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Research Article

Fatigue Performance of SFPSC under Hot-Wet Environments and Cyclic Bending Loads

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A new structural material named "steel fiber polymer structural concrete (SFPSC)" with features of both high strength and high toughness was developed by this research group and applied to the bridge superstructures in the hot-wet environments. In order to investigate the fatigue performance and durability of SFPSC under hot-wet environments, the environment and fatigue load uncoupling method and the coupling action of environment and fatigue load were used or developed. Three-point bending fatigue experiments with uncoupling action of environments and cyclic loads were carried out for SFPSC specimens which were pretreated under hot-wet environments, and the experiments with the coupling action of environments and cyclic loads for SFPSC specimens were carried out under hot-wet environments. Then, the effects of hot-wet environments and the experimental methods on the fatigue mechanism of SFPSC material were discussed, and the environmental fatigue equations of SFPSC material under coupling and uncoupling action of hot-wet environments and cyclic bending loads were established. The research results show that the fatigue limits of SFPSC under the coupling action of the environments and cyclic loads were lower about 15%. The proposed fatigue equations could be used to estimate the fatigue lives and fatigue limits of SFPSC material.

1. Introduction

The durability of bridge structures in service has been a frontier research topic in civil engineering field. As a significant part of the durability issues, the study on environmental fatigue performance of structural materials often has decisive significance for assuring the safety and durability of the bridge structures. With the increase of the span of concrete bridge, the common high-strength concrete materials could no longer satisfy the comprehensive requirements of load-bearing capacity, anticracking, antideformation, and durability [1–3], and there is an urgent need to develop a new material with features of high strength and high ductility.

Steel fiber reinforced concrete (SFRC) was a compound with high strength and high ductility developed in the 20th century. After modifications and developments in many decades, SFRC had been gradually applied in the various kinds of building structures [4–6]. In the transportation field, SFRC was used mostly for constructions such as the road pavements, bridge deck pavements, and airport runway pavements. However, in many cases, it had been discovered during the observations of damaged sections of the SFRC specimens that the steel fibers in the damaged sections were broken by being "pulled out" and very few by being "broken." This was due to insufficient cohesive force between the matrixes of the steel fibers and concrete and thus resulted in the low stress levels of the steel fibers during the damage of the specimens, and their tensile properties had not been fully realized. In order to further increase the bonding strength of the steel fiber and concrete and give full play to the good mechanical properties of the steel fibers, Luo et al. [7] of this research group added polymer latex into SFRC and developed the "steel fiber reinforced polymer concrete (SFRPC)." The experimental results showed that the new material had more superior antitensile, antibending, antifatigue, and antiimpact properties [8–10]. SFRPC belongs to medium to low strength modified concrete. Although it had been successfully applied in the construction of highway road pavements and bridge deck pavements [11], due to its insufficient strength, it was still unable to be used for main load-bearing members such as the bridge superstructures. Therefore, this research group conducted secondary development on SFRPC and developed a new high-strength concrete composite material named "steel fiber polymer structural concrete (SFPSC)." After the experiments of systematic mechanical properties and the optimum designs of the structures [12–15], SFPSC was successfully applied in the main girders (box girders) of three large-span concrete continuous rigid frame bridges on two highways in Guangdong Province, China [16, 17].

Regardless of SFRC, SFRPC, or SFPSC, there had been scarce reports about the research results of the environmental fatigue performance/durability of the concrete composite materials containing steel fibers. With regards to the bridge structures servicing in subtropical areas such as Guangdong Province, China, it is necessary to investigate its antifatigue performance/durability under hot-wet environments. Therefore, considering the actual weather conditions in the subtropical areas, the experimental studies on fatigue performance of SFPSC applied in bridges under different temperatures were carried out by this research group [14, 15], and a thermal fatigue equation for SFPSC was proposed. However, the effect of the humidity was not taken into the consideration.

In addition, for the bridge superstructures servicing in a hot-wet environment, the environment and vehicle loads are interacted, and thus their working conditions are different from the traditional environment and load uncoupling experiments. The differences in the environmental fatigue performance/durability of materials and components under uncoupling and coupling action are a scientific problem that needs to be proved but has not been proved. Therefore, in this paper, the superstructures of SFPSC bridges servicing in subtropical areas were taken as the research objects, and the environmental fatigue experimental researches and theoretical analyses were carried out based on the hot-wet environments and cyclic loads coupling and uncoupling (traditional) experimental methods, and the environmental fatigue performance/durability of SFPSC under different hot-wet conditions was discussed.

2. Fatigue Experiments under Hot-Wet Environments

In order to study the environmental fatigue performance/durability of SFPSC material under coupling and uncoupling action of hot-wet environments and cyclic loads and to prove the mechanism of the effect brought by hot-wet environments on the fatigue performance of SFPSC, in this research, three types of fatigue experiments were designed:

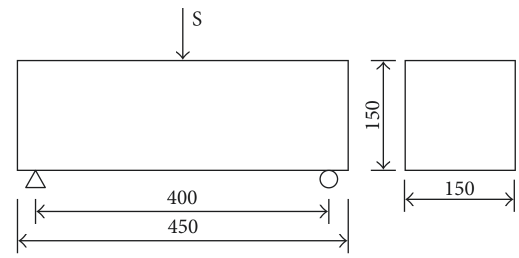


Figure 1: Three-point bending SFPSC beam for fatigue test (unit: mm).

(1) Fatigue experiments under room temperature and atmospheric environment. (2) Fatigue experiments under uncoupling action of hot-wet environments and cyclic loads. This is the traditional method for environmental fatigue tests. SFPSC specimens were pretreated in the hot-wet environments, and then the specimens were transferred to the test machine to carry out the fatigue experiments under room temperature and atmospheric environment. (3) Fatigue experiments under coupling action of hot-wet environments and cyclic loads. The experiments were carried out by the special testing device, and the specimens were treated by the hot-wet environments while the cyclic loads were applied.

2.1. Experimental Materials and Specimens. The specimens used for fatigue experiments were all the same and were three-point bending beams as shown in Figure 1. The specimen materials were based on the design requirements of a long-span bridge girder (box girder) of a highway in Guangdong Province and were designed for 2 types of materials: C55 concrete and SFPSC. The size of a specimen was length $450\,\mathrm{mm} \times$ width $150\,\mathrm{mm} \times$ height $150\,\mathrm{mm}$, and the span length was $L = 400\,\mathrm{mm}$. There were total of 66 specimens produced, including five C55 concrete specimens and 61 SFPSC specimens. The usages of all specimens were as follows: five C55 concrete and five SFPSC specimens were used to test the static mechanical properties of the two types of materials. The remaining 56 SFPSC specimens were used in fatigue experiments, including 10 specimens used for the room temperature and atmospheric environmental tests (controlling experiments), 20 specimens used for the experiments under uncoupling action of hot-wet environments and cyclic loads, and 26 specimens used for the experiments under coupling action of hot-wet environments and cyclic loads.

Based on the design requirements of the superstructures (box girders) of the above bridges, the compressive strength of SFPSC should be slightly higher than that of C55 concrete. Therefore, the C55 concrete used in the experiments was designed with the standard mix ratio. The designs of the mix ratios of SFPSC should be based on the strength requirements of the structures (close to the static mechanical properties of C55 concrete); then, consider the quantity of the steel fiber to be added, the water/cement ratio, sand rate, water consumption of unit volumes, the amount of gel materials, and so on. Considerations should also be given to

Table 1: Static mechanical properties of SFPSC and C55 concrete.

Materials	Steel fiber (v%)	Polymer latex (wt.%)	Static mechanical properties		
			Compressive strength (MPa)	Flexural strength (MPa)	Ultimate bearing capacity (P_u/kN)
C55	0	0	69.0	5.36	36.0
SFPSC	0.580	1.30	70.1	8.68	40.4

the construction of the composite materials, such as liquidity (slump) and economy. Finally, the mix ratio of SFPSC was confirmed to be based on the standard mixture ratio, which was determined as "w(cement) : w(sand) : w(gravel) : w (water) : w(water reducer) = 1 : 1.493 : 2.432 : 0.321 : 0.012," and steel fiber of concrete volume rate of 0.58 v% and polymer latex of cement weight of 1.3 wt.% were mixed.

The details of experimental materials used were as follows: the cement was Huizhou Ta brand P.II42.5R cement; the sand was Dongjiang River natural washed-out sand, with a modulus of fineness of 2.68; the stone was 5~25 mm granite gravels; the steel fiber was the end-hook RS06073/35-800 indentation steel fiber manufactured by Shanghai Zhenjiang Fiber Co., Ltd., with the specification of $0.3 \times 1 \times 30$ mm, the length/diameter ratio of 48, and the tensile strength of 800 MPa; for the polymer latex, the VINNAPAS RE5010N cement modified special styrene butadiene latex produced by German Wacker Co., Ltd., which was kind of vinyl acetate/ethylene copolymerized emulsion powder that can be redispersed when it comes into contact with water; and the water reducer was JB-ZSC polycarboxylate concrete admixtures.

The experimental results (average) of 28 d static mechanical properties of SFPSC and C55 concrete which were designed using the above mix ratios are shown in Table 1.

2.2. Environmental Fatigue Experimental Methods. There were three types of fatigue experiments with different environment. Fatigue experiments for group A specimens (controlling experiments) were carried out under room temperature and the atmospheric environment. In this type of the experiments, the experimental environment was recorded by measuring the temperature and humidity in the lab room during the experimental period and taking the average value (23°C and 78% RH). The methods of environmental treatment and the required devices were different for the fatigue experiments with uncoupling and coupling of hot-wet environments and cyclic loads. The two environmental treatment methods and the loading methods of all fatigue experiments were described as follows.

2.2.1. Environmental Pretreatment for Uncoupling Fatigue Experiments. For the environmental fatigue experiments, the determination of the hot-wet environments were based on the actually measured working temperature and humidity of servicing bridges in Guangdong region, China, and its higher value (severe environment) was taken. Therefore, the experimental environments were divided into 3 groups B~D for the fatigue experiments under uncoupling action of the hot-wet environments and the cyclic loads. Among them, the experimental temperature and humidity for 7 specimens in group B was (50°C and 80% RH), for 6 specimens in group C was (50°C and 90% RH), and for 7 specimens in group D was (50°C and 95% RH).

Regarding the specimens of groups B~D, the environment pretreatment methods were conducted with reference to the relevant stipulations of Chinese national technical standard GB/T 2573-2008 "Test method for aging properties of glass fiber reinforced plastics" [18]. Firstly, the specimens were placed in temperature and humidity test chamber (Type Number Q8-901) and pretreated with constant temperature and humidity for 6 days (144 hours), and then the specimens were removed from the environmental box to be air-cooled for 2 days to ensure the dryness of the specimens. Finally, the fatigue experiments were carried out under room temperature and atmospheric environment.

2.2.2. Hot-Wet Environments for Coupling Fatigue Experiments. Regarding the fatigue experiments of coupling action of hot-wet environments and cyclic loads, the hot-wet environments used were the same with the above uncoupling fatigue experiments and were also divided into three groups. Among them, the temperature and humidity for 9 specimens in group E were 50°C and 80% RH, for 12 specimens in group F were 50°C and 95% RH, and for 5 specimens in group G were 35°C and 95% RH.

Regarding specimens in group E~G, the environmental treatments were completed by using the intelligent environment simulation and the controlling system, which was designed with the MTS810 material testing system by this research group (Figure 2) [19]. In order to ensure that the internal and external hot-wet conditions of the specimens were consistent at the beginning of loading action, the specimens of group E, F, and G were placed in the working box of the environment simulation and the controlling system in advance. Before the loading began, the environment simulation and controlling system was turned on for 4 hours to conduct pretreatment in hot-wet environment to reduce the influence of fatigue life by the difference of internal and external temperature and humidity of SFPSC specimen.

2.2.3. Fatigue Loading Method

(1) Loading way: the loading ways were the same for all fatigue experiments. Three-point bending loading

Figure 2: Intelligent environment simulation and controlling system.

way, stress controlling method, and sinusoid wave were applied; the stress ratio was $R = 0.1$. However, the loading frequencies were different in various experimental methods. Among them, the loading frequency for room temperature and atmospheric condition and for the uncoupling action of hot-wet environments and cyclic loads was fixed at 10 Hz. For the fatigue experiments with coupling action of hot-wet environments and cyclic loads, the loading frequency was reduced to 2 Hz for better coupling action of the environments and loads.

Based on the design specifications of the common concrete structures [19], if the number of loading cycles N reached 2×10^6 times, and the specimen remained unfailed, the fatigue experiment would be stopped. In other words, if the specimen still remained unfailed after 2×10^6 times of loading cycles, then it would be assumed that the specimen could endure infinite times of cyclic loads, and thus the fatigue life would be assumed to be infinite.

(2) Loading (stress) level: in order to obtain the complete fatigue curve (S~N curve), the loading (stress) levels S_R of group A specimens were divided into three grades ($S_R = P_{max}/P_u = 0.70$, 0.75, and 0.80). Among them, P_{max} was the maximum cyclic load, and P_u was the ultimate bearing capacity of SFPSC specimens (Table 2).

For the specimens of uncoupling action of environments and loads, the loading (stress) level S_R was set to 3 levels. Among them, group B was $S_R = 0.65$, 0.70, and 0.75, group C was $S_R = 0.60$, 0.65, and 0.75, and group D was $S_R = 0.60$, 0.64, and 0.68.

For the specimens of coupling action of environments and loads, the loading (stress) level S_R was set to 4 levels. Among them, group E was $S_R = 0.6$, 0.65, 0.70, and 0.75, group F was $S_R = 0.60$, 0.67, 0.72, and 0.77, and group G was $S_R = 0.60$, 0.70, 0.72, and 0.75.

The experimental conditions of group A~D specimens are shown in Table 2, and the experimental conditions of group E~G group specimens are shown in Table 3.

2.2.4. Data Acquisition and Recording. In the fatigue experiments, environmental data such as temperature and humidity were collected and recorded by the intelligent environment simulation and controlling system and are shown in Figure 2. The maximum and minimum loads, the deflections of the specimens (displacements), loading cycle number N, and other experimental data were automatically collected and recorded by the MTS810 testing system, and 8 sets of data were recorded for each loading cycle. The strain data of concrete were automatically measured and recorded by the Wavebook 516E dynamic strain device with 4 strain gages attached in the middle and bottom of the center and the lower edges of the sides of the specimen, and the sampling frequency was 100 Hz.

3. Fatigue Performance under Hot-Wet Environments

3.1. Experimental S~N Curves

3.1.1. Experimental S~N Curves under Uncoupling Action. According to the experimental conditions and the experimental methods described in Section 2, the fatigue experiments were carried out under the uncoupling action of hot-wet environments and cyclic loads for SFPSC specimens of group B~D. The controlling experiments were also carried out for group A specimens under room temperature and atmospheric environment. The experimental results of group A~D specimens are shown in Table 2. Based on the fatigue test data, the fatigue experimental curves (S_R~N curves) represented by the loading level (stress level) S_R were obtained, as shown in Figure 3.

By using the least square method, the experimental data of the specimens of each group were fitted, respectively, and the equations of S~N curves could be determined from the logarithmic coordinates:

$$S_R = A_i + B_i \lg(N) \quad (i = 1, 2, 3, 4), \tag{1}$$

where $S_R = P_{max}/P_u$; i indicates the group number of the specimens, and $i = 1$~4, respectively, represents group A~D;

Table 2: Experimental conditions and results of group A~D specimens.

Specimen number	Temperature, T (°C)	Relative humidity, H (%RH)	Stress level, $S_R = P_{max}/P_u$	Loading frequency, f (Hz)	Fatigue lives, N_f/cycles
A1					>2000000
A2			0.70		>2000000
A3					825899
A4					293301
A5	23	78	0.75	10	328359
A6					349997
A7					>2000000
A8					24099
A9			0.80		35677
A10					36071
B1			0.65		>2000000
B2					1800031
B3					63470
B4	50	80	0.70	10	207900
B5					157413
B6			0.75		92486
B7					50936
C1			0.60		>2000000
C2					1784833
C3	50	90	0.65	10	166591
C4					186596
C5			0.75		7940
C6					1960
D1			0.60		>2000000
D2					>2000000
D3			0.64		22236
D4	50	95		10	62746
D5					21355
D6			0.68		3647
D7					15173

and A_i and B_i were constant coefficients, and their values are shown in Table 4.

As shown in Figure 3, the fatigue performance of SFPSC was affected significantly by the pretreatment under hot-wet environments. In contrast to the specimens under room temperature and atmospheric environment (group A), the fatigue lives of all SFPSC specimens (group B~D) which were pretreated with hot-wet environments have been remarkably decreased. Furthermore, the more severe the hot-wet environment (the higher the temperature and humidity), the less the fatigue life was shown, that is, under the same stress level, the shorter the fatigue lives of the specimens. However, for the specimens of group C (50°C and 90% RH) and group D (50°C and 95% RH), the differences of the experimental S_R~N curves were small. The reason could be that in hot-wet environments, the fatigue performance of SFPSC specimens was mainly influenced by high temperature (50°C), and the relative humidity above 90% RH could cause the saturation of the moisture absorption ability of SFPSC specimens.

3.1.2. Experimental S~N Curves under Coupling Action. According to the experimental conditions and experimental methods described in Section 2, the fatigue experiments were carried out under coupling action of hot-wet environment and cyclic loads for group E~G SFPSC specimens, and the results are shown in Table 3. Based on the fatigue test data of each group, the fatigue experimental curves (S_R~N curves) represented by the loading level (stress level) S_R were obtained, as shown in Figure 4. For the convenience of comparison, the experimental results of SFPSC specimens under room temperature and atmospheric environment (group A) were also shown in the same figure.

Using (1) and paying attention to $i = 1, 2, 3$, and using the least square method, the experimental data of the specimens of each group E~G were fitted respectively. The coefficients A_i and B_i of each S_R~N equation could be determined, and their values are shown in Table 5.

With regard to the fatigue performance of SFPSC material under coupling action of hot-wet environments

Table 3: Experimental conditions and results of group E~G specimens.

Specimen number	Temperature, T (°C)	Relative humidity, H (%RH)	Stress level, $S_R = P_{max}/P_u$	Loading frequency, f (Hz)	Fatigue lives, N_f/cycles
E1					1678342
E2			0.60	2	1048011
E3					410854
E4					470951
E5	50	80	0.65	2	338499
E6					336204
E7			0.70	2	249136
E8			0.75	2	3082
E9					1733
F1			0.60	2	>2000000
F2					>2000000
F3					3106
F4			0.67	2	13237
F5					18525
F6	50	95			50766
F7					4266
F8			0.72	2	15037
F9					16241
F10					223
F11			0.77	2	906
F12					151
G1			0.60		>2000000
G2			0.70		>2000000
G3	35	95	0.72	2	39535
G4			0.75		27171
G5					1549

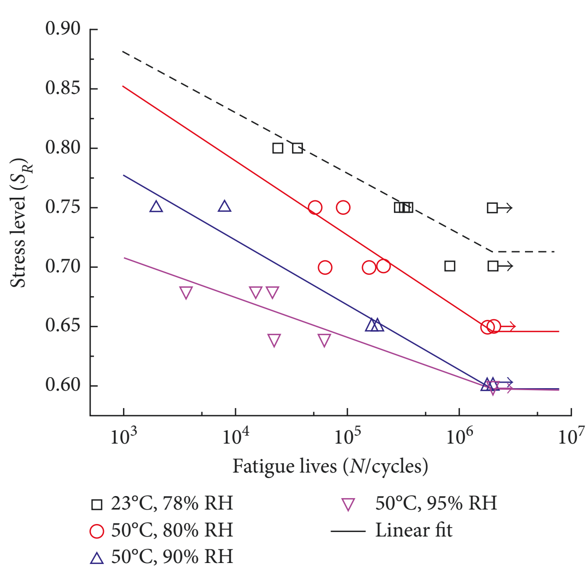


Figure 3: Experimental S_R~N curves under uncoupling of hot-wet environments and cyclic loads.

and cyclic loads, as shown in Figure 4, the experimental results were similar to that under the uncoupling action, and the specimens of each groups under the coupling action also had shorter fatigue lives than those under room temperature and atmospheric environment (group A). Moreover, the higher the temperature and humidity, the shorter the fatigue life of SFPSC under the same stress level. In the same high humidity environment (95% RH), the fatigue life of SFPSC decreased significantly as the temperature increased. In the same high temperature (50°C) environment, the higher the humidity was, the shorter the fatigue life of SFPSC observed. However, with the increase of environmental treatment time, the decrease of fatigue lives of specimens became gradual. When the fatigue life of specimen approached to its fatigue limit, humidity had less influence on fatigue performance of SFPSC.

Table 4: Coefficients A_i and B_i for group A~D specimens.

Coefficients	i (group)			
	1 (group A)	2 (group B)	3 (group C)	4 (group D)
A_i	1.03	1.04	0.940	0.808
B_i	−0.0510	−0.0621	−0.0544	−0.0336

It is shown in Figure 4 that the influence of temperature on fatigue lives of SFPSC specimens was dominant, and the influence of humidity was secondary.

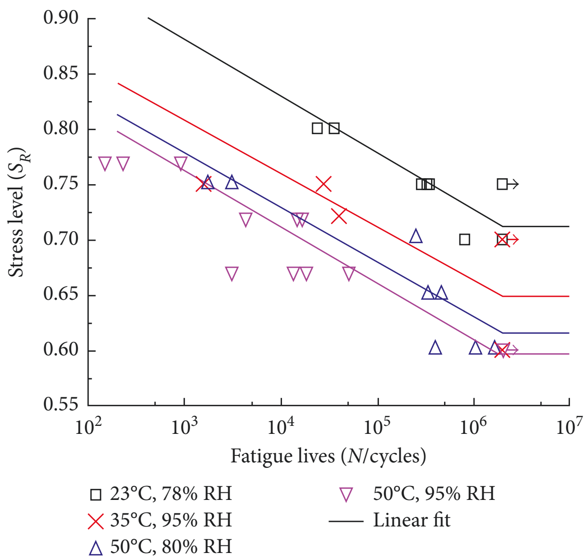


Figure 4: Experimental S_R~N curves under coupling of hot-wet environments and cyclic loads.

Table 5: Coefficients A_i and B_i for group E~G specimens.

Coefficients	i (group)		
	1 (group E)	2 (group F)	3 (group G)
A_i	0.953	0.926	0.914
B_i	−0.0482	−0.0492	−0.0508

3.2. Analysis of Failure Mechanism of SFPSC in Hot-Wet Environments. As shown in the previous sections regarding S_R~N curves, fatigue experiment results of SFPSC specimens under both the coupling/uncoupling action of hot-wet environments and cyclic loads showed that the environmental fatigue lives of the specimens were shorter than those in room temperature and atmospheric environment. Furthermore, the more severe the environments were and the higher the temperature and humidity were, the shorter the fatigue life of SFPSC was, under the same stress level. The fatigue failure mechanism of SFPSC in hot-wet environments could be analyzed as follows:

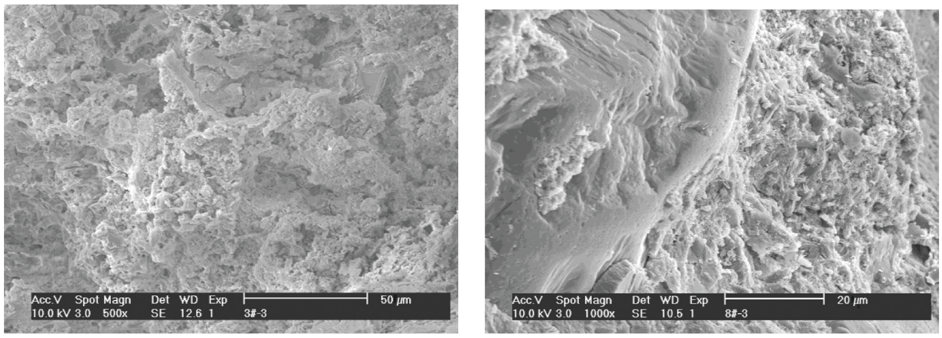
(1) The influences of the temperature and humidity on the interfaces between steel fibers and concrete matrixes. When the hot-wet environment was severe, especially when there was a big difference between the environmental humidity and the internal humidity of the concrete, the transmission of water from the surfaces to internal through the concrete pores would be intensified. Consequently, a higher surface tensile force would be generated on the liquid surfaces of the internal pores of the concrete, and such surface tensile force would intensify the crack growth within the concrete and lead to decrease of the cohesive force of the interfaces between the steel fibers and the concrete matrixes.

(2) The influences of humidity on structural compactness of SFPSC. Figure 5(a) shows that there are a lot of needle-like crystals of calcium vanadium stone and flocculation of C-S-H gel in the hydration products of the concrete without polymer latex, which have many pores with very little connections. The combination of the hydration products was relatively loose with some large hole in the combination. Some crossed microcrack can be observed on the surface of the slurry. After mixing of the polymer latex, as shown in Figure 5(b), the gaps or the cavities of the cement hydration products would be filled up or joined by the membranous substances formed by the polymer latex, which made the hydration products in the concrete more compact, caused reduction of the microcracks, and improved the cracking resistance of the material [20]. In addition, the concrete would show the characteristics of dry shrinkage and wet expansion; the higher the strength of the concrete, the more obvious such phenomenon is. Therefore, during the pretreatment process in the hot-wet environment, when the humidity was high, the gaps and cavities in the concrete, which was originally filled by the latex membrane substance, would expand due to wet expansion, resulting in the decrease of the structural compactness, and the fatigue performance became poor. Moreover, the concrete strength used in this research was higher (C55), and such phenomenon was more obvious.

(3) The influences of temperature on the mechanical properties of polymer latex. The reactions on the mechanical properties of the polymer to temperature were rather sensitive. It was showed by existing research [14] that polymer latex would be softened as the temperature increased, and when the temperature reached to a certain value, the supporting capacities of the polymer would be lost, and thus caused greater influences on the mechanical properties of the polymer concrete.

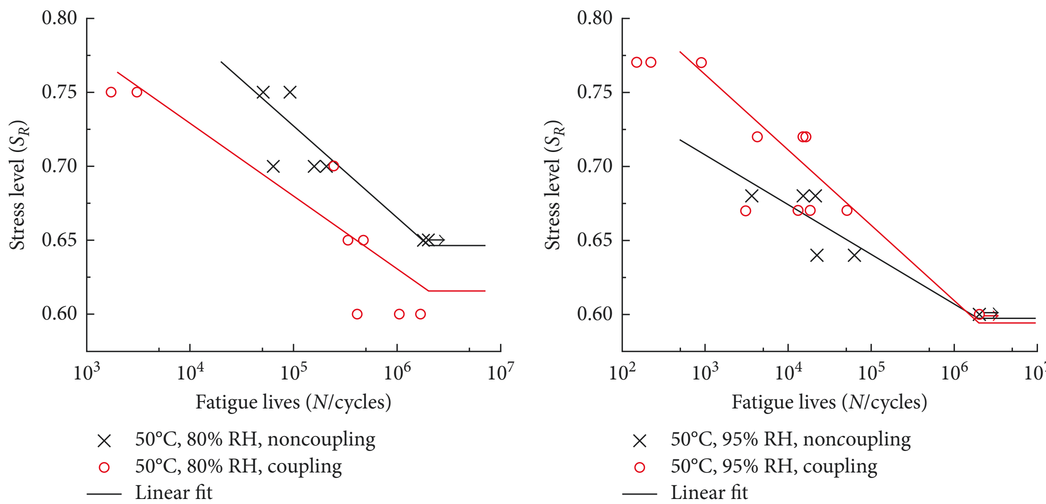
3.3. Influence of Experimental Methods on Fatigue Performance. To study the influence of environmental fatigue test methods on the fatigue performance of SFPSC material, the fatigue experimental data of group B and E (50°C and 80% RH), as well as group C and F (50°C and 95% RH) in Tables 2 and 3 were taken and are shown in Figures 6(a) and 6(b), respectively. Figure 6(a) shows that under lower relatively humidity (80% RH), compared to the experimental method of uncoupling action of environment and loads, the fatigue lives of SFPSC would be lower for the experimental data under coupling action of the hot-wet environment and the cyclic loads, as long as they were under the same loading level regardless of high or low loading level. The whole S_R~N curve under coupling action would be below the former.

Under the same temperature (50°C), when the relative humidity was higher (95% RH), the influence rules of environmental fatigue experimental method of SFPSC to fatigue life would be changed. In such hot-wet environment,



(a) (b)

Figure 5: Effect of the polymer latex on the hydraulic products (SEM photos). (a) Specimens without polymer latex. (b) Specimens with polymer latex.



(a) (b)

Figure 6: Influence of the experimental method on S_R~N curves. (a) 50°C and 80% RH. (b) 50°C and 95% RH.

when the loading level was high, the fatigue lives under the uncoupling action were lower. When the loading level was low and especially close to the fatigue limit of the material, the fatigue lives of SFPSC under coupling action were lower.

For the analysis of the experimental results shown in Figure 6, the effect mechanism of environmental fatigue test methods on the fatigue performance of SFPSC could be considered as follows:

(i) The temperature and humidity set in these environmental fatigue experiments were higher than that in room temperature and atmospheric environment as shown in Tables 2 and 3. For the case of uncoupling action of hot-wet environments and loads, the specimens were pretreated in the environmental box and placed in room temperature and atmospheric environment to dry. Then, the fatigue experiments were carried out. During air cooling and drying, the moisture originally absorbed by concrete material of the specimens in the hot-wet environments (environmental box) gradually vaporized, causing the gaps produced under hot-wet environments to reduce or vanish as the temperature and humidity decreased. The fatigue performance would be partially recovered.

(ii) Previous studies [20] showed that, under the conditions of coupling action of hot-wet environments and loads, the deformation of the specimens caused acceleration of moisture and heat transmission rate into the interior of concrete material and led to a decrease in fatigue performance.

Based on the analysis of (i) and (ii), under common hot-wet environments, the experimental condition was more severe under coupling action compared to uncoupling action, and it would lead to a decrease in fatigue lives, as shown in Figure 6(a).

(iii) For high temperature and high humidity environment (50°C and 95% RH), when the traditional experimental method with uncoupling action of environment and loads was used, as described in (i), the fatigue performance of the specimens would be partially recovered if the specimens were placed in room temperature and atmospheric environment to be dried after the hot-wet pretreatment. The comparison to fatigue performance of the specimens under coupling action of environment and loads could be divided into the following two parts:

Firstly, when the experimental period was short (high loading level and low fatigue lives), high temperature and high humidity would not be able to have sufficient time to cause erosion of the specimens. Therefore, the fatigue lives of specimens were longer under coupling action during this interval.

Secondly, when the experimental time was long enough (low loading level especially close to the fatigue limit and long fatigue lives of the specimens), high temperature and high humidity would have sufficient time to cause erosion of the specimens. Due to the reason described in (ii), the fatigue lives of SFPSC specimens would be shorter than the specimens under uncoupling action of hot-wet environment and loads during this interval.

4. Environmental Fatigue Equations of SFPSC

4.1. Environmental Fatigue Equations. In the components of SFPSC, polymer latex has a consolidation action on the concrete gel and a bonding action on steel fiber. The adhesion and fixation of the steel fiber and the concrete gel were caused by the adhesion and mechanical friction of their contact interface. When SFPSC was cracked due to external loading, the steel fibers dispersed in the damaged section would be pulled out by the two ends of the concrete. However, this adhesion force would form resistance to the cracking and significantly disperse the tensile stress that was originally concentrated. Meanwhile, it would also continuously absorb the fracture energy and cause a dramatic improvement of the anticracking property of SFPSC. When the polymer latex and steel fiber in SFPSC came into contact, the surface of steel fiber would adhere to the hydrophilic base of the surfactant. As the cement hydration effect increased, water was consumed and a large amount of heat was released, and a chemical adhesion of the surface of hydrophilic base and steel fibers could be caused. Furthermore, as the temperature increased and water decreased, the adhesion effect would also increase.

When studying the effect mechanism of serving environmental temperature to the fatigue performance of SFPSC material, this research group [14, 15] considered the influence of temperature would be mainly presented in (1) thermal stress caused by different thermal expansion coefficient of each phase in the composites, (2) influence of temperature on polymer latex performance, (3) the influence of the change in polymer latex properties on the mechanical properties of the interface between steel fiber and the base matrix, and so on.

For the influence of serving environmental humidity to the mechanical properties of SFPSC, this research suggested that (1) the high humidity environment would weaken the adhesion action of polymer latex and steel fibers and reduce the strength; (2) in high humidity environments, moisture absorption stress would be generated in the concrete, and the destruction would be accelerated, and (3) high humidity could accelerate the speed of corrosion reaction for steel fibers, leading to a decrease of its mechanical properties.

For SFPSC materials serving in the hot-wet environment, the effects of temperature and humidity on fatigue performance mentioned above should be taken into consideration. Therefore, when establishing the environmental fatigue equation of SFPSC in this paper, the previous studies by this research group on the thermal fatigue equation [21] and hot-wet fatigue equation [20] for reinforced concrete (RC) beams strengthened with carbon fiber reinforced polymer (CFRP) were used as references. It suggested that for experimental methods of both coupling and uncoupling action of hot-wet environments and cyclic loads, fatigue life $f(N)$ of SFPSC in hot-wet environments under bending loads could be presented by the following formula:

$$f(N) = \frac{[S_R + C_1 + C_2 f(T,H)]}{[C_3 + C_4 f(T,H)]}, \quad (2)$$

where S_R was the loading level (also known as the stress level, $S_R = P_{\max}/P_u$) and $f(T, H)$ was the hot-wet function.

Based on the analysis of the influence mechanism of temperature and humidity on the fatigue performance of SFPSC materials and the mathematical description of the hot-wet function generated by this research group, the expression of $f(T, H)$in this paper was taken as follows:

$$f(T,H) = C_5 e^{C_7 T} + C_6 e^{C_8 H}. \quad (3)$$

In (2) and (3), $C_1 \sim C_8$ were constant coefficients, determined by experiments.

For (2), the fatigue life function $f(N)$ could be described in single logarithmic coordinates, considering the fatigue curves ($S \sim N$ curves) of the material. The expression of $f(N)$ was as follows:

$$f(N) = \lg N. \quad (4)$$

The fatigue equation of SFPSC under hot-wet environments, which was also called the hot-wet fatigue equation, was generated by ((2)~(4)).

By using these equations, the bending fatigue lives and fatigue limits of the SFPSC specimens under coupling and uncoupling action of the hot-wet environments and loads could be conveniently and accurately estimated.

4.2. Environmental Fatigue Equation under Uncoupling Action. Using the experimental data of group B~D specimens shown in Table 2 and the least squares method, the data were fitted in ((2)~(4)), and the coefficients $C_1 \sim C_8$ could be determined. Then, the expression for fatigue lives of SFPSC materials under uncoupling action of the hot-wet environments and three-point bending cyclic loads presented by loading level S_R was determined. The environmental fatigue equation of SFPSC was as follows:

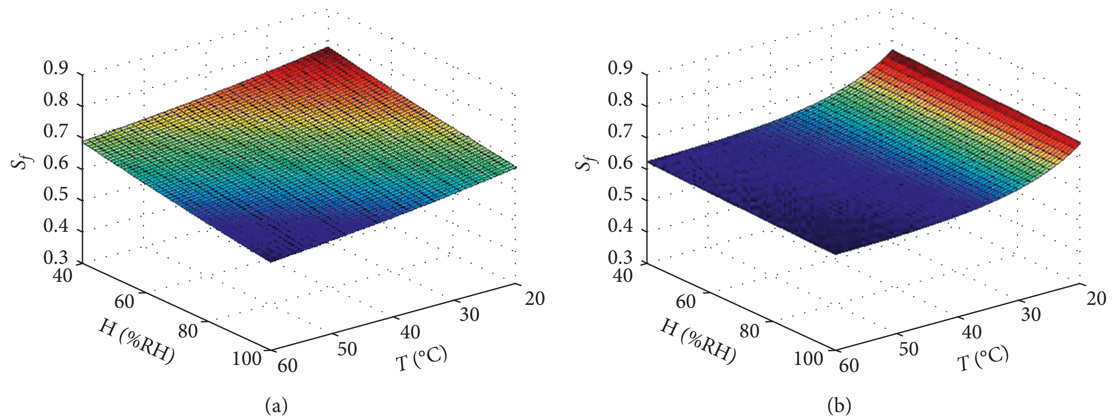


Figure 7: The influence of hot-wet environments on the relative fatigue limit S_f. (a) S_f under the uncoupling action. (b) S_f under the coupling action.

$$S_R = 0.343 + 0.238e^{-0.0174T} + 0.851e^{-0.619H} - \left(0.0137 - 0.00219e^{-0.0174T} + 0.0657e^{-0.619H}\right)\lg(N), \tag{5}$$

where the unit of temperature T is presented in (°C) and humidity H is presented in (% RH).

By using (5), the fatigue lives of the SFPSC materials under uncoupling action of hot-wet environments and cyclic bending loads and the traditional environmental fatigue experimental method could be conveniently and accurately estimated.

4.3. Environmental Fatigue Equation under Coupling Action. Similar to the analysis method shown in Section 4.2, the experimental data of group A, E, F, and G specimens and the least square method were used to fit in ((2)~(4)), and the coefficients of C_1~C_8 could be determined. Then, the expression for fatigue lives of SFPSC materials under coupling action of hot-wet environments and cyclic bending loads presented by loading level S_R was determined. The environmental fatigue equation of SFPSC was as follows:

$$S_R = 0.543 + 1.12e^{-0.0998T} + 0.412e^{-0.114H} - \left(0.0294 + 0.0101e^{-0.0998T} + 0.0221e^{-0.114H}\right)\lg(N). \tag{6}$$

By using (6), the fatigue lives of the SFPSC materials under coupling action of hot-wet environments and cyclic bending loads could be conveniently and accurately estimated.

4.4. Fatigue Limits of SFPSC under Hot-Wet Environments. For general concrete structures, the corresponding loading value of $N = 2\times10^6$ cycles could be defined as the fatigue limit (depending on the specifications, it can also be defined as $N = 4\times10^6$ cycles and 1×10^7 cycles). $N = 2\times10^6$ cycles was substituted into (5) and (6), and the relations of fatigue limits S_f of the bending SFPSC material under coupling and uncoupling action of the environments and cyclic loads presented by S_R to the temperature T and humidity H could be obtained and the expressions were

$$S_f = 0.257 + 0.252e^{-0.0174T} + 0.437e^{-0.619H} \text{ (uncoupling action)}, \tag{7}$$

$$S_f = 0.358 + 1.06e^{-0.0998T} + 0.273e^{-0.114H} \text{ (coupling action)}. \tag{8}$$

Using (7) and (8), the change rules of the fatigue limits S_f of SFPSC material under different hot-wet environments and cyclic bending loads could be obtained and are shown in Figure 7. As shown in Figure 7, when the environmental temperature was increased, the relative fatigue limit S_f decreased; when the environment humidity was increased, the relative fatigue limit S_f would also be decreased. In addition, comparing Figures 7(a) and 7(b), it showed that regardless of coupling or uncoupling action of environments and loads, the rules of changes in relative fatigue limit S_f of SFPSC materials estimated by the environmental fatigue equations due to the shift in temperature T and humidity H remained congruity. However, in general, the relative fatigue limit of SFPSC material under coupling action of environments and loads was lower than that under uncoupling action. In addition, in contrast to room temperature and atmospheric environment, under the high temperature and high humidity (50°C and 95% RH) environment, the fatigue limit S_f of SFPSC would be reduced by about 15%. Therefore, the effects of the hot-wet environments on fatigue lives of SFPSC were very significant. Meanwhile, this also showed that, for the antifatigue/durability designs of the bridge structures using SFPSC material, the adverse effects of the hot-wet environments must be considered.

In order to verify the effectiveness and feasibility of (5) and (6), the experimental conditions of the hot-wet environments shown in Tables 2 and 3 were substituted into (7) and (8) separately, and the environmental fatigue limits of SFPSC under bending loads were obtained respectively, as shown in Table 6. According to Table 6, the actual experimental estimation of relative fatigue limits S_f of SFPSC

Table 6: Relative fatigue limits of SFPSC S_f in the hot-wet environments.

Testing method	Temperature, T (°C)	Relative humidity, H (%RH)	Relative fatigue limit S_f Calculated values by (7) or (8)	Relative fatigue limit S_f Experimental estimation by (1)	Relative error (%)
Coupling action of environments and loads	23	78	0.715	0.709	0.846
	50	80	0.614	0.616	0.325
	50	95	0.611	0.594	2.86
	35	95	0.635	0.649	2.16
Uncoupling action of environments and loads	23	78	0.696	0.709	1.83
	50	80	0.629	0.649	3.08
	50	90	0.613	0.597	2.68
	50	95	0.605	0.596	1.51

obtained from two types of experimental methods well matched with the calculated values, and the average relative errors were presented as 2.28% (uncoupling action) and 1.55% (coupling action), respectively. This explained that using (5) and (6) to estimate the hot-wet environmental fatigue lives and fatigue limits of SFPSC material under coupling and uncoupling action of hot-wet environments and bending loads was effective and feasible in this research.

5. Conclusions

The experimental studies for environmental fatigue/durability of "steel fiber polymer structural concrete (SFPSC)" were conducted using the conventional uncoupling and coupling methods of hot-wet environments and cyclic bending loads. The experiments were carried out under three different hot-wet conditions (50°C and 80% RH, 50°C and 90% RH, and 50°C and 95% RH) for uncoupling action and three different hot-wet conditions (50°C and 80% RH, 50°C and 95% RH, and 35°C and 95% RH) for coupling action. The experimental results were discussed in comparison with the results obtained under room temperature and atmospheric environment (23°C and 78% RH), and conclusions were obtained as follows:

(1) The effects of hot-wet environments on the bending fatigue performance/durability of SFPSC were obvious. Within the range of testing conditions in this paper, when the environmental temperatures were the same, fatigue lives and fatigue limits of SFPSC material would decrease along with the increase of the humidity; when the humidity remained unchanged, the fatigue lives and fatigue limits would decrease along with the increase of the temperature. In comparison to the room temperature and atmospheric environment, the fatigue limit S_f would be reduced by about 15% under high temperature and high humidity (50°C and 95% RH) environment.

(2) Compared with the experimental results of traditional uncoupling environmental fatigue experiments, the fatigue lives and especially the fatigue limits of SFPSC were reduced under coupling action of hot-wet environments and cyclic loads. Therefore, in order to study the environmental fatigue performance of the structures in service and under coupling action such as main load-bearing structures of bridges, it would be necessary to conduct the experiments under a condition close to the actual service environment, and testing method of coupling action should be used.

(3) Environmental fatigue life equations of SFPSC under the uncoupling/coupling action of hot-wet environments and cyclic bending loads (i.e., the hot-wet fatigue equations) were proposed based on the data of environmental fatigue experiments and in combination with the classical theories of fatigue strength. By using the fatigue equations, the fatigue lives and fatigue limits of the SFPSC materials in service under hot-wet environments could be conveniently and accurately estimated.

(4) This research results showed that the adverse effects of the hot-wet environments must be considered for designing of antifatigue/durability of the bridge structures of SFPSC in the subtropical areas in order to avoid safety hazards.

It is necessary to point out that the environmental fatigue equations proposed in this paper should be verified on a greater environmental scale, and more experimental data should be collected to verify its accuracy of calculation and applicability.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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