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Research Article

Study on Evaluation Theory of Bridge Damage State and Methodology on Early Warning of Danger

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When evaluating and prewarning the damage state of bridges, the observation equation and state equation of bridge systems are not constructed in the existing methods, which would cause the evaluation results to be inconsistent with the actual damage state of bridges. Therefore, the existing methods have the problems of low evaluation accuracy, high false alarm rate, and poor real-time performance. In order to solve the above problems, this paper proposes a novel evaluation and judgment theory of bridge damage state and methodology on early warning of danger. The wavelet packet analysis method is used to construct the observation equation and state equation of bridge systems, which could provide a relevant basis for evaluating the damage state of bridges. Then, the fuzzy comprehensive evaluation method is used to construct the fuzzy evaluation model of the bridge damage state to evaluate and judge the damage state of bridges. According to the evaluation results, combined with mathematical-statistical analysis methods and principal component analysis methods, the methodology on early warning of danger for bridge structures can be realized. The experimental results showed that the proposed method has high evaluation and judgment accuracy, low false alarm rate, and good real-time performance and reliability.

1. Introduction

In the bridge operation process, monitoring the durability, integrity, and safety of bridge structures is an important part of bridge safety evaluation [1–5]. The bridge's structural safety is affected by not only natural disasters such as earthquakes and sudden accidents but also a brittle failure due to the damage accumulation of nodes [6–11]. Therefore, the main purpose of monitoring the durability and safety of bridge structures is to evaluate the bridge damage state under the effect of load [12–14]. The long-term structural health monitoring data contains quite a few structural information and could play significant roles in detecting damages in early stage, and neutral axis indicator and machine learning method have been used in the long-term structural health monitoring [15, 16]. At present, most of the bridge structures in China were made of steel, and the design life of most bridges is about to be due. Therefore, it is an urgent problem to evaluate and judge the damage state of such bridges and early warning of dangers [17–20].

So far, some progress has been made in the research of bridge damage state assessment and early warning methods of danger. For example, Geng et al. proposed a method for the bridge damage state assessment and early warning method based on lateral acceleration monitoring [21]. In this method, the root mean square of the lateral acceleration of main girders was taken as a monitoring parameter to analyze the dynamic characteristics of bridges, and the bridge damage state would be evaluated by the correlation model. The principal component analysis was used to analyze the changes of the correlation model due to the changes in environmental factors. According to the analysis results, the early warning index of bridges is determined to realize the early warning of dangers. However, this method does not build the observation equation of the system, and it takes a long time to detect the change of the principal component correlation coefficient of bridge structures, which has the problem of poor real-time performance. In addition, Hua et al. proposed a long-term monitoring and early warning method of bridge structure modal frequency formed by combining principal component analysis and support vector regression [22]. Yabe et al. also proposed a combination of state representation and frequency slice wavelet transform for monitoring and evaluating bridge conditions [23]. Liu et al. proposed a method for the bridge damage state assessment and early warning method based on the improved Bayesian method [24]. This method is based on the analytic hierarchy process (AHP) theory in the existing evaluation systems and decomposes the whole bridge hierarchy according to different parts and functions of bridges. Each subcomponent of bridges is converted into a node in the Bayesian probability network so that the state score of each subcomponent corresponds to the state probability of the node in the Bayesian network one by one, and then the overall state of the bridge at a certain time is determined. Thus, real-time update, transmission, evaluation, and early warning can be carried out on the status information of bridges at different times. However, this method has the problem of poor real-time performance for early warning of bridge damage due to its slow information update speed.

On the other hand, Dong et al. proposed a method for the bridge damage state assessment and early warning method based on a sliding window subspace algorithm [25]. This method combines a data-driven random subspace identification algorithm and sliding window technology to track and identify bridge modal parameters in real time and evaluates the bridge damage state. According to the evaluation results of the bridge damage state, the danger warning for the bridge could be realized based on frequency change rate and frequency value. However, this method does not construct the state equation of the system, which leads to a large error between the evaluation result and the actual bridge damage state, and there is a problem of a high false alarm rate. Huang et al. proposed a method of bridge damage state assessment and early warning method based on finite element analysis [26]. Taking the tested deflection value of a slab girder as a guide, given the law that reducing the elastic modulus of concrete or increasing the bending moment caused by the load will increase the deflection, this method is used to evaluate the damage state of existing bridges. Then, Midas FEA software is used to simulate the bridge damage, and the damage warning method of bridges is designed based on it. However, there is a large gap between the simulated value and the actual value for this method, which causes the problem of high false alarm rate in this method.

In summary, most of the current researches on the damage state assessment and danger warning methods of bridges have problems with poor real-time performance of bridge damage warning or high false alarm rate. In order to solve the problems in the above methods, this paper proposes a novel evaluation and judgment theory of bridge damage state and methodology on early warning of danger. This bridge damage state assessment and early warning method is constructed based on the integration of wavelet packet analysis method, fuzzy comprehensive evaluation method, and principal component analysis method.

2. Dynamic System of Bridge Structure

In the process of studying the evaluation and judgment theory of bridge damage state and methodology on early warning of danger, it is necessary to first construct the dynamic system of bridge structure based on the wavelet packet analysis method. The dynamic system is used to decompose the bridge structure at multiple scales to obtain the observation equation and state equation of bridge structures, which could provide relevant basis and data for evaluating and judging the damage state of bridges.

Assuming that the degree of freedom of the dynamic system is n, the differential equation of motion could be obtained based on the mathematical theory of wavelet packet analysis [27]:

$$\mathbf{M}\ddot{x} + \mathbf{C}\dot{x} + \mathbf{K}x(t) = F(t), \tag{1}$$

where $\boldsymbol{M}$ describes the mass matrix, $\mathbf{M} \in R^{n\times n}$; x is the displacement response vector, $x \in R^{n\times 1}$; $\boldsymbol{C}$ is the damping matrix, $\mathbf{C} \in R^{n\times n}$; $\boldsymbol{K}$ is the stiffness matrix, $\mathbf{K} \in R^{n\times n}$; F is the system excitation vector, $F \in R^{n\times 1}$.

Let $\overline{x}(t)$ be the state vector; the state equation can be used to describe the above equation of motion:

$$\overline{x}(t) = A\overline{x}(t) = B\overline{F}(t), \tag{2}$$

in which

$$\begin{cases} A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \\ B = \begin{bmatrix} 0 & 0 \\ -M^{-1} & 0 \end{bmatrix}, \\ \overline{F}(t) = \begin{bmatrix} F(t) \\ 0 \end{bmatrix}. \end{cases} \tag{3}$$

The p-dimensional continuous signal ($f(t) \in R^{n\times 1}$) is obtained by the acceleration sensor, and the dynamic response of the observed structure can be expressed as

$$f(t) = \mathbf{T}\ddot{x}(t) + v(t), \tag{4}$$

where $v(t)$ describes the observation noise; $\boldsymbol{T}$ describes the observation matrix. Then the continuous signal $f(t)$ can be described as

$$f(t) = \overline{\mathrm{Cx}}(t) + \overline{\mathrm{DF}}(t) + v(t), \tag{5}$$

The output equation and the state equation are discretized in the time domain. Let Δt represent the time interval of the system sampling, and it will obtain the time-domain solution of the state equation in the time domain:

$$\overline{x}(t) = e^{A\Delta t}\overline{x}(t-\Delta t) + \int_{t-\Delta t}^{t} e^{A(t-f)}B\overline{F}(f)\mathrm{d}f, \tag{6}$$

Then, the discrete observation equation and state equation in the time domain are expressed as follows:

$$\begin{cases} \overline{x}(N,k+1) = \overline{A}(N)\overline{x}(N,k) + \overline{B}(N)\overline{F}(N,k), \\ f(N,k) = \overline{C}(N)\overline{x}(N,k) + D(N)\overline{F}(N,k) + v(N,k), \\ \overline{A} = e^{A\Delta t}, \\ \overline{B} = \int_{t-\Delta t}^{t} e^{A(t-f)}B. \end{cases} \tag{7}$$

Suppose that the wavelet packet decomposition scale is i; the observation equation and state equation of the structural system are defined as follows:

$$\begin{cases} f(i,k) = \overline{C}(i)\overline{x}(i,k) + \overline{D}(i)\overline{F}(i,k) + v(i,k), \\ \overline{x}(i,k+1) = \overline{A}(i)\overline{x}(i,k) + \overline{B}(i)\overline{F}(i,k). \end{cases} \tag{8}$$

The state equation of the dynamic system in the case of scale i can be decomposed into the scale (i–1) through the wavelet transform method, and then the system state equation in coarse-scale signal space V_{i-1} is obtained:

$$\begin{aligned} \overline{x}_v^i(i-1,k+1) &= \sum_l h(l)\overline{x}(i,2k-l+2) \\ &= \overline{A}_v^i(i-1)\overline{x}_v^i(i-1,k+1) \\ &\quad + \overline{B}_v^i(i-1)\overline{F}_v^i(i-1,k+1), \end{aligned} \tag{9}$$

where the subscript v describes the projection corresponding to the signal sequence $\overline{x}(i,k)$ of scale i in the coarse-scale signal space V_{i-1}.

The observation equation of the dynamic system is decomposed from scale i to scale (i–1) by wavelet transform method, and the observation equation of the system in the coarse-scale signal space V_{i-1} is obtained:

$$\begin{cases} f_v^i(i-1,k) = \sum_l h(l)f(i,2k-l) = \overline{C}_v^i(i-1)\times\overline{x}_v^i(i-1,k) + \overline{D}_v^i(i-1)\overline{F}_v^i(i-1,k) + v^i v(i-1,k), \\ \overline{C}_v^i(i-1) = \overline{C}(l), \\ \overline{D}_v^i(i-1) = \overline{D}(l), \\ \overline{F}_v^i(i-1,k) = \sum_l h(l)\overline{F}(i,2k-l), \\ v^i v(i-1,k) = \sum_l h(l)v(i,2k-l), \end{cases} \tag{10}$$

In the same way, the state equation of the dynamic system in the fine-scale signal space W_{i-1} is obtained:

$$\begin{aligned} \overline{x}_W^i(i-1,k+1) &= \sum_l g(l)\overline{x}(i,2k-l+2) \\ &= \overline{A}_W^i(i-1)\overline{x}_W^i(i-1,k) \\ &\quad + \overline{B}_W^i(i-1)\overline{F}_W^i(i-1,k), \end{aligned} \tag{11}$$

where the subscript W describes the projection corresponding to the signal sequence $\overline{x}(i,k)$ of scale i in the coarse-scale signal space.

Similarly, the observation equation of the dynamic system is decomposed from scale i to scale (i–1) by wavelet transform method, and the observation equation of the system in the coarse-scale signal space W_{i-1} is obtained:

$$\begin{cases} f_W^i(i-1,k) = \sum_l g(l)f(i\cdot 2k-l) = \overline{C}_W^i(i-1)\overline{x}_W^i(i-1,k) + \overline{D}_W^i(i-1)\overline{F}_W^i(i-1,k) + v_W^i(i-1,k), \\ \overline{C}_W^i(i-1) = \overline{C}(i), \\ \overline{D}_W^i(i-1) = \overline{D}(i), \\ v_W^i(i-1,k) = \sum_l g(l)v(i,2k-l). \end{cases} \tag{12}$$

3. Evaluation and Judgment of Bridge Damage State

Based on the observation equation and state equation of the system, the fuzzy comprehensive evaluation method is used to evaluate and judge the damage state of bridges.

3.1. First-Level Evaluation. The first-level evaluation refers to the fuzzy comprehensive evaluation and judgment for the most basic components including bridge support, deck pavement, bridge piers, and main force-bearing components [28–30].

Let m represent the total number of damaged items that can affect the technical state of components and evaluate each damaged item of bridges. The corresponding impact evaluation matrix $\boldsymbol{R}$ of components can be constructed as follows:

$$\mathbf{R}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{m5} \end{bmatrix}. \tag{13}$$

Suppose that the fuzzy subset on the domain U_1 is the factor existing in the factor set U of the component S_{ij}, which is called $\mathrm{AS}_{ij}=(a_1,a_2,\ldots,a_m)$ for short. Let BS_{ij} be the fuzzy comprehensive evaluation set of damage state corresponding to the component S_{ij}; AS_{ij} and RS_{ij} are used to evaluate the damage state of a single component, which is calculated by

$$\mathrm{BS}_{ij}=\mathrm{AS}_{ij}\cdot\mathbf{R}=\left(b_1',b_2',b_3',b_4',b_5'\right). \tag{14}$$

3.2. Second-Level Fuzzy Comprehensive Evaluation. Let R' represent the evaluation matrix of a single factor corresponding to the substructure S_i, and R' is composed of fuzzy comprehensive evaluation sets of various damage states [29, 31–33], which is expressed as follows:

$$R'=\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{15} \\ b_{21} & b_{22} & \cdots & b_{25} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{n5} \end{bmatrix}. \tag{15}$$

Assume that AS_i represents the fuzzy subset existing in the domain U_1, and its expression is $\mathrm{AS}_i=(a_1,a_2,\ldots,a_i,\ldots,a_n)$, in which a_i is the distribution weight of the i-th subcomponent in the substructure S_i; n is the number of the components in the substructure S_i. BS_i is assumed to represent the fuzzy subset existing in $\boldsymbol{V}$, that is, the fuzzy comprehensive evaluation set corresponding to the damage state of substructure S_i, and its expression is as follows:

$$\mathrm{BS}_i=\mathrm{AS}_i\times R'=\left(b_1',b_2',b_3',b_4',b_5'\right), \tag{16}$$

3.3. Third-Level Fuzzy Comprehensive Evaluation. The first-level and second-level fuzzy comprehensive evaluation values are combined to form an evaluation matrix of a single factor R'':

$$R''=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \cdots & \cdots & \cdots & \cdots \\ r_{51} & r_{52} & \cdots & r_{55} \end{bmatrix}. \tag{17}$$

The fuzzy subset $\mathrm{AB}_i=(a_1,a_2,a_3,a_4,a_5)$ existing in the domain U_1 is the assigned weight of the bridge substructure.

Based on the fuzzy subset AB and evaluation matrix of a single factor R'', the evaluation model BB of bridge damage state is constructed:

$$\mathrm{BB}=\mathrm{AB}\times R''=\left(b_1',b_2',b_3',b_4',b_5'\right). \tag{18}$$

4. Methodology on Early Warning of Danger

According to the evaluation results, combined with mathematical-statistical analysis methods and principal component analysis methods, the methodology on early warning of danger for bridge structures can be realized.

In practice, environmental factors such as wind speed and temperature will affect the modal parameters of bridge structures [34, 35]. The nonlinear principal component analysis method is used to extract the parameters of wind speed and temperature, and the modal parameters are projected in the characteristic parameter space of environmental factors. Then, the hypothesis testing is carried out on the basis of statistical theory to realize the judgment of the operating state of bridge structures for further danger warning.

The nonlinear relationships between the reconstruction vector $\widehat{x}$ and feature vector $\boldsymbol{y}$ as well as the feature vector $\boldsymbol{y}$ and initial data vector $\boldsymbol{x}$ are described as follows:

$$\begin{cases} \widehat{x}_i^{(k)}=\displaystyle\sum_{j=1}^{M}W_{4ij}\Xi\left(\sum_{r=1}^{m}W_{3jr}y_r^{(k)}+b_{3j}\right)+b_{4i}, \\ \widehat{y}_i^{(k)}=\displaystyle\sum_{p=1}^{M}W_{2rp}\Xi\left(\sum_{q=1}^{n}W_{1pq}x_q^{(k)}+b_{1p}\right)+b_{2r}. \end{cases} \tag{19}$$

The square prediction error of statistics ($\boldsymbol{Q}$) describes the deviation degree of modal test value from the principal component model at the k-th moment [36]. Let Q_k represent the statistics of the modal parameters corresponding to $\boldsymbol{Q}$ at the k-th moment, and its calculation equation is as follows:

$$Q_k=\sum_{i=1}^{n}\left(x_i^{(k)}-\hat{x}_i^{(k)}\right)^2=\sum_{i=1}^{n}\left[x_i^{(k)}-\sum_{j=1}^{M}W_{4ij}\Xi\left(\sum_{r=1}^{m}W_{3jr}y_r^{(k)}+b_{3j}\right)+b_{4i}\right]^2, \tag{20}$$

and when the value of Q_k is too large, it indicates that the bridge structure is abnormal [37].

The principal component analysis method is used to test the square prediction error of statistics ($\boldsymbol{Q}$). Let

$x = [x_1, x_2, \ldots, x_n]$ represent the covariance matrix corresponding to the collected modal parameters of bridge structures under the normal operating state at a certain time, and its principal component decomposition is carried out:

$$\mathrm{xx}^T = \mathrm{u}\mathbf{d}\mathrm{u}^T, \quad (21)$$

where $u = [u_1, u_2, \ldots, u_n]$, and u_i is the standard orthogonal eigenvector; $\mathbf{d} = \mathrm{diag}(\lambda_1, \lambda_2, \ldots, \lambda_n)$ is the eigenvalue matrix.

Considering the influence of environmental factors including wind speed and temperature, the principal components of these two environmental factors are selected in the process of danger warning, which can be expressed as

$$\left\{ \theta_k = \sum_{i=3}^{n} \lambda_i^k, h_0 = 1 - \frac{2\theta_1\theta_3}{\theta_2^2}. \right. \quad (22)$$

When the test level i α, the upper limit of confidence interval (Q_α) for the system is calculated by the following equation:

$$Q_\alpha = \theta_1 \left[\frac{c_\alpha \sqrt{2\theta_2 h_0^2}}{\theta_1} + \frac{\theta_2 h_0 (h_0 - 1)}{\theta_1^2} + 1 \right]^{1/h_0}, \quad (23)$$

where c_α represents the critical value of the normal distribution at the test level of α. When the statistic is less than the upper limit of confidence interval (Q_α), it indicates that the bridge structure is normal; otherwise, the bridge structure is abnormal, and a danger warning is required.

5. Experiment and Analysis

In order to verify the overall effectiveness of evaluation and judgment theory of bridge damage state and methodology on early warning of danger, it is necessary to carry out the field tests. The operating system for this test is Windows XP Professional, MATLAB simulation platform was used in this test, and MIDAS software was used for the finite element model of the bridge structure. In this paper, the Nanfeihe Bridge in Hefei, China, was taken as the experimental test object. Its total length is about 764.5 m and the total width is about 40.5 m. The tower of Nanfeihe Bridge is a cable-stayed bridge of a double-cable plane with a total of 84 stay cables. The main bridge of this cable-stayed bridge is divided into two spans, in which the left span is about 160 m long, the right span is about 120 m long, and the total height of the bridge tower is about 90 m away from the bridge deck. The actual view of the Nanfeihe Bridge is shown in Figure 1(a), its plan graph is shown in Figure 1(b), and its elevation is in Figure 1(c).

Based on the design and measured data of Nanfeihe Bridge, the finite element model diagram of its bridge structure can be constructed, and the corresponding finite element model results are illustrated in Figure 2.

The abovementioned finite element model (in Figure 2) was input into the simulation software, and five damage parts (including bridge tower crack, broken cable, concrete crack) were set in the simulation software by reducing Young's modulus. The specific layout of damaged parts is presented in Figure 3, in which the 1^{st} damage part is bridge tower crack, the 2^{nd} damage part is bridge deck crack, the 3^{rd} damage part is concrete crack, the 4^{th} damage part is broken cable, and the 5^{th} damage part is reinforcement corrosion.

In the field tests, the acceleration sensors were arranged at six measure points (i.e., the left, middle, and right endpoints of the main bridge and the lower, middle, and upper endpoints of the cable tower). The signal wave of the measuring point is as shown in Figure 4. Then, the time history function of environmental load could be set in MIDAS software, and the dead weight of the bridge was converted in the model, in which the gravity acceleration is 9.806 m/s^2 and the initial temperature is 0°C. On this basis, the node dynamic load of the bridge was set, the node spacing was 0.5 m, and the vehicle speed was set as 80 km/h.

According to the damage degree of a bridge, the damage of bridge structure could be divided into three levels with three grades, that is, first-level damage (★-I, II, III) only with local surface damages, second-level damage (★★-I, II, III) with serious section damage or steel strength reduction and without structural plastic deformation, and third-level damage (★★★-I, II, III) representing that the component is partially or completely disabled. Three methods have been used to evaluate and judge the damage state of the bridge at different positions:

(1) Method I is the presented evaluation and judgment theory of bridge damage state and methodology on early warning of danger in this paper

(2) Method II is the bridge damage state assessment and early warning method based on lateral acceleration monitoring in [21]

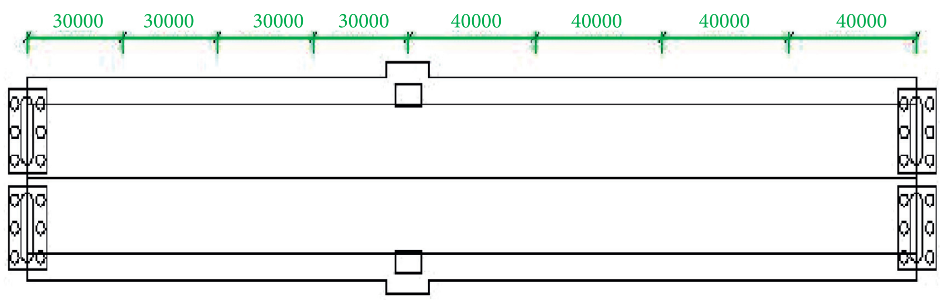
(3) Method III is the bridge damage state assessment and early warning method based on the sliding window subspace algorithm in [25]

The evaluation test results by these three methods are listed in Table 1.

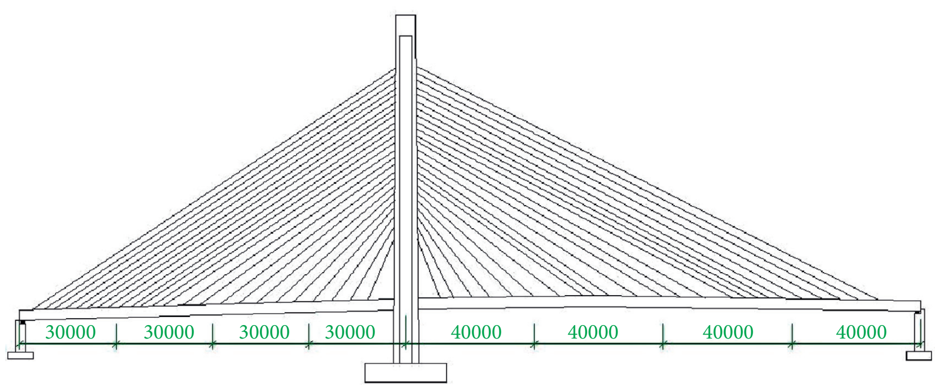
According to the evaluation test results of the damage state of five bridge components in Table 1, it can be seen that the evaluation results of method I are consistent with the actual damage grade of different bridge components, while there are certain errors between the evaluation results of method II [21] or method III [25] and the actual damage grade. This is because method I presented in this paper uses the fuzzy comprehensive evaluation method to construct the evaluation model of bridge damage state based on the observation equation and state equation of bridge systems, which would improve the accuracy of the evaluation and judgment.

When the bridge structure is damaged, the principal component correlation coefficient will increase. These three methods (i.e., methods I, II, and III) were used to evaluate and judge the damage state of the bridge, respectively. The corresponding principal component correlation coefficients calculated by methods I, II, and III are presented in Figure 5. It can be seen from the data analysis in Figure 5 that the principal component correlation coefficient obtained by

(a)



(b)



(c)

Figure 1: The Nanfeihe Bridge tested in this paper. (a) The actual view of Nanfeihe Bridge. (b) The plain graph of Nanfeihe Bridge. (c) The elevation of Nanfeihe Bridge.

method I in this paper of the bridge structure fluctuates greatly around the 60th test. This shows that method I presented in this paper detected and judged the damage of the bridge structure around the 60th test. However, methods II and III showed that the principal component correlation coefficients of the bridge structure increased significantly during the tests of 100~150 and 150~200, respectively, indicating that the damage of the bridge structure was detected until the tests of 100~150 and 150~200.

In order to further compare and analyze the evaluation efficiency of bridge damage for different methods, a time-consumption comparison of damage evaluation was then carried out, and the results are shown in Figure 6. From the above comparison analysis, it can be seen that the consumed time of evaluating the bridge damage state is between 2.7 and 3.9 s for method II in [21], and the consumed time of evaluating the bridge damage state is between 1.5 and 3.0 s for method III in [25]. In contrast, the consumed time of evaluating the bridge damage state is always less than 0.6 s for method I presented in this paper. This fully shows that the presented method in this paper can quickly realize the evaluation and judgment of bridge state damage. The reason is that the presented method I obtains the damage information of bridge system structure through the observation matrix and the state matrix, which provides a basis for the bridge damage evaluation and shortens the evaluation time.

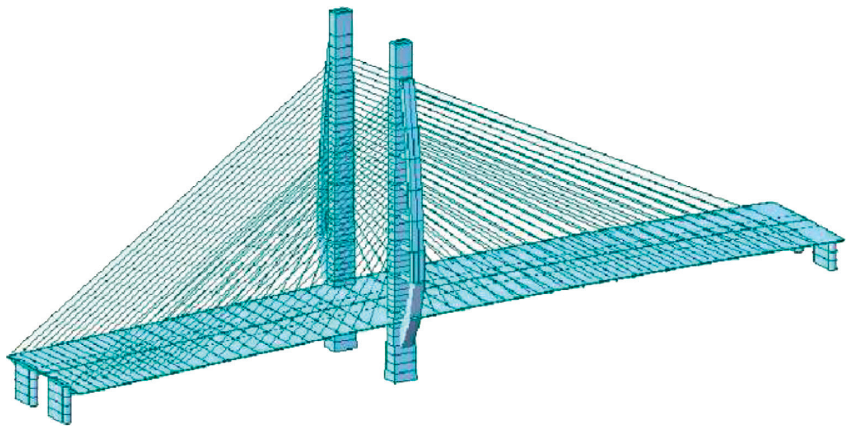


Figure 2: The finite element model of Nanfeihe Bridge structure.

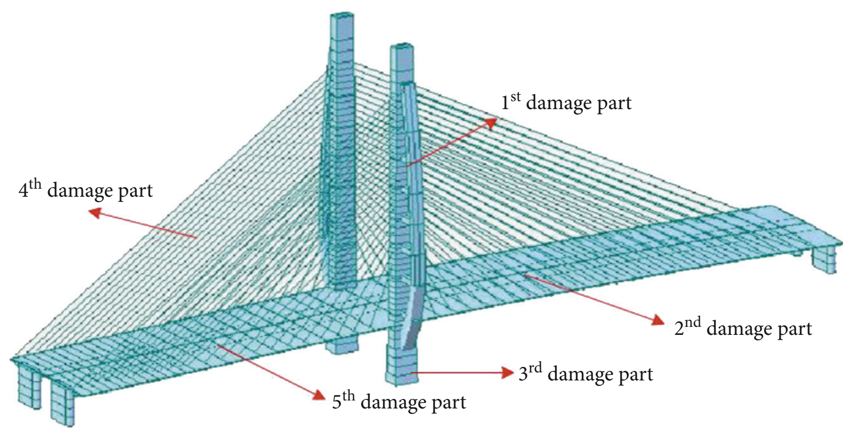


Figure 3: The layout of five damage parts in the finite element model.

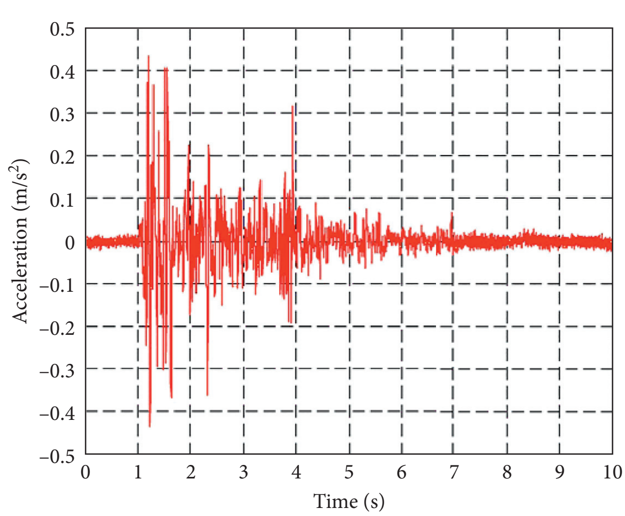


Figure 4: The signal wave of the measuring point.

Table 1: Comparison of evaluation test results among methods I, II, and III.

Bridge components	Actual damage grade	Method I	Method II	Method III
1st damage part	★-II	★-II	★-III	★-I
2nd damage part	★★★-I	★★★-I	★★-III	★★★-II
3rd damage part	★★-II	★★-II	★★★-I	★★★-I
4th damage part	★-I	★-I	★-II	★-II
5th damage part	★-III	★-III	★★-I	★★-II

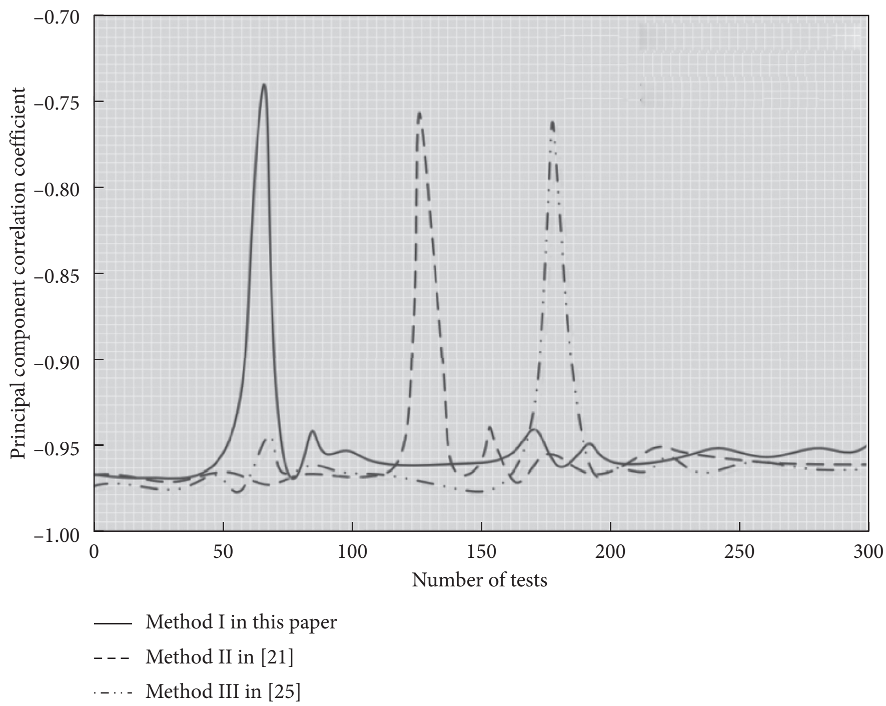


Figure 5: The principal component correlation coefficients calculated by methods I, II, and III.

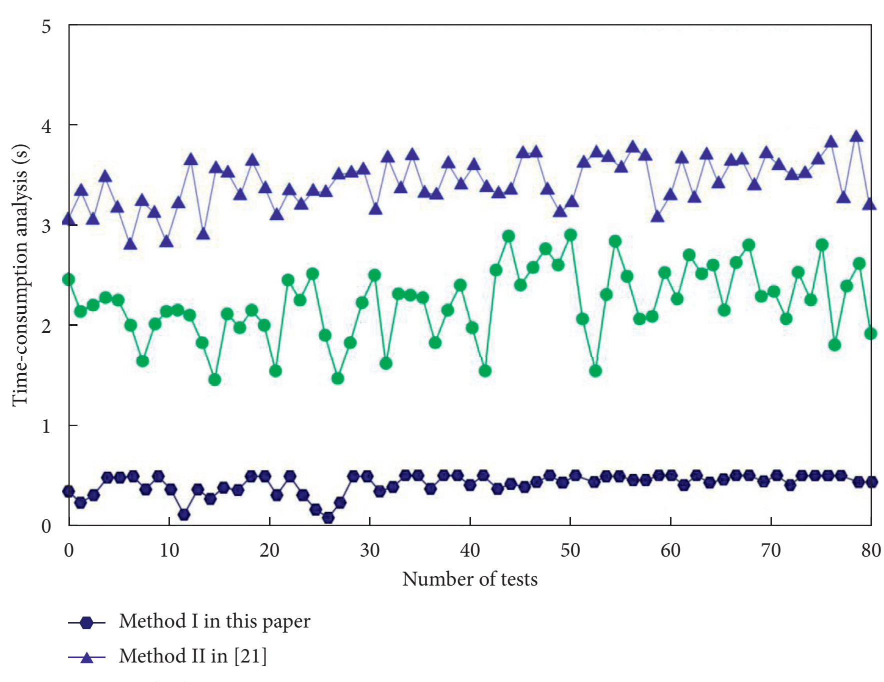


Figure 6: The time-consumption comparison of damage evaluation by methods I, II, and III.

Table 2: Comparison of *FAR* and *WT* among methods I, II, and III.

Test no.	Method I		Method II		Method III	
	FAR (%)	WT (min)	FAR (%)	WT (min)	FAR (%)	WT (min)
1	2.1	8.34	10.7	20.45	11.4	24.77
2	2.4	7.98	11.0	20.47	12.0	29.03
3	1.9	7.88	9.7	22.01	10.8	26.74
4	1.7	9.01	9.9	23.14	10.5	25.64
5	2.0	8.45	11.5	25.16	12.4	23.33

The false alarm rate (*FAR*) represents the proportion of negative samples divided into positive samples in all negative samples and its calculation equation is as follows:

$$\mathrm{FAR} = \frac{N_{\mathrm{NF}}}{N_{\mathrm{NF}} + N_{\mathrm{NT}}}, \tag{24}$$

where N_{NF} is the number of misclassified negative samples and N_{NT} is the number of negative samples correctly classified. The warning time (WT) refers to the time that the warning signal will be issued according to the fault condition.

Table 2 shows the comparison results of FAR and WT among method I presented in this paper, method II in [21], and method III in [25]. From the comparative analysis in Table 2, it can be seen that the FAR of method I in this paper is below 2.5%, which is much lower than those of methods II and III. At the same time, the WT of method I in this paper is within 10 min, which is half of those of methods II and III. Therefore, the presented method I has a low FAR and good WT. The reason is that the presented method I can accurately evaluate and judge the bridge damage state and detect the change of principal component correlation coefficient of bridges in a short time, thereby shortening the WT.

6. Conclusions

Bridges occupy an important position in the process of national economic construction, and their operation safety is one of the basic conditions for stable economic development. When a bridge accident occurs, it will have an adverse impact on society, especially the transportation field, and cause huge economic losses. In order to grasp the actual condition of bridges in time, it is necessary to evaluate and judge and the damaged condition of bridges and perform the early warning of danger. The existing damage state assessment and early warning methods of bridges cannot accurately assess the damage level of bridges, and the existing methods have the problems of low evaluation accuracy, high false alarm rate, and poor real-time performance. Therefore, this paper proposed a novel evaluation and judgment theory of bridge damage state and methodology on early warning of danger. Based on the observation equation and state equation of bridge systems by wavelet packet analysis method, the fuzzy comprehensive evaluation method is used to evaluate and judge the damage state of bridges. Then, according to mathematical-statistical analysis methods and principal component analysis methods, the methodology on early warning of danger for bridge structures can be realized. The Nanfeihe Bridge was taken as the experimental test object to analyze and verify the proposed method in this paper. The experimental results showed that the proposed method can accurately evaluate and judge the bridge damage state in a short time, reduce the false alarm rate, and improve the performance and reliability of the real-time early warning. The proposed method can effectively solve the problems of long warning time and evaluation accuracy of the current methods. Besides, due to the used basic methods, the proposed methodology on early warning of danger can be further promoted in practice. However, this study also has some limitations; for example, it does not use other cases to test the effectiveness of this method. In the future, we will conduct in-depth research on this problem to improve the applicability of this method.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] Q. Al-Kaseasbeh, Z. B. Lin, Y. C. Wang et al., "Electrochemical characterization of steel bridge welds under simulated durability test," *Journal of Bridge Engineering*, vol. 23, no. 10, 2018.

[2] G. J. Tan, W. S. Wang, and Y. B. Jiao, "Flexural free vibrations of multistep nonuniform beams," *Mathematical Problems in Engineering*, vol. 2016, Article ID 7314280, 12 pages, 2016.

[3] H. B. Liu, H. Wang, G. J. Tan et al., "Vibration analysis of reinforced concrete simply supported beam versus variation

temperature," *Shock and Vibration*, vol. 2017, Article ID 4931749, 20 pages, 2017.

[4] H. B. Liu, H. Wang, G. J. Tan et al., "Effect of temperature and spring-mass systems on modal properties of timoshenko concrete beam," *Structural Engineering and Mechanics*, vol. 65, no. 4, pp. 389–400, 2018.

[5] M. J. Osmolska, T. Kanstad, M. A. N. Hendriks, K. Hornbostel, and G. Markeset, "Durability of pretensioned concrete girders in coastal climate bridges: basis for better maintenance and future design," *Structural Concrete*, vol. 20, no. 6, pp. 2256–2271, 2019.

[6] S. Mangalathu, S. H. Hwang, E. Choi et al., "Rapid seismic damage evaluation of bridge portfolios using machine learning techniques," *Engineering Structures*, vol. 201, 2019.

[7] K. R. Karim and F. Yamazaki, "Effect of earthquake ground motions on fragility curves of highway bridge piers based on numerical simulation," *Earthquake Engineering & Structural Dynamics*, vol. 30, no. 12, pp. 1839–1856, 2001.

[8] B. G. Nielson and R. DesRoches, "Seismic fragility methodology for highway bridges using a component level approach," *Earthquake Engineering & Structural Dynamics*, vol. 36, no. 6, pp. 823–839, 2007.

[9] G. J. Tan, J. H. Shan, C. L. Wu et al., "Free vibration analysis of cracked timoshenko beams carrying spring-mass systems," *Structural Engineering and Mechanics*, vol. 63, no. 4, pp. 551–565, 2017.

[10] G. Tan, Y. Liu, Y. Gong, Y. Shen, and Z. Liu, "Free vibration of the cracked non-uniform beam with cross section varying as polynomial functions," *Ksce Journal of Civil Engineering*, vol. 22, no. 11, pp. 4530–4546, 2018.

[11] Y. Jiao, Y. Zhang, W. Shan, Q. Han, Y. Zhao, and S. Liu, "Damage fracture characterization of reinforced concrete beam subjected to four-point bending with parametric analysis of static, dynamic, and acoustic properties," *Structural Health Monitoring*, vol. 19, no. 4, pp. 1202–1218, 2020.

[12] W. C. Shan, X. Q. Wang, and Y. B. Jiao, "Modeling of temperature effect on modal frequency of concrete beam based on field monitoring data," *Shock and Vibration*, vol. 2018, Article ID 8072843, 12 pages, 2018.

[13] G. Tan, W. Wang, Y. Jiao, and Z. Wei, "Free vibration analysis of continuous bridge under the vehicles," *Structural Engineering and Mechanics*, vol. 61, no. 3, pp. 335–345, 2017.

[14] G. J. Tan, W. S. Wang, Y. C. Cheng et al., "Dynamic response of a nonuniform timoshenko beam with elastic supports, subjected to a moving spring-mass system," *International Journal of Structural Stability and Dynamics*, vol. 18, no. 5, 2018.

[15] Y. Xia, X. M. Lei, P. Wang et al., "Long-term performance monitoring and assessment of concrete beam bridges using neutral axis indicator," *Structural Control & Health Monitoring*, vol. 27, no. 12, 2020.

[16] G. V. Demarie and D. Sabia, "A machine learning approach for the automatic long-term structural health monitoring," *Structural Health Monitoring*, vol. 18, no. 3, pp. 819–837, 2019.

[17] S. Ye, X. Lai, I. Bartoli, and A. E. Aktan, "Technology for condition and performance evaluation of highway bridges," *Journal of Civil Structural Health Monitoring*, vol. 10, no. 4, pp. 573–594, 2020.

[18] Y. Q. Ni, Y. W. Wang, and C. Zhang, "A bayesian approach for condition assessment and damage alarm of bridge expansion joints using long-term structural health monitoring data," *Engineering Structures*, vol. 212, 2020.

[19] A. J. Reiff, M. Sanayei, and R. M. Vogel, "Statistical bridge damage detection using girder distribution factors," *Engineering Structures*, vol. 109, pp. 139–151, 2016.

[20] F. Soleimani, "Propagation and quantification of uncertainty in the vulnerability estimation of tall concrete bridges," *Engineering Structures*, vol. 202, 2020.

[21] F. F. Geng, Y. L. Ding, H. W. Zhao et al., "Early warning method of abnormal dynamic performance of high speed railway bridge based on transverse acceleration monitoring," *Railway Engineering*, vol. 9, pp. 1–5, 2016.

[22] X. G. Hua, Y. Q. Ni, J. M. Ko, and K. Y. Wong, "Modeling of temperature-frequency correlation using combined principal component analysis and support vector regression technique," *Journal of Computing in Civil Engineering*, vol. 21, no. 2, pp. 122–135, 2007.

[23] A. Yabe, A. Miyamoto, and E. Brühwiler, "Characteristics of a bridge condition assessment method based on state representation methodology (srm) and damage detection sensitivity," *Journal of Civil Structural Health Monitoring*, vol. 9, no. 2, pp. 233–251, 2019.

[24] L. J. Liu, D. Wu, X. Zhang et al., "Application of improved bayesian method in bridge state assessment," *Journal of Chang'an University: Natural Science Edition*, vol. 37, no. 6, pp. 47–53, 2017.

[25] J. Dong, L. Chen, G. J. Yang et al., "Study on early bridge structure operational warning based on sliding window technique and data-driven stochastic subspace identification algorithm," *Railway Standard Design*, vol. 3, pp. 68–74, 2018.

[26] H. X. Huang, Z. L. Li, and L. Y. Fang, "Research on the simulation methods and criteria of damage state of existing bridges," *Journal of Hebei University of Technology*, vol. 47, no. 2, pp. 60–66, 2018.

[27] Y. Yamamoto and J. W. Baker, "Stochastic model for earthquake ground motion using wavelet packets," *Bulletin of the Seismological Society of America*, vol. 103, no. 6, pp. 3044–3056, 2013.

[28] L. An, "A construction risk early warning model of long-span cable-stayed bridge based on mcmc-ccraa," *Journal of Highway and Transportation Research and Development*, vol. 34, no. 10, pp. 42–50, 2017.

[29] S. Q. Yang, M. Guo, X. L. Liu et al., "Highway performance evaluation index in semiarid climate region based on fuzzy mathematics," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 6708102, 7 pages, 2019.

[30] J. G. Cai, F. H. Dong, and Z. L. Luo, "Durability of concrete bridge structure under marine environment," *Journal of Coastal Research*, vol. 83, pp. 429–435, 2018.

[31] S. J. Hormozabad and A. K. Ghorbani-Tanha, "Semi-active fuzzy control of lali cable-stayed bridge using mr dampers under seismic excitation," *Frontiers of Structural and Civil Engineering*, vol. 14, no. 3, pp. 706–721, 2020.

[32] H. Pragalath, S. Seshathiri, H. Rathod et al., "Deterioration assessment of infrastructure using fuzzy logic and image processing algorithm," *Journal of Performance of Constructed Facilities*, vol. 32, no. 2, 2018.

[33] L. Liang, S. Sun, M. Li et al., "Data fusion technique for bridge safety assessment," *Journal of Testing and Evaluation*, vol. 47, no. 3, pp. 2080–2100, 2019.

[34] F. Magalhaes and A. Cunha, "Automated identification of the modal parameters of a cable-stayed bridge: influence of the wind conditions," *Smart Structures and Systems*, vol. 17, no. 3, pp. 431–444, 2016.

[35] H. Sohn, M. Dzwonczyk, E. G. Straser, A. S. Kiremidjian, K. H. Law, and T. Meng, "An experimental study of

temperature effect on modal parameters of the alamosa canyon bridge," *Earthquake Engineering & Structural Dynamics*, vol. 28, no. 8, pp. 879–897, 1999.

[36] M. R. Hashemi, Z. Ghadampour, and S. P. Neill, "Using an artificial neural network to model seasonal changes in beach profiles," *Ocean Engineering*, vol. 37, no. 14-15, pp. 1345–1356, 2010.

[37] C. Tong, T. Lan, H. Yu, and X. Peng, "Distributed partial least squares based residual generation for statistical process monitoring," *Journal of Process Control*, vol. 75, pp. 77–85, 2019.