Simulation and Modelling in Cracks Prevention of Early Age Concrete

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Abstract. Cracks often arise in mass concrete structures, due to the thermal stress and low tensile strength of early age concrete. To prevent the undesired thermal stress induced crack, controlling the temperature of concrete has been considered as an effective approach. In this paper, a temperature controlling measure evaluation system (TCMES) is proposed, which includes distributed fiber optic temperature monitoring, prediction of temperature and stress fields, and concrete crack risk evaluation. We first experimentally monitor the temperature evolution of the concrete using the distributed fiber optic temperature sensing. Then thermal parameters of in-situ concrete are retrieved by performing back-analysis. Subsequently, the concrete temperature field and thermal stress field can be predicted from the retrieved parameters and the experimental parameters of concrete. Under the concrete crack risk evaluation principles, temperature controlling measures for different stages are proposed. Our analysis indicates that the proposed system is an effective approach to prevent cracks of early age concrete.

1. Introduction
Cracks often appear in mass concrete structures due to high thermal stress and low tensile strength of early age concrete. This phenomenon is widespread in early age concrete of mass concrete dams [1, 2]. Cracks not only affect the beauty and the sustainability of concrete dams, but also decrease the safety of concrete dams when severe cracks occur. To prevent the thermal stress induced cracks, three kinds of measures of temperature controlling have been proposed, including controlling the casting temperature, burying the cooling pipe, and protecting the surface of the concrete. These measures can reduce the concrete cracks to some extent in practice [3, 4]. However, effectiveness of these measures has not been quantitatively evaluated.

To capture the temperature evolution of concrete, thermometers are often buried in concrete. However, due to the limited monitor points, the errors of human-read, and the influence of the construction, the monitored temperature are unreliable. With the development of fiber optical cable, the distributed optical fiber temperature sensing (DTS) has been developed to determine the temperature process. Due to the high sensitivity and online monitoring features of DTS, they have been successfully employed in monitoring the petroleum leakage, high voltage cable, and concrete dams [5, 6 and 7]. Meanwhile, thermal stress devices have also been developed to measure the thermal stress evolution of specimens in laboratories [8]. In engineering practice, numerical simulations are is performed to predict the thermal stress of concrete structure [9, 10 and 11]. Despite these advances, accurate measurement and prediction of temperature and thermal stress evolution is still challenging [12].

Here we proposed a temperature controlling measures evaluation system (TCMES) aiming at preventing the crack of early age concrete. DTS is deployed to capture the temperature evolution of the
mass concrete structure. Then thermal parameters of in-situ concrete are retrieved by performing back-analysis. Using the retrieved thermal parameters together with the experimental mechanical properties of concrete, we predict the temperature and thermal stress evolution of the concrete. Additionally, a set of concrete crack risk evaluation principle is established, which includes the allowed maximum temperature, anti-crack safety factor, and the maximum tensile strength. Under this principle, the effectiveness of the proposed temperature controlling measures is evaluated.

2. Application of TCMES

2.1. Description of Xiluodu Hydropower Station
Xiluodu Hydropower station is located in the Grand Canyon of Jinsha River. The concrete arch dam is 285.50 m in height. The total volume of concrete needed for temperature controlling is 6.34 million cubic meters. Since installed capacity of Xiluodu Hydropower station ranks third in the world, there is a high requirement for the quality, appearance and safety of the dam. The dam locates in the humid climate zone of mid-subtropics, where the winter is dry and mild, and the summer is hot and rainy. The importance of the concrete dam and the special climatic condition determine that it is an arduous task to prevent the concrete crack.

15#-09 and 15#-10 (15# denotes the dam section number, 09 or 10 denotes the block number) are taken as examples to introduce the application process of crack risk evaluation system.

2.2. Back-Analysis of Thermal Parameters and Laboratory Test Results
Fig. 1 shows the present image of Xiluodu dam and the corresponding 3D FEM model. To reduce computational complexity, the dam sections, 14# and 16#, are only considered when the back-analysis for the thermal parameters of 15#-09 concrete is performed. There are 239682 nodes and 221424 units in the FEM model. The time step is 0.25. The temperature monitoring points measured by optical fiber and processed by the back-analysis are DT1–DT7. Fig. II indicates the position of the above points.

![Figure 1. 3D FEM model and Position of cable and location of analysis nodes (Unit: m)](image)

The three formulas are widely used in mass concrete thermal stress calculation in China. In many engineering, good agreement of stresses was noted between the calculated values and the experimental values [13]. Furthermore, it is convenient to mathematical operation in the process of deriving theoretical solutions for thermal stress of massive concrete structures. In the mathematical operation by
the program, these formulas are more suitable for iteration, due to without storing the stress history. Consequently, the equations for a transient elastic modulus, autogenously volume deformation, and creep were proposed in this paper, which is convenient to mathematical operation and well accord with experimental results.

Then the feedback analysis of temperature is undertaken with the concrete thermal parameters obtained by the back-analysis. Fig. 2 shows the temperature process curves measured by DTS and the temperature process curves calculated by FZFX3D. It can be seen from Fig. 2 that the calculation values match with measured values well, which means that the reversed thermal parameters are reliable and can be used to predict the temperature and thermal stress of 15#/10.

**Figure 2.** Comparison between temperature measured by DTS and back-analysis temperature

### 3. Crack Risk Evaluation Principle

Basing on the calculation method given by Bofang Zhu [14], the allowed maximum temperature of the concrete is calculated by Hydro-china Chengdu Engineering Corporation and then verified by the expert panel. Finally, according to maximum allowable temperature difference and the local average temperature in winter, the determined allowed maximum temperature is 27 °C. The anti-crack safety factor obtained from the Design Code for Concrete Arch Dam is 1.5-2.0.

To obtain the tensile strength of concrete, the splitting tensile strength of specimens, sampled from concrete of section 14#/01, is adopted, because the mix proportion of concrete of 14#/01 is basically consistent with that of 15#/10. When concrete of section 14#/01 is cast, the splitting tensile strength of the concrete is tested by Changjiang River Scientific Research Institute (CRSRI), Test Center (TC), Xiluodu Project Department (XPD) and Hydro-china Chengdu Engineering Corporation (HCEC), respectively. Fig. 3 shows the results obtained from the above 4 units. The data exists a certain discretization.

**Figure 3.** The splitting tensile strength of the dam concrete

### Determination of preliminary temperature controlling measures

To obtain the preliminary temperature controlling measures, the temperature and thermal stress are predicted under three cases, based on the reversed thermal parameters and laboratory test results. The details of three cases are tabulated in Table 1.
Table 1. Temperature and thermal stress prediction cases at normal weather

| Prediction cases No. | Casting temperature/°C | Possible temperature control measures | Pipe cooling | Surface insulation |
|----------------------|-------------------------|--------------------------------------|--------------|--------------------|
| 1                    | 14                      | None                                 | None         | None               |
| 2                    | 8                       | None                                 | None         | None               |
| 3                    | 8                       | Steel pipe                           | Vertical and horizontal spacing: 1.5 m, Outer diameter: 32 mm, thickness: 2 mm, Fluid water temperature: 8°C, discharge 72 m³/d | None         | None               |

Fig. 4 displays the temperature process curves of point b under different cases. In three cases, the temperature of the concrete reaches the peak value in 3-5 days, and then the temperature declines. As the maximum temperature envelope of the block shown in Fig. 6, the maximum temperature of the three cases is 31.57°C, 27.96°C and 25.69°C, respectively.

![Temperature process curves of point b under different cases](image1)

**Figure 4. Temperature prediction of typical nodes (node a, b, c: x=16, y=36)**

Fig. 5 shows the thermal stress process curves of point b and point c. The fitting curve of the splitting tensile strength is also plotted for comparison. The minimum anti-crack safety factors of the three cases are 1.42, 3.06 and 1.55, respectively.

![Thermal stress process curves of point b and point c](image2)

**Figure 5. The thermal stress prediction results of typical nodes**
Under the two indicators of evaluation principle, the prediction of temperature and thermal stress indicates that case 3 can be implemented as the preliminary temperature controlling measures to guide the construction of section 15#-10.

### 4. Determination of Latter Temperature Controlling Measures under Abnormal Weather

Section 15#-10 was cast completely on Nov. 10th, 2009. Depending on the meteorological data in the last 5 years, the temperature frequently dropped abruptly during this period, which easily leads to cracks of early age concrete. Therefore, the risk of concrete crack under this abnormal condition needs to be studied. In this part, the maximum temperature drop amplitude that the temperature continuously fell 16 °C in 3 days and then return to normal temperature is adopted as the ambient condition, in order to predict the temperature and thermal stress of the concrete.

Fig. 6 shows the temperature process curves of two points (b and c) near the concrete surface when the weather is normal and temperature drops abruptly. The temperature drop of point c is the biggest and reaches 5 °C. After the concrete surface is insulated by polyethylene benzene plate (a kind of thermal insulation material), the temperature drop amplitude of the concrete is inversely proportional to the thickness of the polyethylene benzene plate.

![Figure 6. The temperature prediction results of typical nodes](image)

Fig. 7 displays the corresponding thermal stress curves of two points (b and c). When the temperature drops abruptly, the temperature stress of point c is far beyond the concrete strength at the same age, while after making the insulation measures, the thermal stress reduces at varying degrees.

![Figure 7. Thermal stress prediction results of typical nodes](image)

### 5. Conclusion

We have proposed a temperature controlling measure evaluation system to prevent the undesired concrete cracks. This system has been deployed in a concrete dam in China. The crack risk evaluation
has been performed for 113 blocks of Xiluodu Dam. No harmful crack appears during the construction period, except for some cracks resulting from the lifting of consolidation grouting and short-time rainstorm. This indicated that the proposed system is an effective approach to prevent concrete cracks. It should be pointed out that to prevent the crack of early age concrete more effectively, additional measures should be taken, such as improving the technique level of the construction teams, maintaining timely to prevent shrinkage, and improving the accuracy of abnormal weather forecast.

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7. References
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