Structural Monitoring and Maintenance, *Vol. 5, No. 1 (2018) 79-92*
DOI: https:// doi.org/10.12989/smm.2018.5.1.079

RAMS evaluation for a steel-truss arch high-speed railway bridge based on SHM system

Han-Wei Zhao[1], You-Liang Ding[*1], Fang-Fang Geng[2] and Ai-Qun Li[3]

[1]Key Laboratory of C&PC Structures of the Ministry of Education, School of Civil Engineering, Southeast University, Nanjing 210096, China
[2]School of Architecture Engineering, Nanjing Institute of Technology, Nanjing 211167, China
[3] Beijing Advanced Innovation Center for Future Urban Design, Beijing University of Civil Engineering and Architecture, Beijing 100044, China

(Received November 5, 2017, Revised February 5, 2018, Accepted February 19, 2018)

Abstract. The evaluation theory of reliability, availability, maintainability and safety (RAMS) as a mature theory of state evaluation in the railway engineering, can be well used to the evaluation, management, and maintenance of complicated structure like the long-span bridge structures on the high-speed railway. Taking a typical steel-truss arch bridge on the Beijing-Shanghai high-speed railway, the Nanjing Dashengguan Yangtze River Bridge, this paper developed a new method of state evaluation for the existing steel-truss arch high-speed railway bridge. The evaluation framework of serving state for the bridge structure is presented based on the RAMS theory. According to the failure-risk, safety/availability, maintenance of bridge members, the state evaluation method of each monitoring item is presented. The weights of the performance items and the monitoring items in all evaluation levels are obtained using the analytic hierarchy process. Finally, the comprehensive serving state of bridge structure is hierarchical evaluated.

Keywords: high-speed railway; steel-truss arch bridge; SHM; RAMS; state evaluation

1. Introduction

Long-span bridges are the vital projects on the high-speed railway lines. With the continuous construction of the high-speed railway network in China, the safe operation and routine maintenance of long-span high-speed railway bridges, which aim at service performance, become the challenges of the civil engineering (Ding *et al*. 2017, Zhao *et al.* 2017). The structural health monitoring system has been assumed to take the important task of the guidance of bridge maintenance and management since its appearance (Nagarajaiah and Erazo 2016). The mean and maximum of structural responses are usually used to evaluate the bridge structure during daily operation. However, the evaluation based on a simple calculation of structural response can not fully reflect the serving performance of existing bridge structures (Guo *et al.* 2016). Hence, a more efficient method to evaluate the serving state of existing bridge structures, which can guide the maintenance and management of bridge, is required (Yi and Li 2016).

The RAMS is an abbreviation of Reliability, Availability, Maintainability and Safety, which

∗Corresponding author, Professor, E-mail: civilchina@hotmail.com

http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

was first proposed and used in the aviation industry. In 1998, the British Standards Institution took the lead to introduce RAMS into the railway engineering, issued the "EN 50126, Railway Applications: Specification and Verification of Reliability, Availability, Maintainability and Safety". Then, the European Committee for Electrotechnical Standardization passed it and enhanced it to the EU standard for the systematic design in the field of rolling stock, communication signal and traction power supply in the next year (CENELEC 1999). In 2002, the standard was elevated to the International Electrotechnical Commission standard (IEC 2002). China absorbed the main contents of IEC 62278-2002 and published the Codes and Examples of Rail Transit Reliability, Availability, Maintainability and Safety (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China & Standardization Administration of the People's Republic of China 2008) in 2008 to guide the manufacture and maintenance of the rolling stock and any other railway equipment. In recent years, some scholars of the railway engineering began to apply the RAMS evaluation method to the maintenance and repair of the high-speed railway track (Pratico and Giunta 2018) and railway signal system (Qiu *et al.* 2014).

Mostly long-span high-speed railway bridges in China are equipped with structural health monitoring (SHM) system to ensure the safety operation of structure. However, the existing evaluation methods of bridge structures are mainly based on the results of periodical inspection. The bridge health monitoring data has not been effectively applied to structural evaluation (Stenstrom *et al*. 2015). As a mature evaluation theory in the railway engineering, the RAMS theory can well integrate massive data of SHM system and be well applied into the evaluation, management and maintenance of long-span high-speed railway bridge structures. Using the Nanjing Dashengguan Yangtze River Bridge, a typical long-span steel-truss arch high-speed railway bridge on the Beijing-Shanghai high-speed railway, as the engineering background, this paper develops a RAMS evaluation method for the bridge structure’s serving state based on the health monitoring system.

2. RAMS evaluation framework based on SHM system

2.1 Bridge description and SHM system

Due to their large stiffness, low usage of steel and the good capability in span compared to other types of bridges (for example the cable-stayed bridge and the suspension bridge) with the same span, the steel-truss arch bridges have been widely constructed on the high-speed railway lines of China, which need to cross the big river, deep valley and bay. The Nanjing Dashengguan Yangtze River Bridge is a key channel of the Beijing-Shanghai high-speed railway to cross the Yangtze River. It is the first 6-tracks arch railway bridge in the world as shown in Fig. 1. com-posed of two tracks on the downstream side for Beijing-Shanghai high-speed railway, two tracks on the upstream side for Shanghai-Wuhan-Chengdu quasi-high-speed railway, and the rest on the outer sides of the bridge deck for Nanjing Metro. It was put into operation in 2011 and at that time the highest train speed of the bridge was designed at 300 km/h (and the train speed has been up to 350 km/h since 2018). The bridge consists of 2 continuous steel-truss arches and 4 approach spans, with a span configuration of 108+192+2×336+192+108 m. The bridge structure consists of three main trusses spaced 15 m apart in the transverse direction. Besides, the whole bridge has three rows of rigid hangers, the longest one among which is approximate 60 m, the truss height is 12~96 m. The three main trusses and the transverse contacting bars between three trusses mostly apply box sections and H-shaped sections, and the joints of the truss members are connected with bolts. The bridge employed specific ball-steel expansion supports on 7 piers and special telescopic devices at the girder end above the Piers 1 and 7.

Owing to the long length of middle span, the extremely heavy train loads, and the high train speed of the Nanjing Dashengguan Yangtze River Bridge, a long-term SHM system was installed on the bridge. There are totally 124 sensors deployed on 21 cross sections of the bridge, monitoring the wind speeds, temperature and humidity, vibration responses of structures, structural strains and displacements (including deflections), as well as train speeds, respectively. The locations of sensors are determined by the mechanical characteristics of bridge structure. Fig. 2 shows the SHM system and the sensor arrangement of bridge.

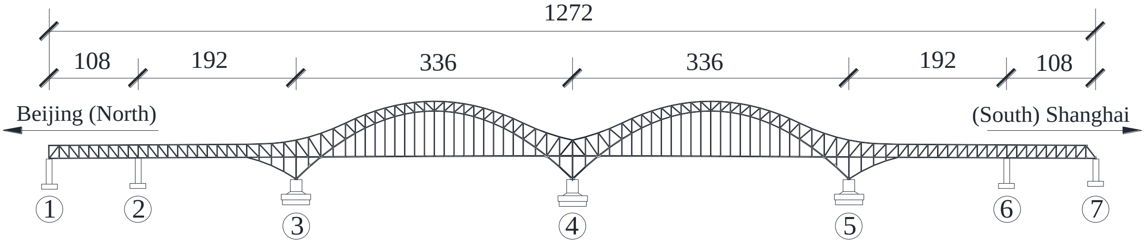

Fig. 1 Elevation of the Nanjing Dashengguan Yangtze River Bridge

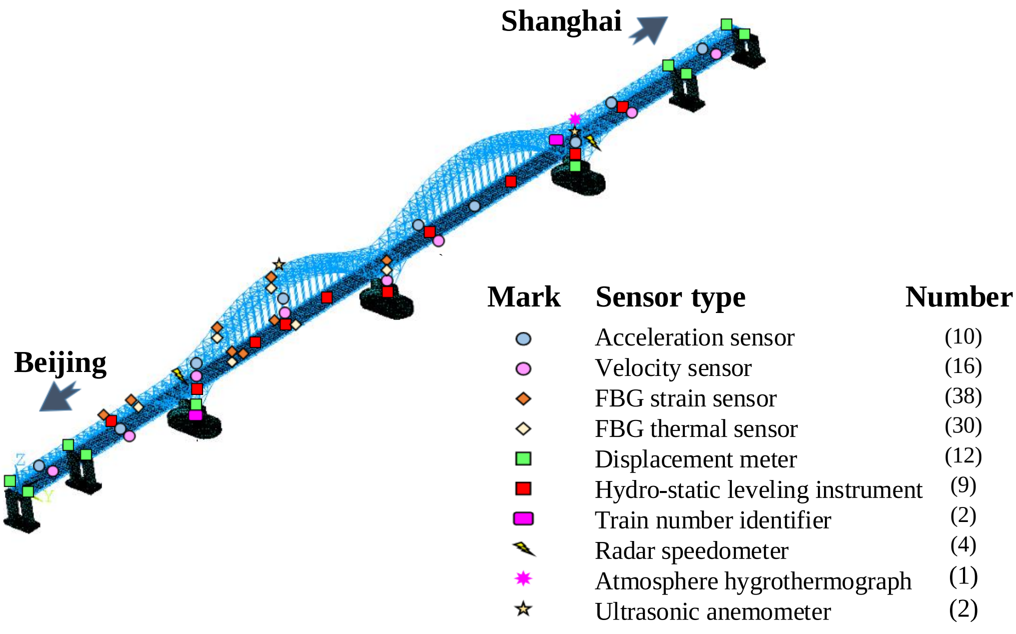

Fig. 2 SHM system of the Nanjing Dashengguan Yangtze River Bridge

2.2 RAMS evaluation framework

Based on various types of monitoring data collected by the SHM system of the Nanjing Dashengguan Yangtze River Bridge, the serving state of the long-span steel-truss arch high-speed railway bridge is possible to be evaluated. The response signals of various members of the bridge structure play an important role in the state evaluation of the existing long-span steel-truss arch high-speed railway bridge (Yang and Nagarajaiah 2015).

Therefore, determining the evaluation indicators and the whole framework based on the response items of the SHM system is the prerequisite for gaining the serving state of the whole bridge structure. In order to stratify and standardize the serving state evaluation of bridge structure, the item system of the RAMS parametric evaluation of the existing steel-truss arch bridge need to be determined first. This paper divides the state evaluation of RAMS into three major aspects: the reliability, the safety/availability and the maintainability. Each monitoring item of the bridge responses is corresponding to a safety or reliability item, and their individual reliability (failure risk) and maintainability (maintenance cost and time) are analyzed. Then, the RAMS score of each individual monitoring item can be calculated. And the comprehensive serving state score of whole bridge structure is summed via the corresponding weight. The framework of this evaluation method is shown in Fig. 3.

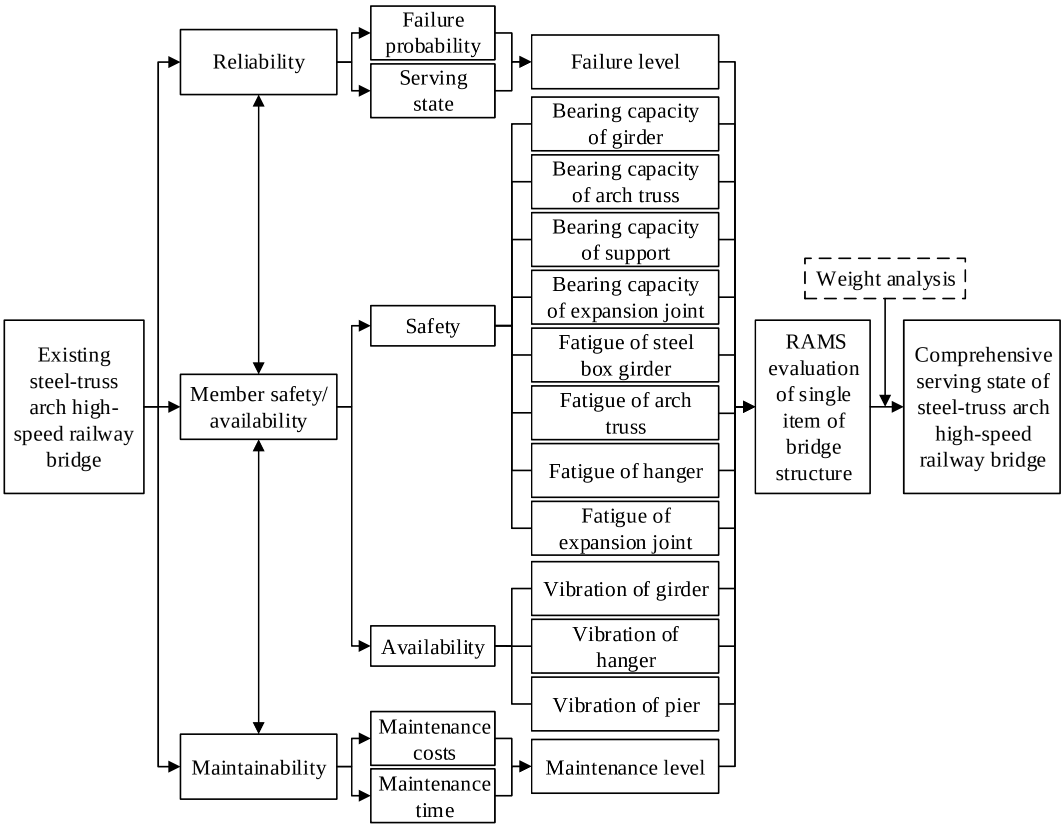

Fig. 3 Evaluation framework of the serving steel-truss arch high-speed railway bridge

In the above RAMS parametric evaluation framework, each single performance (belonging to safety/availability) corresponds to one or more response-monitoring items. Among them, the bearing capacity of girder corresponds to the deflection (displacement) of girder and the strain amplitude of girder chord; the bearing capacity of arch truss corresponds to the strain amplitude of arch chord; the bearing capacity of support corresponds to the displacement and the cumulative displacement of support; the bearing capacity of expansion joint corresponds to the displacement of expansion joint; the fatigue of steel box girder corresponds to the equivalent damage (calculated by the strain data, the same below) of box girder (Guo *et al.* 2015); the fatigue of arch truss corresponds to the equivalent damage of arch truss chord; the fatigue of hanger corresponds to the equivalent damage of hanger; the fatigue of expansion joint corresponds to the equivalent damage of expansion joint; the vibration of girder corresponds to the first natural frequency (identified by the acceleration response, the same below), the acceleration amplitude and the dynamic displacement amplitude (integrated by the velocity data, the same below) of girder; the vibration of hanger corresponds to the first natural frequency, the acceleration amplitude and the dynamic displacement amplitude of hanger; the vibration of pier corresponds to the dynamic displacement amplitude of pier.

Among the above response-monitoring items, there are two items that need to be explained:

1. The long-span bridge generally uses the expansion support who will move and wear on some directions due to the friction under the action of alternating temperature and train braking force. When the cumulative displacement reaches a certain amount on the free direction, the performance of expansion support will drop.

2. The first natural frequency of girder and hanger indirectly reflects the stiffness of girder and hanger. In the monitoring, the deviation of first natural frequency from the theoretical value is generally used to determine the degree of stiffness decline after the normalization of temperature effects.

For a complicated structure like the long-span steel-truss arch bridge with various members, the relationship between bridge (or members) states, failure modes, and risk probabilities are shown in Fig. 4. Based on this relationship, the link between the reliability and the maintainability via failure modes can be established.

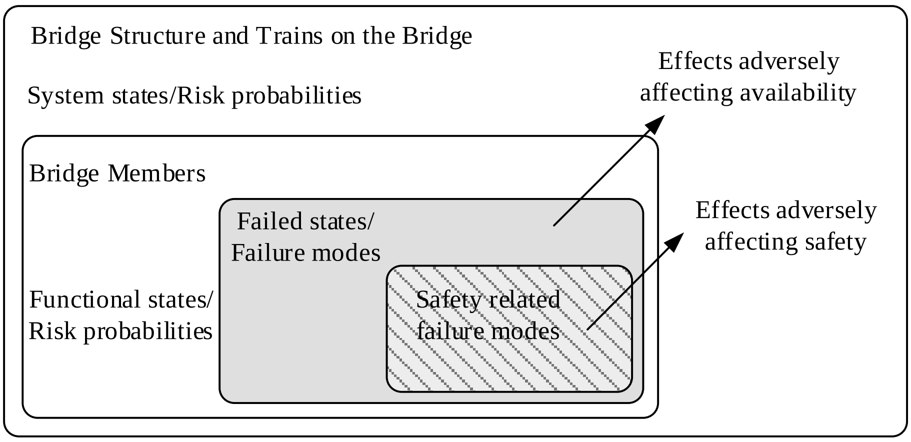

Fig. 4 Relationship between bridge (or members) states, failure modes, and risk probabilities

3. RAMS evaluation for the single monitoring items of bridge

3.1 Failure risk, failure mode, and repair strategy of single monitoring item

The original intention of the bridge health monitoring aims at the detecting of bridge damage as early as possible which can achieve the rapid repair of bridge in the daily operation. After the determination of the safety/availability monitoring items, the reliability and maintainability of each corresponding item can be analysed. The reliability of each monitoring item can be determined by the statistics of long-term monitoring data, the design documents, and the experiences. Assuming the performance function of a single monitoring items can be expressed as

$$Z = g(s, r) = r - s \tag{1}$$

Where *r* is the resistance of the single monitoring item of bridge responses, it is determined by the code limit or the trial result; and *s* is the load effect of the single monitoring item of bridge responses, it is determined by the probability model of monitoring data. Hence the reliability probability and the failure probability can be expressed as

$$P_{\mathrm{R}} = \mathrm{P}(Z > 0) = \int_{0}^{\infty} f_Z(z)\mathrm{d}z \tag{2}$$

$$P_{\mathrm{F}} = \mathrm{P}(Z < 0) = \int_{-\infty}^{0} f_Z(z)\mathrm{d}z \tag{3}$$

Where $f_Z(z)$ is the probability density function of performance function *Z*.

Then, the maintainability of each monitoring item can be obtained by the failure modes and repair strategies (FMRS) based on the statistics of the real-time (or quasi-real-time) monitoring results and the design documents. The FMRS of the steel-truss arch high-speed railway bridge is shown in Table 1. The Table 1 lists the structural failure modes, consequences and their repair methods of the members on the steel-truss arch high-speed railway bridge, which is used to guide the safe operation and maintenance of the bridge structure.

3.2 RAMS evaluation principle of single monitoring item

Based on the RAMS evaluation framework, failure risk, and FMRS of in-serving high-speed railway bridge in the previous, the evaluation of single monitoring item in each performance of serving high-speed railway bridge can be analyzed. the details are shown in Table 2. Each single monitoring item is scored according to the corresponding monitoring results, and the score is calculated by Eq. (4).

$$S_{\mathrm{RAMS}} = R \cdot SA \cdot M \tag{4}$$

Where *R* is the score of reliability, *SA* is the score of safety/availability, *M* is the score of maintainability. *R*, *SA*, *M* should be divided into the corresponding level (Table 2). The scores of these three items are ranked according to the corresponding risks. The higher the S_{RAMS} value is, the higher the grade of the monitoring item is for the corresponding member performance.

Table 1 Failure mode and repair strategy of bridge member based on monitoring item

Member type	Monitoring item	Failure mode	Failure consequence	Repair method
Girder	Deflection (Displacement)	Deflection exceeds limit	Bearing capacity decreases and affects train running safety	Stop operation, structural reinforcement
	Acceleration	1. Amplitude exceeds limit 2. Identified frequency exceeds limit	Stiffness decreases and affects train running safety	Member repair
	Velocity	Dynamic displacement amplitude exceeds limit	Stiffness decreases and affects train running safety	Member repair
	Strain	1. Chord stress exceeds limit 2. Steel box girder fatigue	Deck system degrades and affects train running safety	Stop traffic, member replacement
Hanger	Acceleration	1. Amplitude exceeds limit 2. Identified frequency exceeds limit	Stiffness decreases	Member repair
	Velocity	Dynamic displacement amplitude exceeds limit	Stiffness decreases	Member repair
	Strain	Fatigue	Performance degrades and results in the redistribution of structural force	Stop traffic, member replacement
Arch truss	Strain	1. Truss stress exceeds limit 2. Truss fatigue	Performance degrades and results in the redistribution of structural force	Stop traffic, member replacement
Support (expansion)	Displacement	1. Displacement exceeds limit on the fixed direction 2. Cumulative displacement exceeds limit on the free direction	Members are out of work	Stop traffic, member replacement
Expansion joint	Displacement	Displacement exceeds limit	Members are out of work	Stop traffic, member replacement
	Strain	Fatigue	Members are out of work	Stop traffic, member replacement
Pier	Velocity	Dynamic displacement amplitude exceeds limit of pier top	Stiffness decreases	Member repair

Table 2 RAMS evaluation and its score for the single monitoring items

Reliability (R)		Safety/Availability (SA)		Maintainability (M)		Score
Failure level	Failure probability	Danger level	Threat degree to structure	Maintenance cost	Maintenance method	
High (Inevitable)	> 1/2	Cause disaster	Lead to structural failure and train derailment, with great casualties and property losses	Extremely high maintenance costs and extremely long maintenance time	Stop operation, structural reinforcement	1
	1/3	Extremely high	Lead to train derailment with great casualties and property losses	Extremely high maintenance costs, long maintenance time		2
High (Repeated failure)	1/8	Very high	No brittle structural failure, but affecting system safety	High maintenance costs, long maintenance time	Stop traffic, member replacement	3
	1/20	High	Member failure, affecting system safety	High maintenance costs, relatively-long maintenance time		4
Medium (Occasional failure)	1/80	Medium	Member damage, affecting system safety	Medium maintenance costs, relatively-long maintenance time	Member replacement	5
	1/400	Low	No apparent damage, affecting system safety	Medium maintenance costs, medium maintenance time		6
	1/2000	Very low	Significant degradation of member performance, limited impact on system safety	Medium maintenance costs, short maintenance time		7
Low (Rarely failure)	1/15000	Minor	Some degradation of member performance, limited impact on system safety	Low maintenance costs, short maintenance time	Member repair	8
	1/150000	Extremely minor	Slightly degradation of member performance, limited impact on system safety	Low maintenance costs, maintenance does not affect operation		9
Safety	< 1/1500000	None	Does not affect the system safety	Routine maintenance in operation	Routine maintenance	10

4. Bridge comprehensive evaluation by the weight analysis of single item

4.1 Analysis of the weights of single item

After obtaining of the RAMS score of the single monitoring items, the evaluation score of the comprehensive serving state for the bridge structure can be calculated by weighted synthesis. In the present paper, the analytic hierarchy process (AHP) is used to determine the weights of all items in the safety/availability performance level and the single monitoring item level (in Fig. 3).

The processes of obtaining the weights by the AHP are mainly divided into 3 steps (Saaty 2008):

1) Establish the analytic hierarchy model: It decomposes a complex problem into various components called elements and forms different levels according to their mutual relations and their affiliation. The element of the superior level dominates the corresponding elements in the inferior level.

2) Construct judgment matrix: The judgment is given on the relative importance of the elements in each level. These judgments are expressed by numerical values which scale the relative importance, usually are written as a judgment matrix. For n items needed to be judged, there will a $n \times n$ judgment matrix $\boldsymbol{A}=(a_{ij})_{n\times n}$.

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & a_{ij} & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{5}$$

Where matrix A is a positive reciprocal matrix, which is a scale matrix constructed by a certain ratio of quantitative. The a_{ij} denotes the importance of item i relative to item j. Matrix A has the following properties:

$$a_{ij} > 0 \tag{6}$$

$$a_{ij} = \frac{1}{a_{ji}} \quad (i, j = 1, 2, \cdots, n) \tag{7}$$

$$a_{ij} = 1 \quad (i = j) \tag{8}$$

Table 3 shows the scaling principle of a_{ij} in this paper.

3) Hierarchy order and consistency test:

Calculate the relative importance of a group of items at the inferior level which is relate to an item at the superior level. This kind of ranking calculation is called hierarchical single rank. The calculation of hierarchical single rank is actually the calculation of the largest eigenvalue and its eigenvectors of the judgment matrix. The purpose of calculating hierarchical single rank of the relative weights at all levels is actually to find the relative weight vector $\boldsymbol{W} = (w_1, w_2, \dots, w_n)^T$ based on the judgment matrix $\boldsymbol{A}=(a_{ij})_{n\times n}$. And the calculated weight vector should pass the consistency test before using.

Table 3 Scaling principle of for a_{ij}

Value of relative importance	Meaning
1	Two items have the same importance
3	The former item is slightly more important than the latter item
5	The former item is obviously more important than the latter item
7	The former item is strongly more important than the latter item
9	The former item is extremely more important than the latter item
2,4,6,8	The middle value of the above two adjacent judgments

Table 4 Mean value of random index of consistency

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

(a) Calculate the product of the elements (a_{ij}) in each row of the judgment matrix $\boldsymbol{A}$

$$M_i = \prod_{i=1}^{n} a_{ij} \quad (i, j = 1, 2, \cdots, n) \tag{9}$$

(b) Calculate the n^{th} root of M_i

$$b_i = \sqrt[n]{M_i} \tag{10}$$

(c) Normalize vector $b_i=(b_1, \dots, b_n)^T$

$$w_i = \frac{b_i}{\sum_{i=1}^{n} b_i} \tag{11}$$

Then the vector $\boldsymbol{W} = (w_1, w_2, \dots, w_n)^T$ is the original weight vector.

(d) Calculate the largest eigenvalue $\lambda_{\max}$ of the judgment matrix $\boldsymbol{A}$

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{w_i} \tag{12}$$

Where $(AW)_i$ is the i^{th} element of vector $\boldsymbol{AW}$ for any i= 1, 2, … , n.

(e) Consistency test:

The consistency test generally uses the consistency index (*CI*)

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{13}$$

The smaller the *CI* index, the higher the consistency, the larger the *CI* index, the lower the consistency. Taking it into account that some bias of consistency may also be caused by random factors, it is necessary to introduce the random index (*RI*) of consistency for each *n*, the mean values of random index for each *n* are as shown in Table 4.

The *RI* is related to the order of the judgment matrix (*n*). The larger the order is, the more likely it is to randomly depart from the consistency. After the testing of the consistency index about the judgment matrix, the consistency index *CI* must be compared with the average random consistency index *RI* to obtain the test result, that is the consistency ratio (*CR*) as

$$CR = \frac{CI}{RI} \tag{14}$$

For the first and second order of judgment matrices, the elements in the judgment matrix satisfy $a_{ij}a_{jk}= a_{ik}$ (i, j, k = l, 2, … , n), so there is no need to test consistency. For the third order or above of judgment matrix, when CR<0.1, it is considered that the consistency of judgment matrix is acceptable; when CR>0.1, the original judgment matrix should be properly updated, and then the consistency of the new judgment matrix is recalculated until a judgment matrix with a satisfactory consistency is obtained.

Based on the monitoring items of the Nanjing Dashengguan Yangtze River Bridge SHM system, the 1st to 3rd level of the sub-items used for RAMS evaluation are:

First level: $\boldsymbol{U}_1$={U_l}; U_l ={u_{l1}, u_{12}}={Safety, Availability}.

Secondary level: $\boldsymbol{U}_2$={U_{21}, U_{22}}; U_{2l}={u_{211}, u_{212}, u_{213}, u_{214}, u_{215}, u_{216}, u_{217}, u_{218}}={Bearing capacity of girder, Bearing capacity of arch truss, Bearing capacity of support, Bearing capacity of expansion joint, Fatigue of steel box girder, Fatigue of arch truss, Fatigue of hanger, Fatigue of expansion joint}; U_{22}={u_{221}, u_{222}, u_{223}}={Vibration of girder, Vibration of hanger, Vibration of pier}.

Third level: $\boldsymbol{U}_3$={U_{311}, U_{313}, U_{321}, U_{322}}; U_{311} is belong to the bearing capacity of girder, U_{311}={u_{3111}, u_{3112}}={Displacement amplitude, Strain amplitude}; U_{313} is belong to the bearing capacity of support, U_{313}={u_{3131}, u_{3132}}={Displacement amplitude, Cumulative displacement}; U_{321} is the vibration of girder, U_{321}={u_{3211}, u_{3212}, u_{3213}}={First natural frequency, Acceleration amplitude, Dynamic displacement amplitude}, U_{322} is the vibration of hanger, U_{322}={u_{3221}, u_{3222}, u_{3223}}={First natural frequency, Acceleration amplitude, Dynamic displacement amplitude}.

Table 5 Judgment matrix and weights of U_{21}

	u_{211}	u_{212}	u_{213}	u_{214}	u_{215}	u_{216}	u_{217}	u_{218}
u_{211}	1	1	2	3	5	7	7	5
u_{212}	1	1	2	3	5	7	7	5
u_{213}	1/2	1/2	1	3/2	5/2	7/2	7/2	5/2
u_{214}	1/3	1/3	2/3	1	5/3	7/3	7/3	5/3
u_{215}	1/5	1/5	2/5	3/5	1	7/5	7/5	1
u_{216}	1/7	1/7	2/7	3/7	5/7	1	1	5/7
u_{217}	1/7	1/7	2/7	3/7	5/7	1	1	5/7
u_{218}	1/5	1/5	2/5	3/5	1	7/5	7/5	1
A_{21}	0.2842	0.2842	0.1421	0.0947	0.0568	0.0406	0.0406	0.0568

Table 6 Weights for each sub-item of bridge state evaluation

First level	Weight	Secondary level	Weight	Third level	Weight
Safety	0.75	Bearing capacity of girder	0.2842	Displacement amplitude	0.6667
				Strain amplitude	0.3333
		Bearing capacity of arch truss	0.2842	Strain amplitude	
		Bearing capacity of support	0.1421	Displacement amplitude	0.8333
				Cumulative displacement	0.1667
		Bearing capacity of expansion joint	0.0947	Displacement amplitude	
		Fatigue of steel box girder	0.0568	Equivalent damage by strain	
		Fatigue of arch truss	0.0406	Equivalent damage by strain	
		Fatigue of hanger	0.0406	Equivalent damage by strain	
		Fatigue of expansion joint	0.0568	Equivalent damage by strain	
Availability	0.25	Vibration of girder	0.6522	First natural frequency	0.4
				Acceleration amplitude	0.2
				Dynamic displacement amplitude	0.4
		Vibration of hanger	0.2174	First natural frequency	0.4
				Acceleration amplitude	0.2
				Dynamic displacement amplitude	0.4
		Vibration of pier	0.1304	Dynamic displacement amplitude	

Then the weights of each sub-items can be determined via Eqs. (2)-(11): Firstly, sort the importance of various items of each level affecting the serving performance of bridge according to the judgments of expert. Secondly, construct the judgment matrix (***A***), calculate the maximum eigenvalue (λ_{max}) of the judgment matrix, and obtain the corresponding eigenvector (***W***). Thirdly, test the consistency.

For example, the judgment matrix and the weights A_{21}={a_{211}, a_{212}, a_{213}, a_{214}, a_{215}, a_{216}, a_{217}, a_{218}} of U_{21} is shown in Table 5.

Similarly, the weights of all sub-items are calculated as Table 6.

4.2 Structural comprehensive evaluation of bridge

After obtaining the weights of each sub-item at the 1st to 3rd level, the comprehensive score of bridge structure $S_{\mathrm{RAMS}}^{\mathrm{B}}$ can be synthesized by the S_{RAMS} of each sub-item. Assuming the $S_{\mathrm{RAMS}}^{\mathrm{B0}}$ stands by the intact state of bridge structure which is calculated by the 10 score of each *R*, *SA*, and *M* of the S_{RAMS} of each single monitoring item (in Table 2). Then, the serving state of bridge structure *S* can be expressed as

$$S = \frac{S_{\mathrm{RAMS}}^{\mathrm{B}}}{S_{\mathrm{RAMS}}^{\mathrm{B0}}} \tag{15}$$

Table 7 Comprehensive grade for RAMS evaluation of bridge structure

Grade	A	B	C	D	E
S	1≥ S ≥0.9	0.9≥ S ≥0.8	0.8≥ S ≥0.65	0.65≥ S ≥0.4	0.4≥ S ≥0
State	Basically intact	Slight	Moderate	Severe	Dangerous

The closer S is to 1, the healthier the serving state of bridge structure; the closer S is to 0, the more dangerous the serving state of bridge structure.

According to the value of S, the state of bridge structure can be graded and evaluated (Ministry of Railways of the People's Republic of China 2010). Considering the characteristics of the long-span steel-truss arch high-speed railway bridge, Table 7 gives the comprehensive RAMS evaluation grade of bridge structure.

According to the evaluation method of bridge state above, the comprehensive score of the Nanjing Dashengguan Yangtze River Bridge is 0.9627, the bridge state is basically intact. The engineers of the high-speed railway bridge can make the routine operation and maintenance strategy combination with the comprehensive score of bridge structure (Table 7) and the score of single monitoring item (Table 2), when the score reduces.

5. Conclusions

Based on the SHM system of a typical long-span steel-truss arch high-speed railway bridge, the Nanjing Dashengguan Yangtze River Bridge, this paper develops the reliability, availability, maintainability, and safety (RAMS) evaluation framework. The performance items and single monitoring items of RAMS evaluation are determined. the reliability, safety/availability and maintainability of each single monitoring item are evaluated in parallel, and the calculation method of the RAMS score of single monitoring item is presented. The weights of the performance items and the single monitoring items in Levels 1 to 3 are obtained via analytic hierarchy process, and the comprehensive RAMS evaluation grade of bridge structure is hierarchical evaluated from A to E. To sum up, a new method of state evaluation for the existing steel-truss arch railway bridge has been developed.

Acknowledgments

The research described in this paper was financially supported by the National Basic Research Program of China (973 Program) (No. 2015CB060000), the National Natural Science Foundation of China (Nos. 51438002, 51578138 and 51608258), the Scientific Research Foundation of Graduate School of Southeast University (No. YBJJ1657), the Fundamental Research Funds for the Central Universities and the Innovation Plan Program for Ordinary University Graduates of Jiangsu Province in 2016 (No. KYLX16_0251) and A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

References

CENELEC (2007), *EN 50126, Railway Application-specification of Railway Reliability Availability Maintainability and Safety (RAMS)*, Brussels, Belgium.

Ding, Y.L., Zhao, H.W., Deng L., Li A.Q. and Wang M.Y. (2017), "Early warning of abnormal train-induced vibrations for a steel-truss arch railway bridge: case study", *J. Bridge Eng.*, **22**(11), 05017011.

General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China & Standardization Administration of the People's Republic of China (2008), *GB/T 21562-2008, Railway Application-specification of Railway Reliability Availability Maintainability and Safety (RAMS)*, Beijing, China (in Chinese).

Guo, T., Liu, J. and Huang, L.Y. (2016), "Investigation and control of excessive cumulative girder movements of long-span steel suspension bridges", *Eng. Struct.*, **125**, 217-226.

Guo, T., Liu, Z.X., Zhang, Y.F. and Pan Z.H. (2015), "Cracking of longitudinal diaphragms in long-span cable-stayed bridges", *J. Bridge Eng.*, **20**(11), 04015011.

IEC (2007), *IEC 62278-2002, Railway Application-specification of Railway Reliability Availability Maintainability and Safety (RAMS)*, Washington DC, USA.

Ministry of Railways of the People's Republic of China (2010), *TG/GW103-2010, Repair Rules for Railway Bridge and Tunnel*, Beijing, China (in Chinese).

Nagarajaiah, S. and Erazo, K. (2016), "Structural monitoring and identification of civil infrastructure in the United States", *Struct. Monit. Maint.*, **3**(1), 51-69.

Pratico, F.G. and Giunta, M. (2018), "Proposal of a key performance indicator for railway track based on LCC and RAMS analyses", *J. Constr. Eng. Management*, **144**(2), 04017104.

Qiu, S., Sallak, M., Schon, W. and Cherfi-Boulanger, Z. (2014), "Availability assessment of railway signalling systems With uncertainty analysis using Statecharts", *Simul. Model. Pract. Th.*, **47**, 1-18.

Saaty, T.L. (2008), "Relative measurement and its generalization in decision making why pairwise comparisons are central in mathematics for the measurement of intangible factors the analytic hierarchy/network process (To the Memory of my Beloved Friend Professor Sixto Rios Garcia)", *Revista de la Real Academia de Ciencias Exactas, Físicas y Naturales. Serie A. Matematicas*, **102**(2), 251-318.

Stenstrom, C., Parida, A., Lundberg, J. and Kumar, U. (2015), "Development of an integrity index for benchmarking and monitoring rail infrastructure: application of composite indicators", *Int. J. Transp.*, **3**(2), 61-80.

Yang, Y.C. and Nagarajaiah, S. (2015), "Output-only modal identification by compressed sensing: Non-uniform low-rate random sampling", *Mech. Syst. Signal Pr.*, **56-57**(2015), 15-34.

Yi, T.H. and Li, H.N. (2016), "Innovative structural health monitoring technologies", *Measurement*, **88**, 343-344.

Zhao, H.W., Ding, Y.L., An, Y.H. and Li, A.Q. (2017), "Transverse dynamic mechanical behavior of hangers in the rigid tied-arch bridge under train loads", *J. Perform. Constr. Fac.*, **31**(1), 04016072.