Research on Health Assessment Model and Data Analysis Method of Steel-Concrete Composite Girder Bridge

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Abstract In order to evaluate the health status of Steel-concrete composite girder bridges, a health status assessment model based on the bridge monitoring scheme is proposed, and a matching data analysis method is established on this basis. Firstly, the data are divided into two index layers: monitoring projects and monitoring points, and a health status assessment model is established based on this. Secondly, the fuzzy comprehensive evaluation of the state of Steel-concrete composite girder bridges is realized by the membership vectorization processing of the monitoring data. Finally, the method is applied to an actual bridge to evaluate the health status. The results show that the established model and method can evaluate the state of the Steel-concrete composite girder bridge, and the state of the bridge evaluated by this method is level 1 and the health is better. The health status assessment model and data analysis method of Steel-concrete composite girder bridges establishes a direct connection between objective data and subjective assessment, provides an effective way for the real-time evaluation of bridge health status.

Keywords Steel-concrete composite girder bridge · Health monitoring · State model · Data analysis · Status evaluation

1 Introduction

The safety of bridges is the core issue of bridges in service [1]. With the deep integration of artificial intelligence and engineering, the intelligent operation and maintenance of bridges has received extensive attention [2]. At present, the health

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Y. Yang (ed.), *Advances in Frontier Research on Engineering Structures*, Lecture Notes in Civil Engineering 286, https://doi.org/10.1007/978-981-19-8657-4_13

status assessment of bridges is generally carried out by deploying sensors in key structural parts of the bridges, using sensors to collect data such as service environment and structural response, and then intelligently analyzing and processing the data to achieve monitoring and assessment of bridge status. However, due to the process of data collection and health status assessment containing a large number of uncertain factors, the real-time assessment of the comprehensive status of bridge structures has not been fully realized at this stage [3].

In terms of health status assessment models and methods, Liu et al. [4] refer to the component classification method recommended in the American maintenance management system, and use the method of hierarchical evidence reasoning to establish a bridge condition assessment framework. Liang et al. [5] started from environmental erosion, material aging and external load, and used variable weight and D-S evidence theory to propose a multi-factor bridge condition assessment method based on information fusion. Liu et al. [6] constructed a bridge index system from four dimensions of geometric characteristics, material properties, environmental conditions and action types, and used the dynamic hierarchical clustering method and the entropy weight comprehensive ranking method to propose an evaluation model for the service status of bridges. Qiao et al. [7] constructed a safety evaluation model of simply supported girder bridges based on the extenics theory based on the safety evaluation index system of simply supported girder bridges. The above research uses various index systems as grading standards to establish a state evaluation model, which provides ideas for the model creation in this paper.

In terms of data analysis methods for the health status of steel-concrete composite girder bridges: Wang et al. [8] established a bridge safety assessment system using adaptive fuzzy reasoning and radial basis function neural network. Jia et al. [9] established a discrete dynamic Bayesian network model based on time series to evaluate the bridge state; Qin et al. [10] proposed 3A indicators and comprehensive safety evaluation indicators to evaluate the overall safety state of the superstructure of a bridge. Xu et al. [11] analyzed the change law of the weights of replaceable and non-replaceable components with time, and proposed a state evaluation method based on a time-varying weight model Liu et al. [12] based on improved Bayesian The theory proposes a method for evaluating the overall state of the bridge. The above research uses various algorithms for data processing, which provides a reference for the data analysis of this paper.

In this paper, a state assessment model based on monitoring scheme is proposed. On this basis, a data analysis method matching the model is established to realize the assessment of bridge health status.

2 Assessment Model

2.1 Evaluation Model Based on Bridge Monitoring Scheme

Relying on the monitoring scheme of Steel-concrete composite girder bridges, the monitoring data can be divided into: monitoring project layer and monitoring point layer from high to low.

The monitoring project layer is expressed as:

$$U = \{ U_i \} \quad i = 1, 2, 3, \cdots, m \tag{1}$$

In the formula: U_i is the i-th physical quantity that affects the state of the bridge.

Monitoring point layer: The monitoring point layer is expressed as:

$$U_i = \{ U_{ij} \} \quad j = 1, 2, 3, \cdots, n \tag{2}$$

In the formula: U_{ij} is the j-th monitoring point deployed by the ith-influencing state physical quantity.

According to the bridge monitoring scheme shown in Table 1, a matching model for evaluating the health status of Steel-concrete composite girder bridges is established as shown in Fig. 1.

Table 1 Bridge monitoring scheme

	Monitoring point 1	Monitoring point 2	…	Monitoring point 4
Monitoring project 1	U_{11}	U_{12}	…	U_{1n}
Monitoring project 2	U_{21}	U_{22}	…	U_{2n}
…	…	…	…	…
Monitoring project m	U_{m1}	U_{m2}	…	U_{mn}

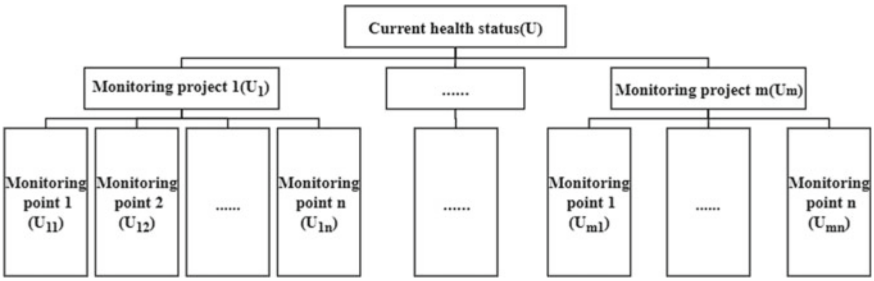

Fig. 1 Health status assessment model of steel-concrete composite girder bridge

2.2 Model Weights

Experts make decisions on the weights of each factor in the model, and construct a judgment matrix A:

$$A = \begin{pmatrix} r_{11} & r_{12} & \ldots & r_{1j} \\ r_{21} & r_{22} & \cdots & r_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ij} \end{pmatrix} \tag{3}$$

In the formula: r_{ij} represents the importance of the i-th factor relative to the j-th factor, and the relative importance is measured on a scale of 1–9:

The consistency test is used for the n-order judgment matrix, and the calculation formula of the index CI is:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

The formula for calculating the consistency ratio CR is:

$$CR = \frac{CI}{RI} \tag{5}$$

In the formula: λ_{max} is the largest eigenvalue of the judgment matrix. RI is the random consistency index, which is only related to the order of the matrix. When CR < 0.1, the judgment matrix is said to be consistent. Find the eigenvector corresponding to the largest eigenvalue, and after normalization, it is the weight vector $\tilde{A}$ of the factor.

3 Data Analysis Methods

3.1 Data Membership Vectorization

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Establish the evaluation level set V of the data on this basis, which is expressed as:

$$V = \{evaluation\,1, evaluation\,2 \ldots evaluation\,i\} \tag{6}$$

The corresponding state space S is established to quantify the evaluation level set, which is expressed as:

Table 2 Membership vector table of monitoring projects

State interval $\left(\frac{\omega_{real}}{\omega_{thr}}\right)$	Membership vector (X)	Evaluation level (V)			
		Evaluation 1	Evaluation 2	…	Evaluation i
(0, C_1]	X_1	$X_1^{(1)}$	$X_1^{(2)}$	…	$X_1^{(i)}$
(C_1, C_2]	X_2	$X_2^{(1)}$	$X_2^{(2)}$	…	$X_2^{(i)}$
…	…	…	…	…	…
(1,∞)	X_j	$X_j^{(1)}$	$X_j^{(2)}$	…	$X_j^{(i)}$

$$S = \{M_1, M_2, \cdots, M_i\} \tag{7}$$

Based on the ratio of the real-time data value ω_{real} of the monitoring project to the response threshold ω_{thr}, the data range of the monitoring project is divided into k state intervals, Establish the membership degree $X_{\mathrm{j}}^{(i)}$ of the i-th evaluation in the j-th state interval. The real-time data ω_{real} in the jth state interval is represented by the membership vector X_j (j = 1, 2,· · · , k):

$$X_j = \left(X_j^{(1)}, X_j^{(2)}, X_{\mathrm{j}}^{(3)}, \cdots, X_{\mathrm{j}}^{(i)}\right) \tag{8}$$

Establish a membership vector table for all monitoring projects, as shown in Table 2.

Further, set a data evaluation period. For the N pieces of data collected in the evaluation period, the data quantity n_j (j = 1, 2,…, k) in each state interval is counted as the weight of the state interval. All data in the evaluation period are represented by a membership vector $\mathbf{r_i}$:

$$\mathbf{r_i} = \frac{\sum_{j=1}^{k} n_j \mathbf{X_j}}{N} \tag{9}$$

3.2 Comprehensive Assessment

Based on the model shown in Fig. 1, and after performing membership vectorization processing on the data, the steps to realize the fuzzy comprehensive assessment of highway health status are as follows:

Comprehensive evaluation of the monitoring point layer: Construct the fuzzy matrix R_i of the monitoring point layer by the membership vector r_i determined by Eq. (9):

$$\mathbf{R}_{\mathrm{i}} == (\mathbf{r_1}\ \mathbf{r}_2\ \mathbf{r}_3\ \ldots\ \mathbf{r}_m)^T \tag{10}$$

Combined with the model monitoring point layer weight $\tilde{A}_{\mathrm{i}}$ to evaluate each monitoring project U_i. Obtain the comprehensive evaluation result B_i of each project monitoring point layer:

$$\mathbf{B}_i = \tilde{\mathbf{A}}_i \cdot \mathbf{R}_i \tag{11}$$

Comprehensive evaluation at the monitoring project layer: After normalizing the comprehensive evaluation results at the monitoring point layer, a fuzzy matrix R at the monitoring project layer is established:

$$\mathbf{R} = (B_{\mathbf{1}}\ B_2\ B_3\ \ldots\ B_n)^T \tag{12}$$

In the formula: n is the number of monitoring projects.

Combined with the monitoring project layer weight $\tilde{A}$ of the model, the comprehensive evaluation B of the current state U of the bridge is realized:

$$B = \tilde{A} \cdot R \tag{13}$$

After normalization, the state space S is used to determine the total score of the state as:

$$F = \mathbf{B} \cdot \mathbf{S}^{\mathbf{T}} \tag{14}$$

Finally, the real-time health status of the bridge is determined by the corresponding relationship between the score and the evaluation level set.

4 Case Studies

In order to evaluate the health status of a small-span Steel-concrete composite girder bridge in real time. The known monitoring scheme established for this bridge is shown in Table 3. In this scheme, the fatigue cracking, deflection response, stress state, and ambient temperature of the bridge are monitored in real time. The layout of the monitoring points is shown in Fig. 2.

4.1 Establish a Health Status Assessment Model

Establish a health status assessment model based on monitoring scheme (Fig. 3):

Set model weights:

Take the weight setting of the monitoring project layer as an example, the constructed judgment matrix A is shown in Table 4.

Table 3 Monitoring scheme of a small-span steel-concrete composite girder bridge

	Monitoring point 1	Monitoring point 2	Monitoring point 3	Monitoring point 4	Monitoring point 5
Fatigue cracking	✓	✓	✓	✓	✓
Deflection response	✓	✓	✓	✓	✓
Stress state	✓	✓	✓	✓	✓
Ambient temperature		✓	✓	✓	

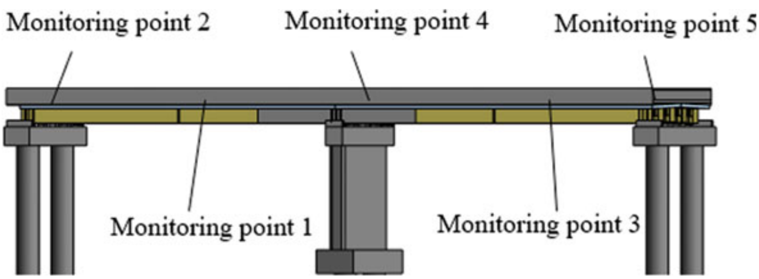

Fig. 2 Deployment diagram of monitoring points of the steel-concrete composite girder bridge

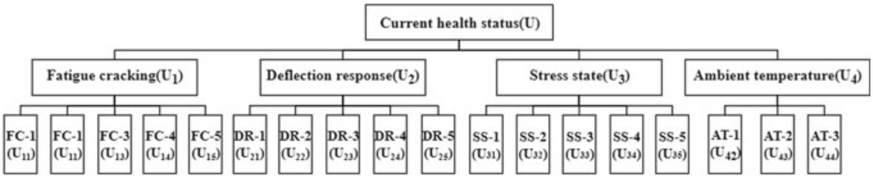

Fig. 3 Health status assessment model of a small-span steel-concrete composite girder bridge

Table 4 Judgment matrix A at the monitoring project layer

A	U_1	U_2	U_3	U_4
U_1	1	2	4	5
U_2	1/2	1	3	4
U_3	1/4	1/3	1	2
U_4	1/5	1/4	1/2	1

Check the judgment matrix: CR = 0.0190 < 0.1, therefore, CR satisfies the judgment matrix consistency requirement. The weight vector of the monitoring item layer after normalization is obtained from the matrix A as:

$$\tilde{A} = \left(0.49\ 0.31\ 0.12\ 0.18\right)$$

The establishment of each judgment matrix of the monitoring point layer adopts the same method, and its weight vectors are: Fatigue cracking: $\tilde{A}_1$=(0.08 0.33 0.08 0.18 0.33); Deflection response: $\tilde{A}_2$=(0.36 0.07 0.36 0.14 0.07); Stress state: $\tilde{A}_3$=(0.06 0.34 0.06 0.20 0.34); Ambient temperature: $\tilde{A}_4$=(0.34 0.36 0.30).

4.2 Data Processing and Comprehensive Evaluation

Data membership vectorization processing.

With reference to the "Maintenance Specification for Highway Bridges and Culverts", establish the evaluation level set V:

$$V = \{Better, Good, Bad, Worse, Worst\}$$

The corresponding state space S is determined as:

$$S = (100, 95, 80, 60, 40)$$

Taking the deflection response as an example, the membership vector table of the deflection response is established as shown in Table 5:

Similarly, the membership vector table of fatigue cracking, stress state and ambient temperature is established.

The data collection period of deflection response is 1.2 min. The evaluation period is set to 1 h. During the evaluation period, the 50 real-time data ω_{real} collected by deflection monitoring point 1 (DR-1) were compared with the deflection response threshold ω_{thr} respectively to determine the state interval of the real-time data. The statistics of the results are shown in Table 6.

Taking the deflection response as an example, use Eq. (9) to process Table 6. During this evaluation period, the deflection response data collected at monitoring point 1 (DR-1) are represented by membership vectors as:

Table 5 Membership vector table of deflection response

State interval $\left(\frac{\omega_{real}}{\omega_{thr}}\right)$	Membership vector	Evaluation level				
		Better	Good	Bad	Worse	Worst
(0,0.1]	X_1	1	0	0	0	0
(0.1,0.3]	X_2	0.3	0.7	0	0	0
(0.3,0.6]	X_3	0	0.25	0.75	0	0
(0.6,1]	X_4	0	0	0.1	0.9	0
(1,∞)	X_5	0	0	0	0	1

Table 6 Statistical table of 50 monitoring data within 1 h of deflection monitoring point 1 (DR-1)

Status level	State interval/$\left(\frac{\omega_{real}}{\omega_{thr}}\right)$	The amount of data/$\left(\mathrm{n_j}\right)$	Membership vector/$\left(X_{\mathrm{j}}\right)$
Level 1	(0,0.1]	4	[1,0,0,0,0]
Level 2	(0.1,0.3]	15	[0.3,0.7,0,0,0]
Level 3	(0.3,0.6]	30	[0,0.25,0.75,0,0]
Level 4	(0.6,1]	1	[0,0,0.1,0.9,0]
Level 5	(1,∞)	0	[0,0,0,0,1]

$$\mathbf{r_1} = \left(0.17\ 0.36\ 0.45\ 0.02\ 0\right)$$

Similarly, the membership vector of the data at the deflection monitoring points 2 ~ 5 (DR-2 ~ 5) in this evaluation period can be calculated as $r_2 \sim r_5$.

Comprehensive assessment of health status:

The fuzzy relationship matrix of the monitoring point layer of the deflection response is established:

$$\mathbf{R_2} = \left(\mathbf{r_1}\ \mathbf{r}_2\ \mathbf{r}_3\ \mathbf{r}_4\ \mathbf{r}_5\right)^T$$

Combined with the deflection response monitoring point layer weight $\tilde{A}_2$, a comprehensive evaluation is carried out:

$$\mathbf{B_2} = \mathbf{\tilde{A}_2} \cdot \mathbf{R_2} = \left(0.27\ 0.34\ 0.37\ 0.02\ 0\right)$$

In the same way, the fuzzy relationship matrices R_1,R_3 and R_4 of monitoring point layers for fatigue cracking, stress state and ambient temperature, and evaluation results B_1, B_3 and B_4 are established. From this, the fuzzy matrix of the monitoring project layer is constructed:

$$\mathbf{R} = \begin{pmatrix} \mathbf{B_1} \\ \mathbf{B_2} \\ \mathbf{B_3} \\ \mathbf{B_4} \end{pmatrix} = \begin{pmatrix} 0.87 & 0.13 & 0 & 0 & 0 \\ 0.27 & 0.34 & 0.37 & 0.02 & 0 \\ 0.51 & 0.32 & 0.13 & 0.04 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Combined with the monitoring project layer weight $\tilde{A}$, a comprehensive evaluation of the current health status of the bridge is carried out:

$$B = \tilde{A} \cdot R = \left(0.65\ 0.21\ 0.13\ 0.01\ 0\right)$$

Calculate the total status score for this evaluation period:

$$F = \mathbf{B} \cdot \mathbf{S^T} = 95.95$$

The value of F is at (95,100], the current status of the bridge is level 1, and the health is better.

5 Conclusion

This paper constructs a multi-attribute comprehensive evaluation model of Steel-concrete composite girder bridges with monitoring projects and monitoring points as the index layers, and proposes a data processing method for the health status evaluation of Steel-concrete composite girder bridges:

Based on the monitoring scheme of the bridge, a model matching the characteristics of the bridge is constructed to realize the evaluation of the bridge state. The method has better adaptability to different bridges;

The monitoring data is processed by membership vectorization using fuzzy mathematics theory. A fuzzy evaluation of the bridge state was carried out. The direct connection between real-time data and fuzzy state is established, which provides a guarantee for the real-time evaluation of the health state of bridges.

The proposed model and data analysis method are used to evaluate the health status of an actual steel-concrete composite girder bridge. The results show that in the set evaluation period, according to the analysis and calculation results of the monitoring data of the bridge, the current state score of the bridge is 95.95, which is in the 1st-level state range, and the health is better.

Acknowledgements This work was partly funded by the Tibet Autonomous Region Science and Technology Project (XZ2019TL-G-03), and partly by the Shaanxi Provincial Department of Transportation (17-21K).

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