Research on Health Evaluation Method of Steel Canopy of Coastal High-speed Railway Station

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Abstract: With the rapid development of high-speed railways, the safety of railway infrastructure is becoming more and more important. Large-span space steel structures are widely used in railway station buildings and platform canopies due to their good performance. However, it's not easy to know exactly how long it will last. In this paper the analytic hierarchy process is used to establish an index system that affects the health of the steel canopy of coastal high-speed railway stations, introducing the entropy method to improve the calculation method of key index weights and reduce the evaluation bias caused by subjective experience. Finally, a steel structure health evaluation model based on fuzzy hierarchy evaluation is established and its effectiveness is verified in a specific engineering case. From the verification results, the evaluation model could provide scientific basis for early-warning diagnosis and health assessment of steel structure projects and decision-making support for project supervision and maintenance and bring certain economic benefits.

1. Introduction

Large-span space steel structures are more sensitive to wind load and temperature [1]. Steel structures in coastal areas are often corroded by chloride ions. After long-term service, the damage of steel structures in such a complex physical environment is inevitable [2]. In order to ensure the safety of high-speed rail transportation and passengers, it is necessary to conduct a health evaluation on the safety of the steel structure of the canopy of coastal high-speed rail during the operation phase.

In the early days, Fu Jiyang et al. [3] conducted vibration monitoring research on the large-span steel structure of the Guangzhou International Convention and Exhibition Center; Xu Chengrong et al. [4] conducted stress and deformation monitoring on the Bengbu Olympic Sports Center Stadium structure, but full use of health monitoring information for steel structure health evaluation research is still lacking. In the 1940s, Shannon put forward the concept of "information entropy". Gu Zhaojun et al.[5] established an industrial control system risk assessment model based on fuzzy sets and entropy. Wang Xue et al. [6] and Wang Xinyi [7] used fuzzy matrix to evaluate the quality of steel structure construction process, but lacked structural health tracking in the later stage of operation.

In this paper, analytic hierarchy process (AHP), entropy weight method and fuzzy theory are used in the assessment of the health status of large-span steel structures. Then an evaluation index system of the health status of the steel structure is established. The entropy weight method is introduced to improve the calculation method of the index weight. Through the fuzzy hierarchy evaluation method, the health state evaluation model of the long-span steel structure of the coastal high-speed railway station is established. Finally, the effectiveness of the method with a specific engineering case is verified..

2. The Model based on Fuzzy Hierarchy Evaluation

The factor set is denoted as $F=\{F_1,F_2,...,F_i\}$ .In the same way, the next level can be divided into several secondary index factor sets, namely $F_i=\{F_{i1},F_{i2},...,F_{ij}\}$ .The evaluation set is denoted as . $V=\{V_1,V_2,...,V_p\}$.

2.1. Calculation of Index Weight

In this paper, the expert survey method is easy to obtain the weight of the primary indicators. But the secondary indicators are relatively complicated. So the entropy method is introduced to improve the calculation of the weights of secondary indicators. The specific steps are as follows.

2.1.1. Expert Investigation Method

By constructing the judgment matrix $A=\left(a_{mn}\right)_{k\times k},(m,n=1,2,...,k)$, calculating its maximum eigenvalue $\lambda_{\max}$ and eigenvector $W=\left(w_1,w_2,...,w_m\right)$, the normalization of it is the weight vector. The maximum eigenvalue $\lambda_{\max}$ and eigenvector W that can be obtained by using Matlab. Finally the consistency of the judgment matrix is checked. Usually when C.R.<0.1, the consistency of the judgment matrix is considered acceptable, otherwise the judgment matrix should be adjusted.

2.1.2. Entropy Method

After the original data matrix $Y=(y_{ij})_{m\times n},i=1,2,...,m;j=1,2,...,n$ normalized and transformed into $X=(x_{ij})_{m\times n},i=1,2,...,m;j=1,2,...,n$, the entropy value of each evaluation index recorded as E_j is calculated as shown in formula (1):

$$E_j=-\frac{1}{\ln m}\sum_{i=1}^{m}\left(\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}}*\ln\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}}\right) \tag{1}$$

The entropy weight recorded as W_j is calculated as shown in formula (2):

$$W_j=\frac{1-E_j}{n-\sum_{j=1}^{n}E_j} \tag{2}$$

2.2. Fuzzy Hierarchy Evaluation

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2.2.1. Paper Title

The fuzzy relationship between factors and grades can be expressed by the degree of membership and denoted as the fuzzy matrix R. According to the weight of each index layer and the fuzzy matrix R, the first and second fuzzy layer evaluation can be obtained through the fuzzy relationship synthesis, as shown in the following formula (3):

$$Q = W(\bullet,\oplus)R = (w_1, w_2, \dots, w_n)(\bullet,\oplus)\begin{pmatrix} r_{11} & \cdots & r_{1p} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{np} \end{pmatrix} = (q_1, q_2, \dots, q_p) \tag{3}$$

Where, the fuzzy composition operator is selected $M(\bullet,\oplus)$, which is $q_k = \min\left\{1, \sum_{i=1}^{n} w_i r_{ik}\right\}, k = 1,2,\dots,p$,The synthesis algorithm could play the role of the evaluation information of a single factor, and reflect the full picture of the evaluation object more objectively and accurately.

3. Engineering Application and the Results

This article is based on the research on the health monitoring project of the canopy steel structure of the Haikou East High-speed Railway Station during the operation phase. Based on the project expert judgment and system monitoring data, combined with the steel structure health fuzzy hierarchical evaluation model proposed in this paper, the health status of the steel structure canopy of the Haikou East High-speed Railway Station is evaluated.

3.1. Construct the Health Evaluation Index System

Since the steel structure health monitoring project in this paper is involved in the operation stage, the impact of structural forces and external environmental loads on the health of the steel structure are mainly considered. In the health monitoring of large-span steel structures, the temperature strain, structural deformation, vibration acceleration and external environment such as environmental temperature, humidity, wind pressure, etc. are necessary. According to the above analysis of influencing factors, AHP is used to establish a three-story steel structure health evaluation index system as shown in Table 1.

Table 1: Health evaluation index of steel structure.

Total index	Primary index	Secondary index
Health status of steel canopy	Structural force	Temperature strain
		Structural deformation
		Vibration acceleration
	External environment	Temperature
		Humidity
		Wind pressure

3.2. Calculate the Index Weight

In order to make the evaluation results more accurate, an expert survey was conducted in the early stage and Matlab software was used to check the consistency of the judgment matrix. The calculation results of the maximum eigenvalue, eigenvector and consistency ratio are as follows: $\lambda_{\max}$=2.0000 , $W=[0.8321 \quad 0.5547]$, $C.R.=0.0000$. So the consistency test meets the requirements and the eigenvector is normalized to the weight vector $\mu=[0.6 \quad 0.4]$.

In order to reduce the impact of train operation and station equipment on vibration data, 20 groups of health monitoring data from December 6, 2020 to December 25, 2020 at 03:00 am are recorded as shown in Table 2 below:

Table 2: Secondary index monitoring data sheet.

Number	Temperature strain(με)	Structural deformation (m)	Vibration acceleration (g)	Temperature (℃)	Humidity(%RH)	Wind pressure(kN/m2)	Monitoring time
1	-27.40399	0.000	0.23409	20.0	76.6	0.003025	2020.12.06
2	-21.56217	0.000	0.11026	19.2	74.9	0.000900	2020.12.07
3	-19.60653	-0.001	0.14649	19.1	71.2	0.001600	2020.12.08
4	-28.03915	-0.001	0.09649	20.3	83.7	0.000156	2020.12.09
5	-26.74375	-0.001	0.03475	19.8	85.3	0.000006	2020.12.10
6	-28.69939	0.000	0.11848	20.8	89.1	0.001225	2020.12.11
7	-29.33455	0.000	0.10087	20.9	91.2	0.000400	2020.12.12
8	-29.99479	0.001	0.10062	22.5	90.2	0.000156	2020.12.13
9	-14.45003	0.000	0.10476	18.6	90.7	0.001056	2020.12.14
10	-13.81488	0.000	0.52607	17.0	86.4	0.013806	2020.12.15
11	-12.44423	-0.001	0.12322	13.6	93.1	0.001806	2020.12.16
12	-13.05430	0.000	0.21333	14.4	91.1	0.004225	2020.12.17
13	-11.88433	-0.001	0.02976	13.6	82.9	0.000006	2020.12.18
14	-10.48859	-0.001	0.18497	13.3	75.0	0.003306	2020.12.19
15	-13.71454	-0.001	0.11493	15.1	68.6	0.001225	2020.12.20
16	-13.78979	-0.001	0.12936	16.7	68.5	0.002500	2020.12.21
17	-14.34969	-0.001	0.41232	18.1	80.3	0.006006	2020.12.22
18	-14.45003	0.000	0.03425	18.7	80.3	0.000006	2020.12.23
19	-15.00994	-0.001	0.12941	18.7	83.3	0.002756	2020.12.24
20	-25.44836	0.000	0.03534	19.5	89.8	0.000006	2020.12.25

The weight of secondary index is calculated by entropy weight method as shown in Table 3.

Table 3: Index weight table.

Total index	Primary index	Weight (W)	Secondary index	Weight (W_i)
Health status of steel structure canopy	Structural force F_1	0.6	Temperature strain F_{11}	0.52179
			Structural deformation F_{12}	0.35152
			Vibration acceleration F_{13}	0.12669
	External environment F_2	0.4	Temperature F_{21}	0.19474
			Humidity F_{22}	0.56932
			Wind pressure F_{23}	0.23594

According to the Haikou East High-speed Railway Station Canopy Steel Structure Health Monitoring System during the operation stage, the steel structure health and early warning frequency from December 6, 2020 to December 25, 2020 2:00-3:59 a.m., included the first, second and the third level alarm frequency which is corresponded to the three health levels of steel structure sub-health, unhealthy, and morbidity, the membership degree is calculated and shown in Table 4 below:

Table 4: Steel structure health status.

Primary index Fi	Secondary index Fij	First-level warning frequency	Second-level warning frequency	Third-level warning frequency	Total frequency	Membership of steel structure health status			
						Health	Sub-health	unhealthy	morbidity
F_1	F_{11}	14637	2442	0	144000	0.88139	0.10165	0.01696	0.00000
	F_{12}	92	0	0	2400	0.96167	0.03833	0.00000	0.00000
	F_{13}	26177	1298	0	144000	0.80921	0.18178	0.00901	0.00000
F_2	F_{21}	25	0	0	2400	0.98958	0.01042	0.00000	0.00000
	F_{22}	83	40	0	2400	0.94875	0.03458	0.01667	0.00000
	F_{23}	21	18	0	2400	0.98375	0.00875	0.00750	0.00000

3.3. Fuzzy Hierarchy Evaluation

According to the fuzzy hierarchical evaluation model, the evaluation matrix for calculating the second-level fuzzy matrix on the second-level index is:

$$Q_1 = W_1(\bullet,\oplus)R_1 = \begin{bmatrix}0.90047 & 0.08954 & 0.00999 & 0.00000\end{bmatrix} \tag{4}$$

$$Q_2 = W_2(\bullet,\oplus)R_2 = \begin{bmatrix}0.96496 & 0.02378 & 0.01126 & 0.00000\end{bmatrix} \tag{5}$$

The final result of the steel structure health evaluation is:

$$Q = W(\bullet,\oplus)R = \begin{bmatrix}0.92627 & 0.06324 & 0.01050 & 0.00000\end{bmatrix} \tag{6}$$

From the calculation results, it can be known that the overall operating status of the large-span steel canopy of the high-speed railway platform is healthy according to the principle of maximum membership degree of the fuzzy hierarchy evaluation method.

4. Conclusions

In this paper, the steel structure of canopy in Haikou East Railway Station is taken as an example and a steel structure health evaluation model is established based on fuzzy hierarchy evaluation. The main conclusions are drawn: Compared with conventional evaluation methods, the complexity and ambiguity of the steel structure health assessment system is considered and the index weights and fuzzy sets are optimized, which objectively reflect the actual health of steel structures safe condition and the model has been proved to have good operability.

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