Analysis and correction of stress error in construction monitoring of cantilever cast prestressed beam bridge

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Abstract: In order to correct the monitoring stress of long-span prestressed concrete girder more accurately, and consider the characteristics of bridge load gradually applied during cantilever construction, this paper proposes an accurate correction method for monitoring stress of long-span prestressed concrete bridge. Based on the linear creep theory and Bauer boltzmann (L.B oltzman) superposition principle, the invariant elastic mode of traditional calculation is replaced by the equivalent elastic modulus from load-to-pre-calculation, and the formula of concrete creep, and the time-varying elastic mode is taken into account. The effect of concrete shrinkage and temperature change softer on the real stress value of the structure is accurately corrected by separating and removing stress-free strain from the measured strain. This method is applied to the calculation of the measured stress in the key section of the main beam of a long-span continuous beam of a high-speed railway. The results show that the modified stress value is in good agreement with the theoretical value and the error is significantly reduced, which verifies the reliability and accuracy of the modified method.

1. Introduction

In order to form a bridge linear shape and meet the design requirements of internal forces, vibrating string strain instruments are often embedded in cantilevered long-span prestressed concrete Bridges to monitor the stress of the main beam of key sections in real time [1]. However, with the increasing span of the bridge, the impact of construction load, concrete shrinkage and ambient temperature is becoming more and more obvious. The stress in the section of cantilever construction becomes more complicated, resulting in a large error between the monitoring results and the actual stress. How to eliminate the influence of concrete shrinkage, creep, temperature and other factors in the measured stress, and correct the measured stress of the beam section in construction, so as to grasp the real change of the stress of the main beam is very necessary.

At present, many scholars at home and abroad have carried out extensive research on the influencing factors of stress monitoring in the construction of long-span Bridges. Ye yushan et al. [2] used the field strain and temperature test results to modify the temperature correction coefficient and shrinkage strain. Li bin et al. [3] summarized various calibration methods of chord-vibrating strain gauge. Zhang xiangdong et al. [4] analyzed the influence of ambient temperature, hydration heat and solar radiation on the test results based on the test principle of vibrating string strain gauge and the method of field test. Praja et al. [5] studied the influence of creep and contraction on stress distribution in long-span bridge structures. Meng jiang et al. [6] used different prediction models to calculate and analyze the shrinkage and creep of concrete. Balevi č ius [7], such as bonding, puts forward the concrete shrinkage, creep and aging of prestressed concrete member after loading stress-strain state and the influence of crack resistance analysis and numerical model. Singh et al. [8] studied the
influence of concrete time-varying and variable elastic modulus on bridge structure, and compared and analyzed three different elastic modulus models. According to the observed temperature data, Gao Dafeng et al. [9] used the temperature at the most unfavorable moment to fit the temperature distribution curve. Based on the above research, it can be seen that the traditional measured stress correction method is to remove and modify the strain value caused by concrete shrinkage, creep and temperature change from the measured total strain. The strain calculation generated by concrete shrinkage and creep is based on the design code for highway reinforced concrete and prestressed concrete Bridges and culvert (JTG d62-2012), and the influence of temporary period, concrete type, humidity and theoretical thickness on the shrinkage and creep strain value is comprehensively considered to calculate the shrinkage and creep strain of concrete beams. However, the above measured strain correction method first ignores the effect of the load on the modification during the construction of the large-span beam bridge section cantilever, and secondly does not consider the characteristics of the development of the concrete elastic mode with the age period, which will lead to the correction of the stress value is still large and theoretical value gap, it can not accurately reflect the real stress state of the structure in the construction process, it is not conducive to effective and accurate control of bridge. Therefore, a large-span pre-stressed concrete cantilever construction bridge main beam stress correction method is proposed. It is characterized by considering the characteristics of load gradually applied during the construction of the large-span pre-stressed concrete bridge, constructing the formula of concrete modification calculation under the segmented stress increment, replacing the invariant elastic mode of traditional calculation with the equivalent elastic mode from load period to the calculation period, and overcoming the defects of the traditional stress correction method.

2. Stress monitoring method of concrete main beam

In a section of bridge cantilever construction, the total concrete strain $\varepsilon(t)$ when strain sensor collects time $t$ can be decomposed into:

$$
\varepsilon(t) = \varepsilon_e(\tau) + \varepsilon_c(t) + \varepsilon_{cs}(t) + \varepsilon_T(t) + \varepsilon_0
$$

(1)

In formula (1), $\varepsilon_e(\tau)$ is the true elastic strain of the main beam at time $t$; $\varepsilon_c(t), \varepsilon_{cs}(t), \varepsilon_T(t)$ is the strain caused by creep, shrinkage and temperature change of $t$ at a certain time. $\varepsilon_0$ is the initial strain of concrete.

2.1. Creep strain of concrete

Traditional creep calculation method:

$$
\varepsilon_c(t) = \varphi(t,t_0)\varepsilon_e(\tau)
$$

(2)

When formula (2) is used to calculate the strain caused by creep, the influence of progressive loading on creep during cantilever construction of the structure is ignored, and the characteristics of concrete elastic modulus with age are not considered, so the creep calculation error is relatively large. When the large-span bridge section cantilever construction, the load also increases gradually with the construction of the main beam section, so the real stress of the main beam is a trapezoidal segment increase. Main beam stress growth is shown in Figure 1.
According to the linear creep theory of concrete, when the working stress of concrete is less than 50% of the strength of concrete, the creep strain has a linear relationship with the stress applied, and the working stress of engineering concrete is all within this range. According to the superposition principle of boltzmann, the total strain under creep stress in time $t$ is the total strain caused by each increment of stress.

In the above two theories, considering the total creep change strain during the age period, regardless of stress, the phased variation of the stress discrete into a single non-influenced stress increment, and then calculate the stress increment of different age periods to produce the creep change strain.

\[
\varepsilon_{c,i} = \frac{\sigma_0}{E(t_0, t_i)} \varphi(t_i, t_0)
\]

\[
\Delta \varepsilon_{c,2} = \frac{\Delta \sigma_i}{E(t_1, t_i)} \varphi(t_i, t_1)
\]

\[
\Delta \varepsilon_{c,j} = \frac{\Delta \sigma_{i-1}}{E(t_{i-1}, t_i)} \varphi(t_i, t_{i-1})
\]

From this, it can be deduced that the total creep strain generated by each stress increment within the age $t_i$ is:

\[
\varepsilon_{c,j} = \frac{\sigma_0}{E(t_0, t_i)} \varphi(t_i, t_0) + \sum_{j=1}^{i-1} \frac{\Delta \sigma_j}{E(t_j, t_i)} \varphi(t_i, t_j)
\]

In formula (6), $\varepsilon_{c,j}$ refers to creep strain value of concrete interim $t_i$, $t_0$, $t_1$, $t_j$ is the concrete age after completion of 0, 1 and $j$ of working conditions, respectively. Sigma 0 is the initial stress under load. $E(t_0, t_i)$ is the equivalent elastic modulus of concrete from interim $t_0$ to interim $t_i$. ($t_0$, $t_i$) is the creep coefficient of concrete from loading interim $t_0$ to calculating interim $t_i$. Sigma $j$ is the stress increment under the JTH working condition. $E(t_j, t_i)$ is the equivalent elastic modulus of concrete from temporary $t_j$ to temporary $t_i$. ($t_j$, $t_i$) is the loading interim $t_j$, and the concrete creep coefficient of interim $t_i$ is calculated according to the design code for highway reinforced concrete and prestressed concrete Bridges and culverts (JTG d62-2012) \[10\].

With reference to the latest domestic specification on creep coefficient "design specifications for highway reinforced concrete and prestressed concrete Bridges and culverts" (JTG d62-2012), the creep coefficient is calculated as follows:

\[
\varphi(t, t_0) = \varphi_0 \cdot \beta_k (t - t_0)
\]

$\varphi_0$ is nominal creep coefficient $\beta_k$ is the development coefficient of creep with time after loading.
Creep coefficient can be calculated according to the standard. Under normal casting, the elastic modulus of ordinary concrete will gradually increase with the development of time. If the elastic modulus is taken as a certain value, the calculation results of creep strain and real elastic stress of the structure will definitely be affected. At present, the prediction model of time-varying elastic modulus given by ceb-fip (1990) \[11\] takes into account the influence of concrete type and age, and at the same time meets the requirement that with the development of time, and the elastic modulus of 28 days can be derived back, which is convenient and accurate in application. When equation (6) is used to calculate creep stress, the time-varying elastic modulus is adopted.

\[
E(t) = E_{28} \left\{ \exp \left[ s \left(1 - \left( \frac{28}{t} \right)^{0.5} \right) \right] \right\}^{0.5}
\]

(8)

The elastic modulus of concrete varies continuously from \(t_j\) to \(t_i\). When calculating the creep strain caused by the stress increment applied within this age range, the elastic modulus is not convenient to value. The equivalent modulus of elasticity \(E_{t_j, t_i}(t)\) is introduced here.

\[
E(t) = \frac{\int_{t_j}^{t_i} E(t) \, dt}{t_i - t_j}
\]

(9)

Thus, the equivalent elastic modulus of concrete aged \(t_j\) to \(t_i\) can be obtained as follows:

\[
E(t) = \frac{\int_{t_j}^{t_i} E(t) \, dt}{t_i - t_j}
\]

(10)

2.2. Strain value caused by temperature difference
Calculation of strain error caused by temperature change:

\[
\varepsilon_T(t) = (\alpha - \beta) \cdot (T - T_0)
\]

(11)

\(\alpha\) is the linear expansion coefficient of concrete, \(10 \times 10^{-6} / ^\circ C\); \(\beta\) is the linear expansion coefficient of steel string, \(12.2 \times 10^{-6} / ^\circ C\); \(T\) is the temperature measured by the strain gauge at time \(T\); \(T_0\) is the initial temperature measured by the strain gauge.

2.3. Strain caused by concrete shrinkage
Concrete shrinkage calculation:

\[
\varepsilon_{cs}(t, t_s) = \varepsilon_{cs,0} \cdot \beta_s \cdot (t - t_s)
\]

(12)

\[
\beta_s(t) = \left[ \frac{(t-t_s)/t_i}{350(h/H_0)} + (t-t_s)/t_i \right]^{-0.5}
\]

(13)

\(\varepsilon_{cs}(t, t_s)\) is the contraction strain of concrete within the temporary period \(t\); \(t_s\) is the age at the beginning of concrete shrinkage, generally taking 3 days to 7 days. \(\varepsilon_{cs,0}\) is the coefficient of contraction development with time. \(\beta_s\) is the theoretical thickness of the component; \(H_0, t_i\) is a constant.

2.4. Measured stress correction
According to equations (6), (11) and (12), the effects of shrinkage, creep, temperature change and initial strain can be separated and eliminated. During the construction of the cantilever, the real elastic stress of the main beam of a large-span pre-stressed concrete bridge can be expressed as:

\[
\sigma(t) = E(t, t) \left[ \varepsilon(t) - \varepsilon_c(t) - \varepsilon_{cs}(t) - \varepsilon_T(t) - \varepsilon_{e_0} \right]
\]

(14)

According to the above ideas, the measured stress correction method for the main beam is constructed, as shown in figure 2.
3. Engineering example

3.1. Project summary
Taking a three-span prestressed concrete double-line continuous box girder bridge as an example, its span layout is 40.6m+64m+40.6m, and the elevation layout of the main bridge is shown in figure 3. The whole bridge is arranged with 11 stress measuring sections, which are respectively located at the root of two t-frame cantilever, 1/4 span, 1/2 span, 1/2 span and closing section of the middle span. Three vibrating string sensors are embedded in the top and bottom plates of each measuring section. The construction stage is divided into 38 working conditions, and the construction of each main beam section includes three working conditions: forward movement of hanging basket, concrete pouring and tensioning of prestressed steel beam. Midas Civil, a space finite element software, was used to establish the finite element model of the bridge and calculate the theoretical stress of the main beam in each section.

Figure 3 elevation of the main bridge of a bridge and sensor layout of block 0#
3.2. Stress contrast analysis

In order to verify the accuracy of the method in this paper, 17 working conditions on the top of xiao-lie-cheng beam of block 0 of pier 4 of the bridge were selected to calculate the stress modification value of the main beam and compare it with the traditional stress modification value and theoretical stress value. The ratios of the 17 working conditions are shown in table 1 and figure 4.

### Table 1 Stress comparison of box girder at the top of pier 4

| Serial number | condition  | Computing age /d | measured temperature /℃ | measured strain /με | theoretical value /MPa | Method of this paper /MPa | conventional approach /MPa |
|---------------|------------|------------------|--------------------------|---------------------|-----------------------|--------------------------|---------------------------|
| 1             | A0# tensile| 12               | 32.1                     | 3231                | -0.61                 | -1.13                    | -1.21                     |
| 2             | A1# tensile| 46               | 20.2                     | 3241                | -0.40                 | -0.69                    | -0.63                     |
| 3             | A1# tensile| 57               | 16.9                     | 3219                | -1.33                 | -1.8                     | -1.49                     |
| 4             | A2# tensile| 64               | 12.9                     | 3227                | -0.92                 | -1.36                    | -1.43                     |
| 5             | A2# tensile| 70               | 21.3                     | 3170                | -2.65                 | -2.79                    | -2.70                     |
| 6             | A3# tensile| 76               | 16.0                     | 3185                | -2.04                 | -2.07                    | -2.52                     |
| 7             | A3# tensile| 81               | 21.2                     | 3133                | -3.95                 | -3.64                    | -3.87                     |
| 8             | A4# tensile| 90               | 18.8                     | 3138                | -3.16                 | -3.08                    | -3.79                     |
| 9             | A4# tensile| 97               | 16.7                     | 3087                | -4.93                 | -5.24                    | -5.65                     |
| 10            | A5# tensile| 139              | 16.9                     | 3065                | -4.00                 | -4.03                    | -6.08                     |
| 11            | A5# tensile| 144              | 23.2                     | 3021                | -5.60                 | -5.51                    | -7.08                     |
| 12            | A6# tensile| 154              | 18.6                     | 3044                | -4.59                 | -4.35                    | -6.57                     |
| 13            | A6# tensile| 161              | 22.0                     | 3000                | -6.34                 | -6.05                    | -7.79                     |
| 14            | A7# tensile| 166              | 17.8                     | 3018                | -5.25                 | -5.09                    | -7.46                     |
| 15            | A7# tensile| 173              | 27.0                     | 2951                | -6.95                 | -7.04                    | -9.03                     |
| 16            | A8# tensile| 179              | 24.9                     | 2977                | -5.76                 | -5.41                    | -8.26                     |
| 17            | A8# tensile| 188              | 30.5                     | 2932                | -7.38                 | -7.02                    | -9.33                     |

Start temperature: 29.8℃, Initial strain: 3279με, Theoretical thickness of member: 670mm, Concrete type: C50, Annual average relative humidity: 70%, Shrink age: 5d

As can be seen from table 1, when working condition 1, the theoretical value of stress on the top surface of the box girder is -0.61MPa, the measured value is -1.66MPa, the traditional modified stress value is -1.21MPa, and the modified stress value of this method is -1.13MPa. With the increase of bridge construction segments, the theoretical stress value of box girder top surface is -7.38mpa, the...
measured stress value is -11.97mpa, the traditional modified stress value is -9.33mpa, and the modified stress value of this method is -7.02mpa.

As can be seen from figure 4, the measured stress value and the deviation from the theoretical value are the largest, and the deviation from the traditional modified value is reduced. However, the modified stress value with this method is in the best agreement with the theoretical value, and the error is significantly reduced, which verifies the reliability and accuracy of the modified method. With the increase of the working condition of the bridge segment, the deviation between the measured stress value and the traditional modified value gradually increases, and the cumulative stress error also increases correspondingly. However, the deviation between the modified value and the theoretical value in this method is relatively stable.

By using this method, the measured stress of the main beam during the cantilever construction of shuangyang bridge is calculated.

4. Conclusion
In this paper, a method for monitoring stress correction of long-span bridge under cantilever construction is proposed and applied to the actual stress correction of a long-span box-girder bridge. The conclusions are as follows:
1) When the concrete bridge is placed in cantilever section, the stress of the main beam changes with the construction condition.
2) The elastic modulus of concrete changes with age, especially in the early stage, which has a great influence on the calculation of structural stress.
3) The modified calculation method in this paper is accurate and reliable, and can effectively correct the stress-free strain caused by creep effect, which can provide a reference for monitoring stress correction in bridge construction control in the future.
4) In the process of construction stress monitoring of prestressed concrete bridge, due to many influencing factors, the measured stress error is large, therefore, it is necessary to accurately analyze the stress error in construction control.

References
[1] Xiang, Z.F., Ran, X., Lai, L. (2016) Stress Modification of Bridge Construction Based on the In-site Experiment of Bridge [J]. Journal of Chongqing Jiaotong university (natural science), 35(3): 7-10.
[2] Ye, Y.S., Mu, T., Zheng, W.t., et al. (2015) Study on Error Analysis and Correction Method for Strain Testing Construction Monitoring of Inclined Pylon and Cable-stayed Landscape Bridge[J]. Construction Technology., 44(11): 56-59.
[3] Li, B., Zhong, W.B., Lin, F.Z. (2013) String vibration type strain gauge mathematical model for comparative analysis [J]. Shanghai Measurement and Testing: 8-11.
[4] Zhang, X.D., Chai, Y., Liu, J.Q., (2015) Vibrating string type strain gauge testing technology to explore in the box girder bridge[J]. Journal of Liaoning Technical University: Natural Science, 34(1): 48-51.
[5] Praja, B.A., (2017) Stress distributions of PSC box girder bridge due to creep shrinkage effect[J]. MATEC Web of Conferences, 138.
[6] Meng, J., Zhao, B.J., Liu, J.M. (2013) Prediction model and influencing factors for concrete shrinkage and creep effects[J]. Journal of Chang'an University(Natural Science Edition), 33(2): 56-62.
[7] Balevičius, R., Augonis, M., (2018) The effects of bond, shrinkage and creep on cracking resistance of steel and GFRP RC members[J]. Composite Structures, 187: 85-101.
[8] Singh Brahama, P., Yazdani, N., Ramirez, G., (2013) Effect of a time dependent concrete modulus of elasticity on prestress losses in bridge girders[J]. International Journal of Concrete Structures and Materials, 7(3): 183-191.
[9] Gao, D.F., Dong, X., Chen, K.X., Lu. J. (2016), (2014) Research on Temperature Effects For
Prestressed Concrete Continuous Box-girder Bridges[J]. Highway Engineering, 41(02): 80-83.

[10] LI, J., (2012) Code for design Highway Reinforced Concrete and Prestressed Concrete Bridge and Culverts[S]. Communications Press, China Beijing

[11] CEB-FIB Model Code, Bull.D’information CEB, 213/214[S]. Lausanne, 1993.