Creep behavior of steel bonded reinforced concrete members under small eccentric compression

Jian Cao¹*, Xinpeng Pan¹, Lingyun Zeng², Jingqi Zeng³

¹School of Civil and Architectural Engineering, Nanchang Institute of Technology, Nanchang, 330099, China
²Yaohu Honors College, Nanchang Institute of Technology, Nanchang, 330099, China
³Corresponding author’s e-mail: 18255670@qq.com

Abstract. In this paper, the creep behavior of steel bonded reinforced concrete members under small eccentric compression is studied. Firstly, based on the existing mechanical characteristics of concrete under multi axial stress state, the stress-strain relationship of steel bonded small eccentric concrete is theoretically deduced and analyzed by considering the reduction coefficient of hoop force. Secondly, according to the creep characteristics of confined core concrete, combined with the existing concrete creep model and the analysis of its influencing factors, the influence of sticking steel on the creep of small eccentric reinforced concrete compression members is discussed. The corresponding creep calculation formula is established. Finally, the existing experimental data are used to verify the proposed formula, and its applicability is analyzed.

1. Introduction
In practical engineering, there are often cases that the building structure can not meet the established design requirements due to improper construction, use, management and maintenance. With the continuous deterioration of the environment, the concrete is subjected to various erosion effects, resulting in corrosion of reinforcement and material performance degradation, which has a severe test on its service life and applicability, and the structure may have been unable to meet the requirements. Therefore, it is urgent to reinforce the members. The former method is to rebuild the concrete structure components which can not meet the bearing capacity, which not only wastes a lot of materials, but also pollutes the environment. Therefore, the reinforcement and restraint of degraded structure can meet the requirements of resource saving, energy saving and environmental protection, and also conform to the concept of sustainable development of civil engineering[1-2].

Although there are many researches on creep reduction of concrete-filled steel tube and steel tube concrete, there are not many researches on steel tube and concrete-filled steel tube under creep coefficient. The problem of deformation coordination between bonded steel and concrete is not considered: there are many connection modes between bonded steel and concrete, and the interface between them still has relative slip after loading, and the deformation is not completely coordinated[3].

In this paper, according to the characteristics of reinforced concrete axial compression members, the formulas of radial and circumferential hoop force coefficients are derived. Then the creep analysis of reinforced concrete small eccentric compression members is carried out. Based on the mechanical
properties of confined concrete compression members with small eccentricity, the stress-strain relationship of small eccentric compression members is deduced by combining the reduction coefficient of hoop force. Moreover, the creep model of steel bonded confined concrete is compared with the existing experimental data, and the usability of the model is analyzed.

2. Mechanical analysis of steel bonded confined concrete members with small eccentricity

2.1. Derivation of equilibrium equation

This section will carry out the stress analysis of small eccentric compression members strengthened with steel plate. Firstly, the stress relationship of the small eccentric compression member considering the hoop force is deduced. Finally, the initial stress of the member under external load is analyzed and deduced.

The cross section of the component is in the form of circular section, the stress diagram is shown in Figure 1.

\[ \sum N = 0 \]  
\[ \sum M = 0 \]

According to formula (3) and (4)

\[ \sigma_c = N_c \left( \frac{1}{A_c} + \frac{er}{I_c} \right) \]  
\[ \sigma_s = N_s \left( \frac{1}{A_s} + \frac{er}{I_s} \right) \]

Where \( N_c \) is the vertical force borne by the core concrete, \( N_s \) is the vertical force borne by sticking
steel. For small eccentric compression members

\[ M = N(e_0 + f) \]  

(7)

Where \( e_0 \) is the initial eccentricity of the applied point of external load, \( f \) is deflection of the member. Under the action of external load, the eccentricity of the member is

\[ e_0 + f = \frac{M}{N} = \frac{r}{2 \cos \beta} \]  

(8)

2.2. Analysis of hoop force

In the reinforced concrete members subjected to small eccentric compression, the hoop force is different from that of axial compression member. Considering the thickness and strength of bonded steel, the reduction coefficient should be considered in the hoop force. In small eccentric compression members, the hoop force will be uneven because of the uneven distribution of cross-section stress.

The core concrete is in three-dimensional stress state with unequal lateral compressive stress. According to Hooke's law, there are

\[ \varepsilon_{c1} = \frac{1}{E_c} \left[ \sigma_{c1} - \mu_c (\sigma_{c2} + \sigma_{c3}) \right] \]  

(9)

\[ \varepsilon_{c2} = \frac{1}{E_c} \left[ \sigma_{c2} - \mu_c (\sigma_{c1} + \sigma_{c3}) \right] \]  

(10)

\[ \varepsilon_{c3} = \frac{1}{E_c} \left[ \sigma_{c3} - \mu_c (\sigma_{c1} + \sigma_{c2}) \right] \]  

(11)

\[ \varepsilon_{s1} = \frac{1}{E_s} \left( \sigma_{s1} + \frac{2 \mu_s \sigma_{c2}}{\alpha} \right) \]  

(12)

\[ \varepsilon_{s2} = \frac{\mu_s (\sigma_{s1} - \frac{2 \sigma_{c2}}{\alpha})}{E_s} \]  

(13)

\[ \varepsilon_{s3} = \frac{1}{E_s} \left( -\mu_s \sigma_{s1} - \frac{2 \sigma_{c2}}{\alpha} \right) \]  

(14)

According to the deformation compatibility hypothesis \( \varepsilon_{c1} = \varepsilon_{s1} \), \( \varphi \varepsilon_{c2} = \varepsilon_{s2} \), \( \varphi \varepsilon_{c3} = \varepsilon_{s3} \)

\[ \sigma_{s1} + \frac{2 \mu_s \sigma_{c2}}{\alpha} = n [\sigma_{c1} - \mu_c (\sigma_{c2} + \sigma_{c3})] \]  

(15)

\[ -\mu_s \left( \sigma_{s1} - \frac{2 \sigma_{c2}}{\alpha} \right) = n \varphi [\sigma_{c2} - \mu_c (\sigma_{c1} + \sigma_{c3})] \]  

(16)

\[ -\mu_s \sigma_{s1} - \frac{2 \sigma_{c2}}{\alpha} = n \varphi [\sigma_{c3} - \mu_c (\sigma_{c1} + \sigma_{c2})] \]  

(17)

\( \varphi \) and \( A \) are radial and circumferential coefficients respectively. \( N \) is the ratio of elastic modulus of steel tube to concrete, and \( \alpha \) is the steel content, that is, the ratio of bonded steel to concrete area. \( \mu_c \) and \( \mu_s \) are Poisson's ratios of concrete and steel pipe respectively.

Equation (15) minus equation (16), with

\[ \sigma_{s1} = \frac{n \sigma_{c1}(1 + \varphi \mu_c) - n (\varphi + \mu_c) \sigma_{c2} - n \mu_c (1 - \varphi) \sigma_{c3}}{1 + \mu_c} \]  

(18)

The formula (15) is sorted out

\[ \sigma_{c3} = \frac{n \sigma_{c1} - (n \mu_c + 2 \mu_c / \alpha) \sigma_{c2} - \sigma_{c1}}{n \mu_c} \]  

(19)

Introduce equation (19) into equation (17)
According to the coordination condition of radial deformation between the maximum compressive strain of core concrete, the strain variation of core concrete is

\[ \varepsilon_{c2} = \frac{1}{\varepsilon_1} \left[ \frac{n\mu_c(1+\varphi\mu_c)}{1+\mu_c} - n\mu_c(1+\mu_c) \right] \]

When reinforced concrete is subjected to creep, the strain on the bonded steel is changed as

\[ \varepsilon_{c1} = q \varepsilon_{c1} \]

By introducing equation (21) into equation (19), it can be concluded that

\[ \sigma_{c3} = \left[ \frac{n - n(1 + \varphi\mu_c)}{1 + \mu_c} - \frac{n\mu_c + 2\mu_s}{\alpha} \right] \sigma_{c1} \]

The above is the expression of the relationship between the hoop stress and the axial stress of small eccentric compression members strengthened with steel plate.

For steel bonded concrete members, according to the formula (21) and (23), the initial stress of concrete can be obtained.

\[ \sigma_{c0} = \frac{N(1 + \mu_c)}{\gamma[n(1 + \varphi\mu_c) - n(\varphi + \mu_c)q - n\mu_c(1 - \varphi)q'] + \gamma(1 + \mu_c)\left(1 + \frac{\varepsilon_r}{I_c}\right)} \]

3. Creep analysis of concrete strengthened with steel plate under small eccentric compression

When reinforced concrete is subjected to creep, the strain on the bonded steel is changed as

\[ \varepsilon_s^c = \frac{\sigma_{c1} + 2\mu_s\Delta P}{E_s} \]

The strain variation of core concrete is

\[ \varepsilon_c^c = \sigma_{c1}c_1 \]

The axial creep of core concrete is

\[ c_1 = J\left[1 - \mu_{c,p,1}(q + q')\right] \]

Where J is the unidirectional creep calculated by concrete creep B4 model[4].

The radial strain of core concrete at the maximum fiber is

\[ \varepsilon_{c2} = (p + \Delta P)c_2 \]

Therefore, the radial strain of the core concrete at the maximum fiber is

\[ c_2 = J\left[1 - \mu_{c,p,2}\left(1 + \frac{q'}{q}\right)\right] \]

According to the coordination condition of radial deformation between the maximum compressive fiber of core concrete and bonded steel, there are

\[ \varepsilon_{c2} = \varphi\varepsilon_{c2}^c \]
Substituting equation (27) and (28) into (30)

\[
(p + \Delta P)c_2 = -\frac{\mu_x \phi (\sigma^c_s - 2\Delta P / \alpha)}{E_s}
\]  

(32)

Based on this, it may obtain

\[
\Delta P = \frac{(\phi \mu_\gamma - qc_2 E_s)\sigma^c_s - qc_2 E_s \sigma_{i0}}{E_s c_2 - 2\phi \mu_\gamma / \alpha}
\]  

(33)

According to the axial creep coordination conditions between the maximum compressive fiber and the core concrete are as follows

\[
e^c_{2i} = e^c_{c1}
\]  

(34)

\[
(\sigma_{c0} + \sigma^c_{c1})c_1 = \frac{\sigma^c_{2i} + 2\mu_1 \Delta P / \alpha}{E_s}
\]  

(35)

Replace equation (29) into the above formula

\[
\sigma^c_{c1} = \frac{\left[2\mu_x qc_2 E_s + E_s c_1 \alpha (E_s c_2 - 2\phi \mu_\gamma / \alpha)\right]}{E_s c_1 \alpha (E_s c_2 - 2\phi \mu_\gamma / \alpha) + \alpha \gamma (E_s c_2 - 2\phi \mu_\gamma / \alpha) - 2\mu_1 (\phi \mu_\gamma - qc_2 E_s)} \sigma_{i0}
\]  

(36)

Therefore, the creep calculation formula of concrete strengthened with steel plate under small eccentric compression can be obtained.

4. Model validation

In this paper, the experimental data of Ref.[5] are selected to analyze and verify the model. The comparison between the model calculation results and the experimental results is shown in Figure 2 and Figure 3, and the calculation results in the Ref.[6] are also used for comparison.

![Figure 2. Comparison of the calculated value with the calculated value (the first group)](image-url)
Figure 3. Comparison of the calculated value with the calculated value (the second group)

From Figure 2 and Figure 3, the calculation results of the model established in this paper are larger than the experimental data, but the development trend is almost the same, which first rises rapidly and then increases slowly. Compared with the concrete-filled steel tube members, the binding force of steel and concrete in the concrete-filled steel tube members is slightly lower, which leads to the difference of deformation between the two before. The binding effect of steel plate on concrete is weakened, the creep deformation of the component is higher than that of concrete-filled steel tube.

From the first group, the calculation results of creep in the first 100 days are nearly 6% higher than the experimental data, and the average value of the latter 100 days is 10% higher than the experimental data, and the highest difference is about 120 days, which is 20% higher than the experimental data; the difference between the second group of data and the first group of data is not much, but the highest difference is 25%; the change trend of the third group of experimental data is consistent with the experimental data 18% more than the experimental value.

From Figure 2 and Figure 3, the radial circumferential coefficient also has an effect on the creep. The larger the radial circumferential coefficient is, the smaller the creep value is. On the other hand, the stronger the constraint is, the smaller the creep is. From the above, the model established in this paper can well predict the creep of concrete members with small eccentricity restrained by bonded steel.

5. Conclusion

This paper mainly analyzes the stress of steel bonded concrete under small eccentric compression, and deduces the stress-strain relationship and the calculation of initial stress. In view of the different connection forms between bonded steel and concrete-filled steel tube, the reduction coefficient is considered in the calculation of hoop force, and the reduction coefficient is verified. Then, the model is verified. According to the calculated data and Tan Sujie's model, the creep data is basically consistent with the trend, and the value of radial circumferential coefficient is analyzed, and it is concluded that the weaker the constraint, the greater the creep of concrete. The B4 model is combined with the stress analysis of small eccentric compression members of steel bonded confined concrete structure, and the calculation formula of concrete creep is obtained. The calculation results are consistent with the actual test results, which proves that the B4 model of concrete creep is suitable for steel bonded confined concrete members.

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