Resistance Deterioration Assessment of Concrete Beam Bridges based on Strain Monitoring Data

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Abstract. The bridge health monitoring system deployed in concrete beam bridge mostly uses strain sensors to collect data and evaluate the working state of bridges. However, the existing evaluation method of bridge working condition based on strain data cannot realize the evaluation of whole bridge bearing capacity. To solve this problem, this paper puts forwards a resistance deterioration assessment method based on strain monitoring data and calculated maximum crack height. Through the engineering project verification, this method has been deemed to be effective.

1. Introduction
Because of the huge amount, concrete beam bridges play a crucial part in the highway transportation network. It is of great significance to obtain the resistance deterioration in time to realize the sustainability of transportation infrastructure and ensure the safe operation. For a long time, the management and maintenance of the medium and small span bridges are mostly carried out by manual inspection and load test, but the former is greatly affected by the subjective ideas of inspector, while the latter needs to close road and consumes a lot. Therefore, to achieve the minimum life cycle cost⁴, Tao⁵ and You⁵ proposed to apply the health monitoring system to the management of medium and small span bridges. Yang⁴ built a health monitoring system on a PC girder bridge and proposed that the health monitoring system of medium and small bridges should be economic. Chen⁵ had studied hollow plate simply supported beam bridge, prestressed concrete simple supported beam bridge and prestressed concrete simple supported composite beam bridge respectively, proposed that stress is the key index to reflect the local bearing capacity and failure of bridge structure members. Monitoring the stress data of the key section can not only provide the basis for evaluating the durability of the bridge, but also judge whether the structure is damaged according to the data variation. Zhou⁶ and Wen⁷ monitored the mid-span strain of a simply-supported beam with prefabricated hollow slabs and evaluated the performance of hinge joints based on the stress variation of adjacent beams. It is a good auxiliary method for concrete beam bridges evaluation, but it cannot solve the problem of overall bearing capacity evaluation. Liang and Wang⁸ established the quantitative relationship between the maximum cracking height of section and the bearing capacity by nonlinear analysis, which was used for the rapid evaluation of concrete beam bridges. It provides a new idea for the evaluation of the medium and small span bridges bearing capacity. This paper combines this assessment method with strain monitoring data and puts forward a resistance deterioration assessment method which is suitable for the health monitoring system of concrete beam bridges.
2. Evaluation of Crack Height based on Strain Monitoring Data

2.1. Extraction of Real Strain Data under Load

The raw strain data consists of the real strain data under load, the strain caused by temperature effect and the noises. To calculate the maximum crack height, the process of isolating the real strain is indispensable. According to the current research result[9], the critical value of frequency between the real strain and the strain caused by temperature is $2.5 \times 10^{-3}$Hz, the critical value of frequency between the real strain and noises is 1Hz. Through empirical mode decomposition (EMD) method, the raw strain data has been decomposed into several intrinsic mode functions (IMF), and then IMF components with frequencies ranging from $2.5 \times 10^{-3}$Hz to 1Hz have been selected and superimposed to obtain the true strain response of the structure.

2.2. Determination of Maximum Crack Height

The strain distribution under the assumption of plane section is shown in the Figure 1.

![Figure 1. The strain distribution of cross section.](image)

The $\varepsilon_{\text{top}}$ and $\varepsilon_{\text{bottom}}$ are the strain at the top and the bottom of cross section, respectively. The $h$ is the height of cross section. The $X_0$ is the original height of neutral axis. After cracking, the maximum height of crack reaches $X_{cr}'$, and the height of neutral axis reaches $X_{n2}$. According to geometry:

$$\psi = \frac{\varepsilon_{\text{bottom}} - \varepsilon_{\text{top}}}{h}$$  \hspace{1cm} (1)

The strain at the height of $X$ is $\varepsilon_X = \varepsilon_{\text{bottom}} - \psi X$:

$$X = \frac{(\varepsilon_{\text{bottom}} - \varepsilon_{\text{bottom}})}{\psi}$$  \hspace{1cm} (2)

When $X = X_{n2}$:

$$X_{n2} = \frac{\varepsilon_{\text{bottom}} - 0}{\psi} = \varepsilon_{\text{bottom}} / \psi$$  \hspace{1cm} (3)

When $X = X_{cr}'$:

$$\varepsilon_X = \frac{f_{tk}}{E_c}$$  \hspace{1cm} (4)

In this equation, the $f_{tk}$ is standard value of concrete tensile strength, the $E_c$ is the elastic modulus of concrete. The following equation can be obtained by combining equation (1), equation (2) and equation (4).

$$X_{cr}' = \frac{(\varepsilon_{\text{bottom}} - f_{tk} / E_c)}{h / (\varepsilon_{\text{bottom}} - \varepsilon_{\text{top}})}$$  \hspace{1cm} (5)

Based on equation (5), the crack height can be determined by two strain values at different heights of sections. It is worth pointing out that if the number of strain measuring points at different heights is more than two, the calculated maximum crack height of the cross section will be more reliable.
3. Resistance Deterioration based on Maximum Crack Height

The relationship between bending moment and maximum crack height can be determined by the fibre model of cross section and overall process nonlinear analysis. The constitutive relation of materials can be selected according to relevant specifications. The fibre model has been shown in Figure 2 and the strain in each fibre is constant.[10]

![Figure 2. The fibre model of cross section.](image)

The following geometric matrix \( \mathbf{L} \) describes the spatial position of each fibre.

\[
\mathbf{L} = \begin{bmatrix}
-y_i & x_i & 1 \\
\vdots & \vdots & \vdots \\
-y_n & x_n & 1
\end{bmatrix}, \quad i = 1, 2, \ldots, n
\]  

(6)

The diagonal matrix \( \mathbf{A} \) describes the area of each fibre.

\[
\mathbf{A} = \text{diag}(A_1, A_2, \ldots, A_n)
\]  

(7)

The matrix \( \mathbf{F} \) describes the force vector on the cross section.

\[
\mathbf{F} = \begin{bmatrix}
M_x \\
M_y \\
N
\end{bmatrix}^T
\]  

(8)

The \( M_x \) and \( M_y \) are bending moment about x axis and y axis respectively. The \( N \) is axial force.

The matrix \( \mathbf{A}' \) describes the deformation on the cross section.

\[
\mathbf{A}' = \begin{bmatrix}
\phi_x \\
\phi_y \\
\varepsilon_0
\end{bmatrix}^T
\]  

(9)

The \( \phi_x \) and \( \phi_y \) are the curvature around the x axis and y axis respectively, the \( \varepsilon_0 \) is the strain on the neutral axis.

According to the plane section assumption, the strain of each fibre can be described as matrix \( \mathbf{\varepsilon}' \).

\[
\mathbf{\varepsilon}' = \mathbf{L} \mathbf{A}'
\]  

(10)

According to the constitutive relation, the stress \( \mathbf{\sigma} \) and the tangent stiffness matrix \( \mathbf{E}'_i \) of fibres can be determined.

\[
\mathbf{E}'_i = \text{diag}(E'_i, \ldots, E'_i)
\]  

(11)

Therefore, the force vector on the cross section \( \mathbf{F}' \) and the tangent stiffness matrix \( \mathbf{k}' \) of cross section can be determined by equation (12) and equation (13).

\[
\mathbf{F}' = \mathbf{L}' \mathbf{A} \mathbf{\sigma}'^T
\]  

(12)

\[
\mathbf{k}' = \mathbf{L}' \left( \mathbf{E}'_i \mathbf{A} \right) \mathbf{L}
\]  

(13)
Assuming $\varphi_n = \varphi_{n-1} + \Delta \varphi$ and $\varphi_1 = 0$, increasing the deformation step by step until the edge concrete reaches its ultimate compressive strain or the reinforcement reaches its ultimate tensile strain, the bending moment $M$, the curvature $\varphi$ and the strain of centroid $\varepsilon_o$ under each step can be determined. Based on calculated curvature and centroid strain, the strain at any height on the cross section can be determined by equation (14).

$$\varepsilon_X = \varepsilon_o - \varphi (X - X_o)$$  \hspace{1cm} (14)

$X_o$ is the height of centroid. Combining equation (14) and equation (4), the relationship between the crack height and the curvature can be obtained, as shown in equation (15).

$$X_{cr}' = \left(\varepsilon_0 - f_{ik}/E_c\right)/\varphi + X_0$$  \hspace{1cm} (15)

Combing the Bending moment – Curvature Curve and equation (15), the relationship between bending moment and crack height can been obtained.

$$M_{cr} = f(X_{cr}')$$  \hspace{1cm} (16)

By theoretical analysis, the theoretical bending moment of cross section $M_T$ can be easily obtained. The ratio of $M_T$ to $M_{cr}$ is the resistance checking coefficient $\zeta$. Considering the material degradation and the increasing traffic load, the resistance checking coefficient should be reduced. The reduction coefficient $\eta$ has been set as 0.5, as shown in equation (17).

$$\zeta = 1 + \eta(M_T / M_{cr} - 1) = 1 + 0.5 \left[ M_T / f(X_{cr}') - 1 \right]$$  \hspace{1cm} (17)

4. Project Case

4.1. Project Overview

The monitoring bridge is a prestressed concrete simple support T-shaped beam bridge constructed in 1988. The whole length is 4475m. The superstructure is PC simple supported beams whose span is 50m. The bridge deck is continuous. The substructure adopts single-row column pier, PC T-shaped cross section bent cap and bored cast-in-place pile foundation. The highway grade is level 1. The design load are Cars – Tier 20 and Trailers – 120. The concrete used in main girder is C50. The prestressed reinforcement is φ15 steel strands. The steel bar is HRB335. The cross section of the main girder has been shown as Figure 3.

![Figure 3. The cross section of main girder.](image-url)
4.2. Strain Data Processing
Raw strain data of one day has been shown in Figure 4. The EMD method has been used to decompose the original data. The data with a frequency between $2.5 \times 10^{-3}$ Hz and 1 Hz, which was caused by vehicle load, has been extracted as shown in Figure 5.

![Figure 4. Raw strain data.](image)

![Figure 5. True strain data.](image)

4.3. Crack Height Calculation
It is assumed that no cracks have been created before the monitoring begins. When the tensile strain of the tensile edge of the section exceeds the ultimate tensile strength of the concrete, the crack occurs. The theoretical value of crack height calculated is shown in the Figure 6. In reality, once the crack occurs, it will exist permanently. Therefore, the height of the crack will only increase rather than decrease. The increase of maximum crack height has been shown in Figure 7.

![Figure 6. Calculation results of crack height.](image)

![Figure 7. The increase of crack height.](image)

The mid-span section nonlinear analysis model has been built by X-trace, as shown in Figure 8. The M-φ curve of mid-span section has been obtained, as shown in Figure 9. According to equation (15) and equation (17), the relationship between crack height and bending moment and the relationship between crack height and resistance checking coefficient can be determined, as shown in Figure 10 and Figure 11.
Figure 8. Nonlinear model of mid-span section.

Figure 9. M-φ curve of mid-span section.

Figure 10. The relationship between crack height and bending moment.

Figure 11. The relationship between crack height and resistance checking coefficient.

According to Figure 11, the resistance deterioration of this bridge can be assessed strain monitoring data. The Figure 7 shows that the maximum crack height is 230.27 mm. The corresponding resistance checking coefficient is 1.013 which is larger than 1. It represents that the crack reduced by traffic load in this day has not caused the structural damage, which is consistent with the actual situation.

5. Conclusion
This paper has introduced a resistance deterioration assessment method of concrete beam bridges based on strain monitoring data. The real strain data under load has been acquired by EMD method. The maximum crack height of monitoring cross section can be determined by real strain. Through nonlinear analysis of monitoring cross section, the relationship between resistance checking coefficient and crack height has been established. Through engineering verification, the method is considered to be effective.

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