FATIGUE PERFORMANCE OF SELF-CONSOLIDATING CONCRETE UNDER FLEXURAL LOAD

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As an advanced construction material, self-consolidating concrete (SCC) is a highly flowable concrete that is able to fill the formwork under its own weight without vibration. This paper presents a study on fatigue performance of SCC under flexural load. An experimental program has been carried out to investigate the fatigue lives of SCC for various levels of the fatigue stress. The fatigue tests on SCC beam specimens (100 × 100 × 400 mm) were conducted. The fatigue test data of SCC is used for regression analysis. The results indicate that the flexural fatigue life distribution of SCC approximately follow the double-parameter Weibull distribution. The regression parameters of the fatigue equation corresponding to different survival probabilities have been obtained. The flexural fatigue strength of SCC for the desired level of survival probability can be estimated by using the fatigue equation.

Keywords: *self-consolidating concrete, fatigue, flexural load, stress level.*

1. Introduction

Self-consolidating concrete (SCC), also known as self-compacting concrete, is a highly flowable concrete mixture that is able to fill the formwork and encapsulate the reinforcement without vibration or tamping after pouring. SCC is the most advanced trend in the field of concrete. There are some obvious advantages of using SCC, such as improved consolidation around reinforcement, easier placing, improved durability, greater freedom in design, labor savings and faster construction. SCC is recognized as one of the greatest advances in the concrete industry over the past few years. Many structures are subjected to flexural fatigue loading, such as highway pavements, bridge decks and airport pavements. With the increasing use of SCC in structures like bridge, airport and highway, it is necessary to quantify the fatigue performance of SCC under flexural loading [1-3]. The flexural fatigue performance of SCC is important design parameter when designing these structures.

In this paper, the flexural fatigue behavior of SCC is experimentally studied. The test results indicate that the flexural fatigue lives of SCC approximately follow the double-parameter Weibull distribution. The regression parameters of the fatigue equation corresponding to different survival probabilities are obtained through the regression analysis.

2. Experimental program

2.1. Materials and mixture proportion

Ordinary Portland cement was used in the experiment. As a supplymentary cementitious material, fly ash was used as a partial replacement for cement in SCC. Fly ash is a byproduct of the coal combustion process at power generation facilities. The use of fly ash in SCC can improve durability, prevent alkali aggregate reaction and reduce total material costs [4,5]. The replacement rate of fly ash was 25% by mass of the binder material. The binder material consisted of cement and fly ash. The specific surface area of cement and fly ash was 462 m^2/kg and 565 m^2/kg, respectively [6]. The main chemical composition of cement and fly ash is presented in Table 1.

The coarse aggregate was crushed stone with a maximum size of 20 mm. The fine aggregate was natural sand with a maximum size of 5 mm. Polycarboxylic ether superplasticizer (SP) was used in SCC to obtain the required workability. The water-to-binder ratio was maintained at 0.32. The details of the mixture proportion are given in Table 2. The SCC beam specimens (100 × 100 × 400 mm) were cast and cured at a temperature of 20℃ and at a relative humidity of 95%.

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Table 1

Chemical composition of Portland cement and fly ash.

Chemical analysis (wt. %)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	Loss on ignition
Portland cement	19.5	4.4	6.22	65.9	1.5	1.09	0.30	1.09
Fly ash	56.5	20.1	8.2	9.7	1.98	0.35	0.48	2.69

Table 2

Mixture proportion of SCC.

Mixture	Proportions (% by mass of binder)		Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	SP (% by mass of binder)
	Cement	Fly ash						
SCC	75	25	367	122	156	909	832	1.6

2.2. Test methods

The workability tests were conducted on fresh SCC following the EFNARC guidelines [7]. The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions. The V-funnel test is used to determine the filling ability of SCC. The L-box test is used to assess the flow of SCC and also the extent to which it is subject to blocking by reinforcement.

The four-point flexural tests were conducted on beam specimens (100 × 100 × 400 mm) with a closed-loop universal testing machine. The support span is 300 mm and the loading span is 100 mm, as shown in Figure 1. The statical flexural tests were carried out to determine the flexural strength of SCC prior to the fatigue tests. The stress level S is defined as: $S = P_{\max}/P_u$, where $P_{\max}$ is the maximum load and P_u is the static ultimate load. The stress levels selected in the fatigue test are 0.90, 0.85, 0.80 and 0.75. The load cycle characteristic value R ($R = P_{\min}/P_{\max}$, $P_{\min}$ is the minimum load) applied in the fatigue test is 0.1. The flexural fatigue test is carried out in load control with a sinusoidal waveform at a frequency of 5Hz (when stress level S is equal to 0.90 and 0.85) or 10 Hz (when stress level S is equal to 0.80 and 0.75). The number of beam specimens used in statical flexural test and flexural fatigue test is given in Table 3.

Table 3

The number of beam specimens used in test.

Flexural fatigue test				Statical flexural test
S=0.9	S=0.85	S=0.80	S=0.75	
4	4	4	4	3

3. Weibull distribution

The fatigue data of SCC usually exhibit larger discreteness because of material heterogeneity. Weibull distribution has been widely adopted to process the data of fatigue test. The Weibull probability density function $f_N(n)$ and cumulative distribution function $F_N(n)$ can be expressed by

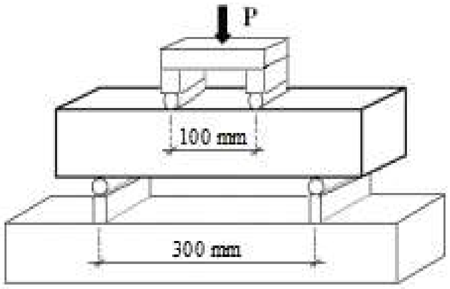

Fig. 1 - Schematic diagram of the loading method.

$$f_N(n) = \frac{\alpha}{u-n_0}\left(\frac{n-n_0}{u-n_0}\right)^{\alpha-1}\exp\left[-\left(\frac{n-n_0}{u-n_0}\right)^{\alpha}\right] \tag{1}$$

$$F_N(n) = 1-\exp\left[-\left(\frac{n-n_0}{u-n_0}\right)^{\alpha}\right] \tag{2}$$

Where, α is the shape parameter or the Weibull slope at stress level S ; u is the scale parameter or the characteristic fatigue life at stress level S ; n_0 is the position parameter or the minimum fatigue life at stress level S .

The value of n_0 may be considered as zero because of the discreteness of fatigue data and safer reliability. This will yield double-parameter Weibull distribution. From Eq.(2), the survivorship function $P(n)$ can be given

$$P(n) = 1-F_N(n) = \exp\left[-\left(\frac{n}{u}\right)^{\alpha}\right] \tag{3}$$

Taking twice natural logarithm for both sides of Eq. (3) gives

$$\ln\left[\ln\left(\frac{1}{P}\right)\right] = \alpha\ln n - \alpha\ln u \tag{4}$$

Setting $Y = \ln\left[\ln(1/P)\right]$, $X = \ln N$, $\beta = \alpha\ln u$, then

$$Y = \alpha X - \beta \tag{5}$$

It can be seen from Eq. (5) that, if a linear trend is observed between Y and X, the fatigue data follow the Weibull distribution.

4. Results and discussion

4.1. Workability of fresh SCC

The results of the workability tests performed for fresh SCC are presented in Table 4. The values of slump flow, V-funnel and L-box for fresh SCC achieved the minimum required value [7]. Fresh SCC can obtain desired workability by proper adjustment of SP dosage.

Table 4

Workability test results of SCC.

Workability test	Parameter	Result
Slump flow	Slump flow diameter (mm)	726
V-funnel	V-funnel flow time (s)	17
L-box	Passing ability ratio	0.90

4.2 Weibull distribution verification

According to the probability theory of Weibull distribution, the empirical survivorship function P can be expressed by

$$P = 1 - \frac{i}{k+1} \tag{6}$$

where, k is the total number of the fatigue data at certain stress level, i is the sequence number of failure specimens at certain stress level.

The linear regression is carried out for the fatigue data according to Eq. (5). Table 5 shows the results of Weibull regression analysis when the stress level S is equal to 0.90, 0.85, 0.80 and 0.75. The corresponding determination coefficients R^2 are 0.956, 0.936, 0.971 and 0.932. Graphs are plotted between $\ln[\ln(1/P)]$ and $\ln N$ in Figure 2, Figure 3, Figure 4 and Figure 5. A linear trend is observed for the fatigue data, which indicates that the relationship between $\ln[\ln(1/P)]$ and $\ln N$ is linear for various stress levels. This indicates that the fatigue data approximately follow the double-parameter Weibull distribution. Consequently, the double-parameter Weibull distribution is a reasonable assumption for the fatigue data of SCC.

Table 5

The results of Weibull regression analysis.

S	β	α	R^2
0.90	9.52	1.51	0.956
0.85	8.78	1.003	0.936
0.80	11.07	1.01	0.971
0.75	33.87	2.82	0.932

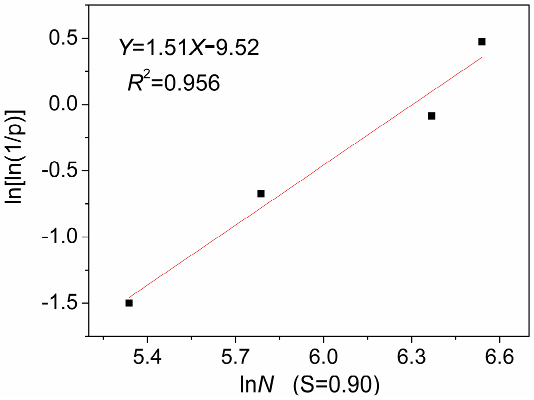

Fig. 2 - Weibull regression analysis of fatigue data(S=0.90).

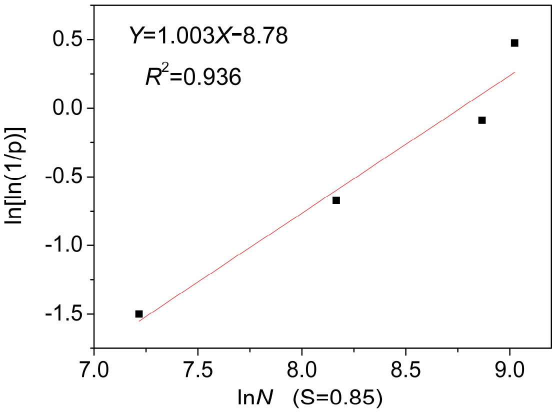

Fig. 3 - Weibull regression analysis of fatigue data(S=0.85).

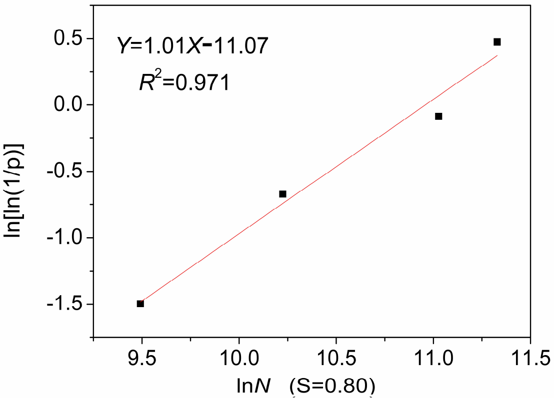

Fig. 4 - Weibull regression analysis of fatigue data(S=0.80).

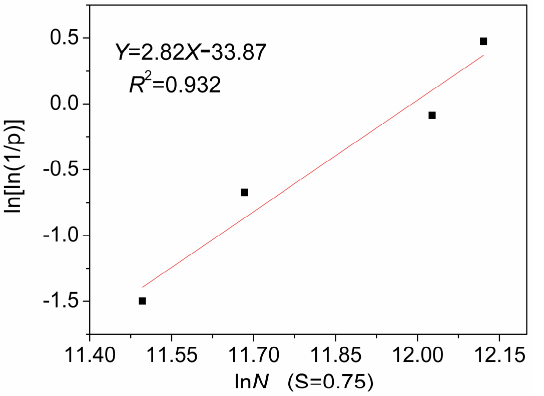

Fig. 5 - Weibull regression analysis of fatigue data(S=0.75).

4.3. Regression parameters of the fatigue equation of SCC

The double-logarithm fatigue equation is used to investigate the fatigue behavior of SCC in this study. The double-logarithm fatigue equation is defined as:

$$\lg S = \lg a - b \lg N \qquad (7)$$

Where, S is the stress level, N is the fatigue life. The parameters a and b of the Eq. (7) can be obtained through the regression analysis. Table 6 shows the regression parameters a and b of the fatigue equation corresponding to different survival probabilities. The Eq. (7) can be used to evaluate the flexural fatigue strength of SCC for the desired level of survival probability [8-12].

Table 6

Regression parameters a and b of the fatigue equation.

P	a	b	R^2
0.95	1.002	0.027	0.977
0.90	1.026	0.028	0.995
0.80	1.052	0.029	0.998
0.70	1.069	0.030	0.991
0.60	1.079	0.030	0.979
0.50	1.089	0.031	0.966

5. Conclusion

The fatigue lives of SCC approximately follow the double-parameter Weibull distribution. The regression parameters of the Weibull distribution for the fatigue lives of SCC are obtained. The regression parameters of the fatigue equation corresponding to different survival probabilities are obtained through the regression analysis. The flexural fatigue strength of SCC for the desired level of survival probability can be predicted by using the fatigue equation.

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