BIAXIAL CREEP OF HIGH-STRENGTH CONCRETE AT EARLY AGES ASSESSED FROM RESTRAINED RING TEST

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Abstract: Creep can relax the restrained stress of concrete structures, thus reducing the crack risk. Concrete structures may be subjected to multiaxial stress when the shrinkage deformation is restrained, however, the multiaxial creep property of early-age concrete is still far from clear. This study employed restrained ring test to investigate the basic creep property of high-strength concrete under biaxial tensile-compressive stress condition at early ages. A finite element analysis based-method was proposed to retrieve the biaxial creep of concrete based on the measured strain of the steel ring. The uniaxial tensile and compressive creep properties of high-strength concrete were also measured at different ages, which were compared with that obtained from the restrained ring test. The results show that concrete creep under both uniaxial and biaxial stress conditions decrease with increasing loading age. However, the creep under the biaxial tensile-compressive stress condition is only about 54~63% (41~75%) of that under the uniaxial tensile (compressive) stress condition, suggesting that the stress condition is a key factor that affects the creep property of high-strength concrete at early ages. The findings in this study can provide new insight into the creep effect on the restrained stress calculation and crack risk assessment of the high-strength concrete structures.

1 INTRODUCTION

Shrinkage deformation of high-strength concrete at early ages is a great concern in engineering. Normally stress will generate in concrete structures when the shrinkage deformation is restrained. Once the tensile stress of the concrete structures exceeds its tensile strength, crack will occur. Creep can significantly relax the restrained stress of concrete structures and thus reduce the crack risk [1-2]. Although there have existed numbers of investigations on concrete creep property, the creep property of high-strength concrete at early ages is far from being well understood.

Concrete structures under service generally work under a complex state of stress. The majority of concrete structures are usually under multiaxial stress condition. It is reported that one of most widely existing stress condition is the biaxial tension-compression [3]. However, researches on the creep property of concrete under biaxial stress condition are relatively limited. Heather et al. [4] investigated the biaxial tensile-compressive creep property of concrete under drying condition through the restrained ring test and found that the creep coefficient of early-age concrete is less than that under the uniaxial tensile stress condition, which suggests that the stress condition will have an important effect on the creep development of concretes. However, the difference between the uniaxial creep and the multiaxial creep is still unclear, therefore, it is necessary to investigate the creep property of early-age concrete under multiaxial tensile-compressive stress condition.

In this study, the basic creep property of high-strength concrete under the biaxial tensile-compressive stress condition was measured through the restrained ring test, the biaxial tensile-compressive stress condition of concrete was created via restraining the shrinkage deformation of concrete ring by the steel ring. Then the biaxial tensile-compressive creep property was back-calculated through finite element analysis. Besides, the uniaxial tensile and compressive creep properties of high-strength concrete were also measured at different loading ages. The difference between the uniaxial creep and the biaxial creep will be discussed, which is expected to provide new insight into the early-age crack assessment of high-strength concrete structures.

2 EXPERIMENTS

2.1 Mixture proportions and mechanical properties

The water to cement (*w*/*c*) ratio of concrete was 0.3. The mixture proportions are summarized in **Table 1**. The maximum size of the coarse aggregate is 12.5 mm.

Table 1: Proportions of concrete mixtures

Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Sand (kg/m^3)	Super-plasticizer (kg/m^3)
810	243	795	530	1.8

The variation of the elastic modulus $E(t)$ of concrete with age t can be expressed as:

$$E(t)=33.6\times\left(1-0.34e^{-0.22t}\right) \quad (1)$$

The shrinkage strain $\varepsilon^{c-s}(t)$ development of concrete within 50 days can be expressed as:

$$\varepsilon^{c-s}(t)=95.7\times10^{-6}\times\left[1-\ln\left(1+0.5869\times t\right)\right] \quad (2)$$

2.2 Creep measurement of high-strength concrete at early age under biaxial stress

The creep property of concrete under biaxial tensile-compressive stress condition was assessed through a restrained ring test under 23±2℃. The restrained shrinkage ring setup is shown in **Figure 1**.

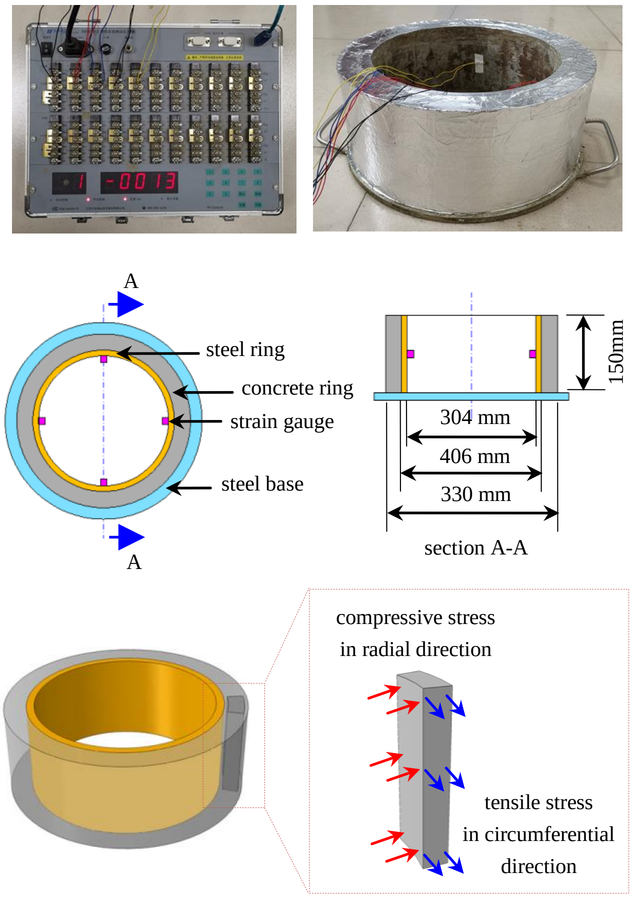

Figure 1: Restrained shrinkage ring setup to measure the biaxial tensile-compressive creep of concrete.

It is obvious that the radial stress is in compression and the circumferential stress is in tension when the shrinkage deformation of the concrete ring is restrained by the steel ring. During the restrained ring test, three layers of self-adhesive aluminium foils were applied at the top and lateral surfaces of concrete ring to create the sealed condition. In this study, the basic creep property of concrete under biaxial tensile-compressive stress condition was back-calculated by finite element analysis based on the measured steel ring strain. The steel strain was measured by four electrical resistance strain gages glued at the inner circumference of the steel ring with 90 degree apart in the mid-height of the steel ring.

2.3 Creep measurement of high-strength concrete at early age under uniaxial stress

The uniaxial tensile creep property of concrete under sealed condition was measured at the age of 1, 7, and 28 days by a servo-electrical loading frame. The deformations of concrete specimen during the uniaxial tensile creep test were measured by two LVDTs with the precision of 1μm. The size of concrete specimens in the uniaxial tensile creep test was Φ100 mm×400 mm. The specimens were sealed by three layers of self-adhesive aluminium foils in all surfaces. The testing temperature was also controlled at 23± 2 ℃. More details about the uniaxial tensile creep measurement can be found in our previous studies [3].

The uniaxial compressive creep test was similar to that under the uniaxial tensile stress condition. The specimen size in the uniaxial compressive creep test is Φ250 mm×100 mm. The uniaxial compressive creep of concrete was measured at the age of 1 and 7 days. The testing environmental condition of the uniaxial compressive creep measurement was the same as that of the uniaxial tensile creep measurement. More details about the uniaxial compressive creep measurement can be found in our previous studies [5].

3 THEORETICAL MODELING

3.1 Creep model of high-strength concrete at early ages

Usually, concrete creep can be characterized by the creep compliance function $J(t,t_0)$, which can be expressed as [6]:

$$J(t,t_0)=\varepsilon(t,t_0)/\sigma(t_0)=1/E(t_0)+C(t,t_0) \quad (3)$$

where, $\varepsilon(t,t_0)$ is the total strain of concrete at time t when it is subjected to a constant stress $\sigma(t_0)$ at time t_0; $E(t_0)$ is the elastic modulus at time t_0; $C(t,t_0)$ is the specific creep function, which denotes the creep strain at time t generated by a unit stress applied at time t_0.

The specific creep function expressed in Eq.4 is employed to characterize the creep property of concrete at early ages due to its easy incorporation into the finite element analysis. Moreover, the specific creep function shown in Eq.4 can significantly reduce the memory space of the simulated results[7].

$$C(t,t_0)=\sum_{i=1}^{2}\left(a_i+b_i t_0^{-c_i}\right)\left[1-e^{-d_i(t-t_0)}\right] +me^{-nt_0}\left[1-e^{-n(t-t_0)}\right] \quad (4)$$

where, a_i, b_i, c_i, d_i, m, and n are constant parameters, which can be determined by the measured data.

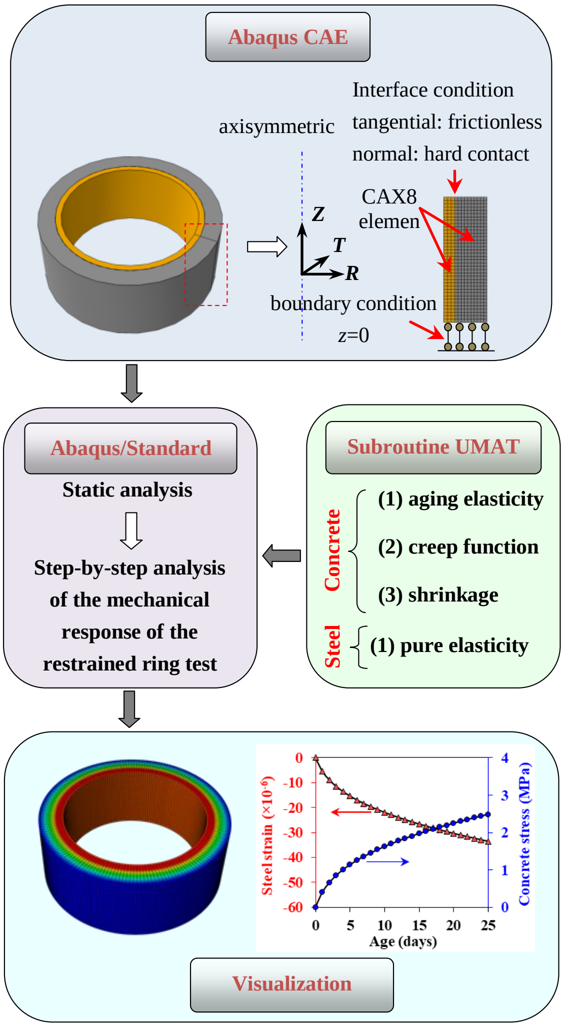

Figure 2: Finite element simulation of the restrained ring test to retrieve the biaxial tensile-compressive creep property of concrete.

3.2 Numerical simulation of restrained ring test to obtain biaxial creep of concrete

In this study, the creep property of concrete under the biaxial tensile-compressive stress condition was back-calculated by finite element analysis using ABAQUS software based on the measured steel ring strain. The procedure of the finite element analysis of the restrained ring test is shown in **Figure 2**. To facilitate the step-by-step analysis of the mechanical response of the restrained ring test, the stress increment and strain increment relations for both the concrete and steel was defined in the subroutine UMAT.

4 RESULTS

4.1 Measured concrete creep under the uniaxial stress condition

The measured basic creep compliance of concrete loaded at the age of 1, 7, and 28 days under the uniaxial tensile stress condition is shown in **Figure 3a**. It can be seen that the measured tensile creep compliance decreases with increasing loading age, which is consistent with the existing findings in the literature [8-9]. The creep model expressed in Eq.3 is used to fit the measured creep property of concrete under uniaxial tensile stress condition, the calibrated parameters of the creep model are summarized in **Table 2**. The fitted creep compliance is also shown in **Figure 3a** as the solid line. It can be seen that the fitted creep compliance is in good agreement with the measured one.

The measured basic creep compliance of concrete loaded at the age of 1 and 7 days under the uniaxial compressive stress condition is shown in **Figure 3b**. The measured compressive creep compliance decreases with increasing loading age, which is the same as the uniaxial tensile creep. The creep model expressed in Eq.3 is used to fit the measured uniaxial compressive creep property of concrete, the calibrated parameters are summarized in **Table 2**. The fitted creep compliance is also shown in **Figure 3b** as the solid line, which can match the measured ones quite well.

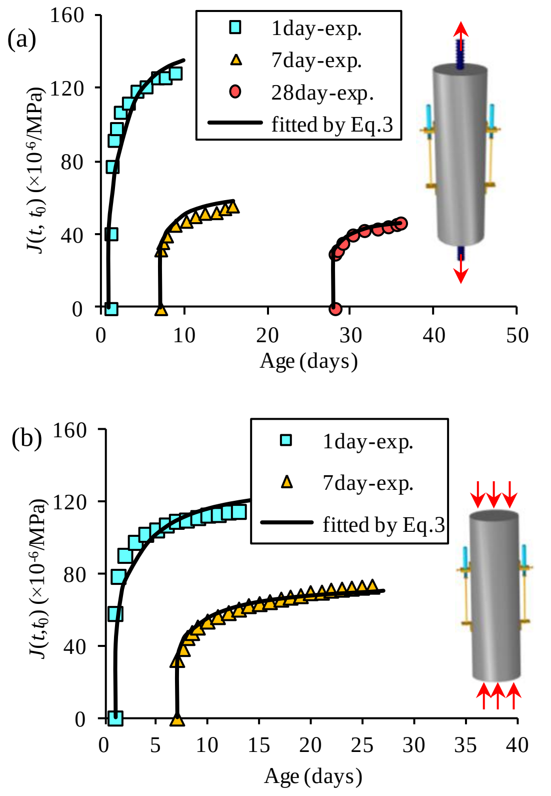

Figure 3: Comparison of the measured basic creep compliance of concrete loaded at different ages under (a) uniaxial tensile stress and (b) uniaxial compressive stress with that fitted by Eq.3.

Table 2: Summary of calibrated parameters of the specific creep function of concrete expressed in Eq.4 under uniaxial and biaxial stress conditions

Parameter	uniaxial tensile stress	uniaxial compressive stress	biaxial tensile-compressive stress
a_1 (×10^{-12}/Pa)	1.42	3.42	0.92
b_1 (×10^{-12}/Pa)	22.54	19.54	14.76
c_1	0.71	0.67	0.54
d_1	1.32	3.21	1.65
a_2 (×10^{-12}/Pa)	11.43	6.34	4.76
b_2 (×10^{-12}/Pa)	54.69	35.43	37.82
c_2	1.54	0.58	1.76
d_2	0.37	0.36	0.45
m	17.43	26.45	8.60
n	0.06	0.08	0.05

4.2 Measured concrete creep under the biaxial stress condition

To obtain the creep property of concrete under the biaxial tensile-compressive stress condition, the calculated strain of the steel ring was matched with the measured one by adjusting the creep parameters shown in Eq.4. It is noted that there is still no consensus on the issue whether the creep property of concrete in tension is the same as that in compression currently. Some researches revealed that tensile creep of concrete is the same as the compressive creep [10], while others presented an opposite result [11]. In this study, it is assumed that tensile creep is equal to the compressive creep for simplicity. Therefore, the back-calculated creep property of concrete from the restrained ring test can be considered as the overall response of tensile creep and compressive creep. The comparison of the measured strain of the steel ring with the calculated one by using the biaxial creep property (solid line) is shown in **Figure 4**. The calibrated parameters of the biaxial creep model are also summarized in **Table 2**. The calculated strain development of the steel ring by elastic analysis (dashed line) is also presented in **Figure 4** for comparison.

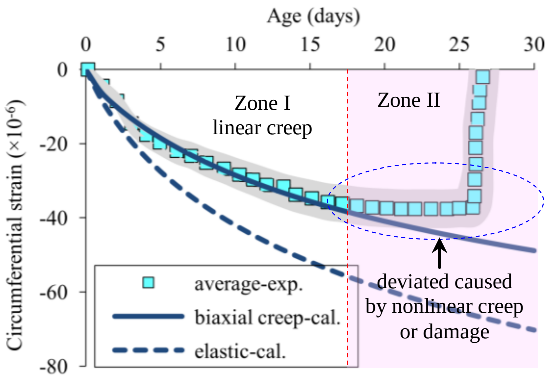

Figure 4: Comparison of the measured strain of steel ring in the restrained shrinkage test with the calculated ones by viscoelastic analysis with biaxial creep and elastic analysis of concrete ring.

It can be seen that the magnitude of the calculated strain of the steel ring obtained by the elastic analysis is about 30~48% greater than the measured one, the main reason lies in the fact that the stress relaxation caused by concrete creep is not considered during the elastic analysis. However, the calculated steel strain obtained by considering the biaxial creep property of concrete can match the measured one quite well until 17 days. The calculated steel strain deviates from the measured one after 17 days, which may be caused by the nonlinear creep or damage of concrete. This will be further discussed in Section 5.2.

5 DISCUSSIONS

5.1 Comparison of concrete creep under uniaxial and biaxial stress conditions

In order to illustrate the influence of stress condition on the creep development of high-strength concrete at early ages, **Figure 5** shows the comparison of the specific creep of concrete loaded at the age of 1, 7, and 28 days under uniaxial tensile stress condition, uniaxial compressive stress condition, and the biaxial tensile-compressive stress condition.

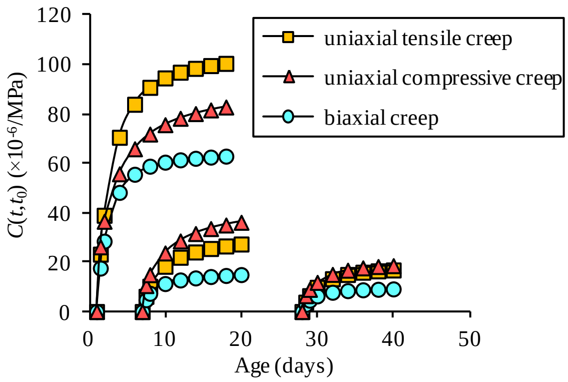

Figure 5: Comparison of the specific creep of concrete loaded at different ages under uniaxial tensile stress condition, uniaxial compressive stress condition, and biaxial tensile-compressive stress condition.

It can be seen from **Figure 5** that the specific basic creep of concrete under the biaxial stress condition is less than those under the uniaxial tensile and compressive stress conditions for all loading ages, which is only about 54~63% (41~75%) of that under uniaxial tensile (compressive) stress. This phenomenon was also observed for early-age concrete tested under drying condition by Heather et al [4]. They found that the biaxial creep of concrete is only 43% of the uniaxial tensile creep under drying condition and concluded that the decrease of concrete creep under the biaxial stress condition is related to the ageing of concrete. In fact, many researches in the literature have revealed that sustained loading will contribute to a gain of strength and stiffness of concrete [12]. Stiffer concrete will exhibit less creep, which may account for the decrease of creep under the biaxial stress condition. Bažant and Kim [13] have also paid attention to this issue and introduced the concept of concrete adaption into the creep model to consider the influence of multiaxial stress condition on the creep development.

5.2 Influence of concrete damage or nonlinear creep on the back-calculation of biaxial creep property of concrete

Unlike the uniaxial creep test under constant stress condition, the internal stress within concrete in the restrained ring test will gradually increase as the restrained shrinkage deformation increases. It is widely accepted that high stress level will result in damage or nonlinear creep of concrete [14], which will affect the mechanical response of concrete structures.

Whether concrete damage or nonlinear creep is the cause for that the biaxial creep property of concrete is less than the uniaxial one will be discussed in this section. Clearly, the stiffness of concrete will be weakened when concrete damage or nonlinear creep occurs, resulting in a decrease of the circumferential strain of the steel ring. As shown in **Figure 4**, the calculated steel strain by considering no damage or nonlinear creep during the viscoelastic analysis can well capture the measured one until 17 days, which is defined as Zone I where concrete exhibits most probably the linear creep property, i.e., the creep deformation increases linearly with the applied stress and the effect of damage or nonlinear creep is limited. However, the predicted steel strain deviates from (greater than) the measured one after 17 days (denoted as Zone II in **Figure 4**), which may be caused by ignoring the influence of the damage or nonlinear creep of concrete during the prediction. Since the stress/strength ratio is greater than 73 % after 17 days based on the direct tensile strength criterion, the damage or nonlinear creep of concrete would have a nonnegligible influence on the reduction of the strain development of the steel ring in Zone II. Therefore, it can be inferred that the calculated steel strain, if the damage or nonlinear creep of concrete is considered, would capture well the measured steel strain in Zone II.

In general, the effect of damage or nonlinear creep of concrete in Zone II is more significant than that in Zone I because of the much higher stress/strength ratio in Zone II, which is expected to cause greater creep. However, this is not the case under the biaxial loading condition, that the biaxial creep of concrete with damage is much less than that of the uniaxial loading condition within the linear stress/strength ratio range. This suggests that the damage effect on the concrete creep under the biaxial loading condition is much complex than that under the uniaxial loading condition. The mechanism is yet not clear and deserves further investigation in the future work.

6 CONCLUSIONS

In this study, the basic creep property of high-strength concrete with *w/c* ratio of 0.3 under the biaxial tensile-compressive stress condition was assessed by the restrained ring test. The main findings are:

Concrete creep under both uniaxial and biaxial stress conditions decreases with the increasing loading age. However, the specific basic creep of concrete under the biaxial tensile-compressive stress condition is less than that under the uniaxial stress condition, which is about 54~63 % (41~75 %) of that under the uniaxial tensile (compressive) stress condition. This suggests that use of the uniaxial creep property to analyze the restrained concrete structure under complex stress condition would lead to an unconservative prediction of the mechanical performance of the structures.

The effect of damage or nonlinear creep on concrete creep under the biaxial tensile-compressive stress condition at early ages is complex, and the mechanism is yet not clear, which deserves further investigation in the future work. The findings in this study can provide new insight into the effect of concrete creep on the restrained stress calculation and crack risk assessment of high-strength concrete structures under multiaxial stress condition.

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