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Early age behavior analysis for reinforced concrete bridge pier

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Abstract. In this study, the construction of a reinforced concrete bridge pier was analyzed from durability point of view. The goal of the study is to analyze the crack iniation condition due to construction and present some recommendations for construction conditions of the reinforced concrete bridge pier. The bridge is located at the western port area of Shenzhen, where the climate is high temperature and humidity. To control the cracking of concrete, a construction simulation was carried out for a heat transfer problem as well as a thermal stress problem. A shrinkage model for heat produced due to cement hydration and a Burger constitutive model to simulate the creep effect are used. The modelling based on Femmasse© is verified by comparing with the testing results of a real underground abutment. For the bridge pier, the temperature and stress distribution, as well as their evolution with time are shown. To simulate the construction condition, four initial concrete temperatures (5℃, 10℃, 15℃, 20℃) and three demoulding time tips (48h, 72h, 96h) are investigated. From the results, it is concluded that a high initial concrete temperature could result in a high extreme internal temperature, which causes the early peak temperature and the larger principle stresses. The demoulding time seems to be less important for the chosen study cases. Currently used 72 hours in the construction practice may be a reasonable choice.

Keywords: construction analysis; bridge pier; heat of hydration; initial concrete temperature; stripping formwork time

1. Introduction

Concrete, as most consumed materials in civil engineering, has a broad range of applications at present time, in which reinforced concrete structures are widely used in various forms. The rate and amount of heat generation due to cement hydration are of importance for a bridge pier with a considerable mass. Non-uniform thermal expansion and contraction due to the combined effects of the heat of cement hydration, creep and shrinkage, environmental temperature and the constraint effects of reinforced steel bar and inter-structural elements restriction may create undesirable

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stresses. The stresses may cause detrimental cracking in the concrete, as a result, reducing its performances regarding, among others, strength and durability. This kind of so called mass concrete requires more attentions during the design and construction processes. Heat of cement-hydration analysis thus becomes important when casting mass concrete structures. It enables us to predict and control temperature and stress distributions inside a concrete structure to avoid potential problems. Whether a mass concrete structure requirs a heat of hydration analysis depends on its dimension, shape, cement type to be used and the construction conditions.

Shenzhen locates in a subtropical marine environment with a relatively high temperature, high humidity and high aggressive environmental actions such as chloride sulfate. According to the China construction ASTRI's research, a considerable portion of the bridge, port, hydraulic, underground structures, civil construction are located in severe aggressive environmental area such as the sea, tidal wave splash and sea fog. Corrosion has caused damage and even collapse in a big number of projects during services. Among other reasons, cracks generated due to thermal stresses in construction phase play an important role.

In 1994, RILEM, TC-119 Committee (1994) held an international symposium concerning avoidance of concrete early thermal cracking. From then on, research on this topic has been mainly carried out in two areas: one is on the early hydration degree, thermodynamic properties, deformation behavior, especially early concrete viscoelasticity and creep, strength, elastic modulus, and the development of damage with time (Briffaut et al. 2011, Azenha et al. 2014, Concei O et al. 2014, Klemczak 2014, Knoppik-Wróbel and Klemczak 2015); The second is on the problem of early concrete cracking, which covers the work of early non-load stress or strain calculation, concrete cracking evaluation indicators and criteria, probability theory, reliability analysis, finite element advanced theories and methods (RILEM TC-119, 1998; Alvarado et al. 2009, Alvarado et al. 2010, Yapar et al. 2015). In China, there are also some literatures related to this field by Zhu (1999), Du et al. (2015a, 2015b). In this paper, a reinforced concrete bridge pier located in Shenzhen western port area is analyzed using a FEM software FEMMASSE© (2010) from the view point of construction, in which heat of cement hydration, as well as the Shenzhen climate information is considered.

2. Basic theories and models

2.1 Heat models

To describe the liberation of heat of hydration of concrete, a shrinkage core model (SCM) is used (Femmasse 2010)

$$H\{M\} = H_T \frac{a(M-d)}{1+a(M-d)} \quad M>d \tag{1}$$

where
$H\{M\}$= liberated heat of hydration at maturity M
H_T = total heat of hydration
d = dormant period (reaction rate very slow)
a = function coefficient
The maturity is expressed by (Bazant 1986)

$$M(t) = \int_{tcon}^{t} e^{\frac{Q}{R}\left[\frac{1}{T_{ref}} - \frac{1}{T+273}\right]} * \frac{1}{1+(a_c - a_c h)^{b_c}} dt \tag{2}$$

where
t = actual time
t_{con} = time at concreting
Q = activation energy
R = universal gas constant
T_{ref} = reference temperature
T = temperature
h = moisture potential
a_c , b_c = coefficients

For modelling of moisture transport in concrete, Bazant model (1986) which is based on the assumption that there is a linear relation between the evaporable moisture content and the moisture potential is used. The diffusion coefficient is non-linear. The model is coupled with the formulation of desorption isotherms as described in Roelfstra (1989).

2.2 Mechanical models

In the computations, both the hygral and plastic shrinkage are considered. The incremental hygral shrinkage is as

$$\Delta\varepsilon_s = \alpha_h \Delta h \tag{3}$$

where
h = change of moisture potential h in the time interval.
$_h$ = shrinkage coefficient

As for plastic shrinkage, which is caused by the interaction of water with fine particles during the hydration process, may show a large value with a low W/C factor and a quantity of silica fume.

As for the creep model, an ageing Burger's Model consisting of a Maxwell and a Kelvin unit placed in a series is used to describe the viscoelastic behaviour of young concrete.

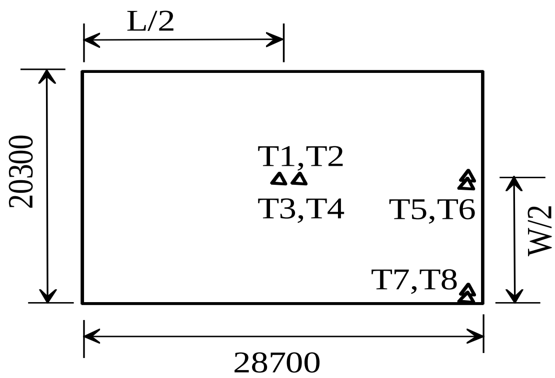

Fig. 1 Temperature measured points (T1-T8) of the concrete underground abutment (mm)

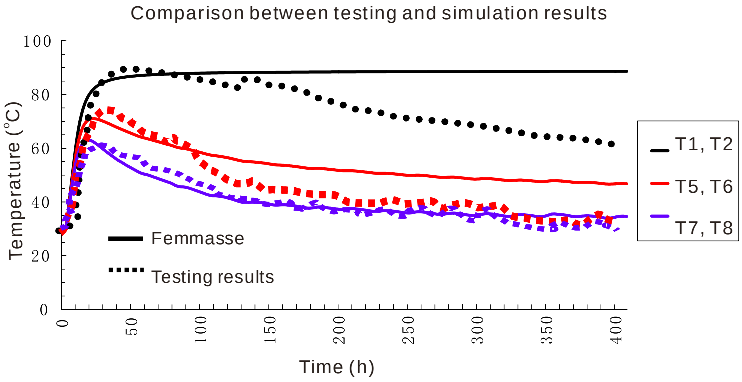

Fig. 2 Temperature evolution of testing points with time

3. Comparisons with testing results

To validate the computing scheme and to carry out the identification of parameters, we investigate an early age concrete hardening for an actual underground abutment dealt with by Ye and Yang (2008), in which the cement was PO42.5, the water-binder ratio, the sand ratio and the 7 day hydration heat was 0.4, 42%, and 306 kJ/kg, respectivly. Figure 1 shows the size of concrete structure and the arrangement of testing points. The temperatures of the testing points (T1-T8) were measured for 399 hours starting at casting concrete.

The testing and the computing results by FEMMASSE are shown in Fig. 2. It is seen that computer simulation obtained similar values and trend with the testing results, especially for the points T5-T8; while for points T1-T2, the temperatures are similar at the initial stage and the peak value, they depart from each other when the temperature passes over the peak. This may be due to the effect of cooling circuits in the real structure, which is not taken into account in our

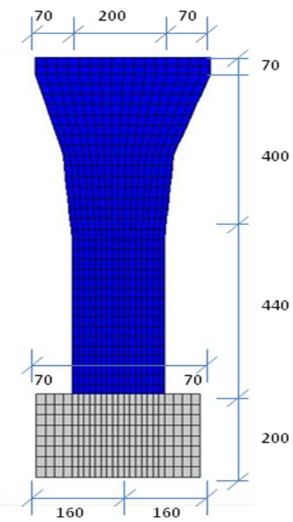

Fig. 3 Scale and mesh of the bridge pier(cm)

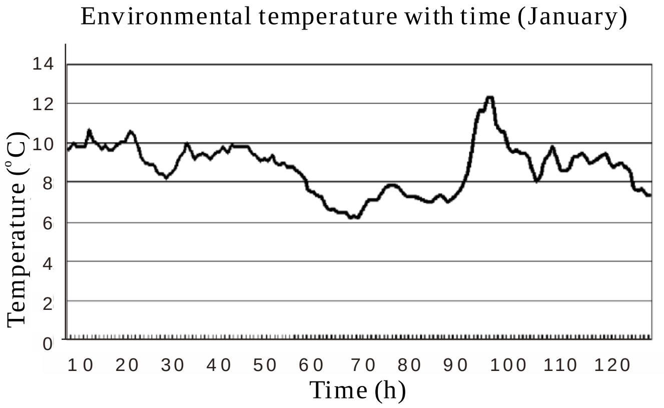

Fig. 4 Typical environmental temperature in January

simulation. Points T5-T8 locate at the boundary, where the influence of cooling circuits should be weak. From the comparison, we can conclude that the approach is accurate enough in prediction of the early age behavoir of real engineering structures.

4. Results for the concrete pier and discussions

A bridge pier at western port area of Shenzhen is included in this study (Fig. 3). To simulate the *in Situ* construction condition, various initial concrete temperatures, different construction seasons in relation to environmental temperatures, and demoulding time tips are considered. The upper part of the pier structure is newly cast fresh concrete, which the hardening and the heat of cement hydration has been simulated, whereas the lower part is the old one, for which only mechanical behaviour is considered. The formwork are placed at the both vertical surfaces the fresh cast concrete pier, whereas the top surface is left free from covering.

4.1 Initial concrete temperature

Suppose the construction is carried out in winter, e.g. January. The measured environmental

Fig. 5 The adiabatic evolution of concrete C35

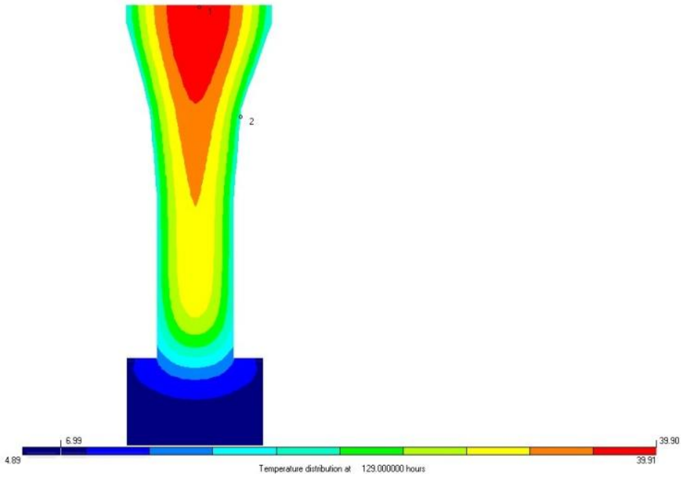
Fig. 6 Temperature distribution at the maximum temperature moment

temperature is typically shown in Fig. 4. The concrete is C35. The adiabatic evolution is shown in Fig. 5, which represents the heat source intensity of the concrete. The formwork is wood, and its removal time is set to 72 hours after casting. To investigate the effect of initial concrete temperature, four cases (5℃, 10℃, 15℃, 20℃) are considered.

For an initial concrete temperature of 5℃, Fig. 6 gives the temperature distribution inside the pier as the maximum temperature is reached. It can be seen that the temperature is decreasing from inside towards the surface. The highest temperature point (Point 1) is located at the top side, which is 39.9℃ at a time of 129 hours.

Fig. 7 gives the major stress distribution at the maximum stress moment for the initial concrete temperature of 5℃. It can be seen that the stresses are increased from core to the outside. The maximum stress point (Point 2) situates at the upper curved parts of the pier. The maximum major stress can be up to 2.096 MPa at a time of 90 hours.

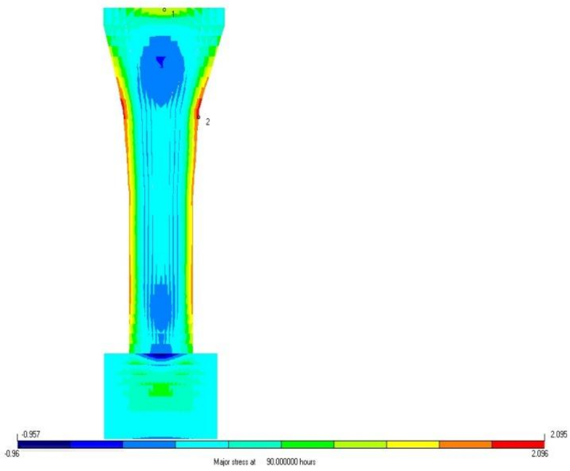
Fig. 7 Major stress distribution at the maximum stress moment

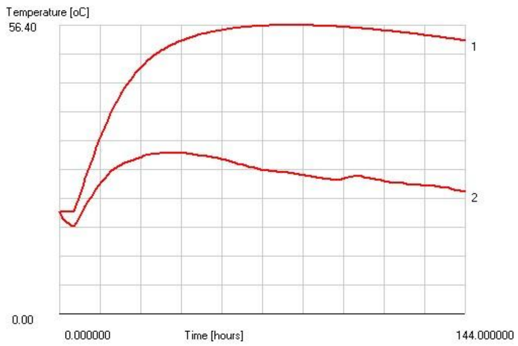

Fig. 8 Temperature evolution for the highest temperature point (1) and the maximum stress point (2)

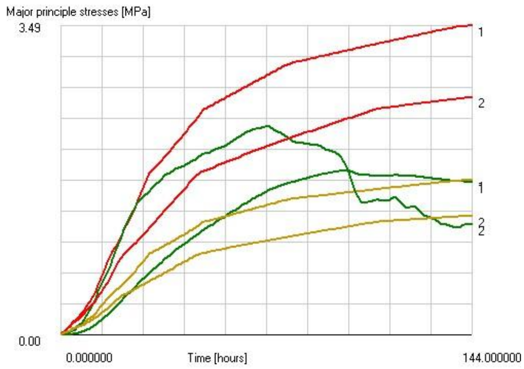

Fig. 9 Major stress evolution for the highest temperature point (1) and the maximum stress point (2)

Figs. 8 and 9 show the temperature and major principal stress evolution, respectively, for the highest temperature point (1) and the maximum stress point (2) for an initial concrete temperature of 20℃. From Fig. 8, it is seen that the concrete temperatures increase to the peak at some time and then go down slowly. However the overall trends are different for point 1 and 2. In Fig. 9, the Green, red, and yellow curves represent the real stress, concrete strength, and the factored concrete strength (with a safety margin), respectively. The concrete strengths increase monotonously, whereas the real major stresses for the two considered points increase to some extent and then decrease. The stress values should locate in a safe limit.

For the four considered initial concrete temperatures (5℃, 10℃, 15℃, 20℃), the temperature and stress distributions inside the pier are quite similar. Table 1 gives the highest temperature and the maximum major stresses and their happening time and positions. It can be seen that both the highest temperature and the major stress are increased with increasing the initial concrete temperature, whereas both the time to occur becomes short. The occurring time for the maximum major stress is earlier than that for the highest temperature. The time variation for reaching the highest temperature (129-81=48h) is larger than that for reaching the maximum major stress (90-72=18h). The maximum major stress occurs to a relatively stable time at about 72-73 hours with increasing the initial concrete temperature from 10-20℃. The highest temperature and the maximum major stress value are obtained for the initial concrete molding temperature of 20℃. The internal temperature and the major stresses obtained are not particularly large in some sense because of a low level of environmental temperature and the initial concrete temperature in winter.

Table 1 Highest temperature and maximum major stress for four initial concrete temperature cases

		Initial concrete temperatures			
		5℃	10℃	15℃	20℃
Heat	Temperature (℃)	39.90	45.28	50.82	56.41
	Time (h)	129	108	93	81
	Position	Top side	Top side	Top side	Top side
Mechanical	Major stress (MPa)	2.10	2.17	2.27	2.37
	Time (h)	90	73	72	72
	Position	Lateral side	Lateral side	Lateral side	Lateral side

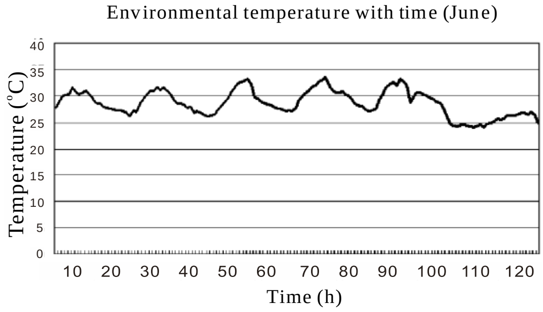

Fig. 10 Typical environmental temperature in June

4.2 Stripping formwork time

To simulate the construction stage, for the formwork of wood, three stripping time tips (48h, 72h, 96h) are considered. Suppose that the construction is carried out in summer, e.g. June. The measured environmental temperature is typically shown in Fig. 10, whereas the waves represent the temperature variation during day and night cycle. The initial concrete temperature is 30℃. The thickness of the formwork is 25 mm; its convection coefficient is 3.3w/m^2k. The convection coefficient of free surface is 6.4w/m^2k.

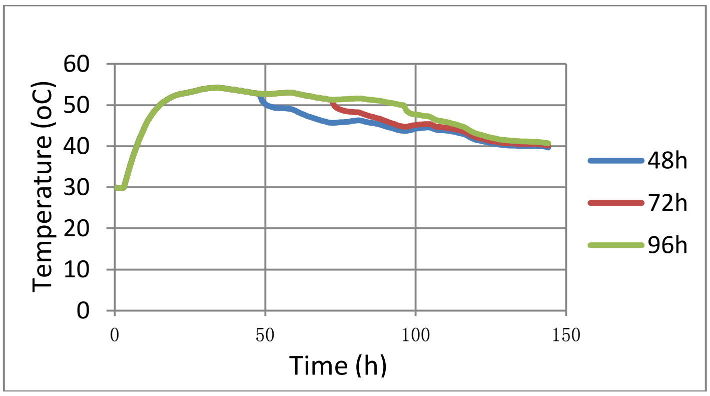

Fig. 11 Concrete temperature evolution under different stripping time

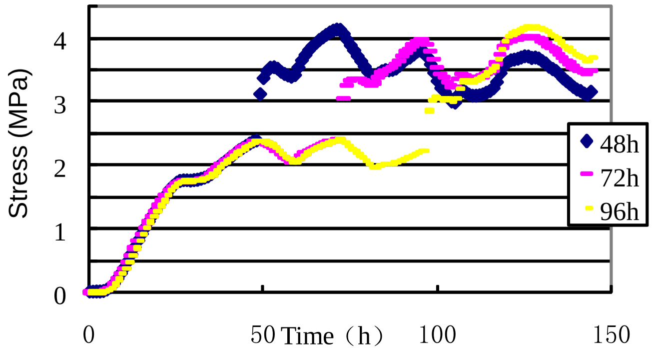

Fig. 12 Variation of stresses under different stripping time

Table 2 Highest temperature and maximum major stress of point 2 under stripping time *(48h, 72h, 96h)*

		Stripping time tips		
		48h	72h	96h
Heat	Temperature (℃)	54.23	54.23	54.23
	Time (h)	34	34	34
Mechanical	Major stress (MPa)	4.15	4.10	4.24
	Time (h)	71	125	128

Figs. 11 and 12 show the temperature and the stress evolution, respectively for point 2 at the various stripping time tips of formwork, namely 48h, 72 and 96h. Table 2 shows the highest value of temperature and major stress and their occurring time. It is seen that due to the removal of formwork, temperature curves have sudden drops at that moment; as stresses have rising gaps. The temperature and the stress show similar trend for the three stripping time tips: The stresses increase monotonously to a certain value, after the gap is reached, the stresses may continuously vary around a steady value. The waves should be due to temperature difference in day and night cycle.

5. Conclusions

The construction of a concrete bridge pier is analyzed for different initial concrete temperatures, and stripping time tips of the formwork. From the results, it is concluded that a high initial concrete temperature could result in a high extreme internal temperature, which causes the early peak temperature and the larger principle stresses. The demoulding time seems to be less important for the chosen study cases. Currently used 72 hours in the construction practice may be a reasonable choice.

It is known that construction execution is very important and often ignored, it is a grey area in the whole building process. Especially, the quality control and assurance is difficult compared to design and others. This paper suggests a real time execution procedure with quality control. The simulation may be carried out before and as execution. The results can be used to guarantee the quality control process. This should be significant from the execution point of view.

For the future research, one is to improve the computing model, it may include more accurate hydration heat model, mechanical model considering hygral effect et al; the other is to combine the simulation with more and more real construction and then present a common procedure under rational quality control approach.

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