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Fatigue reliability analysis of the brake pads considering strength degradation

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Highlights

- Reliability model of the brake pads was established based on dynamic SSI model considering the influence of random degradation strength and impact load.
- The analysis results show that random strength degradation, impact load and initial strength have great influence on reliability prediction of the brake pads.
- The dynamic SSI model expanded in the paper is more consistent with the actual operation of mechanical products and can improve the calculation accuracy of structural reliability.

Abstract

Reliability prediction of the brake pads is indispensable to guarantee their safety. In the paper, the fatigue reliability of brake pads is analyzed by dynamic stress-strength interference (SSI) model considering strength degradation. Firstly, reliability model of the brake pads was established based on stress-strength interference model considering the influence of impact load. Then reliability of the brake pads was predicted under different impact load frequency and initial strength. Finally, the influence of random degradation strength on reliability was studied by contrast. The analysis results show that random strength degradation, impact load and initial strength have great influence on reliability prediction for the brake pads. Therefore, the reliability prediction of the brake pads fatigue strength considering strength degradation is more in line with the actual situation and the calculation accuracy is higher.

Keywords

stress–strength interference model, dynamic reliability, strength degradation, impact load.

Acronyms and Abbreviations

SSI	Stress-Strength interference.
BS	Break system.
EM	Element method.
AWM	Archard wear model.
AWF	Archard wear formula.

Notations

S	Strength.
σ	Stress.
$h(s)$	Probability density function of stress.
$f(s)$	Probability density function of fatigue strength.
y_i	Refers to stress component of load.
Δ	Comprehensive strength.
x_i	Strength component of yield limit.
$g(s)$	Density functions of S.
$f(\sigma)$	Density functions of σ.
$G(\sigma)$	Distribution function of S.
$F(\sigma)$	Distribution function of σ.
L_{o+s}	Total load.
L_0	Continuous work load.
L_s	Impact load.
$K(t)$	Appearance of impact load at time t.
$\lambda(t)$	Impact load obeys Poisson distribution.
$f_{L_{0+S}}$	Probability density function of complex load.
φ_0	Initial strength.
φ	Bounds of the integral variables.

1. Introduction

As an important guarantee device for the safe operation of vehicles, the performance of vehicle brake directly affects the reliable operation of vehicles and the safety of drivers. Vehicle brakes mostly adopt the way of friction braking. In a vehicle braking system, brake pads are vulnerable and fail due to wear. Therefore, it is very important to study the reliability and life of brake pads for vehicle safety performance. The wear of brake pads relates to friction materials, the brake temperature, speed, brake disc material, manufacturing condition, the distributions of braking force and personal driving habits and so on. The reliability and life calculation for the brake pads is very difficult [3].

Many existing studies have analyzed the reliability of braking system. For example, Tu et al. established the fault tree of the air braking system using the fault tree analysis technique and reliability assess-

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ment method based on the analysis of the typical failure modes of the non-service air braking system of railway vehicles. Combined with the importance index and the weight integration method based on multi-objective decision theory, the subjective and objective comprehensive weight was proposed and applied to the evaluation of system reliability [29].Taking the braking system of medium-low speed maglev train in Beijing S1 line as the research object, Tan et al. established the reliability function of emergency braking using FTA analysis method [27]. Jian and Min established the reliability model using GO method to reduce the failure rate of CRH1 bullet train foundation brake system. The results showed that this method can obtain all the factors and weak links of the brake system and provide theoretical basis for the maintenance and fault diagnosis [11]. However, few people pay attention to the reliability analysis of the brake pads in the braking system.

Stress-Strength interference model is widely used in structural reliability analysis of mechanical parts.The traditional SSI model regards structural stress and strength as independent random variables. However, due to the complexity and diversity of statistical characteristics of structural stress and strength in practical engineering, the traditional SSI model has some limitations in the structural reliability analysis under certain conditions. Therefore, dynamic SSI model and fatigue SSI model are proposed. Some researchers have contributed to dynamic SSI model. Huang and An evaluated the structural reliability of strength degradation with time. The strength degradation was represented by gamma process and the structural stress was expressed by random variable. The SSI model changing over time was established using the general generating function[8]. Yan and Li carried out the reliability analysis and optimization of car clutch. Compared with actual cases, probability and statistics theory is used to compare the failure rate and reliability, and the method was verified feasible [33]. Based on the drop test of mobile phones, Thiruppukuzhi and Arslanoglu considered the strength degradation of the tested component caused by each drop. The dynamic probability density function of strength was established to analyze the reliability of the mechanism under repetitive loading [28]. Noortwijk et al. used gamma process to express the strength attenuation, while poisson process was applied to represent the fluctuating load.The dynamic SSI model varying with time was established [23]. An developed a dynamic SSI model under impact load. According to the characteristics of maximum sequence statistics, the equivalent load model of impact load was derived [1]. Other scholars have focused on the fatigue SSI model. To evaluate the fatigue reliability of rotor components, reliability model comined with high and low cycle fatigue loadings was developed on the basis of the SSI method considering the strength degeneration by Yue et al. In this method, low frequency fatigue load, high frequency fatigue load and residual strength were taken as random variables. The predicted results demonstrated that the proposed model presents a higher prediction accuracy than Miner, Manson-Halford model does [39]. A nonlinear residual strength degradation model based on SSI model and an improved nonlinear fatigue damage accumulation model were proposed by Yuan et al. A new method was developed, which combined with the presented nonlinear fatigue damage accumulation model and residual strength degradation model. The method can be used to predict the fatigue life and reliability of the product under constant and variable amplitude loading [38]. Xie and He presented a method for calculating fatigue reliability under cyclic loading with uncertain constant amplitude in the stress range [32].

Dynamic SSI model will be used to predict the reliability of brake pads considering the effect of strength degradation and impact load in this paper. The remainder of the paper is organized as follows: The traditional and dynamic SSI model is described in Section 2. The effects of random load, initial strength and strength degradation on reliability of the brake pads are analyzed based on dynamic SSI model in Section 3. Discussion and conclusion will be given in Sections 4 and 5, respectively.

2. The theory of stress–strength interference (SSI) model

2.1. The traditional SSI model

The external loads acting on unit area of mechanical structure is often called stress represented by σ. The maximum external loads acting on unit area of mechanical structure is known as strength denoted by S, which reflects the load bearing capability of material [2]. The structure work at normal state when the strength bigger than the stress. The structural failure will occur while the strength smaller than the stress. The condition of normal work can be expressed as:

$$S - \sigma > 0 \tag{1}$$

Only stress and strength are certainly values, Eq. (1) could be used to judge whether the structure is in normal work. However, stress and strength are all random variables, which obey statistical distributions within certain range.

Fig. 1 illustrates typical interference relationship of stress-strength. In Fig. 1, $h(s)$ and $f(s)$ is probability density function of stress and fatigue strength, respectively. The shaded part expresses the region of stress-strength interference. Existence of smaller interference region is allowed for general mechanical parts under the premise of average value of strength bigger than stress. It is indicated that there is a failure probability greater than zero [4, 5].

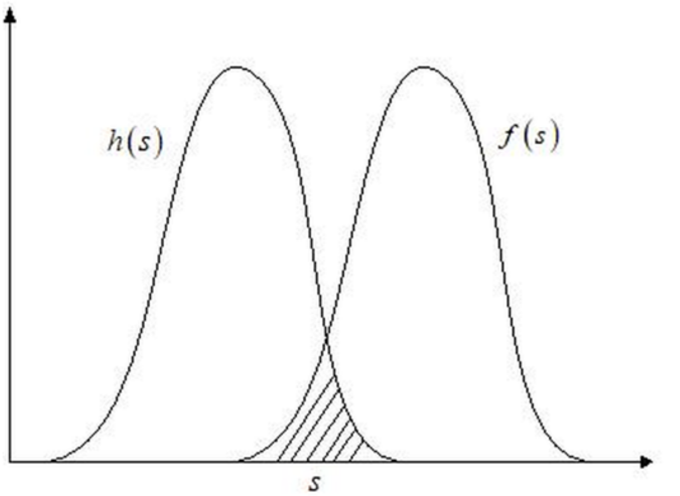

Fig. 1. Stress-strength interference diagram

2.2. Dynamic SSI modelling

Besides continuous work load, equipment also bears discrete impact load. If discrete impact load appears at time t, the total load applied to product is the sum of two impact loads, where $L_{o+s}(C,t) = L_0(\mathrm{C,t}) + L_s$. Otherwise, product is only subjected to continuous work load, where $L_{o+s}(C,t) = L_0(\mathrm{C,t})$. Because of age or abrasion, the strength of the system is generally regarded as degradation. Degradation is divided into deterministic and random degradation [6, 13, 22].

Continuous work load is random process and impact load is random variable for a given system[37, 40]. When degradation of strength is deterministic, strength $S(\phi,t)$ is constant in any case. When strength degradation is deterministic, SSI model is shown in Fig. 2.

According to SSI model, dynamic reliability model at time t can be expressed as [12]:

$$R(t) = \Pr\left\{L_{0+s}(C,\tau) < S(\phi,\tau), \forall \tau \in (0,t)\right\} \tag{2}$$

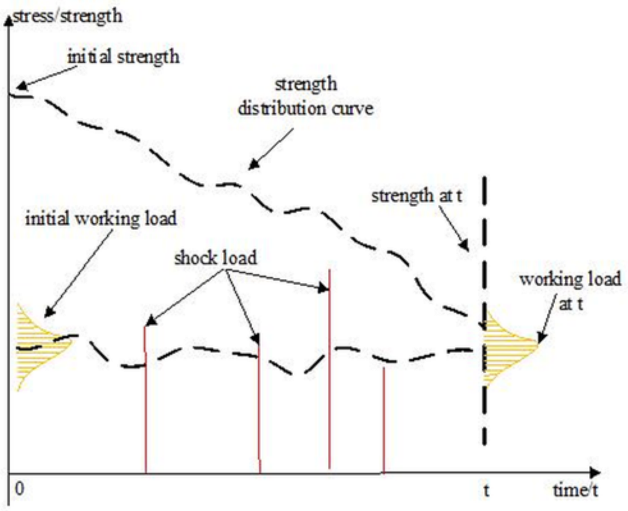

Fig. 2. SSI model considering complex loads and deterministic strength degradation

where $L_{0+s}(C,\tau)$ is comprehensive load, which is the sum of work and impact loads.

Supposing that $K(t)$ expresses the appearance of impact load at time t_1 and $\bar{K}(t)$ is that of not appearance. Assuming impact load obeys Poisson distribution $\lambda(t)$.

For $\forall\tau \int (t,t+\Delta t)$, the following formulas can be obtained:

$$\Pr\{K(\tau)\} = \lambda(\tau)\Delta t + o(\Delta t) \tag{3}$$

$$\Pr\{\bar{K}(\tau)\} = 1 - \Pr\{K(\tau)\} = 1 - \lambda(\tau)\Delta t + o(\Delta t) \tag{4}$$

The overall probability yield rate can be expressed as:

$$\begin{aligned} R(t+\Delta t) &= R(t)\times[\Pr\{L_{o+s}(C,\tau) < S(\phi,\tau)\}\times\Pr\{K(\tau)\}] + R(t)\times\Pr\{\bar{K}(\tau)\}, \forall\tau\in(t,t+\Delta t) \\ &= R(t)\times\Pr\{L_{o+s}(C,\tau) < S(\phi,\tau)\}\times[\lambda(\tau)\Delta t + o(\Delta t)] + R(t)\times[1-\lambda(\tau)\Delta t + o(\Delta t)], \forall\tau\in(t,t+\Delta t) \end{aligned} \tag{5}$$

Eq. (6) can be written as:

$$\frac{R(t+\Delta t)-R(t)}{\Delta t} = R(t)\times\Pr\{L_{0+s}(C,\tau)<S(\phi,\tau)\}\times\left[\lambda(\tau)+\frac{o(\Delta t)}{\Delta t}\right] - R(t)\times\lambda(\tau)+\frac{o(\Delta t)}{\Delta t} = \forall\tau\in(t,t+\Delta t) \tag{6}$$

When $\Delta t \to 0, \tau \to t, \frac{o(\Delta t)}{\Delta t} \to 0$, Eq. (6) can be represented as:

$$\frac{dR(t)}{dt} = R(t)\times\lambda(t)\times\left[\Pr\{L_{0+s}(C,\tau) < S(\phi,\tau)\} - 1\right] \tag{7}$$

When R(0)=1, reliability function can be obtained:

$$R(t) = e^{\int_0^t \lambda(\xi)\times\left[\Pr\{L_{0+s}(C,\xi)<S(\phi,\xi)\}-1\right]d\xi} = e^{\int_0^t \lambda(\xi)\times\left[\int_{-\infty}^{S(\phi,\xi)} f_{L_{0+S}}(C,\xi)dC-1\right]d\xi} \tag{8}$$

where $f_{L_{0+S}}(.)$ is probability density function of complex loads.

When strength degradation is a random process, strength is random at any time and the overall strength degrades randomly [41]. The SSI model is shown in Fig. 3.

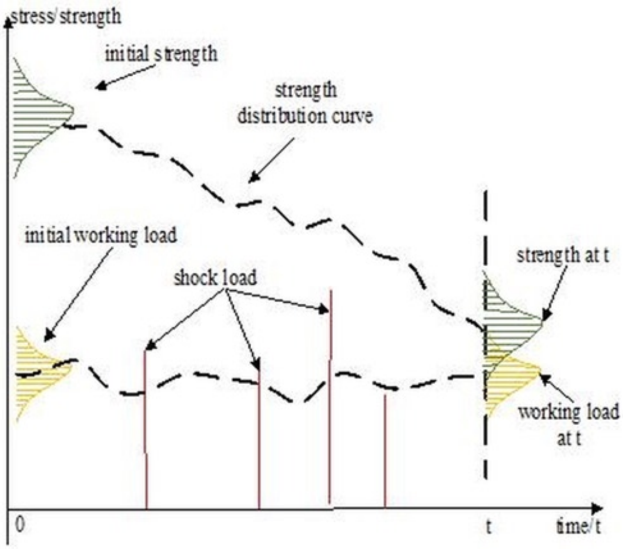

Fig. 3. SSI model considering complex load and random strength degradation

Combined with Eq. (8), the reliability of the brake pads at time t can be obtained:

$$R(t) = \int_{\varphi} R[t\,|\,S(\Phi,t) = S(\varphi,t)]f_{\Phi}(\varphi)d\varphi = \int_{\varphi} e^{\int_0^t \lambda(\xi)\times\left[\int_{-\infty}^{S(\varphi,\xi)} f_{L_{0+S}}(C,\xi)dC-1\right]d\xi} f_{\Phi}(\varphi)d\varphi \tag{9}$$

3. Dynamic reliability analysis

The stress of the brake pads includes mechanical stress and thermal stress. The mechanical stress is acted on the brake pads, which is caused by device during braking. The temperature of the friction pair rises due to heavy load, high running speed and large energy absorb. The local region of contact surface appears "flash point". The thermal stress lead to material damage, cracks and heat fade[3,9].

The stress-intensity of the emergency conditions is analyzed, because the emergency braking is more likely to appear heat fade, cracks and fatigue failure than the normal braking. The reliability of the brake pads will be calculated through adding mechanical and thermal stress as continuous working stress.

In the actual working condition, the brake pads are not only subjected continuous working stress but also random impact stress. So the combined stresses act on the brake pads. The initial strength is diverse due to different materials and techniques. During application the strength of the brake pads will degenerate due to abrasion, shaking and so on. The strength degradation is divided into deterministic and random strength degradation based on whether the strength is constant at some point [3,30].

According to the actual working condition, continuous working stress of the brake pads is assumed to obey normal distribution [7, 10, 20]. It can be expressed as:

$$\sigma_H \sim N(\mu,\sigma^2) \tag{10}$$

Assuming that the impact load of the brake pads follow Poisson distribution λ(t)=1.0hr-1, where u=526.8MPa, σ=40MPa.

Supposing that stress of the brake pads under impact load conforms to normal distribution. It can be written as:

$$\sigma_H^{'} \sim N\left(\mu,\sigma^2\right) \tag{11}$$

where u=100MPa, σ=20MPa.

The reliability of the brake pads will be analyzed under different working conditions and degradation types through solving the dynamic stress-strength interference model. The reliability variation of the brake pads will be analyzed as follow with deterministic and random strength degradation [17].

3.1. Reliability analysis with deterministic strength degradation

The reliability of the brake pads will be calculated with deterministic strength degradation under different conditions, which include considering and without considering impact load, different frequency of random load and different initial strength [14, 15, 33].

According to 6σ criteria, the calculation formula of reliability for the brake pads under the action of continuous working stress can be obtained [34, 19]:

$$\begin{cases} f_1(t)=\int_0^t\left\{\int_{u_{L_0(\xi)}-6\sigma_{L_0(\xi)}}^{800-0.2\xi}\frac{1}{\sqrt{2\pi}\sigma_{L_0(\xi)}}e^{-\frac{[C-u_{L_0(\xi)}]^2}{2\times[\sigma_{L_0(\xi)}]^2}}dC-1\right\}d\xi \\ R(t)=e^{f_1(t)} \end{cases} \tag{12}$$

where the initial strength φ_0 is 800MPa and $S(\Phi,t)=\varphi_0(1-0.00025t)$.

Reliability curve can be obtained by solving the Eq. (12), as shown in Fig. 4.

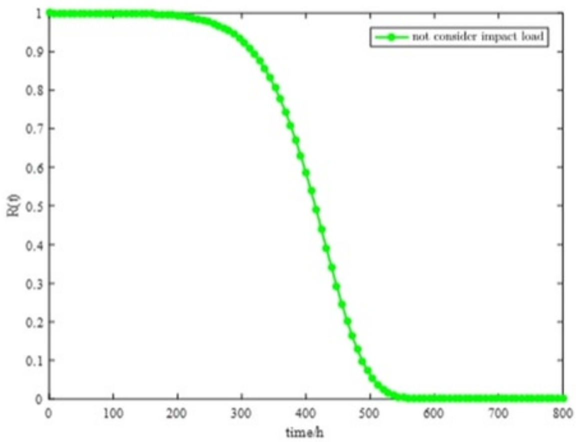

Fig. 4. Reliability curve considering deterministic strength degradation

As seen in Fig.4, the brake pads have high-reliability when service time is less than 400h and it is significantly reduced after 400h. However, impact load may appear due to operation environment and misoperation in practice. When the impact load appears, assuming that the amplitude of the impact load follows normal distribution with $\lambda(t)=1.0hr^{-1}$. Due to additivity property of the normal distribution, the following formulas can be obtained [25, 31]:

$$u_{L_0+s(t)}=u_{L_0}+u_{L_{s(t)}} \tag{13}$$

$$6\sigma_{L_0+s(\xi)}=6\sqrt{\sigma_{L_0}^2+\sigma_{L_S}^2} \tag{14}$$

The calculation formula of reliability for the brake pads considering impact load can be represented as:

$$\begin{cases} f_1(t)=\int_0^t 1\times\left\{\int_{u_{L_0+s(\xi)}-6\sigma_{L_0+s(\xi)}}^{800-0.2\xi}\frac{1}{\sqrt{2\pi}\sigma_{L_0+s(\xi)}}e^{-\frac{[C-u_{L_0+s(\xi)}]^2}{2\times[\sigma_{L_0+s(\xi)}]^2}}dC-1\right\}d\xi \\ R(t)=e^{f_1(t)} \end{cases} \tag{15}$$

Fig. 5. illustrates the reliability curve by solving the Eq. (15).

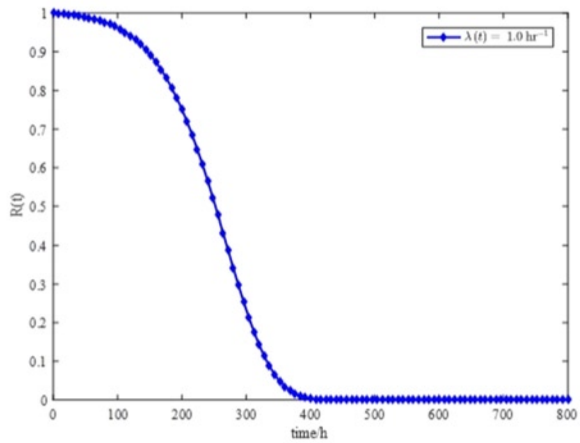

Fig. 5. Reliability curve considering impact load

Comparison diagram of the reliability curves considering and without considering impact load is shown in Fig. 6.

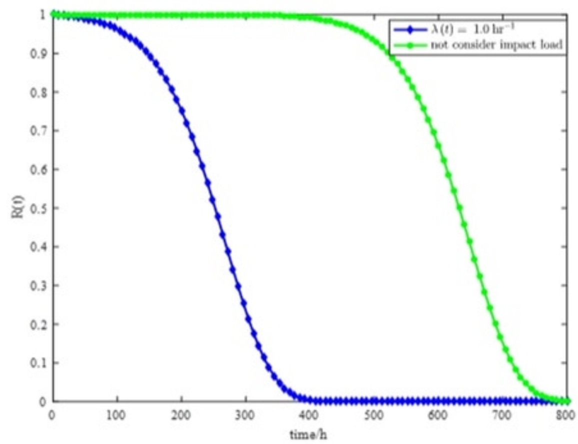

Fig. 6. Comparison of Reliability curves considering and without considering impact load

It can be seen from Fig. 6, reliability of the brake pads considering and not considering impact load has great difference. The life time of the brake pads considering impact load is only half of not considering. The reliability of the brake pads considering impact load starts to fall significantly after 100h, which is less than that of not considering. The descending rate of reliability curve for considering impact load is faster than that of not considering. Serious error will arise ignoring the influence of impact load. Therefore, the influence of impact load should be considered sufficiently.

Product strength generally varies along with material characteristic, structure and manufacturing process. Reliability curve of product changes with initial strength [16, 18, 34]. Reliability of certain type of the brake pads is calculated when initial strength is 720 MPa, 800 Pa and 850 MPa, respectively. Comparison diagram of reliability for the three different initial strengths is shown in Fig. 7.

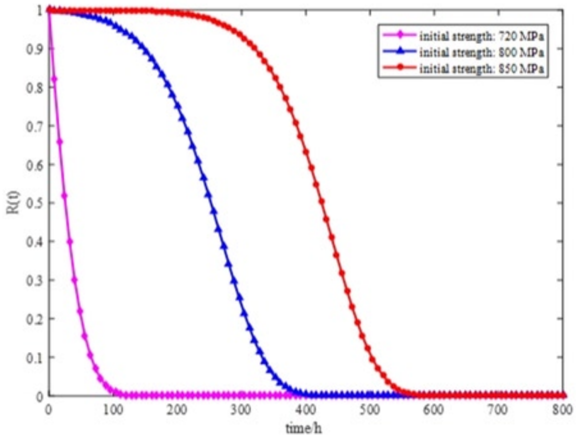

Fig. 7. Comparison of Reliability curve for different initial strength

It is shown that initial strength of the brake pads has remarkable influence on the reliability. The reliability is almost proportional to initial strength before the reliability closing to zero[36]. The time that its reliability began to decline increase with the increase of initial strength. The larger initial strength brings the slower falling rate of reliability and the longer time of the reliability decreasing to zero. The rule of the reliable degree obtained from the comparison chat can guide the selection of brake friction lining [21, 24, 34].

Random impact load could appear due to the influence of emergency brake, shift gears and driving environment in the course of driving. Supposing that impact load conforms to Poisson distribution. The strength of random impact load varies with occurrence number of emergency brake, shift gears and so on. The effects of different strength of random impact load on the reliability of the brake pads were analyzed, as shown in Fig. 8.

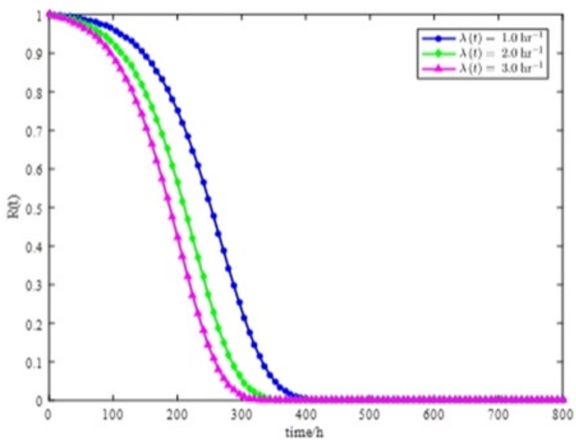

Fig. 8. Reliability curves under different strengths

According to the Fig. 8, the reliability is negatively correlated to the frequency of random load. The time that its reliability starts to decline obviously decreases with the increase of frequency of random load. The frequency of random load is higher, the time of reliability declining to zero is shorter. Therefore, attention should be paid to avoid random impact load in the process of use the brake pads.

3.2. Reliability analysis considering random strength degradation

To truthfully reflect the operational process of the brake pads, random strength degradation need to be considered. Assuming that initial strength obeys normal distribution $\varphi_0 \sim \left(800, 20^2\right)$ and the degradation law follows $S(\Phi,t) = \varphi_0(1-0.00025t)$. Based on 6σ criteria, the reliability calculating formula for the brake pads considering random strength degradation can be expressed as [19, 20, 26]:

$$\begin{cases} f_2(\varphi,t) = \int_0^t 1 \times \left\{ \int_{u_{L_0+s(\xi)}-6\sigma_{L_0+s(\xi)}}^{\varphi_0(1-0.00025\xi)} \frac{1}{\sqrt{2\pi}\sigma_{L_0+s(\xi)}} e^{-\frac{[C-u_{L_0+s(\xi)}]^2}{2\times[\sigma_{L_0+s(\xi)}]^2}} dC - 1 \right\} d\xi \\ R(t) = \int_{680}^{920} e^{f_2(\varphi,t)} \frac{1}{\sqrt{2\pi}\times 20} e^{-\frac{[\varphi-800]^2}{2\times 20^2}} d\varphi \end{cases} \tag{16}$$

where the bounds of the integral variable φ is 680MPa and 920 MPa, respectively.

The finite difference method was applied to solve the Eq. (16), the reliability curve for the brake pads can be obtained, as shown in Fig. 9.

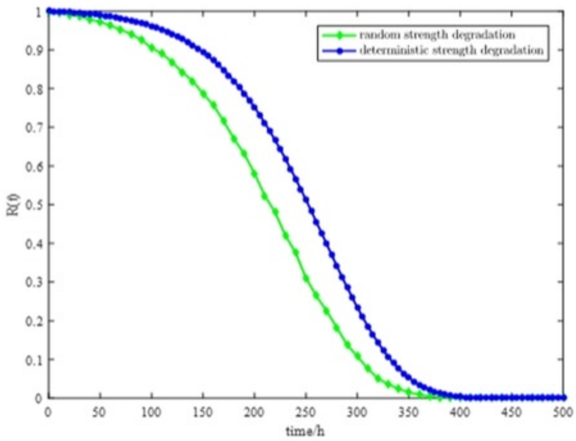

Fig. 9. Reliability curve considering random strength degradation

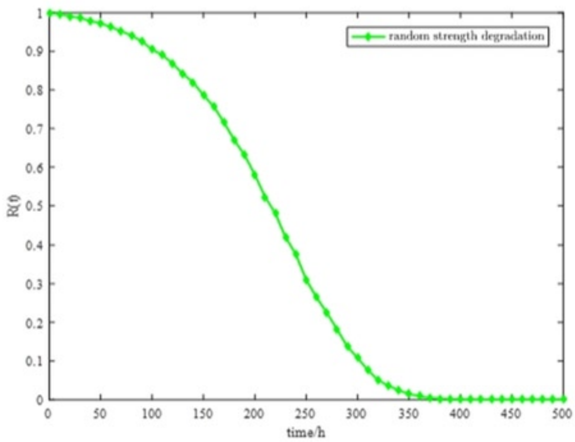

Fig. 10. Reliability curve considering random and deterministic strength degradation

To further analyze the impact of random degradation strength on the reliability, the reliability curve considering random strength degradation was compared with that of with deterministic strength degradation when the initial strength is 800 MPa, as shown in the Fig. 10.

According to Fig.10, the downward trend of the two cases is basically the same. Considering that the reliability of random strength declines, a downward trend appears earlier. When reaching 400 hours, the reliability curve considering random strength degradation and the reliability curve of deterministic strength degradation both decrease to 0 at the same time. Because the brake pads will be impacted by random loads during use, only considering the determination of the load estimate will have a certain deviation in the reliability result analysis. Therefore, it can be concluded that, considering the random strength drop, a more accurate value can be obtained in the reliability analysis of the brake pad. In addition, taking the service life as the research object, by simplifying the random intensity degradation, the reliability error can be accepted.

4. Discussion

The brake pads are an important part of brake system. The reliability is affected by friction materials, speed, processing conditions and so on. The brake pads are subject to both mechanical and thermal stress. According to theory of SSI model, failure will occur when the stress acting on the brake pads is more than its structural strength. When using SSI model, the brake pads are considered as subjected to continuous working stress, structural stress and strength are regarded as static values. Initial strength directly affects the reliability of the brake pads. Besides continuous working stress, the brake pads are affected by impact load in the actual braking process. The results of reliability analysis can be affected due to neglecting the influence of impact load and also be impacted by the frequency of random load. The errors of reliability are acceptable through simplified random strength degradation. The more accurate calculating value of reliability can be obtained through considering the random influence of strength degradation in the reliability analysis.

5. Conclusion

The dynamic SSI model of the brake pads was established considering random strength degradation and the different frequency of impact load. The following conclusions can be drawn:

(1) Considering the influence of random degradation strength, composite stress and impact load, the reliability accuracy of brake pads is high, which can be used to guide the timely replacement of brake pads and improve the reliability of brake system.

(2) The dynamic SSI model expanded in the paper is more consistent with the actual operation of mechanical products and can improve the calculation accuracy of structural reliability.

(3) Various loads act alternately on the mechanical product during its full lifecycle. Only considering the limit load, the safety performance of mechanical products is better, but the product utilization rate is not high enough. Therefore, the effect of various loads can be equivalent to the comprehensive load in the dynamic SSI model, which can further improve the calculation accuracy of reliability.

Acknowledgement

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