Creep Prediction Model of Concrete-Filled Steel Tube under Different Core Concrete Conditions

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Abstract. To reasonably predict the creep law of concrete-filled steel tubular (CFST) members under different working conditions, four groups of creep tests were carried out, and the creep curves of CFST specimens with defects were obtained. Based on the creep prediction formula given in the code for the design of CFST highway arch bridges issued in 2015, the creep prediction models of CFST under different core concrete conditions are studied. The results show that the concrete microcracks around the cavity defects are continuously generated and expanded during the compression process, resulting in the dislocation and sliding of the concrete. It increases the additional deformation of CFST; debonding defects hinder the redistribution of stress between the steel tube and the core concrete, weaken the interaction effect between the steel tube and the concrete, and increase the creep deformation of the core concrete. According to different core concrete states, appropriate reference factors are selected to modify the creep prediction formula of CFST, which greatly improves the creep prediction accuracy of CFST members and defective members.

Keywords. Concrete-filled steel tubular; defect; creep; prediction model.

1. Introduction
When a load of concrete remains unchanged, the phenomenon that the deformation increases with time is called creep, which is one of the main factors affecting the mechanical performance, long-term deformation, and durability of concrete structures [1]. CFST is a kind of structural form with good mechanical properties and durability developed on the basis of spiral reinforced concrete structure and steel tube structures, which is widely used in buildings, bridges, and underground engineering structures. In recent years, CFST structures have been more and more widely used in China. In 2015, China issued the design specification for highway concrete-filled steel tubular arch Bridges (JTG/T D65-06-2015), in which a prediction model for the creep of concrete-filled steel tubular structures was proposed.

Creep will lead to structural deformation, redistribution of internal forces, and other prominent problems of CFST structure. Therefore, with the wide application of CFST in the field of civil engineering, the creep performance of CFST members and structures has attracted more and more attention of scholars abroad: Zhang et al. studied the influence of the content of expansion agent, stress ratio, steel content, steel tube side limit on the creep performance of concrete [2]; Yu et al. studied the nonlinear creep behavior of concrete-filled steel tubes with circular cross-section [3,4]; Luo et al. studied...
the long-term behavior and stability of concrete-filled steel tubular arches [5]. However, the creep prediction model that is fully applicable to CFST has not been put forward in the codes of various countries. It is easy to produce large deviation when using the creep prediction model to calculate the creep of CFST [6]. In addition, the air remained in the concrete due to the bad exhaust or discontinuous pouring during the concrete pouring process is easy to cause the hollow defects of the concrete-filled steel tube, the excessive water-cement ratio of the concrete, the corrosion of the inner wall of the steel tube, and the insufficient micro expansion amount are easy to cause the debonding defects between the steel tube and the concrete, the existence of the defects will weaken the mechanical combination characteristics of the steel tube and the concrete, and change the concrete-filled steel tube creep behavior, and then affect the safety and life of the structure [7-10]. Therefore, it is of great significance to predict the creep deformation of CFST members under long-term load to design CFST structures.

Therefore, to get the accurate prediction model of concrete-filled steel tube creep under different core concrete conditions, according to the prediction formula of concrete-filled steel tube creep given in the public 15 code, different parameters are selected for different core concrete to modify the formula to get the long-term creep prediction model suitable for the defective components of concrete-filled steel tube.

2. Creep Test Overview

2.1. Properties of Raw Materials

- Cement: The cement used for the concrete configuration is P.O42.5 cement produced by the Qilian Mountain cement factory. The basic parameters are as follows: Specific surface area: 326m2·kg-1, Alkali content: 0.43%, Ignition loss: 1.52%, Initial set: 185min, Final set: 325min, Compressive strength: 3d is 21.7MPa, 28d is 48.6MPa, Alkali content: 2mm.
- Fine aggregate: Fine aggregate is natural sand whose fineness modulus is 2.9 produced by The Hongjian group. The basic parameters are as follows: Apparent density: 2630kg/m3; Silt content 1.6%; Compact density 1730kg/m3; Alkali activity index 0.18%; Compact porosity 34%.
- Coarse aggregate: The coarse aggregate is 5-20mm continuously graded central broken basalt, The basic parameters are as follows: Apparent density 2680kg/m3, Packing density 1540 kg/m3, Bibulous rate 1%, Alkali content 0.07%, Sulfur trioxide content 0.28%, Crush indicators 3.2%, Compact density 43 kg/m3.
- Water reducing agent: The water-reducing agent is AN4000 polycarboxylic acid water-reducing agent produced by the Beijing Institute of construction engineering. The basic parameters are as follows: Water reducing rate 30%; Air content 2.8%, 1 h air content after the change 35%, Shrinkage rate than 100%, Initial set 105min, Final set 110min, Compressive strength: 3d 173%, 7d 160%, 28d 155%.
- Expander: The expander is a uea-h type expansion agent produced by the Beijing Institute of construction engineering. The basic parameters are as follows: Magnesium oxide conten3.38%, Total alkali content 0.58%, Chlorine ion content 0.009%, Initial set 174min, Final set 259min.
- Steel pipe: Steel tube diameter 140mm, length 350mm, wall thickness 3mm, elasticity modulus 210GPa, compressive strength 235MPa.

2.2. Component Fabrication

According to the actual situation of the site, four kinds of concrete-filled steel tubular members with different core concrete conditions, including no defect, center hole defect, edge hole defect and circular through debonding defect, were designed, and three specimens were made in each condition. C50 concrete is selected according to the actual working conditions, and the concrete mix proportion is shown in table 1.

One end of the steel pipe shall be welded with a 200*200mm steel plate with a thickness of 5mm, and then the configured concrete shall be poured into the steel pipe. After pouring, the other end of the steel pipe concrete shall be welded with steel plates of the same Specification, placed in the standard curing room for 28 days before the creep test.
Table 1. Concrete mix ratio (kg/m$^3$).

| Water | Cement | Sand | Stone | Expansive agent | Water reducer |
|-------|--------|------|-------|------------------|--------------|
| 180   | 465    | 764  | 1056  | 37.2             | 5.58         |

(1) A fabrication method of cavity defect: When pouring concrete, a cylindrical sandbag with a radius of 36mm and a height of 80mm shall be fixed to the center and edge of the steel pipe according to the cavity defect, and the center section of the sandbag and the center section of the steel pipe shall be controlled at the same plane position. After curing for three days, the sand is discharged from the reserved conduit. The defect rate (the ratio of cavity volume to core concrete volume) is 6.6% for the central cavity defect component of the concrete-filled steel tube and the edge cavity defect component of the concrete-filled steel tube [11-14].

(2) The fabrication method of debonding defects: Before pouring concrete, the 1mm plastic sheet coated with release oil on both sides shall be close to the inner wall of the steel pipe, and then the concrete shall be poured into the steel pipe, and the debonding defect component of the steel pipe concrete can be obtained by pulling out the plastic sheet 24 hours later. Defects of concrete-filled steel tube are shown in figure 1.

![Defect diagram of concrete-filled steel tube](image)

**Figure 1.** Defect diagram of concrete-filled steel tube: (a) Annular debonding defect; (b) Edge cavity defect; (c) Central cavity defect.

2.3. Test Method
A creep test of concrete-filled steel tube is carried out according to the test method for long-term performance and durability of ordinary concrete issued by China [7]. The SSX-XB50 spring type three bar creep loading instrument produced by Tianjin Huatong experimental instrument factory was used for loading after 28 days of sealing maintenance. According to the load strength, which is less than 40% of the theoretical calculation bearing capacity of concrete-filled steel tube, the applied long-term load is 235kN, and the steel tube and concrete are loaded at the same time. Control the test environment temperature to (20±1)°C and relative humidity to (60±5)%%. The creep deformation of concrete-filled steel tube is measured by chord strain gauge, and dial indicator arranged symmetrically on both sides of the component. The dial indicator (with magnetic base and gauge distance of 350mm) is read manually. The strain gauge (gauge distance of 150 mm) is collected by connecting to the comprehensive supporting tester. Preload the empty steel pipe before the test to ensure the normal operation of the measuring equipment.

When loading, firstly, the concrete-filled steel tube component and the creep instrument are geometrically aligned. Then the nuts on the steel tie rod are tightened successively to make the control load of the pressure sensor reach the set value. At the same time, to ensure that the component is in the axial compression state, the strain gauge and the dial indicator should be the same when loading. As the creep of concrete will cause the continuous deformation of CFST members, the load applied to CFST
will change constantly. To keep the load constant, when the load variation is more than 2%, the CFST will be supplemented. The creep value of each working condition is the average value of the measurement results of three-component dial indicators and strain gauges. The instrument layout can be found in figure 2.

![Typical photos during loading.](image)

**Figure 2.** Typical photos during loading.

3. Analysis of Test Results

After 257d loading, the creep strain of concrete-filled steel tube without defect is $140.6 \times 10^{-6}$, and that of edge cavity, center cavity, and circular debonding concrete-filled steel tube is 104.0%, 112.0%, and 125.5% of that of concrete-filled steel tube without defect. The results show that defects increase the creep deformation of CFST, and the influence degree of different defect types on CFST is different. Among them, debonding defects have a greater impact on the creep performance of CFST, and edge void defects have a smaller impact on the creep performance of CFST. The influence degree of center void defects on the creep performance of CFST is between debonding defects and edge void defects. Figure 3 shows the creep curve of four working conditions.

For the debonding members in this experiment, because the load of CFST is only 40% of the theoretical calculation bearing capacity and there is debonding space between the two, the interaction between the steel tube and concrete interface is small, with the steel tube and concrete generally in the state of unidirectional compression and the collaborative deformation capacity of the two weakened, so the CFST debonding members under long-term load Creep deformation is large. All or most of the interfaces between steel tubes and concrete are tightly bonded for the components with cavity defects. Because the transverse deformation coefficient of concrete is greater than that of steel tube in the long-term loading process, the steel tube can produce a hoop effect on the core concrete in the loading process. At the same time, the axial stress continuously redistributes between the steel tube and concrete, and the core concrete and the external steel. The creep deformation of the void component is smaller than that of the debonding component.
According to the theory of microcracks [1], many tiny cracks exist on the material interface composed of multi-phase concrete before loading. In the normal stress range, the interface of cracks transfers the load through friction, and the micro-cracks will increase the creep deformation of components. When the core concrete has cavity defects, the cross-sectional area of the concrete that produces the cavity decreases, and the concrete around the cavity is prone to stress concentration, which aggravates the generation and expansion of new cracks. Because the concrete around the cavity lacks restraint, the concrete around the cavity will have dislocation and slip, which increases the additional deformation of the core concrete. Compared with the central cavity component, when the cavity occurs near the junction of steel tube and concrete, the concrete deformation around the cavity is limited by the steel tube, resulting in the reduction of the number and expansion of concrete micro-cracks and the additional deformation of concrete-filled steel tube due to the dislocation and slip of cracks is reduced. Therefore, the creep deformation of the edge void is smaller than that of the center void.

4. Revision of Creep Model

4.1. Correction of Flawless Creep Model

To ensure that the 15 codes can accurately predict the deformation of CFST, the measured data of the core concrete flawless specimen is compared with the theoretical prediction value of 15 codes as can be seen in equations (1)-(9).

\[ \Phi'(t, t_0) = \frac{\Phi(t, t_0)}{1 + \frac{\rho \Phi(t, t_0)}{a_s}} \]  \hspace{1cm} (1)

\[ \Phi(t, t_0) = \Phi_0 \times \beta_c(t - t_0) \]  \hspace{1cm} (2)

\[ \Phi_0 = \Phi_{RH} \times \beta(f_{cm}) \times \beta(t_0) \]  \hspace{1cm} (3)

\[ \beta(f_{cm}) = -\frac{5.3}{(f_{cm}/f_{c0})^{0.5}} \]  \hspace{1cm} (4)

\[ \beta(t_0) = -\frac{1}{0.1 + (t_0/t_1)^{0.2}} \]  \hspace{1cm} (5)

\[ \Phi_{RH} = 1 + \frac{1-RH/RH_0}{0.46(h/h_0)^{0.5}} \]  \hspace{1cm} (6)

\[ \beta_c(t - t_0) = \left[ \frac{(t-t_0)/t_1}{\beta_{H} + (t-t_0)/t_1} \right]^{0.3} \]  \hspace{1cm} (7)
\[ \beta_H = 150 \left[ 1 + \left( 1.2 \frac{RH}{RH_0} \right)^{18} \right] \frac{h}{h_0} + 250 \leq 1500 \]  

\[ \rho = \frac{1}{1 - e^{-\Phi(t,t_0)}} - \frac{1}{\Phi(t,t_0)} \]

whereas, \( A_s, A_c \)— cross-section area of steel tube and concrete; \( a_s \)— steel content of section, \( a_s = \frac{A_s}{A_c} \); \( \rho \)— empirical parameter; \( t_0 \)— concrete age of loading time (d); \( t \)— concrete age at the predicted time (d); \( \Phi_0 \)— Nominal creep coefficient; \( \Phi(t,t_0) \)— the creep coefficient of concrete when the loading age is \( t_0 \) and the calculation age is \( t \); \( f_{cm} \)— average cube compressive strength of concrete at 28d; \( RH \)— annual average relative humidity; \( h \)— theoretical thickness of member (mm); \( RH_0=100\% \); \( h_0=100\text{mm} \); \( t_1=1\text{d} \); \( f_{cm0}=10\text{MPa} \).

According to the above formula, the comparison diagram of the creep deformation curve between predicted and measured values is shown in figure 4.

![Figure 4. Comparison of predicted and measured values for no defect specimen.](image)

According to the long-term load, when the core concrete changes from the low-stress state to the high-stress state, the Poisson's ratio of concrete will increase from 0.2 to about 0.5, which is far greater than 0.23 of Q235 steel pipe, and the member will produce hoop effect. The pore structure of concrete-filled steel tubular (CFST) will be reduced after loading, while the lateral deformation will be restrained, and the volume of core concrete will be reduced. Therefore, the pore closure of core concrete is one of the important components of the creep of CFST. According to Zhang Rongling’s study in 2015, the amount of pore structure will affect the creep performance of concrete under certain other conditions. The larger the structural porosity is, the larger the creep deformation is. From this conclusion, it can be inferred that the existence of pore structure will accelerate the creep deformation rate of the CFST structure. Compared with JTG/T D65-06-2015 formula, the influence of pore structure is not considered, so the influence coefficient \( \varepsilon_k \) is introduced to supplement the effect. Because the bridging of pore structure belongs to the additional deformation caused by the original transverse deformation of the core concrete constrained by the steel tube, and when the internal pores are bridged, the creep deformation of the component will be further increased, so the specific coefficient correction equation is obtained as shown in equation (10). The modified creep prediction model is as shown in equation (11).

\[ \varepsilon_k = \frac{1}{1 - \ln \left( \frac{t}{t_0} \right)} \]  

\[ \Phi''(t,t_0) = (1 + \varepsilon_k)\Phi'(t,t_0) \]  

The curve comparison between the predicted creep value and the measured creep value of the revised CFST is shown in figure 5.
According to the analysis of the image, the error between the modified prediction model and the measured value is controlled within 8%, and the accuracy is greatly improved.

4.2. Correction of Creep Model for Cavity Defects

The influence of void defects on CFST members is mainly reflected in the fact that the concrete structure around the void is free from constraints and can produce deformation and sliding towards the interior of the void defects. As the void structure inside the member, it can be regarded as one of the pore structures of the member, and the creep deformation will increase due to the increase of the interior pore structure. Therefore, the void defect rate $\gamma$ is introduced into the creep prediction model.

Void defects can be divided into edge void defects and center void defects. The main difference between them is that the hooping effects of steel pipe on defects around defects are different. Because the concrete around the edge cavity is close to the steel tube, the steel tube will restrict the deformation of concrete and the shrinkage of the cavity caused by creep, so the creep deformation of the edge cavity is smaller than that of the center cavity. According to this, the distance $r$ between the inner surface of the steel tube on the cross-section and the core of the defective section is introduced to characterize the strength of the hoop effect of the steel tube on the concrete around the defect, as an important parameter to distinguish the center defect and edge defect of CFST. See equation (12) for the edge hole defect correction model and equation (13) for the center hole defect correction model.

$$\phi''(t, t_0)_b = \left(\frac{1}{1-\gamma}\right) \times \left(1 + \varepsilon_k + \varepsilon_k \times \gamma \times \frac{r}{R}\right) \times \phi'(t, t_0)$$ \hspace{1cm} (12)

$$\phi''(t, t_0)_c = \left(\frac{1}{1-\gamma}\times \frac{R}{r}\right) \times \left(1 + \varepsilon_k + \varepsilon_k \times \gamma\right) \times \phi'(t, t_0)$$ \hspace{1cm} (13)

whereas, $R$—Core concrete radius (mm).

The predicted values calculated by the modified creep model were compared with the experimental values, and the comparison of specific creep deformation curves was shown in figures 6 and 7.
According to the analysis of the images, the error between the modified prediction model and the measured value is controlled within 8%, and the accuracy is greatly improved.

4.3. Correction of Creep Model for Circumferential Debonding Defects

The circumferential debonding defects will weaken the interaction between the core concrete and the steel tube. Because of the existence of pores, the bonding ability between the two is weakened, and the cooperative deformation ability is weakened because of the weakening of the bonding force. The interaction between the steel tube and the core concrete is mainly reflected in that the steel tube shares the core concrete pressure. Therefore, based on the original formula, the pressure distribution coefficient $\theta$ is introduced to characterize the interaction between the steel tube and the concrete under the one-way pressure.

Because of the debonding pores, the bond strength between the core concrete and the steel tube is weakened, and it changes from a three-way compression state to a one-way compression state. At this time, the creep property of core concrete is similar to that of plain concrete to some extent, but the lateral slip and lateral deformation of core concrete are still limited due to the constraints of steel tubes. Therefore, the sand-stone ratio $\lambda$ of core concrete is introduced into the formula to characterize the influence of concrete's factors on creep under uniaxial compression. See equation (14) for specific creep.
prediction model formula.

\[ \phi''(t, t_0) = \lambda \times \theta \times (1 + \varepsilon_k) \times \phi'(t, t_0) \]  

(14)

Draw the predicted value of the revised creep model and the measured value curve, as shown in figure 8.

![Figure 8](image_url)

**Figure 8.** Comparison of modified predicted and measured values for debonding defect.

Figure 8 shows the curve comparison between the predicted value and the measured value of the revised creep model. According to the graphic analysis, the modified formula can predict the creep deformation under long-term load. In the later stage, the error decreases gradually, and the maximum error is 7%. It can be concluded that the formula can predict the creep deformation of debonding members in the later stage.

5. Conclusions

- The creep strain of the edge cavity, center cavity, and ring debonding concrete-filled steel tube increased by 4.0%, 12.0%, and 25.5%, respectively, compared with the concrete-filled steel tube without defects after 257 days of loading. The core concrete defects have a negative impact on the creep performance of concrete-filled steel tubes, and the debonding defects had a greater reduction on the creep performance of concrete-filled steel tubes than the cavity defects.
- Based on the creep prediction model of highway 15 code, the pore structure change coefficient is introduced to modify the model, and the correction model of flawless core concrete with an error less than 10% is obtained.
- The prediction model of void defects is based on the modified Specification for the design of concrete-filled steel tube arch Bridges for highways’ model, which mainly considers the influence coefficient of the defect rate on the structural creep. For the central cavity defect and the edge cavity defect, the distance between the cross-section core and the steel pipe wall is used to characterize the strength of the steel pipe to the hoop, and the creep value is reduced. The model error is less than 10%.
- For the circumferential debonding defects, the model is based on the modified prediction model under the no defect condition of core concrete. Considering the distribution coefficient of the force between the concrete and the steel tube and the ratio of sand to stone, the creep prediction model with the later error controlled within 7% can be obtained by the model modification.

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