Post-Design Evaluation Analysis of Continuous Rigid Frame Bridge

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Abstract: In order to solve the problem of “attaching importance to the construction while neglecting the evaluation” in construction of continuous rigid frame bridges in China, a post-construction evaluation system was established by taking the elasticity modulus of concrete, frictional loss of prestress and loss of prestress as the indexes, and a three-level fuzzy comprehensive post-design evaluation model was built. The continuous rigid frame bridge on the Chongqing-Hechuan segment of Lanzhou-Haikou Expressway was taken as an example to conduct a comprehensive post-design evaluation. The results showed that the studied bridge was evaluated and categorized into Category II in the bridge design evaluation system, indicating a good design and operation state of this bridge. Suggestions and countermeasures were proposed for the design of continuous rigid frame bridges, with a vision to provide a basis for construction of bridges of the same type.

1. Introduction
With the rapid growth of the overall national strength of China, its construction quality of continuous rigid frame bridges has also been increasing at a high speed, but various problems and deficiencies remain in the process of bridge construction and development. Despite the achievements made in design and construction of most bridges, it is not until the later phase that attention is paid to bridge maintenance. In 2006, Charles Ernie put forward the basic concepts of grey theory in detail and implemented the post-construction evaluation of bridges [1]. Wang et al. put forward a fuzzy expert evaluation system for bridge service properties in 1996 [2]. In 2009, Li conducted the post-construction evaluation of the Jinping Hydropower Station Project in Honghe Autonomous Prefecture, and tested the correctness of its construction decisions and effectiveness of engineering construction and management specifications [3]. In 2012, Wang et al. systematically analyzed the evaluation methods after the project investment, such as with and without comparison method and analytic hierarchy process (AHP), and then analyzed and expounded their characteristics and problems worth noting [4]. In 2013, by analyzing some main disease characteristics of continuous rigid frame bridges, Fan combined the finite element analysis to construct an AHP-based evaluation method [5].

Although accomplishments have been made in the design and construction technology of continuous rigid frame bridges and the follow-up bridge maintenance management has been improved somehow, “attaching importance to construction while neglecting the evaluation” remains a problem in construction of bridges in China. Not only can the construction level of completed continuous rigid frame bridges be judged, but problems can also be identified through the comprehensive evaluation of their design, construction, maintenance, etc. In Chongqing, “a city of bridges” and a model city in western China, the bridge construction has presented a rocketing growth trend. It only took five years...
(since 2005) to construct a 2,000 km expressway. By virtue of a long span, continuous rigid frame bridges are the preferred alternative in the main bridge design, playing a very significant role in expressway bridges in Chongqing. Therefore, a three-level fuzzy comprehensive evaluation model was constructed in this study to realize the comprehensive post-design evaluation of continuous rigid frame bridges based on the factors influencing their service properties. Reliable measures and suggestions were provided for the follow-up bridge design, construction, management and maintenance.

2. Main Post-Design Evaluation Indexes of Construction Quality

2.1 Elasticity modulus of concrete

Generally, concrete strength and prestress (not a single one can be omitted) are the two key factors influencing and controlling the degrees of down-warping and cracking at the bridge midspan in the design study of continuous rigid frame bridges. Nevertheless, the hidden key factor, namely, elasticity modulus of concrete, is usually omitted during the design and construction process.

![Figure 1: Relational Graph between Elasticity Modulus of Concrete and Midspan Down-Warping Degree](image1)

![Figure 2: Full-Bridge Deflection Curves Corresponding to Different Elasticity Modulus Values of Concrete](image2)

The elasticity modulus of concrete influences the midspan deflection of continuous rigid frame bridges and their deflection in the later operation phase to a great extent. As shown in Figure 1, the elasticity modulus of concrete nearly presents a proportional linear relation with the deflection at the bridge midspan, and the maximum deflection nearby the bridge midspan increases with the reduction of elasticity modulus of concrete. When the elasticity modulus is decreased by 5%, the variable quantity of deflection at the bridge midspan is about 0.07-0.1 cm.

2.2 Frictional loss of prestress

Inaccurate position and size deviation of the prestressed duct are common problems in the prestressed
concrete construction of continuous rigid frame bridges, all of which will result in the increase of the frictional loss of prestress without any doubt. In relevant specifications, the frictional loss of prestress is defined using the frictional coefficient $k$ influencing per meter local deviation of pipeline and the frictional coefficient $u$ between prestressed tendon and pipeline wall. The deflection value will vary with the values of $k$ and $u$ as seen in Table 1.

Table 1: Deflection Values under Different Values of $k$ and $u$

| Values of $k$ and $u$ | Maximum deflection nearby the midspan |
|-----------------------|---------------------------------------|
| $k=0.0015$, $u=0.17$  | 0.0861                                |
| $k=0.0015$, $u=0.25$  | 0.0954                                |
| $k=0.015$, $u=0.35$   | 0.1068                                |
| $k=0.003$, $u=0.25$   | 0.1150                                |

As Table 1 shows, when $k$ is fixed and $u$ decreases from 0.25 to 0.17, the corresponding midspan deflection is reduced by 0.9 cm; when $u$ increases from 0.25 to 0.35, the midspan deflection is elevated by 1.14 cm; when $u$ remains constant, $k$ increases from 0.0015 to 0.003, and the corresponding midspan deflection is elevated by 0.8 cm. In other words, the estimated frictional loss of prestress will greatly affect the down-warping degree at the midspan of continuous rigid frame bridge. The continuous rigid frame bridges with different span structures have different values of $k$ and $u$ under different environmental conditions.

2.3 Loss of prestress

In general, the greater the loss of prestress is, the larger the down-warping degree of the bridge will be. Therefore, reducing the loss of prestress to the minimum level can significantly solve the down-warping problem at the bridge midspan. Under normal circumstances, the maximum deflection value at the bridge midspan is varied under different flexural-tensile stresses (Table 2).

Table 2: Maximum Down-Warping Values at Bridge Midspan under Different Flexural-Tensile Stresses

| Position of loss of prestress | Flexural-tensile stress (MPa) | Maximum deflection nearby midspan (m) |
|-------------------------------|------------------------------|---------------------------------------|
| Top plate                     | 1,339.2                      | 0.1089                                |
|                               | 1,116                        | 0.1444                                |
|                               | 976.5                        | 0.1685                                |
| Web                           | 1,339.2                      | 0.1089                                |
|                               | 1,116                        | 0.1160                                |
|                               | 976.5                        | 0.1210                                |
| Baseplate                     | 1,339.2                      | 0.1089                                |
|                               | 1,116                        | 0.1127                                |
|                               | 976.5                        | 0.1243                                |

As Table 2 shows, the maximum deflection nearby the bridge midspan and the flexural-tensile stress present a growth trend at a linear scale. The loss of prestress at top plate had a great impact on the midspan deflection, followed by the those at web and baseplate. When the top plate loses about 30% of prestress, the maximum deflection at the bridge midspan increases by 6 cm, indicating that the maximum deflection at the bridge midspan is greatly impacted by the loss of prestress, thus seriously influencing the follow-up serviceability of bridge.
3. Post-Design Evaluation System and Modeling

3.1 Establishment of a post-design evaluation index system
The evaluation results of bridge construction were analyzed from three aspects: design, construction, and operation, management & maintenance. The post-design evaluation, post-construction evaluation and post-operation, management & maintenance evaluation were taken as the second-level sub-item indexes in the evaluation system; the classification indexes served as the third-level indexes for various factors used to evaluate the sub-item indexes, namely, the criterion layer under the sub-item indexes, and the level of upper-layer sub-item index could be obtained through the evaluation of the third layer. The evaluation indexes at the bottom layer were the basic indexes of this evaluation system. Before the evaluation, the fundamental bottom-layer evaluation indexes should be surveyed, judged and described in detail, and the grade of third-layer classification indexes could be obtained via the qualitative or quantitative judgment of bottom-layer indexes.

Through the detailed description and judgment of indexes at all levels, the evaluation was started from the bottom-layer indexes using the fuzzy comprehensive evaluation method, the technical evaluation was completed from bottom up and layer by layer, and the final comprehensive post-design evaluation result of continuous rigid frame bridges was obtained.

3.2 Post-design evaluation modeling
As Figure 3 shows, the post-design evaluation system of continuous rigid frame bridges was divided into three layers: overall objective (target layer), classification indexes (first-level criterion layer) and bottom-layer basic evaluation indexes. Based on the three-layer evaluation system, the three-level fuzzy comprehensive evaluation model was used to realize the post-construction performance evaluation of continuous rigid frame bridges on expressways. The establishment of the comprehensive post-construction evaluation model will be introduced in detail in this section, followed by the design of the
design evaluation, construction evaluation and operation, management & maintenance evaluation of continuous rigid frame bridges according to this model.

① Establishment of the influence factor set \{U\} of classification indexes

The third-layer classification indexes are set as \( U_i \equiv \{ u_{i1}, u_{i2}, \ldots, u_{in} \} \), among which \( u_{in} \) is the fourth-layer (bottom-layer) index of the evaluation system, \( i \) is the \( i \)th evaluation index at this layer corresponding to the evaluation index at the upper layer; \( n \) represents the \( n \)th bottom-layer evaluation index corresponding to the evaluation index at this layer.

② Determination of the evaluation set

According to the previous hierarchical classification of related post-construction evaluation indexes of continuous rigid frame bridges, the evaluation set was divided into \( V \) classes.

\[ V = \{ \text{Excellent, fairly good, good, ordinary, poor} \} \]

③ Construction of the fuzzy relation matrix

According to empirical analysis and judgment of experts, the grading standard of classified evaluation indexes was combined with the influence degrees of different factors on the indexes to determine the evaluation vector of evaluation indexes, and the single-factor fuzzy evaluation method was selected to construct a fuzzy relation matrix. On this basis, the fuzzy relation matrix between each classification index and influence factor was set as \( R_i \).

\[
R_i = \begin{bmatrix}
\alpha_{i1} & \alpha_{i2} & \alpha_{i3} & \alpha_{i4} & \alpha_{i5} \\
\alpha_{i1} & \alpha_{i2} & \alpha_{i3} & \alpha_{i4} & \alpha_{i5} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\alpha_{i1} & \alpha_{i2} & \alpha_{i3} & \alpha_{i4} & \alpha_{i5}
\end{bmatrix}
\]

④ Weight determination of influencing factors

The relative weight vector of the influence factor of each classification index was determined by comparing the influence degrees of evaluation indexes, namely, the AHP method was adopted. The weight vector was denoted as \( W_i = (w_1, w_2, \ldots, w_s) \).

⑤ First-level fuzzy comprehensive evaluation

The evaluation result \( R_n \) of classification indexes was obtained according to \( R_i \) and \( W_i \) obtained in Steps ③ and ④.

\[
R_n = W_n \circ R_i = (r_{i1}, r_{i2}, \ldots, r_{in})
\]

where

- \( R_n \) — the membership vector of a classification index, which corresponds to sub-item indexes (design, construction and maintenance), at the evaluation level;
- \( W_n \) — the weight vector of a classification index related to an influencing factor (namely between concrete indexes);
- \( \circ \) — the synthetic fuzzy operator \( M(\cdot, \oplus) \), which obtains the final evaluation result through numerical multiplication and bounded summation.

⑥ Second-level fuzzy comprehensive evaluation

The second-level fuzzy evaluation followed the evaluation of sub-item indexes, and its influence factor set was \( U_i' = (U_{i1}, U_{i2}, \ldots, U_{in}) \).

The corresponding evaluation set is as below:

\[ V' = \{ \text{Category I, Category II, Category III, Category IV and Category V} \} \]

The membership vector \( (R_{i1}, R_{i2}, R_{i3}, R_{i4}, R_{i5}) \) of the first-level fuzzy evaluation result for sub-item indexes was used as the single-factor evaluation set for the second-level fuzzy comprehensive evaluation, and then the corresponding fuzzy relation matrix was acquired as follow:
The weight value of each first-level classification index was determined by following the method of step 4, and then the weight vector of influence factors was presented as below:

\[ W = (w_1, w_2, w_3, \ldots, w_n) \]

According to the above fuzzy operator, the fuzzy evaluation vector of second-level sub-item indexes was calculated, namely, \( Z_{\text{sub-item index}} = W \circ R \).

Processing of evaluation vector

As the evaluation result was a fuzzy vector of inaccurate values, weighted averaging should be done for the final evaluation vector, to be more specific, the weighted sum of the evaluation vector was solved with a group of equidistant quantitative values, and the final quantitative result was obtained as follows:

\[ Z_{\text{sub-item index}} = \left( Z_1, Z_2, \ldots, Z_n \right) \]

\[ A_i = (a_1, a_2, \ldots, a_n) \]

\[ P_{\text{sub-item index}} = \frac{\sum a_i \cdot z_i}{\sum z_i} \]

where A is the equidistant quantitative value, and the sub-item index includes the post-design evaluation, post-construction evaluation and post-operation, management & maintenance evaluation in the evaluation system.

The post-design evaluation score of the continuous rigid frame bridge (construction or operation, management & maintenance) was obtained as P design.

4. Instance Analysis

The comprehensive post-construction evaluation of technical performance and service properties of the bridge was implemented through the field survey on the basic service conditions of the continuous rigid frame bridge on the Chongqing-Hechuan segment of Lanzhou-Haikou Expressway. An in-depth discussion was carried out with third-party design, construction, and operation, management & maintenance units by combining the data saved by the relevant bridge management department. The indexes were judged and the category of the studied continuous rigid frame bridge was determined using the abovementioned evaluation indexes, evaluation method and classification criteria in accordance with related provisions. Table 3 shows the major evaluation and classification indexes.

| Evaluation and classification indexes | Concrete evaluation index                                      | Evaluation vector |
|--------------------------------------|----------------------------------------------------------------|-------------------|
| Fine design of bridge construction   | Fine design of main beam construction                           | Excellent | Fairly good | Good | Ordinary | Poor |
|                                      | Fine design of main pier construction                           | 0          | 0.5        | 0.5  | 0       | 0    |
|                                      | Fine design of other structural constructions                  | 0.3       | 0.6        | 0.1  | 0       | 0    |
| Fine design of prestressed system    | Phase I fine design of prestress                                | 0          | 0.5        | 0.4  | 0.1     | 0    |
|                                      | Phase II fine design of prestress                               | 0          | 0.5        | 0.4  | 0.1     | 0    |
| Fine design of pre-camber            | Construction pre-camber design                                  | 0          | 0.4        | 0.4  | 0.2     | 0    |
|                                      | Pre-camber design of completed bridge                           | 0          | 0.4        | 0.4  | 0.2     | 0    |
| Durability design                    | Material durability design                                      | 0          | 0.2        | 0.4  | 0.4     | 0    |
Establishment of the fuzzy relation matrix

The fuzzy relation matrix $R$ was used to characterize the relationship between the classification indexes and influencing factors. The fuzzy relation matrices between each bottom-layer index (fine design of bridge construction, fine design of prestress, fine design of bridge pre-camber, structural durability design, and bridge design control parameters) in the post-design evaluation system of continuous rigid frame bridge and their influencing factors were $R'_1$, $R'_2$, $R'_3$, $R'_4$, and $R'_5$.

Based on the evaluation vector table of indexes at all levels (Table 3), the fuzzy relation matrices of the continuous rigid frame bridge on the Chongqing-Hechuan segment were obtained as follows:

$$
R'_1 = \begin{bmatrix}
0.1 & 0.4 & 0.5 & 0 & 0 \\
0.3 & 0.5 & 0.2 & 0 & 0 \\
0 & 0.4 & 0.6 & 0 & 0 \\
0 & 0.5 & 0.3 & 0.1 & 0 \\
0.1 & 0.1 & 0.7 & 0.1 & 0
\end{bmatrix},
R'_2 = \begin{bmatrix}
0.2 & 0.4 & 0.4 & 0 & 0 \\
0 & 0.5 & 0.3 & 0.1 & 0 \\
0.1 & 0.1 & 0.7 & 0.1 & 0 \\
0.1 & 0.2 & 0.2 & 0.5 & 0 \\
0 & 0.7 & 0.1 & 0.2 & 0
\end{bmatrix},
R'_3 = \begin{bmatrix}
0.15 & 0.43 & 0.42 & 0 & 0 \\
0.13 & 0.33 & 0.47 & 0.05 & 0.02 \\
0.36 & 0.26 & 0.34 & 0.4 & 0 \\
0.05 & 0.3 & 0.25 & 0.30 & 0.1 \\
0 & 0.7 & 0.1 & 0.2 & 0
\end{bmatrix},
R'_4 = \begin{bmatrix}
0.15 & 0.43 & 0.42 & 0 & 0 \\
0.13 & 0.33 & 0.47 & 0.05 & 0.02 \\
0.36 & 0.26 & 0.34 & 0.4 & 0 \\
0.05 & 0.3 & 0.25 & 0.30 & 0.1 \\
0 & 0.7 & 0.1 & 0.2 & 0
\end{bmatrix},
R'_5 = \begin{bmatrix}
0.15 & 0.43 & 0.42 & 0 & 0 \\
0.13 & 0.33 & 0.47 & 0.05 & 0.02 \\
0.36 & 0.26 & 0.34 & 0.4 & 0 \\
0.05 & 0.3 & 0.25 & 0.30 & 0.1 \\
0 & 0.7 & 0.1 & 0.2 & 0
\end{bmatrix}.
$$

The bottom-layer weight vectors of the continuous rigid frame bridge on the Chongqing-Hechuan segment were obtained via the AHP method:

- $W'_1 = (0.6, 0.3, 0.1)$
- $W'_2 = (0.5, 0.2, 0.3)$
- $W'_3 = (0.4, 0.6)$
- $W'_4 = (0.5, 0.5)$
- $W'_5 = (1)$

First-level fuzzy comprehensive evaluation

The aforementioned fuzzy operation method was used to calculate the fuzzy comprehensive evaluation result of each evaluation index.

The first-level fuzzy comprehensive post-design evaluation vectors of indexes (fine design of bridge construction, fine design of prestress, fine design of bridge pre-camber, structural durability design, and bridge design control parameters) of this continuous rigid frame bridge were $R'_1$, $R'_2$, $R'_3$, $R'_4$, and $R'_5$:

$$
R'_1 = W'_1 \cdot R'_1 = (0.15, 0.43, 0.42, 0, 0),
R'_2 = W'_2 \cdot R'_2 = (0.13, 0.33, 0.47, 0.05, 0.02),
R'_3 = W'_3 \cdot R'_3 = (0.36, 0.26, 0.34, 0.4, 0),
R'_4 = W'_4 \cdot R'_4 = (0.05, 0.3, 0.25, 0.30, 0.1),
R'_5 = W'_5 \cdot R'_5 = (0, 0.7, 0.1, 0.2, 0).
$$

Second-level fuzzy comprehensive evaluation

The first-level fuzzy comprehensive evaluation vectors ($R'_1$, $R'_2$, $R'_3$, $R'_4$, $R'_5$) obtained in the last step were taken as the evaluation set of each single influence factor in the second-level fuzzy comprehensive evaluation, the abovementioned operations of fuzzy relation matrix and weight vector were repeated, and then the second-level fuzzy comprehensive post-design evaluation results of this bridge were displayed as follows:

$$
R = \begin{bmatrix}
R'_1 \\
R'_2 \\
R'_3 \\
R'_4 \\
R'_5
\end{bmatrix} = \begin{bmatrix}
0.15 & 0.43 & 0.42 & 0 & 0 \\
0.13 & 0.33 & 0.47 & 0.05 & 0.02 \\
0.36 & 0.26 & 0.34 & 0.4 & 0 \\
0.05 & 0.3 & 0.25 & 0.30 & 0.1 \\
0 & 0.7 & 0.1 & 0.2 & 0
\end{bmatrix}.
$$

The following is the second-level weight vector:

$$
W = (0.15, 0.15, 0.25, 0.25, 0.2).
$$

The second-level fuzzy comprehensive evaluation was performed by combining the results of relation matrix and weight vector as below:

$$
Z_{\text{design}} = W \circ R
$$

The second-level fuzzy comprehensive evaluation results are as follows:
The abovementioned post-construction evaluation method was used to obtain the comprehensive post-design evaluation result of the continuous rigid frame bridge on the Chongqing-Hechuan segment:

\[
P_{\text{design}} = \frac{5 \times 0.1445 + 4 \times 0.394 + 3 \times 0.301 + 2 \times 0.3975 + 1 \times 0.028}{0.1445 + 0.394 + 0.301 + 0.3975 + 0.028} = 3.1957
\]

This result indicates that the studied bridge belongs to Category II in the grading system of post-design evaluation. The evaluation results are specifically as follows: From the fine design of bridge construction, the main beam is well designed without any obvious crack, so is the main pier, where the voids and pits and concrete peeling occur only on a small part. From the aspect of fine design of prestressed system, the losses of the first and second flexural-tensile prestresses are small, with favorable fineness. As for the fine design of pre-camber, the down-warping degree at the midspan of main beam is high, exceeding the pre-camber in the design and construction, so the fineness is ordinary. When it comes to durability, the material and structural durability is good thanks to the environmental conditions. The design parameters selected are ordinary in the aspect of bridge design requirements and control. As the variation trends of concrete strength and elasticity modulus in the construction process are not explained, improvements should be made in the follow-up design by reference to the following design suggestions for continuous rigid frame bridges.

5. Conclusions
(1) The current development situation of domestic (Chinese) continuous rigid frame bridges and the existing problems were summarized, and the importance and necessity of post-construction comprehensive evaluation for continuous rigid frame bridges were pointed out.

(2) The indexes influencing the post-construction evaluation of continuous rigid frame bridges were analyzed from the perspective of bridge design. According to the divided hierarchical system structure, the three-level fuzzy comprehensive evaluation method was used to comprehensively evaluate the completed continuous rigid frame bridges.

(3) The continuous rigid frame bridge on the Chongqing-Hechuan segment of Lanzhou-Haikou Expressway in Chongqing was taken for example to expound the comprehensive post-construction evaluation process of the bridge in detail, a comprehensive post-construction evaluation model applicable to continuous rigid frame bridges was proposed, and the problems appearing in the service of completed bridges were summarized, in an effort to provide a basis for construction of bridges of the same type.

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