

Comprehensive evaluation method for superstructures of prestressed concrete girder bridges

Huang Qiao^{1,2} Lin Yangzi¹ Ren Yuan¹

(¹Institute of Bridge Engineering, Harbin Institute of Technology, Harbin 150090, China)

(²Institute of Bridge and Tunnel Engineering, Southeast University, Nanjing 210096, China)

Abstract: A multi-level evaluation model for the superstructure of a damaged prestressed concrete girder or beam bridge is established, and the evaluation indices of the model as well as the rating standards are defined. A normal relative function about the evaluation indices of each element is developed to calculate the relative degree, and for each element there are no sub-level elements. When evaluating the elements in the sub-item level or the index level of the model, the weights of elements pertain to one adopted element, taking into account their degrees of deterioration. Since the relative degrees and structure evaluation scales on the damage conditions are applied to characterize the superstructure of damaged prestressed concrete girder bridges, this method can evaluate the prestressed structure in detail, and the evaluation results agree with the *Code for Maintenance of Highway Bridges and Culvers* (JTG H11—2004). Finally, a bridge in Jilin province is taken as an example, using the method developed to evaluate its damage conditions, which gives an effective way for bridge engineering.

Key words: bridge engineering; comprehensive evaluation; analytic hierarchy process (AHP) method; relative degree; weight modification

It has been a global problem that bridges get aged and damaged. In recent years, the bearing capacity of many highway bridges in China has been gradually declining, owing to long-term exposure in the atrocious environment and artificially imposed damage during the service lives of the bridges, and so, most of these bridges are in urgent need of maintenance and reinforcement. An accurate and integrative

evaluation of damaged bridges is a prerequisite for drawing up a bridge maintenance strategy and reinforcement design^[1-2].

In this paper, particular attention is paid to establishing a multi-level evaluation model for the superstructure of damaged prestressed concrete girder bridges, and to presenting the evaluation indices, of which the rating standards are defined. Each evaluation index is influenced by numerous factors, and, based on the Liapunov theorem, a normal relative function is developed to calculate the relative degrees concerning the evaluation indices of each element, without sub-level elements to each rating grade being taken into consideration. When evaluating the elements in the sub-item level or the index level of the model, the weights of elements that pertain to one element are adopted, taking into account their degrees of deterioration. Uniform with the code JTG H11—2004, the damage conditions of the superstructure of a damaged prestressed concrete girder bridge are characterized by relative degrees and a structure evaluation scale. Finally, based on actual bridge engineering, a practical calculation example is presented.

1 Evaluation Model and Evaluation Rating Standards

The multi-level evaluation model for the prestressed concrete bridge girder superstructure includes the index level, the sub-item level, the item level and the goal level, as shown in Fig. 1. Based on the current code JTG H11—2004, the existing engineering experience and experimental results, and the

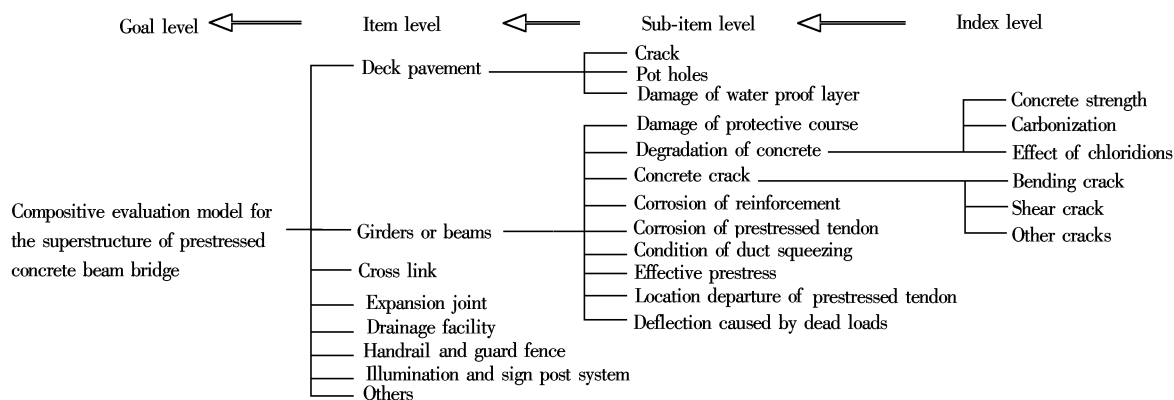


Fig. 1 Multi-level evaluation model for prestressed concrete bridge superstructures

Received 2007-01-05.

Biography: Huang Qiao (1958—), male, doctor, professor, qhuanghit@126.com.

Foundation item: The Science and Technology Program for Western Communication Construction of Ministry of Communications (No. 200538181215).

Citation: Huang Qiao, Lin Yangzi, Ren Yuan. Comprehensive evaluation method for superstructures of prestressed concrete girder bridges[J]. Journal of Southeast University (English Edition), 2008, 24(1): 64 – 68.

advice of experts, the evaluation indices and corresponding grading standards are presented for prestressed concrete bridge superstructures, as shown in Tab. 1.

For a relative simple loading condition or conformation without sub-elements, the components can be estimated empirically just according to all - round and careful exterior

Tab. 1 Evaluation rating standards of each element on prestressed concrete bridge superstructures

Evaluation elements	Evaluation index	Evaluation grade and value sections				
		I	II	III	IV	V
Bending crack	$\alpha W_b/\text{mm}$	0	(0, 0.02)	(0.02, 0.1)	(0.1, 0.30)	(0.3, 0.6)
Shear crack	$\beta W_s/\text{mm}$	0	(0, 0.05)	(0.05, 0.2)	(0.2, 0.4)	(0.4, 0.7)
Other cracks	$\gamma W_o/\text{mm}$	(0, 0.05)	(0.05, 0.1)	(0.1, 0.2)	(0.2, 0.5)	(0.5, 0.8)
Concrete strength	$(R_d - R_m)/R_d$	(-0.02, 0)	(0, 0.05)	(0.05, 0.1)	(0.1, 0.2)	(0.2, 0.3)
Carbonization	d_m/C	(0, 0.2)	(0.2, 0.45)	(0.45, 0.7)	(0.7, 1.0)	(1.0, 1.4)
Effect of chloridion	Chloridion content/%	(0, 0.15)	(0.15, 0.3)	(0.3, 0.45)	(0.45, 0.6)	(0.6, 0.8)
Damage of protective course	Rate of protective course damage	(0, 0.05)	(0.05, 0.1)	(0.1, 0.2)	(0.2, 0.35)	(0.35, 0.6)
Corrosion of reinforcement	Loss rate of cross-sectional area	(0, 0.015)	(0.015, 0.05)	(0.05, 0.12)	(0.12, 0.2)	(0.2, 0.3)
Corrosion of prestressed tendon	Loss rate of cross-sectional area	(0, 0.01)	(0.01, 0.03)	(0.03, 0.1)	(0.1, 0.15)	(0.15, 0.2)
Condition of duct squeezing	Degree of unsaturation	(0, 0.05)	(0.05, 0.1)	(0.1, 0.2)	(0.2, 0.35)	(0.35, 0.5)
Effective prestress	$ \sigma_d - \sigma_m /\sigma_d$	(0, 0.05)	(0.05, 0.1)	(0.1, 0.15)	(0.15, 0.2)	(0.2, 0.35)
Location departure of prestressed tendon	$ \Delta y/y_p $	(0, 0.02)	(0.02, 0.05)	(0.05, 0.08)	(0.08, 0.12)	(0.12, 0.2)
Deflection caused by dead loads	$(f_m - f_{DL})/f_{DL}$	(-0.3, 0)	(0, 0.2)	(0.2, 0.5)	(0.5, 1)	(1, 1.5)

inspection and detection. The evaluation values of those components can be confirmed directly, including handrails, expansion joints, bearings, etc. For the evaluation standards of other components one can refer to previous research results^[3-4].

In Tab. 1: ① The prestressed structure means integrated or partially prestressed structure. ② α, β, γ are the correction coefficients of crack measure values, considering the formation causes of cracks, environmental factors and development trends. ③ Δy is the location departure of prestressed tendons of the design position; y_p is the designed eccentric distance of the position of prestressed tendons relative to the gravity axis. ④ f_{DL} is the calculated deflection caused by dead load and prestress force, considering the long-term effects. ⑤ The chloridion index is adopted to apply in environment II, and it can be adjusted for other environments.

2 Evaluation Method

2.1 Confirm the initial weight

Referencing the recommended weight values in Ref. [4], and according to the present bridge conditions, estimate experts can adjust and confirm the recommended weights. One requirement is that the weight of each element be equal to the sum of the weights of its lower elements; i. e.,

$$W_{i,j} = \sum_{j'=1}^l W_{i+1,j'} \quad i = 1, 2, 3, 4 \quad (1)$$

where j' represents the sub-elements of the element j ; l is the sub-element number of the element j ; and i represents the sub-item level, the item level and the goal level.

Finally, for the goal level:

$$W_1 = 100 \quad (2)$$

2.2 Relative degree and its application

In the theory of fuzzy matter-element analysis, relative degree is defined as the measure of relevance between one thing and the standard thing^[5]. Because of the uncertainties in the bridge structures, such as the material characteristics, geometrical features, distribution of loads along with the deterioration parameters, etc., it is difficult to make an exact evaluation for an existing bridge or component. Therefore, it is reasonable to take the “relative degree” as the basic parameter in the bridge evaluation model.

Generally, the distributions of the above factors, such as material characteristics, geometrical features, etc., follow the normal distribution^[6-7]. Based on the Liapunov theorem, it can be thought that the element evaluation index approximately follows the normal distribution. The main factors affecting relative degrees of the element evaluation index and evaluation grades are as follows: ① The distance between the evaluation index measured value and the corresponding interzone spacing of the grade; ② The dimensions of the corresponding interzone spacing of the grade.

Therefore, a normal relative function as shown in Eq. (3) is taken to calculate the relative degrees, which are then standardized. It means that the sum of the relative degrees between the element evaluation values and evaluation grades should be equal to 1.0. Based on this, we have

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-x_j)^2}{2\sigma^2}\right) \quad (3)$$

Assuming that the relative degree between the evaluation index measured value x_j and the grades n is K'_{jn} , the following equation is calculated:

$$K'_{jn} = \begin{cases} \frac{(b_{jn}-a_{jn})\left(f(a_{jn})+f\left(\frac{a_{jn}+b_{jn}}{2}\right)+f(b_{jn})\right)}{3} & x_j \notin (a_{jn}, b_{jn}) \\ \frac{(b_{jn}-a_{jn})(f(a_{jn})+f(x_j)+f(b_{jn}))}{3} & x_j \in (a_{jn}, b_{jn}) \end{cases} \quad (4)$$

For the boundary conditions, when $x_j \leq a_{j1}$, $K'_{j1} = 1$, $K'_{jn} = 0$ ($n \neq 1$); when $x_j \geq b_{j5}$, $K'_{j5} = 1$, $K'_{jn} = 0$ ($n \neq 5$).

The relative degree is then standardized:

$$K_{jn} = \frac{K'_{jn}}{\sum_{n=1}^5 K'_{jn}} \quad n = 1, 2, \dots, 5 \quad (5)$$

According to existing engineering, test experiences, and the advice of experts, the mean square deviation is taken as

$$\sigma = \frac{b_{j4} - a_{j2}}{m} \quad (6)$$

where K_{jn} is the relative degree between the evaluation index of element j and the grade n ; x_j is the evaluation index measured or the evaluation value of element j ; b_{jn}, a_{jn} are respectively the upper and lower limits of the n -th evaluation

grade space interval of element j ; n means the evaluation grade, and it is divided into 5 grades; m is the coefficient of the mean square deviation. Based on a great deal of tentative calculation, it is temporarily assumed as 12.

2.3 Evaluation of item level and sub-item level

When evaluated, the weights of the elements in the sub-item and index levels need to be revised, considering the contribution of various elements to the evaluation of the upper-level elements, which depends on their degrees of damage. Because the elements in the sub-item and index levels are not completely independent, or some of them do not exist, and the conditions of the elements with more damage characterize the damage conditions of its upper-level elements to a greater extent^[8], the correction coefficients of the elements should be large, if the lower evaluation grade (i. e. grade V) is large, which means the damage to the element is severe; and the correction coefficient of the element should be small, if the higher evaluation grade (i. e. grade I) is large. Then the relative degrees between an element condition and each evaluation grade are

$$K_{jn} = \frac{\sum_{j'=1}^l W'_{j'} K'_{j'n}}{\sum_{j'=1}^l W'_{j'}} \quad (7)$$

of which the adjusted weight $W'_{j'}$ is

$$W'_{j'} = \frac{\eta_{j'} W_{j'} (W_j - \sum_{j''=1}^k W'_{j''})}{(W_j - \sum_{j''=1}^k W'_{j''})} \quad (8)$$

When adjusting the weight of each element, it should follow the sequence from a large correction coefficient $\eta_{j'}$ to a small one. The correction coefficient $\eta_{j'}$ can be calculated by

$$\eta_{j'} = 1 + \frac{\sum_{n=1}^5 2(n-1) K_{jn}}{5} \quad (9)$$

After a certain element weight is adjusted by Eq. (8), if $W'_{j'} \geq W_j - \sum_{j''=1}^k W'_{j''}$, which means that the sum of the weight

of the element of the lower level exceeds the weight of the element of the upper level, the correction coefficient does not adapt any more, and the weights of this element and the remaining ones should be adjusted by

$$W'_{j'} = \frac{W_{j'} (W_j - \sum_{j''=1}^k W'_{j''})}{W_j - \sum_{j''=1}^k W'_{j''}} \quad (10)$$

where k is the number of adjusted weight elements, $W_{j'}$ is the initial weight of adjusted weight elements, and $W'_{j'}$ is the adjusted weight of the adjusted weight elements.

2.4 Evaluation of goal level

When calculating the relative degree of elements in the goal level, the method of directly weighted means is used, without consideration to adjusted weights. Because each element of the item level in the multi-level evaluation model is comparatively independent, for the prestressed concrete structure, referring to Ref. [4], the evaluation results of the goal level or the item level are expressed by relative degrees and the element evaluation scale R_j .

The relative degrees between the item and goal levels are calculated by

$$K_{jn} = \frac{\sum_{j'=1}^l W_{j'} K_{j'n}}{\sum_{j'=1}^l W_{j'}} \quad (11)$$

$$R_j = \sum_{n=1}^5 \frac{5(n-1) K_{jn}}{4} \quad (12)$$

Referring to the evaluation grades in Ref. [4], the evaluation scales are classified into five categories. The relative technology status and classifications are shown in Tab. 2. Moreover, in the situation that the evaluation scale of the goal level $R_j \leq 3$ and the evaluation scale of some components in the item level $R_j \geq 3$, the repair and maintainance of some damaged components should not be ignored, whether or not the synthetic evaluation is perfect or good (i. e. bridge of class I or II).

Tab. 2 Evaluation of girder sub-item level

Evaluation elements	Initial weight	Evaluation value	Relative degree of each evaluation grade					Adjusted weight
			I	II	III	IV	V	
Concrete crack	3.0		0.000	0.001	0.058	0.533	0.407	4.700
Concrete deterioration	3.0		0.848	0.152	0.000	0.000	0.000	1.240
Damage of protective course	2.5	0.01	0.866	0.133	0.001	0.000	0.000	1.010
Corrosion of reinforcement	5.5	0.001	0.763	0.235	0.002	0.000	0.000	2.436
Corrosion of prestressed tendon	6.0	0	1.000	0.000	0.000	0.000	0.000	2.267
Condition of duct squeezing	2.5	0.08	0.165	0.623	0.212	0.000	0.000	1.513
Effective prestress	6.0	0.15	0.000	0.005	0.566	0.429	0.000	6.801
Location departure of prestressed tendon	3.0	0	1.000	0.000	0.000	0.000	0.000	1.133
Deflection caused by dead loads	6.5	1.6	0.000	0.000	0.000	0.000	1.000	16.900

3 Evaluation Example

There is a three-span prestressed concrete continuous beam bridge(48.2 m + 2 × 49 m) located in Jilin province. Limited by the length, only the main girder, which is the most complex member of the bridge, is evaluated in this paper.

There are serious traversing cracks in the middle of the second span and the largest crack width is about 0.3 mm; there are two shear cracks in the web and the crack widths are 0.2 to 0.3 mm; there are also vertical cracks in the second span joint and the largest crack width is around 0.2 mm.

The concrete strength satisfies the design requirements. The carbonization depth of the concrete is less than 1 mm, and the equilibrium content of chlorine hydronium in the concrete is 0.12. There is no damage in the protection course.

Though individual technical evaluation indices still cannot be exactly measured, based on meticulous measurements and calculations, it is found that the effective prestress is reduced to about 85% of the design values. There are some inter-spaces in the prestress grouting duct, but there are not the corrosion phenomena of the tendon. The tendon position is in agreement with the design drawings. The reinforcing bar has gentle corrosion phenomena.

The deflection in the middle of the second span is 10.4 cm, and it is still growing.

Based on the *Code for Maintenance of Highway Bridges and Culvers*(JTG H11—2004), it is confirmed that the initial weight of the main girder in this bridge is 38 by evaluation experts.

Considering that most bending cracks have developed up to the web, and the width is still developing, the bending crack correction coefficient α is 1.2.

After calculation, the relative degree between the concrete crack conditions and each evaluation grade is

$$(0, 0.001, 0.058, 0.533, 0.407)$$

The relative degree between the concrete deterioration conditions and each evaluation grade is

$$(0.848, 0.152, 0, 0, 0)$$

In accounting for the index level evaluation results and the inspection results of other elements in the sub-item level, the sub-item level elements of the main girder are evaluated and the results are shown in Tab. 2. The initial weight of each element is confirmed according to individual importance, and it should be satisfactory that the sum is equal to the initial weight of the main girder element.

By adjusting the weights, the element condition that is more serious can characterize the damage condition of the upper-level element to a greater extent.

To sum up, by Eq. (11), the relative degrees between the main girder conditions and each evaluation grade are

$$(0.196, 0.049, 0.117, 0.143, 0.495)$$

Moreover, according to Eq. (12), the element evaluation

scale R_j of the main girder is 3.365. The corresponding conditions class is IV, and it needs greater repair and traffic control.

4 Conclusions

1) Based on the above relative degree analyses, a multi-level evaluation model of prestressed concrete bridge superstructure damage conditions is developed. Furthermore, the evaluation indices and grading standards of prestressed concrete bridge structures are presented.

2) Considering the formation causes of cracks, environmental factors and development trends, it is suitable to adopt correction coefficients to the measured values of cracks. Therefore, an adjusted value can better characterize the crack effects.

3) A normal relative function is derived to calculate and analyze the relative degrees, considering the uncertainties of the factors in the bridge structures. Moreover, the weights of the elements in the sub-item and index levels are adjusted, according to the damage extent of each element. When evaluating the elements in the goal level, we can adopt the method of the directly weighted mean. Therefore, evaluation results can be better made in accordance with the actual conditions of a bridge.

4) We can evaluate the elements under an item level with relative degrees, and express the evaluation results of the goal level and the item level with both relative degrees and element evaluation scales. Therefore, the method is in accord with the *Code for Maintenance of Highway Bridges and Culvers* (JTG H11—2004).

5) Based on actual bridge engineering, a practical calculation example is presented. The evaluation results demonstrate the validity of this method.

The evaluation method aimed at prestressed concrete bridge superstructure conditions has not yet been mentioned in the current code(JTG H11—2004). In addition, the method presented in this paper will enhance the accuracy and reliability of the technological status evaluation for prestressed concrete bridge superstructures, and provide scientific reference for bridge maintenance strategies.

References

- [1] Estes Allen C, Frangopol Dan M. Bridge lifetime system reliability under multiple limit states[J]. *Journal of Bridge Engineering*, 2001, 6(6): 523 – 528.
- [2] Wang Youzhi. *Reliability evaluation and reinforcement for bridges*[M]. Beijing: China WaterPower Press, 2002: 160 – 195. (in Chinese)
- [3] Zhang Xinzhan. Study on bridge management systems[D]. Xi'an: Chang'an University, 2000. (in Chinese)
- [4] JTG H11—2004 Code for maintenance of highway bridges and culvers[S]. Beijing: China Communications Press, 2003. (in Chinese)
- [5] Li Hongji. *Basics of fuzzy math and its practicality applications*[M]. Beijing: Science Press, 2005: 352 – 386. (in Chinese)
- [6] Zhang Xinpei. *Construction reliability analysis and design* [M]. Beijing: Science Press, 2001: 69 – 95. (in Chinese)
- [7] Zhang Jianren, Liu Yang, Xu Fuyou, et al. *Structure reliability theory and its applications in bridge engineering*[M]. Bei-

jing: China Communications Press, 2003: 99 – 119. (in Chinese)

[8] Ren Baoshuang, Qian Jiaru, Nie Jiangou, et al. Synthesized

evaluation method for existing simple supported beam type RC bridge structures[J]. *China Civil Engineering Journal*, 2002, **35**(2): 97 – 102. (in Chinese)

预应力混凝土梁桥上部结构综合评价方法

黄 侨^{1,2} 林阳子¹ 任 远¹

(¹ 哈尔滨工业大学桥梁工程研究所, 哈尔滨 150090)
(² 东南大学桥梁与隧道研究所, 南京 210096)

摘要:建立针对缺损预应力混凝土梁桥上部结构的多层次评估模型,提出模型中各项评价指标并初步确定其分级标准.构造正态关联函数计算确定无下属层元素评价指标与相应各评价等级的关联度,并在对模型中分项层及指标层元素进行评价时,考虑同下属于某元素的各元素的缺损状态进行权重修正计算.采用关联度及结构评定标度共同表征预应力混凝土梁桥上部结构的缺损状态,故该方法可针对预应力结构进行细致的评价,并且结果与现行《公路桥涵养护规范》的评价方法相统一.最后,对吉林省某一实际桥梁缺损状态进行了详细的评估,可作为算例供工程参考.

关键词:桥梁工程;综合评价;层次分析法;关联度;权重修正

中图分类号:U447