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Experimental and model study on dynamic behaviour and fatigue damage of tunnel invert

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HIGHLIGHTS

- Strain and damage changes of invert under different stress levels was elaborated.
- Established model can effectively reflect the relationship between damage and stress.
- Vibration amplitude have obvious effects on TIC fatigue behaviour.
- Fatigue life in this paper is much higher than that in three point bending test.

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ABSTRACT

The growth of train axle loads enhances the dynamic response of the invert of a tunnel, and affects the damage behaviour of tunnel invert concrete. This article focuses on the fatigue damage of tunnel invert concrete under a cyclic bending load. The fatigue behaviour of the tunnel invert concrete under multi-directional loading is experimentally investigated in this work. The effect of the vibration amplitude is first investigated by comparing the strain and damage evolution in the tunnel's mechanical environment. Combined with the expression of *S-N*, a new fatigue damage model including a stress level parameter is proposed. The model parameters are also given and redefined to quantify the effect of the vibration amplitude and invert mechanical condition. Based on the experimental results, it is found that the vibration amplitude has a significant effect on the damage increment of tunnel invert concrete. The observed process of fatigue damage is similar to that of strain variation, and the whole process can be divided into three different stages, initial growth stage I, slow growth stage II, and rapid growth stage III. When the stress level is higher than 0.6, the damage and dynamic strain increases nonlinearly and fatigue failure occurs. Moreover, the fatigue life of tunnel invert concrete is 10 times more than that of the concrete under the three-point bending condition.

1. Introduction

With further development of high speed passenger trains and heavy haul for freight on the railways, heavy haul transportation is naturally one of the main directions of railway development [1]. China has become the country with the largest numbers, largest scale and fastest growth in tunnel construction. However, the problem of fatigue of tunnel concrete under dynamic loading and surrounding static pressure needs to be investigated in order to ensure the safety of tunnel structures.

Fatigue damage of concrete materials is very important for structures under cyclic loadings. In the early stages, Holmen [2] studied the effect of various load histories and obtained an *S-N-P* empirical expression. Aas-Jakobsen [3] investigated the effects of a variable stress level on the fatigue damage. Tepfers and Kutti [4], Hsu [5], and Cornelissen [6] also discussed the fatigue life curve in detail via experimental study, and these research results have been applied widely.

Research on cyclic loading is presented by Hsu [5], Leeuwen and Siemes [7], Weigler and Klausen [8], and Shi et al. [9], and Zhao et al. [10]. As a result of their efforts, the fatigue life curve including the most important features were established and improved by the uniaxial tension and compression testing of concrete, and the relations between damage variables and the various physical quantities were also studied. In this current work, we focus on the

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vibration amplitude of cyclic loading to evaluate the fatigue life of concrete under tunnel stress states.

Several concrete damage models based on continuum damage mechanics have been developed for static and cyclic loads [11,12]. The traditional approach that is used to describe the damage caused by static and cyclic loading does not apply to cyclic loading with different vibration amplitudes [13,14]. Study of the damage characteristics of concrete members is often applied to develop empirical models. However, the prediction of damage life and the whole deformation-process of the concrete material have been analyzed with a number of empirical models. In general, these models cannot exactly determine the damage life and damage process. Moreover, in those models, the effect of stress levels is generally ignored, which actually does not comply with the real properties of concrete under different vibration amplitudes.

Dyduch and Szerszen [15] found that the fatigue damage of concrete became more sensitive to cyclic loads when the compressive load was more than 60% of the static strength. When the loading level rose to 80%, the number of cycles to failure showed hardly any variation with the effects of time. As the stress level increased, the fatigue strength proved to be more sensitive to time-dependent effects.

This work investigates the fatigue behaviour of tunnel invert concrete under special multi-directional loading. The strain and the damage variation will be calculated and analyzed to correlate the strain response and damage behaviour of tunnel invert concrete. The effects of the stress levels caused by the vibration amplitudes on their fatigue behaviour will be discussed. Based on the experimental results and continuum damage mechanics, a fatigue damage model containing the stress level parameter is proposed to analyze and quantify the effects of train loads on practical tunnel structures.

2. Experimental

2.1. Materials and sample preparation

Based on the characteristics of tunnel lining structures in China, the cement was ordinary Portland cement with a grade of 42.5. Fine aggregate with a fineness modulus of 2.7 and apparent density of 2.67 kg/m^3 was used. Crushed limestone with a size of 5–25 mm was used as coarse aggregate in the concrete. The strength grades of all concrete samples were designed as per C35. All the specimens were made with the same mixing proportions as given in Table 1.

Specimens were moulded in two different dimensions, demoulded after 24 h, and employed standard curing periods of more than 28 days. Three series of specimens were tested, as listed in Table 2. Series A were tested under bending load, and series C were tested under static compression load. Series B with dimensions of 100 × 100 × 100 mm were used to test the compressive strength of approximately 12.3 MPa and an initial elastic modulus E_0 = 31.7 GPa.

Non-destructive tests were performed on specimens, and the measured values were investigated by an Emodumeter dynamic instrument. The mechanical parameters, such as *E*-modulus, *G*-modulus, compressive strength and Poisson's ratio, were obtained, as given in Table 3.

Table 2
Specimens tested.

Series of specimens	Size (mm)	Quantity	Form of loading
A	100 × 100 × 300	16	Bending loads
B	100 × 100 × 100	3	Static compression

2.2. Fatigue testing system

The invert of a tunnel has a complicated mechanical environment, affected by static loads and dynamic loads as shown in Fig. 1. Static loading and dynamic loading should be considered in the design of tunnel invert. Surrounding rock pressure and tunnel structure weight are the main static loads in tunnel invert design, whereas dynamic load is mainly caused by train cyclic loading. In the mechanical environment, the invert can be simplified by an elastic foundation beam model, which is constrained symmetrically at both ends and is always subjected to bending-shear.

As shown in Fig. 2, a special device is designed to simulate the mechanical environment, consisting of counter-spring plates, a hydraulic jack and a counter-force plate. The hydraulic jack and counter-force plate are connected to form a static pressure device, providing the static lateral loads for simulating the circular confining pressure acting on the tunnel invert.

According to Winkler's theory used in tunnel engineering, the contact relations between the lining and surrounding rock can be simulated by the counter-spring plates. The stiffness coefficient is the most important parameter to describe classification of surrounding rock and the higher the coefficient, the better its surrounding rock grade.

Then the contact force between the lining and surrounding rock can also be calculated and analyzed by using the method of loading-structure. The stiffness of the spring can be computed by using stiffness similarity method. And a simplified calculation formula for the spring and surrounding rock has been given, as follows:

$$k\delta_i ab = k_0\delta_0 m \tag{1}$$

where a is the length of specimens and a = 0.3 m, b is the width of specimens and b = 0.1 m, m is the number of springs and m = 27, K_0 is the stiffness of the spring and K_0 = 2.157 × 10^6 N/m, K is the stiffness of the surrounding rock and K = 194.1 MPa/m is the V rock, $S = f_{max}/f_t$ and δ_i is the deformation of the surrounding rock and spring.

The type of fatigue testing machine is MTS815. Using self-developed devices and a fatigue testing machine, the combined loading system provides an accurate mechanism to simulate the tunnel dynamics environment, and the experimental study on the fatigue behaviour of concrete under multi-directional loading is carried out.

An impedance analyzer was used for concrete damage monitoring with a piezoelectric ceramic slices (PZT) [16]. The type of PZT sensor is PZT-5A presented in Fig. 3(a), and its dimensions are 10 mm × 10 mm × 0.3 mm with the positive and negative on the same side of the PZT. The type of impedance analyzer is PV80A, which can acquire signals in a frequency range of 1 kHz–1 MHz.

For measuring the electromechanical admittance signals in different frequency ranges, PZT sensors collect information. The impedance analyzer to complete the signal processing, and to generate the conductance data. The algorithm with data preprocessing is given in Section 4.1.

Table 1
Mix proportions of concrete.

Water-binder ratio	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Fly ash (kg/m^3)	Super plasticizer (kg/m^3)	Water (kg/m^3)
0.40	277	747	1075	108	3.85	153