Dynamic Response of High-Speed Railway Pier Based on Time-Dependent Deterioration of Concrete

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Abstract. To study the dynamic characteristics of simply supported girder piers of high-speed railroads under long-term deterioration, the impact of concrete deterioration on the dynamic response of piers is analyzed based on the theory of concrete strength degradation. The time-frequency and energy distribution characteristics of the vibration acceleration of piers are further revealed using the Local Maximum Synchrosqueezing Transform (LMSST). The results show that under the high-speed railway train load, the vertical acceleration of the piers in service for 40~100 years increased by 29.8%, and the lateral acceleration increased by 62.7%. LMSST analysis shows that the vertical and lateral vibration energies increased by 17.5% and 64%, respectively, during the period of 60~100 years. The research results can provide a reference for high-speed railway pier performance assessment, safety warnings, and maintenance.

Keywords: simply supported beam pier; time-dependency deterioration of concrete; dynamic response; local maximum synchronous extrusion transform

1 Introduction

Piers are a crucial component of high-speed railway bridge structures, significantly enhancing the stress conditions and overall stability of the bridge[1]. Currently, most high-speed railway bridges have been constructed within the last 20 years, and the deterioration of the piers is not yet significant. Considering that simply supported girder piers of high-speed railways are subjected to repeated train loads and environmental factors over long-term service, their mechanical properties are prone to degradation posing a potential safety hazard. To ensure the operational safety of high-speed railways, it is essential to conduct in-depth studies on the long-term service performance evolution of simply supported beam piers. This will provide a reference for durability assessment, service safety warnings, and maintenance and repair of these structures.

Previous studies have utilized various methods to analyze the deterioration and dynamic response of railway piers, such as finite element modeling and experimental testing[2,3]. However, these methods often lack a comprehensive consideration of the combined effects of long-term environmental factors and repeated loading conditions. By

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addressing these gaps, this study aims to provide a more holistic understanding of the deterioration mechanisms.

The author intends to analyze the time-dependent deterioration law of high-speed railway piers based on the theory of time-dependent deterioration of concrete. By analyzing the dynamic response of piers, the study aims to reveal the influence mechanism of time-dependent deterioration on the service performance evolution of high-speed railway simply supported girder piers. This research seeks to provide a scientific method and theoretical basis for the engineering application of high-speed railway piers in terms of performance evaluation, safety early warning, and maintenance and repair.

2 Characterization of Time-Dependency Deterioration of Piers

2.1 Concrete Strength Time-Dependency Deterioration Law

The mechanical properties of concrete materials used in simply supported girder piers for high-speed railroads can undergo significant changes over time. The dynamic environment is more severe than the atmospheric environment. Under the combined influence of external factors and high-speed railroad vibration loads, the mechanical properties of concrete gradually degrade over time, with compressive strength gradually diminishing. According to extensive concrete carbonation tests and data statistics, the time-varying model of concrete carbonation proposed by Niu [4] for the general atmospheric environment is used:

$$\mu_f(t) = \mu_{f_0}\left[1.4529e^{-0.0246(\ln t - 1.7154)^2}\right] \quad (1)$$

$$\sigma_f(t) = \sigma_{f0}(0.0305t + 1.2368) \quad (2)$$

Where $u_f(t)$ and $\sigma_f(t)$ are the mean and standard deviation of the axial compressive strength of concrete after t years, and u_{f0} and σ_{f0} are the mean and standard deviation of the 28-day compressive strength of concrete, with t is the age of deterioration.

According to the Code for the Design of Concrete Structures (GB50010-2010), the standard value of axial compressive strength of concrete is calculated as follows:

$$f_{ck}(t) = \mu_{f_0}(t) - 1.645\sigma_{f_0}(t) \quad (3)$$

The conversion formula for the standard value of axial compressive strength of concrete f_{ck} and the standard value of axial compressive strength of concrete cubes $f_{cu,k}$ is:

$$f_{ck} = 0.88\alpha_{c1}\alpha_{c2}f_{cu,k} \quad (4)$$

The cubic compressive strength time-varying function is obtained by bringing Eqs. (3) and (4) into Eqs. (1) and (2):

$$f_{cu,k}\left(t\right)=\frac{1}{0.88\alpha_{c1}\alpha_{c2}}\left(\mu_{f}\left(t\right)-1.645\sigma_{f}\left(t\right)\right) \tag{5}$$

Where, α_{c1} is the ratio of axial compressive strength of concrete prism to axial compressive strength of cube specimen, which is taken as 0.76 for concrete below C50; α_{c2} is the brittleness discount factor of concrete, which is taken as 1.

The high-speed railway pier is made of C35 concrete and a standard deviation of 5 MPa. By combining Eq. (1) through Eq. (5), he time-varying law of axial compressive strength and cubic compressive strength of concrete can be derived, as shown in Fig 1:

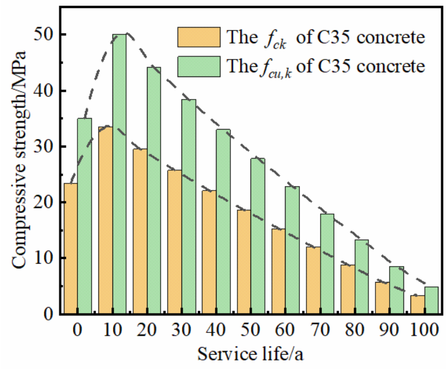


Fig. 1. Time-varying diagram of concrete strength

As shown in Figure 1, as the service life of the piers increased, the concrete strength generally showed a decreasing trend. According to the Design Code for Concrete Structures (GB50010-2010) the formula for the variation of the modulus of elasticity of concrete with the compressive strength of the cube:

$$E_{C}\left(t\right)=\frac{100000}{2.2+\frac{34.7}{f_{cu,k}\left(t\right)}} \tag{6}$$

where $E_{C}\left(t\right)$ is the modulus of elasticity of concrete after year t.

The time-varying modulus of elasticity of the structural concrete of the piers, derived by substituting the calculated cubic compressive strength of the concrete into Eq. (6), is shown in Table 1 below:

Table 1. Time-varying elastic modulus of pier concrete

Service life/a	10	20	30	40	50
Elastic modulus /GPa	34.57	33.49	32.23	30.76	29.02
Service life/a	60	70	80	90	100
Elastic modulus /GPa	26.89	24.21	20.73	15.98	10.74

3 Finite Element Modeling of Bridge Structures

3.1 Finite Element Modeling

Using a double-line simply supported girder bridge of the Beijing-Harbin high-speed railway as an example, ABAQUS software was employed to establish a dynamic model of a 32.6 m simply supported box girder bridge with a girder spacing of 0.1 m. CRTS II type plate ballastless track was installed on the main girder of the bridge, as shown in Figure 2. The pier was designed as a 15 m high equal-height round-end shaped solid pier with a 2.5 m thick bearing platform at the bottom, a pile foundation with a diameter of 1 m, and a pile length of 27 m. The pier, bearing platform, and pile foundation were all made of C35-grade concrete to ensure structural safety under high-speed railway vibratory loads. TIE constraints were used to simulate the interaction between the pile foundation and the soil body.

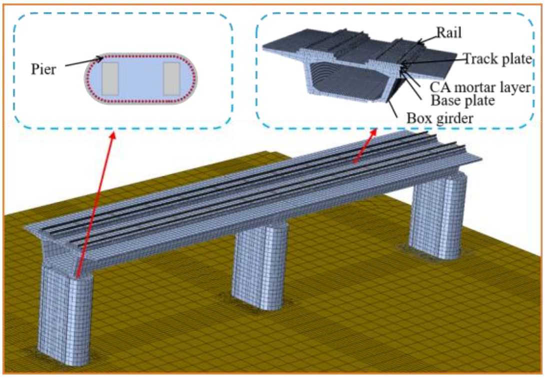


Fig. 2. Model of a simply supported beam bridge for high-speed railway

3.2 Load Simulation of High-Speed Railway Trains

The excitation function describes the effects of unevenness and rail surface waveform abrasion induced by high-speed railway train loading [5]

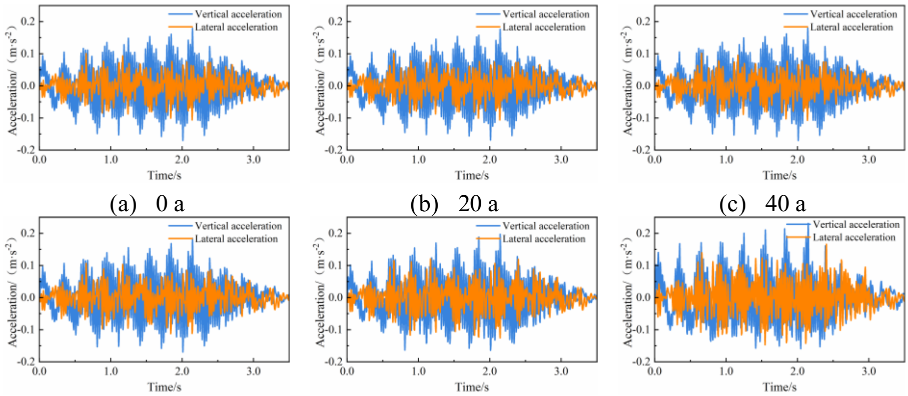
$$F(t) = k_1 k_2 \left[P_0 + P_1 \sin(\omega_1 t) + P_2 \sin(\omega_2 t) + P_3 \sin(\omega_3 t) \right] \tag{7}$$

Where k_1 and k_2 is the wheel and rail force coefficients, P_0 is the unilateral wheel static load, $P_i = M_0 a_i \omega_i^2$ (i=1,2,3), P_i is a typical vibration load for unsteady control conditions, M_0 is the unsprung mass of the train, a_i is the geometric upset vector height corresponding to the unsteady control condition, reflecting the way condition, ω_i is the circular frequency of vibration at the corresponding vehicle speed, which is calculated as $w_i = 2\pi v / L_i$, v is the train operating speed and L_i is the wavelength of the geometrically uneven curve.

4 Dynamic Response Analysis of Piers

4.1 Acceleration Characteristics of Piers

Figure 3 presents the time course curves of vertical and lateral acceleration at the base of the pier under the load of a high-speed railway train. From Figure 3 the amplitude of the vertical acceleration of the pier is consistently larger than that of the transverse acceleration. To facilitate comparison of the results, the peaks of the vertical and lateral accelerations of the piers under different service lives are plotted in Figure 4.



(a) 0 a (b) 20 a (c) 40 a

(d) 60 a (e) 80 a (f) 100 a

Fig. 3. Acceleration time history curves for different service years

The peak acceleration of high-speed railway piers over time is shown in Figure 4. From the figure, it can be observed that during the pre-deterioration period of the pier (0~40 years), both vertical and transverse accelerations remain stable, with little change in amplitude. In the late stage of the pier deterioration period (after 40 years), both vertical and transverse accelerations start to show an increasing trend. Specifically, from 40 to 100 years, the vertical acceleration increases from 0.178 m/s² to 0.231 m/s², a rise of 29.8%. The transverse acceleration increases from 0.102 m/s² to 0.166 m/s², an increase of about 62.7%.

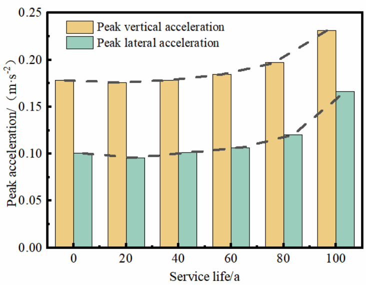
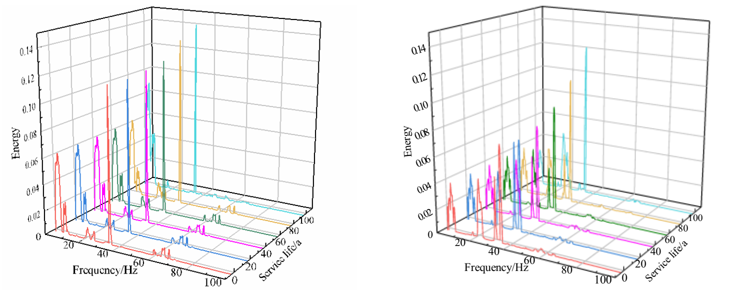


Fig. 4. Changes in peak acceleration

4.2 Time-Frequency Characterization of Vibration Acceleration of Piers Based on Local Maximum Simultaneous Squeeze Transform (LMSST)

Compared to traditional methods, LMSST better addresses the energy dispersion phenomenon, resulting in more aggregated and accurate rearranged band energy[6] The vibration signals were analyzed using the LMSST method, and the energy distribution characteristics of the vertical and transverse vibration signals of the pier over the service life were obtained as shown in Fig. 5.



(a) Vertical acceleration energy profile Lateral acceleration energy profile

Fig. 5. Time-varying distribution

As seen in Figure 5, during the 0~100year service life energy of the pier's vertical and lateral vibration signals is mainly concentrated in the frequency range of 0~40 Hz. The vertical vibration signal energy is consistently greater than the lateral vibration signal energy. With the increase in deterioration years, the peak energy of the vertical vibration signal increased by 17.5%. Similarly, the peak energy of the transverse vibration signal increased by about 64.0%. This demonstrates that both vertical and transverse vibrations of the pier increase with the increase in deterioration time.

5 Conclusion

(1) Based on the concrete strength degradation law, the time-dependent deterioration theory of high-speed railway simply-supported girder piers is deduced. The time-varying laws of their strength and elastic modulus are derived, and an analytical method for characterizing the long-term dynamic response of high-speed railway piers under the effect of deterioration is proposed.

(2) Under the load of high-speed railway train, the vertical acceleration response of the pier is always larger than the lateral acceleration. During the pre-deterioration period, the peak acceleration of the pier changes minimally. However, between 40 and 100 years, the vertical acceleration increases by 29.8%, and the lateral acceleration increases by 62.7%. Deterioration has a greater impact on the lateral acceleration of the pier compared to the vertical acceleration.

(3) Based on the time-frequency analysis using LMSST, the vertical vibration energy is larger than that of the transverse direction. In the frequency domain, the vibration energy is mainly concentrated in the frequency bands of 0~20 Hz and 30~40 Hz. With the increase in time-dependent deterioration years, the vertical and transverse vibration energies of the pier structure increased by 17.5% and 64.0%, respectively, during the service period of 60~100 years.

These findings have significant practical implications for railway engineering practices. The developed time-dependent deterioration theory and analytical methods can be directly applied to assess the long-term performance and safety of high-speed railway piers. Additionally, the identified critical frequency bands for vibration energy concentration provide valuable insights for designing effective vibration mitigation strategies.

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