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Experimental investigation into stressing state characteristics of large-curvature continuous steel box-girder bridge model

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HIGHLIGHTS

- Characterizing structural working behavior by structural stressing state theory.
- Updating structural failure load of a bridge using the Mann-Kendall criterion.
- Revealing structural progressive failure characteristics.
- Proposing and modelling stressing state submodes.
- Demonstrating structural coordinative working performance.

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ABSTRACT

This paper conducts the experimental investigation into the whole working process of a large-curvature continuous steel box-girder bridge model to reveal its behavior characteristics and unseen failure mechanism, based on the structural stressing state theory. Firstly, the structural stressing state and corresponding characteristic parameters are expressed by the generalized strain energy density (GSED) derived from the experimental strain data. Then, the Mann-Kendall (M-K) criterion is introduced to distinguish the structural stressing state leaps of the bridge model, leading to the updated definition of the structural failure load and the revelation of structural progressive failure. Furthermore, this paper proposes stressing state submodes and evaluates their roles in the structural "failure". Finally, the coordinative working performance of the divided sub parts is modeled through the ratios between the GSED sums of individual sub parts and the ensemble.

1. Introduction

Curved continuous girder bridges have been widely adopted for their economic and functional advantages as well as rational working performance. Though the early analysis on the ultimate bearing capacity of curved girders can be traced to the 1960s [1–5], analytical methods still fell behind engineering applications. Consequently, some functional accidents, such as too much lateral displacement of main girders or too much torsional deformation, took place for some times resulting from the absence of some necessary researches for design reference [6], which urges researchers to deeply study the structural working behavior. Currently, there are two important issues which have drawn researchers' much attention:

- In terms of the mechanic complication, curved girders under vertical loads are subjected to not only bending but also torsional deformation, with the co-existence of shear stress, warping stress and bending normal stress on cross sections. Usually, the level and distribution of stresses relate to a variety of factors, such as geometric shapes, bending and torsional rigidity of cross sections, support conditions and loading cases [7]. And when going into the elastic-plastic stage where sectional bending and torsional stresses no longer maintain the previous proportion, the curved girder embodies a fairly complicated structural stressing state [8]. In addition, past research results showed that the effect of curvature on the stressing state of a curved girder is also significant [9]. Especially for large-curvature girders, the second-order effect will significantly decrease the ultimate load level [10]; also, the reduction degree of structural torsional rigidity owing to the development of plasticity and its contribution to the lateral flexural-torsional

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buckling are quite difficult to describe in quantity. Hence, it is hard to find the analytical solutions to relative governing equations [11].

- Structural failure mechanism has always been vital but also complicated since the high-nonlinearity and great variation in the structural working behavior. Present studies did not evidently imply when a structure starts to lose its normal and stable working state or to enter its "failure" state, and focused on the ultimate collapse state mostly [1,4,12–15]. Besides, the existing ultimate limit state for structural design is commonly semi-theoretical and semi-empirical judgment. As a result, it is expected in structural analysis and engineering practice that a rational definition of structural "failure" and corresponding distinguishing methods will come into being.

In order to address these two issues, the authors deeply investigate the characteristics of structural stressing states embodied in the experimental data of the 1/10 scaled bridge model [16,17], based on the theory of structural stressing state. The investigation models the structural stressing state by using the generalized strain energy density (GSED) sum [18]. Then, with an innovative application of the Mann-Kendall (M-K) method to the GSED sum-load curve, the structural stressing state leap is distinguished. This leap is rightly verified to be the termination of the previous stable stressing state of the bridge, leading to an updated definition of structural failure and promoting a general criterion for distinguishing the structural "failure" load. Moreover, we reveal two structural stressing state characteristics: (1) Stressing state submodes and their roles in structural working process; (2) Structural progressive failure behavior. Finally, the concept of coordinative working performance of individual sub parts is introduced and structural failure mechanism is revealed further.

2. Structural stressing state and M-K criterion

2.1. Concept of structural stressing state and GSED curve

The stressing state of a structure is defined as the structural working behavior characterized by the distribution patterns of GSED values, displacements, strains and stresses of key points. Generally, the strain energy density E_0 of the ith point can be calculated by

$$E_{0,i} = \int \sigma_1 d\varepsilon_1 + \sigma_2 d\varepsilon_2 + \sigma_3 d\varepsilon_3 \tag{1}$$

where σ_1, σ_2, σ_3 and ε_1, ε_2, ε_3 are three principal stresses and strains, respectively; $E_{0,i}$is the ith strain energy density. Referring to the concept of strain energy density, this paper chooses the generalized (or quasi) strain energy density (GSED) as the characteristic parameter to express the stressing state at a point [18]. Thus, Eq. (1) is simplified as

$$E_i = \frac{1}{2}\sum_{j=1}^{3} E\varepsilon_j^2 \tag{2}$$

where E_i = GSED value of the ith point; ε_j = the jth principal strain; and E = elastic modulus. The GSED sum of a group of key points can be calculated by

$$E_j' = \sum_i E_i \tag{3}$$

where $E_j' =$ GSED sum of the jth group to express the stressing state of a sub part. Furthermore, the GSED sum $E' = \sum E_j'$ of all groups (sub parts) is adopted to characterize the structural stressing state at each load step F. It can be seen in the Section 4.1 that the $E' - F$ curve can vividly exhibit differential structural stressing states and corresponding characteristics.

2.2. M-K criterion

In order to distinguish the stressing state leap of the structure through the $E' - F$ curve, the Mann-Kendall (M-K) method is applied, for it is a widely used trend analysis tool currently without necessity for samples to comply with certain distributions or interference of a few outliners [19–21]. Here, it is assumed that the sequence of $\{E'(i)\}$ (the load step i = 1, 2, ..., n) is statistically independent. Actually, the relevant and independent ingredients coexist in the structural stressing state at different load steps to a certain extent. According to the Saint Venant's principle, structural components which are located far away from each other have little spatial relevance or mutual effects, leading to considerable ingredients of independence in the experimental data (strains, displacements, etc.) at different locations. Besides, the inherent randomness in the experimental model and material properties result in a significant independent content at different load steps as well. The authors have tried the same M-K procedure to a significant amount of simulated data, but the results are not as satisfying as the corresponding experimental data, which is an auxiliary evidence for the independent contents of the experimental data at different load steps. Also, from the effectiveness of the M-K criterion, which will be discussed later, this analytical method could also be valid in view of the "result-oriented" consideration. Hence, the mutation of the structural working behavior can be detected approximately through the M-K criterion. Then, a new stochastic variable d_k at the kth load step can be defined by

$$d_k = \sum_{i=1}^{k} m_i (2 \leqslant k \leqslant n), m_i = \begin{cases} +1, & E'(i) > E'(j)(1 \leqslant j \leqslant i) \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where m_i is the cumulative number of the samples; "+1" means adding one more to the existing value if the inequality on the right side is satisfied for the jth comparison. The mean value $\mathrm{E}(d_k)$ and variance $\mathrm{Var}(d_k)$ of d_k are calculated by

$$\begin{aligned} &\mathrm{E}(d_k) = k(k-1)/4 \ (2 \leqslant k \leqslant n), \\ &\mathrm{Var}(d_k) = k(k-1)(2k+5)/72 \ (2 \leqslant k \leqslant n) \end{aligned} \tag{5}$$

Under the assumption that the $\{E'(i)\}$ sequence is statistically independent, a new statistic UF_k is defined by

$$UF_k = \begin{cases} 0 & k = 1 \\ (d_k - \mathrm{E}(d_k))/\sqrt{\mathrm{Var}(d_k)} & 2 \leqslant k \leqslant n \end{cases} \tag{6}$$

Thus, all the UF_k data can form a $UF_k - F$ curve. A similar procedure is proceeded to the inverse $\{E'(i)\}$ sequence, namely, the $\{E_2'(i)\}$ sequence where

$$E'(i) = E_2'(n - i + 1) \tag{7}$$

and n is the sample capacity. Similarly, the stochastic variable d_{2k} at the kth load step is defined as

$$d_{2k} = \sum_{i=1}^{k} m_i (2 \leqslant k \leqslant n), \ m_i = \begin{cases} +1, & E_2'(i) > E_2'(j) \ (1 \leqslant j \leqslant i) \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where m_i is the cumulative number of the samples; "+1" means adding one more to the existing value if the inequality on the right side is satisfied for the jth comparison. The mean value $\mathrm{E}(d_{2k})$ and the variance $\mathrm{Var}(d_{2k})$ of d_{2k} are calculated by

$$\begin{aligned} &\mathrm{E}(d_{2k}) = k(k-1)/4 \ (2 \leqslant k \leqslant n), \\ &\mathrm{Var}(d_{2k}) = k(k-1)(2k+5)/72 \ (2 \leqslant k \leqslant n) \end{aligned} \tag{9}$$