LOW-CYCLE COMPRESSION FATIGUE BEHAVIOR OF STEEL-FIBER REINFORCED CONCRETE

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ABSTRACT

A lot of structures are often subject to repetitive cyclic loads such as vibration, wind and earthquake. As the results of repeated loading, the structure may eventually lead to fatigue failure. Steel-fiber reinforced concrete is expected to enhance the tensile properties such as strength and stiffness of the resulting composite material. In this study low-cycle compression fatigue performance to be enhanced by steel-fiber reinforced concrete is discussed. Low-cycle fatigue loading tests conducted on total 24 cylinders, i.e. 7 plain concrete cylinders and 17 steel-fiber reinforced concrete cylinders in order to obtain basic data on their compression fatigue behavior are reported. Three types of volume fraction of fiber, 0.0%, 0.3% and 0.5%, have been tested and their fatigue performance compared. The maximum stress levels were selected, $0.8f_c'$ and $0.9f_c'$. The tests show that improvement effect of fatigue behavior was confirmed.

Keywords: low-cycle, compression fatigue behavior, steel-fiber reinforced concrete, fatigue life, fatigue strength

INTRODUCTION

In recent years, Fiber Reinforced Concrete (hereafter referred to FRC) materials has been developed and studied for application to structural members. Fibers have been used to enhance tensile characteristics of concrete by suppressing crack growth and improving mechanical behavior[1].

Fatigue may be defined as a process of progressive, permanent internal structural changes in a material subjected to repeated loading[2]. In concrete, these changes are mainly associated with the progressive growth of internal micro-cracks, which results in a significant increase of irrecoverable strain. At the micro-level, this will manifest itself as changes in the material's mechanical properties[2~5]. Fatigue loading is usually divided into three categories, i.e., low-cycle, high-cycle and super-high-cycle fatigue loading as shown in **Table 1**[2]. Low-cycle loading involves the application of a few load cycles at high-stress level, i.e., $0.8f_c'$ or $0.9f_c'$. On the other hand, high-cyclic loading is characterized by a large number of cycles at lower stress level, i.e., $0.5f_c'$ or $0.6f_c'$.

Concrete is a heterogeneous material which is inherently full of flaw. The mechanism of fatigue behavior in concrete or mortar can be divided into three distinct stages[5]. The first stage involves the weak regions within the concrete or mortar and is termed flaw initiation. The second stage is characterized by slow and progressive growth of the inherent flaws to a critical size and is generally known as micro-cracking. In the final stage, when a sufficient number of unstable cracks have formed, a continuous or macro crack will develop, eventually leading to fatigue failure. It has been surmised that under the different loading cycle produce different failure mechanisms within concrete. For low-cycle fatigue, the dominant mechanism is the formation of mortar cracks leading to continuous cracked networks. On the other hand, high-cycle fatigue produces bond cracks in a slow and gradual process[5].

Table 1 Classes of fatigue load cycle[2]

Type	Low-cycle fatigue			High-cycle fatigue				Super-high-cycle fatigue		
No. of cycle	1	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9
Target	Structures subjected to Earthquakes			Airport pavements and Bridges		Highway and bridges		Mass rapid transit structure		Sea structures

The search for construction materials with enhanced properties such as strength, ductility, toughness and durability has leads to an increasing interest in materials like FRC and high-performance concrete[6]. The limited knowledge about the long-term behavior or the effects of repeated loading on the properties of these materials has caused a growing interest on the fatigue performance of concrete. The most important improvement attained by the addition of fibers to concrete is the increase in toughness and ductility. Nevertheless, it is also possible to improve other properties such as the strength and stiffness. In practical applications, however, steel-fibers are added in percentages of about 0.5 percent in volume for which it is unlikely to obtain higher strengths[6, 7]. One of the most common uses of steel-fiber reinforced concrete (hereafter referred to SFC) is in paving applications including highway, bridge decks and coupling beams to the coupled shear wall system. Therefore, the fatigue characteristics of SFC are important performance and design parameters. Several studies have been conducted on the compressive fatigue response of SFC[6~8]. These latest studies have focused on the effects of the addition of relatively low fiber volume, i.e., 0.5 ~ 1.0 percent, and relatively long fibers, i.e., 51mm. It has been demonstrated that flexural fatigue strength and endurance limit increase substantially with the addition of fibers[8]. However, the fatigue tests are time consuming, relatively expensive, and have a high degree of variability.

This study investigates compressive fatigue life and strength of buildings subjected to a long-period and long-duration earthquake. Therefore, this paper examined the compressive fatigue life and strength at 200 fatigue cycles. Low-cycle fatigue tests are conducted on 7 normal concrete (V_f=0.0%, hereafter referred to NC) and 17 SFC cylinders, whose volume fraction of fiber are 0.3 and 0.5 percent. This study provides a general review of the fatigue behavior, fatigue life and fatigue strength of SFC in compression.

MATERIALS

Two series of compressive fatigue tests on NC and SFC were carried out. The cylinders tested were 100 mm in diameter and 200 mm in height. **Table 2** shows the concrete mix proportion. The target compressive strength was 60 N/mm^2 at 28 days. The identical concrete mixture except for water reducing admixture and air entraining agent as shown in **Table 2** was used for all cylinders.

Table 2 Concrete mix proportion

Con'c	F_c' (N/mm^2)	V_f (%)	Slump (cm)	W/C	Air	Water	Cement	Aggregate (kg/m^3)		Admixture (kg/m^3)	
				(%)		(kg/m^3)		S[*1]	G[*2]	WR[*3]	AE[*4]
NC	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 admixture, *4 air entraining agent

Table 3 Mechanical properties of steel-fiber

Diameter and Length (mm x mm)	Specific Gravity	Tensile Strength (N/mm^2)	Young's Modulus (x10^5 N/mm^2)	Aspect Ratio
φ0.62 x 30	7.85	1,050	2.06	48.4

Table 3 shows the mechanical properties of the steel-fiber that used this study. The steel-fiber has hooked-ends.

The compressive strengths at 28 days and at the time of testing are summarized in **Table 4**. The compressive strengths of the plain and steel-fiber reinforced concretes varied from 63.4 to 72.1 N/mm^2 at the time of testing. **Fig. 1** shows three compressive stress–strain relationships obtained from each type of concrete under monotonic loading at the time of testing. The results show that the compressive strength of SFC was 12.1 percent smaller than the one of NC. However, the strain at compressive strength of SFC was 11.1 percent bigger than the one of NC.

Table 4 Concrete mechanical properties under monotonic loading

Time	Concrete type	Compressive strength, f_c' (N/mm^2)	Secant modulus of elasticity at 1/3f_c' (x 10^4 N/mm^2)	Strain at f_c' (%)
28-Day	NC	66.2	3.12	0.25
	SFC03	65.9	3.40	0.29
	SFC05	62.8	3.48	0.30
At the time of testing	NC	72.1	5.84	0.24
	SFC03	63.4	4.87	0.25
	SFC05	65.9	5.29	0.27

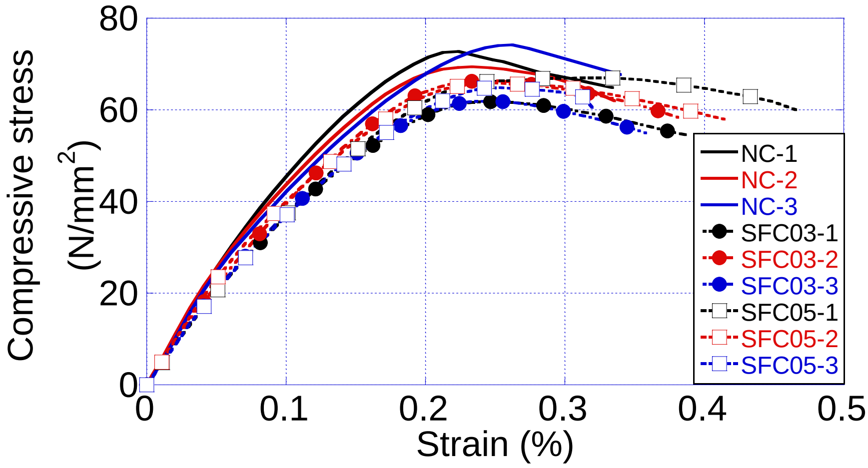


Fig. 1 Compressive stress – strain relationships under static monotonic loading at the time of testing

TEST SETUP

Fig. 2 shows the test setup of this research. All tests were conducted under load control. A 700kN oil jack for loading was used as shown in **Fig. 2**. **Fig. 3** shows the loading plan. The fatigue tests were carried out with between the minimum stress level S_{min} and the maximum stress level S_{max}. Controlling load S_{min} is 5 percent of the compressive strength and S_{max} was 80 or 90 percent of the compressive strength. The frequency of loading cycle was 0.25Hz. The loading was stopped at failure. If the cylinder survived 10,000 cycles of loading, the loading was stopped.

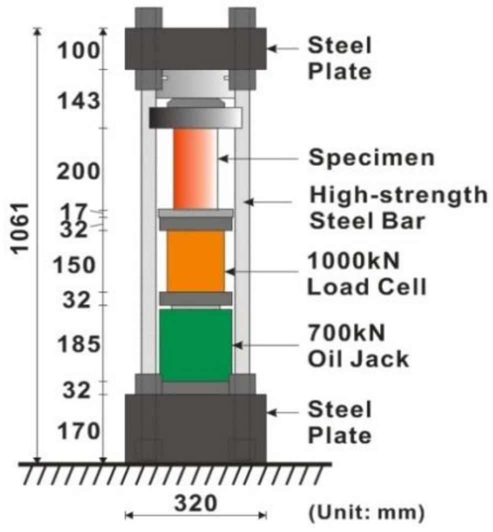


Fig. 2 Test setup

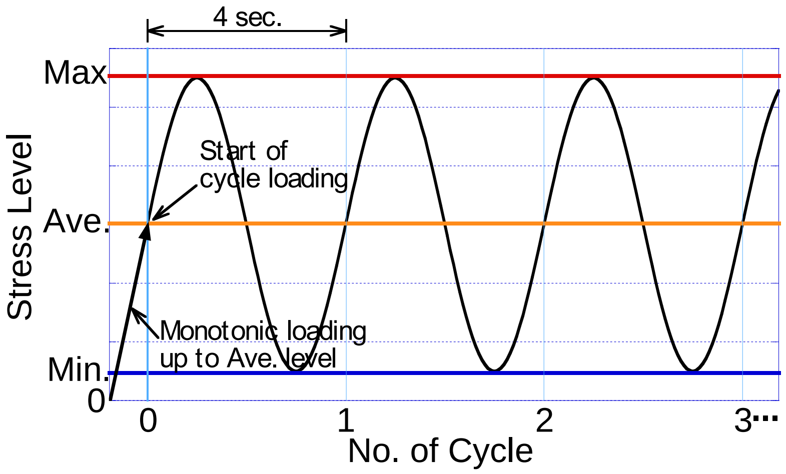


Fig. 3 Loading pattern

FATIGUE TEST RESULTS AND DISCUSSIONS

Table 5 summarizes the numbers of cycles to failure for all cyclically tested cylinders. The cylinders that did not fail up to 10,000 cycles are named '>10,000'. All cylinders whose S_{max}=0.8f_c' had fatigue life of more than 200 cycles. All the cylinders of NC and SFC05 failed during the fatigue tests. The cylinders with S_{max}=90% had a fatigue life of less than 200 cycles except for two cylinders of SFC05.

Table 5 Number of cycles to failure

No. of cylinder	NC		SFC03		SFC05	
	0.8f_c'	0.9f_c'	0.8f_c'	0.9f_c'	0.8f_c'	0.9f_c'
No.1	1,401	15	1,094	137	2,419	248
No.2	652	72	>10,000	83	1,244	101
No.3	335	17	>10,000	53	1,849	384
No.4	1,240	--	3,530	14	497	64
No.5	--	--	--	--	1,027	--
Average	907	35	2,299	72	1,408	200

※The minimum stress level, S_{min}, of all cylinder is 5 percent.

S_{max} - log$N$ RELATIONSHIP BY VOLUME FRACTION OF STEEL-FIBER

Fig. 4 shows the S_{max} – log$N$ relationship of 24 tested cylinders. The straight line in **Fig. 4** expresses Eq. (1) by the Standard Specification for Concrete of Japan Society of Civil Engineers[9].

$$\log N = K\frac{1-S_{max}}{1-S_{min}} = K\left(1-\frac{S_r}{1-S_{min}}\right) \qquad \text{Eq. (1)}$$

where, K : 10 in the case of lightweight aggregate concrete and 17 for other cases, S_{max} : the maximum stress level ratio, S_{min} : the minimum stress level ratio, S_r=S_{max}-S_{min}.

The value 17 was used for K in this research. All the fatigue life of NC, SFC03 and SFC05 with S_{max}=80% is shorter than the one obtained by Eq. (1).

Table 6 shows the calculation results of factor K. Two cylinders of SFC03, which did not fail up to 10,000 cycles are not considered for calculation of K. In case of S_{max}=80%, the factors of NC, SFC03 and SFC05 were 13.8, 15.6 and 14.7, respectively. The factor K of NC, SFC03 and SFC05 with S_{max}=90% were 13.5, 16.5 and 20.9, respectively.

Fig. 5 shows the factor K-volume fraction of fiber relationship. In case of S_{max}=80%, the factor K of SFC03 and SFC05 were 13.0% and 6.5% larger than the one of NC. However, the factor K of SFC03 and SFC05 with S_{max}=90% were 22.2% and 54.8% larger than the one of NC. As the stress level is high, the influence of volume fraction of

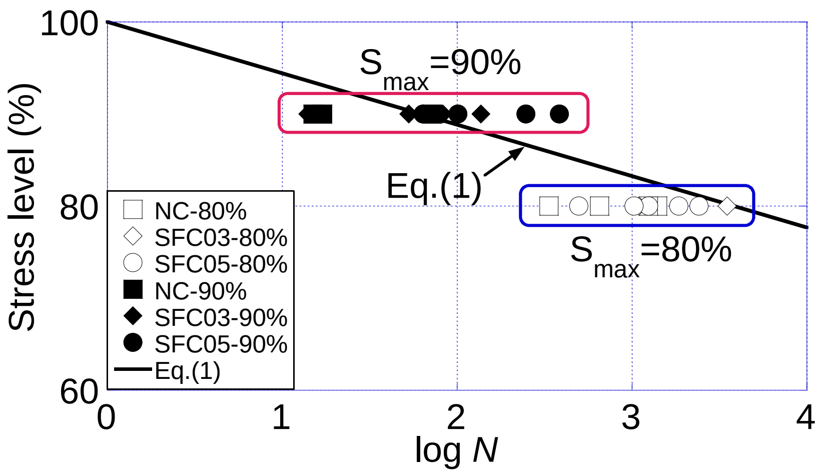


Fig. 4 S_{max} – log$N$ relationship

Table 6 Calculation results of factor K

S_{max} (%)		No. of cycles to failure	K	S_{max} (%)		No. of cycles to failure	K
80	NC	1,401	15.0	90	NC	15	11.2
		652	13.4			72	17.6
		335	12.0			17	11.7
		1,240	14.7				
		Ave.	13.8			Ave.	13.5
	SFC03	3,503	16.8		SFC03	137	20.3
		>10,000				83	18.2
		>10,000				53	16.4
		1,094	14.4			14	10.9
		Ave.	15.6			Ave.	16.5
	SFC05	2,419	16.1		SFC05	248	22.8
		1,244	14.7			101	19.0
		1,849	15.5			384	24.6
		497	12.8			64	17.2
		1,027	14.3				
		Ave.	14.7			Ave.	20.9

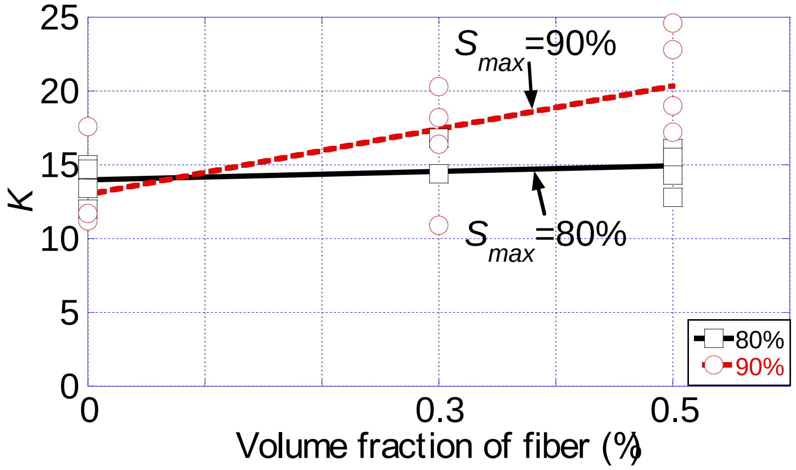


Fig. 5 Factor K – volume fraction of fibers relationship

fiber on the factor K is large. Results from K – volume fraction of fiber relationship, in case of S_{max}=90%, tend to increase the factor K by the increase volume fraction of fiber.

The fatigue test results of 98 cylinders in this research and references are plotted in **Fig. 6**. The compressive strength ranges from 34.5 N/mm^2 to 65.9 N/mm^2. The volume fractions of fiber were 0.25, 0.5, 0.75 and 1.0%. The data from previous studies[8,10], the range of S_{max} is from 60 to 95%. The experimental results of SFC03 are included in a group of V_f=0.25%.

Table 7 shows the fatigue strength of SFC at 200 cycles based on the regression analysis results illustrated in **Fig. 6**. The regression equations in **Table 7** were determined by the least square method.

$$Stress\ level = \mathrm{A} + \mathrm{B}\log N \qquad \text{Eq. (2)}$$

Since it is assumed that long-period and long-duration earthquakes, consisted of 200 cycles of repetitions. The fatigue strength of SFC at N=200 cycles does not show an increase or decrease trend by the increase volume fraction of fiber as shown in **Table 7**.

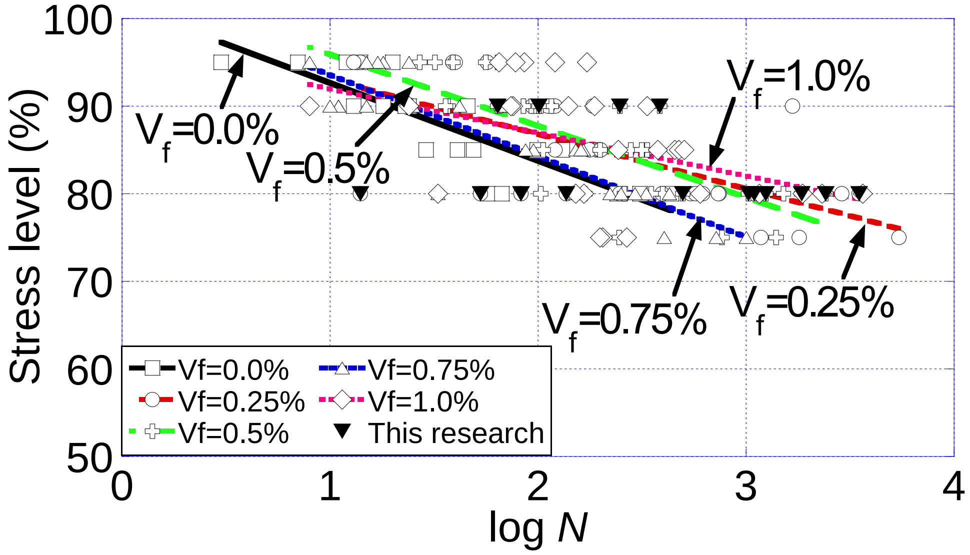


Fig. 6 Regression analysis results of stress level – log N relationship

Table 7 Fatigue strength of SFC at 200 cycles

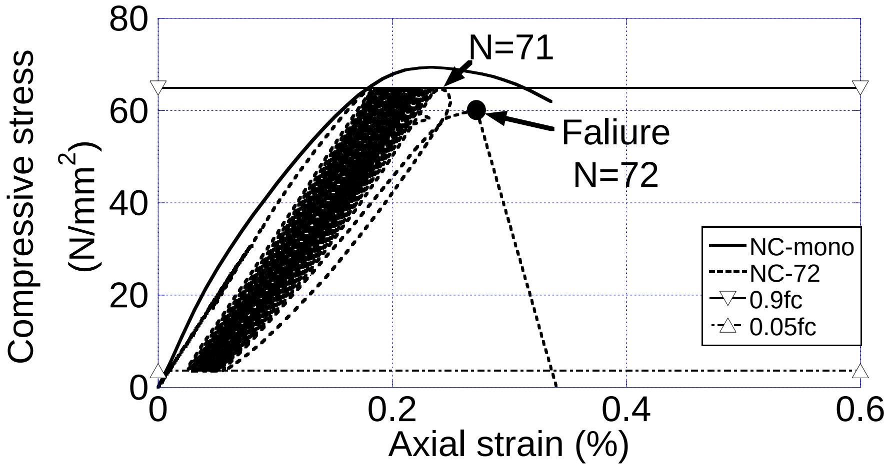
Range of compressive strength	Volume fraction of steel-fiber	Result of regression analysis	Fatigue strength at 200 cycles
34.5～65.9N/mm^2	V_f=0.0%	S_{max}=101.5-8.9log$N$	81.0%
	V_f=0.25%	S_{max}=99.3-6.2log$N$	85.0%
	V_f=0.50%	S_{max} =104.1-8.2log$N$	85.3%
	V_f=0.75%	S_{max} =102.9-9.3log$N$	81.5%
	V_f=1.00%	S_{max} =97.0-5.0log$N$	85.5%

※S_{max}: the maximum stress level, log$N$: average fatigue life, V_f: volume fraction of fiber

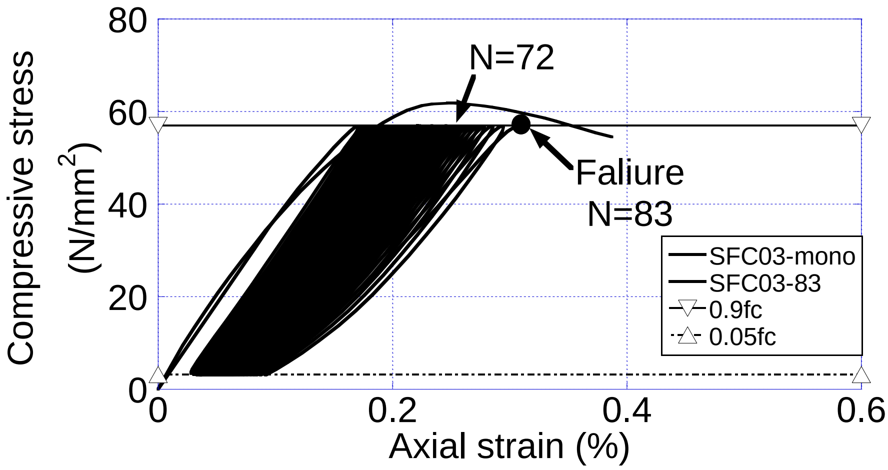
STRESS-STRAIN RELATIONSHIPS

Fig. 7 shows the compressive stress-axial strain relationships of NC-72, SFC03-83 and SFC05-248 with S_{max}=90%. **Fig. 8** and **Fig. 9** show the axial and lateral strain increment-cycle relationships of NC-72, SFC03-83 and SFC05-248. The numerical value at the end of the cylinder name indicates the number of cycles to failure.

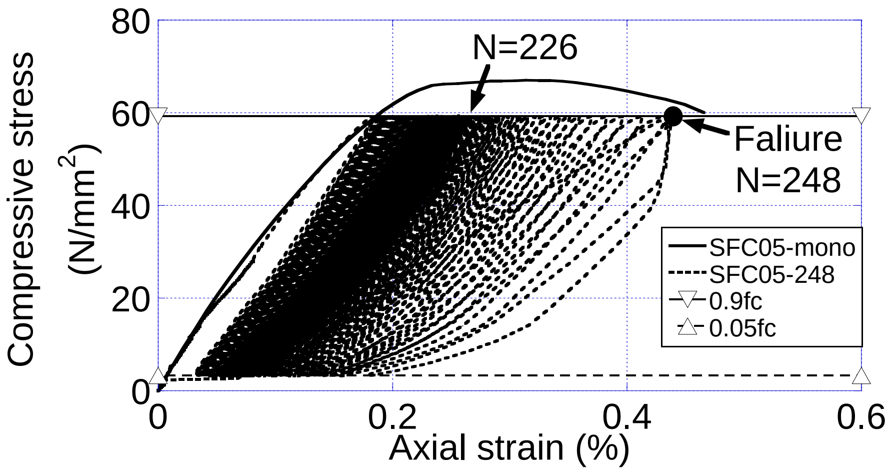
The axial strain increment is the increment between the peak strain at the N^{th} cycle and the peak strain at N-1th cycle. In NC-72 from **Fig. 8(a) and (b)**, the axial strain increment was almost constant up to 70th cycle. As shown in **Fig.7 (a)**, the axial strain suddenly increased at the 71th cycles, which resulted in fatigue failure. On the other hand, the axial strain increment of SFC03-83 and SFC05-236 were constant up to 72 and 226 cycles, respectively as shown in **Fig. 8(a) and (b)**. In addition, as shown in **Fig. 9(a) and (b)**, the lateral strain increment of NC-72 could not be measured because it brittly failed. However, the lateral strain increment of SFC03-83 and SFC05-248 was increased little by little, and failed.



(a) NC-72

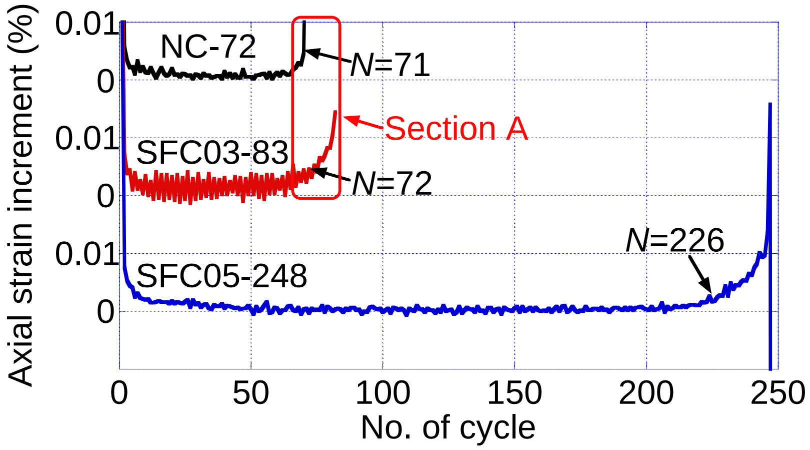


(b) SFC03-83

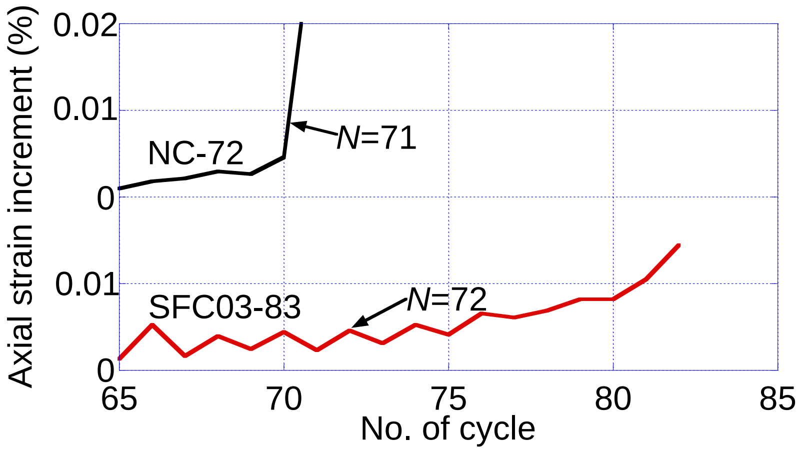


(c) SFC05-248

Fig. 7 Compressive stress – axial strain relationships (S_{max}=90%)

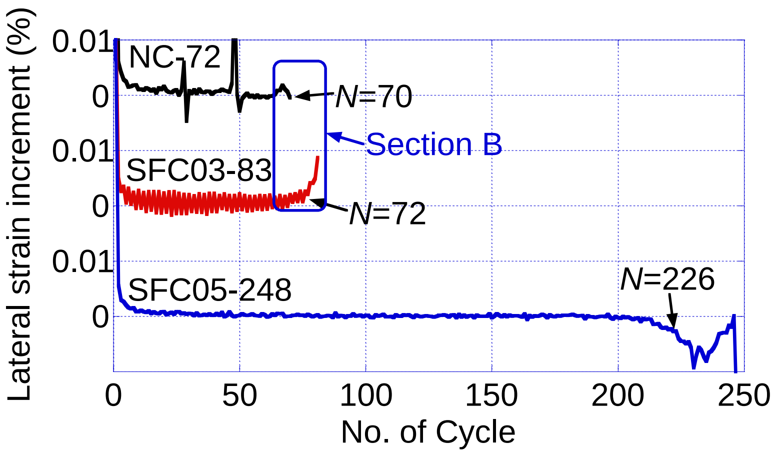


(a) Axial strain increment – No. of cycle



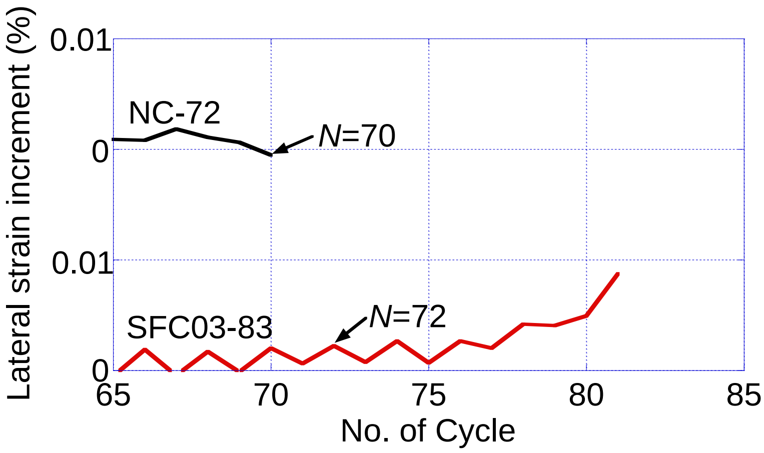
(b) Section A of axial strain increment – No. of cycle

Fig. 8 Axial strain increment – No. of cycle relationships



(a) Lateral strain increment – No. of cycle

Fig. 9(1) Lateral strain increment – No. of cycle relationships



(b) Section B of lateral strain increment – No. of cycle

Fig. 9(2) Lateral strain increment – No. of cycle relationships

FAILURE MODE

Photo 1 shows the cylinders of NC, SFC03 and SFC05. The left column of photographs are the cylinders with S_{max}=80 percent, and the photographs in the right column are the cylinders with S_{max}=90 percent. Regardless of S_{max}, it can confirm that there are more remains concrete portions of SFC03 and SFC05 than plain concrete NC. In addition, the spalling of concrete is reduced by the mixed steel-fiber at the time of fatigue failure as shown in **Photo 1**. The concrete fragments connected with the cylinder main part by the steel-fiber were also observed.

Photo 1(1) Failure mode

S_{max} = 80%	S_{max} = 90%
	
(a) NC	

Photo 1(2) Failure mode

S_{max} = 80%	S_{max} = 90%
	
(b) SFC03	
	
(c) SFC05	

CONCLUSIONS

With respect to the objectives of this research and within the limitations of its experimental program, the following tentative conclusions can be drawn;

1. In the case of steel-fiber reinforced concrete, especially, at S_{max}=90 percent, tended fatigue life of the steel-fiber reinforced concrete is longer than the plain concrete. In addition, the improvement effect of fatigue behavior was confirmed such as concrete scattering and spalling suppression by steel-fiber.

2. The factor K variation due to the increase of volume fraction of fiber is not big in case of S_{max}=80 percent cylinder. However, in case of S_{max}=90 percent, tends to increase

greatly factor *K* by the increase of the volume fraction of fiber. Thus, for the factor *K* of SFC with compressive strength and volume fraction of fiber the same, because the variation trend of factor *K* due to the stress level is different, it is necessary to consider the stress level.

3. The steel-fiber reinforced concrete could not be confirmed tend to be certain increase or decrease of fatigue strength due to the increase volume fraction of fiber. This is because of the influence of such admixtures and volume fraction of fiber on the fiber dispersion.

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