EFFECT OF AUTOGENOUS SHRINKAGE OF ULTRA HIGH-STRENGTH CONCRETE ON BENDING BEHAVIOR OF REINFORCED CONCRETE COLUMN

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ABSTRACT:
In this research, moment calculation for reinforced concrete column using ultra high-strength concrete under constant axial load with assumption of liner strain distribution, which was so-called “fiber model”, was conducted. This calculation took account of volume change of concrete regarding autogenous shrinkage and creep. Using the proposed fiber model, bending behavior of reinforced concrete (RC) column with ultra-high strength concrete is simulated. As a result, autogenous shrinkage make the very small difference in maximum bending moment of RC column, and the autogenous shrinkage affect much on the curvature at the yielding of compressive rebar.

Keywords: ultra high-strength concrete, fiber model, autogenous shrinkage, creep, maximum bending moment

1. INTRODUCTION
Due to development of DSP technique and super plasticizer, it becomes relatively easy to use ultra high strength concrete for reinforced concrete structure recently. The concrete whose nominal compressive strength is more than 150 MPa come to be utilized in Japan nowadays.

Autogenous shrinkage of them, however, is quite large due to self-dessication in the cement paste matrix, and effect of autogenous shrinkage on the structural behavior of reinforced concrete member is still under discussion. According to former research, it is reported that autogenous shrinkage reduces the cracking moment of beam, increases cracking width and deflection of beam [1], and decrease the load when the diagonal crack occur in the beam without stirrups [2].

In this study, effect of autogenous shrinkage on the bending behavior of reinforced concrete column was focused and discussed with numerical results.

2. FIBER MODEL CONSIDERING VOLUME CHANGE OF CONCRETE
2.1 Overview
“Fiber model” is composed of finite elements of a section of target reinforced concrete member, and calculates neutral axis and bending moment, assuming linear strain distribution and given curvature [3]. The point in the proposed method is to take into account of the shift of zero-stress point due to volume change of concrete, such as autogenous shrinkage and creep strain. The schematic figure of comparison of proposed model with existing model is shown in Figure 1.

2.2 Constitutive model - Instantaneous behavior
In the proposed model, constitutive model of concrete and rebar is needed. Regarding constitutive model for...
the ultra high-strength concrete, recent research by Komuro et al., [4] is applied. This model is based on the research by Muguruma & Watanabe [5]. The modification is introduced to the Komuro’s model, as is shown in Figure 2, the zero-stress point shifting due to volume change of concrete is considered.

The following equations are used for representing stress-strain relationship.

(1) Cover concrete
\[
\sigma_c = E_u (\varepsilon_c - \varepsilon_0) + \left( f' - E_u (\varepsilon_c - \varepsilon_0) \right) (\varepsilon_c - \varepsilon_0) \]

where, \( \sigma_c \): compressive stress, \( \varepsilon_c \): strain of concrete (compressive is positive), \( \varepsilon_0 \): zero-stress strain, \( f' \): stress at \( \varepsilon = \varepsilon_0 \), \( E_u \): maximum strength of core concrete at \( \varepsilon = \varepsilon_0 \).

(2) Core concrete
\[
\sigma_c = \frac{f''}{\varepsilon_c - \varepsilon_0} (\varepsilon_c - \varepsilon_0) + \sigma_{cm}
\]

where, \( \sigma_{cm} \): maximum strength of core concrete at \( \varepsilon_0 \), \( f'' \): compressive strength of plain concrete, \( \varepsilon_0 \): strain when the stress attains \( f'' \), \( \sigma_c \): stress when the strain attains \( \varepsilon_0 \).

Cover concrete:
\[
\varepsilon_{c} = 0.0 \quad [0 , \varepsilon_0] (7)
\]
\[
\varepsilon_{c} = 0.7 (\varepsilon_{c} - \varepsilon_0) \quad [\varepsilon_0 , \varepsilon_0] (8)
\]
Core concrete:
\[
\varepsilon_{c} = 0.0 \quad [0 , \varepsilon_0] (9)
\]
\[
\varepsilon_{c} = 0.4 (\varepsilon_{c} - \varepsilon_0) + 0.9 (\varepsilon_{c} - \varepsilon_0) \quad [\varepsilon_0 , \varepsilon_0] (10)
\]
\[
\varepsilon_{c} = 0.4 (\varepsilon_{c} - \varepsilon_0) + 0.9 (\varepsilon_{c} - \varepsilon_0) \quad [\varepsilon_0 , \varepsilon_0] (11)
\]

In this paper, in the case of instantaneous loading, the tensile stress in the concrete is ignored. As for stress-strain relationship of rebar is modeled as bilinear model, and Bauschinger effect is not considered in the case of cyclic loading.

2.2 Constitutive model - long time behavior
In the proposed model, the shrinkage induced stress before instantaneous loading is considered. As for calculation of this self-induced stress in the reinforced concrete (RC) column, the properties of concrete is based on the experimental results [7]. Water to binder ratio of concrete is 0.15, and binder basis is low heat Portland cement with 10%-replaced silica fume. The cylinder (φ100x200) strength of concrete is evaluated by temperature adjusted concrete age:
\[
f'_{\text{cylinder}}(t) = 155 \exp(0.3 \{ 1 - (t - 28/t)^2 \})
\]

where \( t \) is temperature adjusted concrete age [7].

Developing of Young’s modulus is modeled as a function of compressive concrete strength (eq. 12) as follows:
\[
E_c(t) = 6.0 f'_{\text{cylinder}}(t)^{0.422}
\]

Regarding autogenous shrinkage, which is very affected at the elevated temperature due to heat of hydration, is modeled with temperature adjusted concrete ages and maximum temperature in the temperature history. This is also based on the experimental result [8].
\[
\varepsilon_{sa}(t) = \varepsilon_{sa0} \left[ 1 - \exp\left( -0.8 (t - 0.5)^2 \right) \right] (14)
\]
\[
\varepsilon_{sa0} = 500 + 8(T_{\text{max}} - 29) (15)
\]

where \( T_{\text{max}} \): the maximum temperature (°C), \( \varepsilon_{sa} \): ultimate autogenous shrinkage, \( \varepsilon_{sa}(t) \): autogenous shrinkage.

Crep behavior of ultra high-strength concrete is based on the experiment by Suzuki et al.[9]. This experiment was under compressive loading, and in the constant temperature (20 °C) and sealed condition. The following equations are derived from the experimental results:
\[
\phi(\varepsilon_c, t) = \phi_0 \left( \frac{(t - t_0)}{t_1 - t_0} \right)^{0.3} (16)
\]
\[
E_c(t) / E_c(28) \leq 0.7 \quad (17)
\]
\[
\phi_0 = 3.87 \left[ E_c(t_0) / E_c(28) - 1.0 \right]^{0.6} + 1.16 \quad (18)
\]
\[
\phi_0 = 1.16 \quad (19)
\]
where \( \phi(\varepsilon_c, t) \): creep coefficient at \( t \), when the loading age is \( t_0 \), \( \phi_0 \): ultimate creep coefficient, \( t_1 \): 1day, \( E_c(28) \): Young’s modulus at 28 days.

2.3 Calculation of self-induced stress of concrete in RC member
The self-induced stress in concrete can be calculated using step by step method [10]. Based on the linear creep, and incremental method leads following the relationship between incremental strain and incremental stress of concrete [11]:
\[
\Delta \sigma_c = \Delta \sigma_c J(t_{i+1/2}, t_i) + \sum_{j=1}^{\infty} \left( \Delta \sigma_c J(t_j, t_{j-1}) \right) + \left( \Delta \sigma_c J(t_{i+1/2}, t_{i}) \right) (19)
\]
where \( i = 1, 2, \ldots \); \( \Delta \sigma_c \): incremental stress, \( J(t_{i+1/2}, t_i) = 1 / E_c(t) + \phi(t_{i+1/2}, t_i) / E_c(28) \): compliance of concrete, \( (\Delta \sigma_c J(t_{i+1/2}, t_{i})) \): incremental free deformation of concrete, such as autogenous shrinkage, drying shrinkage, and thermal expansion. \( \Delta \sigma_c J(t_j, t_{j-1}) \): incremental creep strain during time interval \( t \) when the loading age is \( t_j \).
If the reinforcement ratio is \( p \), output of stress history can be calculated using eqs. (20) - (23) with the input of free deformation, development of Young’s modulus, and creep coefficients. These are derived according to the force balance between concrete and reinforcements, and compatibility condition of strain

\[
\Delta \varepsilon_{j} = \Delta \varepsilon_{p,j} + \left( 1 + \frac{p}{E} \right) \left[ \frac{1 + \varepsilon_{p,j}}{E} \right] \varepsilon_{f,j} + \frac{\phi(t_{0} - t_{j})}{E_{23}} \Delta \varepsilon_{j} \quad (20)
\]

\[
\Delta \sigma_{j} = \sum_{i} \Delta \sigma_{j,i} = \left( 1 + \frac{p}{E} \right) \left[ \frac{1 + \varepsilon_{p,j}}{E} \right] \sigma_{p,j} + \frac{\phi(t_{0} - t_{j})}{E_{23}} \Delta \sigma_{j} \quad (21)
\]

\[
\Delta \varepsilon_{j} = -p \cdot E \cdot \Delta \varepsilon_{j} \quad (22)
\]

\[
\Delta \sigma_{j} = E \cdot \Delta \varepsilon_{j} \quad (23)
\]

where \( E \): Young’s modulus of rebar, \( \Delta \varepsilon_{j} \): incremental stress of rebar.

Now, according to the eqs. (20)-(23), the zero-stress stress of concrete at the loading period \( t_{0} \) can be determined by eq. (24).

\[
\varepsilon_{f,j} = \varepsilon_{f,j} + \sigma_{p,j} \cdot t_{0} / E \quad (24)
\]

In the time span just after casting to the age at loading, the concrete can bear tensile stress due to mainly autogenous shrinkage, while in the case of instantaneous loading, the tensile stress of concrete ignored. This is due to flowing reasons. 1) Before instantaneous loading, it is important to consider the stress in concrete, because normal reinforcement ratio of RC column is rather small and this cause ignorable compressive stress in rebar due to autogenous shrinkage. 2) During instantaneous loading, for the calculation of bending moment and neutral axis in section, the effect of tensile stress is rather small, i.e. \( f_{s}^{*} = (1/20) \).

3. ANALYSIS

3.1 Unidirectional Loading

For the basic understanding of the effect of autogenous shrinkage on the bending behavior, the unidirectional loading (one way loading) is simulated. Parameters for this purpose is axial force ratio \( 0.2, 0.3, 0.4, \) reinforcement ratio \( 1.8, 3.7, 4.6\% \), yielding stress of rebar (500, 700, 1000MPa), and amount of autogenous shrinkage of concrete (0, 500, 800\( \mu \)).

![Figure 3 Section of RC column.](image)

Table 1. Materials used in Experiment.

| No. | \( q \) | \( p \) | \( \varepsilon_{e,0} \) | \( \phi_{r} \) | \( P_{sc} \) | \( P_{st} \) | \( P_{sc}\alpha \) | \( P_{rb} \) | \( \phi(m^2) \) | Curve
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**Curvature \( \phi (m^2) \)** shows the maximum strength, \( P_{cr} : \) curvature when core concrete attains the ultimate autogenous shrinkage of concrete. **\( P_{st} \)**: yielding stress of reinforcement, **\( P_{sc} \)**: output of stress history of bending moment, **\( P_{c} \)**: maximum strength, **\( P_{rb} \)**: curvature when core concrete attains the maximum bending compressive strain.
In the case that autogenous shrinkage is $0 \mu$, creep strain is also ignored for comparison to the existing model. The autogenous shrinkage of 500 and 800 $\mu$ is corresponding to the autogenous shrinkage at 20 °C, and 70 °C of the maximum temperature in its history respectively.

Lateral reinforcement ratio is not parameter in the series of this analysis, and 1% is set. 4 points were evaluated on the M-\(\phi\) curvatures, namely, the point when tensile rebar attains yielding point (Pst), the point when compressive rebar attains yielding point (Psc), the point when cover concrete shows the maximum strength (Pcvm), and the point when core concrete attains the maximum bending compressive strain (Pcrb).

In the simulation process, axial force was loaded at 182 days after casting, and instantaneous loading was simulated at 3 year after casting. The cylinder compressive strength at 3 year is about 200 MPa, and Young's modulus is 62 GPa. The plain concrete strength that includes the size effect is considered as 170 MPa, whose ratio to the cylinder strength is 0.85 [12]. The axial force was calculated from the cylinder concrete strength of 180 MPa at 91 days. The assumed section of RC column is shown in Figure 3.

Simulation results is summarized in Table 1 and the zero-stress strain due to autogenous shrinkage and creep strain regarding in the case that axial force ratio is 0.3 is listed in Table 2.

Table 2 Effect of autogenous shrinkage

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<th>$\sigma_{int}$</th>
<th>$F_{int}$</th>
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$\omega_{T}$: ultimate autogenous shrinkage of concrete, $\sigma_{int}$: stress in rebar just before instantaneous loading, $F_{int}$: total force of reinforcement, $\varepsilon_{u}$: zero-stress strain of concrete.

As an example, case 73, 74, and 75 are shown in Figure 4, 5, and 6. Figure 4 represent the strain development with time elapsed of different autogenous shrinkage, and these cases are corresponding to the axial force ratio of 0.3. In the case of autogenous shrinkage of 800 $\mu$ shows about 1800 $\mu$ just before instantaneous loading, and this value is about 800 $\mu$ difference from the one who did not consider the volume change of concrete. This value does not seem to be ignorable.

In figure 5, M-\(\phi\) envelopes with the marks of 4 points, where the point at yielding of rebar and maximum strength of cover concrete, and maximum strain of core concrete, are shown. As is shown here, the order of 4 points is altered by the autogenous shrinkage. This figure indicates that if the yielding of tensile rebar is designed to be preceded that the core concrete attain the maximum strain, autogenous shrinkage may alter this order, while the maximum moment of the section is not affected by autogenous shrinkage as is shown in Figure 6.

Based on these results, parametric study is summarized as follow:

1) Autogenous shrinkage will not affect on the maximum bending moment in the section.
2) In the case of low reinforcement ratio, autogenous shrinkage invoke yielding of compressive rebar which is designed to be preceded the yielding of tensile rebar.
3) In the case of high axial force ratio, autogenous shrinkage invoke compressive failure of core concrete which is designed to be preceded the yielding of tensile rebar.
4) Autogenous shrinkage reduces the outer bending moment or axial force in allowable stress design.

3.2 Cyclic Loading
Cyclic loading is also simulated for grasp the effect of autogenous shrinkage precisely. For this simulation, the first cycle of $\phi=0.2\text{m}^{-1}$ was added, then the incremental curvature of $\Delta\phi=0.05$ was added on each cycle. Figure 7, 8, and 9 shows the effect of autogenous shrinkage on the M-\(\phi\) relationship, stress of rebar, and stress of concrete, respectively. Figure 7 shows that the effect of autogenous shrinkage on the M-\(\phi\) relationship can not seen after both compressive and tensile rebars are yielded. Additionally, in the case of 55 and 57, both case shows the yield of compressive and tensile rebar, while yielding of tensile rebar is not seen in the unidirectional loading. And in the case of 1 and 3, yielding of compressive rebar precedes the yielding of tensile rebar, but after cyclic loading, both types of yielding are observed in the calculation these results.
Stress history of tensile and compressive rebar in the initial 3 cycles are shown in Figure 8. As is shown here, the compressive yielding is facilitated by the shrinkage-induced stress, while the difference can not be seen after compressive and tensile yielding is observed.
Figure 9 shows the stress of compressive and tensile rebar, as well as the stress of core concrete in the fiber located at the most close to the limb as a function of step of calculation. This figure also supports that no effect of autogenous shrinkage after rebars are yielded.

Shrinkage induced stress in rebar is produced larger compressive stress in rebar under axial loading than that without autogenous shrinkage. Therefore, the yielding of compressive rebar is caused by smaller outer bending moment under instantaneous loading. But a part of incremental stress of concrete after yielding of compressive rebar is the stress of concrete that is reduced by the autogenous shrinkage. And if the yielding of compressive and tensile rebar is observed and zero-stress point of rebar is shifted to the $\varepsilon_{\mu}$, the effect of autogenous shrinkage on the bending loading can be ignored. This indicates that, from the balance of forces, performance of RC column, which does not take into account of the effect of autogenous shrinkage, at the instantaneous loading is not differ from the one with autogenous shrinkage, on the condition that yielding of rebar precedes the compressive failure of core concrete.
In addition, only the difference is that the bending zone of column indicates the shrinkage of $\varepsilon_{\mu}$.

4. CONCLUSIONS
This paper propose a fiber model which take into account of the volume change of concrete, and using this proposed model, the effect of autogenous shrinkage of ultra high-strength concrete is evaluated with parametric calculation.
In that parametric study, autogenous shrinkage is ranging from 0 to 800 $\mu$, reinforcement ratio is from 1.8 to 4.6 $\%$, axial force ratio is from 0.2 to 0.4, and yielding stress of rebar is from 500 to 1000 MPa.
Followings are derived from the limit of this study:
1) Autogenous shrinkage will not affect on the maximum bending moment in the section, and M-\(\phi\) envelope.
2) In the case of low reinforcement ratio, autogenous shrinkage may invoke yielding of compressive rebar which is designed to be preceded the yielding of tensile rebar.
3) In the case of high axial force ratio, autogenous shrinkage may invoke compressive failure of core concrete which is designed to be preceded the yielding of tensile rebar.

4) Autogenous shrinkage reduces the outer bending moment or axial force in allowable stress design.

5) In the case of instantaneous loading, yielding of compressive rebar which precedes yielding of tensile rebar due to autogenous shrinkage does not affect the performance of RC column. This can be explained by the fact that a part of incremental compressive stress of concrete after yielding of compressive rebar is stress reduced by the autogenous shrinkage.

The conclusions listed above is derived from the fiber model, therefore, the buckling of compressive rebar, lateral expansion after yielding of compressive rebar and resultant peeling of cover concrete, stress distribution in the section (especially in the lateral direction [13]), and cracking due to autogenous shrinkage is not taken into account. The effect of these on the performance of RC column is future tasks.

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