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Fatigue reliability quantitative analysis of cement concrete for highway pavement under high stress ratio

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Abstract: In order to obtain the change law of the fatigue reliability of cement concrete for highway pavement under high stress ratios, first, the probability densities of monotonic random variables including concrete fatigue life are deduced. And then, the fatigue damage probability densities of the Miner and Chaboche-Zhao models are deduced. By virtue of laboratory fatigue test results, the fatigue damage probability density functions of the two models can be obtained, considering different stress ratios. Finally, substituting load cycles into them, the change law of cement concrete fatigue reliability about load cycles can be acquired. The results show that under the same stress ratio, with the increase in the load cycle, the fatigue reliability declines from almost 100% to 0% gradually. No matter under what stress ratio, during the initial stage of the load action, there is always a relatively stable phase for fatigue reliability. With the increase in the stress ratio, the stable phase gradually shortens and the load cycle corresponding to the reliability of 0% also decreases. In the descent phase of reliability, the higher the stress ratio is, the lower the concrete reliability is for the same load cycle. Besides, compared with the Chaboche-Zhao fatigue damage model, the Miner fatigue damage model is safer.

Key words: cement concrete; fatigue life; fatigue damage; probability density function; high stress ratio; fatigue reliability

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As a widely used building material, in many cases, cement concrete needs to undergo repeated loads. Especially, for highways and urban roads paved with a cement concrete surface course, the demand of the cement concrete anti-fatigue property is furthermore quite high. As we know, in the short term, the phenomenon of vehicle overload is difficult to effectively control in our country. A considerable vehicle overload brings a high stress level to the concrete slab directly. And as a result, the durability of the pavement will be affected adversely[1-2]. In the research field of cement concrete fatigue properties, the fatigue test is one of the most important methods. By the fatigue test, the fatigue equation can be obtained. Thus, the fatigue life under different stress ratios can be determined. In addition, based on the fatigue test, damage can be expressed as some certain functions of the load cycle so as to further analyze fatigue damage[3-4].

In fact, because of the random fluctuations of load cases and the inherent heterogeneity of cement concrete, even under the same condition, the same concrete may perform differently. And as a result, the pavement structure will show the dispersion of the fatigue life to a certain degree[5-6]. For the above reasons, based on several fatigue damage models, a quantitative analysis of the fatigue reliability of cement concrete for the highway pavement is carried out so as to find out the change law of the fatigue reliability of cement concrete under different stress ratios and load cycles.

1 Probability Density of Monotonic Random Variable

Let the probability density function of random variable ξ be $f(x)$ and the probability density function of random variable η be $p(y)$. If η is a monotonic function of ξ, $\eta = \phi(\xi)$, $p(y)$ can be obtained from $f(x)$.

The derivation process is as follows [7-8]:

1) $y=\phi(x)$ is a monotonic function, so the single-valued inverse function $x=\psi(y)$ exists.

2) It can be proved in theory that if and only if $x<\xi<x+\mathrm{d}x$ occurs, $y<\eta<y+\mathrm{d}y$ will occur. That is to say, $P(y<\eta<y+\mathrm{d}y)=P(x<\xi<x+\mathrm{d}x)$ and $p(y)\mathrm{d}y=f(x)\mathrm{d}x$.

3) Substituting $x=\psi(y)$ and $\mathrm{d}x=\mathrm{d}\psi(y)$ into $p(y)\mathrm{d}y=f(x)\mathrm{d}x$, obviously, $p(y)=f[\psi(y)]\dfrac{\mathrm{d}\psi(y)}{\mathrm{d}y}$ (increasing function) or $p(y)=f[\psi(y)]\left|\dfrac{\mathrm{d}\psi(y)}{\mathrm{d}y}\right|$ (decreasing function).

2 Probability Density of Concrete Fatigue Life

As a kind of composite material, there are many micro-pores and micro-cracks in cement concrete. Under repeated loads, the micro-pores will extend gradually, forming macro-cracks finally. The emergence of macro-cracks

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means the fracture of concrete and this fracture is fatigue damage fracture. The load cycle before fatigue damage fracture is fatigue life.

Usually, after carrying out logarithmic transformation to fatigue life N_ξ, mathematical statistics and mechanical analysis are then executed. In general, the logarithm of fatigue life X is subject to a normal distribution. That is to say, $X \sim N(\mu; \sigma)$ and its probability density function is $f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$. Where, μ and σ are the population mean and variance of the logarithm of fatigue life, respectively. If $X = \lg N_\xi$, obviously, $N_\xi = 10^X$ and N_ξ is an exponential function of X. Its probability density function can be set as $p(N)$.

Because $x = \lg N$, $\mathrm{d}x = \frac{\mathrm{d}N}{N\ln 10}$.

Besides, $P(N < N_\xi < N + \mathrm{d}N) = P(x < X < x + \mathrm{d}x)$ and $X \sim N(\mu; \sigma)$, consequently,

$$P(x < X < x + dx) = f(x)\,dx = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)\mathrm{d}x$$

and

$$\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)\mathrm{d}x = P(N < N_\xi < N + \mathrm{d}N) = p(N)\,\mathrm{d}N$$

Substituting $x = \lg N$ and $\mathrm{d}x = \frac{\mathrm{d}N}{N\ln 10}$ into the above formula, the probability density function $p(N)$ of fatigue life N_ξ is obtained easily,

$$p(N) = \frac{1}{\sigma N\sqrt{2\pi}\ln 10}\exp\left[-\frac{(\lg N-\mu)^2}{2\sigma^2}\right] \tag{1}$$

3 Probability Density of Concrete Fatigue Damage

3.1 Several fatigue damage models

In terms of damage mechanics, no matter how many times of fatigue life are and no matter what change law of loading during the entire fatigue life is, the essence of fatigue is a gradual course of damage accumulation with the increase in load cycles. Therefore, in the fatigue damage model, damage is usually expressed as certain functions of the load cycle.

The most simple and widely used fatigue damage model is the Miner linear model. In the Miner fatigue damage model, n/N is defined as fatigue damage D. For cement concrete, N is the fatigue life of cement concrete under a particular stress level and n is load cycles having been exerted on this material.

Based on continuum damage mechanics, Chaboche and some other researchers put forward a new fatigue damage model taking the dissipative structure theory of thermodynamics into account:

$$\frac{\mathrm{d}D}{\mathrm{d}n} = A\left(\frac{\sigma}{1-D}\right)^p (1-D)^{-q} \tag{2}$$

where A, p and q are test parameters. For the concrete material, q can usually be set as 0. Then, the model is simplified as

$$\frac{\mathrm{d}D}{\mathrm{d}n} = A\left(\frac{\sigma}{1-D}\right)^p \tag{3}$$

The boundary conditions of the model are as follows: When $n=0$, $D=0$; when $n=N$, $D=1$. So, after carrying out integral operations on Eq. (3), a couple of equations can be obtained.

$$N = \frac{1}{A}\left(\frac{1}{\sigma}\right)^p\int_0^1 (1-D)^p\mathrm{d}D = \frac{1}{A(p+1)}\left(\frac{1}{\sigma}\right)^p \tag{4}$$

$$n = \frac{1}{A}\left(\frac{1}{\sigma}\right)^p\int_0^D (1-D)^p\mathrm{d}D = \frac{1}{A(p+1)}\left(\frac{1}{\sigma}\right)^p\left(1-(1-D)^{p+1}\right) \tag{5}$$

Dividing Eq. (4) by Eq. (5), the fatigue damage D of the Chaboche model can be obtained easily,

$$D = 1 - \left(1 - \frac{n}{N}\right)^{1/(1+p)} \tag{6}$$

Moreover, according to the concrete fatigue life equation of Aas-Jakobsen, $R = 1 - (1-\rho)\beta\lg N$, Zhao et al. [1] deduced another concrete fatigue damage model based on actual stress ratio change:

$$D = 1 - \frac{1}{1 - \frac{(1-\rho)\beta}{R}\lg\left(1 - \frac{n}{N}\right)} \tag{7}$$

where R is the stress ratio; ρ is the characteristic value of the load cycle (the ratio of the minimum and maximum of the cyclic load); β is the test parameter and according to Aas-Jakobsen's recommendation, β can be set as 0.064 0; N is the fatigue life of cement concrete.

3.2 Probability density of Miner fatigue damage model

Let the probability density function of fatigue damage $D_\xi = n/N_\xi$ be $q(D)$. Evidently, D_ξ is a monotonic decreasing function of N_ξ. From $D = \phi(N) = nN^{-1}$, $N = \psi(D) = nD^{-1}$ and $\left|\frac{\mathrm{d}\psi(D)}{\mathrm{d}D}\right| = nD^{-2}$ can be acquired. Further, the following equation can be obtained according to the deducing process of the probability density function mentioned above:

$$q(D) = \frac{1}{\sigma D\sqrt{2\pi}\ln 10}\exp\left[-\frac{(\lg n - \lg D - \mu)^2}{2\sigma^2}\right] \tag{8}$$

According to statistics, it can meet the requirements of unbiasedness and consistency using sub-sample mean $\bar{x}$ and variance s^2 as the estimators of population mean μ and variance σ^2. So, μ and σ in Eq. (8) can be obtained by the fatigue test of cement concrete. The beam-bent fatigue test is adopted in this paper. The characteristic value ρ is generally set as 0. 1[9-10]. The stress ratio R can be taken as 0. 70, 0. 75 and 0. 80. The test data are displayed in Tab. 1.

Tab. 1 Fatigue test results of cement concrete

Specimen number	$R=0.70$ Fatigue life N	$R=0.70$ lg$N$	$R=0.75$ Fatigue life N	$R=0.75$ lg$N$	$R=0.80$ Fatigue life N	$R=0.80$ lg$N$
1	10 184	4. 008	10 003	4. 000	2 110	3. 324
2	11 808	4. 072	10 943	4. 039	2 275	3. 357
3	21 684	4. 336	11 882	4. 075	2 659	3. 425
4	21 747	4. 337	12 413	4. 094	3 105	3. 492
5	43 683	4. 640	14 762	4. 169	3 758	3. 575
6	49 392	4. 694	19 048	4. 280	4 165	3. 620
7	50 997	4. 708	20 284	4. 307	4 749	3. 677
8	70 937	4. 851	20 328	4. 308	5 073	3. 705
9	72 266	4. 859	23 286	4. 367	5 981	3. 777
10	77 122	4. 887	26 291	4. 420	6 844	3. 835
11	79 778	4. 902	26 539	4. 424	7 161	3. 855
12	82 905	4. 919	26 561	4. 424	8 027	3. 905
13	100 411	5. 002	40 095	4. 603	8 345	3. 921
14	101 918	5. 008	53 683	4. 730	8 411	3. 925
15			58 835	4. 770		

Under ordinary traffic loads, the stress ratio in the cement concrete slab of the pavement structure varies from 0. 20 to 0. 65[11]. However, heavy traffic is becoming more and more severe due to the temptation of economic interests. In traffic composition, the proportion of heavy vehicles and overload vehicles is constantly increasing. For the pavement structure designed under normal axle loads and traffic composition conditions, its actual stress level is already in the high stress ratio range. A survey shows that under certain traffic loads, the stress ratio may exceed 0. 65 and even reach 1. 00. According to the research by the Key Laboratory of Highway Engineering in Special Region of Ministry of Education, Chang'an University, if the stress ratio R is more than 0. 60, the pavement structure will damage rapidly in a short time and the economical efficiency of the thickness of the pavement structure mentioned above will be very poor[12]. On the basis of the above, R is taken as 0. 70, 0. 75 and 0. 80.

According to Tab. 1, the mean $\bar{x}$, variance s^2 and standard deviation s of the logarithm of the fatigue life from the above-mentioned tests can be calculated. The statistical results are shown in Tab. 2.

Substituting the data of Tab. 2 into Eq. (8), the concrete

Tab. 2 Statistical analysis for fatigue test results

Stress ratio R	Sub-sample mean $\bar{x}$	Sub-sample variance s^2	Sub-sample standard deviation s
0. 70	4. 659	0. 113	0. 337
0. 75	4. 334	0. 057	0. 239
0. 80	3. 671	0. 044	0. 211

fatigue damage probability density functions $q_1(D)$, $q_2(D)$ and $q_3(D)$ corresponding to the stress ratios of 0. 70, 0. 75 and 0. 80 can be obtained. Of course, respective characteristic values of the load cycle are all 0. 1 here.

When $R=0.70$,

$$q_1(D)=\frac{1}{\sigma D\sqrt{2\pi}\ln 10}\exp\left[-\frac{(\lg n-\lg D-\mu)^2}{2\sigma^2}\right]=0.514\,\frac{1}{D}\exp\left[-\frac{(\lg n-\lg D-4.659)^2}{0.227}\right]$$

When $R=0.75$,

$$q_2(D)=\frac{1}{\sigma D\sqrt{2\pi}\ln 10}\exp\left[-\frac{(\lg n-\lg D-\mu)^2}{2\sigma^2}\right]=0.726\,\frac{1}{D}\exp\left[-\frac{(\lg n-\lg D-4.334)^2}{0.114}\right]$$

When $R=0.80$,

$$q_3(D)=\frac{1}{\sigma D\sqrt{2\pi}\ln 10}\exp\left[-\frac{(\lg n-\lg D-\mu)^2}{2\sigma^2}\right]=0.821\,\frac{1}{D}\exp\left[-\frac{(\lg n-\lg D-3.671)^2}{0.089}\right]$$

Obviously, given n, the form of the probability density function of concrete fatigue damage can be entirely determined.

3.3 Probability density function of Chaboche-Zhao fatigue damage model

Let the probability density function of fatigue damage $D_\xi=1-\left(1-\frac{n}{N_\xi}\right)^{1/(1+p)}$ be $q(D)$.

Evidently, D_ξ is a monotonic decreasing function of N_ξ. From $D=\phi(N)=1-\left(1-\frac{n}{N}\right)^{1/(1+p)}$, $N=\psi(D)=\frac{n}{1-(1-D)^{p+1}}$ and $\left|\frac{\mathrm{d}\psi(D)}{\mathrm{d}D}\right|=\frac{n(p+1)(1-D)^p}{[1-(1-D)^{p+1}]^2}$ can be acquired. Further, the following equation can be obtained according to the deducing process of the probability density function mentioned above:

$$q(D)=\frac{1}{\sigma\sqrt{2\pi}\ln 10}\exp\left\{-\frac{[\lg n-\lg(1-(1-D)^{p+1})-\mu]^2}{2\sigma^2}\right\}\cdot\frac{(p+1)(1-D)^p}{[1-(1-D)^{p+1}]}\tag{9}$$

To ascertain the parameter p in Eq. (9), Eq. (7) is indispensable. By Eq. (7), the corresponding relationships between n/N and D under the stress ratios of 0. 70, 0. 75 and 0. 80 can all be obtained. Here, the characteristic value of the load cycle substituted into Eq. (7) is 0. 1 as well. In addition, according to Eq. (6), $\frac{1}{1+p}\ln\left(1-\frac{n}{N}\right)=\ln(1-D)$. Using the corresponding relationships between n/N and D mentioned above, regression models can be established so as to ascertain the value of p under different stress ratios, as shown in Tab. 3. So in this paper, the Chaboche fatigue damage model is christened as the Chaboche-Zhao fatigue damage model. Its probability density function is called the Chaboche-Zhao fatigue damage probability density function.

Tab. 3 Parameter p corresponding to different stress ratios

Stress ratio R	0.70	0.75	0.80
Parameter p	31.362	33.364	35.364

Substituting the data of Tab. 2 and Tab. 3 into Eq. (9), the concrete fatigue damage probability density functions $q_4(D)$, $q_5(D)$ and $q_6(D)$ corresponding to the stress ratios of 0.70, 0.75 and 0.80 can be obtained. Of course, respective characteristic values of the load cycle are all 0.1 here.

When $R = 0.70$,

$$q_4(D) = 0.514\exp\left\{-\frac{[\lg n - \lg(1-(1-D)^{32.362}) - 4.659]^2}{0.227}\right\}\cdot \frac{32.362(1-D)^{31.362}}{[1-(1-\mathrm{D})^{32.362}]}$$

When $R = 0.75$,

$$q_5(D) = 0.726\exp\left\{-\frac{[\lg n - \lg(1-(1-D)^{34.364}) - 4.334]^2}{0.114}\right\}\cdot \frac{34.364(1-D)^{33.364}}{[1-(1-D)^{34.364}]}$$

When $R = 0.80$,

$$q_6(D) = 0.821\exp\left\{-\frac{[\lg n - \lg(1-(1-D)^{36.364}) - 3.671]^2}{0.089}\right\}\cdot \frac{36.364(1-D)^{35.364}}{[1-(1-D)^{36.364}]}$$

Obviously, given n, the form of the probability density function of concrete fatigue damage can be entirely determined.

4 Concrete Fatigue Reliabilities Based on Two Fatigue Damage Models

Theoretically, D_c, the critical value of fatigue damage, can reach 1. However, a large number of tests show that the crack formation stage will generally end before fatigue damage approaches 1. For most materials, $0.2 < D_c < 0.8$. In this paper, as the material is cement concrete, its critical fatigue damage can be set as 0.5. That is to say, when the fatigue damage is within 0 to 0.5, cement concrete is during the crack formation stage. Given n, and according to the above-mentioned range, definite integral operations on the probability density function of concrete fatigue damage can be carried out. In this way, the probability of cement concrete in the crack formation stage can be calculated. The probability is none other than the fatigue reliability of cement concrete.

Hypothetically, the load cycles are set as 100, 200, 400, 800, 1 600, 3 200, 6 400, 12 800, 25 600, 51 200 and 102 400. Then, the concrete fatigue reliability based on the Miner fatigue damage model, $Q_1 = \int_0^{0.5} q_1(D)\mathrm{d}D$ $(R = 0.70)$, $Q_2 = \int_0^{0.5} q_2(D)\mathrm{d}D$ $(R = 0.75)$ and $Q_3 = \int_0^{0.5} q_3(D)\mathrm{d}D$ $(R = 0.80)$ can be calculated. The calculation results are illustrated in Fig. 1.

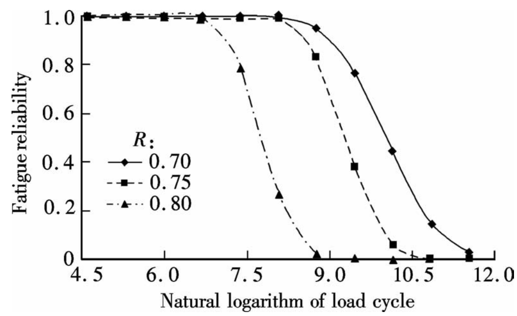

Fig. 1 Fatigue reliability of cement concrete based on the Miner fatigue damage model

From Fig. 1, we can see that under the same stress ratio, the fatigue reliability of cement concrete gradually decreases from almost 100% to 0% with the increase in the natural logarithm of the load cycle. No matter under what stress ratio, during the beginning period of the load cycle, there is always a comparatively stable phase for the reliability of concrete. With the increase in the stress ratio, the stable phase shortens and the natural logarithm of the load cycle corresponding to the fatigue reliability of 0% also decreases. Accordingly, in the reduction stage of the fatigue reliability, for the same load cycle, the higher the stress ratio is, the lower the fatigue reliability of the cement concrete is.

According to the load cycles assumed above, the concrete fatigue reliability based on the Chaboche-Zhao fatigue damage model, $Q_4 = \int_0^{0.5} q_4(D)\mathrm{d}D$ $(R = 0.70)$, $Q_5 = \int_0^{0.5} q_5(D)\mathrm{d}D$ $(R = 0.75)$ and $Q_6 = \int_0^{0.5} q_6(D)\mathrm{d}D$ $(R = 0.80)$ can be calculated. The calculation results are illustrated in Fig. 2.

From Fig. 2, it can be clearly seen that the change law of the fatigue reliability of cement concrete based on the Chaboche-Zhaofatigue damage model about the natural logarithm of the load cycle is almost the same as that based on the Miner fatigue damage model.

By comparing Fig. 1 and Fig. 2, it can be found that under the same stress ratio, during the initial stage of the load cycle, the stable phase of the concrete reliability based on the Chaboche-Zhao fatigue damage model is

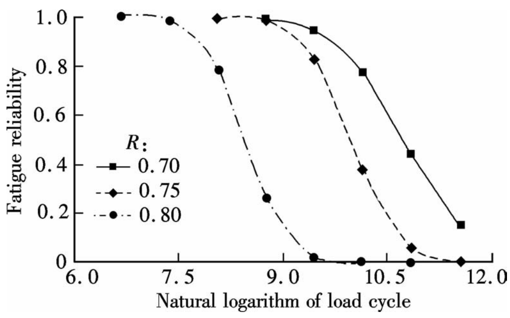

Fig. 2 Fatigue reliability of cement concrete based on the Chaboche-Zhao fatigue damage model

more than that based on the Miner fatigue damage model. When the reliability reduces to 0%, the corresponding natural logarithm of the load cycle based on the Chaboche-Zhao fatigue damage model is also more than that based on the Miner fatigue damage model. During the reduction stage of concrete fatigue reliability, for the same load cycle, the fatigue reliability of cement concrete based on the Chaboche-Zhao fatigue damage model is greater than that based on the Miner fatigue damage model. It illustrates that the Miner fatigue damage model is safer than the Chaboche-Zhao fatigue damage model.

5 Conclusions

1) The change law of fatigue reliability of cement concrete based on the Chaboche-Zhao fatigue damage model about the natural logarithm of the load cycle is almost the same as that based on the Miner fatigue damage model.

2) Under the same stress ratio, the fatigue reliability of cement concrete gradually decreases from almost 100% to 0% with the increase in the natural logarithm of the load cycle.

3) No matter under what stress ratio, during the beginning period of the load cycle, there is always a comparatively stable phase for the reliability of concrete. With the increase in the stress ratio, the stable phase diminishes and the natural logarithm of the load cycle corresponding to the fatigue reliability of 0% also decreases.

4) During the reduction stage of fatigue reliability, for the same load cycle, the higher the stress ratio is, the lower the fatigue reliability of cement concrete is.

5) Under the same stress ratio, during the initial stage of the load cycle, the stable phase of the concrete reliability based on the Chaboche-Zhao fatigue damage model is more than that based on the Miner fatigue damage model.

6) When the reliability decreases to 0%, the corresponding natural logarithm of the load cycle based on the Chaboche-Zhao fatigue damage model is also more than that based on the Miner fatigue damage model.

7) The Miner fatigue damage model is safer than the Chaboche-Zhao fatigue damage model.

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高应力比下路用水泥混凝土疲劳可靠度量化分析

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摘要：为获得路用水泥混凝土在高应力比作用下其疲劳可靠度的变化规律，首先推导了包括混凝土疲劳寿命在内的单调随机变量的概率密度，然后推导了 Miner 与 Chaboche-Zhao 疲劳损伤模型的概率密度. 借助室内疲劳试验结果，获得这 2 种模型的疲劳损伤概率密度函数. 最后，将荷载作用次数代入上述函数，从而获得水泥混凝土疲劳可靠度随荷载作用次数的变化规律. 结果表明：随着荷载作用次数的增加，相同应力比下，疲劳可靠度从 100% 逐渐衰减为 0%；无论何种应力比，在荷载作用初期，疲劳可靠度均有一个较为稳定的阶段；随着应力比的增加，该稳定阶段逐渐缩短，且可靠度为 0% 时对应的荷载作用次数也减小；在可靠度衰减阶段，对于相同荷载作用次数，应力比越高，则混凝土可靠度越低；此外，Miner 疲劳损伤模型比 Chaboche-Zhao 疲劳损伤模型偏安全.

关键词：水泥混凝土；疲劳寿命；疲劳损伤；概率密度函数；高应力比；疲劳可靠度

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