SHM-Based Bridge Rating System for Long-Span Cable-Supported Bridge

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Abstract

This paper aims at developing a structural health monitoring (SHM)-based bridge rating method for bridge inspection of long-span cable-supported bridges. The fuzzy based analytic hierarchy approach is employed, and the hierarchical structure for synthetic rating of each structural component of the bridge is proposed. The criticality and vulnerability analyses are performed largely based on the field measurement data from the SHM system installed in the bridge to offer relatively accurate condition evaluation of the bridge and to reduce uncertainties involved in the existing rating method. The procedures for determining relative weighs and fuzzy synthetic ratings for both criticality and vulnerability are then suggested. The fuzzy synthetic decisions for inspection are made in consideration of the synthetic ratings of all structural components. The SHM-based bridge rating method is finally applied to the Tsing Ma suspension bridge in Hong Kong as a case study. The results show that the proposed method is feasible and it can be used in practice for long-span cable-supported bridges with SHM system.

Key words: Structural Health Monitoring, Bridge Rating System, Long-Span Cable-Supported Bridges, Inspection

1. Introduction

The functionality and safety of long-span cable-supported bridges are crucial to sustainable economical growth and social development. They are currently monitored mainly by visual inspection and some non-destructive tests at preset time interval according to a bridge rating system (1-3). These inspections are, however, not only labour intensive and time consuming but also superficial and subjective in nature. Structural health monitoring (SHM) systems have been recently installed in some long-span cable-supported bridges aiming to offer accurate condition evaluation of bridge health by means of advanced sensing devices, data acquisition systems and communication technology (4). Nevertheless, SHM systems have yet to be effectively utilized in bridge management systems. In this regard, this paper presents a SHM-based bridge rating method for bridge inspection of long-span cable-supported bridges. The SHM-based F-AHP rating method is then applied to the Tsing Ma suspension bridge in Hong Kong as a case study.

2. Decision for Bridge Inspection through F-AHP

2.1 Formation of a Hierarchical Structure

The analytic hierarchy process (AHP) was developed by Saaty based on an axiomatic foundation (5). The main steps in the application of analytic hierarchy process (AHP) to the current problem are as follows: (i) to decompose a general decision problem into hierarchical sub-problems that can be easily comprehended and evaluated; (ii) to determine the priorities of the items at each level of the decision hierarchy; and (iii) to synthesize the priorities to determine the overall priorities of the decision alternatives. Since a long-span cable-supported bridge is a very complex system and the decision making takes place in a situation in which the pertinent data and the sequences of possible actions are not precisely known, it is important to adopt fuzzy data to express such situations in decision making of inspection, leading to the so-called F-AHP bridge rating method used in this study.

In the proposed rating system, the top level can be assigned as an objective level upon which the best decision for inspection could be made for each structural component. The next level of the hierarchical structure can be defined as a criterion level upon which the criticality rating and the vulnerability rating can be respectively determined for each structural component based on the criticality and vulnerability rating criteria in the next level called the index level. After the hierarchical structure is constructed, one can then determine the relative weights of the items at each level of the decision hierarchy based on the mathematical properties of AHP. Finally, one can synthesize the relative weights at all the levels to make the best decision for inspection. The hierarchical structure for synthetic rating of each structural component of a bridge is shown in Fig. 1. The criticality rating criteria of each component are composed of five criticality factors from C1 to C5. The vulnerability rating criteria are set up based on three vulnerability factors V1 to V3. Each of the vulnerability factors is rated in three serial effects of VA, VB, and VC.

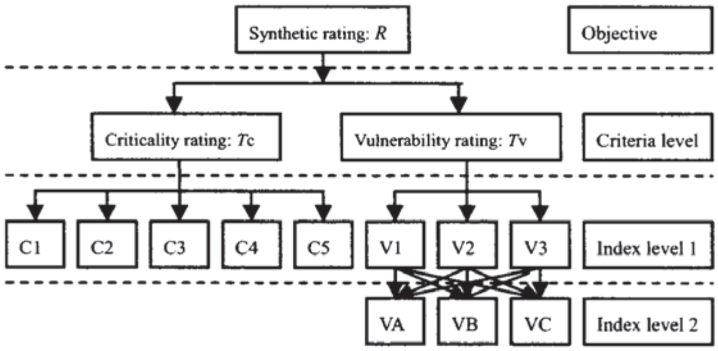

Fig. 1 Analytic hierarchical structure for each bridge component

2.2 Relative Weights for Each Level

The AHP often uses the eigenvalue solution of comparison matrices to find the best relative weights for different elements in each level. The first step is to carry out pair-wise comparisons of elements in each level. By assuming that the index level for criticality rating consists of $A_1, A_2 \cdots A_n$ items, the comparative matrix $[A]$ can be constructed by comparing objective i with objective j to obtain the relative weights $\alpha_{ij} = \omega_i / \omega_j$ (i, j= 1, 2,…n).

A decision-maker could provide only the upper triangle of the above comparison matrix. The reciprocals placed in the lower triangle do not need any further judgment because of the following characteristics.

$$\begin{aligned} &\alpha_{ij} > 0 && i,j=1,2,\cdots n \\ &\alpha_{ij} = 1/\alpha_{ji} && i,j=1,2,\cdots n \\ &\alpha_{ii}=1 && i=1,2,\cdots n \end{aligned} \tag{1}$$

In most of the practical problems, the pair-wise comparisons are not perfect, and one must find the principal right-eigenvalue that satisfies

$$[A]\{\omega\} = \lambda_{\max}\{\omega\} \tag{2}$$

where $\{\omega\}$ is the eigenvector with respect to eigenvalue n; and $\lambda_{\max} \approx n$. The next step is to check the consistency of comparison matrices in terms of the consistency ratio CR. The consistency ratio CR is determined by first estimating $\lambda_{\max}$ of matrix $[A]$. The consistency index CI of the matrix $[A]$ is defined as

$$\mathrm{CI} = (\lambda_{\max} - 1)/(n-1) \tag{3}$$

Then, the consistency ratio CR is calculated by dividing CI with the random index RI (5). Each RI is an average random consistency index derived from a sample of size 500 of randomly generated reciprocal matrices. If the previous approach yields a CR greater than 0.10 then a re-examination of the pair-wise judgments is recommended until a CR less than or equal to 0.10 is achieved (5).

If the consistency of the comparison matrix is satisfied, the relative weights are calculated based on the normalized eigenvector corresponding to the maximum eigenvalue.

2.3 Fuzzy Synthetic Ratings

The criticality and vulnerability ratings for each structural component are based on the criticality and vulnerability factors. Although the utilization of the SHMS will reduce the uncertainties in the estimation of these factors, the accuracy of the factors is still not precisely known. Therefore, it is important to treat the factors as fuzzy data in the decision making for inspection. Furthermore, the numerical numbers for each of the factors range from 0 and 100 to facilitate the decision making using the F-AHP based rating method.

The triangular fuzzy numbers (6) are preferred in this study. A fuzzy number M on $U \in (-\infty, +\infty)$ is defined to be a triangular fuzzy number if its membership function $u_{\mathrm{m}}(x) : U \to [0,1]$ is equal to

$$\mu_{\mathrm{m}}(x) = \begin{cases} \dfrac{x-r}{m-r} & x \in [r,m] \\ \dfrac{x-u}{m-u} & x \in [m,u] \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where $r \leq m \leq \mu$; r and u stand for the lower and upper values of the support for the decision of the fuzzy number M, respectively; m is the modal value. The triangular fuzzy number is denoted as M=(r, m, u). Let us select the five-point fuzzy rating set $\{G\}$ as

$$\{G\} = \{0 \quad 25 \quad 50 \quad 75 \quad 100\} \tag{5}$$

The triangular fuzzy numbers (0, 0, 50), (0, 25, 75), (0, 50, 100), (25, 75, 100), (50, 100, 100) can be generated to improve the decision making of criticality and vulnerability ratings. Figure 2 shows the five triangular fuzzy numbers defined with the corresponding membership function.

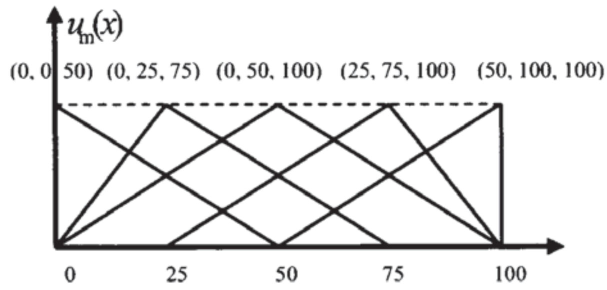

Fig. 2 Fuzzy membership functions for the five point fuzzy rating set

In the F-AHP based bridge rating method, the criticality rating for each structural component can be determined by the following steps:

(a) Figure out the criticality factors for each structural component using SHM-based computation simulations or engineering judgments (see Section 3).

(b) Work out the membership degrees matrix $[R_\mathrm{c}]$ based on the fuzzy membership functions and the criticality factors.

$$[R_\mathrm{c}] = \begin{pmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{pmatrix} \tag{6}$$

where n is the number of items in the criticality index level; m is the number of the fuzzy rating values in the fuzzy rating set $\{G_\mathrm{c}\}$; r_{ij} denotes the membership degree of the ith item to the jth fuzzy membership function; the subscript c means the criticality.

(c) The fuzzy synthetic rating vector $\{B_\mathrm{c}\}$ for criticality can then be determined by

$$\{B_\mathrm{c}\} = \{\omega_\mathrm{c}\}^\mathrm{T} [R_\mathrm{c}] \tag{7}$$

(d) The fuzzy synthetic rating T_c for the criticality of the concerned structural component can be finally obtained as

$$T_\mathrm{c} = \{G_\mathrm{c}\}\{B_\mathrm{c}\}^\mathrm{T} \tag{8}$$

In the F-AHP based bridge rating method, the vulnerability rating for each structural component can be determined by the following steps:

(a) Figure out the vulnerability factors for each structural component in the vulnerability index level 2 (see Section 3).

(b) Calculate the vulnerability factors for each structural component in the vulnerability level 1 using the weighted product model.

$$\begin{cases} V1 = VA1^{1/3} \times VB1^{1/3} \times VC1^{1/3} \\ V2 = VA2^{1/3} \times VB2^{1/3} \times VC2^{1/3} \\ V3 = VA3^{1/3} \times VB3^{1/3} \times VC3^{1/3} \end{cases} \tag{9}$$

(c) Work out the membership degree matrix $[R_\mathrm{v}]$ based on the fuzzy membership functions and the vulnerability factors, where the subscript v means the vulnerability.

(d) The fuzzy synthetic rating vector $\{B_\mathrm{v}\}$ for vulnerability can then be determined by

$$\{B_\mathrm{v}\} = \{\omega_\mathrm{v}\}^\mathrm{T} [R_\mathrm{v}] \tag{10}$$

(e) The fuzzy synthetic rating T_v for the vulnerability of the concerned structural component can be finally obtained as

$$T_\mathrm{v} = \{G_\mathrm{v}\}\{B_\mathrm{v}\}^\mathrm{T} \tag{11}$$

2.4 Fuzzy Synthetic Decision

The fuzzy synthetic rating R at the objective level can be calculated based on the fuzzy synthetic ratings, T_c and T_v, and the relative weights at the criterion level.

$$R = \{\omega_\mathrm{cv}\}^\mathrm{T} \begin{Bmatrix} T_\mathrm{c} \\ T_\mathrm{v} \end{Bmatrix} \tag{12}$$

After the fuzzy synthetic ratings of all the structural components are obtained, the prioritization for inspection frequency can be determined. The larger the value of R, the smaller is the inspection time interval. One example is shown in Table 1.

Table 1. Fuzzy synthetic decision for inspection

Scale of fuzzy synthetic rating R	Time interval for inspection
$75 \le R < 100$	6 months
$57.5 \le R < 75$	1 Year
$25 \le R < 57.5$	2 Years
$0 \le R < 25$	6 Years

3. F-AHP SHM-Based Criticality and Vulnerability Analysis

3.1 Criticality Factors

The criticality factors include five items in this study for a long-span cable-supported bridge. Table 2 shows the definitions, range and points for each criticality factor. The numerical values of the five criticality factors range from 0 to 100.

Table 2. Criticality Factor (CF): definitions and values

CF	Definition	Range	Points
C1	Any alternative load path?	No	100
		Yes, affect global structural performance	67
		Yes, not affect global structural performance	0
C2	Design normal combined loads (based on strength utilization factor)	0% - 100%	0-100
C3	Design fatigue loads (based on fatigue life)	High: < 200 years	100
		Normal: between 200-300 years	67
		Low: > 300 years or not applicable	0
C4	Known or discovered imperfections but not serious enough to warrant immediate repair	Any, non-repairable	100
		Any, repairable	67
		None	0
C5	Failure mechanisms	Catastrophic collapse	100
		Partial collapse	67
		Structural damage	33

3.2 Vulnerability Factors

The vulnerability factors include three items in this study. Table 3 shows the definitions, range and points for each vulnerability factor.

Table 3. Vulnerability Factor (VF): definitions and values

VF	Definition	Range	Points
V1. Corrosion	Exposure or degree of protection (VA1)	Internal or Adequate	0
		Partial or Average	50
		Extreme or None	100
	Likelihood of detection in superficial inspection (VB1)	Likely	0
		Possible	50
		Unlikely	100
	Likely influence on structural integrity (VC1)	Likely	0
		Possible	50
		Unlikely	100
V2. Damage	Exposure to damage(VA2)	None	0
		Medium	50
		High	100
	Likelihood of detection in superficial inspection (VB2)	Likely	0
		Possible	50
		None	100
	Likely influence on structural integrity (VC2)	Low	0
		Medium	50
		High	100
V3. Wear	Relative wear rate per annum (VA3)	Low	0
		Medium	50
		High	100
	Likelihood of detection in routine maintenance (VB3)	Likely	0
		Medium	50
		Unlikely	100
	Likely influence on structural integrity (VC3)	Low	0
		Medium	50
		High	100

4. Case Study

The Tsing Ma suspension bridge in Hong Kong is taken as a case study to demonstrate the feasibility of the proposed SHM-based F-AHP rating method as guidance in determining the time intervals for inspection. The Tsing Ma Bridge is a suspension bridge with an overall length of 2,132 m and a main span of 1,377 m. The height of the two reinforced concrete towers is 206 m. The two main cables of 1.1 m diameter and 36 m apart in the north and south are accommodated by the four saddles located at the top of the tower legs. The bridge deck is a hybrid steel structure consisting of Vierendeel cross frames supported on two longitudinal trusses acting compositely with stiffened steel plates.

4.1 Classification of Structural Components

The key structural components of the Tsing Ma Bridge are classified into 15 groups and 55 components for criticality and vulnerability analyses (3). The 15 groups, which are basically the key components of the Tsing Ma Bridge for direct and indirect load-transfer, are: (1) suspension cables, (2) suspenders; (3) towers, (4) anchorages, (5) piers; (6) outer-longitudinal trusses; (7) inner-longitudinal trusses; (8) main cross frames; (9) intermediate cross-frames; (10) plan bracings; (11) deck; (12) rail way beams, (13) bearings; (14) movement joints; and (15) Tsing Yi approach deck. The details of classification in each group are illustrated in Table 4.

4.2 Criticality and Vulnerability Factors

This section takes the criticality factors C2 and C3 as an example to explain how to use the measurement data recorded by the SHMS to determine these factors.

To determine the criticality factor C2 for each of the structural components of the Tsing Ma Bridge, the criticality analysis of the bridge is performed on strength of the bridge under design normal combined loads in terms of the strength utilization factor. To fulfill this task, the SHM-oriented finite element model of the Tsing Ma Bridge is established (see Fig. 3) based on the approach of one analytical member representing one real member at a stress level using the ABAQUS software package (7). Seven types of loads (dead loads, super-imposed dead loads, temperature loads, highway loads, railway loads, wind loads, and seismic loads) and three load combinations have been considered in the stress analysis of the bridge. Except for the dead loads, the super-imposed dead loads and the seismic loads, there are 2, 24, 8 and 3 load cases for the temperature loads, the highway loads, the railways loads and the wind loads, respectively. In the three load combinations, there are also a total of 52 load cases. For each load case, the stresses in the major structural components are determined, and the stress distributions are obtained for each of the major structural components. Based on the obtained stress distribution results, the stresses in the structural components at 5 key bridge deck sections are provided. The strength utilization factors of the major structural components are calculated, from which the critical locations of each major structural components are identified. With the computed strength utilization factors for the major structural components of the bridge, the point can be assigned according to Table 2.

Fig. 3 A 3-D finite element model of Tsing Ma Bridge

To determine the criticality factor C3 for each of the structural components of the bridge, the criticality analysis of the bridge is performed on fatigue life of the structural components. The railway loading and highway loading are considered to be major contributors to fatigue damage of the bridge (8). The railway and highway loadings measured by the SHMS are then used to derive the actual train and road vehicle spectrum for fatigue assessment. A traffic induced stress analysis method is proposed based on the

Table 4. Classification of structural components of Tsing Ma Bridge

Name of Group	Name of Component	Group No.	Component No.	Serial No.
Suspension Cables	Main Cables	1	(a)	1
	Strand Shoes		(b)	2
	Shoe Anchor Rods		(c)	3
	Anchor Bolts		(d)	4
	Cable Clamps & Bands		(e)	5
Suspenders	Hangers	2	(a)	6
	Hanger Connections: Stiffeners		(b)	7
	Hanger Connections: Bearing Plates		(c)	8
Towers	Legs	3	(a)	9
	Portals		(b)	10
	Saddles		(c)	11
Anchorages	Chambers	4	(a)	12
	Prestressing Anchors		(b)	13
	Saddles		(c)	14
(Piers: M1, M2, T1, T2, T3)	Legs	5	(a)	15
	Cross-Beams		(b)	16
Outer-Longitudinal Trusses	Top Chord	6	(a)	17
	Diagonal		(b)	18
	Vertical Post		(c)	19
	Bottom Chord		(d)	20
Inner-Longitudinal Trusses	Top Chord	7	(a)	21
	Diagonal		(b)	22
	Vertical Post		(c)	23
	Bottom Chord		(d)	24
Main Cross-Frames	Top Web	8	(a)	25
	Sloping Web		(b)	26
	Bottom Web		(c)	27
	Bottom Chord		(d)	28
Intermediate Cross-Frames	Top Web	9	(a)	29
	Sloping Web		(b)	30
	Bottom Web		(c)	31
	Bottom Chord		(d)	32
Plan Bracings	Upper-Deck	10	(a)	33
	Lower-Deck		(b)	34
Deck	Troughs	11	(a)	35
	Plates		(b)	36
Railway beams	T-Sections	12	(a)	37
	Top Flanges		(b)	38
	Connections		(c)	39
Bearings	Rocker Bearings at Ma Wan Tower	13	(a)	40
	PTFE Bearings at Tsing Yi Tower		(b)	41
	PTFE Bearings at Pier T1		(c)	42
	PTFE Bearings at Pier T2		(d)	43
	PTFE Bearings at Pier T3		(e)	44
	PTFE Bearings at Tsing Yi Anchorage		(f)	45
	Rocker Bearings at M2		(g)	46
	PTFE Bearings at M1		(h)	47
	Hinge Bearing at Lantau Anchorage		(i)	48
Movement Joints	highway Movement Joint	14	(a)	49
	Railway Movement Joint		(b)	50
Tsing Yi Approach Deck	Top Chord	15	(a)	51
	Diagonal		(b)	52
	Vertical Post		(c)	53
	Bottom Chord		(d)	54
	Diagonals (K-Bracings)		(e)	55

SHM-oriented finite element model of the bridge and the influence line method for the determination of stress time histories. The fatigue-critical locations are identified for different bridge components. Finally, the fatigue lives due to both train and road vehicles at the fatigue-critical components are estimated using the vehicle spectrum method recommended in British Standard (9). With the computed fatigue lives of fatigue-critical locations of each bridge component, the point can be assigned according to Table 2.

Other criticality factors and vulnerability factors are not explained here, and the criticality factors of each bridge component used in this study are listed in Table 5.

Table 5. Scores of criticality factors

Group No.	Serial No.	Criticality Factors				
		C1	C2	C3	C4	C5
1	1	100	65	0	0	100
	2	67	67	0	0	100
	3	67	67	0	0	100
	4	67	67	0	0	100
	5	67	67	0	0	33
2	6	67	16	0	0	33
	7	67	100	0	0	33
	8	67	100	0	0	33
3	9	100	40	0	0	67
	10	100	67	0	0	67
	11	100	67	0	0	67
4	12	100	33	0	0	100
	13	67	100	0	0	67
	14	100	67	0	0	67
5	15	100	33	0	0	100
	16	100	67	0	0	67
6	17	100	62	0	0	67
	18	100	75	100	0	67
	19	100	20	67	0	67
	20	100	76	100	0	67
7	21	67	100	67	0	67
	22	67	53	0	0	67
	23	67	32	67	0	67
	24	67	100	67	0	67
8	25	67	71	0	0	67
	26	100	67	67	0	67
	27	100	100	0	0	67
	28	100	100	0	0	67
9	29	67	31	0	0	67
	30	67	67	67	0	67
	31	67	100	67	0	67
	32	67	100	67	0	67
10	33	100	85	0	0	67
	34	100	57	0	0	67
11	35	67	100	67	0	67
	36	67	100	0	0	67
12	37	100	0	67	0	67
	38	100	33	0	0	67
	39	100	33	0	0	67
13	40	100	100	0	0	67
	41	100	100	0	67	67
	42	100	100	0	67	67
	43	100	100	0	67	67
	44	100	100	0	67	67
	45	100	100	0	67	67
	46	100	100	0	0	67
	47	100	100	0	67	67
	48	100	100	0	0	67
14	49	100	67	100	0	33
	50	100	67	100	0	33
15	51	67	38	0	0	67
	52	67	36	0	0	67
	53	67	28	67	0	67
	54	67	78	67	0	67
	55	67	19	67	0	67

Table 6. Comparison matrix and relative weights for CR1

Index level	C1	C2	C3	C4	C5	Relative weight
C1	1	1/3	1/2	1	1	0.1237
C2	3	1	2	3	3	0.3945
C3	2	1/2	1	2	2	0.2343
C4	1	1/3	1/2	1	1	0.1237
C5	1	1/3	1/2	1	1	0.1237

Table 7. Comparison matrix and relative weights for VR1

Index level	V1	V2	V3	Relative weight
V1	1	2	2	0.5
V2	1/2	1	1	0.25
V3	1/2	1	1	0.25

Table 8. Decision on time intervals for inspection

Group No.	Serial No.	Score of fuzzy rating	Time interval for inspection (year)
1	1	53.3	2
	2	51.9	2
	3	51.9	2
	4	51.9	2
	5	45.3	2
2	6	44.3	2
	7	57.6	1
	8	57.6	1
3	9	50.5	2
	10	50.1	2
	11	50.1	2
4	12	51.1	2
	13	55.1	2
	14	52.2	2
5	15	51.1	2
	16	50.1	2
6	17	50.6	2
	18	60.5	1
	19	50.1	2
	20	60.6	1
7	21	56.8	2
	22	45.1	2
	23	47.3	2
	24	56.8	2
8	25	51.4	2
	26	54.9	2
	27	59.0	1
	28	59.0	1
9	29	43.0	2
	30	52.8	2
	31	57.0	2
	32	57.0	2
10	33	54.4	2
	34	47.4	2
11	35	56.8	2
	36	55.1	2
12	37	48.0	2
	38	50.2	2
	39	50.2	2
13	40	59.6	1
	41	59.2	1
	42	59.2	1
	43	59.2	1
	44	59.2	1
	45	59.2	1
	46	59.6	1
	47	59.2	1
	48	59.6	1
14	49	62.3	1
	50	62.3	1
15	51	44.7	2
	52	44.2	2
	53	46.4	2
	54	53.8	2
	55	47.3	2

4.3 Relative Weights

According to the AHP procedure described in Section 2.2, the comparison matrix and the relative weights for the criticality index level 1 (CR1) are found and listed in Table 6. The counterparts for the vulnerability index level 1 (VR1) are listed in Table 7. If the importance of criticality is regarded to be the same as that of vulnerability, the relative weight vector for the criterion level can be taken as $\{\omega_{cv}\} = \{0.5, 0.5\}^{T}$.

4.4 Inspection Based on Fuzzy Synthetic Decision

Based on the relative weights decided and according to the proposed SHM-based F-AHP rating method, the decision on the time intervals for inspection can be determined and the results are listed in Table 8. It can be seen that for the bridge components concerned, the time intervals for inspection are either 1 year or 2 years.

5 Conclusions

A SHM-based F-AHP bridge rating method for long-span cable-supported bridges has been proposed in this study. The proposed bridge rating method has been applied to the Tsing Ma Bridge in Hong Kong. For the bridge components concerned, the time intervals for inspection are either 1 year or 2 years. The results from the case study indicate that the proposed bridge rating method is feasible and can be used in practice for long span cable-supported bridges with SHMS.

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Acknowledgements

The work described in this paper was financially supported by The Hong Kong Polytechnic University through its Niche Area Program on Performance-Based Structural Health Monitoring of Large Civil Engineering Structures, and the Hong Kong Highways Department through a contract research on bridge health and engineering. All views expressed in this paper are entirely those of the authors.