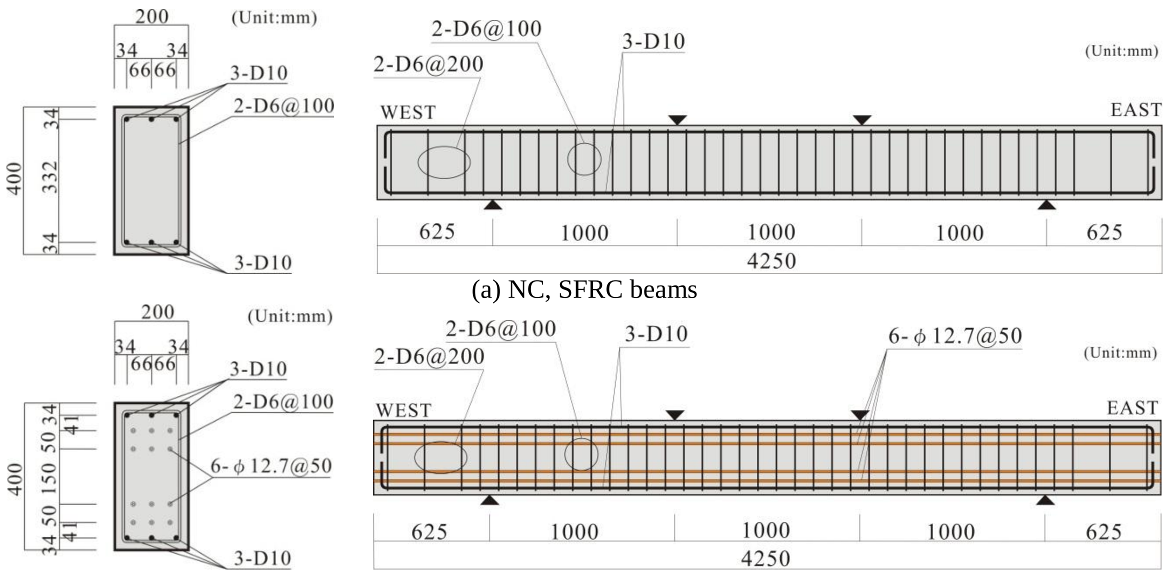
The test specimens are summarized in **Table 2.1** with the effective prestressing force P_e and the effective prestressing ratio η (=$P_e/(bDf_c')$). The effective prestressing force P_e and the ratio η were calculated based on the strain measured immediately before loading by the strain gauges attached to the strands. Five specimens were constructed; one reinforced concrete beam without steel-fiber, two steel-fiber reinforced concrete beams and two pretensioned beams using SFRC.

The cross sections of all beams were of the same size, 200 x 400 mm and the total length of 4,250 mm as shown in **Figure 1**. The beams were simply supported. The main variable in the tests was the volume fraction of steel-fiber; 0.0, 0.3 and 0.5 percent. All the specimens were designed to fail in concrete crashing after tensile reinforcement yielded. The prestressing tendons used in the tests were 12.7 mm diameter strands. The prestressing force was introduced to the beams one day after concrete casting. Thereafter, the specimens were removed from the pretensioning bed and moist-cured for 28 days.

Table 2.1. Steel-fiber contents and Effective prestressing forces

Specimen	V_f^{*1} (%)	P_e^{*2} (kN) (η^{*3})
NC	0.0	Non-prestressed
SFRC03	0.3	
SFRC05	0.5	
PreSFRC03	0.3	1,150 (0.264)
PreSFRC05	0.5	1,178 (0.264)

*1: volume fraction of fibers, *2:effective prestressing force at the time of testing, *3:ratio of effective prestressing force (=$P_e/(bDf_c')$)



(a) NC, SFRC beams

(b) PreSFRC beams

Figure 1. Details of specimen

2.2 Details of Materials

The base concrete mixtures were designed to give the compressive strength of 60 N/mm^2 at 28 days. The identical concrete mixture except for water reducing admixture and air entraining agent shown in **Table 2.2** was used for all specimens. The compressive and splitting tensile strengths at the time of testing are summarized in **Table 2.3**. The compressive strengths of the plain and steel-fiber reinforced concretes varied from 54.4 to 66.2 N/mm^2. The splitting tensile strength of the plain concrete was 4.77 N/mm^2 while the one of SFRC concretes varied from 4.50 to 4.85 N/mm^2 with 0.3 and 0.5 percent fiber volume contents.

Figure 2 and **3** show stress-strain relations in compression and tension. The average strain in tension was measured by a 60mm strain gauge attached horizontally across a vertical crack.

Table 2.2. Design of mix proportion

Concrete	Design strength (N/mm^2)	V_f (%)	Slump (mm)	W/C (%)	Air (%)	Water (kg/m^3)	Cement (kg/m^3)	Aggregate (kg/m^3)		Admixture (kg/m^3)	
								S^{*1}	G^{*2}	W.R.A.^{*3}	A.E.A.^{*4}
NRC	60	0.0	15.0	42.0	4.5	158	376	805	943	1.88	0.19
SFC03		0.3								2.44	0.00
SFC05		0.5								3.16	

*1: fine aggregate, *2: coarse aggregate, *3: water reducing agent, *4: air entraining agent

Table 2.3. Concrete mechanical properties at the time of testing

Specimen	Concrete	Compressive strength, f_c' (N/mm^2)	Splitting tensile strength, f_t (N/mm^2)	Secant of elasticity at 1/3 f_c', E_c ($\times 10^4$ N/mm^2)	Poisson's ratio
NC	NRC	66.2	4.77	3.12	0.193
SFRC03	SFC03	65.9	4.80	3.40	0.184
SFRC05	SFC05	62.8	4.85	3.48	0.217
PreSFRC03	SFC03	54.4	4.50	3.55	0.214
PreSFRC05	SFC05	55.8	4.52	3.28	0.209

*The batch was different in SFRC03 and PreSFRC03, and in SFRC05 and PreSFRC05 although their mixtures were the same.

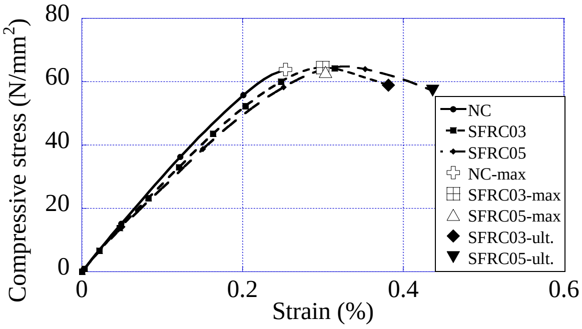


Figure 2. Compressive strength – strain

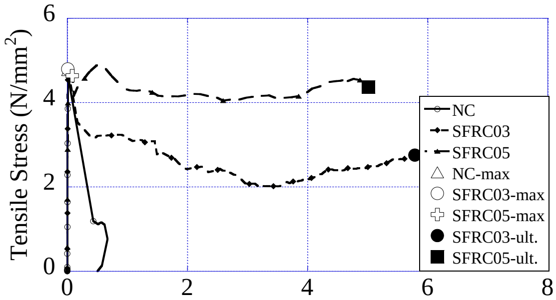


Figure 3. Splitting tensile strength – strain

Table 2.4. Properties of reinforcement

Reinforcement	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Young's modulus ($\times 10^5$ N/mm^2)
D6 (SD295)	425	516	1.90
D10 (SD295)	368	515	1.89
ϕ 12.7(SWPR7BL)	1,793	1,975	1.96

Table 2.5. Properties of steel-fiber

Length and diameter (mm x mm)	Tensile strength (N/mm^2)	Young's modulus ($\times 10^5$ N/mm^2)	Specific gravity	Aspect ratio
ϕ 0.62$\times$30	1,050	2.06	7.85	48.4

The compressive strain at the compressive strength of NC, SFRC03 and SFRC05 were 0.253, 0.299 and 0.303%, respectively. The strain at the peak splitting tensile strength of NC, SFRC03 and SFRC05 were 0.84, 0.83 and 0.84 % as shown in **Figure 3**. SFRC was tougher than NC after the peak load. NC lost the strength immediately after it reached the strength in the compressive and splitting tensile tests.

Table 2.4 shows the mechanical properties of the reinforcements and prestressing strands. The average yield strengths of D6 and D10 were 425 and 368N/mm^2, and Young's modulus were 1.90 x 10^5 and 1.89 x $10^5 N/mm^2$, respectively. D6 was used for the stirrups and D10 for the longitudinal bars. All the specimens had the same longitudinal rebar ratio of 0.29% and the shear reinforcement ratio of 0.31%. The reinforcement ratio at balanced failure of NC/SFRC and PreSFRC were 4.68 and 1.37%, respectively. Therefore, in NC and SFRC beams, steel-fiber was expected to enhance the flexural strength while in the prestressed beams it was not expected to increase the flexural strength because the flexural strength was reached by concrete crashing before the reinforcement yielding. Prestressing strands were 7-wire strands of 12.7 mm diameter with yield strength of 1,793 N/mm^2 and Young's modulus of 1.96 x 10^5 N/mm^2. **Table 2.5** shows the properties of steel-fibers. The volume fractions of 0.3% and 0.5% corresponded to fiber contents of 23.5 and 39.5 kg/m^3, respectively.

2.3 Loading

The loading tests on all five beams were conducted 48 to 74 days after concrete casting. The loading setup is illustrated in **Figure 4**. **Figure 5** shows the location of displacement transducers and strain gauges. Displacement controlled cyclic loading was applied. The first loading cycle was up to R=0.1%, and was followed by a series of member rotation controlled cycles comprising two full cycles to each of the member rotation of 0.25%, 0.5%, 0.75%, 1.0%, 2.0%, 4.0% and 6.0%.

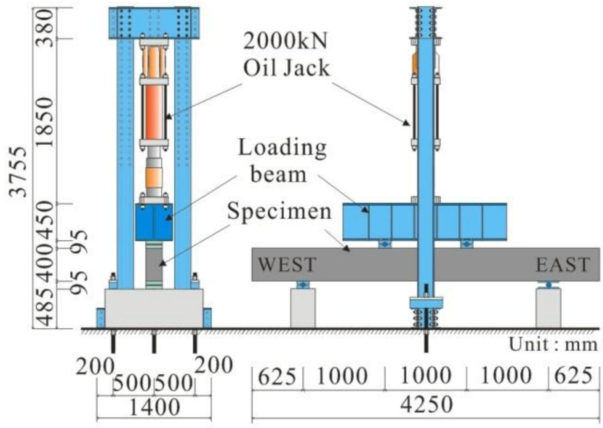


Figure 4. Loading setup

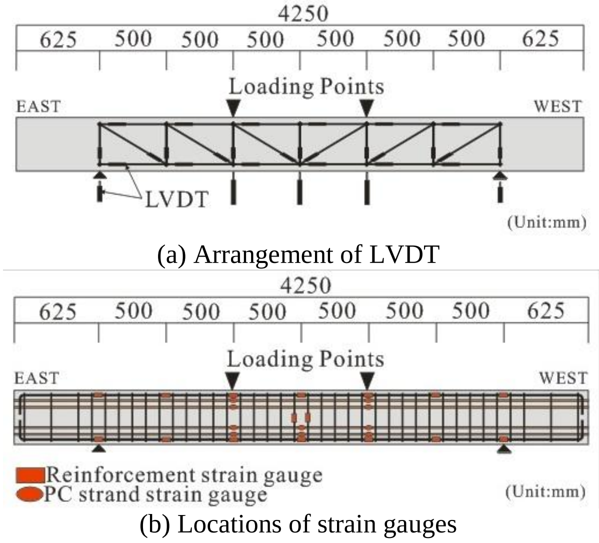


Figure 5. Locations of LVDTs and strain gauges

3. TEST RESULTS

Table 3.1 summarizes the test results of all beams;

Yield: the measured strains of longitudinal mild steel rebar or prestressing strands reached the yield strains.

Maximum: the maximum load was attained.

Ultimate: the load reduced to 80% of the maximum load or longitudinal reinforcement fractured.

Figure 6 shows the load-deflection curves of all beams. NC and SFRC03 could not be loaded up to failure because of the limitation of the oil jack stroke. SFRC05 failed at smaller deflection due to fracture of the tensile reinforcement than NC and SFRC03. In SFRC05 the deformation concentrated at one particular crack, where the reinforcement fractured.

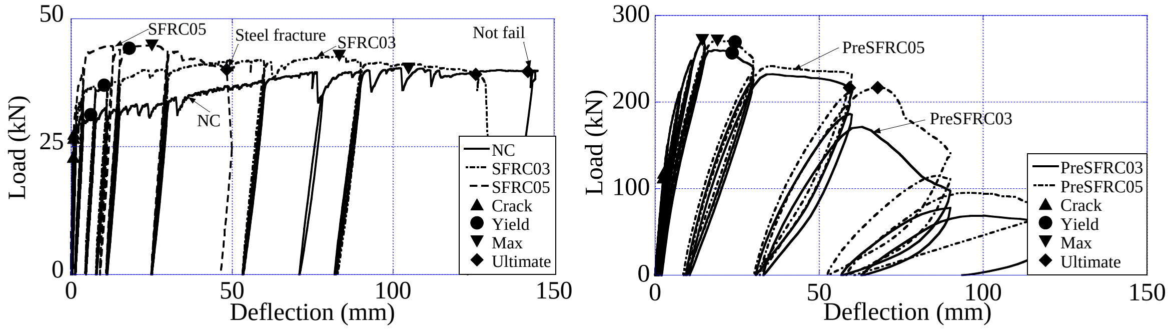
Figure 7 shows the envelope curves of the load-deflection curves indicated in **Figure 6**. To see how large toughness due to steel fiber was obtained the areas under the envelope curves were calculated and compared. The areas of NC, SFRC03 and SFRC05 were 5,172 kN.mm, 4,964 kN.mm and 1,730 kN.mm, respectively while PreSFRC03 and 05 were 13,290 kN.mm and 15,374 kN.mm. Toughness improvement due to steel fiber could not be observed because of the oil jack stroke limitation in NC, and the premature fracture of longitudinal bar in SFRC05. In the pretensioned members it was revealed that steel fiber improved toughness of the member by about 13.6%.

Difference between the yield and the ultimate deflections of PreSFRC03 and PreSFRC05 were 35.8 and 43.5 mm, respectively. The yield deflections were almost the same while the ultimate deflection of

Table 3.1. - Test results

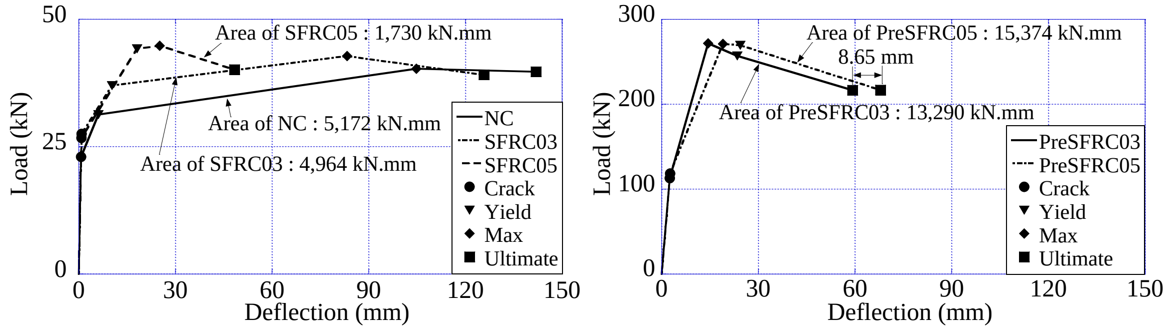
Specimen	First cracking		Yield*1		Maximum*2		Ultimate	
	Q_{crack} (kN)	δ_{cr} (mm)	Q_{yield} (kN)	δ_{yield} (mm)	Q_{max} (kN)	δ_{max} (mm)	Q_{ult} (kN)	δ_{ult} (mm)
NC	23.0	0.72	31.3	6.10	40.3	104.8	--	--
SFRC03	27.5	0.91	37.0	10.3	42.8	83.3	39.1*3	125.7*3
SFRC05	26.7	0.80	44.2	18.1	44.8	25.1	40.1*4	48.3*4
PreSFRC03	113.0	2.54	256.9	23.5	271.7	14.4	216.4*5	59.3*5
PreSFRC05	118.4	2.62	269.4	24.4	271.0	19.0	216.6*5	67.9*5

*1: at the yield of PC strand or rebar, *2: at reached the peak load, *3: at the decay of strength rapidly, *4: at the steel fracture, *5: at the load reduced to 80% of the Q_{max}



(a) NC, SFRC03, SFRC05 (b) PreSFRC03, PreSFRC05

Figure 6. Load - deflection curves



(a) NC, SFRC03, SFRC05 (b) PreSFRC03, PreSFRC05

Figure 7. Comparison of toughness

PreSFRC05 was 8.65 mm larger than the one of PreSFRC03. Improvement in ductility due to steel -fiber observed in the tests was smaller than expected.

3.1 First Flexural Cracking Load

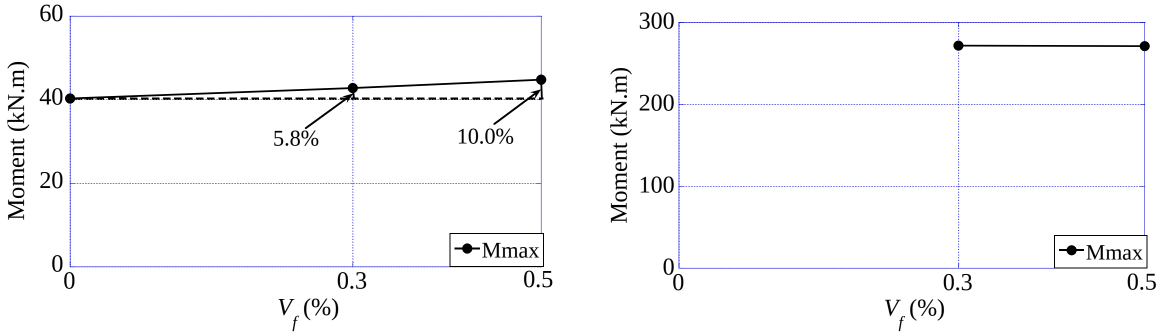
The first flexural crack in all the beams occurred in the constant moment region on the tension side of the beam. As the load increased, cracks formed over the entire length of the constant moment region. In NC and SFRC05 flexural cracking was initiated at the center of the constant moment zone in the first loading cycle to 0.05% while in SFRC03 it was initiated in the second loading cycle to 0.1%. Increment in the first cracking strength was not expected because there was no difference in the splitting tensile strengths. However, the first crack strengths of SFRC03 and SFRC05 were bigger than NC about 16.4% and 13.9%, respectively. PreSFRC05 had 4.6% bigger cracking strength than PreSFRC03 with 0.2% larger volume of fibers.

3.2 Flexural Strength

Figure 8 shows the maximum flexural strength – volume fraction of fiber relations. The figure indicates that at most 10% larger maximum flexural strength was obtained by 0.5% volumetric ratio of steel-fiber. However, the maximum strengths of PreSFRC03 and PreSFRC05 were almost the same in spite of 0.2% volume difference in the fiber contents. Steel-fiber is expected to reinforce both compression and tension sides of the beam section. Steel-fiber partly plays a role of longitudinal reinforcement, which may increase flexural strength of the beam section. This is more significant in a beam which fails in tension. For a beam section which tends to fail in compression such as the pretensioned beams in this study, improvement in flexural strength is less significant.

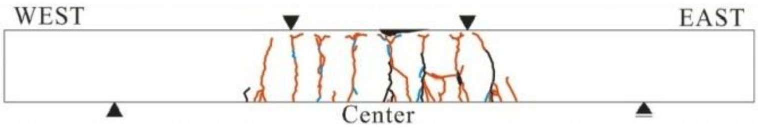
3.3 Crack Characteristics

Figure 9 illustrates the specimens observed at the end of loading. Cracks in NC, SFRC03 and SFRC05 developed up to the extreme compression fiber of the beam section as shown in **Figure 9(a) ~ (c)**. Reinforcement ratios of these beams were small and the neutral axis depth was also small.

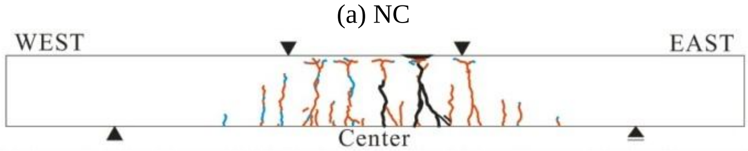


(a) NC, SFRC03, SFRC05 (b) PreSFRC03, PreSFRC05

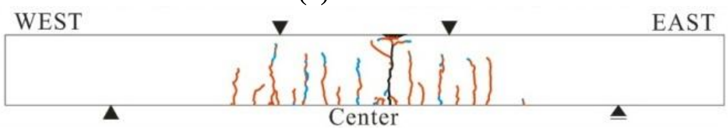
Figure 8. Maximum flexural strength - V_f relations



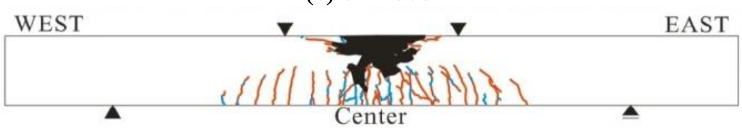
(a) NC



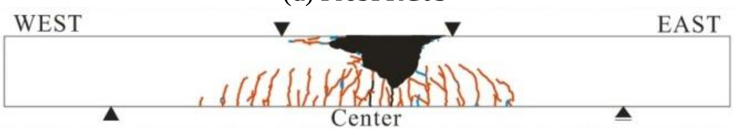
(b) SFRC03



(c) SFRC05



(d) PreSFRC03



(e) PreSFRC05

Figure 9. Cracking after testing

Only one crack developing up to the extreme compression fiber in the mid-span of the beam was observed in SFRC05, which resulted in fracture of the longitudinal reinforcement. The larger amount of steel-fiber was provided, the more cracks were expected. However, not so large difference was seen in the number of cracks in NC, SFRC03 and SFRC05. In the pretensioned members, larger number of cracks were observed, which showed more effect of steel fibers on crack development than the reinforced concrete beams.

In order to verify the effect of steel-fibers on crack width control, the maximum crack widths under service load were compared. The maximum crack widths of NC, SFRC03 and SFRC05 at the load 25 kN were 0.17, 0.16 and 0.13mm, respectively. SFRC03 and SFRC05 show the effect of crack width controlled by steel-fiber reinforcement. However, the maximum crack widths of PreSFRC03 and PreSFRC05 at the load of 150 kN were almost the same crack widths, 0.106 and 0.105mm, respectively. Comparison of crack widths between the reinforced concrete beams and the pretensioned beams indicated that crack widths have been suppressed by PC strands.

4. ANALYTICAL INVESTIGATION BY METHODS PROPOSED IN PAST

Several methods have been developed to empirically or analytically predict the ultimate flexural strength of beams reinforced with mild steel bars and steel-fibers. In this study, the methods proposed by Swamy and Henager are examined.

A method by Swamy employs the law of mixtures and take into account a random distribution factor, bond stress, fiber stress and other factors. Swamy proposed the ultimate flexural strength of SFRC shown in Equation (1).

$$M_u = F_c(d_n - k_2) + F_{sc}(d_n - d') + F_{st}(d - d_n) + F_{ft}\frac{(D - d_n)}{2} \cdots\cdots\cdots\cdots (1)$$

in which F_c = concrete compression force; F_{sc} = force in compression steel; F_{st} = force in tension steel or force in PC strand; F_{ft} = force in fibers in tension zone; d_n = depth of neutral axis; d' = depth of compression steel or PC strand; k_2 = depth of centroid of compression block.

Henager has presented an analytical method to predict the ultimate flexural strength of steel-fiber concrete beams with bar reinforcement in which the bond stress, fiber aspect ratio, and volume fraction of fibers were taken into account. Henager proposed the ultimate strength of SFRC by Equation (2).

$$M_u = A_s \cdot \sigma_y\left(d - \frac{a}{2}\right) + \sigma_t \cdot b(h - e)\left(\frac{h}{2} + \frac{e}{2} - \frac{a}{2}\right) \cdots\cdots\cdots\cdots (2)$$

in which A_s = area of tensile rebars or PC strand; σ_y = yield stress of rebar or PC strand; d = effective depth of cross section; a = depth of rectangular stress block; σ_t = tensile stress of fiber reinforced concrete; b = width of cross section; h = height of cross section; e = distance from extreme compression fiber to top of tensile stress block of fibrous concrete.

Table 4.1 summarizes the analytical results of Equations (1) and (2). In this paper, in order to apply these equations to the pretensioned members, a term considering PC Strand's contribution was included. The equations give a conservative estimation in general.

The contribution of the fibers to the flexural strength was calculated. The fiber contribution ratios of SFRC03 and SFRC05 were 2.54% and 4.94%, respectively by Equation (1), and 5.31% and 9.75%, respectively by Equation (2). The test results showed that 5.8% in SFRC03 and 10.0% in SFRC05 were obtained as an enhancement of flexural strengths. The results agreed well to the ratios obtained from Equation (2). The difference in calculation of PC strand contribution between these equations is the position of F_{ft}. As for the pretensioned beams, the steel-fiber contributions to flexural strengths are 0.13% for PreSFRC03 and 0.24% for PreSFRC05 by Equation (1), and 0.34% and 0.66%, respectively by Equation (2). The steel-fiber contribution was not significant as observed in the loading tests.

Table 4.1. – Comparison of calculated ultimate flexural moments and test results

Specimens	Swamy	Henager	Test results		Swamy / Test		Henager / Test	
	M_{swa} (kN・m)	M_{hen} (kN・m)	M_{max} [*1] (kN・m)	$M_{0.3\%}$ [*2] (kN・m)	M_{swa} /M_{max}	M_{swa} /$M_{0.3\%}$	M_{hen} /M_{max}	M_{hen} /$M_{0.3\%}$
SFRC03	30.3	30.3	42.8	41.3	0.71	0.73	0.71	0.73
SFRC05	31.8	32.1	44.8	44.8	0.71	0.71	0.72	0.72
PreSFRC03	245.4	258.4	271.7	245.4	0.90	1.00	0.95	1.05
PreSFRC05	246.9	260.8	271.0	254.2	0.91	0.97	0.96	1.03

*1: moment at reached peak load, *2: moment when concrete strain is 0.3%

5. CONCLUSIONS

This paper presents experimental data on the maximum flexural strength, the cracking behavior of steel-fiber reinforced concrete beams and pretensioned beams using steel-fiber reinforced concrete. The following conclusions are derived from the experimental results.

1. The presence of fibers did affect the flexural cracking load of SFRC. At most 16.4% larger flexural cracking moment than the ordinary reinforced concrete beam was obtained.
2. The maximum flexural strength of the SFRC beams was at most 10.0% larger than NC. However, PreSFRC05 had almost the same flexural strength as PreSFRC03.
3. The maximum crack widths of NC, SFRC03 and SFRC05 at the load 25 kN were 0.17, 0.16 and 0.13mm, respectively. SFRC03 and SFRC05 show the effect of crack width controlled by steel-fiber reinforcement. However, the maximum crack widths of PreSFRC03 and PreSFRC05 at the load of 150 kN were almost the same crack widths, 0.106 and 0.105mm. Comparison of crack widths between the reinforced concrete beams and the pretensioned beams indicated that crack widths have been suppressed by PC strands.
4. The analytical methods proposed by Swamy and Henager gave a conservative estimation. An evaluation method considering the resistance capacity of the compressive concrete by fiber reinforcement needs to be developed.

REFERENCES

Minoru Kunieda, Keitetsu Rokugo (2006), “Recent progress on HPFRCC in Japan”, *Journal of Advanced Concrete Technology, JCI*, Vol. 4, No.1, 19-33.

Haruhiko Suwada, Hiroshi Fukuyama (2007), “Experimental and analytical study on influencing factors on shear strength and deformation capacity of damper using high performance fiber reinforced cementitious composite”, *J. Struct. Constr. Eng., AIJ*, No.612, 171-178. (in Japanease)

Haruhiko Suwada, Hiroshi Fukuyama (2006), “Nonlinear finite element analysis on shear failure of structural elements using high performance fiber reinforced cement composite”, *Journal of Advanced Concrete Technology, JCI*, Vol. 4, No.1, 45-57.

Gregor Fischer and Victor C. Li (2003), “Deformation behavior of fiber-reinforced polymer reinforced engineered cementitious composite (ECC) flexural members under reversed cyclic loading conditions”, *Structural Journal, ACI*, Vol. 100, No. 1, 25-35.

Bilal S. Hamad, Mohamad H. Harajli, and Ghaida' Juma (2001), “Effect of fiber reinforcement on bond strength of tension lap splices in high-strength concrete”, *Structural Journal*, *ACI*, Vol. 78, No.36, 395-405.

R. N. Swamy, Sa'ad A. Al-Ta'an (1981), “Deformation and ultimate strength in flexure of reinforced concrete beams made with steel fiber concrete”, *Structural Journal*, *ACI*, Vol. 78, No.36, 395-405.

Charles H. Henager, M. ASCE and Terrance J. Doherty (1976), “Analysis of reinforced fibrous concrete beams”, *Journal of Structural Division*, *ASCE,* Vol. 102, No.ST1, 177-188.

S. K. Padmarajaiah and Ananth Ramaswamy (2001), “Behavior of fiber-reinforced prestressed and reinforced high-strength concrete beams subjected to shear”, *Structural Journal*, *ACI*, Vol. 98, No.5, 752-7.