Simulation analysis of the temperature filed of a hollow concrete piers

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Abstract
By taking hollow concrete bridge piers as research objects, this work analyzed the distribution of internal temperature field for hollow concrete bridge piers. Meanwhile, the effect of wall thickness on hydration heat temperature was investigated to obtain the general law of hydration heat temperature field for concrete box girder. In addition, ANSYS, as a large finite element software, was utilized to simulate the hydration heat temperature field of high hollow concrete piers. The data obtained were compared with that of measured data. Results indicated that the hydration heat temperature of the concrete increased rapidly within 24 h after being cast. The heat in the centre was more difficult to be dissipated with increasing wall thickness of the pier. It was noted that the hydration heat led to the apparent increase of the temperature in centre of the pier. The finite element model constructed in this research can be as precise as that of the temperature field measure.

Key words: HOLLOW CONCRETE BRIDGE PIERS, FINITE ELEMENT, TEMPERATURE FIELD, HYDRATION HEAT.

Introduction

In civil engineering, the problems caused by hydration heat of concrete are usually found in dams with hydraulic structure, tall building, and large sized industrial equipment foundation, the anchor in suspension bridge and large base slab in bridge engineering. Presently, the span, height and thickness of bridges have been constantly increasing. However, the hydration heat temperature filed of hollow and thick concrete bridge piers has been rarely studied. In the hardening process of hollow and thick concrete bridge piers after cast, hydration heat is produced due to the reaction between concrete and water and then it increases. The temperature inside concrete rises gradually, and increase to more than 70℃[1-3].

Owing to the concrete components with ordinary size show good dissipating conditions, serious cracks induced by hydration heat are usually not formed because slight difference between the temperatures inside and outside concrete. However, for the large-sized concrete, hydration heat is likely to be more produced. The heat of the outside concrete surface can be dissipated in a fast way, so does the decrease of temperature, while the heat accumulated in the inside concrete is unlikely to be dissipated shortly. In this way, the deformation resulting from uneven temperatures due to the temperature gradient formed by high temperature of inside concrete and low temperature of outside concrete surface tends to produced large temperature stress by subjecting to structural constraint and external constraint. The larger the volume, the more difficult the dissipation of the heat accumulated for inside concrete, the greater the temperature difference, the higher the temperature stress produces[4-6]. With the improper process and ill control, the stress is likely to induce the crack of concrete surface if it exceeds the tensile strength of concrete. And it can bring about potential risks in the application of structure and safety. The practical and theoretical researches show that the temperature stress arising from hydration heat is considered as one of the main reason leading to the crack of large-sized concrete.

It is difficult for the internal heat to be dispersed due to the huge size of concrete components being casted. Therefore, the temperature variation induced by hydration heat requires to be considered and some corresponding measures need to be taken to control the crack at maximum[7,8]. By taking No 3. hollow concrete bridge pier as the research object, the authors explored the distribution of temperature field in hollow concrete bridge piers and studied the influences of wall thickness on hydration heat temperature field. This research may lay an experimental foundation for controlling the temperature crack and calculating temperature stress.

Finite element analysis

General introduction to the engineering

This work used a three-span rigid frame bridge with hollow pile and thick wall. It has continuous rigid frame in the span of（100+192+100）m and C55 prestressed concrete beam with 11.2 m in width, 13.5 in height for top pier beam,and 7.2 m in the mid-span beam height. The pier in its main bridge is thin-walled and hollow. The No. 3 pier is 69 m in height with the pier bottom in the size of 25×11m, pier top of 9.2×11m, and hollow size of 6.8×8m. With pile base, No. 3 pier applies C40 in-site mixed concrete and casted by dividing segments at average temperate at 12℃ in construction.

ANSYS finite element modeling

Hydration heat, as an important factor that influences the temperature stress of concrete, is significantly associated with time. In the research, it is represented by the following composite exponential expression [9]:

$$Q(\tau)=Q_0\left(1-\exp(-a\tau^b)\right) \quad (1)$$

Where $Q(\tau)$ is the hydration heat accumulated at time τ; Q_0 is the total amount of hydration heat of cement (kJ/kg), coefficients a and b are constants; and τ is time.

The adiabatic temperature rise of concrete can be inferred using the expression of hydration heat of cement and represented as

$$\theta(\tau)=Q(\tau)(W+kF)/cp \quad (2)$$

Where W is the amount of cement used, c is the specific heat of concrete, ρ is the density of concrete, F is the amount of admixture used, k is reduction factor and k=0.25 for fly ash.

For any object without inner heat source, the instable temperature field is calculated using the following basic differential equations of finite element computation:

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=c\gamma\frac{\partial T}{\partial \tau} \quad (3)$$

$$T_{t=0}=T(x,y,z,t) \quad (4)$$

$$\lambda\frac{\partial T}{\partial n}|_\Gamma=q(t) \quad (5)$$

$$\lambda \frac{\partial T}{\partial n}|_{\Gamma} = h[T_a(t) - T] \qquad (6)$$

Where, equation (3) is Fourier heat conduction differential equation; equation (4) is initial condition; equation (5) is the second boundary condition; equation (6) is the third boundary condition; Γ is the boundary of object; $q(t)$ is the heat flux density expression of known boundary; h is comprehensive heat exchange coefficient; and $T_\alpha(t)$ is the temperature of outside air.

The heat exchange of concrete bridge pier and outside environment includes not only the heat flux of solar radiation, but also convection and radiation heat exchange with outside environment. Therefore, the boundary condition of concrete pier that in actual environment is the combination of above second and third boundary conditions, which is represented as:

$$\lambda \frac{\partial T}{\partial n}|_{\Gamma} = h[T_a(t) - T] + q(t) \qquad (7)$$

To simplify the computation, the combined boundary condition of equation (7) is general converted into a same boundary condition. It can be converted to the third one, that is, let $T_a^{'}(t) = T_a(t) + \frac{q(t)}{h}$, then the boundary condition is

$$\lambda \frac{\partial T}{\partial n}|_{\Gamma} = h[T_a^{'}(t) - T] \qquad (8)$$

Equation (8) shows that, to accurately and reasonably simulate complex boundary condition of heat exchange, the comprehensive heat exchange coefficient h and equivalent air temperature $T_a^{'}(t)$ have to be accurately described using proper numerical model according to the geographic position and weather condition of the pier site.

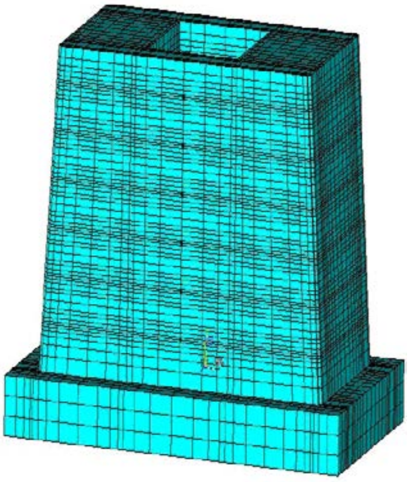


Figure 1. Finite element model for the hollow concrete pier

Finite element solution of temperature field

Based on the constructing procedure, a birth-death element method was used to process casting element by taking casting block as a unit. SOLID70 heating element, as a 3-D element with thermal conductivity, has 8 nodes with temperature as degree of freedom (DOF). Moreover it is a hexahedron element with each node containing only one temperature DOF. It was used to conduct transient thermal analysis. On this basis, the experimental model was applied to APDLparametric modeling[10]. Afterwards, a spatial finite element model was constructed and employed in the calculation analysis. There are 39, 640 nodes and 35, 876 elements. The ANSYS finite element model is demonstrated in figure 4.

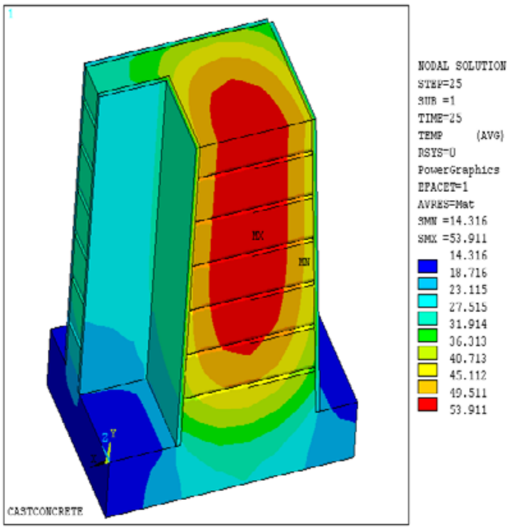


Figure 5. Temperature variation cloud picture of hollow concrete pier

In this research, ANSYS finite element analysis was utilized to perform the calculation by considering the factors including laminate casting, wall thickness, hydration heat temperature variation, creep, the differentiation of various materials, casting temperature, and convection boundary condition in real construction. According to the real experimental series, the load step was reasonably selected by considering effect of constructing interval. Daily mean temperature measured was adopted. Figure 5 suggests the temperature calculated of typical time.

The comparison of calculated results and measured data concerning hydration heat temperature field of the concrete pier

The results of hydration heat temperature field in the pier calculated using finite element analysis were compared with that of measured data. The results are shown in figures 6 to 8.

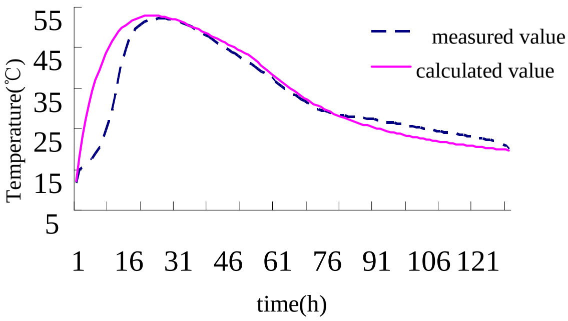


Figure 6. Variation curves of measured temperature and computed temperature of surface point

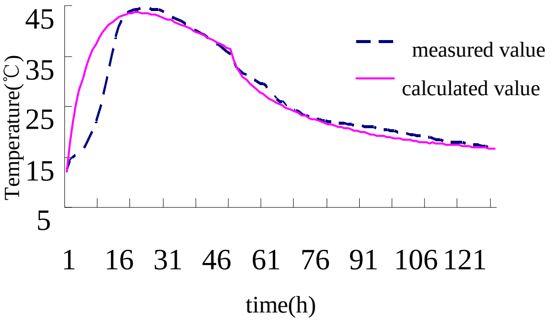


Figure 7. Variation curves of measured temperature and calculated temperature of central point

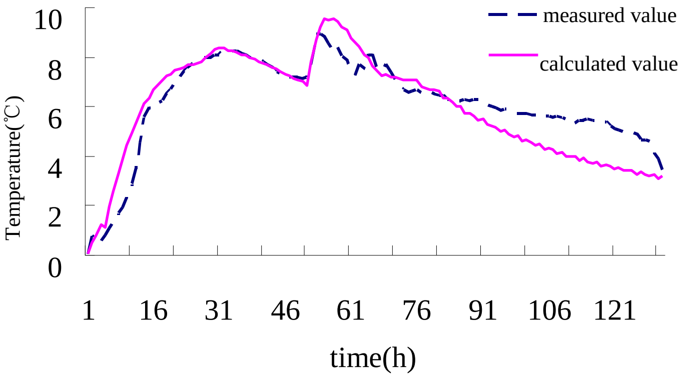
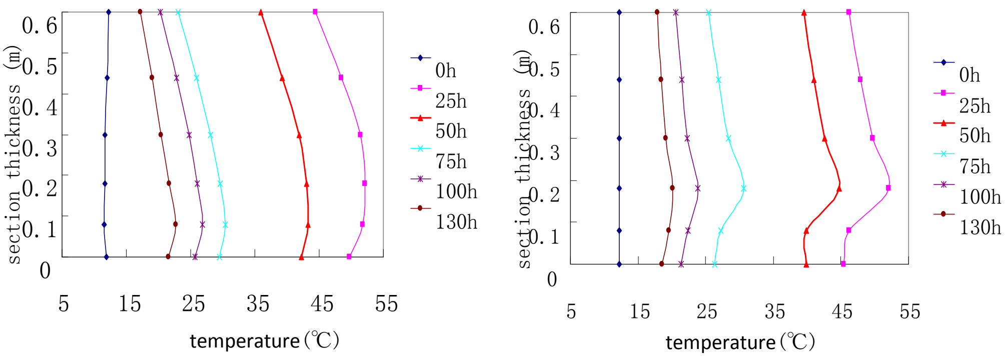


Figure 8. Temperature difference curves between measured and calculated temperatures of internal and surface points that vary with time

For the sake of comparing the temperature differences between the concrete surface and inside concrete, the change of hydration heat temperature along with the direction of section thickness is indicated in figure 9.



(a)ANSYS based theoretical computation results (b)Measured data

Figure 9. Temperature distribution along cross section direction at different times

According to the temperature curve calculated and the measured temperature curve, it is found that both curves show consistent variation trends, so does the time that both peaks appear. In initial period, there is a greater difference between the temperature increasing curve of measured data and the temperature variation in the experiment. This is because there are many uncertain factors and uneven casting in the initial casting process; finite element analysis fails to simulate accurately each detail in initial casting period and is unable to precisely describe constructing parameters which consist of geometric structure model, natural conditions, and design variables in construction process. The description of the geometric structure model is carried out by subjecting to the progress and methods of constructions. Moreover, due to the common parameters for environment variation including the temperature, water temperature, ground temperature, sunshine, and wind speed in construction process, the difference error is likely to be produced owing to the difficulty in controlling the simulating results.

Conclusions

The hydrated cement after concrete being cast is considered as a complex chemical reaction process. Hydration heat is able to form transient temperature field in concrete structure. On the basis of principle of thermal conductivity finite element method, a finite element model was built to simulate the temperature field through simulating hydration heat and convection boundary condition. The potential risks brought by hydration heat of concrete pier call for enough attentions of engineer in the case of pier with greater wall thickness. Based on the comparison results of measured data and calculated values, the results of hydration heat temperature calculated using ANSYS were proved to be reliable. Those results can be used as reference data before casting concrete in pier as well as the degree of taking measures in controlling temperature and selecting location.

After fulfilling the concrete cast of pier, a jump between the temperatures of the center and surface was found after removing the casting template in a short time. So it is essential to properly choose removal time of template. Besides, some corresponding measures require to be taken to decrease the jump of temperature difference so as to reduce the possibility of crack in pier surface. As the wall thickness of pier increases, the temperature in center of pier induced by hydration heat rises, therefore it is difficult for the heat in the centre to be dissipated. Using a removal delay method to decrease temperature difference between inside and surface pier shows limits. To avoid the occurrence of initial crack in pier, it is suggested to reduce the temperature difference through using recirculating cooling water by setting certain number of cooling pipes in pier.

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