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Experimental research on high-frequency fatigue behavior of concrete

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ABSTRACT: The fatigue strength of concrete under cyclic loads of vehicles is an important problem in calculation and design of bridge engineering. Based on this viewpoint, the fatigue tests of plain concrete under constant-amplitude and stepping-amplitude cyclic loads were conducted. The damage mechanism of plain concrete specimens under high-frequency fatigue loads was analyzed and the nonlinear accumulative fatigue damage formula was proposed. The fatigue equation *P–S–N* considering the failure probability p' was given. The above-mentioned research results made a good preparation for further study on high-frequency fatigue tests of concrete cylinders reinforced with carbon fibers.

1 INTRODUCTION

Bridge structures of highway and railway suffer cyclic loads from vehicles. The failure characteristics of these structures and their components under cyclic loads show that the fatigue failure loads are far lower than their original strength. The fatigue failure is abrupt and the consequences are very serious.

In this paper, fatigue tests of plain concrete under constant-amplitude and stepping-amplitude cyclic loads were carried out, the damage mechanism was analyzed, the nonlinear fatigue accumulative damage model was established and loading frequency correction coefficient considering the effect of loading frequency on fatigue life was put forward. In addition, probability statistics analysis was conducted on the tests data and a fatigue equation considering the failure probability was proposed.

2 HIGH FREQUENCY FATIGUE TESTS OF PLAIN CONCRETE

The loading frequency of common fatigue tests is usually below 30 Hz, while the loading frequency of high frequency fatigue tests can reach 100 Hz. With high frequency, time and costs for reaching the fatigue limit and strength of the material are dramatically reduced. Here high frequency fatigue tests with constant amplitude and stepping amplitude are conducted.

2.1 *High frequency fatigue tests under constant-amplitude and stepping-amplitude cyclic load*

2.1.1 *Static loading tests*

33 cylindrical C30 concrete specimens with 70 mm in diameter, 100 mm in height were prefabricated for the tests. The specimens were manufactured in plastic moulds and were tested after having been maintained for 28 days at the temperature 20 ± 3°C.

Through the static loading tests it was obtained that the ultimate loading capacity of cylindrical specimens is $F_u = 112.11$ kN, and so the axial compressive strength is $f_{co} = 29.1$ MPa. The compressive strength of cubic samples is $f_{cu} = 36.6$ MPa, and the elastic modulus amounts to $E_c = 4.73 \times 10^4$ MPa.

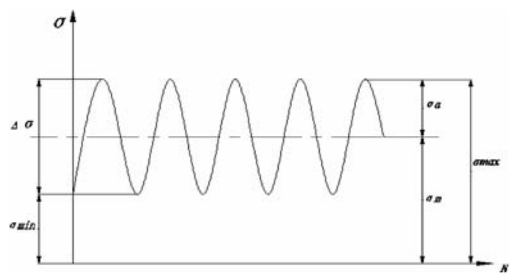

Figure 1. Relationship between fatigue load parameters.

Table 1. The loading condition of high-frequency fatigue tests.

	Group	σ_m	σ_a	σ_{max}	σ_{min}	Ratio of σ_{min} to $\sigma_{max} R$	Number of specimens
Constant-amplitude cyclic loading tests	Group1	0.45	0.4	0.85	0.05	0.059	4
	Group2	0.45	0.35	0.8	0.1	0.125	3
	Group3	0.45	0.32	0.77	0.13	0.169	3
	Group4	0.45	0.3	0.75	0.15	0.200	4
	Group5	0.45	0.28	0.73	0.17	0.233	3
Stepping-amplitude cyclic loading tests	Group1	0.45	0.28	0.73	0.17	0.233	4
			0.3	0.75	0.15	0.200	
			0.32	0.77	0.13	0.169	
			0.34	0.78	0.11	0.141	
			0.4	0.85	0.05	0.059	
	Group2	0.45	0.3	0.75	0.15	0.200	4
			0.35	0.8	0.1	0.125	

2.1.2 *The introduction of high frequency fatigue testing machine*

The high frequency fatigue tests were conducted in AMSLER HFP (High Frequency Pulsator)—100 HFP 5100 testing machine, which was produced by ZWICK/ROELL company. The basic technical parameters of testing machine include the maximum test load (100 kN), maximum vibration frequency (150 Hz), maximum static loading capacity (100 kN) and maximum dynamic loading capacity (100 kN ± 50 kN).

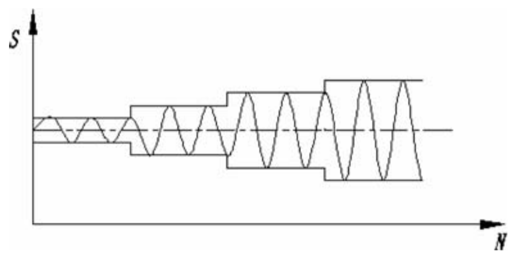

Figure 2. The loading form of stepping-amplitude cyclic loading tests.

2.1.3 *Test schemes*

1. Constant-amplitude cyclic loading tests:

   The test parameters include upper limit fatigue load F^f_{max}, lower limit fatigue load F^f_{min}, mean load F^f_m, the biggest stress σ_{max}, the smallest stress σ_{min}, mean stress σ_m, the stress amplitude σ_a and the difference between σ_{max} and σ_{min}, $\Delta\sigma$. The relationship among the parameters is shown in Figure 1.

   Table 1 indicates the loading condition for the high frequency fatigue tests under constant-amplitude cyclic loads.
2. Stepping-amplitude cyclic loading tests:

   Figure 2 shows the loading form of stepping-amplitude cyclic loading tests and Table 1 shows the loading condition.

2.2 *Test results*

Constant-amplitude cyclic loading tests were carried out at 5 stress levels using 17 specimens while stepping-amplitude cyclic loading tests were divided into 2 groups using 8 specimens in total. The fatigue life of specimens is shown in Tables 2 and 3. Among the data, two are invalid (tests were not successful) and indicated with delete line, three exceed the limit fatigue life of the national norm 2×10^6 and are indicated with underline.

Table 2. Fatigue life results of high-frequency fatigue tests with constant amplitude.

	Specimen	σ_{max}	σ_{min}	Fatigue life	Mean fatigue life
Group 1	PCF15	0.85	0.059	10331	26710
	PCF16			944	
	PCF19			14708	
	PCF24			55090	
Group 2	PCF13	0.8	0.125	61063	59518
	PCF17			41773	
	PCF20			75718	
Group 3	PCF5	0.77	0.169	244165	248550
	PCF21			252934	
	PCF22			3870	
Group 4	PCF6	0.75	0.200	804676	1515514
	PCF12			2100011	
	PCF18			2100000	
	PCF23			1057368	
Group 5	PCF7	0.73	0.233	2100003	1405245
	PCF8			940873	
	PCF9			1174859	

Table 3. Fatigue life results of high-frequency fatigue tests with stepping amplitude.

		Fatigue life			
σ_m	Specimen	PCF11	PCF12	PCF14	PCF25
Group 1	σ_a				
0.45	0.28	2000000	2000000	2000000	2000000
	0.3	2000000	2000000	2000000	2000000
	0.32	2000000	2000000	2000000	2000000
	0.34	2000000	1032433	1551877	2000000
	0.4	60589	–	–	202896
Group 2	Specimen	PCF3	PCF4	PCF18	PCF10
0.45	0.3	2000000	2000000	2000000	2000000
	0.35	814144	943842	595244	485954

2.3 *High-frequency fatigue failure mechanism of C30 concrete specimens*

According to the results of high-frequency fatigue tests, there are 2 main modes of fatigue failure:

1. Vertical failure. In the loading process, the loading plates of fatigue testing machine fully coincide with the end planes of concrete specimen. stress, the vertical micro-cracks will arise and develop into vertical macro-cracks, which will result in the rupture of specimen.
2. Conical failure. In the process of loading, the cracks of concrete specimens don't develop along the loading direction. The final rupture macro-cracks look like cones.

From the fatigue testing results, it is found that the vertical failure is the main failure mode. For the stepping-amplitude cyclic loading tests, due to long time vibration, inner and surface cracks fully developed, some specimens even crushed.

3 THE NONLINEAR ACCUMULATIVE HIGH-FREQUENCY FATIGUE DAMAGE FORMULA OF C30 PLAIN CONCRETE

Based on the axial fatigue testing results of high strength concrete, Wu modified the linear accumulative fatigue damage formula with consideration of the discreteness of fatigue tests and the effect of loading order. He put forward the following formula for computing the accumulative fatigue damage and predicting the residual fatigue life:

$$D = \gamma_1 \gamma_2 \cdot \sum_i \frac{n_i}{N_{fi}} = 1 \tag{1}$$

where, γ_1 and γ_2 are correction coefficients in consideration of the discreteness of fatigue tests and the effect of loading order respectively. N_{fi} is the fatigue life and n_i is the cyclic loading number, both correspond to the stress level i.

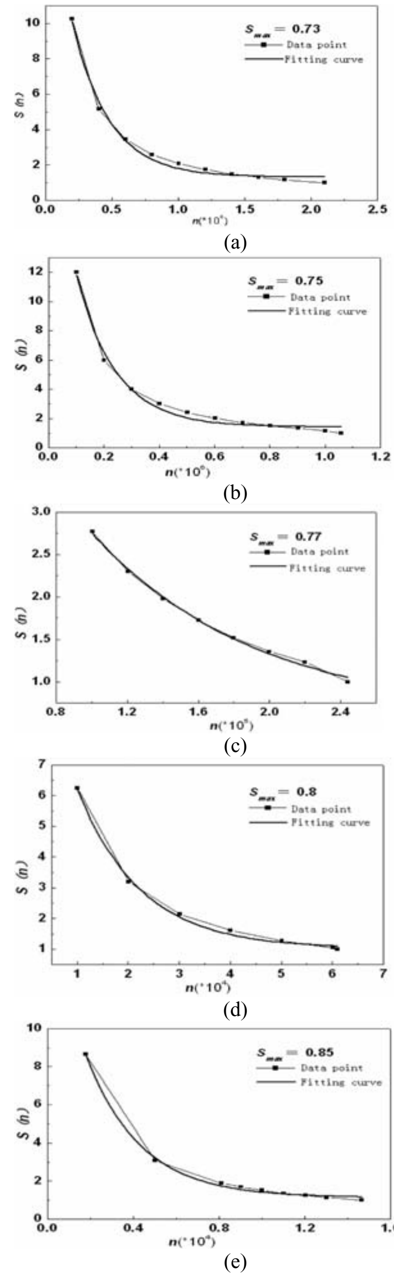

Figure 3. $s_i(n_i) \sim n_i$ curves under constant-amplitude cyclic loads at five stress levels.

Cao (2004) replaced $\gamma_1\gamma_2$ with the function $s_i(n_i)$, and gave the accumulative damage formula at the stress level i after n_i cycles of loading:

$$D_t = s_i(n_i)\frac{n_i}{N_{fi}} \tag{2}$$

Figure 3 shows $s_i(n_i) \sim n_i$ curves for concrete specimens in the constant-amplitude cyclic loading tests at 5 stress levels. The following equations are obtained through curve fitting.

$S_{\max} = 0.73 : s(n) = 2.08524n^{-0.99139}, R = 1;$
$S_{\max} = 0.75 : s(n) = 2.41503n^{-0.99854}, R = 1;$
$S_{\max} = 0.77 : s(n) = 1.48873n^{-0.41478}, R = 0.95248;$
$S_{\max} = 0.80 : s(n) = 6.28489n^{-0.98726}, R = 0.99974;$
$S_{\max} = 0.85 : s(n) = 1.51394n^{-1.01304}, R = 0.99994;$

In the above-listed equations, $S_{\max}$ is maximum stress level, R is correlation coefficient.

Five above-listed equations could be unified as:

$$s_i(n) = a_i n^{b_i} \tag{3}$$

where a_i and b_i are material properties corresponding to the stress level i, which can be obtained by constant-amplitude cyclic loading tests.

Hence, the following accumulative damage formula is suggested.

$$D = \sum_i s_i(n_i)\frac{n_i}{N_{fi}} = \sum_i a_i n_i^{b_i} \cdot \frac{n_i}{N_{fi}} \tag{4}$$

Equation 4 is not only suitable for computing the fatigue damage under constant-amplitude cyclic loads, but also suitable for analyzing the development of fatigue damage under stepping-amplitude cyclic loads.

4 BASQUIN FUNCTIONS

Figure 4 shows $\lg S \sim \lg N_f$ curves obtained from normal low-frequency fatigue tests and high frequency fatigue tests with constant-amplitude cyclic loads respectively. The data of low frequency fatigue tests are obtained from the reference (Cao 2004) and the compressive strength of concrete is 20.47 MPa.

Compared with the data of low-frequency fatigue tests, it could be found that at the same stress level, fatigue life in high-frequency fatigue tests is longer, which reflects the effect of loading frequency on fatigue performance of concrete.

In 1910, Basquin established the famous Basquin equation for constant-amplitude cyclic loading tests, which shows the relationship between stress amplitude and fatigue life.

$$\sigma_a = \sigma_f'(2N_f)^b \tag{5}$$

where σ_a is the stress amplitude, N_f is the fatigue life corresponding to the stress amplitude σ_a, b is Basquin

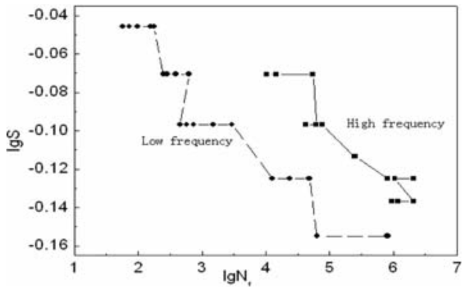

Figure 4. $\lg S \sim \lg N_f$ curves under high-frequency and low-frequency fatigue loads.

index, and σ_f' is the coefficient of fatigue strength. Basquin equation is also suitable for the description of $\sigma_a \sim N_f$ relation in high-frequency fatigue tests.

By making logarithmic transformation in both sides of Equation 5,

$$\lg \sigma_a = \lg \sigma_f' + b \lg(2N_f) \tag{6}$$

The Basquin equations for the curves in Fig. 7 are:

High frequency: $\sigma_a = 0.774587 \times (2N_f)^{-0.06597}$ (7)

Low frequency: $\sigma_a = 0.426177 \times (2N_f)^{-0.03455}$ (8)

The fatigue limit σ_a corresponding to different cyclic loading number can be calculated from Equations 7 and 8.

5 CORRECTION COEFFICIENT FOR HIGH FREQUENCY FATIGUE TESTS

According to Chinese national norm, $N = 2 \times 10^6$ is adopted as the limit low-frequency fatigue life of concrete for designing highway bridge.

From the comparison between the low-frequency and high-frequency fatigue test results in Fig. 7, it can be drawn that high frequency can improve the fatigue characteristics of concrete. When the results of high-frequency fatigue test are applied to solve the practical low-frequency fatigue problems, the effect of high loading frequency should be considered.

5.1 *The definition of correction coefficient*

High frequency correction coefficient is defined as the ratio of fatigue limit σ_{aL} under low frequency condition to fatigue limit σ_{aH} under high frequency condition:

$$\phi = \frac{\sigma_{aL}}{\sigma_{aH}} \tag{9}$$

Normally, with the increase of the loading frequency, the anti-fatigue characteristics of materials are improved, so ϕ is less than 1. The smaller ϕ is, the more positive is the reaction of the materials to the high loading frequency. Conversely, the closer ϕ to 1 is, the smaller is the influence of loading frequency to fatigue characteristics. When ϕ is equal to 1, the high loading frequency and the low loading frequency have the same fatigue characteristics.

From Equations 5 and 9, the following equation is obtained:

$$\phi = \phi_0 (2N_f)^{\Delta b} \qquad (10)$$

where

$$\phi_0 = \frac{\sigma'_{fL}}{\sigma'_{fH}} \qquad \Delta b = b_L - b_H$$

ϕ_0 is the ratio of strength coefficient of low frequency fatigue test to that of high frequency fatigue test, while Δb is the difference between strength index of low frequency fatigue test and that of high frequency fatigue test.

Table 4. High-frequency and low-frequency fatigue limits along with high-frequency correction coefficient corresponding to various fatigue cycles.

Cycle	High frequency fatigue limit	Low frequency fatigue limit	High frequency correction coefficient ϕ
1×10^4	0.403	0.303	0.868
1×10^5	0.346	0.280	0.887
1×10^6	0.297	0.258	0.807
2×10^6	0.284	0.252	0.751

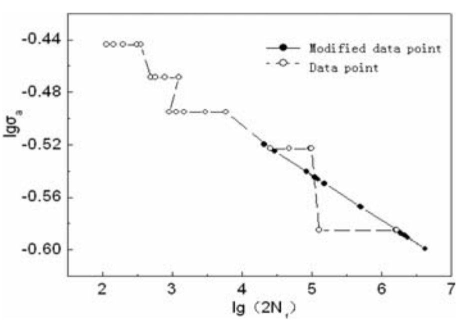

Figure 5. $\lg \sigma_a \sim \lg(2N_f)$ curves obtained from modified curves of high-frequency fatigue tests and low-frequency fatigue tests.

5.2 *The correction of high-frequency fatigue test results*

If the high-frequency correction coefficient ϕ is known, then the fatigue characteristics of concrete under low-frequency loading condition could be obtained from the results of high-frequency fatigue test through the following equation:

$$\sigma_{aL} = \phi \sigma'_{fH} (2N_f)^{b_H} \qquad (11)$$

Table 4 shows the high-frequency correction coefficient ϕ corresponding to different fatigue life from 1×10^4 to 2×10^6, which is obtained from high and low frequency fatigue tests.

Figure 5 shows two $\lg \sigma_a \sim \lg(2N_f)$ curves obtained from modified results of high-frequency fatigue test and results of low-frequency fatigue test, respectively. Two curves are very good congruent. So it is feasible to calculate the results of concrete fatigue under low-frequency condition from that of high-frequency fatigue tests.

6 FATIGUE CURVES AND FATIGUE EQUATION

6.1 *Fatigue curves*

$S - \lg N$ data points from the high-frequency fatigue tests and the corresponding fitting curves are shown in Figure 6. S is the stress level and N is the corresponding fatigue life.

6.2 *P–S–N fatigue equation considering failure possibility*

For the given failure possibility p', the equivalent fatigue life $\overline{N} = \overline{\eta} \left| \ln(1 - p') \right|^{\frac{1}{b}}$ can be calculated. The results are listed in Table 5. Table 6 shows the regression coefficients c, d and correlation coefficient r that

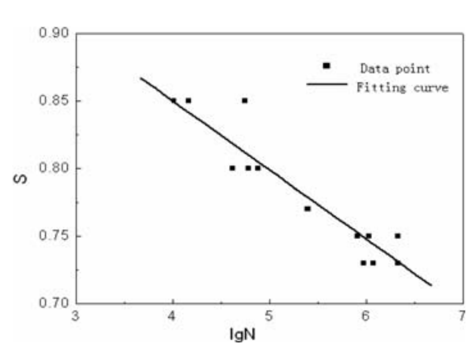

Figure 6. $S - \lg N$ data points from the high frequency fatigue tests and the corresponding fitting curves.

Table 5. Equivalent fatigue life corresponding to failure probability, *p*.

Failure probability p'	Stress level S				
	0.85	0.80	0.77	0.75	0.73
0.05	348	18562	161234	179158	152066
0.1	1148	24481	164712	273516	224914
0.2	3986	32669	168418	425147	338242
0.3	8677	39124	170776	560093	436497
0.4	15744	44918	172605	691754	530647
0.5	26119	50511	174174	827678	626441

Table 6. Regression coefficients *c* and *d* along with correlation coefficient *r*, corresponding to various fatigue failure probability, *p*.

Failure probability p'	Regression coefficient d	Regression coefficient c	Correlation coefficient r
0.05	0.9645	0.0212	−0.9331
0.1	1.0158	0.0252	−0.9557
0.2	1.0882	0.0304	−0.9734
0.3	1.1425	0.0339	−0.9749
0.4	1.1849	0.0364	−0.9656
0.5	1.2162	0.0380	−0.9467

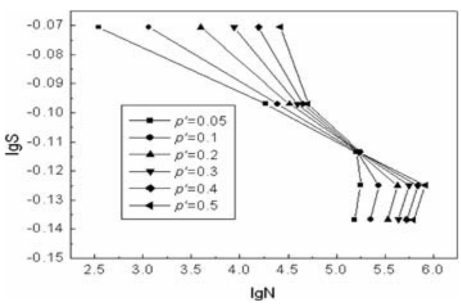

Figure 7. $\lg S \sim \lg N$ fatigue curves corresponding to different failure probabilities.

correspond to various fatigue failure probability p', which could be obtained from the linear regression of the data in Table 5 using $\lg S = \lg d - c(1 - R^2)\lg N$.

p' could be determined from the reliable possibility requirement, and then c, d could be received from Table 6. *P–S–N* equation can be obtained by substituting c, d into:

$$\lg S = \lg d - c\,(1 - R^2)\lg N$$

The fatigue equation with failure possibility 5% is:

$$\lg S = -0.01568 - 0.0212\,(1 - R^2)\lg N \qquad (12)$$

The fatigue equation with failure possibility 50% is:

$$\lg S = 0.08502 - 0.0038\,(1 - R^2)\lg N \qquad (13)$$

7 CONCLUSIONS

The following conclusions can be drawn:

1. There are two main failure modes of plain concrete in the high frequency fatigue tests. They are vertical failure and conical failure.
2. The results of low-frequency fatigue tests can be calculated from the results of high-frequency fatigue tests using high-frequency correction coefficient ϕ.
3. It is more reasonable to establish the *P–S–N* fatigue equation corresponding to certain failure possibility.
4. The research work contributes to the discussion of the characteristics of fibre reinforced concrete column in high-frequency fatigue tests.

Figure 7 shows the $\lg S \sim \lg N$ fatigue curves with different failure probability.

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