Fatigue Model of Composite Concrete Structure under Flexure

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Abstract. Taking the CRTS II type slab ballastless track structure as the test prototype, the "concrete - CA mortar composite model specimen "(100) was built 100 mm\(^3\) 400), based on fatigue tests under four-point bending loading conditions of composite model specimens and applied fatigue loads MTS universal servo hydraulic fatigue testing machines, Six static flexural tests also conducted to determine the static flexural strength of CCS prior to fatigue testing. Based on the experimental results, the fatigue expression of CCS specimens under flexural fatigue load is proposed. the evolution curves of damage variables and fatigue deformation are obtained.

Introduction

CRTS II type slab track is one of the series ballastless tracks of china CRTS track system with independent intellectual property rights. Nowadays, CRTS II type plate track has been widely used in more than 10 high-speed railways or passenger dedicated lines, such as Beijing-Tianjin Intercity, Shanghai-Hangzhou, Beijing-Shanghai, Nanjing-Hangzhou, Hangzhou-Ninghang, Hangyong, Heclam, Jingshi, Shiwu, Jinqin, Hangzhou-Changhefu, etc. Nearly 5000 km, are the most ballastless track structure types laid in 350 km/h high-speed railways.

Through investigation of many high-speed railway lines, fatigue load and the cycle numbers of fatigue load were played a major role on deformation and damage of CRTS II slab track. Some research has analyzed the damage problem of CA mortar and deformations of CRTS II slab track[1-3]. However, most of these works focused on deterioration analysis of CA mortar material or concrete material separately [4-11].

This study investigates the fatigue behavior of CCS under flexural cyclic loadings for the first time, focusing on the deflection variation, fatigue residual deformation variation and the fatigue modulus of fatigue CCS concrete specimens. Here, forty-one CCS specimens of size 400 × 100 × 100 mm were tested and discussed the fatigue behavior of the CCS.

Experimental Program

A Subsection

The test specimens were made of 56 “concrete- CA mortar composite model specimens”(as shown in figure 1) with CRTS II type slab track as the prototype, of which 6 were used for bending static load test and 50 for four-point bending fatigue test. The specimen was manufactured in the laboratory of Guizhou Xingda Construction Materials Company. The size (length × width × thickness) is set at :100×100×400mm\(^3\), the strength grade of concrete is the C40, the mix of CRTS II cement emulsified asphalt mortar is referred to the mix ratio of high-speed CA mortar, and the specimens completed by pouring and curing are shown in Figure 1.
Experiment Program

The test was carried out on 50 KN MTS fatigue testing machine, the static load test was controlled by displacement, the speed was 0.01 mm/s; the fatigue test was controlled by load, the load was loaded with uninterrupted sine wave, and the loading frequency was 20 HZ.

The static and fatigue load test device is shown in figure 1. The stress state of approximate bending is obtained in the middle part of the specimen (pure bending section) by simply supported loading with four-point bending. the test support is sliding with one end rolling and one end sliding, and the upper span (loading distance)100 mm, of the spacing 300 mm, is arranged at the left and right 1/3 span.

The static bending test is carried out first. According to the results of static load bending strength test, the stress level of fatigue loading stress level S, fatigue test is determined S the ratio of maximum fatigue stress to average bending strength. For this test, the fatigue stress level S take 0.75,0.85,0.95, three stress levels. The characteristic value of load cycle of fatigue test is R the ratio of minimum fatigue stress to maximum fatigue stress, R=0.1 is taken in this paper.

For the components composed of cement-based materials, the number of cycles under fatigue load up to 2 million times has not been destroyed, it is generally considered that the structural specimens can meet the fatigue resistance requirements. During this bending fatigue test, the test was stopped when the "concrete - CA mortar composite model specimen" specimen was destroyed or the load cycle reached 2 million times.

Fatigue Model for CCS under Flexure

Fatigue Modulus Degradation

Fatigue modulus $E_{fa}$, the first parameter used in this paper to represent CCS force characteristics under bending loads, is defined as follows\(^{[13-14]}\):

$$E_{fa} = \frac{f_{max}}{\varepsilon_{fu}}$$  \hspace{1cm} (1)

In formula (1), $f_{max}$ is the maximum stress acting on the specimen, it represents the maximum strain produced under load.

Under the action of fatigue load, when the amplitude acting on the specimen remains constant, the magnitude of the fatigue modulus is related to a variety of factors, such as: environmental factors, fatigue strain, the irregularity of the experiment itself, etc. But some factors cannot be assessed. however, the relationship between the variation curve of fatigue strain and fatigue life of self-compacting concrete specimens (stress level S=0.66) under bending fatigue load is observed in this paper. as shown in Figure 2.
As the second parameter to study the fatigue life of the self-confined concrete composite model specimen under fatigue load, the fatigue damage D can be defined as:

The fatigue damage is defined as:

$$D = 1 - \frac{E_{fa}}{E_0}$$

(2)

In formula (2), $E_0$ is the initial elastic modulus of the concrete fatigue specimen before the test.

Fatigue Damage for CCS

The change of mid-span deflection is used to characterize the fatigue damage process of CCS. One example of the relations between the cycle counts and average fatigue strain for $S=0.66$ are showed in Figure 2.

![Figure 2. Relationship of cycle counts and average fatigue deflection.](image)

Where $a$ and $b$ are cycle counts of stage 2 and end, $\delta_1$ and $\delta_2$ are fatigue deflection of stage 2 start and end. Observing that the stage 2 shape follows a linear relation, Because the stages 1 and 3 are very small cycle counts proportion in the whole fatigue damage, experimental data show that the first stage is between 1-5%\(^{[14]}\), the stage 3 only a few cycles generally, So it can be considered that the number of cycles at stages 2 represents the fatigue life of the experiment.

Therefore, it is possible to predict the fatigue life of CCS by using deflections, which is mainly based on stages 2.

$$\delta_s = \delta_1 + kn$$

(3)

Where $\delta_1$ and $\delta_s$ are the deflection at the beginning and the end of the stage 2, respectively, $k$ is slope, $n$ is cycle counts. When $\delta_s = \delta_2$, the $n$ approximately equal to the fatigue life is the cycle counts of $a$ and $b$. Experimental data show that $\delta_2/\delta_1$ is between 1.07~1.29, the average value is 1.18.

From Fig 9, the relationship plain concrete between cycle counts and average fatigue strain can be expressed as ($S=0.66$):

$$\delta_s = 0.094 + 9.002 \times 10^{-9}n$$

(4)

By using this method, the value of $\delta_1$ and $k$ under stress levels of 0.59~1 can be obtained according to the test results, as shown in Table 1.
Table 1. Results of $\delta_1$ and $k$ under different stress levels.

| S     | 0.59 | 0.66 | 0.72 | 0.79 | 0.86 | 0.93 | 1   |
|-------|------|------|------|------|------|------|-----|
| $\delta_1$ | 0.241 | 0.094 | 0.147 | 0.112 | 0.036 | 0.138 | 0.047 |
| $k$ | 9.068×10^{-9} | 9.002×10^{-9} | 8.637×10^{-9} | 1.011×10^{-8} | 1.293×10^{-8} | 8.923×10^{-8} | 6.956×10^{-8} |

Fatigue Damage for CCS

The change of deflection can be used to explain the fatigue damage process of CCS as stated in previous section, so mid-span deflection can describe damage variations $D$. From Eq. (2), the $D$ can be expressed as:

$$ D = 1 - \frac{\delta_1}{\delta_s} $$

(5)

Where $\delta_1$ and $\delta_s$ are the strain at the beginning and the end of the stage 2. $D$ is the damage variable, that is, when the number of fatigue times is $N_1$ times, the fatigue specimen is destroyed. Substituting Eq. (5) into Eq. (3), the expression of the fatigue life prediction model proposed in this paper can be defined as:

$$ N = \frac{D\delta_s}{(1 - D)k} $$

(6)

Where $D$ is determined by Eq. (5). $k$ and $\delta_s$ are constants to be determined by relationship of cycle counts and fatigue deflection. Eq. (3), (5) and (6) constitute the fatigue model for CCS under flexure cyclic loading with constant loading range.

Figure 3 compare the fatigue damage evolution for CCS ($S=0.66$), from the experiments and theoretical predictions (Eq. (6)). It can be seen from fig9 that the predicted fatigue life of CCS is $1.981\times10^6$ times, Compared with the average fatigue test results of $2\times10^6$ the fatigue life is smaller, so the predictions are more likely to be safer.

![Figure 3. Comparison of fatigue life.](image)

The results of fatigue life prediction parameters for CCS in flexural test were summarized in table 5. And the average life of fatigue tests were also presented in table 6 corresponding to different stress levels.
Table 5. Values of parameters using fatigue mode.

| S         | δ₁ | k       | δ₂ | D     | Nᶠ | Nᶠ    |
|-----------|-----|---------|-----|-------|----|-------|
| 0.59(0.85)| 0.241 | 9.068×10⁻⁹ | 0.2589 | 0.0671 | 1.981×10⁶ | 2×10⁶ |
| 0.66(0.95)| 0.094 | 9.002×10⁻⁹ | 0.1119 | 0.1601 | 1.989×10⁶ | 2×10⁶ |
| 0.72(1.05)| 0.147 | 8.637×10⁻⁹ | 0.1625 | 0.1017 | 1.798×10⁶ | 1.879×10⁶ |
| 0.79(1.15)| 0.112 | 1.011×10⁻⁸ | 0.1305 | 0.1153 | 1.765×10⁶ | 1.879×10⁶ |
| 0.86(1.25)| 0.036 | 1.293×10⁻⁸ | 0.0576 | 0.3763 | 1.675×10⁶ | 1.788×10⁶ |
| 0.93(1.35)| 0.138 | 8.923×10⁻⁸ | 0.1464 | 0.0541 | 0.837×10⁶ | 0.945×10⁶ |
| 1(1.45)   | 0.047 | 6.956×10⁻⁹ | 0.0514 | 0.0692 | 0.441×10⁶ | 0.369×10⁶ |

The prediction model of CCS composite specimens based on fatigue damage D and fatigue strain is proposed. The results of test and prediction CCS life analysis show that formula (1), formula (3) and (6) as the prediction life model proposed in this paper can predict the fatigue life of concrete composite model specimens to a certain extent, but its accuracy needs to be further improved.

**Conclusion**

Based on the investigation of site damage of ballastless track, the fatigue load test of composite concrete CA mortar specimens under bending fatigue load is completed. Based on the test results, the expressions of fatigue modulus and fatigue damage are presented, and the fatigue behavior of CCS composite specimens is studied. It provides an experimental basis for the study of ballastless track damage in high-speed railway.

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