Study on maintenance time based on deterioration prediction model of main girder

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Abstract. With the increasing number of bridges in Shanxi Province, the difficulty and complexity of bridge maintenance and management tasks have increased significantly. In this paper, based on the existing prediction model, combined with the characteristics of local heavy traffic and large temperature difference environment, the prediction model of concrete carbonation, girder cracking, prestress loss and concrete shrinkage and creep is established. According to the linear law of deterioration curve, the best maintenance time of girder suitable for local characteristics is determined, which can provide guidance for later maintenance management of bridge.

1. Introduction
Prestressed concrete continuous box girder has been widely used in China. As a big coal province, the traffic on the highway is mainly heavy-duty vehicles, and the climate of Shanxi Province is large temperature difference, which puts forward higher requirements for the maintenance of highway bridges in Shanxi Province. Because most of the bridges in Shanxi Province have been built in recent years, the bridge age is relatively short, but some bridges still appear more diseases too early, so we need to pay attention to it.

Many prediction models of carbonation depth are put forward by scholars at home and abroad when studying concrete carbonation. Zhang Yu establishes the prediction model of concrete carbonation depth according to the concrete carbonation mechanism[1].Niu Ditao comprehensively analyzes the factors affecting the durability of concrete structure and establishes a prediction model of concrete carbonation depth[2].

Guo Ju has put forward simplification for the calculation of six types of prestress loss, and get the simplified calculation model of each loss[3].Lu Zhifang and others put forward that the main causes of the bridge diseases are shrinkage creep and large loss of prestress[4]. At present, the relevant calculation methods of shrinkage creep and prestress loss are not perfect.

The mathematical prediction models of concrete shrinkage and creep are CEB-FIP series model, ac1209 series model, BS series model, B-P series model, GZ (1993) model and gl2000 model. The factors that influence these models consider are different, and the calculation accuracy is not identical.

According to the existing research foundation, considering the influence of heavy traffic and large temperature difference environment factors in Shanxi Province, the main girder deterioration prediction model suitable for highway bridges in Shanxi Province is established. According to the change rule of deterioration curve, the maintenance time of main beam is determined and passive maintenance is turned into active maintenance.
2. Influencing factors of girder deterioration

The deterioration of main girder includes four aspects: concrete carbonization, cracking of main girder, prestress loss, shrinkage and creep, etc.

Carbonation of concrete is a complex physical and chemical process in which carbon dioxide in the air interacts with alkaline substances in the cement stone to change its composition, microstructure and properties, and the properties of materials are attenuated. After carbonization, the concrete loses its protective effect on the steel bar and accelerates the corrosion of the steel bar. In addition, the carbonation process also accelerates the shrinkage and creep of concrete, leading to the cracking and damage of concrete structure, which is closely related to the deterioration of the main beam[5~6].

Reinforced concrete members are basically working with cracks. Some cracks with smaller width are invisible to the naked eye and harmless to the structure. Some cracks develop continuously under the combined action of load and environment, causing concrete cover falling off and failure, steel corrosion, reducing the strength and stiffness of the main beam and the performance of the main beam[7~8].

The prestress loss includes friction loss, anchorage loss, elastic compression loss, concrete shrinkage and creep loss, relaxation loss, etc. after several years of operation, the prestress loss makes the main girder appear midspan deflection, cracks and other phenomena[9].

Concrete shrinkage and creep is an inevitable process in the process of concrete strength formation, which is closely related to the concrete carbonation, girder cracks, prestress loss and so on. Therefore, it has research value in the deterioration process of girder[10].

There are many reasons for the above deterioration, and the influencing factors are listed as follows:

Table 1. Influencing factors of deterioration.

| Cracking content | Carbonation of concrete | Cracking of main girder | Prestress loss | Shrinkage and creep |
|------------------|-------------------------|------------------------|---------------|--------------------|
| Materials        | cement varieties and admixtures | reaction of cement and alkali aggregate material properties of steel | cement type |
| Environmental    | temperature and humidity, CO₂ concentration | temperature and humidity | temperature and humidity | temperature and humidity |
| Design           | water cement ratio | section size and mix proportion | thickness of protective layer | water cement ratio |
| Construction     | compactness of concrete | the vibration is not dense | over tension | loading age and holding time |
| other aspects    | / | temperature crack and deformation | / | / |

3. Study on deterioration model of main girder

3.1. concrete carbonation

Concrete carbonation is a complex physical and chemical process. Because of the randomness of the environment of the bridge and the quality of the concrete, the non-stationary random process should be used to simulate the concrete carbonation process.

The research shows that the carbonation velocity coefficient in the process of carbonation obeys the normal distribution. Taking the box girder section as an example, the calculation shows that the carbonation coefficients of six parts of the box girder section are: \( \alpha_1 = 2.30 \), \( \alpha_2 = 2.04 \), \( \alpha_3 = 2.92 \), \( \alpha_4 = 2.56 \), \( \alpha_5 = 2.72 \), \( \alpha_6 = 1.94 \). The carbonation depth of concrete is predicted according to the following calculation model:
\[ X_t = (m_a + \beta \cdot \sigma_a) \cdot \sqrt{t} \]  
\[ m_a = \frac{1}{n} \sum_{i=1}^{n} \alpha_i \]  
\[ \sigma_a = m_{\mu_a} \cdot m_a \]  
\[ m_a = \frac{1}{6} \times (2.30 + 2.04 + 2.92 + 2.56 + 2.72 + 1.94) \]  
\[ = 2.413 \]  
\[ \sigma_a = 0.262 \times 2.413 = 0.632 \]  
\[ X_t = (2.413 \times 1.645 \times 0.632) \times \sqrt{t} = 3.453 \sqrt{t} \] 

Therefore, the final prediction model of concrete carbonation depth of box girder section is as follows:

\[ X_t = 3.453 \sqrt{t} \]  

Figure 1. prediction curve of concrete carbonation depth of box girder

Figure 2. performance attenuation curve of main girder after cracking

In the first five years of bridge operation, the carbonation rate of concrete is the fastest, with the increase of time, the concentration of alkaline substance in concrete decreases gradually, and the chemical reaction rate also decreases gradually.

3.2. main beam cracking

3.2.1. Change model of concrete strength after cracking

In the case of no change in the role of the structure, once the concrete cracks, the resistance of the structure will be reduced, because the concrete cracking will lead to the decline of concrete strength. With the decrease of structural resistance, the cracking situation will further deteriorate; The further deterioration of cracking leads to the deterioration of concrete strength. In some directions, the degree of cracking is also a measure of concrete strength[11].

The main analysis method is as follows: the irregular crack set E is covered by the square n with the division side length R, and the change R is determined if n meets the requirements.
\[
N(r) = \eta r^{-D} \quad (\eta > 0)
\]

Where \( \eta \) is the ratio constant; \( D \) is defined as the fractal dimension of set \( E \), then:
\[
\log N(r) = -D \log(r) + \log \eta
\]

Table 2. Statistics of average strength and fractal dimension of cracks of concrete.

| Average strength of concrete | Fracture fractal dimension D |
|-----------------------------|----------------------------|
| 49.2                       | 1.279                      |
| 48.65                      | 1.293                      |
| 48.5                       | 1.303                      |
| 48.25                      | 1.359                      |
| 47.85                      | 1.394                      |
| 47.15                      | 1.459                      |
| 47.05                      | 1.476                      |
| 45.95                      | 1.551                      |

According to the above table, it can be seen that there is a linear relationship between the compressive strength of concrete after cracking and the fractal dimension of cracks. Linear fitting and regression analysis are carried out. The fitting curve formula is as follows:
\[
f_a = f_{a0} \left[1.249 - 0.21D\right]
\]

Where: \( f_{a0} \) is the compressive strength of the concrete at the beginning of cracks; \( f_a \) is the compressive strength of concrete after cracks appear; \( D \) is the fractal dimension of surface cracks.

3.2.2. Performance degradation model of main girder after cracking

Considering that the stiffness of the main girder will be reduced and the resistance performance of the main girder will also be attenuated after cracks occur in the main girder under the influence of different factors, based on the comprehensive research of a large number of scholars, the performance attenuation formula for the main girder of prestressed concrete bridges in Shanxi Province after cracks is proposed as follows:
\[
R = 1.5 \times 10^{-2} t^2 - 1.89t + 100
\]

Where, \( R \) is the main beam performance index, \( t \) is the service time.

The degradation curve is drawn as shown in the figure 2:

According to the curve development trend in the figure above, the whole can be divided into the following three main stages: initial stage (SJ-1), deterioration stage (SJ-2) and failure stage (SJ-3)

SJ-1 is from the starting point to the mutation point (about 5.5 years). At this time, the slope of the main girder changes suddenly, which indicates that the service performance index of the main girder in the first 5.5 years is good; SJ-2 is from the mutation point to the control point (about 20 years), it shows that the mechanical properties of the main girder decrease with the increase of traffic volume and time, and enter the deterioration stage; SJ-3 is from the control point to the later stage of service (34 years), indicating that the main girder will be damaged after 34 years of service without maintenance means.

3.3. Prestress loss

According to the stress balance equation of prestressed tendons and concrete and their deformation coordination conditions, based on the Latin hypercube sampling method, and taking into account the time-varying shrinkage and uncertainty, the method of calculating the comprehensive value of long-term prestress loss has not been put forward in the current code of our country. A calculation method of long-term prestress loss of concrete structure considering shrinkage, creep and stress relaxation is formed:
\[
A = \left(\frac{\alpha}{\beta}\right)^{\frac{1}{1-m}}, \quad r = \beta(1-m), \quad c = \frac{1}{1-m}
\]
\[ s(t) = A \left(1 - Le^{-rt}\right) \quad t, \quad r > 0, c > 1 \quad (12) \]
\[ s(t) = 279 \times \left(1 - 0.8 \times e^{-0.01t}\right)^{5.5} \quad (13) \]

Figure 3. Prestress loss prediction curve

3.4. Shrinkage and creep
In reference [10], the author established a prediction model of concrete shrinkage and creep based on JTGD62-2004.

3.4.1. Shrinkage prediction model
The annual average humidity of Shanxi Province is about 60%. Therefore, the average humidity of the bridge environment in Shanxi Province is 60%, and the nominal shrinkage coefficient of concrete is 0.529; The correction coefficient of concrete shrinkage and creep is 1.380;

Taking a 30m box girder bridge as an example, the calculation shows that:

\[ \beta_s(t-t_s) = \left[ \frac{(t-t_s)/t_1}{4586+(t-t_s)/t_1} \right]^{0.5} \quad (14) \]
\[ \varepsilon_{cs}(t,t_s) = \xi(t-t_s) \cdot \varepsilon_{iso} \cdot \beta_s(t-t_s) = 0.73 \cdot \left( \frac{t-3}{4586-t} \right)^{0.5} \quad (15) \]

3.4.2. Creep prediction model
The modified prediction model of concrete creep coefficient is as follows:

\[ \beta_H = 150 \left[ 1 + \left( \frac{1.2 \cdot RH}{RH_0} \right)^{18} \right] \frac{h}{h_0} + 250 = 793 \quad (16) \]
\[ \beta_c(t-t_0) = \left[ \frac{(t-t_0)/t_1}{\beta_H + (t-t_0)/t_1} \right]^{0.3} = \left[ \frac{t-t_0}{793+(t-t_0)} \right]^{0.3} \quad (17) \]
\[ \phi(t,t_0) = \eta(t-t_0) \cdot \phi_0 \cdot \beta_c(t-t_0) = 2.289 \times \left[ \frac{t-t_0}{793+(t-t_0)} \right]^{0.3} \quad (18) \]
Draw the shrinkage and creep curves of 30m box girder, as shown in Fig. 4 and Fig. 5

Figure 4. prediction curve of concrete shrinkage strain of box girder bridge

Figure 5. prediction curve of creep strain of box girder concrete

4. Conclusion
This paper mainly studies the factors that affect the deterioration of the main girder from four aspects: concrete carbonization, concrete cracking, prestress loss, shrinkage and creep. Combined with the characteristics of local environment and traffic load in Shanxi Province, the deterioration prediction calculation model is proposed.

According to the development law of the prediction curve, the best time of girder maintenance in Shanxi Province is 5.5 years.

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