Parametric analysis of the influence coefficient of round-end concrete-filled steel tubular members

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Abstract. The long-term load has great influence on the internal force distribution, deformation, bearing capacity and other mechanical properties of round-end concrete-filled steel tubular member. Parameter analysis is carried out on the influence coefficient kcr of the round-end concrete-filled steel tubular members under the influence of long-term effects. The parameter analysis results show slenderness ratio, concrete strength, steel content and load eccentricity have great impact on the influence coefficient kcr.

1. Introduction
Round-end concrete-filled steel tubular (RCFST) columns characterized by favorable external shape and loading properties are increasingly applied in engineering practice. In normal cases, core RCFST columns undergo creep and shrinkage under long-term load [1], causing problems such as internal force redistribution, stress concentration, and even structural damage. To explore the mechanical properties of RCFST members under long-term load, a substantial number of experimental studies [2-5] and theoretical analysis [6-9] have been carried out. Given that existing methods for RCFST member design overlook the effect of long-term load, it is essential to develop calculation methods specific to RCFST members under long-term load.

2. Mechanical performance analysis model
The paper established an analysis model for RCFST members by ABAQUS[10], the load-deformation curve of RCFST columns was worked out on the condition that the effect of long-term load was considered.

2.1. Steel-concrete constitutive relationship model
The steel was simulated through the isotropic elastic-plastic model provided by ABAQUS, confirming that it met the von Mises yield criterion. The core concrete in the long-term load phase was simulated by the viscoelastic model, and the core concrete in the bearing capacity phase was simulated by the plastic damage model. Also, a viscoelastic constitutive model that takes into account the time effect was used to simulate the mechanical properties of concrete under long-term load. The compressive stress-strain relationship model for core concrete that considers the confining effect from steel tubes was modified on the assumption that the long-term load does not affect concrete strength, but solely affects the changes of strain. Under the condition that the stress coordinate values remain unchanged, the strain in the concrete stress-strain relationship model under short-term load was amplified and
displaced, in which the effects of creep and shrinkage were considered. As such, the paper identified the relationship between the strain when the effect of long-term load was considered and the strain in the stress-strain relationship under corresponding short-term load.

2.2. Finite element modeling
Finite element modeling was conducted for RCFST columns under long-term load using ABAQUS. In the finite element model, 4-node shell elements were used for steel tubes, and 8-node 3D shell elements were used for concrete; the interface model between steel tubes and concrete used hard contact in the normal direction of the interface and the coulomb friction model in the tangential direction [10]. In the thickness direction, the steel tube adopted 4-node shell elements (S4R) that have nine integration points in Simpson’s rule, while both the concrete and end cover plates used 8-node elements with reduced integration (C3D8R) for 3D shell element simulation, with the end cover plates set to be rigid. For the convenience of calculation, 1/4 model of the member was cut out for analysis. In the long-term load action stage, long-term eccentric load NL was applied to the concrete-filled steel tubs through force loading. The NL remained unchanged until the end of the long-term load. In the bearing capacity calculation stage, a load was continuously applied to the member through displacement loading until it was destroyed.

2.3. Boundary conditions
For the entire member, both its top and bottom boundary conditions were displacement/rotation conditions. The freedom of the member’s top end plate was confined in five directions U2, U3, UR1, UR1, UR3, while the freedom of its bottom was confined in six directions U1, U2, U3, UR1, UR2, UR3. The eccentrically compressed member was loaded in such a way as to apply linear load in the directions of the strong and weak axes of the top end plate, and to apply load in the direction of the end plate U1.

The member was loaded with the effect of long-term load considered. To be specific, Stage I was to apply displacement loading in the U1 direction until the end. Stage II was to work out the applied force load value, that is, the long-term load value NL necessary to maintain the load, according to the long-term load ratio and the ultimate bearing capacity at the first stage. The load value NL was kept unchanged through force loading until the end of creep. Stage III was composed of two analysis steps, namely NL force loading and displacement loading.

2.4. Verification of RCFST axial-compression member model
In preliminary research [10], axial compression experiments for RCFST columns had been carried out, simulating 3 RCFST specimens under axial compression and eccentric compression separately. It has been shown that the finite element method can well simulate RCFST members. In order to verify the correctness of the finite element model that takes into account the effect of long-term load, the paper simulated the existing concrete-filled steel tubular columns under long-term load, including 4 square and rectangular concrete-filled steel tubular specimens [11] and 2 concrete-filled steel tubular specimens. We attempted to deal with the problem of the finite element calculation of the strain-time (ε-t) curve under long-term load and to compare it with the experimental curve. The calculated results were satisfactorily consistent with the experimental ones, suggesting that the model can provide accurate and stable prediction results.

3. Parametric analysis of the influence coefficient of the bearing capacity of RCFST eccentric-compression members
On the basis that the correctness of the model was verified, efforts were made to explore the working mechanism of RCFST eccentric-compression members with the effect of long-term load taken into consideration, in an attempt to identify the mechanical properties of eccentric loading columns under the effects of the long-term load. Calculation example: the member diameter of section D=800 mm, section width B=400 mm, C60 concrete (fcu=60MPa), final creep coefficient φu=0.9; steel ratio αs.
=0.1, Q355 steel \((f_y = 355\text{MPa})\), slenderness ratio of 40, eccentricity ratio \(e/r = 0.5\) (where, the strong axis \(r = D/2\), the weak axis \(r = B/2\)), \(n = 0.4\); the loading age was set 28 days, and the loading age limit was set 50 years.

Analyses were made to identify the influence law of each parameter on the influence coefficient \(K_{cr}\) of the bearing capacity of RCFST members with the effect of long-term load considered.

\[
K_{cr} = \frac{N_{ul}}{N_{u0}}
\]

Where, \(N_{ul}\) is the ultimate capacity of RCFST members when the effect of the long-term load is considered; \(N_{u0}\) is the ultimate capacity of RCFST members when the effect of the long-term load is not considered, and it can be worked out by referring to \[8\].

3.1. The effects of slenderness ratio and concrete strength on \(K_{cr}\)

Figure 1 presents the effects of slenderness ratio and concrete strength on \(K_{cr}\). As illustrated in the figure that compares the effects of eccentric compression in the strong and weak axes on \(K_{cr}\), the slenderness ratio has a large and complicated effect on the bearing capacity of RCFST members with the effect of long-term load considered. For RCFST members under eccentric compression in the strong axis, when the slenderness ratio is smaller than 20, it has an insignificant effect on \(K_{cr}\); when the slenderness ratio is between 20 and 60, \(K_{cr}\) decreases greatly as the value increases; when the value exceeds 60, its effect on \(K_{cr}\) tends to be stable. For RCFST members under weak-axis eccentric compression, when the slenderness ratio is smaller than 20, \(K_{cr}\) is hardly influenced by it; when the slenderness ratio is between 20 and 80, \(K_{cr}\) decreases greatly as the value increases; when the value exceeds 80, its influence on \(K_{cr}\) tends to be stable.

Under the same slenderness ratio, the bearing capacity influence coefficients of the eccentric compression in the strong and weak axes shared a similar change trend, but comparatively speaking, the strong shaft bias compression has smaller \(K_{cr}\) value than the weak-axis eccentric compression. The reason behind it may be that for short members with small slenderness ratio, they mainly show strength failure, and the increased second-order effects caused by shrinkage and creep exert no significant adverse impact on the bearing capacity; however, for long members with a relatively big slenderness ratio, the second-order effects caused by the long-term load has a more obvious impact on the bearing capacity. Under the same slenderness ratio and concrete strength, since the members under strong shaft bias compression have a larger length than those under weak-axis eccentric compression, the large volume of concrete may cause the concrete creep to increase, thereby lowering the influence coefficient \(K_{cr}\) of the bearing capacity of RCFST members. In the premise of the same slenderness ratio, a long-term load has a larger effect on the members under strong shaft bias compression than on those under weak shaft bias compression.
As illustrated in Figure 1, in the premise of the same slenderness ratio that is below 20, concrete strength has a relatively small influence on $K_{cr}$; but when the ratio is between 20 and 120, $K_{cr}$ decreases as the concrete strength increases from 30 MPa to 90 MPa. This may be attributed to the significantly increasing creep of concrete under long-term load as a result of the increase in concrete strength, that is, the increase in concrete strength leads to a growing effect of long-term load on the bearing capacity of RCFST members.

3.2. The effects of slenderness ratio and steel yield strength on $K_{cr}$

Figure 2 presents the effects of slenderness ratio and steel strength on $K_{cr}$. As illustrated, when the steel is under strong shaft bias compression and with a slenderness ratio in the range of 20-100 or the steel is under weak-axis eccentric compression and with a slenderness ratio in the range of 60-120, the higher the yield limit of the steel, the slightly larger the value $K_{cr}$. On the whole, steel yield strength $f_y$ has almost no effect on the influence coefficient $K_{cr}$ of the bearing capacity of RCFST members.

3.3. The effects of slenderness ratio and long-term load ratio on $K_{cr}$

Figure 3 shows the effects of slenderness ratio and long-term load ratio on $K_{cr}$. It can be seen that at a fixed slenderness ratio, the influence coefficient $K_{cr}$ of the bearing capacity of RCFST members
showed changes, which, however, were insignificant. As illustrated in Fig. 3 and 1, for members under strong shaft bias compression, as the slenderness ratio increased in the range of 20-60, $K_{cr}$ was significantly decreased; as the slenderness ratio increased in the range of 80-120, the effect of slenderness ratio on $K_{cr}$ tended to be stable.

![Graph](image1)

Figure 3. The effects of slenderness ratio and long-term load ratio on $K_{cr}$

### 3.4 The effects of slenderness ratio and steel ratio on $K_{cr}$

Figure 4 presents the effects of slenderness ratio and steel ratio on $K_{cr}$. As illustrated, the nominal steel ratio has similar influence rules on the influence coefficient $K_{cr}$ of the bearing capacity of RCFST members under strong shaft bias compression and those under weak-axis eccentric compression: at the same slenderness ratio that is below 40, the steel ratio has a little effect on $K_{cr}$; when the slenderness ratio is between 40 and 120, the value $K_{cr}$ increases with the increase of the steel ratio. The higher the steel ratio, the greater the proportion of the steel tube in the section of a RCFST member, the higher the ratio of stress borne by the steel tube accordingly. Consequently, weakens the effects of concrete creep in the circular arc segment and the straight segment. Therefore, an increased steel ratio, to a certain degree, offsets the effect of long-term load on the bearing capacity of RCFST members.

![Graph](image2)

Figure 4. The effects of slenderness ratio and steel ratio on $K_{cr}$
3.5. The effects of slenderness ratio and eccentricity on $K_{cr}$

Figure 5 shows the effects of the slenderness ratio and eccentricity on $K_{cr}$. As illustrated, when the slenderness ratio is between 40 and 100, the value $K_{cr}$ tends to increase on the whole and then gradually becomes stable; when the slenderness ratio is 20, eccentricity has a small effect that tends to be gentle on $K_{cr}$. For members with a large slenderness ratio, the compression zone of the mid-span section of the concrete decreases with eccentricity, which weakens the effect of long-term load. Consequently, with the increase of the steel ratio, the value $K_{cr}$ increases and then gradually tends to stable.

![Figure 5. The effects of the slenderness ratio and eccentricity on $K_{cr}$](image)

3.6. The effects of slenderness ratio and cross-sectional aspect ratio on $K_{cr}$

Figure 3-6 is the effects of slenderness ratio and cross-sectional aspect ratio on $K_{cr}$. As illustrated, for members under strong shaft bias compression, the cross-sectional aspect ratio has an effect on $K_{cr}$ but the effect is insignificant. For members under strong shaft bias compression and with a slenderness ratio of 60-120 and members under weak-axis eccentric compression with a slenderness ratio of 40-120, the smaller the cross-sectional aspect ratio, the slightly higher the value $K_{cr}$, that is, the effect of long-term load on the bearing capacity of RCFST members tends to decrease.

![Figure 6. The effects of slenderness ratio and cross-sectional aspect ratio on $K_{cr}$](image)
4. Conclusion

With the finite element method, the paper built a RCFST column model under long-term load, by which the effects of slenderness ratio, concrete strength, steel yield strength, steel ratio, long-term load ratio, eccentricity, and cross-sectional aspect ratio on the bearing capacity of RCFST members under long-term load were investigated.

(1) Parameters including steel yield strength, long-term load ratio, and cross-sectional aspect ratio were found to have a small effect on the influence coefficient $K_{cr}$ of the bearing capacity of RCFST members under long-term load.

(2) Parameters including slenderness ratio, concrete strength, steel ratio, and eccentricity were found to have a large effect on the bearing capacity of RCFST members under long-term load.

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