

Fatigue Behavior of Steel Fiber Reinforced High-Strength Concrete under Different Stress Levels

Chong Zhang^{1,*}, Danying Gao^{1,2} and Zhiqiang Gu¹

¹School of Water Conservancy and Environment, Zhengzhou University, Zhengzhou, 450001, China

²Henan University of Engineering, Zhengzhou, 451191, China

*Corresponding author e-mail: zcbelief@163.com

Abstract. The investigation was conducted to study the fatigue behavior of steel fiber reinforced high-strength concrete (SFRHSC) beams. A series of 5 SFRHSC beams was conducted flexural fatigue tests at different stress level S of 0.5, 0.55, 0.6, 0.7 and 0.8 respectively. Static test was conducted to determine the ultimate static capacity prior to fatigue tests. Fatigue modes and S-N curves were analyzed. Besides, two fatigue life prediction model were analyzed and compared. It was found that stress level S significantly influenced the fatigue life of SFRHSC beams and the fatigue behavior of SFRHSC beams was mainly determined by the tensile reinforcement.

1. Introduction

In practical engineering, a large number of structures such as bridge decks, offshore installations and airport runways often bear cyclic loads. These loads such as wind loads, and wave loads could result in progressive and continuous micro cracks, which leads to the increased permanent strains and decreased stiffness of the structure. The fatigue failure will eventually occur by the damage. Therefore, considerable interest has been developed on the fatigue performance of the concrete structures. The mechanism of fatigue in concrete can be divided into three distinct stages. The first stage is termed as flaw initiation and involves flaws forming within weak regions of the concrete. The second stage is known as micro cracking and is featured by slow growth of flaws to a critical size. The third stage occurs when a continuous macro cracks form, eventually leading up to the final failure [1]. The first and third stage make up approximately 10% of the total curve separately, while the second stage accounts for the remaining 80% [2]. The addition of fiber reinforcing can increase the fatigue performance of the concrete under flexural fatigue loading and explained that the fibers would be able to bridge cracks and prolong fatigue life under tensile forces [3]. The effects of the fiber content, fiber aspect ratio and notch-to-depth ratio on the concrete fracture and fatigue behaviour were studied, and the fatigue strengths of SFRC beams were calculated. According to the regression technique, some empirical formulas for predicting the fatigue strength of SFRC beams were also suggested [4]. 11 beams reinforced by a new kind of steel (20 MN Siv) under static loading and fatigue loading with constant amplitudes were tested and the calculation method of concrete strain on the edge of compressive zone and the tensile stress of longitudinal reinforcements was put forward [5]. Fatigue test of RC beams was conducted, and the conclusion was that the mode of failure was related with stress level. In low stress level, fatigue specimens broke in the mode of bending failure with the sign of brittle fracture of reinforcement, and in



high stress level, fatigue specimens broke in the mode of shear failure [6]. Much emphasis was put on the fatigue life, energy absorption and damage accumulation. Fibers dissipated much more additional energy at lower stress levels than at higher stress levels [7]. Three different arrangements of web reinforcement were considered, namely: without web reinforcement, with vertical web reinforcement only, and with inclined web reinforcement. The test revealed that the arrangements of web reinforcements had significant influence on the structural response of deep beams under fatigue loading [8]. Tests of fatigue behavior of steel fiber concrete were systematically conducted from cyclic axial compression and four-point bending [9]. The statistical distribution of equivalent fatigue-life of steel fiber reinforced concrete at a given stress level was studied, S approximately followed the two-parameter Weibull distribution [10]. Various approaches were used in the fatigue life assessment of structural elements. A widely accepted approach for engineering practice is based on empirically derived $S-N$ diagrams, also known as Wohler curves. In addition, the effects of minimum stress in the loading cycle may be represented in so-called Goodman diagrams or Smith diagrams, which are also known as constant life diagrams in the analyses of metals [11].

The current paper dealt with its investigation, starting from the effect of stress level $S (S = P_{\max} / P_u, P_{\max} = \text{maximum fatigue capacity}, P_u = \text{ultimate static capacity})$ on fatigue behavior of SFRHSC beams. With the combination of steel fiber and high-strength reinforcement (HRB500) in concrete structure under fatigue loading, fatigue behavior of SFRHSC beams could be effectively boosted by the steel fiber and high-strength bar.

2. Experimental Program

2.1. Mix Proportion, Specimen Geometry, and Materials.

In this study, a total of six beams with the size of 1200 mm×120 mm×200 mm was carried out in flexural fatigue at different stress levels. The steel fiber used in the specimens was hooked in both ends, and the properties are listed in Table 2. The 3D-65/35-BG Dramix fiber from Bekaert. The volume fraction of steel fiber and tensile reinforcement ratios are 1.0% and 0.94%, respectively, for all beams. One beam for static flexural test was conducted to determine the static flexural strength prior to fatigue testing. The reinforcements were arranged by GB50010—2010 [12] and CECS 38: 2004 [13]. The concrete mix design, reinforcement properties and the detailed information of the beams are shown in the following tables.

Table 1. Concrete mix design. (kg/m³)

Strength	GP cement	Water	Sand	Aggregate	Super plasticizer	Steel fiber
CF60	529	164	646	1110	5.819	78.5

Table 2. Steel fiber properties

Fiber properties	Fiber type
	Dramix RC-65/35
Length (mm)	35
Diameter (mm)	0.55
Aspect ratio	65
Ultimate tensile strength (MPa)	1345
End condition	Hooked end

Table 3. Steel properties

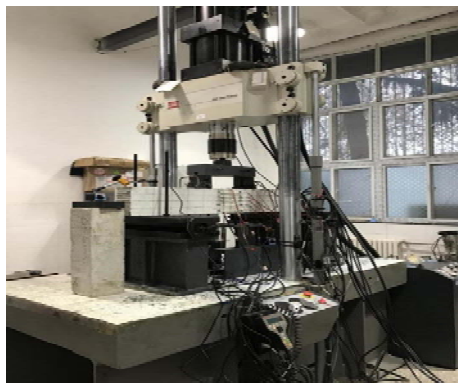
Steel grade	Diameter mm	Yielding strength N/mm ²	Tensile strength N/mm ²	E_s N/mm ²	Elongation %
Tensile reinforcement HRB500	12	575	705	2.05×10^5	22
Stirrup HPB300	8	425	550	1.87×10^5	28.5

Table 4. Detailed information of the beams

Specimen ID	Test type	Stress level		Span L (mm)	f_{cr}	E_c (GPa)	f_c (MPa)	f_m (MPa)	No. of cycles
		Max	Min						
BJ1.0-5	Static			1200	1%	41.6	87.6	57.4	--
BS1.0-5	Fatigue	0.5	0.1	1200	1%	40.8	83.4	59.1	>2000000
BS1.0-55	Fatigue	0.55	0.1	1200	1%	41.6	87.6	57.4	869751
BS1.0-6	Fatigue	0.6	0.1	1200	1%	42.4	86.3	65.1	799389
BS1.0-7	Fatigue	0.7	0.1	1200	1%	39.4	85.7	65.3	407724
BS1.0-8	Fatigue	0.8	0.1	1200	1%	39.4	85.7	65.3	65296

2.2. Testing Setup.

The **MTSTM** fatigue testing machine with capacity of 500 kN was employed for this fatigue test. The constant-amplitude sinusoidal load pulses could be captured by the control system of machine. Beams were tested in four-point with a span of 1000 mm. Before the test, the beams were preloaded 2 times to ensure the adequate contact between beams and supports. A range of stress levels were applied on the beams from as low as 0.5, 0.55, 0.6, 0.7, to as high as 0.8, and the minimum stress level was set as 0.1. The testing setup is shown in Figure 1.

**Figure 1.** Testing setup MTSTM

2.2.1. Static Test. The beam BJ1.0-5 was loaded to determine the ultimate static capacity P_u prior to fatigue tests. Before the initial crack appears, the beam was loaded at 10 kN per step. The load steps should be more intense when the first crack and failure were impending to happen. At every step, the crack development was observed for 5 to 10 minutes. When the initial crack appeared, the load was changed to 20 kN per step, followed by an observation of 5 to 10 minutes. The test was finished until the load decreased to 80% of the ultimate bearing capacity after peak load.

2.2.2. Fatigue Test. First, all fatigue beams were loaded to the designed stress level step by step in the preliminary static test, then unload to zero. For example, beam BS1.0-5 was loaded to $0.5P_u$ step by step. Crack development was marked at certain intervals. Fatigue part started after the preliminary static test was finished. Numbers of cycle began from 0.1×10^4 , 0.2×10^4 , 0.5×10^4 , $1 \times 10^4 \dots 10 \times 10^4$, $20 \times 10^4 \dots 100 \times 10^4$, 150×10^4 , until 200×10^4 then stopped. At every step, the crack development was observed for 5 to 10 minutes. The number of load cycles N to failure was the fatigue life of the beam (N_f is the cycle number of failure). Specifically, when the number of load cycles N reached 2 million, if the beam did not experience failure, the test was considered over.

2.2.3. Measurement. Concrete and reinforcement resistance strain gauges and LVDTs were arranged and displayed, shown as in the following figures.

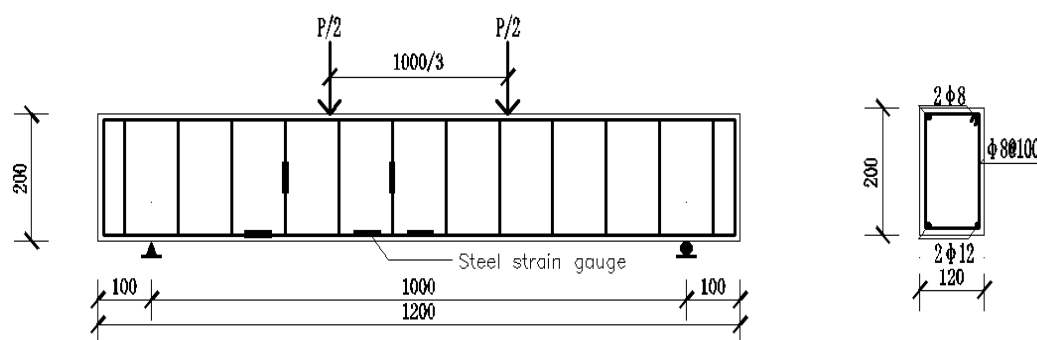


Figure 2. Arrangement of reinforcement and layout of strain gauges (all dimensions are in mm).

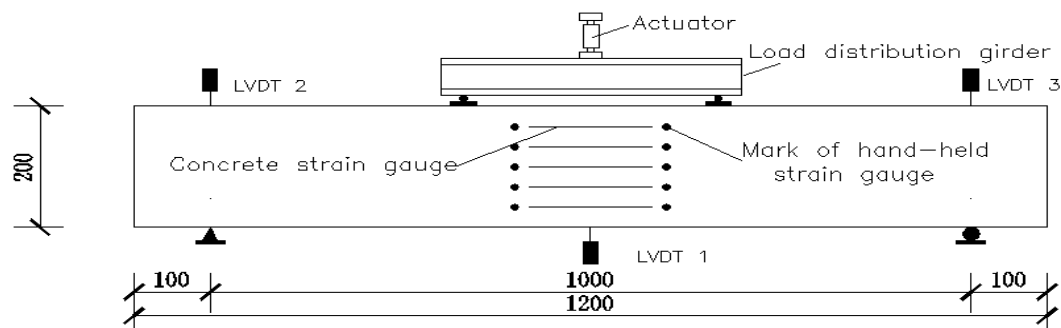


Figure 3. Sketch map of testing apparatus (all dimensions are in mm).

3. Result of fatigue test data and discussion

3.1. Static test.

Results of static test were obtained through the beam BJ1.0-5. The ultimate static capacity P_u was 195.6 kN, which was taken as ultimate capacity loads for the whole fatigue series. In static test, beam BJ1.0-5 was crushed at the compression zone and the tensile reinforcement stress increased to the yielding strength, which resulted in the final failure.

3.2. Fatigue life and fatigue modes.

Five fatigue beams were tested under cyclic load until failure. It is clear that as the stress level increased, fatigue life decreased dramatically. Stress level imposed large impact on the fatigue failure mode in particular. At higher stress levels, the failure appeared almost immediately after the initiation of the major visible crack. At lower stress levels, the steel fiber concrete beams can bear sufficient number of load cycles even after initiation of major visible crack [14]. With an increase of the number of load

cycles, the crack propagated and widened, which significantly contributed to the failure of the beams. However, the decisive factor lead to the failure of the beams was the sudden brittle fracture of the high-strength bar. Suddenly after the vast majority crack extending up to top of the beam, brittle failure of high-strength bar happened, and the test stopped. Steel fibers contained in the SFRHSC beams were partly pulled out, partly fractured and snapped. Steel fibers improve resistance to crack growth, reducing the stress level in the tensile reinforcement decrease, so as to prolong the fatigue life of concrete under cyclic loading. Although the addition of steel fiber can effectively inhibited the development of cracks and reduced the stress level in the tensile reinforcement, however it cannot change the failure modes. The selected load ranges and fatigue life and failure modes of all the beams are shown in Table 5.

Table 5. Load ranges, fatigue life and failure modes

Specimen ID	Stress level	Load range/(kN)	No. of cycles	Failure mode
BS1.0-5	0.5	19.56-97.8	2000,000	did not break
BS1.0-55	0.55	19.56-107.58	869,751	sudden brittle fracture of bar
BS1.0-6	0.6	19.56-117.36	799,389	sudden brittle fracture of bar
BS1.0-7	0.7	19.56-136.92	407,724	sudden brittle fracture of bar
BS1.0-8	0.8	19.56-156.48	65,296	sudden brittle fracture of bar

3.3. Analysis of S-N curve and fatigue life prediction model.

Stress level versus the numbers of cycles until failure is known as Wöhler diagram or S-N curve. It is often used to predict the fatigue life of concrete structure. Because fatigue data is always widely scattered, and S-N relations are typically plotted on a log-scale, a small variation in stress range can lead to a large variation in fatigue life. Generally, the fatigue tests are required to be conducted at different stress levels to plot the S-N curve. In this paper, variable of stress level for the whole series was considered. Stress level versus the fatigue lives of the beams are plotted in Figure 4.

$$S = 1.822 - 0.209 \lg N \quad (1)$$

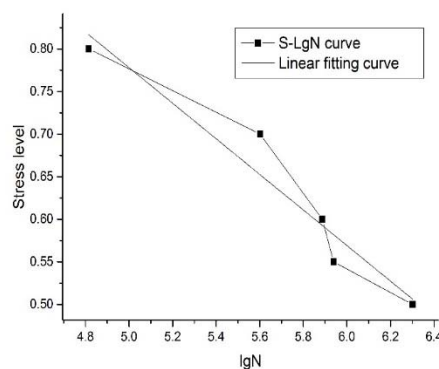


Figure 4. Stress level versus lg N

$R^2 = 0.916$, R^2 is the coefficient of determination, which means the linear fitting curve aligns well with the S-N curve. A large number of theories and models have been proposed to predict the fatigue life of engineering structures. Presently, the most widely used cumulative damage theory is the Miner's linear damage theory. Compared to other predictions theories, the Corten-Dolan's is another model which has a high accuracy and wide application. In this study the precision of the two models were compared

$$\sum \frac{n_i}{N_i} = D \quad (2)$$

$$N = \frac{N_1}{\sum (\sigma_i / \sigma_1)^d} \quad (3)$$

$$\frac{N}{N_1} = \left(\frac{\sigma_1}{\sigma_i} \right)^d \quad (4)$$

$$\lg N = d \lg \frac{\sigma_1}{\sigma_i} \quad (5)$$

Where

n_i = Number of cycles that incurred at σ_i

N_i = Life at load level L_i

D = Total fatigue damage

σ_1 = Maximum stress of fatigue beam

N_1 = Number of cycles to failure at σ_1

N_g = Total number of cycles to failure

σ_i = Stress of i -th level stress

d = Corten–Dolan exponent

N = Number of cycles to failure

N_c = Number of cycles to failure

D_c = Number of cycles to failure

N_m = Number of cycles to failure by Miner theory

D_m = Number of cycles to failure

For SFRC, d reflects the energy absorption capacity which is the material constant related to the concrete, steel reinforcement and steel fiber. Because of the similar material used in the paper [15] d can be used as 7.38 through the regression analysis of the experiment results.

Table 6. Comparison between the two fatigue prediction models

Specimens ID	Stress range (MP a)	N	N_c	N_m	D_c	D_m
BS1.0-5	24.95	2,000,000	2,038,184	2,115,236	0.98	0.95
BS1.0-55	28.13	869,751	993,545	1,219,339	0.88	0.71
BS1.0-6	31.32	799,389	515,159	702,894	--	--
BS1.0-7	37.29	407,724	174,931	233,572	--	--
BS1.0-8	43.51	65,296	65,296	77,616	1	0.84

4. Conclusion

The behaviour of SFRHSC beams with HRB500 bars under fatigue loading has been studied. The conclusions are summarized as follows:

(1) In this investigation, there is a difference in failure mode between the static test and fatigue test. In static test, for beam J0.5 the clear majority crack extended up to the top of the beam, at the same time the tensile reinforcement stress suddenly increased to the yielding strength. Then the constant compression zone was crushed to failure. The yield failure of steel reinforcement shows good ductility. While in the fatigue all beams showed a different feature. For beam BS1.0-5, it did not fail within 2 million number of cycles. For the rest beams failure was all because of the brittle fracture of steel reinforcement.

(2) Under cyclic loading, as the increase of stress level, maximum crack width, steel strain and steel strain range showed similar three-stage trend. In the first stage all these characteristic values increased rapidly. Then followed by the second stage which increased more gradually and lasted for the longest time of the whole process. In the last stage, taking steel strain as example, the damages of the tensile

reinforcement accumulated, and the increase of strain became rapid again, which lead to the eventual failure of the reinforcement.

(3) Among the two-prediction model, Corten–Dolan’s rule was more accurate than Miner’s rule partially because Miner’s rule was on the basis of empirical nature. Moreover, it may result in evident errors due to the effects of loading frequency and load-interaction. In addition, for SFRC, coefficient d of material properties such as concrete, steel reinforcement and steel fiber were introduced in Corten–Dolan’s rule. Therefore Corten–Dolan’s rule could offer a better prediction for the fatigue life of SFRHSC beams.

Acknowledgments

This work was financially supported by the New Construction Materials and Construction Research Centre in Zhengzhou University.

References

- [1] L. Gao and T. T. C. Hsu, “Fatigue of concrete under uniaxial compression cyclic loading.” *ACI Materials Journal*, vol. 95, no. 5, pp. 575-581, 1998.
- [2] H. Cornelissen and H. Reinhardt, “Uniaxial tensile fatigue failure of concrete under constant-amplitude and program loading.” *Magazine of Concrete Research*, vol. 36, no. 129, pp. 216-226, 1984.
- [3] B. I. C. Barr and M. K. Lee, “Dynamic analysis of cracked sections (Literature Review) report from test and design methods for steel fiber reinforced concrete.” Technical report, EU Contract-BRPR-CT98-813, University of Wales, Cardiff, UK 2001.
- [4] C. Dong-II and C. Won-Kyu, “Flexural fracture and fatigue behavior of steel-fiber-reinforced concrete structures.” *Nuclear Engineering & Design*, vol. 156, no. 1, pp. 201-207, 1995.
- [5] X. F. Li, P. G. Wu and G. Y. Zhao, “Experimental research on bending fatigue behavior of high-strength concrete beams.” *China Civil Engineering Journal*, vol. 30, no. 5, pp. 37-42, 1997.
- [6] T. S. Chang and C. E. Kesler, “Fatigue behavior of reinforced concrete beams.” *ACI Journal Proceedings*, vol.55, no. 8, pp. 245-254, 1958.
- [7] Z. C. Deng, “Research on the behavior of steel fiber reinforced concrete under cyclic compressive loading.” *Building Structure*, vol. 30, no.9, pp. 53-56, 2000.
- [8] S. Teng, W. Ma and F. Wang, “Shear strength of concrete deep beams under fatigue loading.” *ACI Structural Journal*, vol.97, no. 4, pp. 572-580, 2000.
- [9] S. P. Singh and S. K. Kaushik, “Fatigue strength of steel fiber reinforced concrete in flexure.” *Cement & Concrete Composites*, vol. 25, no. 7, pp. 779-786, 2003.
- [10] B. H. Oh, “Fatigue analysis of plain concrete in flexure.” *Journal of Structural Engineering*, vol. 112, no. 2, pp. 273-288, 1986.
- [11] G. P. Sendeckyj, Constant life diagrams — a historical review. *International Journal of Fatigue*, vol. 23, no. 4, pp.347-353, 2001.
- [12] GB 50010—2010 Code for design of concrete structures. Beijing: China Architecture & Building Press, 2010 (in Chinese)
- [13] CECS 38: 2004 Technical specification for fiber reinforced concrete structures. Beijing: China Planning Press, 2004 (in Chinese)
- [14] A. Parvez, S.J. Foster, “Fatigue Behavior of Steel-Fiber-Reinforced Concrete Beams.” *Journal of Structural Engineering*, vol. 141, no. 4, pp. 04014117, 2015.
- [15] S. Q. Li, H. K. Ji, S. Y., Experimental Study of Stress Ratio to Fatigue Life of Steel Fiber Reinforced High-Strength Concrete Beams. *Journal of Water Resources and Architectural Engineering* vol. 14, no. 4, pp.157-160, 2016.