Self-induced stress in reinforced ultra high-strength concrete

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ABSTRACT: In order to grasp the effect of autogenous shrinkage of ultra high-strength concrete (UHPC) on self-induced stress in reinforced concrete (RC) column, basic properties of autogenous shrinkage of cement paste, self-induced stress of RC prism, and temperature and strain distribution in real size RC column are tested. Additionally several numerical analyses are adopted for these experimental results. As a results, followings are drawn from the experiment and analyses: 1) autogenous shrinkage of UHSC has a temperature dependency, and the higher temperature history produce larger autogenous shrinkage, 2) micro-crack around reinforcing bar can be produced due to autogenous shrinkage and bond stiffness is decreased due to the micro-crack, 3) self-induced stress in the section of RC column due to temperature dependent autogenous shrinkage may cause vertical split of under bending-shear loading condition.

1 INTRODUCTION
Regarding autogenous shrinkage of high-strength concrete, whose risk of cracking was pointed out in 1990’s (Tazawa & Miyazawa 1992), not only effect on the durability but also on the mechanical behavior of reinforced concrete (RC) member has became clear.

Cracking moment, curvature, and crack width are affected by the amount of autogenous shrinkage and their evaluation method are recently developed (Tanimura et al. 2007).

Additionally, it was experimentally confirmed that shear strength of RC beam without stirrups was degraded by the autogenous shrinkage, and evaluation method is proposed by Sato et al (Sato et al. 2008).

This paper deals with the autogenous shrinkage of ultra-high strength concrete (UHSC), whose compressive strength is more than 150 MPa, and their effect on the self-induced stress and cracking in RC column.

2 TEMPERATURE DEPENDENT AUTOGENOUS SHRINKAGE
2.1 Cement paste
For evaluation of basic properties of cement paste which is the principle cause of autogenous shrinkage of UHSC. Additionally, autogenous shrinkage of UHSC with different temperature of fresh concrete and curing temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Notation</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low heat cement</td>
<td>LC</td>
<td>C₃S:29%, C₅S:50%, C₃A:4.3%, C₆AF:9.6%, 3.22g/cm³</td>
</tr>
<tr>
<td>Ordinary cement</td>
<td>NC</td>
<td>C₃S:50%, C₅S:24%, C₃A:9.5%, 3.16g/cm³</td>
</tr>
<tr>
<td>Portland cement</td>
<td>P</td>
<td>C₃S:9.6%, 3.16g/cm³</td>
</tr>
<tr>
<td>Silica fume</td>
<td>SF1</td>
<td>SiO₂:94%, Blaine: 20.0m²/g</td>
</tr>
<tr>
<td>Silica fume</td>
<td>SF2</td>
<td>SiO₂:95%, Blaine: 18.6m²/g</td>
</tr>
<tr>
<td>Silica fume cement</td>
<td>SLC</td>
<td>0.9<em>LC + 0.1</em>SF2</td>
</tr>
<tr>
<td>Silica fume cement</td>
<td>SNC</td>
<td>0.9<em>NC + 0.1</em>SF1</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>S</td>
<td>Density:2.62g/cm³, Absorption: 2.53%</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>G1</td>
<td>Density:2.93g/cm³, Absorption: 0.39%, Max.:20mm</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>G2</td>
<td>G1 was crushed. Max.: 5mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Notation</th>
<th>Cement type</th>
<th>W ¹</th>
<th>C²</th>
<th>S</th>
<th>G</th>
<th>SP³</th>
<th>D⁴</th>
<th>Air</th>
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<tbody>
<tr>
<td>SFLC-P</td>
<td>SLC</td>
<td>316</td>
<td>2108</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.2</td>
<td>0%</td>
</tr>
<tr>
<td>SFLC-C</td>
<td>SLC</td>
<td>161</td>
<td>1074 456</td>
<td>926</td>
<td>1.5</td>
<td>0.2</td>
<td>0%</td>
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<tr>
<td>SFNC</td>
<td>SNC</td>
<td>155</td>
<td>1033 398</td>
<td>1000</td>
<td>2.6</td>
<td>0.6</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>SFLCEX</td>
<td>SLC</td>
<td>155</td>
<td>970 398</td>
<td>1000</td>
<td>2.6</td>
<td>0.6</td>
<td>2%</td>
<td></td>
</tr>
</tbody>
</table>

Materials used in this research are summarized in Table 1. In the chapter 2, cement paste containing silica fume with w/b=0.15 and emulated concrete which has the comminuted coarse aggregate G2 is...
adopted for imitating similar volumetric ratio of general ultra-high strength concrete, such as SFLC in Table 2. Mixture proportions for this research are listed in Table 2.

For experiment of autogenous shrinkage, parameters are temperature of fresh state (10, 20, 30°C), and elevated temperature emulating heat production in the concrete member (constant, +25, +45°C). Specimen size is 10x60x300 mm$^3$ and temperature was controlled from the copper mould with temperature controlled water (accuracy is ±0.2°C). Specimen size was determined for the ability of temperature control and it was experimentally confirmed in pre-test that temperature distribution in the specimen is less than 0.2°C during the test. Deformation of specimen was measured by laser displacement meter whose accuracy is 0.2 μm. Thermal expansion coefficient (TEC) was determined from temperature pulse with ±5°C with 0.2°C /min which is seen in top figures in Figure 1. Using this TEC, autogenous shrinkage was experimentally determined.

From the Figure 1, it is experimentally confirmed that the autogenous shrinkage of cement paste containing silica fume with w/b=0.15 was affected not only by temperature of fresh state but also elevated temperature. The lower temperature of fresh state increases the autogenous shrinkage, i.e. autogenous shrinkage of 10°C series (temperature of fresh state is 10°C) is about 200μ larger than those of 20°C series. And the elevated temperature also increase intensively the autogenous shrinkage. 45°C-elevated specimens shows nearly double autogenous shrinkage of constant temperature condition.

2.2 Concrete

For the case of concrete (SFLC-C in table 2), same experiment as that for cement paste was conducted. Figure 2 shows the summary of experimental results of autogenous shrinkage. As is shown in Figure 2, the same trend of effect of temperature on the autogenous shrinkage as those of cement paste was experimentally observed. Autogenous shrinkage of concrete become nearly double due to elevated temperature in early age. This indicates that the risk of cracking at the center part of real size column is much larger than that in miniature specimen due to heat production by cement hydration.

3 CRACKING AROUND DEFORMED BAR

3.1 Experiment

Two types of UHSC, namely SFNC and SFLC-EX shown in Table 2, are used for self-induced stress
test with RC-prism specimen and inspection of cracking around deformed bar. SFLCEX is composed of low heat cement and silica fume with expansive additive and shrinkage reducing agent, and this aims for different shrinkage strain as a parameter. Detail of the specimen of self-induced stress (Figure 3(1)) and inspection of cracking (Figure 3(2)) are shown in Figure 3.

Self-induced stress was calculated from reinforcement ratio (8.7 %) and balance of forces. The stored force in rebar was obtained by nominal Young’s modulus of rebar (181 GPa) and the strain of rebar which was measured by wire-strain gauges installed on upper and bottom surface at the center of the rebar.

The inspection of cracking around rebar was by absolute ethyl alcohol with oil based ink. Embedded rebar in RC-prism specimen was grooved. Until 10 hours after placing, the groove was filled with brass bars, and after that, brass bars were pulled out and pore the colored alcohol as is shown in Figure 3. When the cracking occur under restraint condition, the colored alcohol is sucked into the micro-cracking. The benefit of using ethyl alcohol is that it has less activity with cement and small surface tension. The specimens were split at 9 days to observe colored part of concrete around rebar. Additionally measuring of autogenous shrinkage of concrete whose size is φ100x400 mm by embedded gauge, Young’s modulus (results shown in Figure 4), and tensile splitting strength (Figure 5) were measured. All the specimens were cured at 20°C and sealed with aluminium adhesive tape of 0.05 mm thickness to prevent the evaporation of water after 1 day.

Experimental results of autogenous shrinkage of SFNC and SFLCEX is shown in Figure 6 and self-induced stress of concrete is shown in Figure 7. As is shown in Figure 6, SFNC attained 800 μ of autogenous shrinkage at 9 days, while SFLCEX shows relatively small autogenous shrinkage, namely 200μ at 9 days. Self-induced stress of concrete was reflected by the results of autogenous shrinkage. Average stress of SFNC attains about 2.5 MPa at 8 days, while SFLCEX shows compressive stress of 1.3 MPa.

Figure 8 shows the results of inspection of cracking. As is shown here, cracking around deformed bar was detected in the SFNC specimen, while specimen of SFLCEX did not show any colored part. This figure make it appear that autogenous shrinkage of concrete produces cracking around deformed bar.

3.2 Analysis

For evaluating self-induced stress of concrete in RC-prism specimen, effect of cracking around deformed bar due to autogenous shrinkage should be take into account. In this section, “time-dependent micro-crack model” for finite element (FE) method, which is based on the smeared crack model, is proposed. In order to take into account of the effect of cracking, which is distributed in concrete rather homogeneously in Figure 6, smeared crack model based on the crack band model (Bazent & Oh 1983) is applied. For tension softening behaviour, 1/4 model (Rokugo et al. 1989) is applied, and ratio of 0.25 to shear stiffness of sound concrete is applied for shear softening. This ratio is used only for parallel direction of cracked plane. The data of fracture energy of
1 N/m at 0.5 day, 182 N/m at 1 day and 209 N/m at 28 days are used with logarithmic interpolation (Fuchiwaki et al. 2000). These values were of concrete with W/B=0.23.

In addition, for time-dependent micro-crack model, following assumptions are adopted:

- Rate of hydration in cracked element is not affected by presence of cracking.
- Stiffness of concrete element is determined by the maximum crack width in its history and fracture energy of concrete. But in compressive situation, the stiffness of concrete is assumed to be the same as that of sound concrete.
- Plasticity is ignored in concrete and instant behaviour is always on the pass through the origin.
- Once crack occur, the crack plane is fixed.
- After cracking, creep strain is considered except for vertical direction to cracked plane.

Those assumptions are described schematically in Figure 9. Additionally, concrete element around rebar is affected by bond and shows tension stiffening. And if there exist plural crack is occurred in one element, using the fracture energy for concrete element, which is derived from one crack, is inappropriate. Based on the concept of RC-constitutive laws proposed by Salem & Maekawa (1999), quintuple fracture energy is assumed for concrete affected by bond in the proposed analysis.

As for basic time dependent behavior of concrete, logarithmic interpolation of experimental data of Young’s modulus and splitting tensile strength are used for the analysis. For the creep behaviour, linear creep analysis method (called step by step method) proposed by the authors (Ito et. al. 2004), as well as creep function which is based on the MC90 (CEB 1990) and derived from the experimental results of concrete with w/b=0.23-0.30 (Ito et. al. 2004) are adopted.

In this incremental 3D-FE stress analysis, shrinkage, thermal deformation, and creep strain is considered as equivalent nodal force. The Poisson’s ratio of concrete is assumed to be constant even after showing creep deformation. Mesh for this analysis is shown in Figure 8, which is composed of 8040 isoparametric elements.

Figure 9 shows the analytical results. As is shown here, proposed 3D-FE linear creep analysis with time dependent cracking model shows rather favourable results than that by conventional linear creep analysis. On the contrary, smaller self-induced stress compared to that of linear analysis, which means the sound bond stiffness, accounts that bond stiffness is deteriorated by cracking around deformed bar.

4 EXPERIMENT OF FULL SCALE RC COLUMN

4.1 Experiment

Special and temporal distribution of temperature and strain in full scale RC column was measured. Detail of specimen and the points for measuring strain and temperature are shown in Figure 10. Strain of concrete was measured by embedded strain gauge whose Young’s modulus is 40 MPa, and strain of reinforcements are measured by wire strain gauge.
Temperature was also measured at the same places, and using this temperature history, effect of temperature on the data is calibrated with zero-shift curve that were experimentally obtained in pre-test. Additionally, basic properties of concrete, such as compressive strength (sealed curing, water-submerged at 20 °C curing, semi-adiabatic curing condition, core of RC column at 28 day), Young’s modulus were tested. Finally at 28 days, Section A and B were cut by a diamond saw in order to observe the crack in the RC specimen.

Experimental results of compressive strength and Young’s modulus are shown in Figure 11 and 12 respectively. Temperature distribution in the center section of RC column is shown Figure 13. The maximum temperature in the column was about 75 °C.

Figure 14 represent vertical (parallel to main rebar) strain distribution in the section, and horizontal (perpendicular to direction of main rebar) strain distribution in the section. As is shown in this figure, vertical strain at the center marked the smallest strain, while the horizontal strain at the center is the largest on the contrary. This phenomenon indicates that self-induced stress in the RC column is stored in not only vertical direction but also horizontal direction. Because the largest strain suggests the larger tensile stress if the autogenous shrinkage is isotropic. This self-induced stress will be discussed in analytical way in following section.

After cutting, crack around rebar was observed as is Figure 15. Figure 15 shows close-up of a rebar, and cracking pattern in Section A. Around all the rebar, cracking is observed.

4.2 Analysis for horizontal stress in RC column
Linear FE analysis same as that of 3.2 was carried out for validation of horizontal stress in RC column. Temperature dependent autogenous shrinkage is modeled as following equation:
5 CONCLUSION

Following conclusions are derived from the present research:
- Ultra high strength concrete containing silica fume shows temperature dependent autogenous shrinkage.
- Cracking around deformed bar due to autogenous shrinkage is experimentally confirmed.
- Time dependent micro-crack model for FE analysis is proposed to take into account of cracking of concrete under hydration process, and this proposed model shows preferable results.

6 ACKNOWLEDGEMENT

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Maruyama, I., Suzuki, M., Sato, R., 2005. Prediction of Temperature in Ultra High-Strength Concrete Based on Temperature Dependent Hydration Model, ACI SP-228, 1175-1186

\[
e_{sh}(t) = e_{sh,\text{max}} \left[1 - \exp\left(-\left(t - 0.8\right)^{0.5}\right)\right]
\]

(1)

\[
e_{sh,\text{max}} = 320 + 8(T_{\text{max}} - 20)
\]

(2)

where \(e_{sh}(t)\): autogenous shrinkage (\(\mu\)), \(t\): temperature adjusted concrete age (days), \(T_{\text{max}}\): maximum temperature in history, \(e_{sh,\text{max}}\): ultimate shrinkage value.

Temperature history in the RC column was evaluated by 3D-FE heat transfer analysis. Adiabatic temperature curve as a exothermic term is predicted by hydration model proposed by authors (2005). Simulated results of temperature history of RC-column is shown in Figure 17 with predicted adiabatic temperature curve. Based on this data, autogenous shrinkage of each element is calculated using eq. (1), and 3D-FE analysis was conducted with concrete properties shown in Figure 11 and 12. Strain and stress at the center and surface are represented in Figure 18 and Figure 19 respectively. From these figures, smaller strain in vertical direction and larger strain in horizontal direction is analytically reproduced. And in Figure 19, large amount tensile stress is confirmed in horizontal direction. According to this analysis, it is demonstrated that temperature dependent autogenous shrinkage produce tensile stress horizontally in RC-column, while analytical values may be invalid due to lack of creep data and precise temperature dependent autogenous shrinkage equation.

- In full scale RC column, self-induced stress in the direction perpendicular to main rebar is stored due to temperature dependent autogenous shrinkage.