Research on Early Age Concrete Temperature-moisture-stress Multi-physics Coupling Calculation Considering Damage

Erzhao Lou and Sheng Qiang

ABSTRACT

Under the coupled effect of temperature and moisture of concrete, the structure may produce a larger shrinkage deformation and stress, inducing the micro defects and damage accumulation, and leading to the attenuation of the macro mechanical properties of concrete. Ultimately, macro cracking or material damage may happen. So the coupling analysis should be done in order to describe the state of the concrete more accurately. According to the coupling principle, a concrete multi-physics coupling simulation process in early age is put forward. The corresponding calculating program is compiled based on the above process. The example calculation results show that: (1) the difference of moisture diffusion in the surface and the internal is easy to form a large humidity gradient in the concrete surface area; (2) the stress field calculated will be more consistent with the actual state of concrete, considering interaction between the temperature and humidity field; (3) The damage will influence the temperature field, humidity field and stress field. By the simulation analysis considering the coupling, the rationality of the new program is proved. It will provide a more reliable tool for the future engineering simulation. The acquisition of some coupling parameters still relies on the further experiment research.

INTRODUCTION

Variation of temperature and humidity in concrete structures is an important factor leading to cracks in hydraulic engineering. And the temperature field and humidity field of concrete affect each other. Professor Bazant has proposed that the shrinkage deformation of concrete is a kind of wet and hot deformation[1], which reveals that the internal heat and moisture coupling is the main cause of volume

Erzhao Lou1,2, Sheng Qiang1*
1College of Water Conservancy and Hydropower Engineering, Hohai University, 210098, Nanjing, China
2Water Conservancy Bureau of Ninghai, 315600, Ningbo, China
Corresponding author: sqiang2118@163.com.
deformation. Under the coupled effect of temperature and moisture of concrete, the structure may produce a larger shrinkage deformation and stress, inducing the micro defects and damage accumulation, and leading to the attenuation of the macro mechanical properties of concrete. Ultimately, macro cracking or material damage may happen. The damage will also affect the temperature field, humidity field and stress field of concrete [2].

Although the concrete temperature field, humidity field, stress field and damage have had a lot of achievements, most of all are separate analysis of changes of the field, or only consider the coupling effect between the two. There are few literatures considering all the above factors, especially in early age.

Based on the basic theory of temperature field, humidity field, stress field and damage, the coupling effect is analyzed systematically. Then a concrete multiphysics coupling simulation process in early age is put forward. The corresponding calculating program is compiled based on the above process. Finally, an example is given to analyze the coupling process of temperature, humidity, stress and damage of concrete.

**BASIC THEORY**

**Basic Principle of Temperature and Humidity Coupling of Concrete**

Temperature field affect humidity field mainly through the influence of temperature on the moisture diffusion coefficient. And the influence of the humidity field on temperature field is mainly through nominal thermal diffusivity[3]. The coupling equation of temperature and humidity in concrete can be expressed as [4]:

$$\frac{\partial T}{\partial \tau} = \alpha_e \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial \theta}{\partial \tau}$$  \hspace{1cm} (1)

$$\frac{\partial h}{\partial \tau} = D(h,T) \left( \frac{\partial h}{\partial x^2} + \frac{\partial h}{\partial y^2} + \frac{\partial h}{\partial z^2} \right) + \frac{\partial h}{\partial \tau}$$  \hspace{1cm} (2)

Where $T$ is the concrete temperature; $\alpha_e$ is nominal thermal diffusivity; $\theta$ is the adiabatic temperature rise; $D(h,T)$ is the moisture diffusion coefficient.

**Damage Model Of Power Exponential Function**

Power exponential function damage model [5-6] has considered initial damage of concrete. The model divides the development of damage into two stages. Damage develop linearly with strain, assuming that the effective stress and strain is linear before reaching the peak stress. After reaching the peak stress, the power exponent function model is used to simulate the stress-strain curve. The damage evolution process can be expressed as:

$$D(\varepsilon) = D_0 + \frac{\varepsilon}{\varepsilon_f} (D_f - D_0) \quad (0 \leq \varepsilon \leq \varepsilon_f)$$  \hspace{1cm} (3)


\[ D(\varepsilon) = 1 - (1 - D_f) \left\{ \exp \left[ - \left( \frac{\varepsilon - \varepsilon_f}{\varepsilon_u - \varepsilon_f} \right) \cdot f(\varepsilon) \right] - \left( \frac{\varepsilon - \varepsilon_f}{\varepsilon_u - \varepsilon_f} \right) \right\} \quad (\varepsilon > \varepsilon_f) \]  

(4)

\[ f(\varepsilon) = B \left( \frac{\varepsilon - \varepsilon_f}{\varepsilon_u - \varepsilon_f} \right) \]  

(5)

Where \( D_0 \) is the initial damage; \( D_f \) is the damage when strain value is \( \varepsilon_f \); \( \varepsilon_u \) is the ultimate strain; And B and C are constant which can be determined by experiment.

Based on the the relevant theory of Mazars [7], the one-dimensional state of power exponential function damage mode can be extended to the three-dimensional stress state by equivalent strain. And the curves of stress and damage with strain are shown in Figure 1.

![Curves of stress and damage with strain changing of Exponential function model.](image)

**Figure 1.** Curves of stress and damage with strain changing of Exponential function model.

**Discussion On The Basic Parameters**

The damage will affect the thermal conductivity of concrete, so the establishment of the relationship between the thermal conductivity and the damage of concrete is helpful to make the temperature field calculation more in line with the actual situation. And the damage cause the increase of micro cracks in concrete, which leads to the decrease of effective thermal conductivity. According to heat conduction law of Fourier, when the damage variable is \( D \), the coefficient of thermal conductivity can be expressed as[8]:

\[ \lambda(D) = \lambda_0 (1 - D) \]  

(6)

Where \( \lambda(D) \) is the coefficient of thermal conductivity in damage state; \( \lambda_0 \) is the initial thermal conductivity of concrete.

The moisture diffusion coefficient of concrete is an important parameter in the calculation of concrete humidity field. Considering the effects of humidity, temperature and damage, the moisture diffusion coefficient can be expressed as[9-11]:

\[ D_h(h,T,D) = \frac{D_{h0}}{1 - D} \left\{ \alpha_0 + \frac{1 - \alpha_0}{1 + \left[ (1-h)/(1-h_0) \right]^\alpha} \right\} \cdot \frac{T}{T_0} \exp \left[ \frac{Q}{RT_0} - \frac{Q}{RT} \right] \]  

(7)

\[ \alpha_0 = \frac{D_{h0}}{D_{h0}} \]  

(8)
Where $D_{00}$ is the moisture diffusion coefficient of saturated concrete; $D_{\text{hmin}}$ is the minimum value for the moisture diffusion coefficient; $h_c$ is the pore relative humidity when maximum moisture diffusion coefficient drops to half; $Q$ is the energy of hydration reaction.

When considering the damage of concrete, elastic modulus changing with the age can be expressed as [12-13]:

$$E(\tau, D) = E_0(1-e^{-a\tau^b})(1-D)$$

Where $\tau$ is the concrete age; $E_0$ the final elastic modulus when $\tau$ tends to infinity; $D$ is the concrete damage; $a$ and $b$ are constants.

**SOLUTION AND PROGRAMMING OF MULTI FIELD COUPLING SYSTEM**

The concrete temperature and humidity coupling equations are parabolic equations with variable coefficients. Based on finite element meshing in the spatial domain and the finite difference in time domain, the calculation process is divided into several periods. The specific calculation steps are:

1. The temperature field, humidity field and damage state of concrete has been known at the beginning of the period;
2. The temperature field at the beginning of the next period is calculated, considering the influence of damage on the thermal conductivity;
3. The average temperature and humidity of each unit are calculated by the temperature field calculated from the previous step and the initial humidity field. According to the damage state of the unit, the moisture diffusion coefficient is calculated. Next, calculate the humidity field at the beginning of the next period;
4. The equivalent strain of each element is calculated according to the principal strain of each element;
5. Based on the equivalent tensile strain and the selected damage model, the damage state of each unit is calculated and recorded, and the influence of damage on the relevant parameters is done at the next moment;
6. In the formation process of the whole stiffness matrix, consider the influence of damage on elastic modulus. Based on the calculated temperature field and humidity field, the corresponding displacement, strain increment and stress increment are solved in order to calculate the concrete creep stress field;
7. Repeat step (1) ~ (6) to do the calculation of the next period of time.

According to the above calculation procedures, the coupling calculation program THSD is obtained. The following is a numeral case to further verify the rationality of the program.

**NUMERICAL CASE ANALYSIS**

**Basic Information**

The finite element model is established to analyze the coupling effect of the multi physical fields, and the dimensions of concrete specimen is 200mm, 200mm
and 60mm, as shown in figure 2. The whole model consists of 2400 units and 3087 nodes. The constraint is applied to the bottom of the test block. And the bottom and top surfaces of the test block are adiabatic and impermeable. Parameters of calculation refer to the engineering practice, scientific research and empirical.

Figure 2. 3D finite element model of the test block.

In the calculation of the temperature field, the thermal conductivity is 190.2338 m²/d. The heat transfer coefficients are respectively 100 kJ/(m²·d °C) and 750 kJ/(m²·d °C) under the condition of heat preservation and exposure. The adiabatic temperature rise of concrete is expressed in exponential form [13], as shown in equation (10).

\[ f_t(\tau) = 2.6 \times [1 - e^{-0.29\tau}] \]  

(10)

In the humidity field calculation, the relative humidity of the environment is 70%. The concrete surface humidity transfer coefficients are respectively 5×10⁻³ m/d and 5×10⁻⁴ m/d in moisture and exposure state. It is assumed that the variation of dry shrinkage strain and relative humidity of concrete is linear [14]. And the shrinkage coefficient is 0.35×10⁻³. The elastic modulus of concrete is expressed in exponential form \( E(\tau) = 30 \times (1 - e^{-0.38e^{0.01\tau}}) \).

The power function model is used to analyze the damage. According to the literature [7], the initial damage is 0.15 and the damage threshold is taken as the value of 0.33.

Three cases are set up to analyze the rationality of the coupling simulation program:

Case 1: only consider the concrete temperature field and temperature stress;

Case 2: only consider the coupling effect between concrete temperature field, humidity field, stress field.

Case 3: consider the coupling effect between concrete temperature field, humidity field, stress field and damage comprehensively.

Simulation Result Analysis

According to the simulation results, the maximum damage occurred in the 17th day in case 3, as shown in Figure 3, and the first principal stress nephogram is shown in figure 4. The characteristic points A and C are selected to analyze the variation of temperature, humidity, stress and damage, as shown in figure 5.
The results of the temperature field were the same in case 1 and 2 as the parameters of the temperature field in case 1 and 2 were the same. According to the figure 6 and 7, the peak value of temperature of A was 22.35 ℃ in case 2, and the temperature of A in case 2 was higher than that in case 3 in the first 6 days. This was mainly due to the damage in case 3, which made the thermal conductivity of concrete decrease. The heat transfer effect was weakened, and the heat supply of the surface point was reduced, so the temperature in case 3 was lower than the value in case 2. According to the figure 8 and 9, the temperature difference of C in case 2 and 3 went through a process from being less than zero to being greater than zero due to the redistribution of heat in concrete under the combined action of concrete hydration heat and weakened heat conduction.

According to figure 10 and 11, the humidity of A fell to environmental humidity in about 30 days, and the relative humidity of A in case 2 was lower than that in case 3 in first 6 days, later on the contrary. This was mainly because case 3
considered the effect of damage on the moisture diffusion coefficient. Damage accelerated the moisture diffusion process by making the moisture diffusion coefficient increase. But the concrete surface humidity transfer coefficient was small because of early moisture conservation. So the surface point A got more moisture added in case 3. After the moisture curing, the relative humidity of the surface point A in case 3 fell faster than that of case 2. Therefore, the relative humidity of A in case 2 was higher than that of case 3 later. The relative humidity of the internal point C decreased slowly, and the relative humidity of C in case 2 was higher than that of case 3, which is mainly due to the role of the damage in case 3.

![Figure 10. Relative humidity duration curve of A.](image1)

![Figure 11. Relative humidity difference duration curve of A between case 2 and case 3.](image2)

![Figure 12. Relative humidity duration curve of C.](image3)

![Figure 13. Relative humidity difference duration curve of C between case 2 and case 3.](image4)

According to figure 14 and 15, the peak stress of A and C in case 2 was the largest, and in case 1 was the smallest. The main reason is that the temperature stress is only taken into account in case 1, while the temperature stress and shrinkage stress were considered in case 2 and 3. In addition, the influence of damage on concrete temperature field, humidity field and stress field was exerted in condition 3.

Through the analysis of stress can also be found that humidity had a greater effect on the stress of the concrete surface area. This was mainly because the concrete surface moisture diffused faster, while the internal relative humidity of concrete decreased very slowly. It was easy to form a large humidity gradient on the surface, resulting in a large dry shrinkage stress.
According to the figure 16 and 17, the maximum value of damage of A was 0.273, and the maximum value of damage of C was 0.171. Compared with the interior point C, the surface point A had a larger damage, which was consistent with the temperature, humidity and stress change of A and C.

CONCLUSIONS

(1) The difference of moisture diffusion in the surface and the internal is easy to form a large humidity gradient in the concrete surface area;

(2) The stress field calculated will be more consistent with the actual state of concrete, considering interaction between the temperature and humidity field;

(3) The damage will influence the temperature field, humidity field and stress field.

(4) Based on the analysis of concrete temperature field, humidity field, stress field and damage, the rationality of the program is proved;

(5) The computation load of multi fields coupling is very large, and a large number of iterations are needed in each time step. And the coupling parameters related to the various fields need to be further studied.

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REFERENCES