1 Introduction

1.1 The Significance of Thermal Stress in Mass Concrete

Mass concrete plays an important role in modern construction, especially in hydraulic and hydroelectric construction. In China, more than 10 million m^3 mass concrete are poured every year in hydraulic and hydroelectric engineering. Besides, the structure of harbor engineering and foundations of heavy machines are often built with mass concrete.

The following are the peculiarities of a massive concrete structure:

1. Concrete is a kind of brittle material, the tensile strength of which is only about 8% of its compressive strength and the tensile deformability is poor. For short-time loading, the ultimate tensile strain is about $(0.6 \sim 1.0) \times 10^{-4}$, which is equal to the strain caused by 6−10°C temperature drop. For long-time load, the ultimate tensile strain is about $(1.2 \sim 2.0) \times 10^{-4}$.
2. As the section size of a massive concrete structure is quite large, after the pouring of concrete, the internal temperature increases dramatically due to the heat of hydration. As the modulus of elasticity of concrete is relatively small and the creep is relatively large at this time, the compressive stress caused by the temperature rise is not large; however, when the temperature gradually decreases with time later on, the modulus of elasticity is large and the creep is small, it will cause considerable tensile stress.
3. Mass concrete is often exposed to the air or water, the changes of air and water temperature will cause considerable tensile stress in a massive concrete structure.
4. In a reinforced concrete structure, tensile stresses are undertaken by steel reinforcement and concrete only bears the compressive stresses. Due to the immense thickness, if the tensile stresses in a massive concrete structure are undertaken by steel reinforcement, the volume and cost of steel reinforcement will be very big, thus generally there is no steel reinforcement in mass concrete and the tensile stresses must be undertaken by concrete itself.

Based on the features above, in the design of a massive concrete structure, it is required to have no or little tensile stress. For the external load like deadweight and water pressure, this requirement is not difficult to achieve. But in the process of construction and operation, the changes of temperature will cause large tensile stress in mass concrete, and it is not easy to control the tensile stress in an allowable value, so cracks often appeared in mass concrete.

As shown in Figure 1.1, the cracks in mass concrete can be classified into three kinds, namely through cracks, deep cracks and surface cracks. Through cracks cut the structure section and may probably destroy the stability and integrity of the structure. Leakage may occur if the cracks reach to the upstream surface. They are

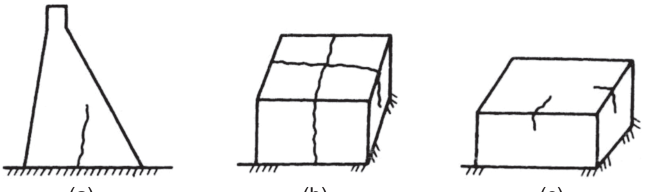

Figure 1.1 Sketch of different kinds of cracks in a massive concrete structure: (a) through crack, (b) deep crack or surface crack, and (c) surface crack.

very dangerous. Deep cracks partly cut the structure, and they are also dangerous. For surface cracks, if they do not extend, the impact is not serious. But upon reservoir impoundment, pressurized water enters the cracks, and the surface crack at upstream face of the dam may extend to a deep crack or even a through crack. Surface cracks in the region above foundation or old concrete may also develop to deep cracks or even through cracks during the cooling process of the internal concrete.

Cracks in concrete can also come from dry shrinkage, but the changes of humidity are small in mass concrete, and these changes are limited to a very shallow range near the surface, so it is not difficult to solve the problem by curing.

Experiences show that it is possible but not easy to prevent hazardous cracks of mass concrete. For the project of Qingtongxia Hydropower Station, which was built during the early stage of new China, because the engineers lacked experience and did not fully realize the importance of thermal stress, the riverbed power plants constructed in cold areas are designed with thin-wall structure and lack of effective temperature control measure. As a result, severe cracks occurred after construction started. The construction was subsequently stopped and delayed for several years. In the 1950s, several slotted gravity dams were built by the Soviet Union in the cold Siberi region. There were severe cracks in all these dams. Consequently, the hydropower stations are all built with solid gravity dams, and the Toktogul method was developed for preventing cracks.

In a massive concrete structure, the changes of temperature can not only lead to cracks but also have an important impact on the stress state of the structure. Sometimes, the thermal stress can exceed the sum of the stresses caused by other external loads. For instance, as is shown in the study of the stress state around the orifice of the Sanmenxia gravity dam, the alignment of stress values caused by different loads from high to low is caused by the temperature, the internal water pressure, self-weight, and external water pressure, and the thermal stress is larger than the sum of stresses caused by all other loads. The changes of temperature also have a remarkable impact on the stress state of arch dams.

The thermal stress is closely related to the type of structure, the weather conditions, the construction process, the properties of material, and the operating conditions. The variation of thermal stress is very complicated. It is more complex to analyze the thermal stress than the stresses caused by water, self-weight, and other external loads.

In conclusion, the analysis of the thermal stress, the temperature control, and the measures to prevent cracking are the crucial topics in the design and construction of massive concrete structures [104−110].

1.2 The Features of Thermal Stresses in Concrete Structures

Here we use an example to explain the features of the thermal stresses in concrete structures. As is shown in Figure 1.2(a), we assume that there is a steel bar AB whose ends are fixed. The temperature change is $T(\tau)$ which is a function of time: when $\tau = 0$, $T(0) = 0$, at the beginning, $T(\tau)$ increases as the time proceeds; after it reaches the highest temperature T_0, the steel bar gradually cools down, and finally $T(\infty)$ equals 0. The elastic modulus of steel is a constant E_s. Since the steel bar is fixed at both ends, the thermal stress of steel bar AB is

$$\sigma_s(\tau) = -E_s \alpha_s T(\tau) \tag{1.1}$$

The thermal stress $\sigma_s(\tau)$ of the steel bar is proportional to $T(\tau)$, and the proportional factor is $-E_s\alpha_s$, where α_s is the linear expansion coefficient of steel. When the temperature reaches its highest from the original 0°C, the stress also reaches its highest from the zero stress. When the temperature gradually cools down to 0°C, the stress also decreases to 0, and finally they return to the initial state.

As for the concrete bar AB, since the elastic modulus of concrete is varying with age τ, the thermal stress cannot be calculated using Eq. (1.1). Instead, we should use an incremental method to calculate. Dividing the time τ into a series of time intervals $\Delta\tau_i$ ($i = 1 - n$) in the ith time interval $\Delta\tau_i$, the increment of temperature is ΔT_i, the average elastic modulus is $E(\tau_i)$, so the increment of elastic stress should be

$$\Delta\sigma_i = -\alpha E(\tau_i)\Delta T_i$$

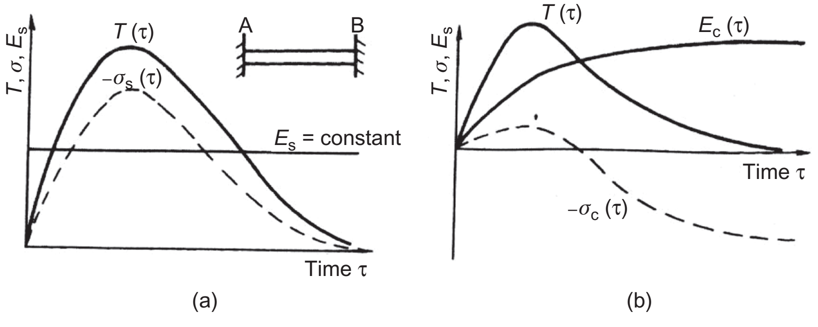

Figure 1.2 Comparison of the thermal stress between steel structure and concrete structure: (a) thermal stress in a steel bar with fixed ends and (b) thermal stress in a concrete bar with fixed ends.

After accumulation, the elastic stress is

$$\sigma_c(t) = -\alpha \sum E(\tau_i)\Delta T_i \tag{1.2}$$

Considering the influence of creep of the concrete, we should use the following equation to calculate:

$$\sigma_c(\tau) = -\alpha \sum E(\tau_i)K(t,\tau_i)\Delta T_i \tag{1.3}$$

where $K(t,\tau_i)$ is the stress relaxation coefficient, its definition is referring to Eq. (8.72). Assuming that the concrete is subjected to stress $\sigma(\tau)$ at age τ, if the strain remains at a constant, because of the creep effect, at time t, the stress will decrease to $\sigma(t) = \sigma(\tau)K(t,\tau)$, and the relaxation coefficient is the ratio of $\sigma(t)$ to $\sigma(\tau)$, namely

$$K(t,\tau) = \sigma(t)/\sigma(\tau) \tag{1.4}$$

Figure 1.2(b) shows the changes of temperature $T(t)$ and stress $\sigma(t)$ with time τ. In the early stage of temperature rising, compressive stress is developed in the bar. But since in early stage the elastic modulus of concrete and the relaxation coefficient is small, the compressive stress is not large. In the later cooling stage, the elastic modulus of concrete is relatively large, as are the relaxation coefficient and the increment of stress produced by unit temperature difference. As the temperature of the bar gradually decreases, not only the early compressive stress is canceled, but large tensile stress will be created in the bar. Finally, when the time $\to \infty$, the temperature $T(\infty) \to 0$. If the stress is not 0, there will be a large surplus tensile stress. In practice, when the temperature drop reaches 12−20°C, as for the fully restrained concrete bar, the later tensile stress is big enough to pull the concrete to failure.

We can conclude from the above examples that the changing pattern of thermal stress between the concrete structure and steel structure is totally different, the reasons accounting for this being (1) the elastic modulus of concrete is changing with age τ and (2) the impact of the creep effect of the concrete.

1.3 The Variation of Temperature and Thermal Stress of Mass Concrete with Time

1.3.1 The Variation of Temperature of Mass Concrete with Time

Because of the large size, the variation of temperature in a mass concrete structure is shown in Figure 1.3; the placing temperature T_p is the concrete temperature just after pouring. If the concrete cannot be completely cooled, it would be in an adiabatic state, and the temperature will increase according to the adiabatic rise of

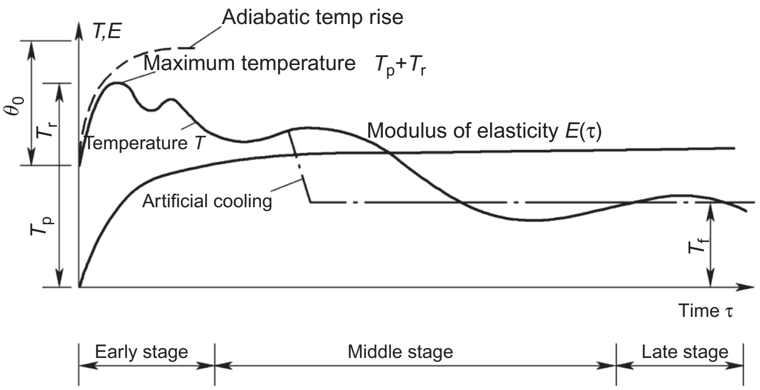

Figure 1.3 The variation of the temperature and elastic modulus of mass concrete with time.

temperature curve, as shown by the dotted line in the figure. In practice, since some heat may be lost from the top and the sides of the pouring layer, the concrete temperature will change along the solid line in the figure. The temperature rises to its highest $T_p + T_r$ and then decreases. T_r is the temperature rise due to the heat of hydration of cement. After being covered with newly poured concrete, the old concrete will be influenced by the heat of hydration produced by the newly poured concrete, and temperature recovers slightly. After the second peak temperature, the temperature will continue to decrease. If the point is more than 7 m far from the lateral surface, the temperature of this point will not be affected by the external temperature changes and is influenced only by the placing temperature, the hydration heat, and the temperature of the top of the placing layer. As is shown by the solid line in the figure, finally the temperature will vary with a small difference about the steady temperature T_f and is called the quasi-steady temperature.

In the concrete dam, the interior temperature cools down from the highest temperature to the steady temperature very slowly. It normally takes several decades or hundreds of years. In order to accelerate the cooling process, cooling pipes are adopted.

1.3.2 The Variation of the Thermal Stress in Mass Concrete

Since the elastic modulus of concrete varies with age, in a massive concrete structure, the development of thermal stress can be divided into three stages:

1. *Early stage*: It is about 1 month from the start of concrete pouring to the finish of the heat release of cement. There are two features in this stage: Firstly the temperature field will change dramatically because of the intense heat of cement hydration. And secondly, the elastic modulus of the concrete will change rapidly with time.
2. *Mid stage*: This stage starts from the end of heat release of cement and ends when the concrete is cooled down to a final steady temperature. The thermal stress in this stage is

caused by the cooling of the concrete and the changes of external temperature. In the mid stage, the elastic modulus will change slightly with time.

3. *Late stage*: The operation stage after the concrete is completely cooled down. Thermal stress is mainly caused by the changes of external air temperature and water temperature. The stresses of the three stages accumulated to form the final stress state of concrete.

1.4 Kinds of Thermal Stress

There are two kinds of thermal stress in mass concrete:

1. Self-stress

   For structures without any external constraint or statically determinate structure, if the internal temperature is linearly distributed, no stress will appear; if the internal temperature is nonlinearly distributed, the stress caused by restraint of the structure itself is called self-stress. For instance, when a concrete wall is cooled in the air, the surface temperature is low and the inner temperature is high. The shrink of the surface is restrained by the inner concrete. The tensile stress appears at the surface, and the compressive stress appears in the interior. At any section, the area of tensile stress must be equal to the area of compressive stress, as shown in Figure 1.4(a).

2. Restraint stress

   When the whole or part of the boundaries of the structure is restrained, the structure cannot deform freely with the change of temperature. The stress produced by this reason is called restraint stress, for instance, the stress in a concrete block caused by the restraint of the rock foundation when the concrete is cooling as shown in Figure 1.4(b).

   In the statically determinate structure, only self-stress will appear, but in the statically indeterminate structure, both self-stress and restraint stress will appear.

1.5 Analysis of Thermal Stress of a Massive Concrete Structure

1. Analysis of temperature field of mass concrete

   The temperature field of mass concrete depends on the weather conditions and the construction process. The problem can be treated by solving a heat conduction equation with given boundary condition and initial condition. For the simple cases, theoretical

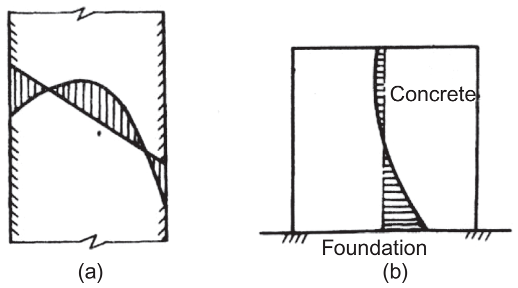

Figure 1.4 Sketch of two types of thermal stress: (a) self-stress and (b) restraint stress.

solution can be found; as for the practical complex cases, the finite difference method or finite element method can be used.

2. Analysis of thermal stress field of mass concrete

It is more difficult to analyze the thermal stress in a given temperature field. A theoretical solution can be found only in simple cases. The numerical method is mostly used. The finite element method is commonly used at present.

The creep of concrete will influence thermal stress. When calculating the concrete thermal stress, impact of concrete creep must be considered.

Shrinkage stress is similar to thermal stress. The method used to analyze thermal stress can also be used to analyze shrinkage stress.

1.6 Thermal Stress—The Cause of Crack

The cracks will appear when the tensile stress of concrete exceeds its tensile strength. The tensile stress depends not only on temperature difference but also on the constraint condition. As shown in Figure 1.5, there are concrete plates on rock foundation and soil foundation. Since rock foundation has a large deformation modulus, the restraint to the deformation of the concrete plate is large; however, soil foundation has small deformation modulus, and the restraint to the deformation of the concrete plate is small. Even though the thickness and temperature drops of the two concrete plates are the same, the concrete plate on the rock foundation may crack, but the concrete plate on the soil foundation may not crack.

The thermal stress of concrete can be approximately represented as

$$\sigma = RK_{\mathrm{p}}E\alpha\,\Delta T \tag{1.5}$$

where

σ—thermal stress
R—restraint coefficient
K_{p}—stress relaxation coefficient caused by the creep of concrete
E—elastic modulus of concrete
α—coefficient of linear expansion of concrete
ΔT—temperature difference of concrete.

To prevent cracks, we must control the thermal stress so that it does not exceed the allowable tensile stress, as

$$\sigma = RK_{\mathrm{p}}E\alpha\,\Delta T \le \frac{R_{\mathrm{t}}}{K} \tag{1.6}$$

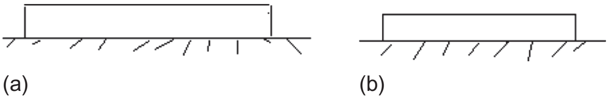

Figure 1.5 Concrete plate on (a) rock and (b) soil foundation.

where

R_t—tensile strength of concrete
K—safety factor.

From the above equation, it is clear that to prevent concrete crack, the following three aspects should be considered:

1. Control temperature difference ΔT
2. Minimize the restraint coefficient R
3. Enhance the tensile strength R_t.

The restraint factor R includes the external restraint and the internal restraint.

1.7 Technical Measures for Control of Thermal Stress and Prevention of Cracking

Once cracks appear in a massive concrete structure, it is difficult to restore the integrity of the structure by repairing. Experiences show that it is possible but not easy to prevent cracking in mass concrete. It requires careful design, careful study, and careful construction.

The following aspects should be considered when dealing with cracks in a massive concrete structure:

1. Rational choice of the type of structure and joint spacing.

   As experience shows, the type of structure has a great impact on the thermal stress and cracks. In the 1950s and 1960s, the Soviet Union constructed several slotted gravity dams in the cold Siberia area, such as the Mamakansky dam, Bratsky dam and the Boohtarminsky dam. Cracks emerged in all of these dams. The engineers learnt from this experience. They constructed solid gravity dams instead in later projects.

   The size of pouring block may influence the thermal stress. The bigger the pouring block, the larger the thermal stress. So rational joint spacing is important to prevent cracks. Practical experience and theoretical analysis have shown that when the size of the pouring block is controlled for about 15 m × 15 m, the thermal stress is low, and the constraint height of the foundation is only about 3−4 m. In temperate areas, cracks are less likely to happen. But in cold areas, because of the extensive temperature difference, a pouring block of this size is still difficult to prevent cracks, so some rigorous heat preservation actions are needed.

   Elevation difference of foundation should be avoided in the same pouring block. Stress concentration should be avoided or reduced in structure design.

2. Choosing the raw material of concrete and optimizing the mix of concrete.

   The purpose of choosing the raw material of concrete and optimizing the mix ratio of concrete is to improve the crack resistance of the concrete. Specifically, it requires concrete to have low adiabatic temperature rise, large extensibility, and low linear expansion coefficient. It is fine if the autogenous volume deformation is micro-expansion or at least low shrinkage:

   a. Choice of cement. Crack resistance, low heat, and high strength are important factors for choice of cement for internal concrete. As for external concrete, despite the crack resistance, it requires resistance to freezing, thawing and erosion, high strength, and low shrinkage.

b. Mixed with admixture to lower the adiabatic temperature rise and to improve crack resistance of concrete. At present, fly ash is widely used.

c. Mixed with agent, including water reducing agent, air entraining agent, retarder, early strength agent, etc. Water reducing agent is the most commonly used. It can help to reduce water and to increase plasticity. With the same level of slumps and strength, it can help to reduce the water consumption, save cement, and reduce the adiabatic temperature rise. Air entraining agent helps to create large quantities of small bubbles in concrete in order to improve the freezing−thawing resisting durability of concrete. Retarder is used in summer construction and early strength agent is used in winter construction.

d. Optimize the concrete mix. To guarantee of the strength and fluidity of concrete, efforts should be made to save cement to reduce the adiabatic temperature rise of concrete.

3. Rigorous control of the temperature of concrete.

Rigorous control of the concrete temperature is the most important measure to prevent crack.

a. Reduce the placing temperature of concrete. Cooling the mixing water, adding ice to mixing water, pre-cooling aggregate, and other methods are used to reduce the concrete temperature at the exit of the concrete mixer. Increasing the strength of concrete pouring, cooling of pouring surface, and other methods are used to reduce the temperature rise during the pouring process.

b. Pipe cooling. Cooling pipes are embedded in the concrete to reduce the concrete temperature.

c. Superficial heat insulation. Insulation material is used to cover the surface of the concrete to reduce the inside and outside temperature difference and reduce the surface temperature gradient of concrete.

4. Emphasis on the preparation work before construction.

In the early stage of the construction, preparation work of temperature control of concrete must be emphasized, such as the installation and testing of the cooling plant and ice machine, cooling water pipe, and preparation for heat insulation material.

5. Strengthen the management of construction.

a. Improve the quality of concrete construction. To prevent cracks, despite the rigorous control of concrete temperature, reinforcement of construction management and improvement for construction quality are also needed. Obviously, the strength distribution in a concrete block is nonuniform. Cracks emerge firstly at the most vulnerable place. A survey was conducted at the Dan Jiang Kou dam site, and hundreds of concrete layers were investigated. The results showed that the emergence of the cracks had significant connection with the strength distribution of the concrete. When the quality of concrete is poor and the deviation coefficient of concrete strength C_v is large, there will be more cracks. Projects with good concrete construction quality may have fewer cracks; otherwise, there will be many cracks. So it is important to strengthen the construction management to improve the concrete construction quality.

b. Even rising with thin layer and short interval. For the schedule of concrete pouring, it is better to pour concrete with thin layer, short interval (5−10 days) and even rising. Avoid pouring concrete in a rush and resting for a long time; avoid large height difference between adjacent dam blocks; especially avoid "thin block, long interval."

c. Better to pour concrete above foundation in cold weather.

d. Strengthen curing and prevent shrinkage.

1.8 The Experience of the Temperature Control and Crack Prevention of Mass Concrete in the Last 30 Years

1. Enhancement of pipe cooling in the local area makes the control of the maximum tensile stress in concrete dams no longer a challenge.

In the past, since the steel water pipe has too many connections, it takes time to set up and can only be set on the surface of the old concrete layer. The vertical spacing of water pipe is equal to the thickness of the pouring layer. In recent years, steel water pipe is substituted by the plastic water pipe. The plastic water pipe is flexible and can be paved during the pouring process. The vertical spacing of the water pipe can be reduced to the thickness of pouring layer, which is about 0.3−0.7 m; the horizontal space can be reduced to about 1.0 m. Cooling of water pipe with small spacing can greatly reduce the temperature rise caused by the heat of hydration. The combination of pipe cooling and pre-cooling of the concrete makes the control of the maximum tensile stress in the concrete dam no longer a challenge. Moreover, the height of cooling area with closely arranged cooling pipes is only 0.1−0.2 the length of the pouring block. The range of cooling area with closely arranged cooling pipes is not large, and the cost is low.

2. Application of the plastic foam board can effectively help to control the surface tensile stress.

In the past, straw bags were mainly used to insulate the surface of the concrete dam. But the straw bags become damp and rot. Moreover, the straw bags are inflammable and their heat insulation effect is poor. The poor heat insulation at the surface is the significant cause of "No dam without cracks" in the past. After 1980, plastic foam boards were applied in the superficial thermal insulation of mass concrete, and the effect is excellent. Construction with plastic foam board is easy, and the cost is not high. Plastic foam board can be used for long-term heat insulation.

3. It is a trend to built concrete dams without cracks.

In the past, there were cracks in almost all concrete dams. It is an objective fact that there is "No dam without cracks." Nowadays, with the remarkable development of the technique of temperature control, several concrete dams have been constructed without cracks, such as the third stage of Three Gorges concrete gravity dam and the San Jiang He arch dam.

Today, if the dam is well designed, well studied, and well constructed, a concrete dam can be constructed without cracking and the cost is not high. Thus the trend in the future is to construct mass concrete without cracking.